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UNCONSOLIDATED SEDIMENTARY AQUIFERS: REVIEW NO 3 - GEOPHYSICAL LOGGING IN BOREHOLES

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Sigatoka River flood plain, Fiji

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Other Reviews available in this Series

1 Design of Boreholes (BGS Technical Report WC/94/27)

2 Borehole Performance Maintenance (BGS Technical Report WC/94/44)

UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

PREFACE

This Review is one of a set of reports prepared as part of a project entitled 'Groundwater Development in Alluvial Aquifers, Project No R5561 (BGS 93/2), under the ODA/BGS Technology Development and Research (TDR) Programme of aid to the developing countries. The project addresses all unconsolidated sedimentary aquifers (UNSAs) not only alluviums.

This particular review describes the application of geophysical logging techniques in boreholes drilled in unconsolidated aquifers.

This review is a compilation of existing knowledge. It is intended to be updated, as appropriate, following the results of research which will be carried out during the lifetime of the project, which is scheduled to run until 1996.

The project is funded by ODA as part of their research and development programme designed to improve living standards and conditions in the world's developing countries.

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A GUIDE TO THE SEDIMENTOLOGY OF UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

INTRODUCTION

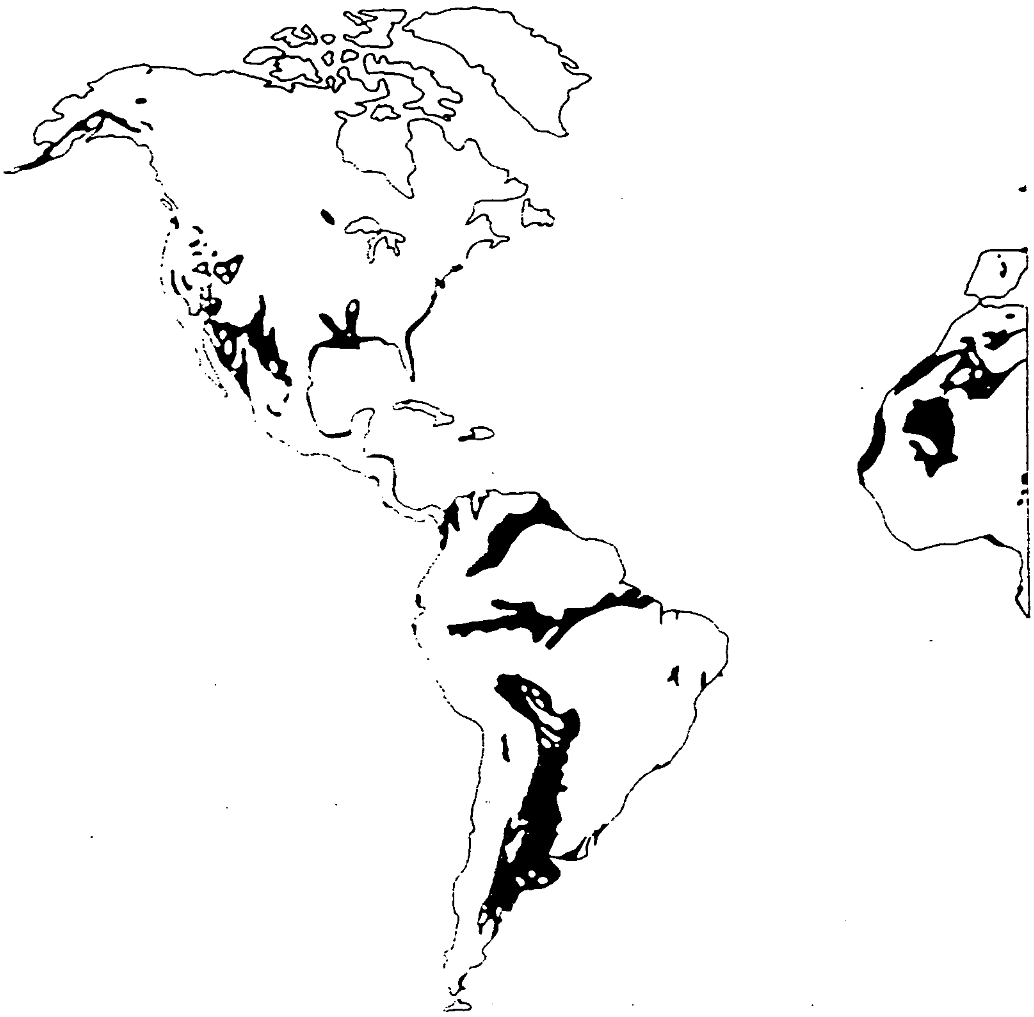
WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

UNSAs are unconsolidated sedimentary aquifers. These are the water-bearing strata within the swathes of unconsolidated sediment that mantle much of the earth's surface. There is no clear dividing line between UNSAs and aquifers in consolidated rocks, as lithification is a gradational process: deposits a hundred years old can be lithified, while some deposits 500 million years old are still essentially unlithified. However, for most purposes, UNSAs can be understood as deposits which have accumulated over the past few million years, that is during Quaternary and Neogene (late Tertiary) time. They are important sources of water in many parts of the world, and in particular constitute the only major sources of groundwater for vast areas throughout the developing world. In the influential text book ***Hydrogeology*** by Davies and De Weist it says:

> *"The search for ground water most commonly starts with an investigation of non-indurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where ground water levels are close to the surface and where, as a consequence, pumping lifts are small. Third, the deposits are commonly in a favourable location with respect to recharge from lakes and rivers. Fourth, non-indurated sediments have generally higher specific yields than other material. Fifth, and perhaps most important, permeabilities are much higher than other natural materials with the exception of some recent volcanic rocks and carvernous limestones".*

To date, though, few attempts have been made to understand the detailed internal structure of unconsolidated aquifers even though such knowledge may be crucial to the long term success of any water development project. This shortcoming is probably the reason why the operational lives of many water boreholes are frequently much shorter than expected.

Understanding of the internal structure or 'architecture' of many types of sedimentary deposit has, however, advanced greatly over the past couple of decades. Part of this research has been academic, but much has been sponsored by the oil industry, so as to better predict the possible location of oil within sedimentary traps. Oil, like water, is most profitably located within bodies of relatively coarse-grained and porous sediment. Thus, there is obvious scope for applying this recently gained understanding to hydrogeological problems. Advances have also been made in the understanding of the geometry of complex 'soft-rock' deposits by the application of



MAJOR AREAS OF UNCONSOLIDATED SEDIMENTARY AQUIFERS WORLDWIDE

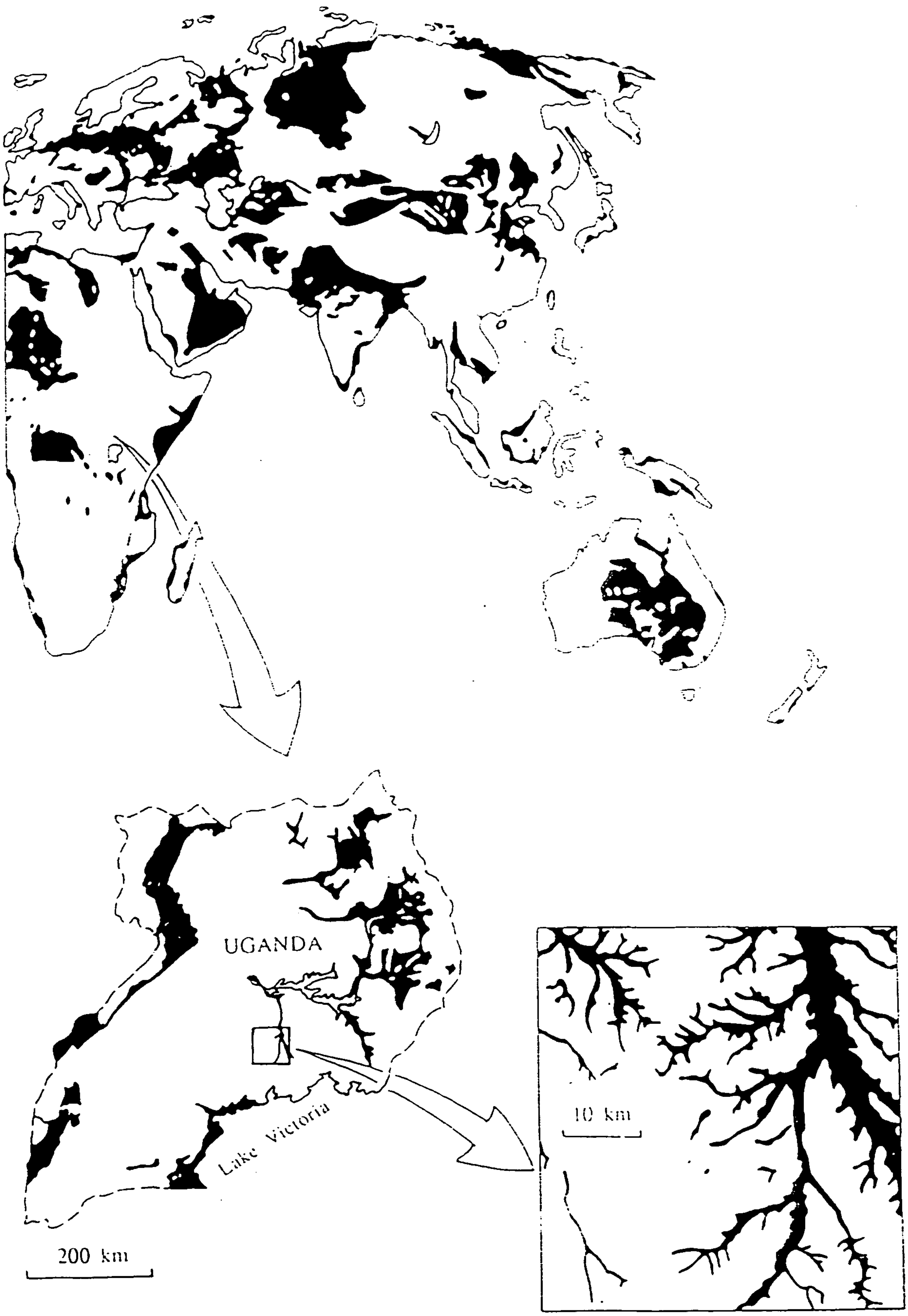
* The map shows the distribution of the thickest and most extensive Quaternary deposits in the world. The great majority of these are unconsolidated, and many include water-bearing deposits (UNSAs).

* A generalised world map such as this, though, severely under-estimates the true extent of UNSAs worldwide. this is because:

  - unconsolidated pre-Quaternary deposits are omitted; these too have a wide distribution, though are difficult to delineate (as they grade into consolidated deposits); they too can include significant UNSAs.

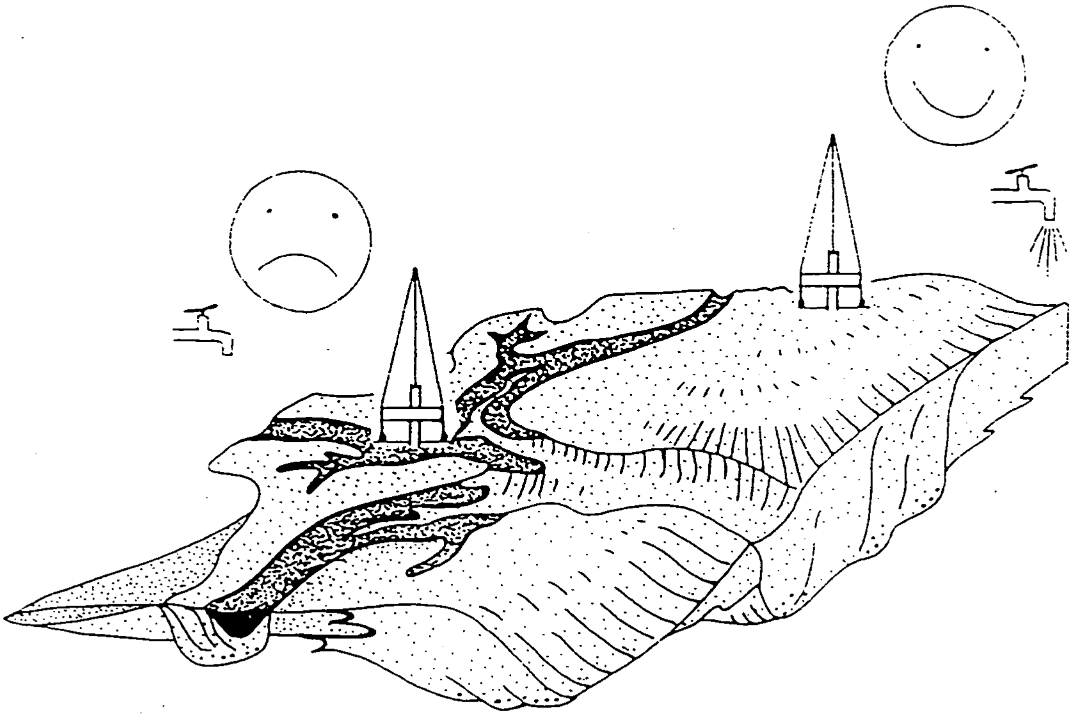
  - the simplification of linework necessary at this scale means that a large proportion of unconsolidated deposits have had to be omitted. The inset map shows the example of Uganda, which seems to have no unconsolidated sedimentats at the global scale, while significant and extensive deposits 'appear' once the country is looked at more closely. At a yet larger scale the unconsolidated sediments appear yet more widespread. The message is clear. *Unconsolidated sediments, and therefore UNSAs, are ubiquitous.*

Diagram data modified from various sources.



UGANDA
Lake Victoria
200 km
10 km

appropriate combinations of investigative techniques, including remote sensing, rapid geophysical methods and new drilling techniques. The combination of these bodies of knowledge can provide a framework for locating and assessing UNSAs.



Sedimentary bodies are characterised by variably complex geometry and internal structure. These properties exert a strong internal control on the location, quantity and quality of groundwater. Diagram adapted from Galloway and Hobday (1983).

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METHODS SUMMARY: GEOPHYSICAL LOGGING IN BOREHOLES

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List of Log Abbreviations Used

Figure	Abbreviation	Explanation
2.2.4	R_{xo}	Flushed zone resistivity
	R_o	Water-saturated formation resistivity
	R_t	True formation resistivity
2.2.5	IL_m	Induction log medium investigation
	IL_d	Induction log deep investigation
	LL-8	Laterolog 8 electrode tool (resistivity)
2.5.3	GR	Gamma ray (cps)
	16RE	16-inch normal resistivity (ohm.m)
2.5.4	AM	Current electrode - potential electrode spacing
	R_a	Apparent resistivity
2.5.5	R_{mf}	Mud-filtrate resistivity
(2.5.15)	R_w	Formation water resistivity
2.5.6	GR1	Gamma ray, open hole, (cps)
	08R-64R	8-16-32 and 64-inch normal resistivity
	CAL	Caliper (in)
	SP	Spontaneous potential (mV)
2.5.12	CNL*	Compensated neutron log
	CPS	Counts per second
3.1.1	GR1 (screen)	Gamma ray log in wellscreen (cps)
	GR (open hole)	Gamma ray log in open hole (cps)
3.4.2	GAM	Gamma ray log (cps)
	SPR	Single point resistance (ohms)
	10FE	Focussed resistivity (guardlog) (ohm.m)
3.4.3	CCL	Casing collar locator
	CAL	Caliper (in)
	NGAM	Gamma ray (cps)

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* *Schlumberger* Trademark

Figure	Abbreviation	Explanation
3.4.8	Focvsd RES	Focussed resistivity (guardlog) (ohm.m)
	Fluid ECQ1	Fluid electrical conductivity whilst pumping (µS/cm)
	Fluid EC	Fluid electrical conductivity non-pumping (µS/cm)
	Fluid TP01	Fluid temperature whilst pumping (°C)
	Fluid Temp	Fluid temperature (°C)
	Diffn ECQ1	Differential ECQ1 (µS/cm)
	Diffn TPQ1	Differential TPQ1 (°C)
3.4.14	GR	Gamma ray (cps)
	DEN	Density (g/cm^3)
	TQ	Fluid temperature whilst pumping (°C)
	FSC	Flowmeter stop counts (cps)
	NØ2	Sound energy level (mV) at 200 Hz and above
	NØ6	Sound energy level (mV) at 600 Hz and above
	N1K	Sound energy level (mV) at 1 KHz and above

GEOPHYSICAL BOREHOLE LOGGING OF UNCONSOLIDATED AQUIFERS

1. AIMS OF THE REVIEW

The following review describes the methods and techniques of geophysical borehole logging that are suitable for investigating unconsolidated aquifers. The aims of the review are:

- to provide an overview of geophysical borehole logging techniques that can be used to study unconsolidated materials,

- to emphasise the value and application of the measurements and to outline some of the limitations imposed by the borehole construction,

- to provide text reference to more detailed information on geophysical logging.

1.1 Background

Geophysical logging is a most cost-effective method of examining subsurface variation in properties within a drilled borehole. It is particularly relevant in unconsolidated materials where samples returned during drilling are often not a reliable guide to the lithological variation existing at depth. Detailed and accurate information is required on the nature and depths of subsurface units during drilling of unconsolidated materials for the purpose of casing, wellscreen and gravel pack design for borehole completion and geophysical logging supplies much of this information. After the wellscreen has been installed geophysical logging is again used to examine the productivity and the effects of development, to identify contributing horizons, and to observe fluid salinity. Geophysical logging is also used in existing screened boreholes to investigate and evaluate lithology variations in yield or fluid salinity which may be due to various causes, including inappropriate design, screen failure, overpumping or contamination.

1.2 Review Structure

The Preface and Introductory Section are common to the series of BGS/ODA technical reports and briefly describe the worldwide occurrence of unconsolidated aquifers and define the scope of other reports in the series. Section 1 describes the aims of the present review of geophysical logging in unconsolidated aquifers. Section 2 sets out the main objectives of geophysical logging programmes that can be undertaken in the open hole borehole during and after drilling, before casing and screening. The main logging techniques that can be applied are discussed and their interpretation is summarised in terms of the geological, hydrogeological and other information they provide, which influence the borehole design and completion. A separate chapter discusses log trends and the interpretation of depositional environment.

Section 3 sets out the main objectives of geophysical logging of completed cased and screened boreholes, summarises the methods that can be used and the limitations imposed by typical constructions. The log measurements are interpreted in terms of the information they provide on construction, contributing horizons, well yields, effects of development and changes in well yield and salinity with time. Section 4 lists topics and log applications worthy of further research. Section 5 provides a list of references, and a generaly bibliography of sources of information on geophysical logging is given in Section 6. The Methods Summary describes features to be aware of when planning and running logging suites and offers comments on log quality controls. This review is different from others in the family of reports in that Method Summary Sheets are not given. Rather, the Methods Summary gives an overview of what is possible. This is done because it is felt the technique is best handled by experts in borehole logging at most levels of planning and implementation.

2. GEOPHYSICAL LOGGING IN OPEN HOLE

Most drilling of unconsolidated aquifers is by the rotary method either using direct circulation mud flush or by reverse circulation water flush. The drilling mud may be a bentonite or polymer fluid and is used to support the borehole wall and to minimise fluid loss to the formation. Application of rotary drilling means that the samples of the perforated strata obtained may not be fully representative of the downhole lithology variation. Alternative sampling strategies such as percussion coring or taking side-wall samples are rather expensive and do not provide a complete record of the lithologies present. Geophysical logging is therefore used widely to provide accurate downhole information on the units penetrated. It is used *a priori* to identify the lithological units and their boundaries but is capable of providing much additional information on the lithology, stratigraphy and physical properties of the penetrated sequence and its contained fluids.

The logging programme undertaken is influenced to some extent by the manner of borehole construction. Boreholes drilled using bentonite or polymer drilling fluid to support their walls may have minimum diameters of 100 mm (4") and are suitable for most logging. Boreholes drilled by reverse circulation technique are likely to have a minimum diameter of 400 mm (~16") and the large diameter influences the logging techniques that can be used and how they are applied. In such large diameter hole corrections are required to the log measurements for quantitative evaluation of the results. These are not always applied and the often uncorrected log data is used in a qualitative manner. In some circumstances it may only be possible to run a gamma ray log inside drillpipe.

Certain logs (e.g. electrical resistivity) may be run before the hole is fully complete usually at intervals during drilling when it is necessary to run casing to support the borehole wall, or to seal excessive circulation loss. However logging is generally run immediately on completion of the drilling, i.e. on pulling the drillpipe. The borehole is then kept full of fluid to maintain a positive pressure to keep the hole open for the logging. With modern combination logging tools run at the speed of the slowest log (usually 5 m/min) a suite of five or six measurements can be typically made in a 100 m borehole in one or two runs in 1-2 hours.

2.1 The Objectives of Open Hole Logging

The objectives of open hole logging are both qualitative and quantitative. Qualitatively geophysical logs are run to distinguish the lithology and identify the boundaries of the subsurface units present. Usually a distinction between permeable and impermeable horizons and between sand and clay lithology, can be made immediately and this allows a preliminary assessment of the sections and depths where blank casing and wellscreen will be required. The units recognised by logging are later compared with the sample lithologies from drilling and in conjunction with grain size information from granulometric analysis of the samples, wellscreen slot width (aperture) and screen intervals are chosen and the design and screen setting depths finalised.

The geophysical logs may be interpreted quantitatively to determine the lithology, the clay content percentage, the porosity and the pore fluid salinity. They may also provide an estimate of the hydraulic conductivity. By pattern recognition of various log shapes and study of the vertical sequence, the logs may be used to interpret the depositional environment.

2.2 The Logging Environment

An undisturbed formation environment does not exist in a drilled borehole. The formation is disturbed by the drilling and the borehole itself is a disturbing element for the log measurements because it represents a missing portion of the formation. Thus all geophysical log measurements are an attempt to measure the in-situ formation properties. The log measurements are variously influenced by the borehole diameter, the fluids used for drilling, their relative invasion of the formation pore fluid, and at times limitations of the logging probes in making the physical measurements. Certain log measurements are more strongly influenced by these environmental effects and corrections are made to account for these influences.

2.2.1 Disturbances created by drilling

During rotary drilling the pressure of the drilling fluid is kept in excess of the formation pressure to keep the borehole stable and to avoid rapid degradation of quality of the drilling fluid. Where porous and permeable horizons are encountered the drilling fluid therefore moves into the formation. The porous rock acts as a filter and separates the drilling fluid into its liquid and solid constituents. The drilling mud filtrate therefore flows into the formation leaving the solid constituents: clays, silts, sand and cuttings deposited on the well face as a mudcake (Figure 2.2.1). The excess pressure of the drilling fluid can also create hole enlargements where soft layers are washed out. Conversely certain clay horizons may absorb water and expand thus reducing the diameter to less than that of the drillbit size. In practice boreholes rarely remain the same diameter as the drill bit (Figure 2.2.2).

Drilling fluid invasion

The replacement of the formation fluids in porous and permeable zones by drilling fluid is known as invasion. The invasion process is halted when the mudcake solids

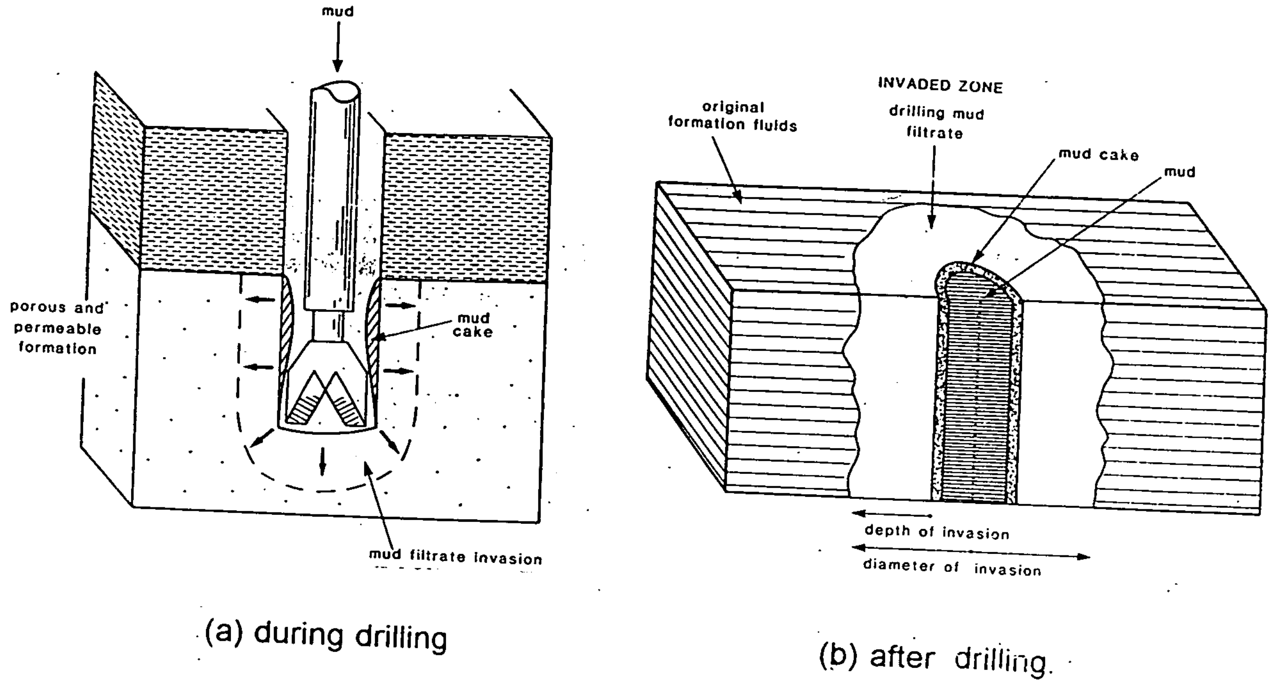


Figure 2.1.1 Schematic representation of invasion (after Rider, 1986).

become sufficiently thick and impermeable to seal the fluid loss. Excessive fluid loss (lost circulation) may require special materials to be added to the drilling fluid to form an effective seal. The mudcake which forms alongside the porous and permeable zones may be only a millimetre or several centimetres thick. Thick mudcake can be recognised by geophysical logging where it is seen as smooth-walled sections narrower than drill bit size on caliper logs (Figure 2.2.2).

The distance reached by the invading fluid is referred to as the invasion depth and may be only a few centimetres to in excess of 2 m. It is deepest in low porosity high permeability zones when high water-loss muds are used, and is least in high porosity, low permeability materials drilled with a low water-loss (viscous) drilling fluid (Table 1).

Hole diameter (in) (mm)	**17½ 445**	**12¼ 311**	**8½ 216**	**Ratio invasion diameter:hole diameter**
Porosity (%)	**Depth of invasion (cm)**			
1-8	200.0	140.0	97.0	10
8-20	90.0	62.0	43.0	5
20-30	22.5	15.5	11.0	2
30+	≈3.0	≈2.0	≈1.7	<2

Table 1. Guide to depth of invasion for different porosities
(after Miesch and Albright, 1967).

Washouts and clay squeezing

If the invading fluid is less saline than the pore fluid certain clays present may absorb filtrate and swell. This is known as swelling or sloughing and is helped by stress relief into the drilled void. The squeezing horizon may then interfere with the logging or may interfere with access to the borehole for running wellscreen.

Sections of much larger diameter than drill bit size are generally caved or washed out. These effects are recognised by caliper logging and may be associated with a particular lithology or grain size.

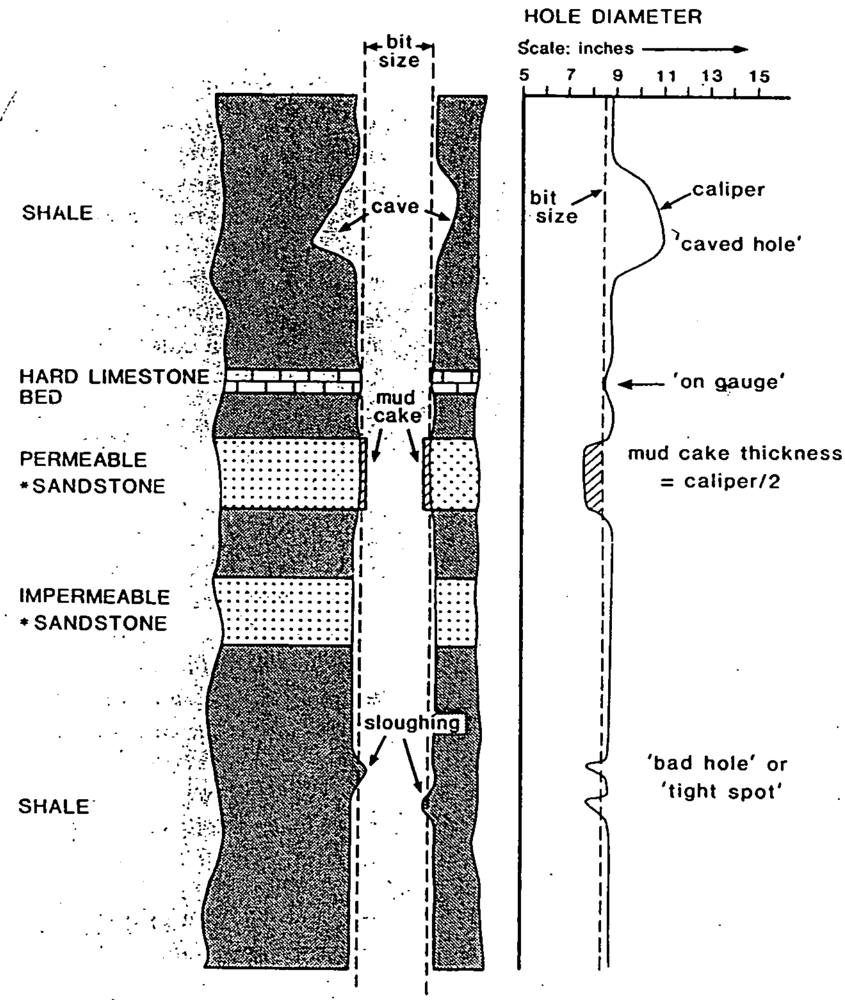


Figure 2.2.2 Schematic caliper log in mud drilled borehole (from Rider, 1986).

Environmental effects on log responses

The borehole void, its shape and diameter and the presence of fluid invasion affect the log measurements made because they are all part of the measurement volume of the logging tool. The magnitude of the effect depends upon the particular measurement and the type of logging tool used. Omnidirectional tools that are free-swinging are commonly used and are most strongly affected whilst wall-contact pad-type logging tools are least influenced by the environmental factors. In petroleum logging where quantitative interpretation of the log measurements is crucial a wide range of environmental corrections are made (Table 2).

Measurement	Correction	Origin
Neutron Porosity	Borehole size Temperature Pressure Standoff Lithology Salinity Cement/casing	Experimental and extension by mathematical modelling
Laterolog	Oval hole centered Cross corrections Shoulder/no invasion Shoulder/invasion Dip Gröningen	Mathematical modelling 3-D mathematical modelling Mathematical modelling Mathematical modelling Mathematical modelling Approximation
Induction	Borehole conductivity Shoulder/no invasion Shoulder/invasion Dip Cross corrections	Mathematical modelling Mathematical modelling Mathematical modelling Mathematical modelling Mathematical modelling
Density	Mudcake P_e on density Hole size Pad tilt Mudcake on P_e Boundary shape	Experimental and extension by mathematical modelling
Spectral gamma ray	Borehole, no barite Casing, water in annulus No barite Barite Casing, barite Potassium mud	Experimental
Microlaterolog	Mudcake Hole size Tilt/channelling Anisotropy	Mathematical modelling

Table 2. Some environmental corrections applied to log data in petroleum logging. (from Theys, 1991)

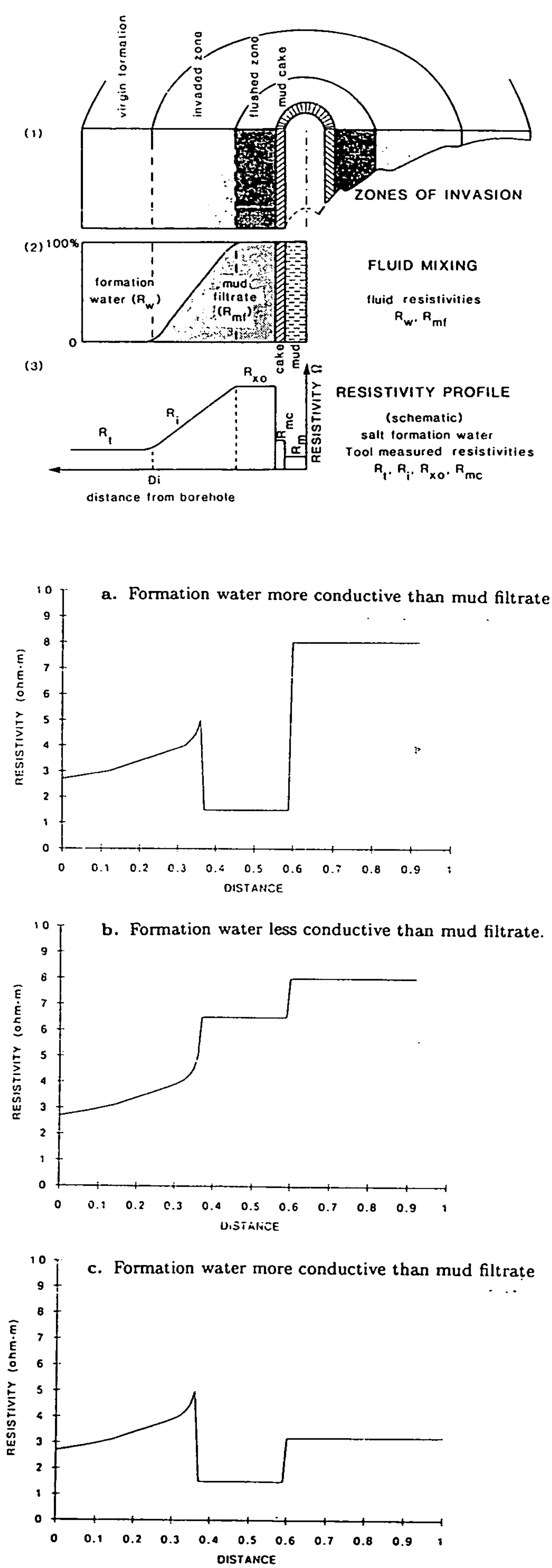


Figure 2.2.3 Schematic zones of invasion and resistivity profiles (after Theys, 1991).

When logging for hydrogeological purposes in unconsolidated aquifers such comprehensive corrections are not routinely applied and the measurements are often used only qualitatively. The main environmental influences on log measurements in unconsolidated materials are fluid invasion which is often only slight because of general high porosity, and the effects of large diameter because of the need to log in large diameter reverse-circulation drilled holes or to accomodate washouts. The effects are most pronounced on electrical resistivity and porosity log measurements.

Electrical resistivity logging is a common technique used to examine lithology and pore fluid properties. Invasion of the drilling fluid introduces an unwanted resistivity variation surrounding the drilled borehole and becomes included in the log measurement. The resistivity variations arising from invasion can be depicted by a graph of resistivity versus distance from the borehole and vary depending upon the relative fluid salinities (Figure 2.2.3). For this reason resistivity tools have different depths of penetration to investigate the resistivity of the different zones.

Unconsolidated aquifers tend to be drilled using freshwater based drilling fluid and the formation pore fluids at shallow depth are usually fresh or brackish. The resistivity of the invaded zone immediately surrounding the borehole is therefore usually similar to or higher than the pore fluid resistivity of the undisturbed formation. By using resistivity logging tools having differing depths of penetration, the individual zones surrounding the borehole can be measured and the influence of invasion observed (Figure 2.2.4). For example, if saline pore fluid is present in a freshwater drilled borehole it can be recognised by a lower resistivity of a deeper reading resistivity device (e.g. 64 inch normal, deep induction), relative to a shallow reading device (e.g. 16 inch normal resistivity, ILm, Figure 2.2.5).

The effect of isolated hole enlargements or washouts is to increase the contribution from the borehole void volume surrounding the probe. Depending upon the borehole fluid properties this usually leads to a decreased resistivity and an anomalously low density. Log measurements can be corrected to compensate for diameter changes within a certain range usually up to but not exceeding 400 mm (16"). When borehole diameter increases the log measurements become less representative of the true formation physical properties.

In large diameter holes exceeding 400 mm (16") typical of reverse circulation drilling, various precautions must therefore be taken for the logging. Omnidirectional tools should be either deliberately run along the borehole wall (sidewalled) by use of a bowspring decentraliser or a single-arm decentralising caliper (particularly density, neutron, sonic measurements) or they should be deliberately centred, e.g. induction, focused resistivity measurements. Such measurements are qualitative and ideally contact pad device logging tools where the sensors are mounted in an arm pressed against the borehole wall should be used in diameters exceeding 16 inches (400 mm). These are commonly used in oilwells but are not in routine use in hydrogeological applications.

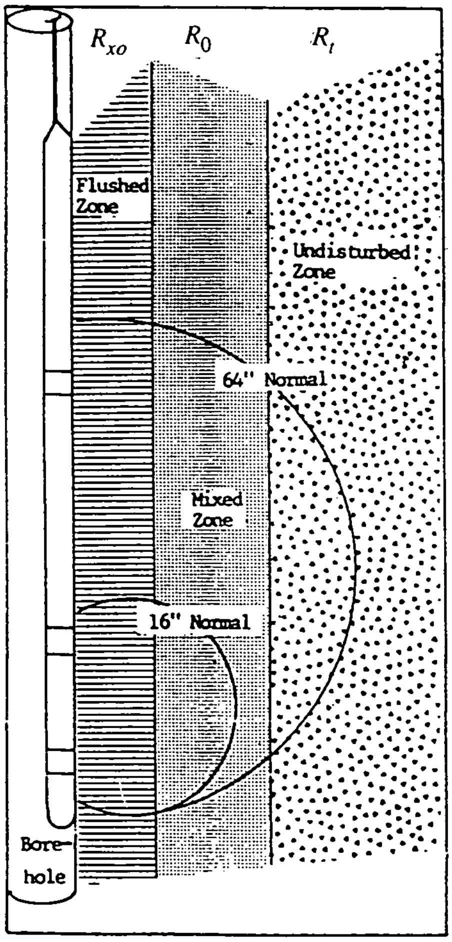


Figure 2.2.4 Representation of different depths of investigation of a 16 and 64 inch normal resistivity tool (from IAEA, 1982).

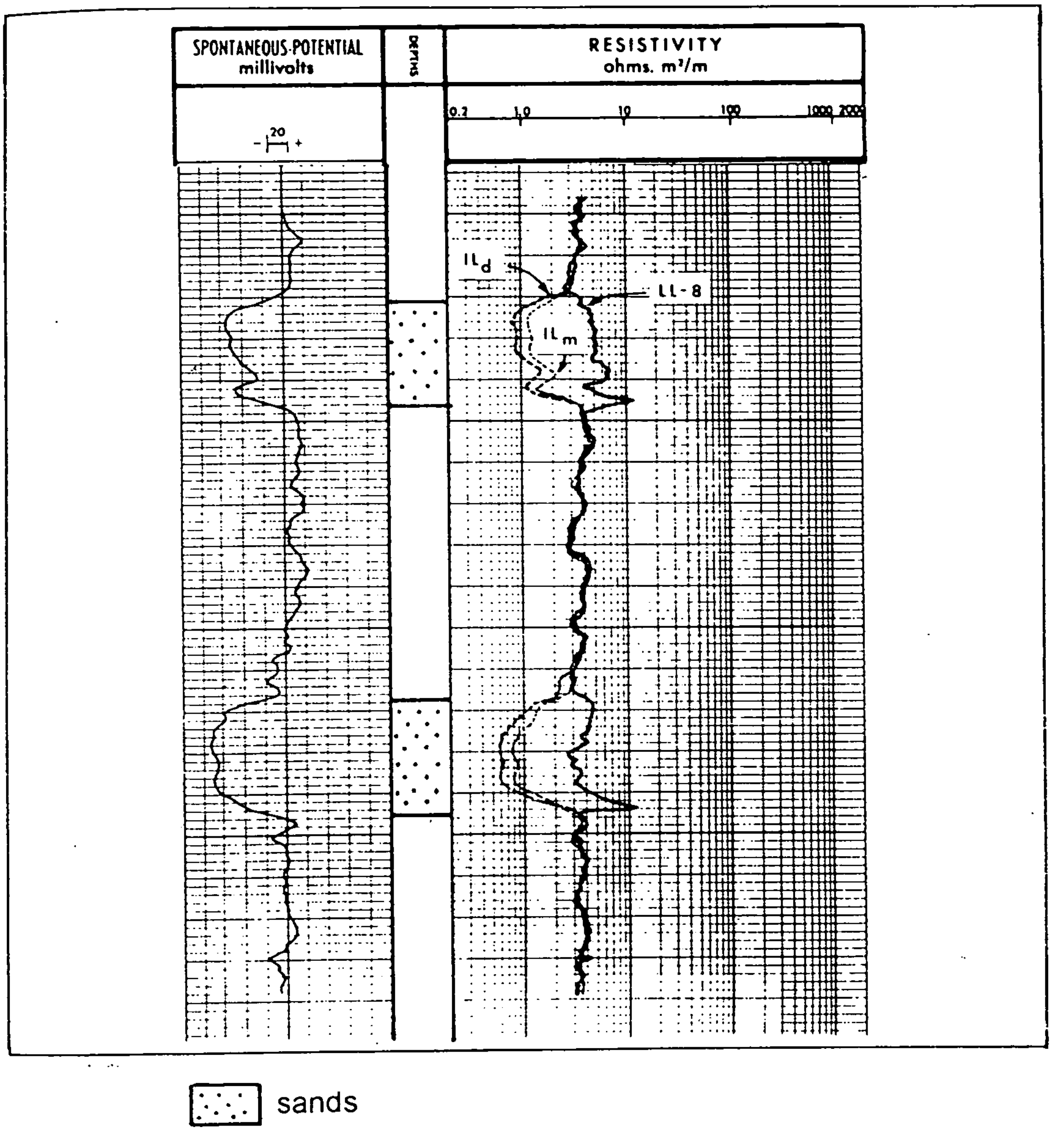


Figure 2.2.5 Saline-saturated sands in a freshwater mud drilled borehole identified by resistivity and SP logs (from Dewan, 1983).

2.3 Suitable Logging Tools

Most unconsolidated aquifers drilled to shallow depths (~100 m) are logged with hydrogeophysical type logging equipment rather than petroleum logging tools. Hydrogeophysical logging tools are slim diameter (usually $1^{11}/_{16}$ inches) and are lightweight (<50 kg), though robust and heavy enough to cope with drilling mud and squeezing clays. For details of slimline tools suitable for use in hydrogeophysical and other shallow logging applications see for example IAEA (1982), Brandon (1986) and Repsold (1989).

Petroleum logging tools on the other hand are designed for great depth, temperatures and pressures in the environment where oil is found. They are therefore large and heavy ($3^{5}/_{8}$ inch diameter, 50+ kg) and often have large sensor spacings (Table 3). They are not as well suited to shallow unconsolidated material logging. Slimline petroleum logging tools designed for restricted access in production boreholes (production logging tools) are however better suited and are sometimes used in water boreholes. For details of typical petroleum logging tools see for example Desbrandes (1985).

2.4 The Logging Methods

Geophysical logging methods are not referred to in a standard way. The techniques may be referred to by the nature of the physical measurement (e.g. gamma ray, neutron, electrical resistivity) or the measuring device (e.g. caliper, flowmeter, dipmeter) or by the trade name (e.g. Laterolog-8, Densilog, Microlog). There are however three basic physical measurements:

1. Measurement of radiation, e.g.

    - gamma ray
    - neutron
    - density

2. Measurement of electrical properties, e.g.

    - electrical resistivity
    - induction
    - spontaneous potential

3. Measurement of acoustic properties, e.g.

    - sonic velocity
    - sonic amplitude (CBL)
    - televiewer

Some measurements are hybrid or outside these categories, e.g.

- caliper
- borehole television
- borehole flowmeter

Type	Outside Diameter		Minimum Borehole Diameter		Maximum Pressure[1]		Maximum Temperature		Length		Mass	
	mm	"	mm	"	MPa[1]	psi	°C	°F	m	ft	kg	lb
D.IND[2]	92	3⅝	146	5¾	124.2	18000	176	350	7.82	25'8"	152.4	336
D.IND[2]	86	3⅜	114	4½	172.5	25000	204	400	7.24	23'9"	136	300
DLL[2]	8	3⅜	146	5¾	138.0	20000	204	400	8.84	29"	158	350
CNL[3]	86	3⅜	127	5	138.0	20000	204	400	2.30	7'6"	60	132
CNL[3]	43	1 11/16	50[4]	2	113.8	16500	176	350	6.86	22'6"	45	100
CNL[3]	70	2¾	108[5]	4¼	172.5	25000	260	500	3.86	12'8"	72	158
FDC[3]	92	3⅝	152	6	138.0	20000	176	350	4.01	13'2"	158	349
PN	43	1 11/16	50[4]	2	113.8	16500	162	325	7.70	25'3"	47	103
FDC[3]	70	2¾	108[5]	4¼	172.5	25000	260	500	3.12	10'3"	73	162

(1) 1 MPa = 10 bars
(2) Dresser Atlas data
(3) Schlumberger data
(4) Logging tools which can be "pumped", minimum inside diameter of drillpipes or tubing
(5) High-temperature logging tools

D.IND: Dual Induction; DLL: Dual Laterolog; CNL: Compensated Neutron Log; FDC: Compensated Formation Density; PN: Pulsed Neutron

Table 3. Some typical petroleum exploration logging tools (from Desbrandes, 1985)

The main geophysical logging techniques used in hydrogeological studies are shown in Table 4 which lists the various techniques, summarises the principles of the measurements and describes the main limitations of the methods in both consolidated and unconsolidated formations.

Geophysical borehole logging is very much a specialist activity and in unconsolidated materials the information obtained directly affects the design of the borehole and the wellscreen. Furthermore there is often only one opportunity for open hole logging and it is recommended therefore that the log acquisition and interpretation in unconsolidated materials be undertaken by specialists.

Summary method sheets describing the main logging methods for hydrogeologists have therefore not been prepared and the reader is referred to the bibliography in Section 6 for specialist information on the various logging techniques, running logs, their measurement principles, calibration and disturbing influences on the measurements. Instead a Methods Summary has been written to describe important aspects of logging programs, running geophysical logs and various log quality control checks to be aware of when logs are run to ensure reliable and representative measurements are made by the logging contractor.

2.5 Geophysical Log Interpretation

It is becoming more widely recognised that subsurface information can be more readily appreciated when it is displayed graphically as in the form of a geophysical log, rather than as a listed sample description. In early log interpretation absolute log values were not critical, it was the relative shape and differences on logs which permitted geologists to recognise formation boundaries and make a qualitative assessment of the lithology. Where simple log shapes could be recognised in several boreholes, a correlation of the layers could be made to provide a framework of the subsurface layering and structure.

Geophysical logs are physical measurements of the rock and fluid properties and they may be analysed quantitatively. This is routine in petroleum logging where the aim is to identify the hydrocarbon volume in place in the reservoir. Geophysical log measurement in petroleum exploration are therefore mainly standardised, routinely corrected for environmental factors and carefully calibrated so that they may be used quantitatively. Outside of petroleum practice there is not a comparable standardisation of the measurements, and there are fewer log corrections and calibrations. This may be because the logging objectives are wider, or not so clearly defined, or because the budgets are much less. However with modern digital data acquisition hydrogeophysical logging is becoming increasingly quantitative and of better quality.

In unconsolidated aquifers the **qualitative** interpretation of logs is concerned mainly with identifying rock lithology and layer boundaries for the purpose of wellscreen design and borehole completion, and **quantitative** interpretation is concerned with calculation of:

- clay content
- lithology

LOG TYPE		Measurement	Units	Dry hole	Open hole ⊗		Steel cased or screened ⊗		non-metallic cased or screened ⊗		Main purposes
					unconsolidated	consolidated	unconsolidated	consolidated	unconsolidated	consolidated	
CALIPER	o	borehole or casing diameter	mm, inches	✓	✓	✓	✓	✓	✓	✓	Borehole diameter, relative hardness, lithology, confirm construction features, log corrections
GAMMA RAY	o	total radiation of gamma rays	cps, API	✓	✓	✓	*(1)	*(1)	*(1)	*(1)	Determine lithology, particularly sand/clay indication, clay content, correlation of strata
SINGLE POINT RESISTANCE	o	relative resistance of formations, symmetrical response	ohms	-	✓	✓	-	-	*(2)	*(2)	Determine approximate lithology, sand/clay, correlation of strata
SPONTANEOUS POTENTIAL	o	imbalance of ion concentration in borehole fluid	mV	-	✓(3)	✓(3)	-	-	-	-	Porosity and permeability indicator, relative sand/clay indicator, fluid salinity
ELECTRICAL RESISTIVITY	o	resistivity of formations near borehole	ohm.m	-	✓	✓	-	-	*(4)	*(4)	Relative lithology indicator, correlation of strata, fluid salinity
(i) 16, 64 inch normal		short to medium penetration, asymmetrical response	ohm.m	-	✓	✓	-	-	*(4)	*(4)	Near to far invaded zone resistivity, lithology indicator, correlation of strata
(ii) focussed resistivity		absolute resistivity of formations, deep penetration, symmetrical response	ohm.m	-	✓	✓	-	-	*(4)	*(4)	Deep reading, true formation resistivity measurement. Lithology indicator, correlation
(iii) micro-resistivity		resistivity of immediate vicinity of borehole using contact pad devices	ohm.m	-	✓	✓	-	-	-	-	Borehole wall and near-invaded zone resistivity measurement, fracture indicator
INDUCTION		measurement of rock conductivity	mS/m	✓	✓	✓	-	-	✓	✓	Determination of true, moderate (<100 ohm.m) to low resistivity in all holes except steel lined
DENSITY		scattered gamma ray population (~ electron density)	cps, g/cm³	-	✓	✓	(5)	*(5)	*(5)	*(5)	Determination of formation bulk density, porosity, lithology
NEUTRON POROSITY		thermal neutron or capture gamma ray population	cps, % matrix porosity	-	✓	✓	*(1)	*(1)	*(1)	*(1)	Determination of porosity lithology, fluid level, position of plastic casing
SONIC VELOCITY		acoustic velocity	m/s, μs/ft	-	*(6)	✓	-	-	-	-	Determination of rock porosity, fracturing and relative lithology
CEMENT BOND LOG		acoustic amplitude	% bond	-	-	-	✓	✓	-	-	Monitoring the intensity of casing cementation
CASING COLLAR LOCATOR		flux variation of an open electromagnetic array	-	-	-	-	✓	✓	-	-	Location of collars and joints in steel casing and well screen
FLUID CONDUCTIVITY	o	resistivity or conductivity of borehole fluid	μS/cm	-	✓	✓	✓(7)	✓(7)	✓(7)	✓(7)	Determination of fluid salinity, identifying fluid inflow and fluid movement
FLUID TEMPERATURE	o	temperature of borehole fluid	°C	-	✓	✓	✓*(7)	*(7)	*(7)	*(7)	Determination of geothermal gradient, identifying fluid inflow and fluid movement
FLUID FLOWMETER	o	velocity of fluid in the borehole	m/s, mm/s	-	-	✓(8)	*(8,9)	*(8,9)	*(8,9)	*(8,9)	Determination of water inflow and outflow and relative contributions to yield of different layers
FLUID SAMPLER		sampling of fluid at depth	volume	-	-	✓(8)	*(8,9)	*(8,9)	*(8,9)	*(8,9)	Taking water samples from specific depths
INCLINATION		gravitational, magnetic field strengths and directions	tilt and azimuth	✓	✓	✓	-(10)	-(10)	-	-	Determination of spatial position and tilt of borehole
DIPMETER		high resolution micro resistivity	dip and azimuth	-	*(11)	✓	-	-	-	-	Determination of dip and strike of bedding, identifying fractures and fissures
BOREHOLE VIDEO		Optical, borehole television images	-	✓	-	✓(12)	✓(12)	✓(12)	✓(12)	✓(12)	Observe lithology, borehole construction, fluid inflows

⊗ water or mud drilled
o frequently used method
✓ no limitations
* some limitations

cps : counts per second
API : American Petroleum Institute gamma ray unit

(1) - attenuated by high density material, e.g. casing, or large diameter.
(2) - resistance profile possible in plastic screen. Can identify slotted and blank sections.
(3) - SP development requires contrast in salinity between borehole and formation fluids, not always seen in waterwells.
(4) - resistivity profile possible in plastic screen. No quantitative interpretable possible. Includes invaded zone.
(5) - shallow investigation depth may only read properties of the gravel pack.
(6) - matrix velocity uncertain in unconsolidated materials hence porosity estimates poor.
(7) - fluid EC change in borehole fluid may be influenced by screen slot positions.
(8) - natural fluid movement or whilst pumping.
(9) - construction features may give false indication of inflow.
(10) - magnetic measurements not possible in steel cased holes.
(11) - sharp changes in microresistivity not always present.
(12) - requires clear water or empty (dry) holes.

For measurements with omnidirectional tools, optimum hole diameter is 100-200 mm (4-8 inches) and maximum hole diameter is 500 mm (20 inches) except for neutron, density and sonic methods where recommended maximum diameter is 300 mm (12 inches)

TABLE 4. Summary of the main geophysical logging techniques used in hydrogeological studies.

- porosity
- pore fluid salinity
- estimation of hydraulic conductivity

2.5.1 Qualitative interpretation

Direct information on the subsurface lithology is furnished by the samples collected during drilling and from the mud log record of the well prepared by the geologist. This information may be supplemented by other measurements e.g. drilling penetration rate, and can be compared with the geophysical log data.

Gamma ray (GR)

The lithological record from cuttings obtained from rotary drilling is often not reliable because of mixing, loss of circulation, and in deeper boreholes the delay in arrival time at the surface. Geophysical logs provide more reliable information on the formations and their boundaries. A comparison of lithology deduced from cuttings and from geophysical logging is shown in Figure 2.5.1.

The gamma ray log is particularly useful in unconsolidated materials. It has a universal application and can be used in open holes and empty (air-filled) holes, and in cased and screened holes. It is most often used to identify lithological variation, the formation boundaries, as well as clay content and an approximate grain size indicator. It is also useful for correlation purposes.

The gamma ray log is of particular value in unconsolidated materials because the radioactive elements responsible for the gamma ray activity are naturally concentrated in clay minerals which are found in the finer-grained units. They are less abundant in medium- and coarse-grained sediments. The log can therefore be used directly to differentiate sand and clay units and to calculate clay percentage (Figure 2.5.2).

Electrical resistivity (RES)

Electrical resistivity log measurements investigate the resistivity of the formation surrounding the borehole. The measurement is influenced by the matrix material and salinity of the pore fluid. Depending on the logging tool used, the measurement may reflect the invaded zone resistivity or read deeper into the undisturbed formation beyond the invaded zone. Resistivity logs are only possible below fluid level and cannot be made in empty (dry) holes. Nor can they be run inside steel or plastic cased holes although a measurement is possible "through" slotted plastic wellscreen. Induction conductivity logs may be run instead in empty (air-filled) and plastic-lined boreholes to provide resistivity (conductivity) information on layers above the watertable or behind plastic casing.

The value of electrical resistivity logs in unconsolidated materials is that they provide much information on the grain properties and they usually complement the gamma ray measurements (Figure 2.5.3). Clay-rich high gamma layers tend to be electrically conductive and therefore of low resistivity, whilst coarse clean sand units containing freshwater tend to be high resistivity and low gamma ray. These logs are therefore

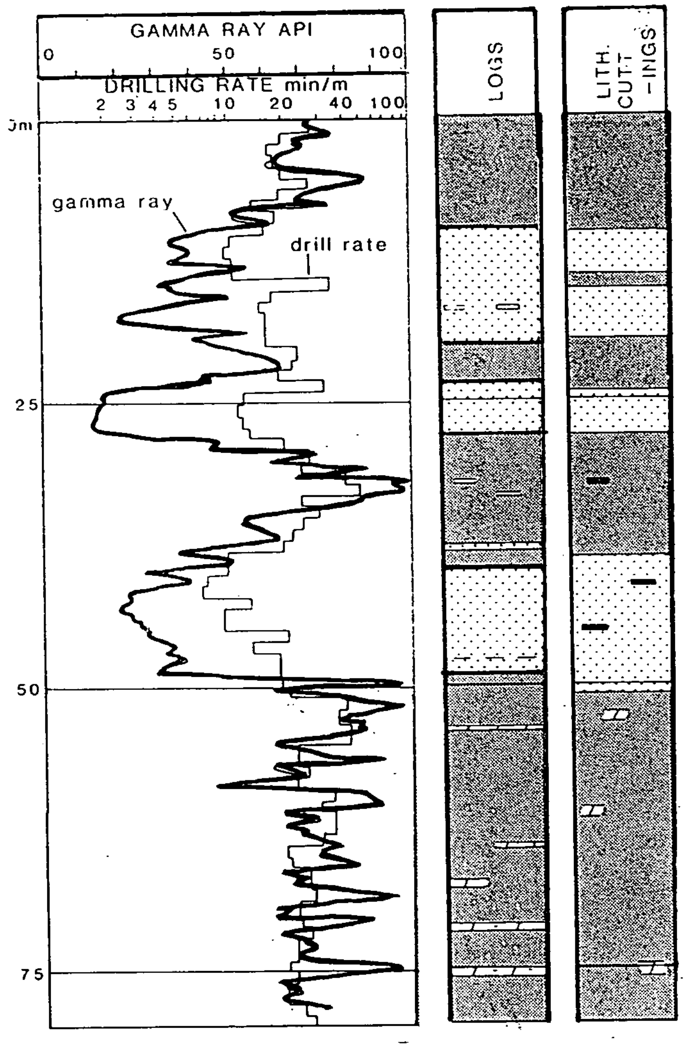


Figure 2.5.1 A geophysical log, penetration rate and mud logging information (from Rider, 1986).

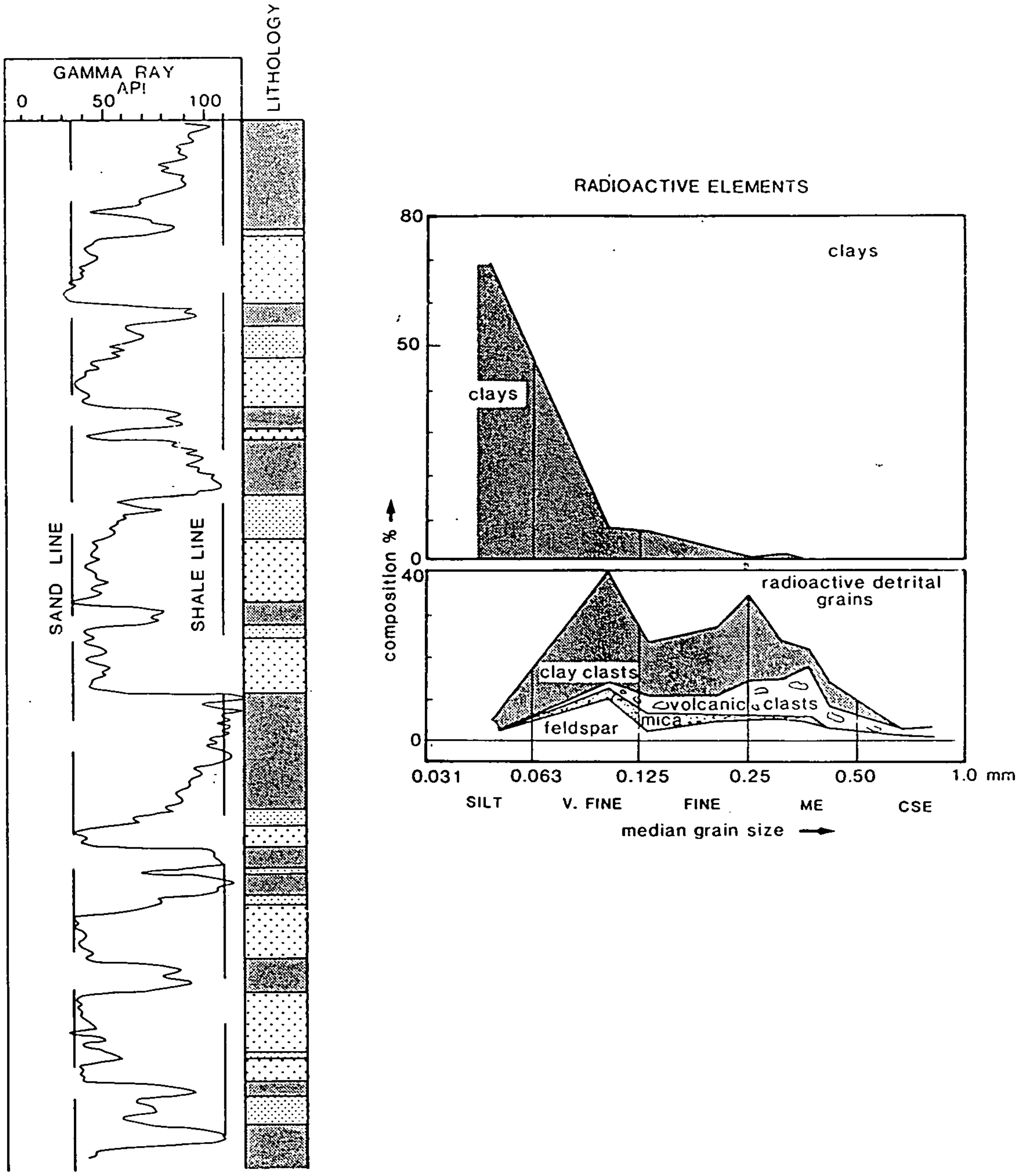


Figure 2.5.2 Gamma ray log in deltaic sand/clay sequence and typical concentration of radioactive elements in the finer-grained fractions (after Rider, 1986).

often approximate mirror-images. The resistivity log is also influenced by pore fluid salinity whilst the gamma ray is not, so that changes in salinity of pore fluid can be observed where the gamma ray log signifies this is not due to a change in clay content.

A drawback of multi-electrode electrical resistivity logs is that the curves produced have certain shapes that are due to the electrode configuration of the probe rather than due to changes in formation property. The ratio between bed thickness and electrode separation and the actual resistivity contrast between adjacent layers all influence the curve shape obtained (Figure 2.5.4). Multi-electrode resistivity logs therefore need to be interpreted with care. Certain resistivity tools have a symmetrical response to bed boundaries, e.g. focussed resistivity, induction, or point resistance measurements and these are to be preferred. Resistivity measurements respond to subtle changes in lithology and provide a detailed log of the variation. They are valuable logs for correlation purposes provided one is aware the curve shape can be influenced by change in fluid salinity.

Spontaneous potential (SP)

The penetration of porous and permeable formations by the borehole, and fluid invasion of the formation by the drilling fluid can induce chemical gradients and hydraulic flow between different layers which promotes an unbalanced distribution if ions in the borehole fluid. The imbalance is measured as the potential difference between an electrode in the fluid (downhole) and a reference electrode of similar material at the surface and is referred to as the spontaneous potential or SP. SP's are entirely passive, no current is applied and they may be several millivolts to several volts.

In petroleum logging SP logs are important logs and are used *a priori* to identify porous and permeable zones, to calculate formation water resistivity and to determine bed thickness and identify oil, water and gas contacts. They also tend to have similar shapes over large areas and can be useful for correlation purposes.

By contrast, in hydrogeophysical logging SP logs are often surprisingly dull, featureless and not very useful. This is because in freshwater-saturated formations there is often little or no contrast in salinity between the drilling fluid (fresh) and the formation pore fluid (fresh) especially at shallow depth to generate significant SP deflections. In petroleum logging the well-developed SP's are usually developed in sand-shale sequences saturated in NaCl brine and salinity contrasts are large.

Three factors are required to generate an SP deflection:

i) Porous and permeable beds surrounded by different or impermeable beds.

ii) Conductive fluid in the borehole.

iii) A difference in salinity between the borehole and formation fluids.

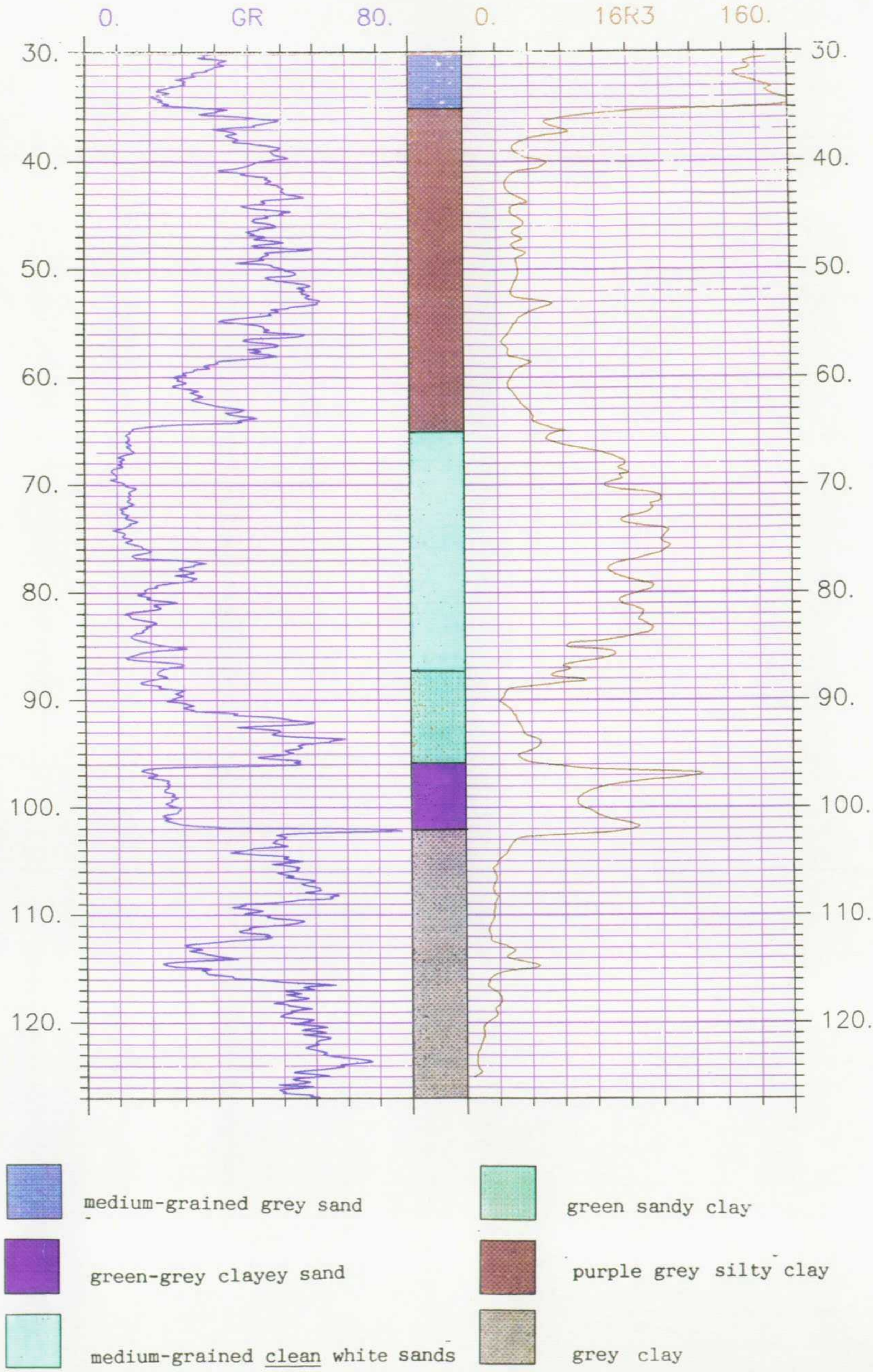


Figure 2.5.3 Gamma ray and resistivity logs showing mirror-image responses in a sand/clay sequence.

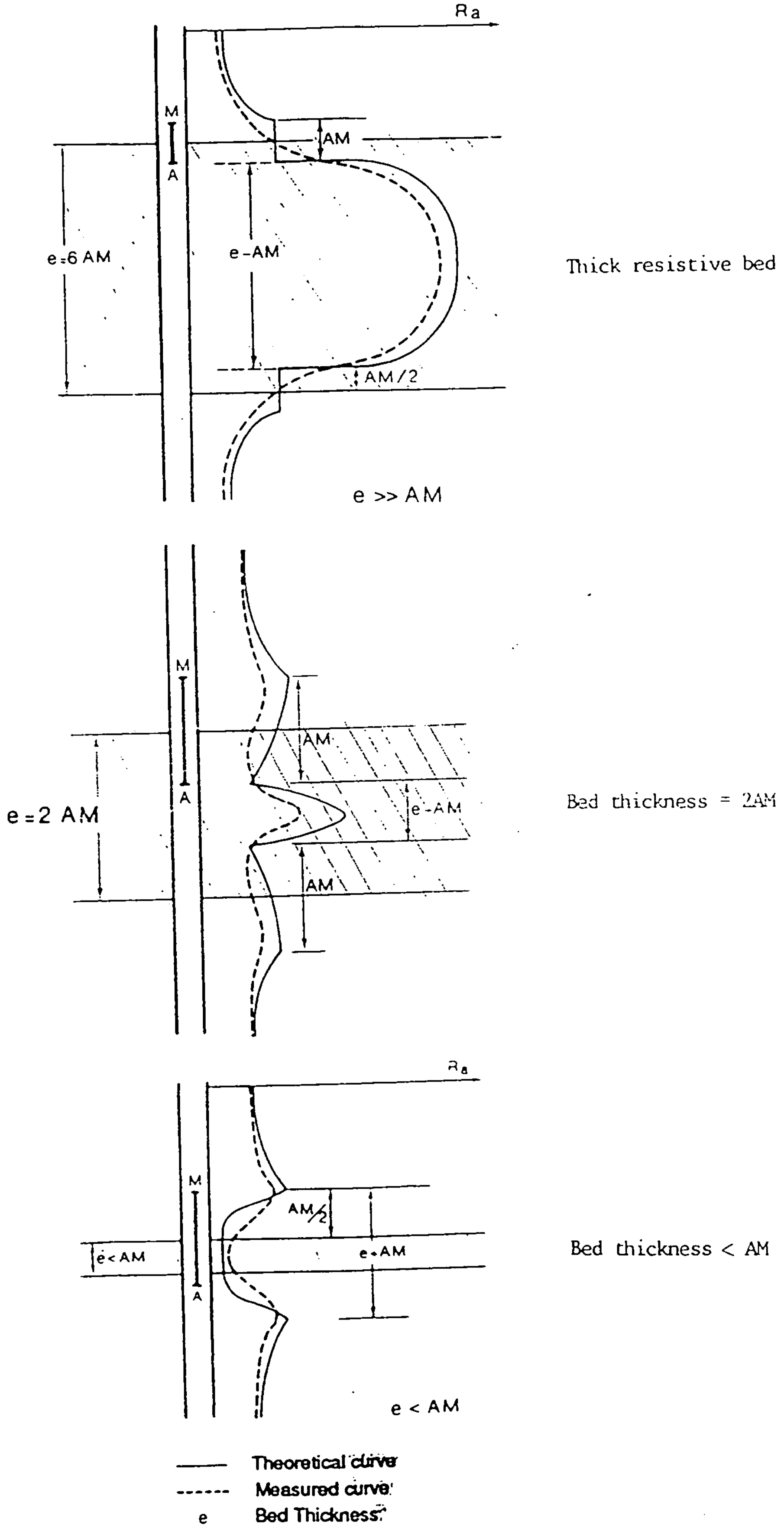


Figure 2.5.4 Effect of bed thickness on normal resistivity curve shape (after Chapellier, 1992).

The SP observed is the net balance of positive or negative ions present at a point in the borehole fluid. Fine-grained materials such as clays and silts having large surface areas tend to bind negative ions to their surfaces so that the fluid alongside in the borehole has excess positive charge and is recorded as a positive SP deflection. Shales and clays thus produce positive SP deflections and log responses similar to those of the gamma ray. In hydrocarbon environments sands are typically saturated with brines or saline water, and the borehole is drilled with relatively fresher drilling fluid. The Na^{2+} and Cl^{-} ions in the sand layer pore space tends to migrate to the weaker concentration fluid. The Cl^{-} ions are more mobile and the fluid alongside the sand thus tends to develop an excess of negative ions displays a negative SP. The opposite occurs where the formation fluid is relatively fresher than the borehole fluid. Thus in porous formations SP deflections to the left generally indicate relatively more saline formation water and SP deflections to the right indicate fresher formation water provided there is no change in sand or clay content.

In freshwater aquifers SP's are only weakly developed and the log is not normally of value. An SP deflection can, nevertheless, be produced by changing the salinity of the borehole fluid by introducing NaCl for example though this is rarely done. Figure 2.5.5 shows examples of SP logs in a brine-saturated petroleum environment. An SP log in a shallow freshwater-saturated sand-clay sequence showing some curve development is shown in Figure 2.5.6.

Horizontal routine

For manual interpretation geophysical logs are plotted together as composite plots with curves alongside each other together with any other information. The lithology record can then be corroborated horizontally with the curve responses in turn. By comparing different log responses horizontally at the same depth, a synergistic evaluation of the lithologies can be made and the log inflexions at layer boundaries are a more reliable guide to the contact depths than the sampling record alone. An example of a composite log plot in unconsolidated sediments is shown in Figure 2.5.6 where gamma ray (GR1) 8, 16, 32 and 64 inch normal resistivity, caliper and SP logs are plotted together. Note the gamma ray and resistivity curves tend to be mirror-images. High gamma activity of finer-grained clay-rich layers is lower resistivity so that an immediate distinction can be made between clay layers at 65-75, 91-93 and 118 m+ and intervening sandier layers. Squeezing of the interpreted clay layer at 65-75 is indicated by the caliper log. Alongside the clay layers there is little difference in measured resistivity of the 4 curves but alongside the permeable sands the effect of invasion is seen by separation of the resistivity curves. Deepest invasion is interpreted at 94-98 and 100-105 m near the top of the Leziate Beds where the highest resistivity is shown. Below 118 m the curves come together showing the clayey Mintlyn Beds are relatively impermeable. Note the resistivity and the SP curves identify a fine-grained layer from 97-100 m which is not indicated by the gamma ray curve and shows the added value of a composite interpretation.

Vertical routine

As well as a horizontal analysis, logs should be examined over their full length when it may be possible to identify consistent minimum or maximum values representing

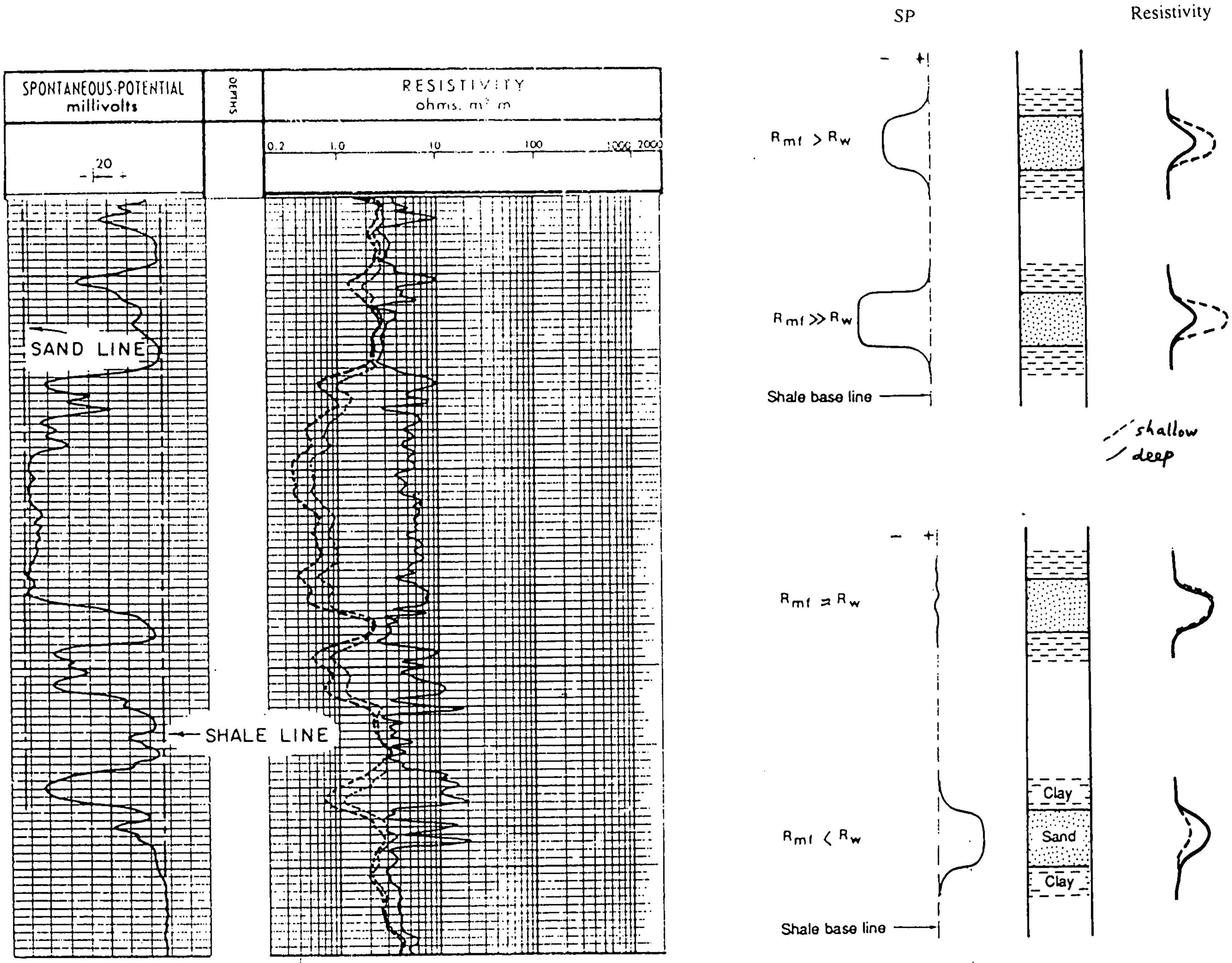


Figure 2.5.5 SP logs in a hydrocarbon environment and the effect of relative salinity (after Bateman, 1985).

clean sands or clays (Figure 2.5.7). It may also be possible to recognise vertical trends in log shape signifying coarsening-upwards (e.g. higher resistivity, lower gamma ray) or fining-upwards units (e.g. lower resistivity, higher gamma ray) within the sequence. This, in turn may provide information on basin depositional history.

Clay content

Gamma ray deflections generally increase with clay content hence an approximate index of the sediment clay content is provided by linear interpolation between the gamma ray deflection of a clean sand (0% clay) and a clay layer (100% clay).

$$\text{Clay \%} = \frac{GR_{(log)} - GR_{(sand)}}{GR_{(clay)} - GR_{(sand)}} \qquad (1)$$

Dresser Atlas (1982) proposed a modification for unconsolidated materials:

$$\text{Clay \%} = 0.083\,(2^{3.7Vcl}-1)$$

where Vcl = clay % as in (1) above

The relationship between clay content and gamma ray activity is approximate and is based on the general principle that the finer-grained sediment fraction is more radioactive and the relationship is linear. There are exceptions and glauconite, for example, is a relatively large grain that is also relatively high gamma ray activity.

The interpretation of the gamma ray curve assumes the borehole diameter and borehole completion is similar throughout. If not, corrections should be made for borehole diameter or casing thickness (see Figure 2.5.8).

An alternative estimate of clay content is given by Dewan (1986) as the difference in porosity between neutron and density logs. Neutron logs respond to total hydrogen content including lattice-bound hydrogen, and the larger the clay content the greater the difference between the neutron and density derived porosities.

$$\text{Clay \%} = (\phi_n - \phi_d)/(\phi n_{clay} - \phi d_{clay}) \qquad \text{Dewan (1986)}$$

where
ϕ_n = neutron porosity of clayey sand
ϕ_d = density porosity of clayey sand
ϕn_{clay} = neutron porosity of clay layer
ϕd_{clay} = density porosity of clay layer

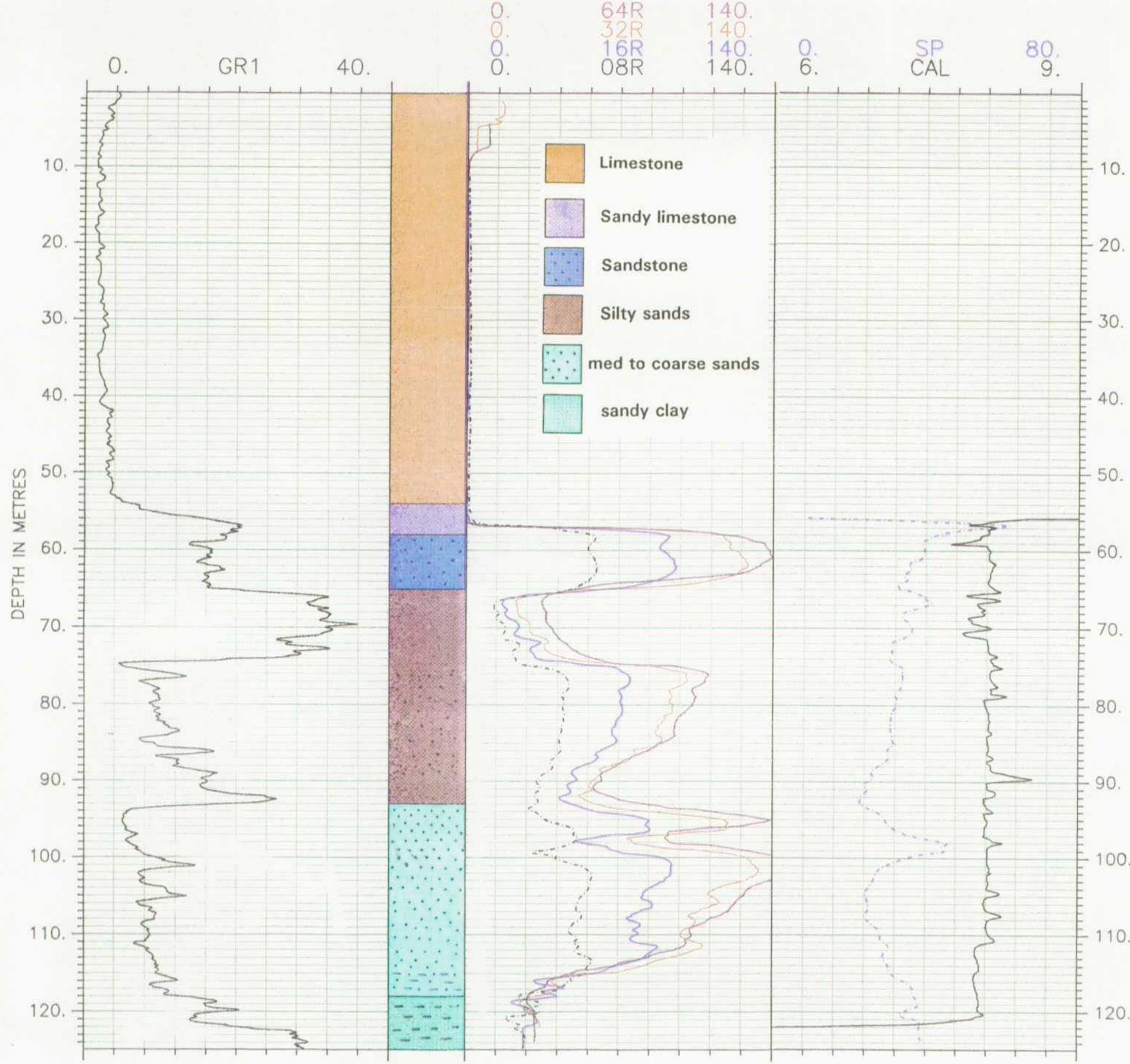


Figure 2.5.6 Open hole logs in freshwater-saturated unconsolidated sand/clay sequence.

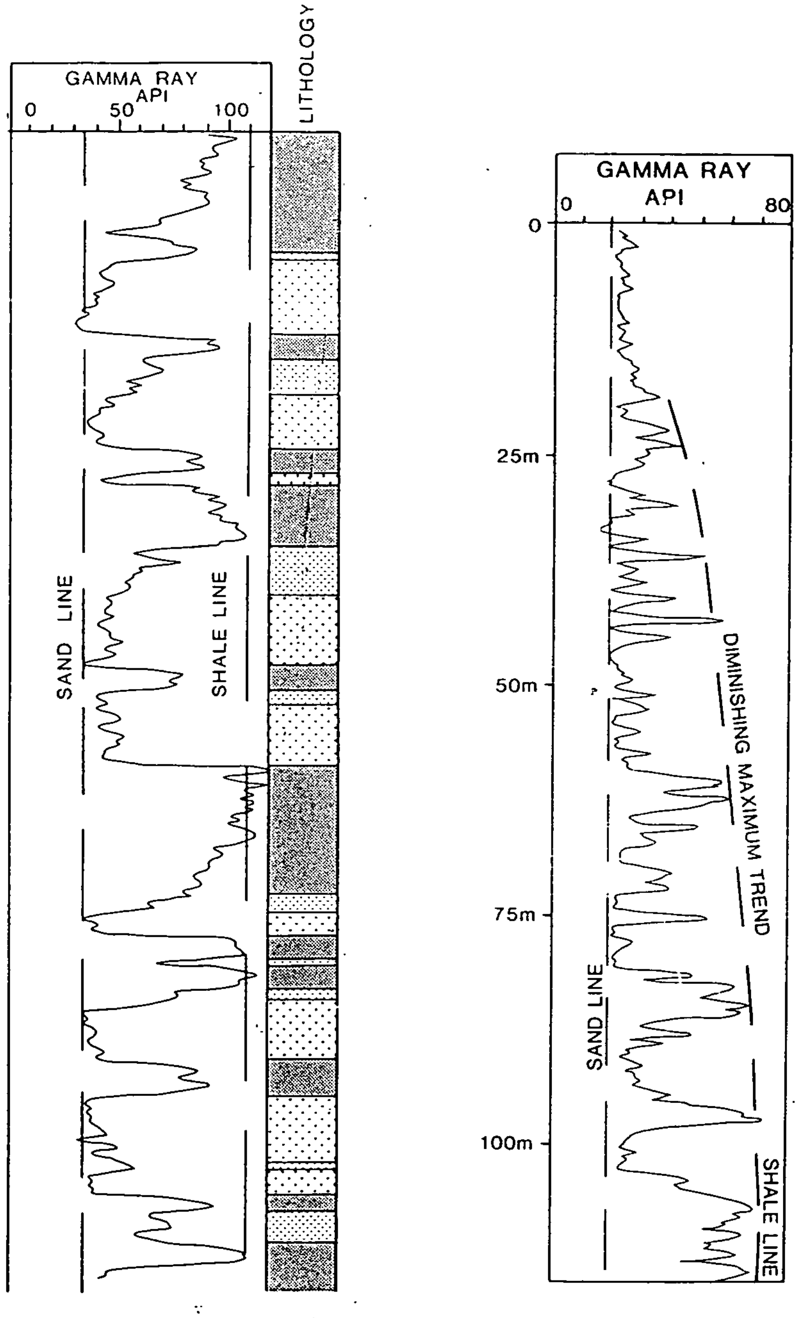


Figure 2.5.7 Gamma ray logs and vertical trends (from Rider, 1986).

Wellscreen and casing setting depths

The junctions identified between sands and clays on open hole logs can be used as a basis for placement of blank casing and wellscreen or the placement of clay seals in the gravel pack. The gamma ray, point resistance (and SP), focussed resistivity and induction logs have symmetrical responses at bed boundaries which are therefore located at curve inflexions. If normal resistivity log measurements are used their assymetric curve response should be taken into account when defining the bed boundaries.

Correlation of layers

An important feature of geophysical logs is that they may provide a correlation of units between boreholes. Where distinctive log shapes or peaks exist and can be recognised in several boreholes as marker horizons, correlation of the distinct horizons can be made. Units chosen for correlation need to be selected carefully. In general, finer-grained facies, which are deposited in deeper-water are likely to be more continuous deposition, and therefore tend to be more reliable for correlation purposes than coarser sand units which may pinch out (see Figure 2.5.9). Volcanic ash is a valuable time-marker that can be identified by geophysical logs. It is deposited over a wide area independently of final depositional environment.

Correlation does not need to be restricted to individual horizons. The vertical routine analysis may show, for example, a series of stacked coarsening upward prograding units which may be recognised in other boreholes as a correlatable sequence.

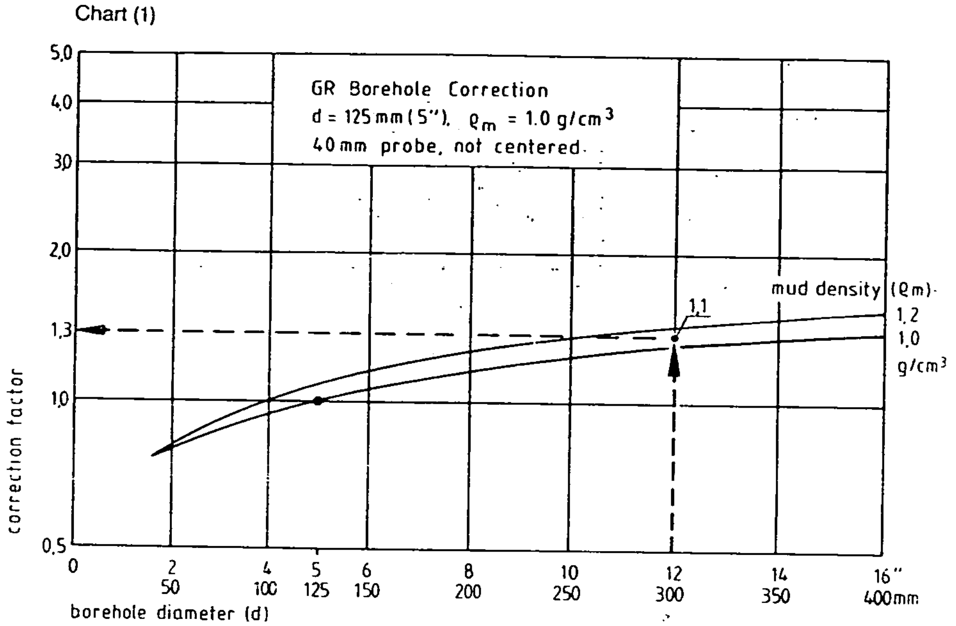
2.5.2 Quantitative identification of lithology

No single log measurement by itself defines a lithology. Instead, the log values are examined together and compared to models of known log responses so that lithology can be determined. Various techniques can be used to identify the lithology.

Histograms and crossplots

Individual log values may be plotted against frequency of log response to provide histograms of particular lithologies (Figure 2.5.10). Once established for a borehole the histograms may be used to diagnose lithologies from the log responses of other boreholes in the area or region.

Fertl (1979) showed that any combination of porosity logs plotted on a common scale can indicate lithology because of the different log responses to the matrix minerals present (Figure 2.5.11). This is satisfactory when the lithologies present are essentially monomineralic. When the lithologies are composite mixtures as they more often are, they are more easily identified by crossplots of 2 logs. The crossplotted logs may be compatible, i.e. they measure the same property (e.g. neutron, density or sonic porosity) or they may be incompatible (e.g. gamma ray, resistivity). The log values can also be crossplotted directly against laboratory values, e.g. resistivity versus grain size or hydraulic conductivity. Details of typical crossplotting and routines are examples given by Bateman (1985), Doveton (1986), Rider (1986), Schlumberger (1989).



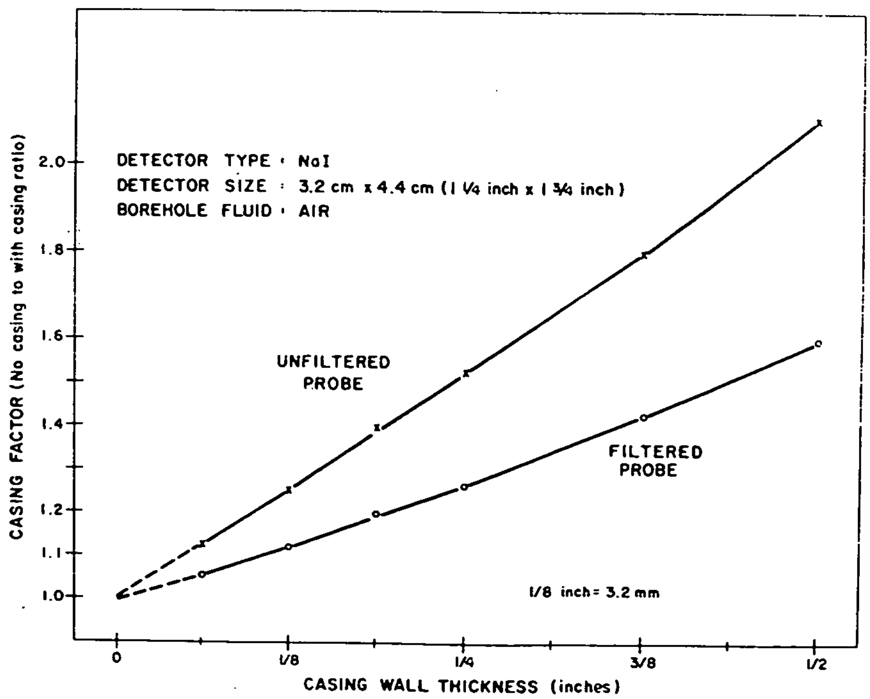


Figure 2.5.8 Gamma ray correction factors for borehole diameter and casing wall thickness (from Repsold, 1989; IAEA, 1982).

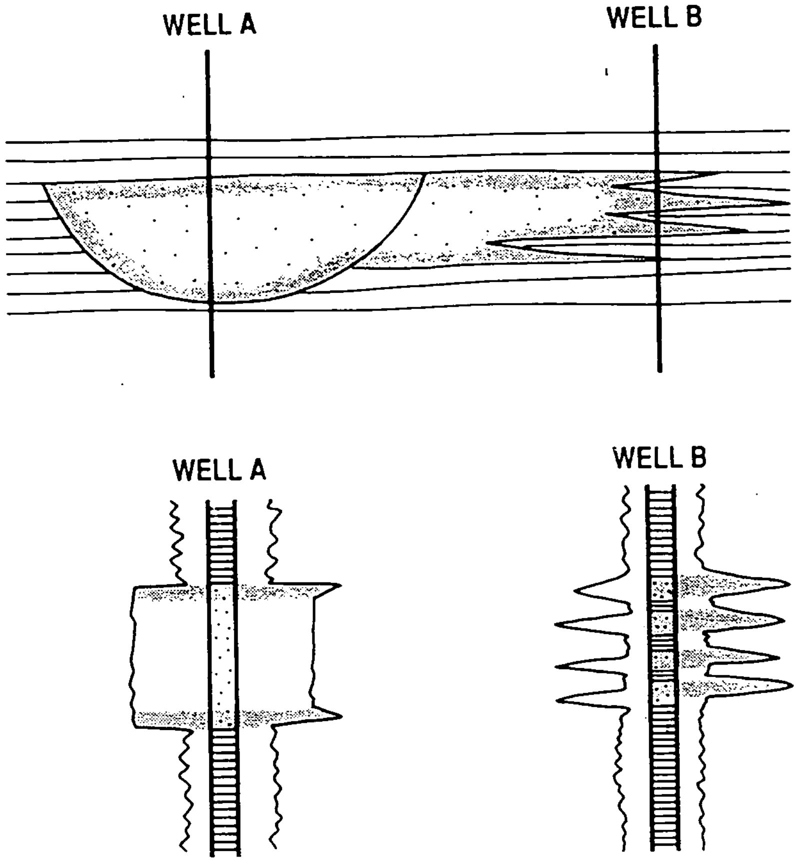


Figure 2.5.9 Change in shape and character of a sand body between boreholes and the effect on logs (after Selley, 1992).

Determination of porosity

Porosity is the fractional volume of the rock occupied by fluids

$$\phi = \frac{V_p}{V_t}$$

where ϕ = porosity
V_p = volume of pore space
V_t = total volume of rock

The porosity of a sediment is a complex function of grain size, grain shape, orientation and sorting. If all grains are a similar size the sediment is said to be well sorted, and the packing of grains determines the porosity. It is a theoretical maximum of 48% for cubic packing. For a given grain size porosity decreases as the sorting gets poorer because the intergranular pore space becomes filled with even smaller grains. Porosity decreases with depth and post-depositional changes such as compaction and cementation. It is increased by solution.

Three geophysical logs provide a measurement of porosity. They are neutron, density and sonic, and measure relative hydrogen content, electron density and compressional wave velocity respectively. The logs of choice for porosity estimation in unconsolidated materials are neutron and density. However both require a radioactive source and their use is governed by strict safety regulations. The sonic log has no such hindrance but provides only a poor estimate of porosity in unconsolidated materials because of the need to estimate an *in situ* matrix compressional wave velocity which is not known precisely.

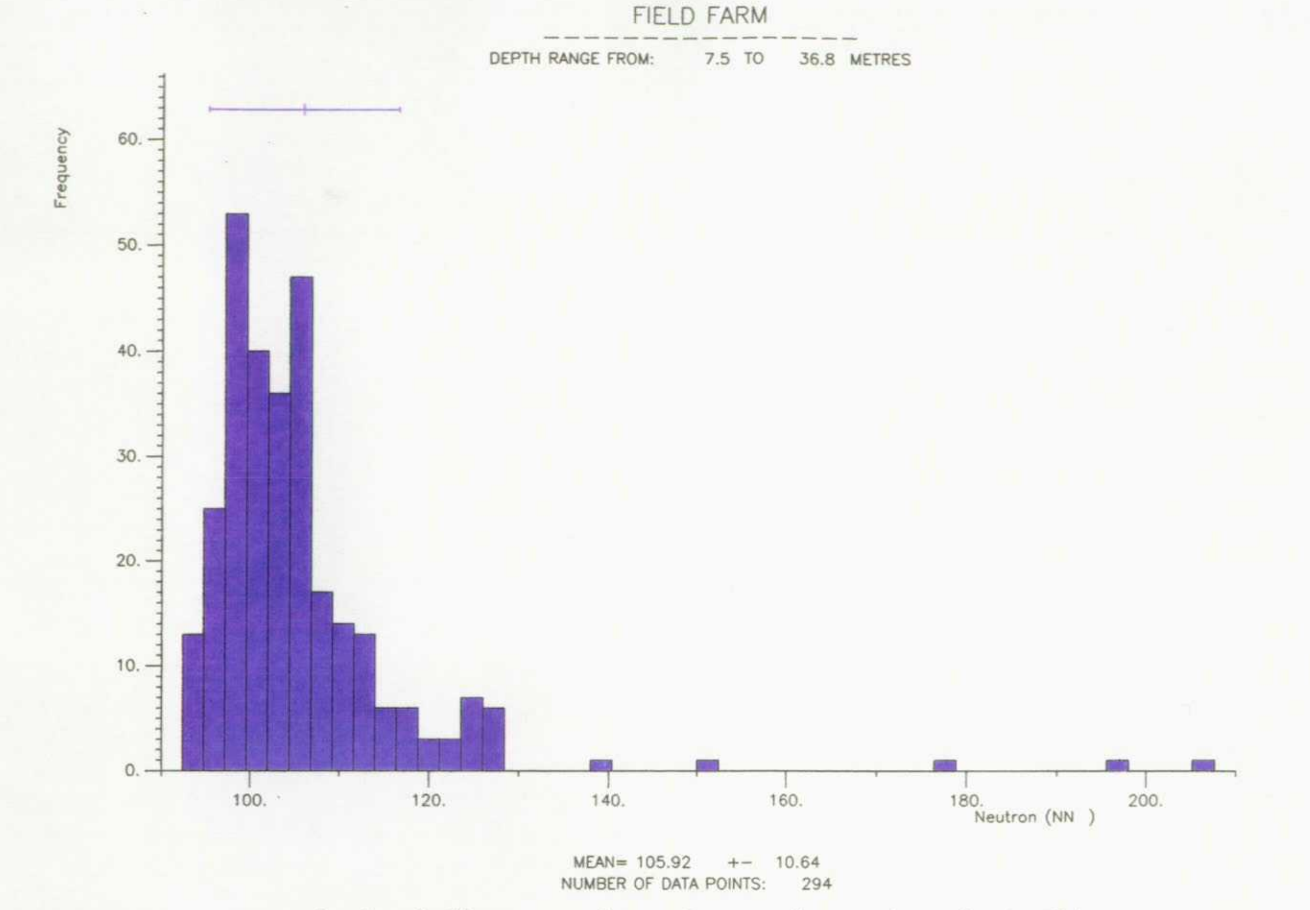
Porosity is calculated from the density and sonic log measurements after an estimate of matrix density and matrix velocity is assumed. Only the hydrogen content measurement of the neutron log approaches a direct measurement. Porosity derived by all three methods represents total porosity (ϕ_T) and does not distinguish the effective porosity (ϕ_e) generally required by hydrogeologists.

$$\phi_e = \phi_T - \phi_r$$

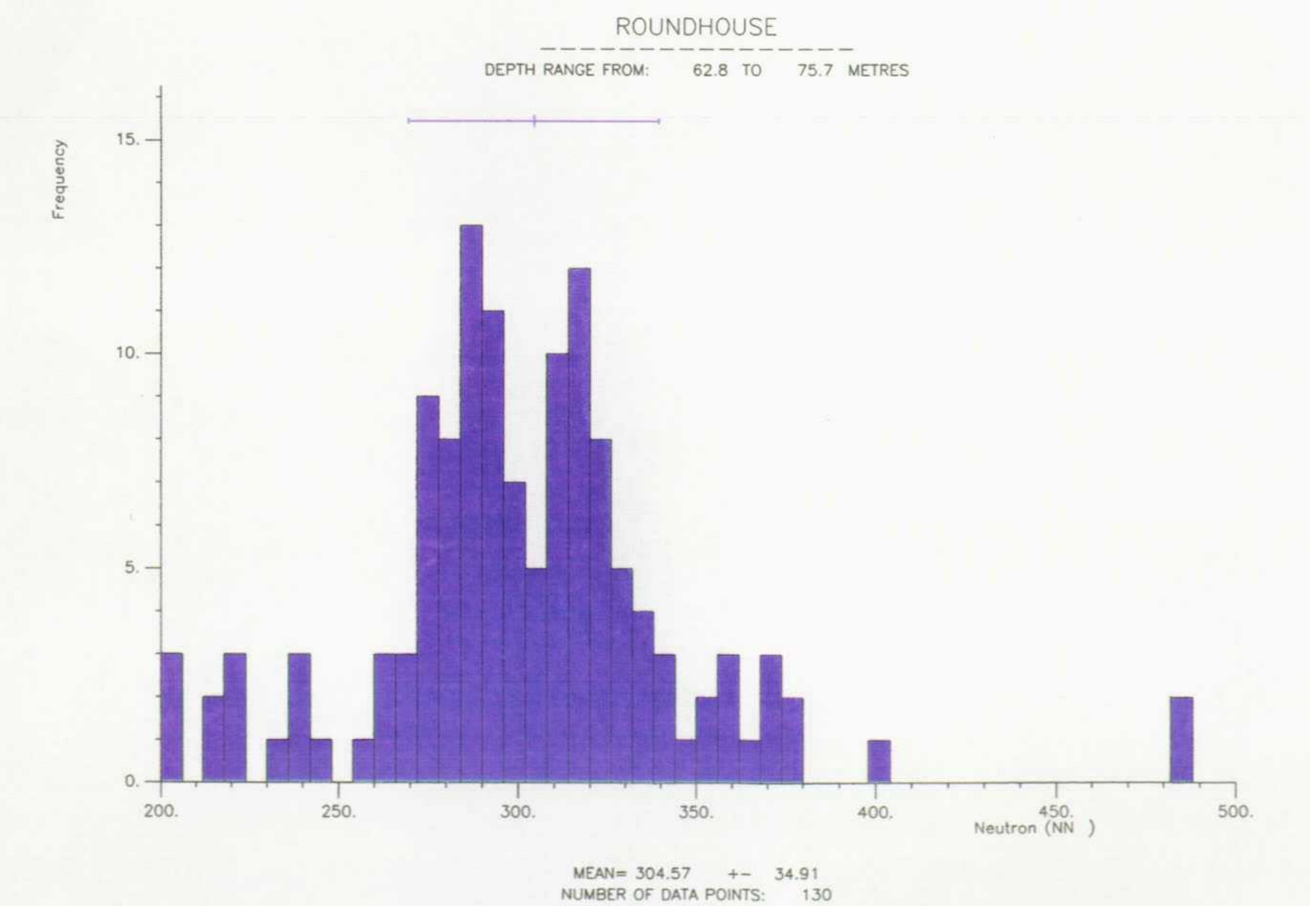
where ϕ_r = specific retention

Specific retention can be indicated by grain size analysis. Alger and Harrison (1989) suggest that an effective porosity can be estimated if a clay content indicator is available.

$$\phi_e = \phi_T (1-V_{clay})$$



Oxford Clay neutron log values, borehole 5A



Blisworth Limestone neutron values borehole 4A

Figure 2.5.10 Histograms of neutron log measurements in different lithologies.

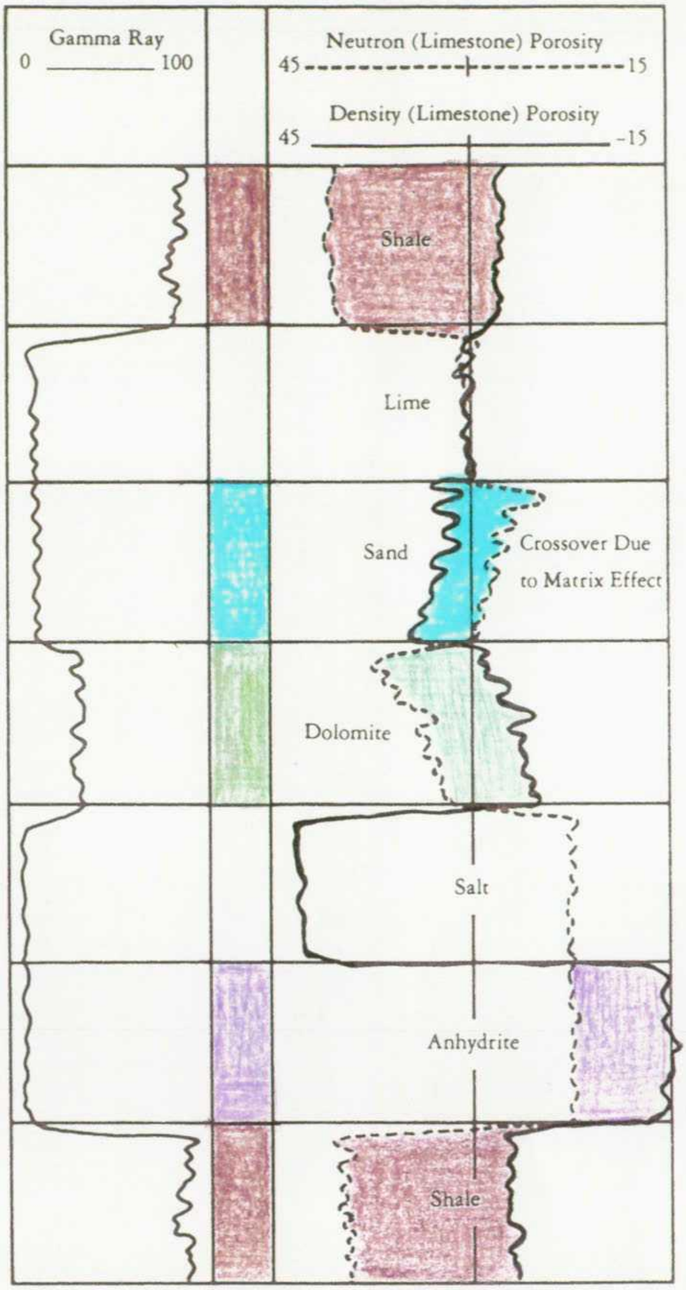


Figure 2.5.11 Schematic example of neutron and density logs plotted on a common scale to identify lithology (after Bateman, 1985).

where V_{clay} is from

$$V_{clay} = \frac{GR_{log} - GR_{clean}}{GR_{clay} - GR_{clean}}$$

(a) neutron log porosity

The neutron tool source emits fast neutrons with an energy of 4-6 MeV at velocities >10000 km/sec. The fast neutrons are progressively slowed by collisions with the nuclei of atoms surrounding the probe and particularly so by hydrogen atoms which have a similar mass. The population of slowed epithermal and thermal neutrons measured at one or more detectors is proportional to the hydrogen atoms present. There are no free neutrons in natural formations so that there is virtually no background neutron population to consider. Hence the neutron log response relates largely to the hydrogen content. The response is inverse and a low neutron population implies a high concentration of hydrogen atoms and high porosity surrounding the probe.

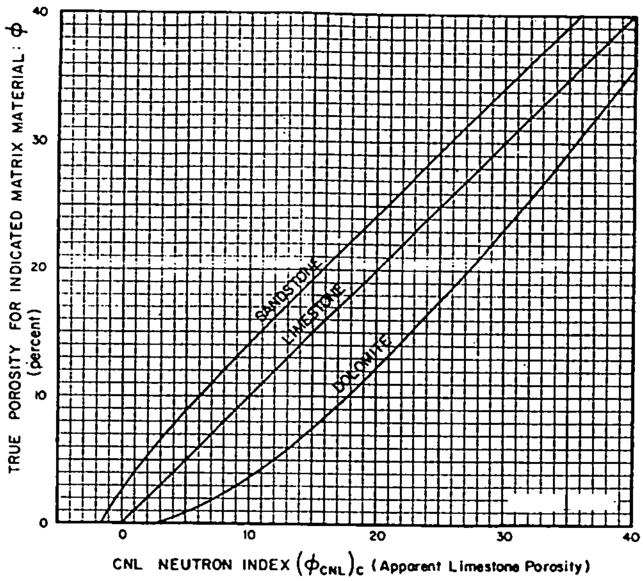
Logging tools used for neutron logging in hydrogeological studies often record the neutron population in terms of a count rate (counts/second). The count rate response may be converted to porosity using empirically prepared charts or from a calibration using an artificial porosity standard (Figure 2.5.12). Because the log measures hydrogen content it is strongly affected by diameter enlargements in fluid-filled holes.

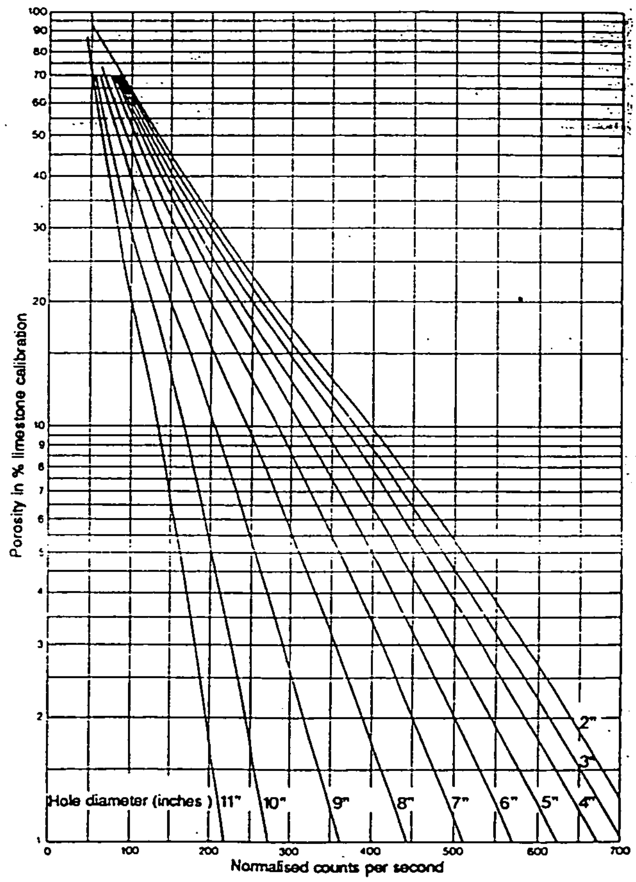
The depth of investigation of neutron tools depends upon the source size and source detector spacing used and changes continuously with changes in the rock porosity. It is greater in low porosity material and least alongside high porosity units (Figure 2.5.13). Generally the measurements represent the flushed zone. Figure 2.5.13 shows that investigation depth is <8 inches (200 mm) when porosity exceeds 24%. For neutron tools with source activity up to 3 Ci (111 GBq) and having source-detector spacings of 13-17 inches (330-430 mm) the optimum hole diameter is 4-8 inches (100-200 mm) and a maximum of 12 inches (300 mm). In larger diameters contact pad devices are recommended.

(b) Density log porosity

Density probes measure formation bulk density by bombarding the rock formation with gamma rays from a gamma ray source and measuring the population of Compton-scattered gamma rays from the electron shells of the formation material. The log thus responds to formation electron density. The tool response is inverse and logarithmic. That is, a high count rate population is observed against low density material and vice versa.

Early density tools were omni-directional devices which were freely suspended in the borehole. They provided a poor measurement of bulk density because the gamma rays were able to travel preferentially through the lower density drilling fluid and not





CPS-porosity conversion chart for a neutron-neutron probe.

Figure 2.5.12 Neutron log porosity relationships (after Schlumberger, 1989; Repsold, 1989).

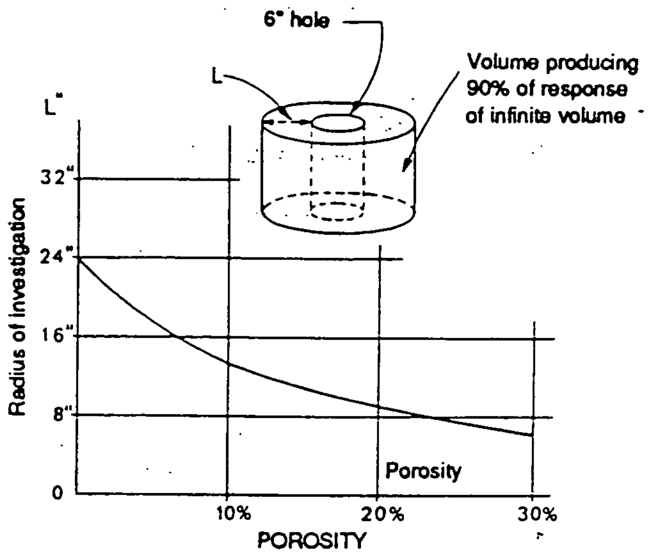


Figure 2.5.13 Investigation depth of a petroleum neutron logging tool (after Chapellier, 1992).

through the formation. Later generation tools were sidewall devices with the source and detector located on a pad or held against the borehole wall by bowspring or a single arm decentraliser, and kept in contact with the borehole wall. The tool is designed to be insensitive to natural gamma rays through use of heavy shielding. Accordingly relatively large gamma ray sources (>100 mCi) are necessary, and the tools are heavy, and because of the gamma ray source strict handling safety procedures must be employed.

The density log is also particularly sensitive to hole diameter and the physical contact with the borehole wall. Where mudcake is present and not removed by the probe it records a lower density than the formation, i.e. a higher count rate. Compensated density tools have two detectors, one close to the source reading thin bed detail and the influence of the mudcake, and a far detector which largely reads formation density. By subtracting the near detector measurement the effect of mudcake or hole enlargement on the far detector can be eliminated (compensated). The detector count rates are converted to bulk density by means of calibration. The probe being placed on blocks of known density (usually acrylic, magnesium and aluminium) (Figure 2.5.14).

The depth of investigation of the density tool is shallow and variable depending upon the source strength, the source-detector spacing used and the formation electron population. For typical source-detector spacing of 40 cm and 100 mCi source strength, the investigation depth in material of 2.0 g/cm is only 6-8 inch (150-200 mm). The probe therefore reads only a narrow zone surrounding the borehole, and the short investigation depth means that measurements made will be strongly affected by diameter enlargements.

The density observed by the probe comprises the sum of the matrix density and the pore fluid density.

$$\rho_b = \rho_{ma} (1 - \phi) + \rho_{f\phi}$$

where ρ_b = bulk density
ϕ = porosity
ρ_f = fluid density
ρ_{ma} = matrix density

from which

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

where ϕ_D = porosity derived from measurement of bulk density.

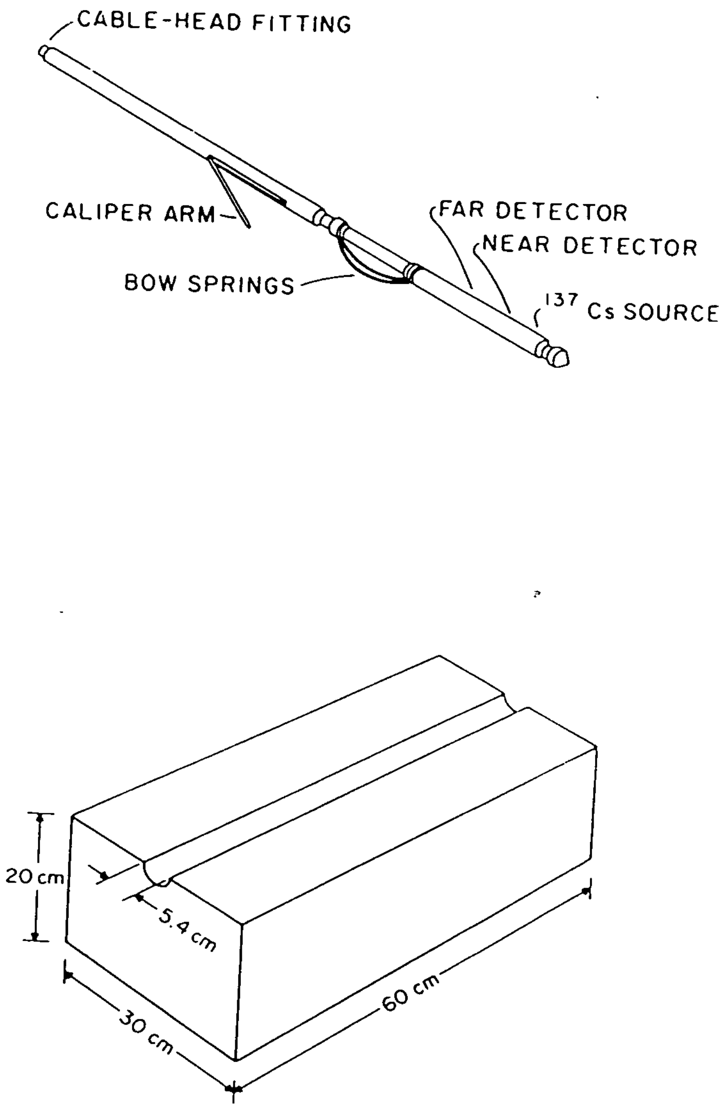


Figure 2.5.14 A typical water well compensated density tool and calibration block (from Scott, 1977).

For freshwater saturation (ρ_f = 1.00) and for common mineral matrix densities of 2.65 g/cm^3 (sand), 2.71 g/cm^3 (limestone), and 2.87 g/cm^3 (dolomite) density-derived porosities are as follows:

$$\phi_d \text{ (sst)} = 160.6\text{-}60.6\ \rho_b$$
$$\phi_d \text{ (lmst)} = 158.5\text{-}58.5\ \rho_b$$
$$\phi_d \text{ (dol)} = 153.5\text{-}53.5\ \rho_b$$

where b = the log reading

The tool measures the bulk density and the porosity obtained depends upon the estimates of fluid density and matrix density chosen. The relationship described is strictly valid when the lithology is monomineralic. Where a mixed lithology is present it is recommended to average the ϕ_D and ϕ_N porosities.

Where clay is present:

$$\rho_b = (1 - V_{cl} - \phi)\rho_{ma} + V_{cl}(\rho_{cl}) + \phi\rho_f$$

where V_{cl} = volume of clay
ρ_{ma} = matrix density
ρ_{cl} = clay density

hence:

$$\phi = \frac{(\rho_{ma} - \rho_b) - V_{cl}(\rho_{ma} - \rho_{cl})}{(\rho_{ma} - \rho_f)}$$

i.e.

$$\phi_{Dcor} = \phi_D - V_{cl}(\phi_{Dcl})$$

where ϕ_{Dcor} = corrected density porosity
ϕ_{Dcl} = apparent density porosity of clay
V_{cl} = volume of clay

The clay content can be obtained from the gamma ray log and the density-derived clay porosity can be calculated from the density log measurements in a suitable clay layer.

$$\phi_{Dcl} = \left[\frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \right]_{Cl}$$

where ρ_{ma} = clay matrix density

Typical clay matrix densities and neutron porosities are available in the literature. See for example Dewan (1983) p231.

(c) Sonic log porosity

Sonic tools measure the velocity of compressional waves in the rock. The tools emit pulses at approximately 15-30 kHz frequency and the compressional waves produced travel through the borehole fluid and are refracted at the borehole wall where they travel through the formation at higher velocity due to the increased density and rigidity. The compressional wave arrival is recorded at receivers placed at different distances on the probe. The length of formation sampled corresponds to the transmitter receiver spacing, which is usually 3 feet and 5 feet (0.91 and 1.52 mm). By convention the compressional wave velocities are displayed on the log as travel times (reciprocal velocity) usually as microseconds/foot (µs/ft).

Pirson (1963) states that the depth of investigation of the sonic measurements varies with the frequency of the emitted pulses and the formation velocity.

$$\text{radius of investigation} = 3\frac{V}{f}$$

V = velocity of the rock (ft/sec)
f = frequency in Hz

The investigation depth is always shallow because it is dictated by the fastest wave to be transmitted from transmitter to receiver.

For 20 KHz tools and typical rocks, the investigation depth is 0.12-1.0 m (4.75-39 inches). The vertical resolution is approximately equal to the distance between the 2 receivers, usually 24 inches (0.61 m). The tool must be centralised in the borehole so that the path distance through the fluid from transmitter to borehole wall and from borehole wall to receiver is approximately the same. Measurements made in lined boreholes record the transit time through the plastic or steel liner and give no information on the formation properties. Steel casing transit time is 57.1 µs/foot and freshwater mudfiltrate is 189 µs/foot and are useful checks on the log measurements.

Wyllie (1956) demonstrated an approximate linear relationship between transit time and porosity where porosity is estimated from a linear interpolation of the transit time of the matrix mineral Δt_{ma} (zero porosity), and the transit time of the pore fluid Δt_f (100% porosity)

$$\Delta t = \phi \Delta t_f + (1 - \phi) \Delta t_{ma}$$

where Δt = formation transit time
ϕ = porosity of zone
Δt_f = transit time of fluid
Δt_{ma} = transit time of mineral matrix

hence

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \qquad \text{(the Wyllie time-average equation)}$$

In unconsolidated materials, application of the Wyllie time-average equation gives porosities that are too high. This is because the transit time through loose sand grains is much slower than through a cemented sandstone of the same porosity. In unconsolidated rocks the matrix framework does not offer the necessary rigidity to support the acoustic wave and cycle-skipping is seen on the logs. The result is that travel times recorded in unconsolidated sands are unusually high and porosity values derived are too high. An approximate correction factor B_{cp} (>1) is usually applied to reduce the calculated porosity.

$$\phi S_{unconsolidated} = \left[\frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \right] \frac{1}{B_{cp}}$$

The correction factor may be obtained by numerical comparison of the apparent sonic porosity with neutron or density porosity, from laboratory measurement, or obtained from an adjacent clay velocity, (Δt clay).

$$B_{cp} = \Delta t_{clay}/100 \ \mu s/ft \qquad \text{(Bateman, 1985)}$$

where Δt_{clay} = travel time of clay layer (μs/ft)

For unconsolidated materials both neutron and density porosities are preferred.

A relatively new logging technique, capable of producing a measurement of porosity, is electromagnetic propagation (EPT) for details of which see Calvert et al. (1977), Wharton et al. (1980), Clavier et al. (1986). The technique does not involve radioactive sources and therefore suffers none of the safety regulation drawbacks of neutron and density methods. It is said to be a viable alternative porosity log (Collier, 1989).

The EPT tool measures the wave amplitude attenuation and phase shift delay of electromagnetic waves generated by the tool. The attenuation and delay are a function of the water-filled porosity. Two tools are available for shallow and deep measurements from Schlumberger and operate at frequencies of 1.1 GHz and 25 MHz (Schlumberger, 1989). They are not in common use in water boreholes.

(d) Porosity from resistivity measurements

In brine-saturated formations the electrical properties are dominated by the brine-filled pore space and there is a relationship between formation resistivity and porosity. But in freshwater-saturated sediments where interface conductivity is important the relationship between porosity and electrical resistivity is not so strong.

Chapellier (1992) gives a formula to approximate porosity using the short normal electrical resistivity measurement.

$$\phi^2 = \frac{R_{mf}}{R_{xo}}$$

where ϕ = porosity
R_{mf} = resistivity of mud filtrate (ohm.m)
R_{xo} = invaded zone resistivity (from 16 inch normal measurement)

Determination of pore fluid salinity

In circumstances where there is no vertical fluid movement in the borehole, pore fluid salinity can be observed by fluid resistivity (conductivity) logging in the open hole or the completed well or by taking fluid samples with a depth sampler and chemical analysis. However in most boreholes vertical fluid movement takes place and this is not a reliable method. In consolidated materials it largely reflects the fissure/fracture water component. In unconsolidated materials SP and resistivity log data in the open hole can be used to derive pore fluid salinity.

(a) Determination from SP

In petroleum logging the SP log is routinely used to derive pore water salinity (Figure 2.5.15). The standard procedure is described by Wyllie (1949), Hilchie (1978, 1982), Schlumberger (1989).

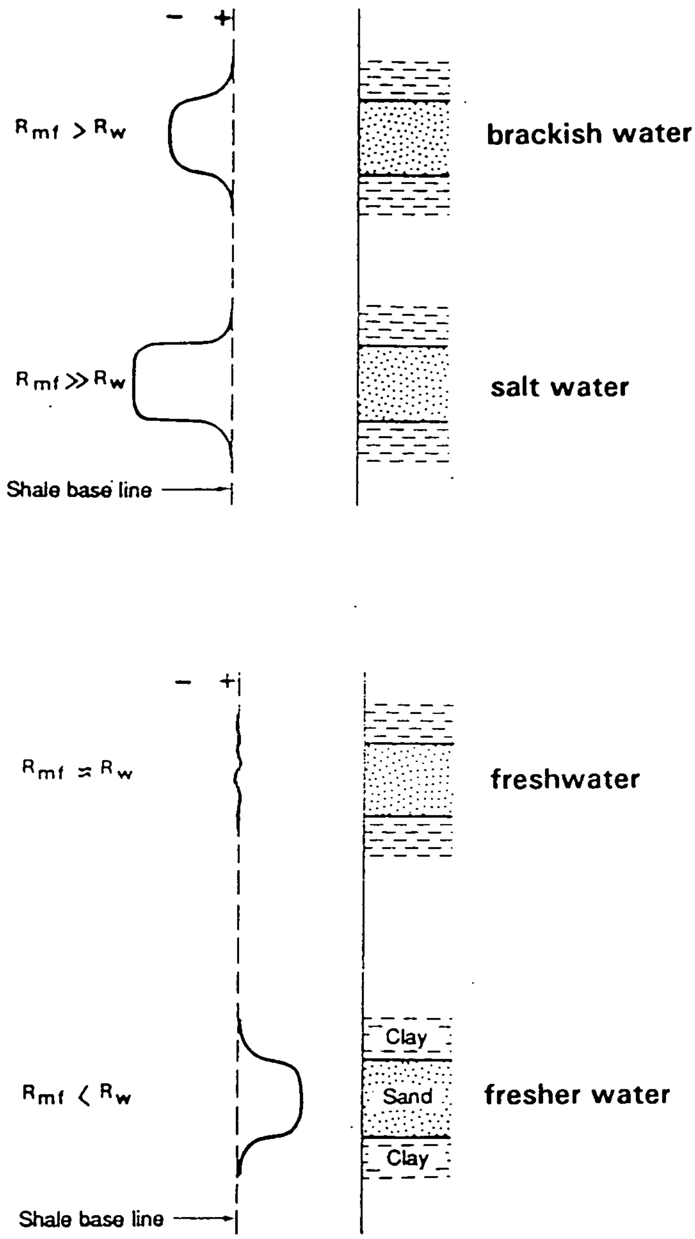


Figure 2.5.15 Influence of relative salinity on SP curves (aftr Chapellier, 1992).

A value of pore water resistivity (R_w) can be obtained from the SP log in clean non-shaly formations.

$$SP = -K \log (R_{mfe}/R_{we})$$

where
- SP = static SP (SSP), i.e. the difference between the shale baseline and the sand line (mV)
- R_{mfe} = effective mud filtrate resistivity (ohm.m)
- R_{we} = effective pore fluid resistivity (ohm.m)
- K = 65 + 0.24T
- T = temperature of layer of interest (°C)

The procedure for using this equation is described in the literature. See, for example, Bateman (1985), p 174.

The formula is strictly applicable in consolidated aquifers saturated with NaCl pore fluid and drilling fluid. In shallow freshwater aquifers the pore fluids and drilling fluids are usually not NaCl but Ca, Mg, and HCO_3 waters. Various modifications of the basic equation above are used to accommodate the bivalent cation fluids encountered in shallow aquifers but their application generally requires a prior knowledge of the local groundwater chemistry which rather defeats the object of the interpretation. In addition, the poorly developed or absent SP deflections often mean that this method is not suitable. Examples of using the SP log to derive fluid salinity, in freshwater aquifers, are given by Alger (1966), Alger and Harrison (1989), Gondouin, Tixier and Simard (1957), Repsold (1989) and Chapellier (1992).

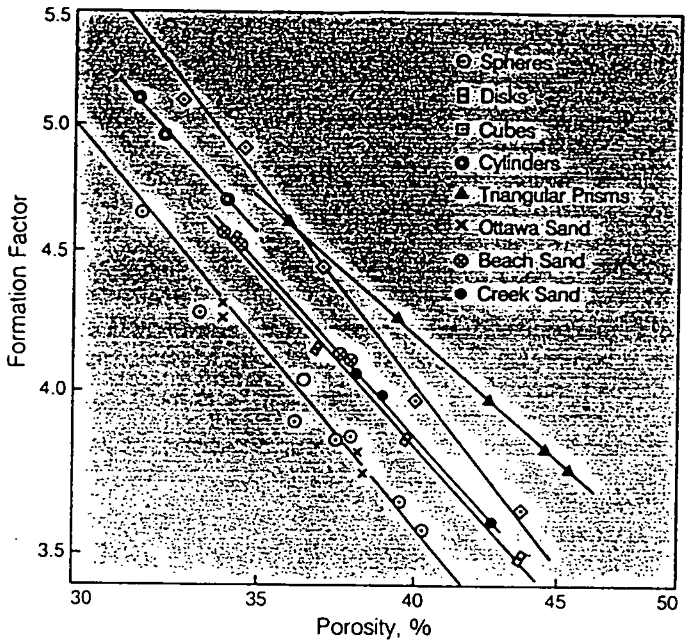
(b) Determination of pore fluid salinity from formation resistivity

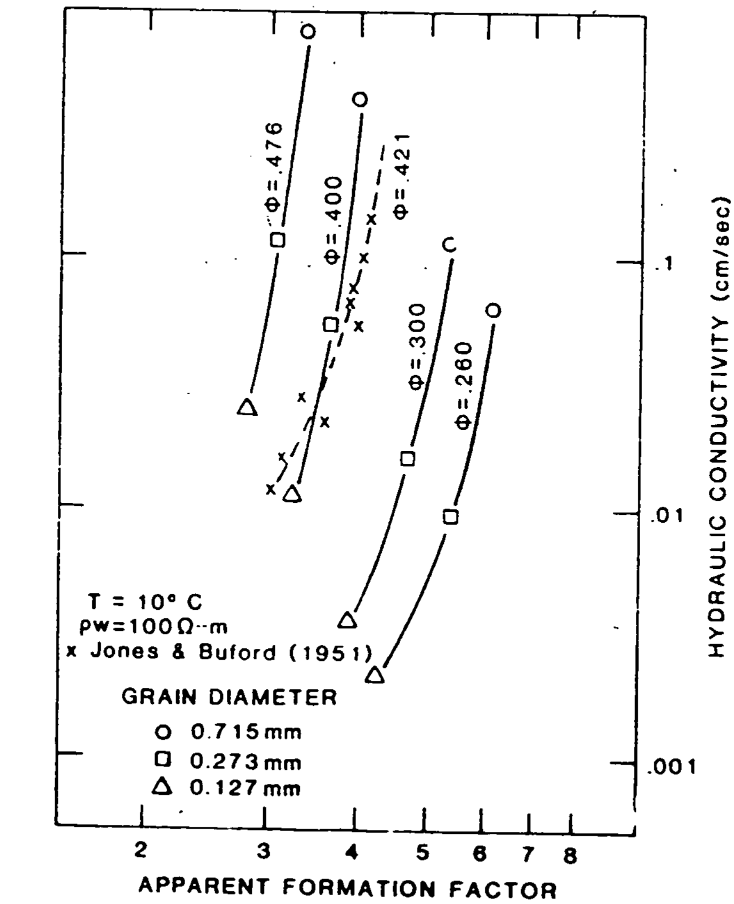
In petroluem environments there is a strong relationship between formation resistivity (R_o), porosity (ϕ) and fluid resistivity (R_w) which was determined by Archie (1942) and is a key relationship known as Archies Law and is used in much petroleum log analysis.

$$R_o = R_w (a\phi^{-m}) \qquad \text{(Archie's Law)}$$

where
- R_o = bulk resistivity of brine-saturated rock (ohm.m)
- R_w = formation water resistivity (ohm.m)
- ϕ = porosity
- m = cementation factor (close to 1)
- a = a factor depending on lithology (close to 2)

The rock texture factors in the Archie relationship ($a\phi^{-m}$) (i.e. grain size, shape, cementation, porosity and tortuosity) are also referred to as formation factor (F),





Variation of hydraulic conductivity with apparent formation factor for spherical particles.

Figure 2.5.16 Formation Factor, porosity and hydraulic conductivity relationships (from the Technical Review (36/3) and Urish, 1981).

i.e. $R_o = R_w F$

$R_w = R_o/F = R_o \phi^m/a$

which can be used to find R_w if a resistivity log and a porosity log is available.

The formation factor has a strong relationship to bulk rock resistivity through porosity because the brine-saturating fluid overwhelmingly influences the resistivity measurement and the resistivity measurement represents the conductive pore volume (Figure 2.5.16). Archie found that the relationship between formation factor and porosity was of the general form:

$$F = a/\phi^m$$

where a is generally close to 1 and m is close to 2.

$$R_w = R_t/F$$

where R_t = true resistivity from a deep-reading device (focussed resistivity, deep induction)

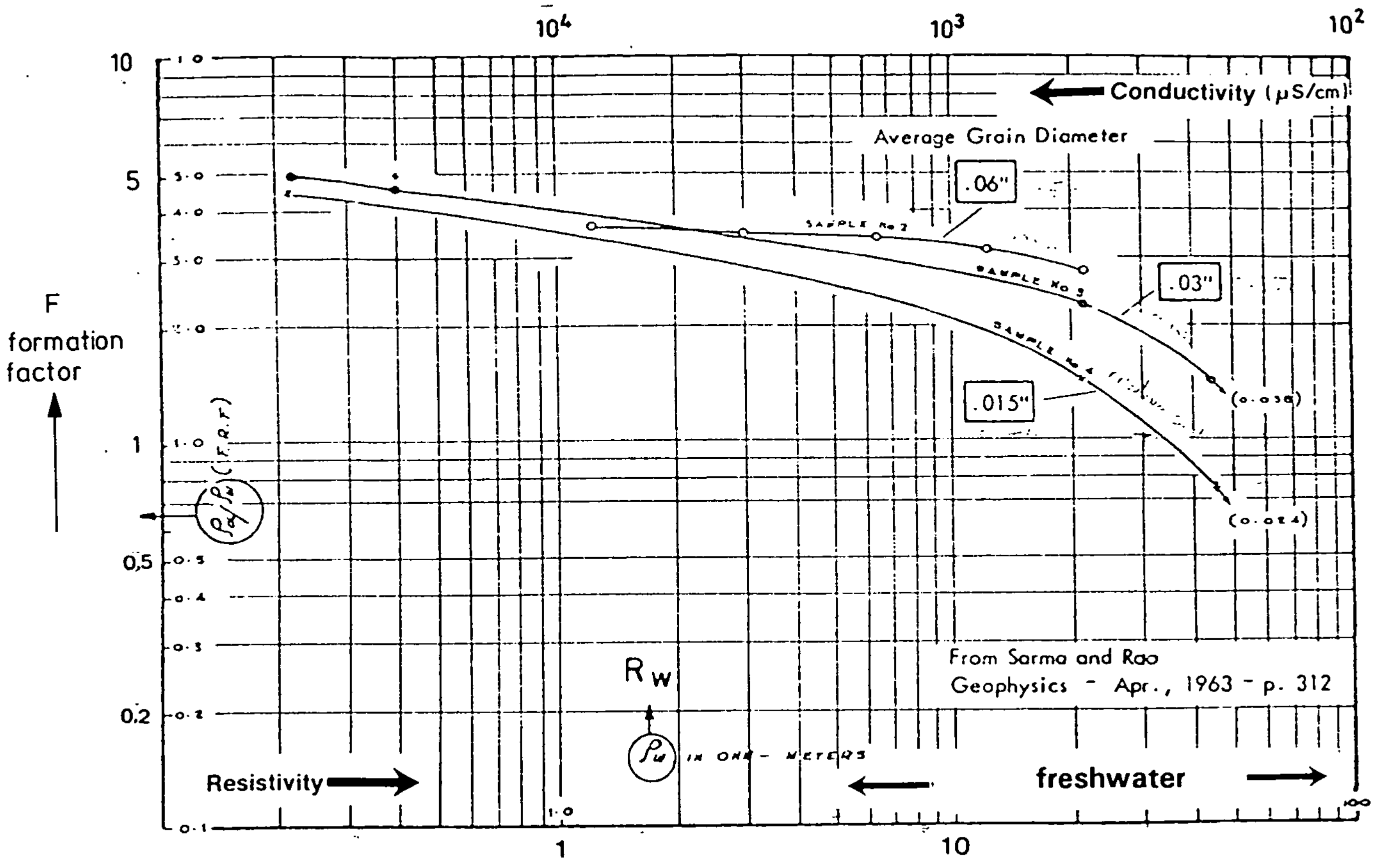
F formation factor computed from a porosity log

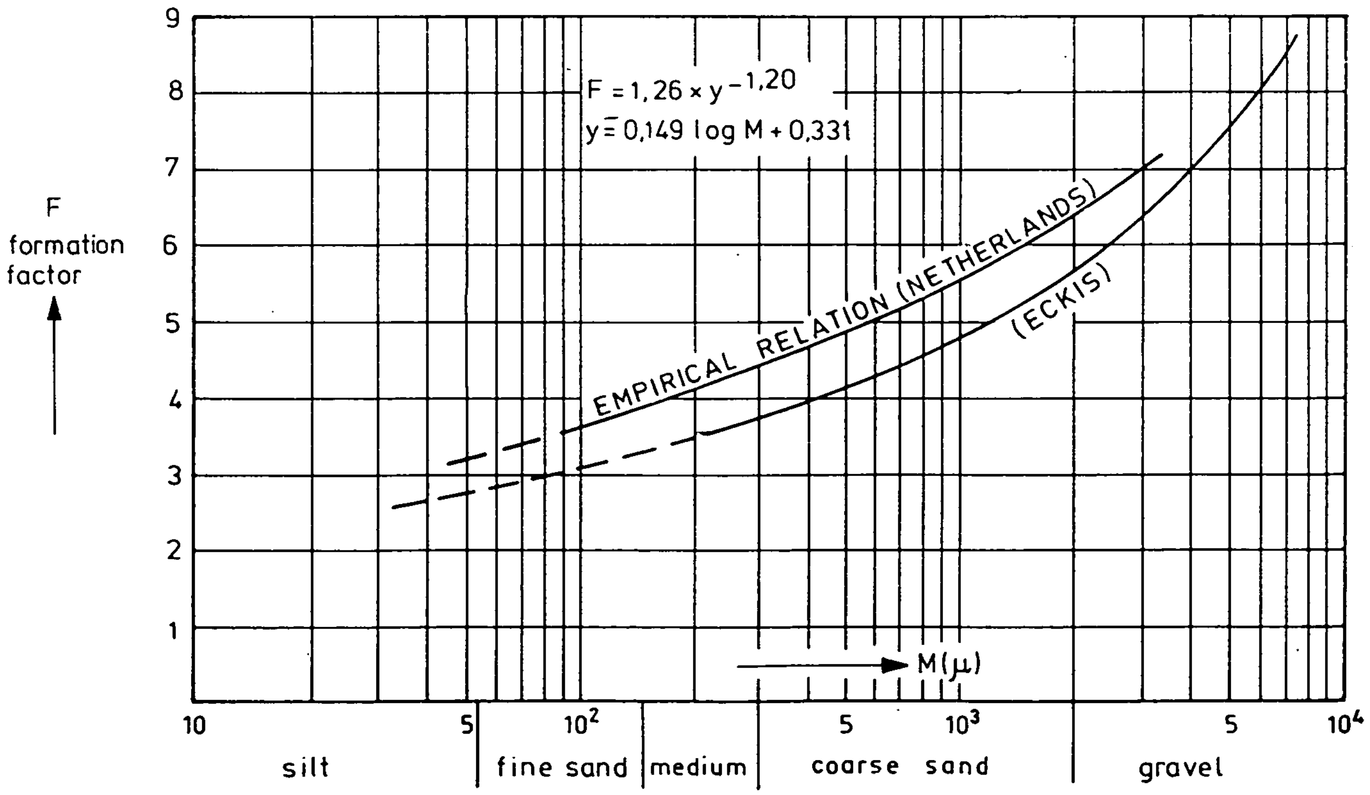
For unconsolidated formations the following formation factor porosity relationships have subsequently proved satisfactory in petroleum log applications:

$$F = \frac{0.62}{\phi^{2.15}}$$

$$F = \frac{0.81}{\phi^2}$$

However the formation factor/resistivity relationship observed in hydrocarbon environments is not strictly valid in shallow freshwater-saturated sediments. This is because the common saturating pore fluids at shallow depths are not sodium chloride brines but divalent freshwaters. There is only a weak relationship between total rock resistivity and the porosity in freshwater-saturated sediments. Furthermore, in relatively resistive freshwaters (>10 ohm.m) and in rocks where resistivity contrasts are not great, a portion of the tool survey current is conducted along the interface between the fluid and the grains (interface conductivity) or along the other preferential routes





FORMATION FACTOR AS A FUNCTION OF GRAINSIZE

Figure 2.5.17 Formation Factor as a function of pore fluid EC and grain size (after Sarma and Rao, 1963; TNO, 1976).

in the rock matrix and by-passes the matrix pore-space. The resistivity and formation factor are therefore not strongly keyed to porosity and instead, relate additionally to a complex function of grain properties, e.g. size, shape sorting, mineral coating etc, as well as to the pore fluid resistivity.

(c) Interface conductivity in freshwater saturated sands

Hill and Milburn (1956), Alger (1966), Waxman and Smits (1968), Rink and Schopper (1974) and others demonstrated the importance of interface conductivity in resistivity measurements of freshwater-saturated sediments and saline-saturated shaly sediments.

In freshwater saturated sediments the following relationships are generally observed:

F varies with R_w (Figure 2.5.17)
F varies with grain size

As a consequence of these relationships log resistivity increases for coarser grain size which is opposite to what is normally encountered in brine-saturated sediment. For increasing freshwater saturation F also reduces so that rock resistivity is increased less than it would if Archie's relationship was strictly applicable. Thus, the derivation of fluid salinity via formation factor from resistivity log and porosity log measurements and Archies Law is not reliable in freshwater saturated sediments.

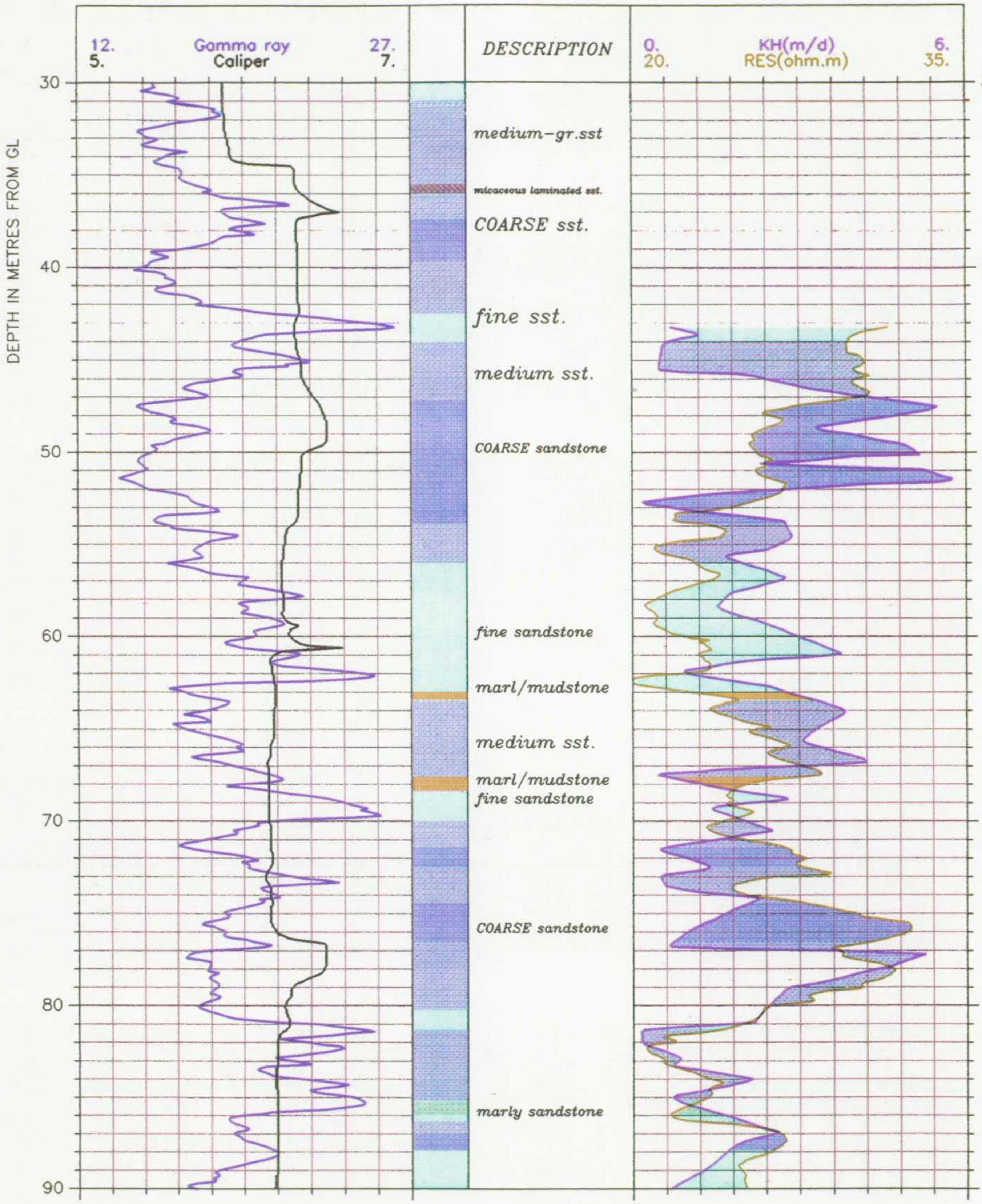
The Archie equation can be used to derive a pore fluid resistivity provided apparent formation factors which take account of the interface conductivity are used. TNO (1976) and Repsold (1989) provide examples but emphasize the value of establishing local empirical relationships between formation resistivity and pore fluid salinity.

An effect of the freshwater saturation and interface conductivity is that the resistivity log measurements provide more information on the sediment properties of grain-size, sorting, texture and composition than they do for saline saturatied sediments and they also relate well to hydraulic conductivity. Clean clay-free layers which are coarse and have high resistivity generally have higher permeability (Figure 2.5.18).

Estimation of hydraulic conductivity from log measurements

Several methods have been used to evaluate hydraulic conductivity from well log data. In oilfield practice most methods use the concept of irreducible water saturation. $S_{w(irr)}$. Irreducible water saturation is the fraction of fluid in pore space which will not flow when the well is put on production. It is therefore analogous to specific retention and is governed by pore throat size and surface area of grains. For example:

$$K^{0.5} = \frac{C\phi^3}{(S_w)_{irr}}$$



KH = horizontal hydraulic conductivity (m/d)

RES = 16 inch normal resistivity (ohm/m)

Figure 2.5.18 Geophysical logs in fine-to coarse-grained sandstones and their relation to intergranular permeability .

where K = hydraulic conductivity (mD)
ϕ = porosity (fraction)
$(S_w)_{irr}$ = irreduicible water saturation (= S_w in aquifers)
S_w = water saturation (fraction) from resistivity logs
C = coefficient depending on fluid density

In oilfields, a linear relationship between logarithm of permeability and porosity and between logarithm of formation factor and logarithm of permeability is noted.

In freshwater-saturated sediments, surface conductivity and the enhanced effect of the grain properties on electrical resistivity logs means that resistivity measurements are more closely related to the hydraulic conductivity. Most studies of aquifers using resistivity log data show a positive relationship between electrical resistivity or apparent formation factor and pumping test hydraulic conductivity. See for example Croft (1971), Worthington (1973), Kwader (1985), Repsold (1989), Alger and Harrison (1989) and Owalabi et al. (1994).

Urish (1981), used uniform spheres of different size and saturating fluids of different salinity to show increasing hydraulic conductivity for increasing grain size and resistivity for a given porosity. Repsold (1989) describes an application of resistivity logging to examine sediment surface area for use in the Kozeny-Carmen equation relating hydraulic conductivity to porosity and internal surface.

Owalabi et al (1994) describe an empirical relationship between hydraulic conductivity, porosity and irreducible water saturation for unconsolidated sands of the East Niger delta.

Other logs have also been related to hydraulic conductivity. Rabe (1956) and Repsold (1989) describe the use of gamma ray logs to derive local hydraulic conductivity values based on specific relationships between gamma ray activity and grain size for particular sediments. Alger and Harrison (1989) report a $GR_{API}+\rho_b$ log transformation gives a better relationship to permeability than either alone. Alger and Harrison (1989) derive a *specific yield* (Sy) of sands from permeability and effective porosity and irreducible water saturation log measurements.

$$Sy = \phi_e - \phi_e * Sw_{irr}$$

where Sw_{irr} = irreducible water saturation
ϕ_e = effective porosity

$$Sy = \phi - \frac{92.5\phi^{3.2}}{K^{0.5}}$$

where ϕ = decimal porosity
K = permeability (millidarcies)

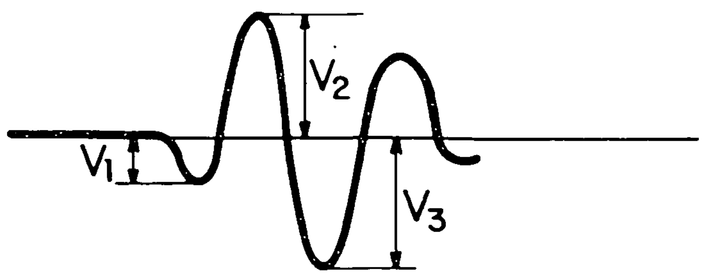


Diagram of an acoustic signal in sonic logging.

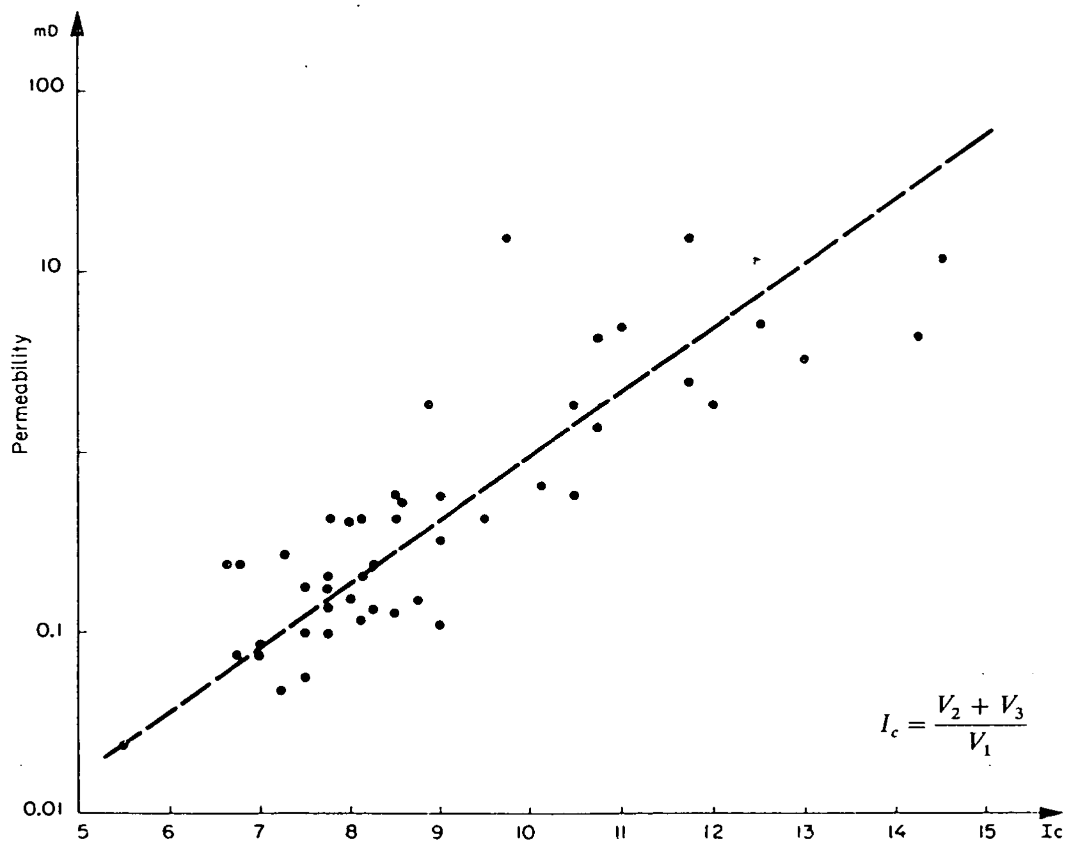


Figure 2.5.19 Sonic waveform shape factor and permeability (after Lebreton, 1978 from Desbrandes, 1985).

In practice no current geophysical log measurement provides a reliable measurement of hydraulic conductivity. Two techniques appear to be promising. Lebreton (1978) showed that the amplitude of acoustic waveforms used in sonic logging varies in a manner related to the permeability of the formation. By measuring amplitudes and characterising the waveform shape a shape index is derived which compares with permeability (Figure 2.5.19).

Oil companies and petroleum logging service companies are investigating nuclear magnetic resonance as a possible technique to recognise moveable fluids and provide a free fluid index related to hydraulic conductivity. Desbrandes (1985) describes the method and gives log examples.

In hydrogeological work packer testing and conventional borehole pump testing provide hydraulic conductivity measurements that are more precise. However there is value in developing empirical relationships between known hydraulic conductivity and log responses in individual studies so that log data can be used to estimate the potential productivity of new boreholes within a site or local area.

2.5.3 Analysis of depositional environment

During the last 25 years it has been appreciated that geophysical logs also provide information on the depositional environment of sediments. The objective of diagnosing a depositional environment is to better predict where sand bodies, which could represent freshwater aquifers (or oil reservoirs) could occur. The basis of this analysis is the identification of a depositional environment for clastic sand bodies. This is achieved by recognition and classification of certain log shapes together with an understanding of the origin of the shapes. It is recognised that water depth, energy of transporting current and sediment provenance change during the developing history of a basin and each have an influence on the nature of the sediments deposited at any particular place and time. These effects are also manifest the in geophysical log responses where they are documented by the log shapes and trends in the vertical sequence. By analysing the log shapes a depositional environment can be deduced from the log trends and the depositional events in the history of a depositional basin can be deduced (Figure 2.5.20). Serra and Sulpice (1975), Serra (1985) and Rider (1986) provide references to extensive literature on this subject.

(a) Log shapes

The basis of using log shape to identify depositional environment is the relationship between clay content and grain size and log response. The main logs used for depositional environment analysis are those which are sensitive to variation in proportion of clay and to grain size, i.e. gamma ray, SP, resistivity . Clay content may show a complex and variable relationship to grain size because of the different hydraulics of sediment deposition. For example fluviatile sediments tend to have a high proportion of dispersed clays and fine-grained fractions which tend to trap clay particles. A strong relationship between gamma ray, SP and resistivity logs and grain size thus exists in these sediments. In marine environments there tends to be more sorting and winnowing and there is not such a strong direct relationship between grain size and log amplitude. It is the partitioning of clays by sedimentary processes of

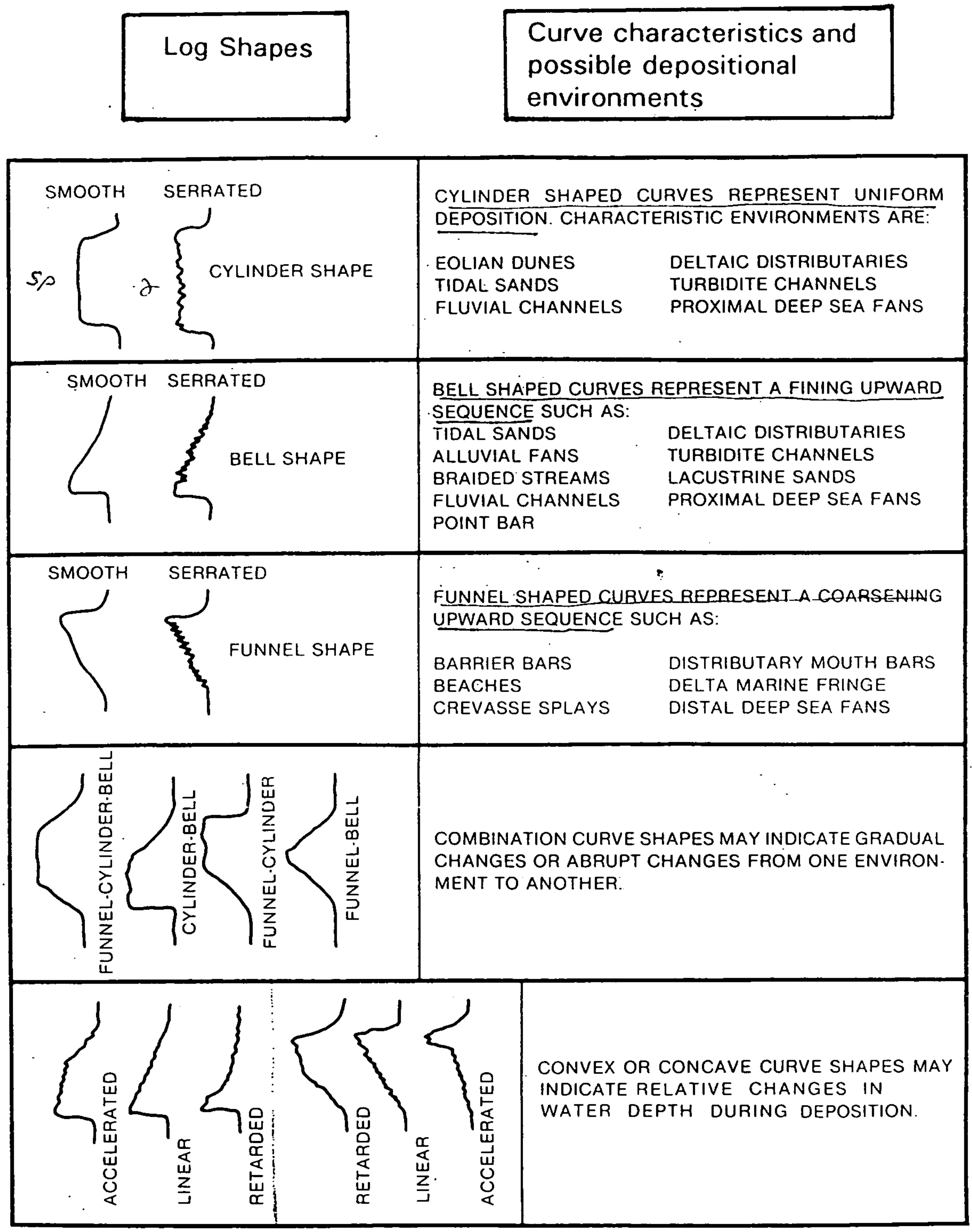


Figure 2.5.20 Some common SP and gamma ray log shapes and possible depositional environments.

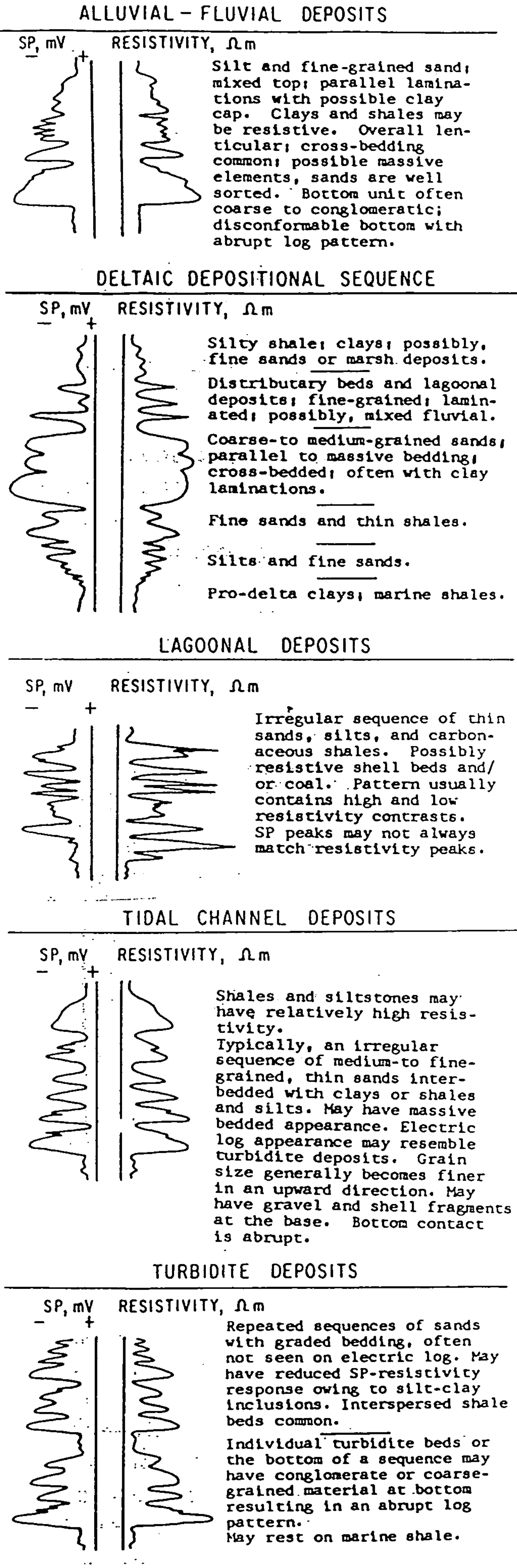


Figure 2.5.21 A selection of SP and resistivity log shapes of sand bodies of different environments (after Allen, 1975).

deposition and their effect on the log measurements that is the fundamental basis of this analysis.

Allen (1975) gives examples and classifications of log shapes of several sand body types (Figure 2.5.21).

(b) Dipmeter data

The dipmeter tool is rarely used in hydrogeological applications. It provides an apparent dip of beds by comparing detailed micro-resistivity curves from opposing sides of the borehole. The tool incorporates a magnetometer or gyrocompass to provide an azimuth orientation for the dip measurements. The dip is computed directly from the offset of the resistivity changes recorded across a junction by multiple electrodes on the arms of the tool in contact with the borehole wall. Early tools provided 3 resistivity curves, modern tools record 6 or 8 curves from 3 or 4 independent arms, and are capable of providing a dip measurement every 0.01 m or so. Dipmeter data was used initially only to deduce structural dips but Campbell (1968) and others showed the dipmeter tool also provides useful sedimentary data.

The dipmeter measurement incorporates both structural and depositional dip information and it is necessary to separate the structural dip, recognised by recurrent more or less uniform azimuth dips, from the higher frequency more variable depositional dips. Gilreath and Maricelli (1964) identified 3 basic formation dip patterns:

i) consistent regional or structural dips.
ii) dip increasing with depth,
iii) dip decreasing with depth.

It is important to recognise whether dip patterns are continuous above, below and through the formation of interest and proper analysis requires good sedimentological experience of depositional structures. Allen (1975) illustrates the use of dipmeter data in the identification of sand bodies and depositional environment.

The proliferation of information furnished by modern dipmeter tools poses a problem of interpretation. Rider (1986) points out that geological models containing orientation and dip measurement with a frequency of one every 10 cm are not available to compare with the log data. The tool information thus surpasses the amount of information that can be supplied by the geologist. Cameron (1992) proposed statistical filtering of the dipmeter data to make the data more manageable. Figure 2.5.22 shows some typical dipmeter presentations.

The dipmeter is one of the most expensive logging tools to run and is usually only run in oilwells.

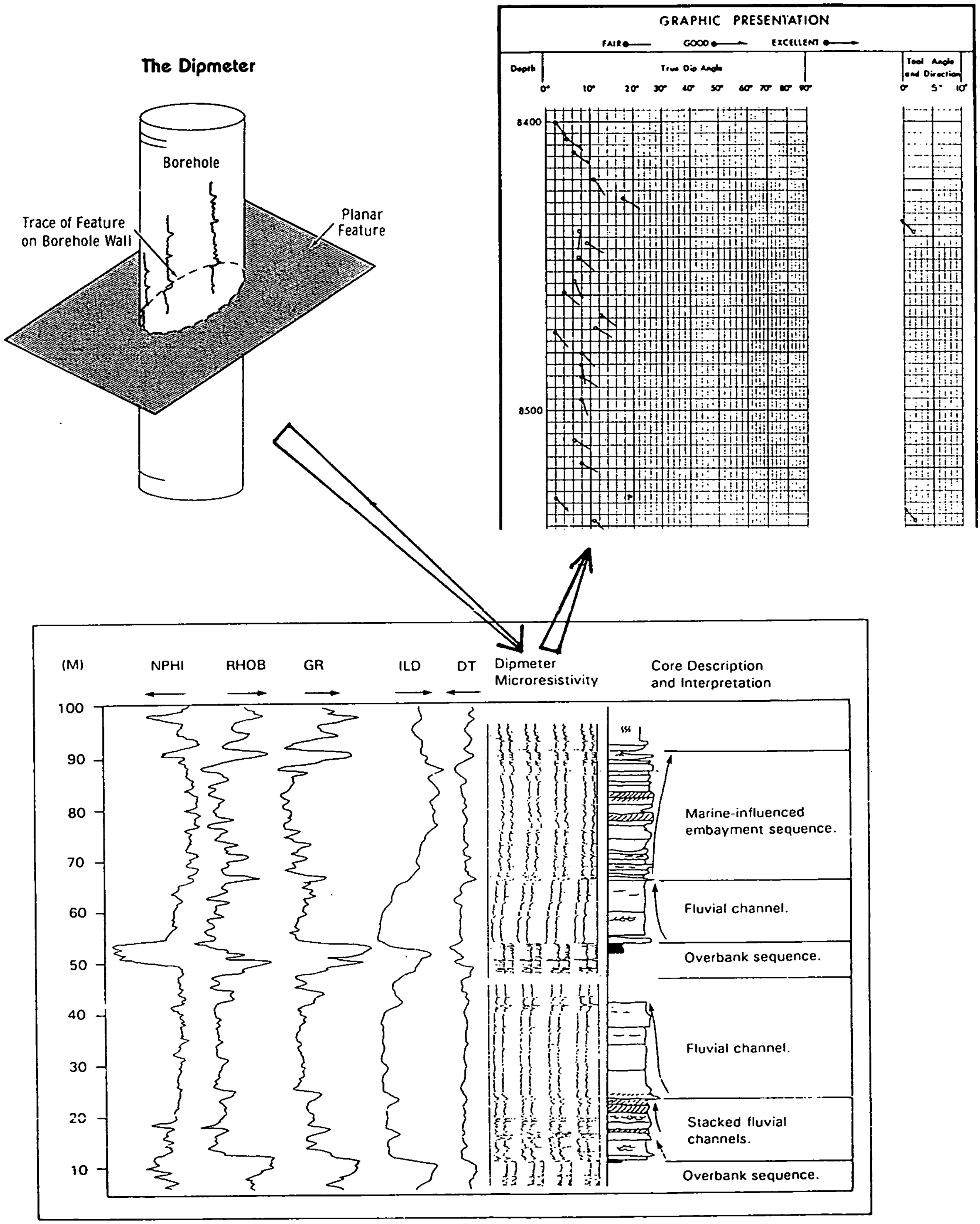


Figure 2.5.22 Typical dipmeter presentations (after Doveton, 1986; Cameron, 1992).

A more recent development of microresistivity log measurement is the Formation Micro Scanner tool (FMS)*. The tool which was introduced by Schlumberger in 1986 and provides orientated, 2-dimensional, high-resolution colour-coded microresistivity images of the borehole wall in 4 orientated strips 90° apart. It identifies fractures and with experience sedimentary features can be seen in the resistivity images. See, for example, Luthi (1990), Bourke (1992).

3. GEOPHYSICAL LOGGING IN COMPLETED BOREHOLES

Borehole completion in unconsolidated aquifers differs from typical open hole borehole completions in consolidated rocks by the need to install wellscreen, gravel pack and casing to support the borehole wall. Geophysical logs run in completed boreholes in unconsolidated materials therefore incorporate features due to the construction and pipework, in the measurements. This means that certain log measurements have to be run before completion. Logging in the wellscreen also provides information on the construction and properties of the wellscreen and the gravel pack. Provided the influence of the well construction is taken into account, fluid log measurements made in wellscreen are satisfactory.

3.1 The Objectives of Completed Well Logging

Geophysical logs are run in completed boreholes in unconsolidated aquifers (observation boreholes, abstraction boreholes) for several purposes:

(i) To obtain information from existing (older) boreholes. This may be for lithological information if they have not been logged previously in open hole, or to investigate water productivity or salinity or their changes with time.

(ii) To examine the condition of newly-completed boreholes and verify the construction.

(iii) To establish the position of water inflow horizons and their relative contribution to the yield.

(iv) To examine the effects of treatment, e.g. development, acidisation.

(v) To examine possible reasons for deterioration, e.g. decline in yield or increase in salinity which may be due to sand pumping, leaky casing, etc.

For some of the objectives the same techniques used in open hole logging are satisfactory. For example provided the gravel pack is not unduly thick or abnormally radioactive, a gamma ray log can be run perfectly well in the cased and screened well to indicate gross lithology (Figures 3.1.1, 3.1.2). Geophysical logging methods that can be used in steel or plastic cased and screened completed boreholes are listed in Table 4.

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* Schlumberger tradename

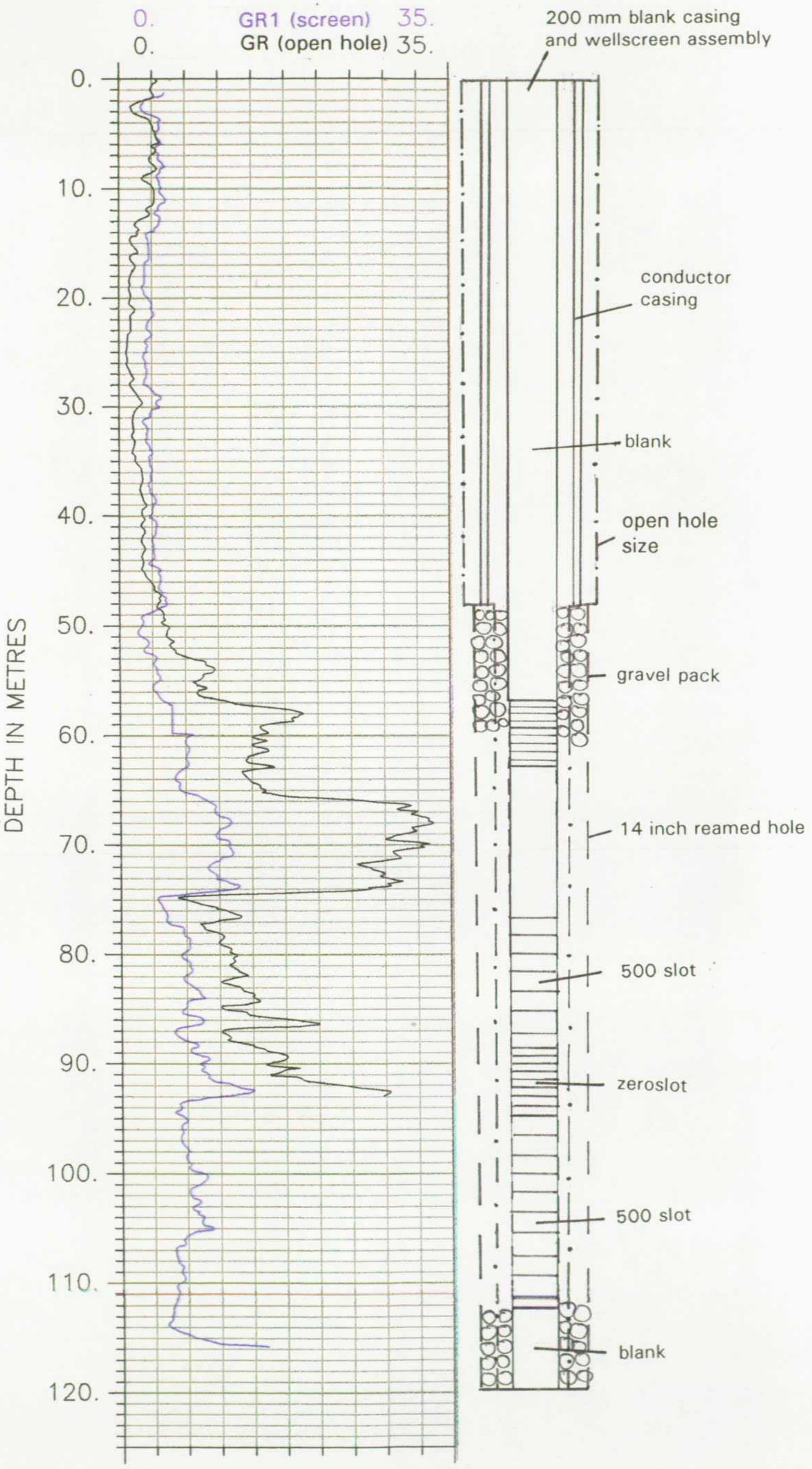

Figure 3.1.1 Gamma ray logs before and after screening.

3.2 The Logging Environment in Completed Wells

The logging environment in completed wells is dictated by the borehole completion and construction features. The completion may be natural whereby the formation is allowed to collapse around the wellscreen, but more often a gravel pack of uniform or graded sand is introduced between the open hole and the wellscreen to fill the annulus and form a filter. The different constructions affect the log measurements as do the different materials used for the casing and wellscreen, which are commonly mild steel, stainless steel, PVC plastic or glass reinforced plastic.

In the case of *Natural completion* the logging probe is separated from the formation by wellscreen or casing only. In the case of *Gravel pack completion* the logging probe is separated from the formations by the pack material and the wellscreen or casing. The pack dimensions may be such that logging probes are relatively far removed from the formation or clay layers may be placed as seals in the gravel pack to prevent excessive vertical fluid movement within the pack (Figure 3.1.2). The gravel pack then influences the log measurements.

All geophysical logs run inside cased and screened constructions will have some influence of the construction features within their measurements. Some logging techniques are designed to specifically examine borehole construction features (e.g. CBL, CCL).

3.2.1 The effect of casing and wellscreen on log responses

Certain logs are more influenced by the presence of casing and wellscreen than others. Sonic velocity measurements only measure the velocity of the liner when used in steel or plastic casing. Electrical resistivity logging can be used to make measurements 'through' the slots in steel or plastic wellscreen but cannot be used in blank sections. Induction resistivity measurements cannot be made in steel casing or wellscreen but can be used in plastic casing or screened holes. Gamma ray log measurements are usually little influenced by blank casing or slots in wellscreen and can be used in virtually all circumstances.

3.2.2 The influence of the gravel pack and clay seals

The effect of a thick gravel pack with non-uniform physical properties may render gamma ray, neutron, density, resistivity and induction log measurements unrepresentative of the formation. Repeatability of such measurements may be demonstrated but the logs may still be unrepresentative of the formation. The depth of investigation of the log measurement is the critical factor. Deeper reading devices are obviously better suited. Density measurements are particularly influenced by high density steel wellscreen. The density measurement has a shallow depth of investigation so that density logs of completed wells often only read the gravel pack. Neutron measurements are more strongly influenced by low density plastic wellscreen than steel casing because it moderates the fast neutrons and gives porosities that are too high, particularly at wellscreen joints.

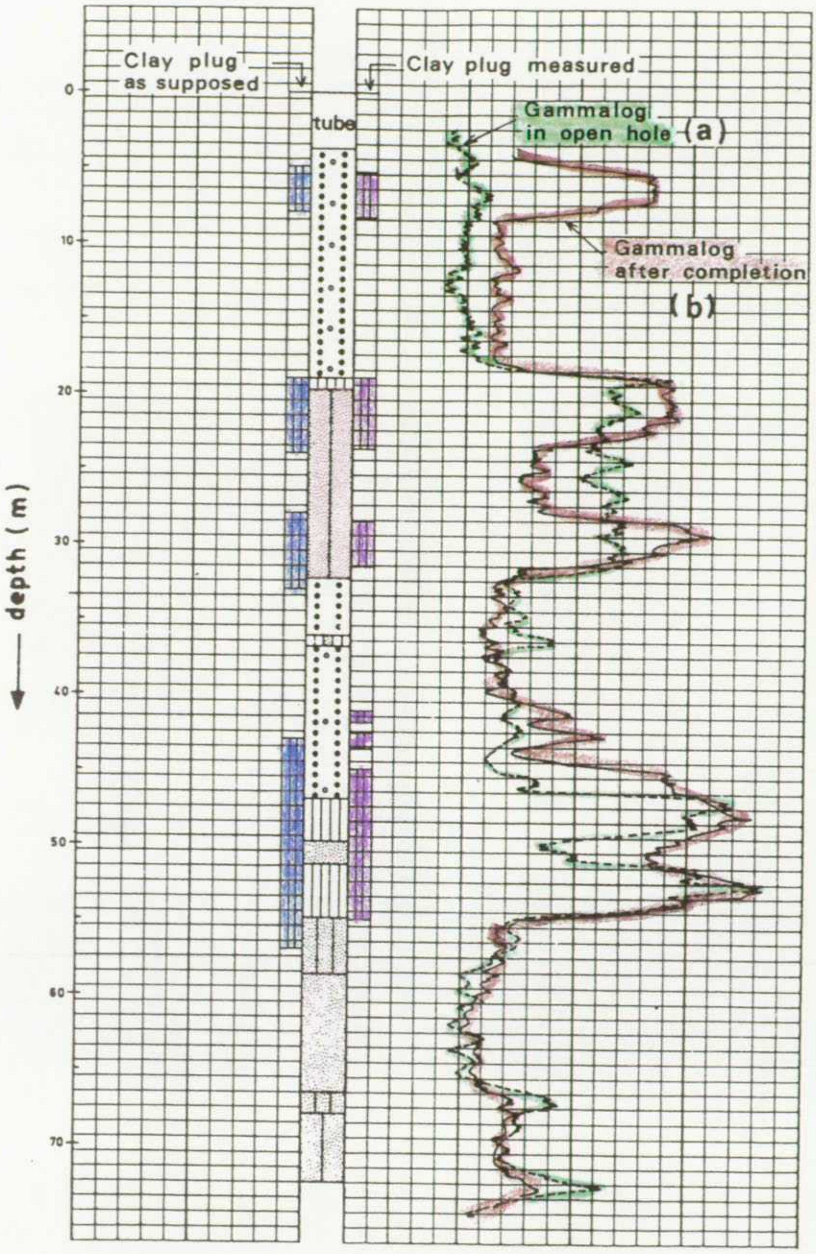

Figure 3.1.2 Gamma ray logs before and after screening and placing clay seals (from TNO, 1976).

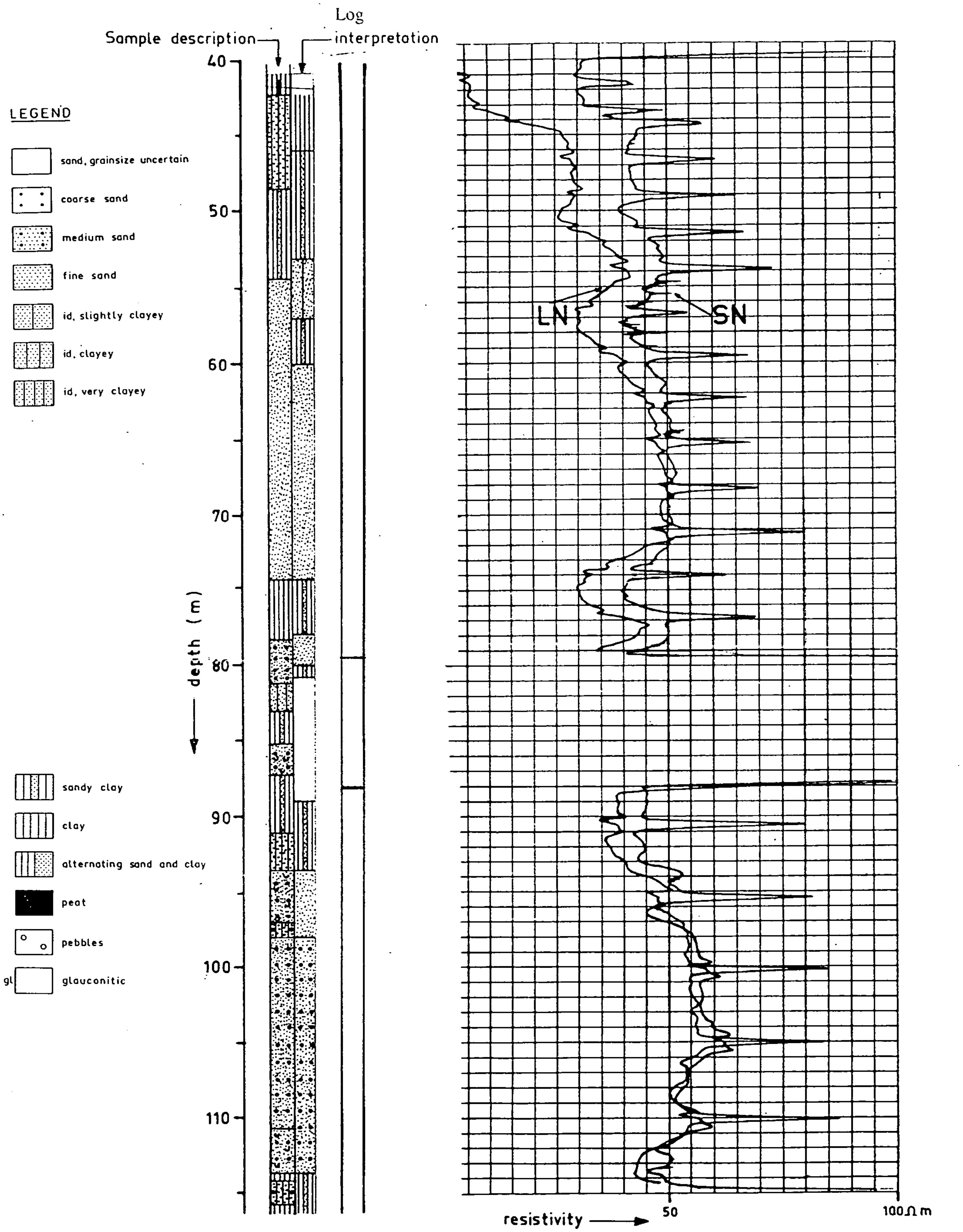

Figure 3.4.1 Short and long normal resistivity logs showing lithological variation measured through slots in plastic wellscreen (from TNO, 1976).

Clay layers may be placed in the gravel pack to seal the hole drilled in the clay in piezometer installations or to isolate screened sections and prevent upward movement of fluid through the gravel pack. These influence gamma ray, neutron, density, electrical resistivity and induction conductivity measurements.

3.3 Logging Techniques in Cased and Screened Wells

Certain logging techniques used in open hole logging can be used with limitations in cased and screened borehole completions, and some log measurements and techniques, including those of production logging, are specific to the completed wells only. Table 4 lists the main logging techniques used in completed wells and describes some of the limitations of the measurements when used in both steel casing and wellscreen and in plastic casing and wellscreen.

3.4 Interpretation of Logs Run in Cased and Screened Holes

3.4.1 Identification of lithology

In completed wells gamma ray measurements are very useful and can resolve lithological differences behind casing and wellscreen alike except where the gravel pack has a significant or variable gamma ray activity.

Electrical resistivity measurements are possible in screened intervals where focused resistivity measurements may 'read' through the slots to give a qualitative indication of bed boundaries (Figure 3.4.1). Where there is a plastic liner induction conductivity measurements are particularly useful and give a qualitative indication of the lithology and bed boundaries both above and below the water table (Figure 3.4.2). Such measurements can be affected by steel reinforcing at joints in the casing or at joints in wellscreen which may appear as regular peaks on the logs (Figure 3.4.3).

Neutron logs can provide information on lithological variation behind casing and wellscreen except in plastic completions where there is strong attenuation of the fast neutrons. In turn such attenuation can identify the presence of the plastic casing and differentiate blank and slotted sections.

The density log is strongly influenced by steel casing and wellscreen and the attenuation of incident gamma rays by the high density pipework means that the log measurements largely represent density variations of the adjacent screen and gravel pack. In turn this can be used to examine the properties of the gravel pack (Figure 3.4.4), or locate the position of slipped sections of casing. Dropped steel casing is easily identified by high density, sonic velocity (57 μS/ft) or its sharp effect on magnetic susceptibility or induction conductivity measurements (Figure 3.4.5).

Figure 3.4.4 is an example of logs run in a screened and gravel packed borehole. The neutron and density logs (NN, DEN) were run 12 hours after the gravel pack was installed and again after 60 hours (NN1, DEN1) when some settlement of the pack had occurred (detected at 29 to 30 m). Notice that casing and wellscreen joints are identified by log peaks every 3 m or so (see log SS, short-spaced density).

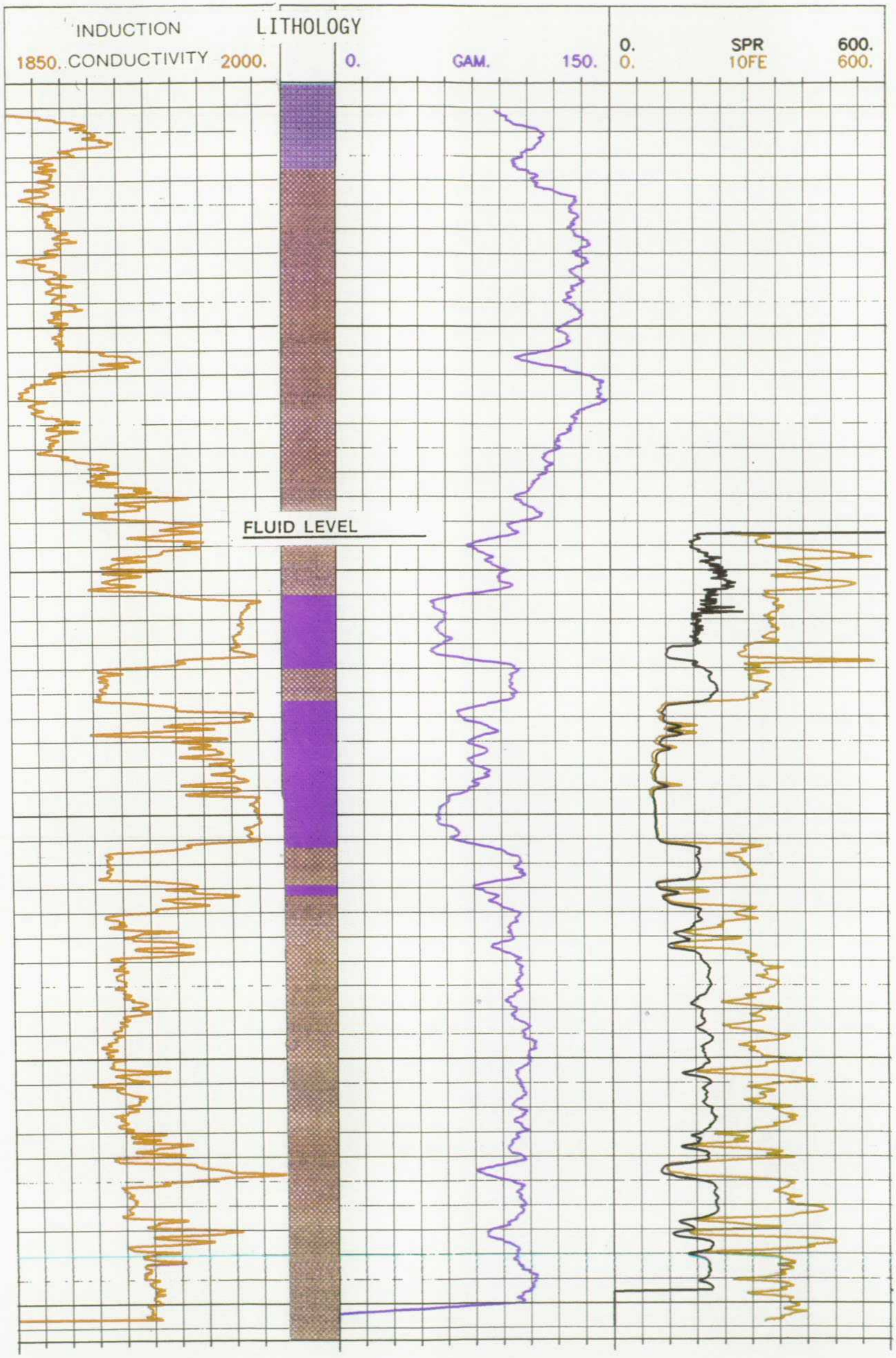

Figure 3.4.2 Induction log showing resistivity variation above and below the water table.

3.4.2 Logs which examine borehole construction

Caliper (CAL)

The three-arm or single arm caliper tool can be run in casing or screen to confirm the diameters and setting depths of telescopic or other constructions. Occasionally it may identify gaps in the casing string or indicate material (clays) squeezing through the wellscreen slots.

Casing collar locator (CCL)

The casing collar locator can be used in combination with several logging tools and is used specifically to identify joints in metallic casing. It was designed to check casing lengths for accurate depth placement of perforation charges in oil wells but can equally well be used to identify the joints in metallic casing or wellscreen in water wells (Figure 3.4.3). The tool contains an electromagnet, the magnetic flux of which is changed by variation in wall thickness of the casing which is seen at joints. The change in magnetic mass induces a voltage in the coil. The amplitude of the induced voltage depends upon the cable speed (linespeed) and increases for faster linespeed.

Cement bonding of casing (CBL)

The cement bond log provides a measurement of the cement bonding of steel casing. It is obtained with a sonic tool having a receiver calibrated to measure not only the arrival time of a compressional wave but the amplitude. The amplitude of a compressional wave travelling between transmitter and receiver in uncemented steel casing is not attenuated and is observed at the receiver as a free pipe signal. Where casing is cemented the wave amplitude becomes reduced and the greater the cement bonding the greater the attenuation of the amplitude (Figure 3.4.5). If the amplitude is thus scaled from free pipe signal (100%, zero bond) to zero amplitude (100% bond) a log of percentage bond can be obtained. It is very important the tool is centralised. Eccentering causes low amplitude and hence fictitiously good bonding. Eccentering by as little as 0.25" can decrease amplitude dramatically. A variable density display (VDL*) of the positive waveforms is helpful in assessing the casing-cement and cement-formation bonding (Figure 3.4.5).

Borehole video

Borehole television video is widely used in consolidated rock open hole boreholes to observe lithology and fluid inflow. It can be used in completed boreholes in unconsolidated formations to examine the completion. It is often brought in to investigate problems of sand entry throught the wellscreen or declining yield when it may identify broken or damaged screen (Plate 1) or corroded casing.

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* trademark of Schlumberger

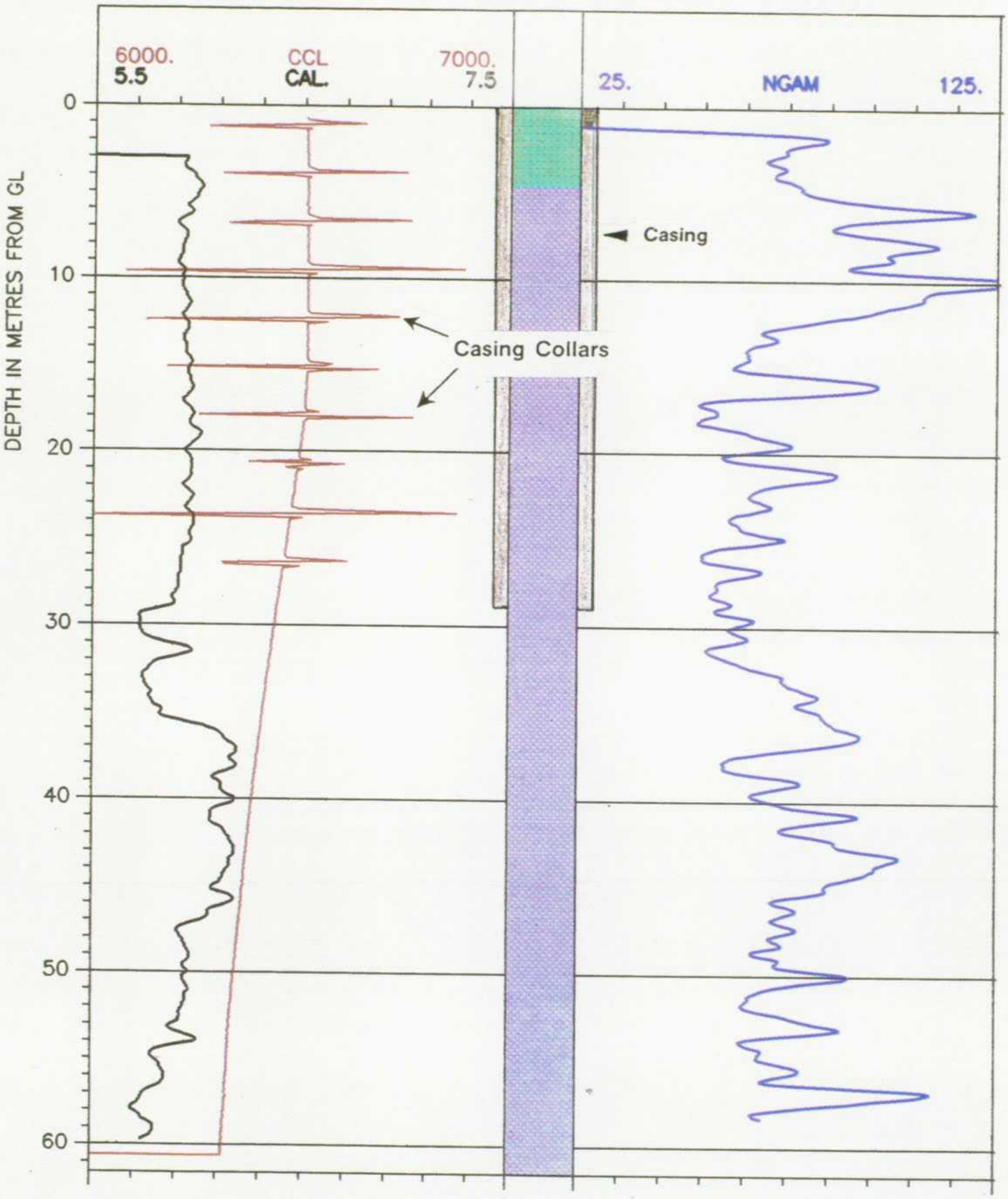


Figure 3.4.3 CCL log showing metal-reinforced joints in plastic casing.

Small diameter 35-50 mm colour chip cameras are currently used which are equipped with forward (axial) and side (radial) viewing lenses and lighting which can be controlled from the surface. Additional information can be put on the screen via a keyboard and depth is recorded automatically by encoded pulses from the cable wheel. The surveys are recorded on video tape or output to a video printer for hard copy. The current depth limit is ~600 m and is governed by the lighting power requirements. Special multi-conductor cables are used. Recently TV cameras that can connect to standard multi-conductor logging cable and are suitable to depths of 1200 m are becoming available.

3.4.3 Identification of fluid inflow

Measurements of fluid temperature (T), fluid electrical conductivity (EC), and fluid velocity (borehole flowmeter) can be used to identify fluid inflow and groundwater movement in the borehole. Small changes in fluid EC and T often occur at fluid inflow positions in the borehole for reasons of different circulation history and residence time of water at different depths. This is most marked in consolidated fractured sedimentary rocks where the circulation history, quality and temperature of groundwater in the fractures may be quite different to that of groundwater in the matrix pore space. Fluid EC and T measurements and flowmeter measurements made in the borehole can identify the positions of fluid entry. In unconsolidated formations such logs are largely restricted to completed wells and the entry positions in the wellscreen and casing also influence the log. Care therefore needs to be taken during interpretation.

Fluid conductivity and temperature measurements (EC, T)

In formations of uniform porosity and permeability and where there is no vertical groundwater movement, the fluid temperature increases approximately linearly with depth according to the geothermal gradient and the thermal conductivity of the rock layers. The geothermal gradient is variable but is commonly 2.0-3.0°C/100 m. The construction of a borehole may connect layers of different hydraulic conductivity and hydraulic head and this gives rise to natural vertical movement of fluids within the borehole. Such movement disturbs the geothermal gradient and can be observed by sensitive temperature and conductivity measurement of the borehole fluid. Vertical flow from one horizon to another is usually seen as a reduction or elimination of the natural temperature gradient and a constant fluid conductivity over the interval where vertical flow occurs. Hence straight sections on fluid T and EC logs usually signify vertical fluid movement either up or down. Inflow of water into the borehole is often seen as small changes in temperature or EC at the point of inflow.

In consolidated rocks such changes can be referred to fluid entry from the formation but in unconsolidated wells containing wellscreen and gravel pack the measurements may additionally relate to fluid entry through available openings in the wellscreen. This can be particularly disturbing where clay seals are not used in the gravel pack and there is significant vertical fluid movement in the gravel pack outside the wellscreen. This often has a tendency to enter the wellscreen over the top part of the wellscreen where it may be difficult to distinguish from a natural higher productivity of upward-coarsening units (Figure 3.4.6).

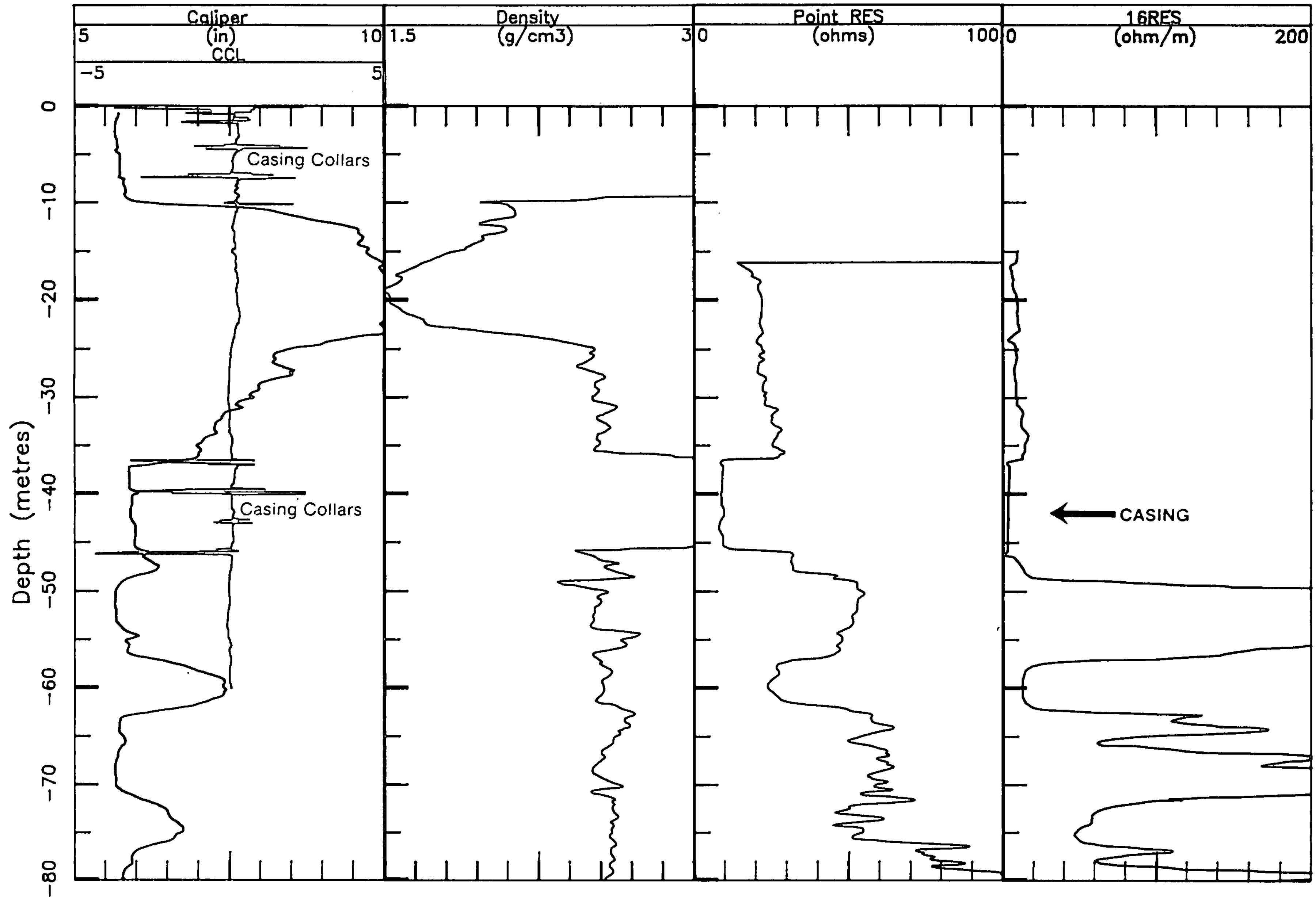


Figure 3.4.4 Geophysical logs showing a section of dropped steel casing.

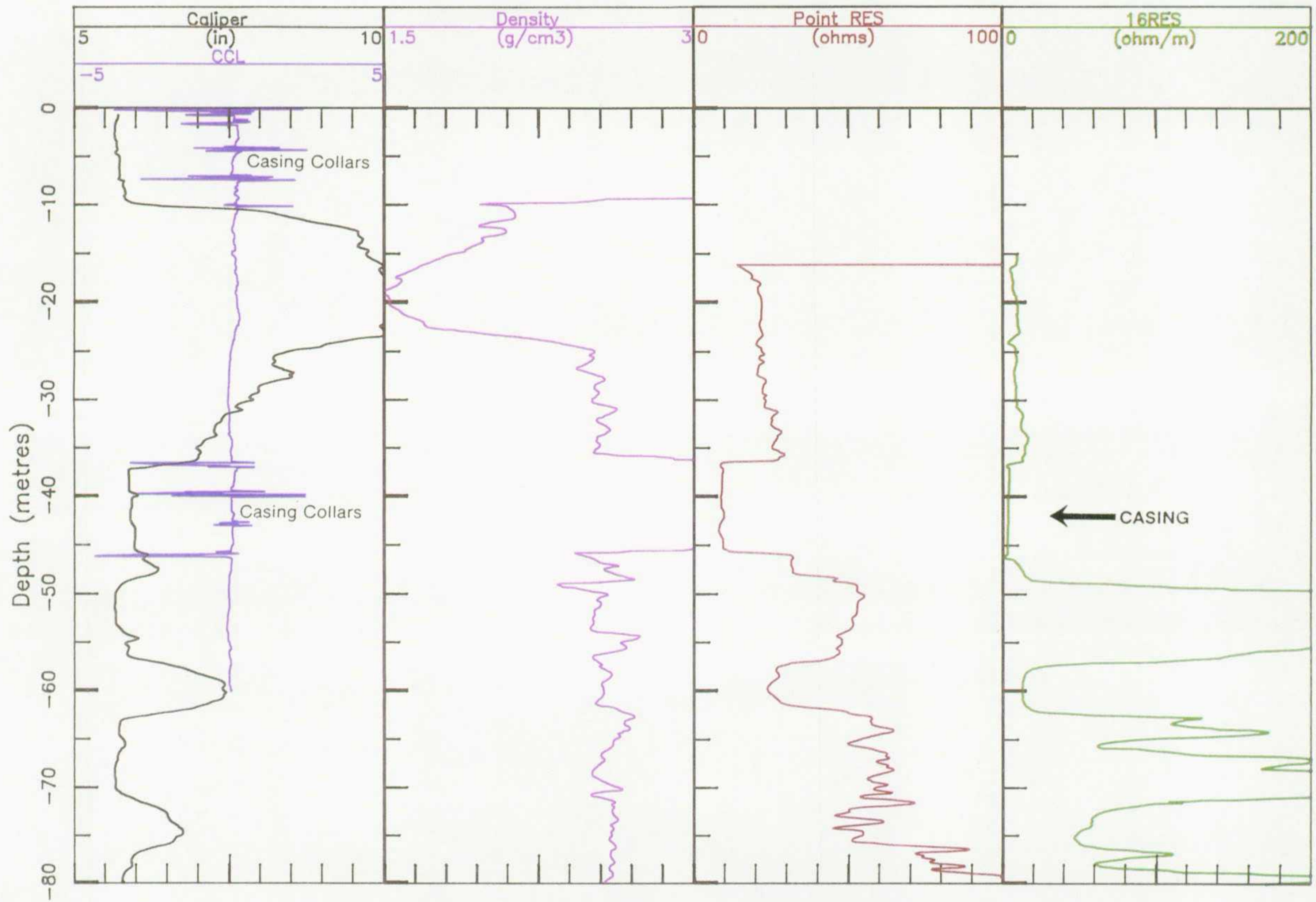


Figure 3.4.4 Geophysical logs showing a section of dropped steel casing.

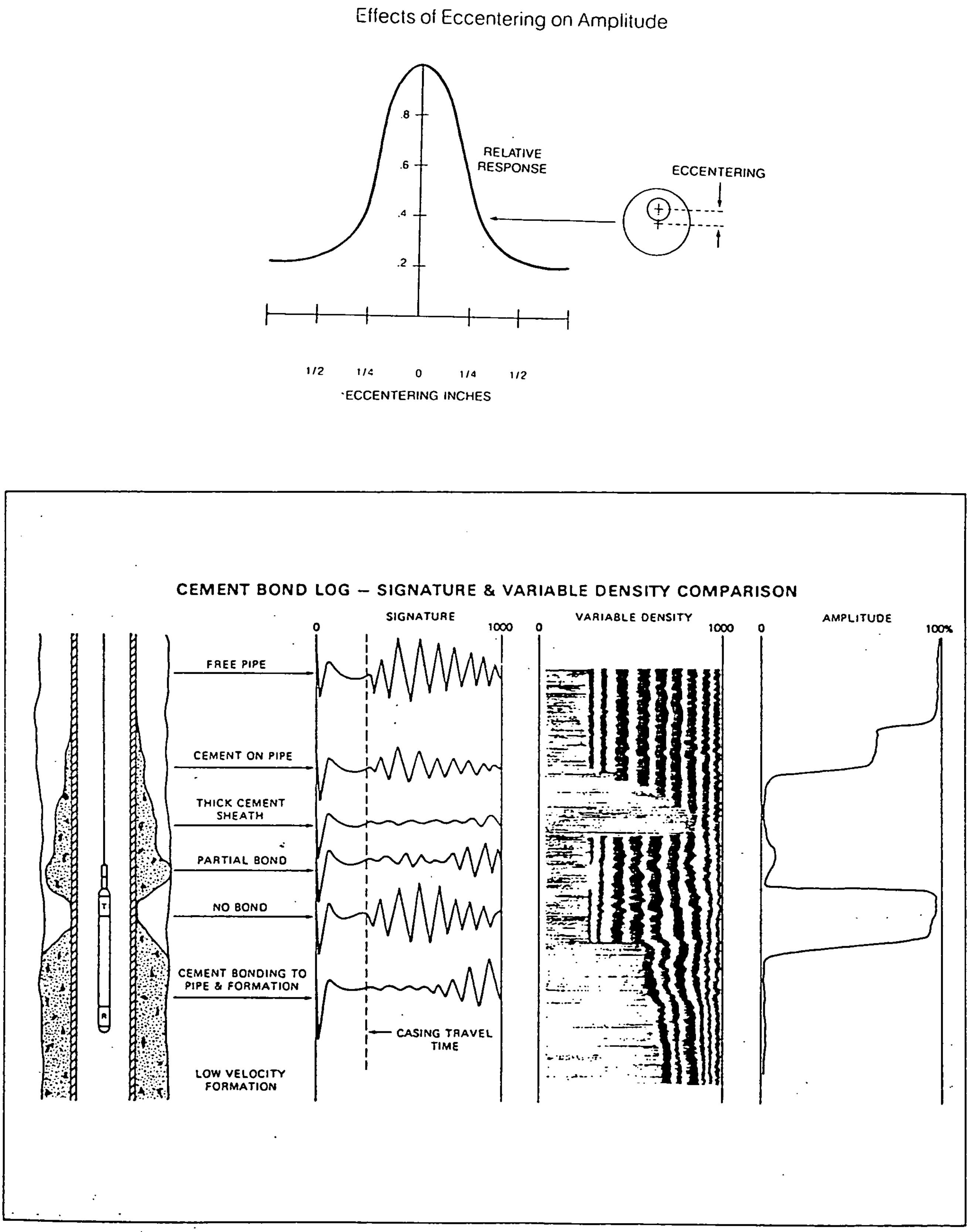


Figure 3.4.5 The effect of cement bond tool eccentering and typical presentations of cement bond log data (from N L McCullough document 1986, and Dresser Atlas document).

A feature of fluid temperature and fluid conductivity measurements is that they are dynamic and change in response to fluid movement and imposed external pressure head. The logs are therefore time-varying. Thus changes in EC and T will take place after drilling in response to recovery from invasion or as a result of development. By observing such changes over a period of time it is possible to identify the fluid movements taking place in the borehole. This is usually done by logging the borehole under radically different hydraulic conditions, e.g. during pumping and when not pumping. Generally fluid EC and T logs, run whilst pumping identify separate inflows, and a flowmeter log quantifies their contribution to the total yield (Figure 3.4.10, 3.4.11).

The temperature log may also be used to monitor the cementation of the casing or the dissipation of heat following acidisation. Hardening of cement is exothermic and newly-cemented casing may heat up the borehole fluid several degrees and the temperature may remain anomalously high for several weeks after grouting (Figure 3.4.7).

It is particularly useful to compare fluid EC/T logs of the well run over a period of time, or under changed hydraulic conditions by direct overlay plotting to show the developing changes (Figure 3.4.8). Monitoring of fluid EC and T over a period of time may reveal progressive increases or decreases at certain horizons due to various influences, e.g. salinisation, pollution.

Leakage through casing joints

Fluid leakage through screwed or welded steel casing joints can often be detected by fluid temperature and conductivity log anomalies where CCL logging identifies coincident joints (Figure 3.4.9). Leaks in plastic casing can similarly be identified by fluid logging in conjunction with focused resistivity measurements.

Borehole flowmeter logging (FM)

Borehole flowmeters that are used in consolidated aquifers may also be used inside wellscreen and casing to measure the vertical velocity of the borehole fluid. This may be under natural conditions, when a low velocity flowmeter of the thermal type (heat-pulse flowmeter) is usually used or more commonly run during pumping when an impeller (spinner) flowmeter is usually used. At inflows the fluid moving to the pump increases velocity and the fluid velocity profile in the borehole, corrected for diameter variation shows the inflow positions and their contribution to the total yield of the well. (Figure 3.4.10). The flowmeter is calibrated against a known fluid velocity or in pipes of known dimensions with allowance for the linespeed. Alternatively the log may be calibrated between zero and 100% by linear interpolation of the measurements using the maximum signal deflection at the pump inlet in blank casing.

In fractured and fissured aquifers in consolidated rocks fluid entry is often from discrete horizons and borehole flowmeter logs have a stepwise profile (Figure 3.4.10). In unconsolidated and granular materials the gradual influx from intergranular pore space produces a more gentle gradient on the flowmeter log curve as flow enters over a length of wellscreen (Figure 3.4.11). The flowmeter may reveal inflow over the

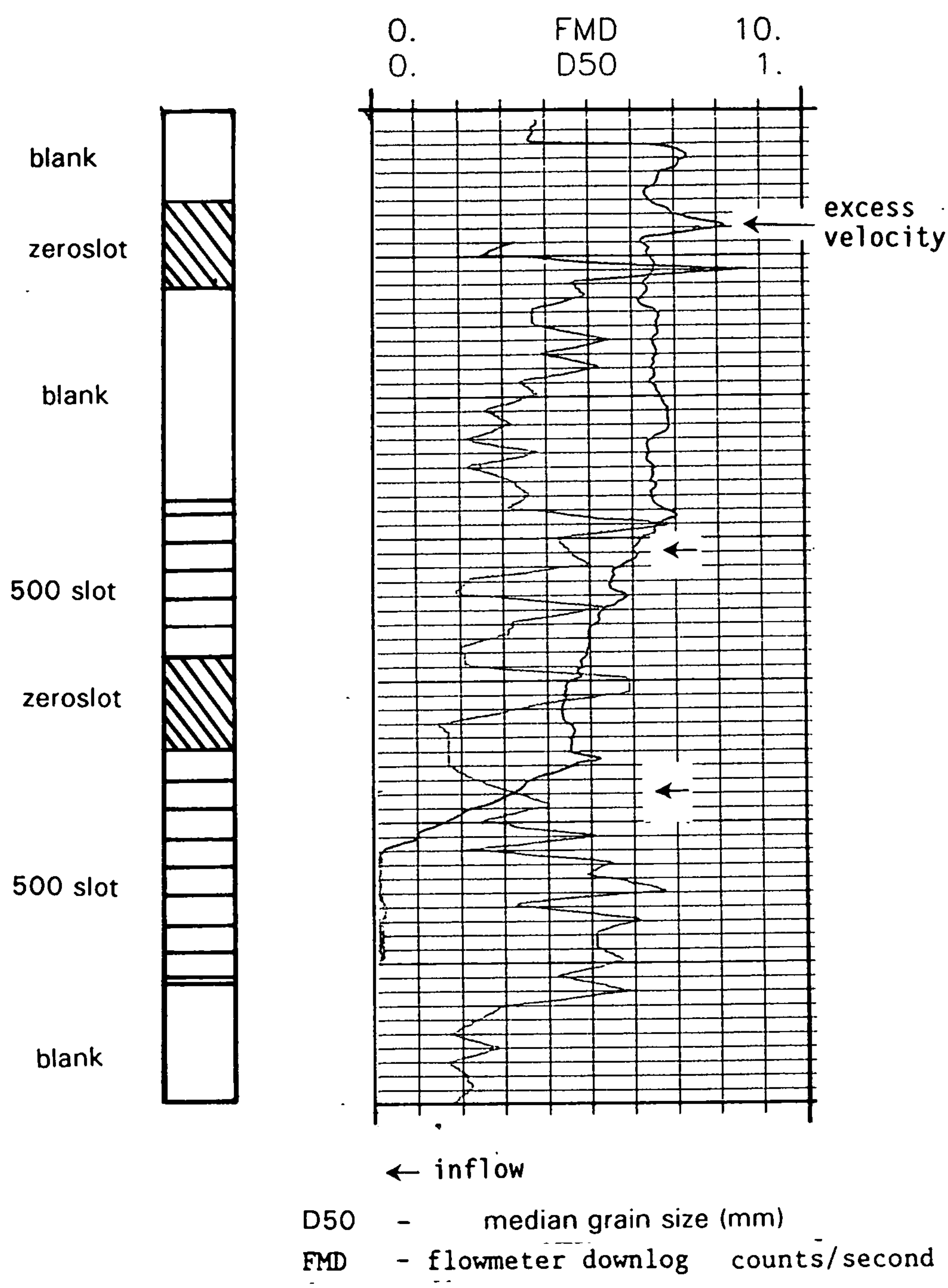


Figure 3.4.6 Flowmeter log in wellscreen showing inflow at top of screened sections.

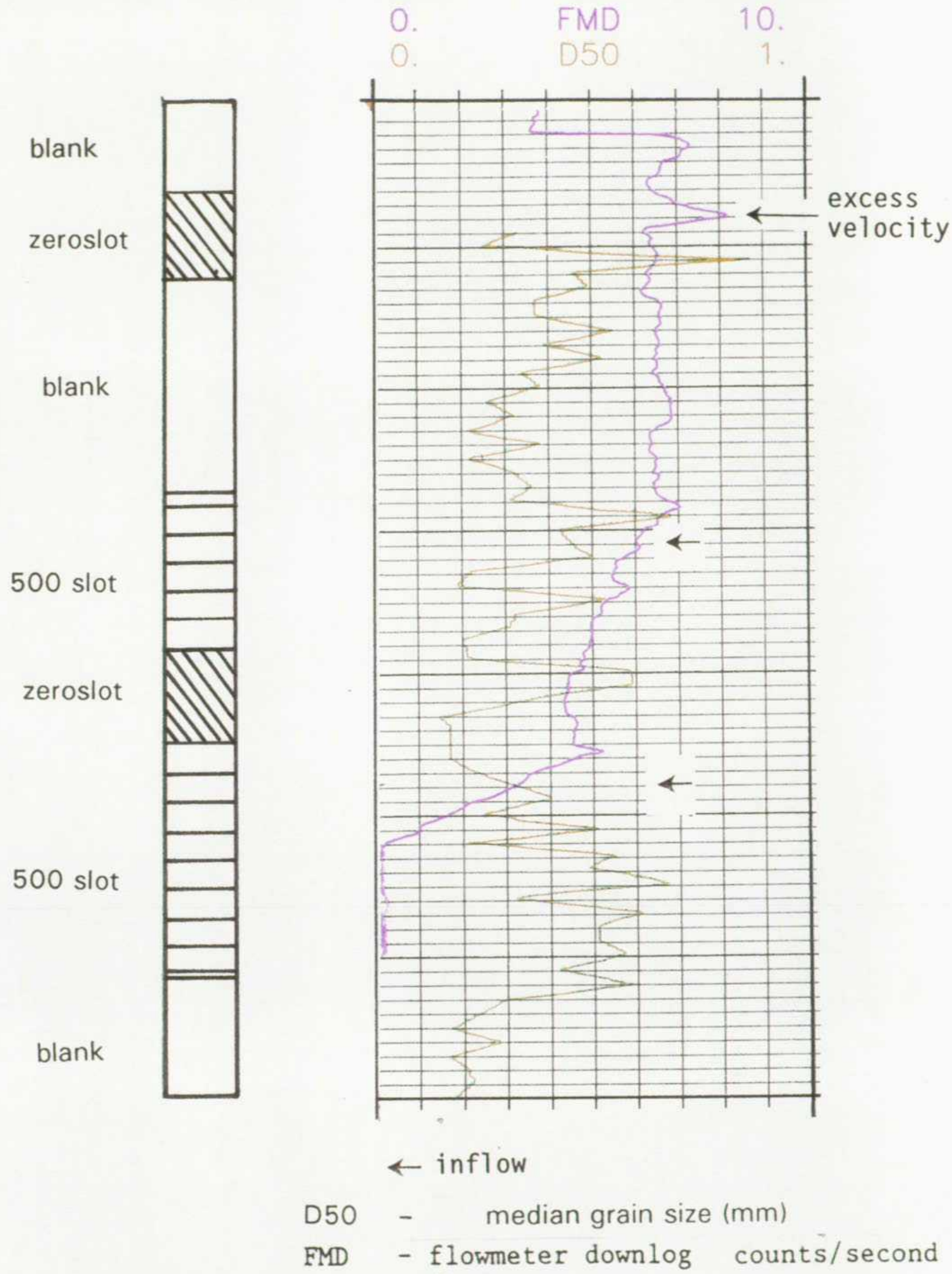


Figure 3.4.6 Flowmeter log in wellscreen showing inflow at top of screened sections.

whole length of screen or over only part of it. If no clay layers are placed in the gravel pack and there is vertical movement of fluid in the gravel pack, fluid entry may be seen concentrated over the slots near the top of the wellscreen.

Flowmeter logging of boreholes which have shown a decline in yield may show that blockage of a particular horizon (by mobilisation of fines) is responsible. A minor feature of flowmeter velocity profiles in wellscreens is the periodic variation in signal due to the change in wall smoothness (or diameter) at the wellscreen joints.

A specific and common feature observed on flowmeter logs in wellscreens is the recording of an 'excess velocity' at the top slot often immediately below sections of blank casing. It is also seen sometimes at the base of casing in consolidated rocks. It occurs where a large volume of water is obliged to enter the borehole radially through the top slots in the wellscreen or at the base of blank casing. The large quantity of radial inflow physically narrows the cross-sectional area over which vertical flow to the pump can take place. The flow is therefore accelerated and centred borehole flowmeters display a local high velocity which can be in excess of the equivalent total pumping discharge rate, hence 'excess velocity'. Excess velocity on flowmeter logs in wellscreen is indicated in Figure 3.4.11.

Composite log example

Figure 3.4.12 is a composite log example illustrating the use of certain geophysical logs in unconsolidated sediments. The borehole had been drilled to 120 m and cased to 50 m. Open hole logs run after drilling included only caliper (CAL), gamma ray (GR1) and 8-16-32 and 64 inch normal resistivity (08R-64R) measurements.

The borehole was drilled a nominal 8" (20 mm) diameter using a polymer drilling fluid. The resistivity logs identify porous and permeable sands by the invasion profiles. The wellscreen assembly lengths were chosen on the basis of the sampling and the gamma ray and resistivity log data and the wellscreen slot specification was based on sieve analysis results.

The open hole gamma ray and resistivity logs show typical mirror-image responses to sand (low GR/high RES) and clay (high GR/low RES) and the caliper log further shows the clayey horizon from 65-72 m is tending to squeeze. Finer-grained and more clayey horizons can be distinguished by increased gamma ray and low resistivity seen typically at the base of the indicated lithological units. The sand horizons are thus recognised as coarsening upward units. Log D_{50} (shown in red) is the sediment D_{50} median grain size constructed from sampling and sieve analysis. It shows the coarser horizons have higher resistivity and the overall median grain size variation in both the sands and clays is generally well matched by the resistivity log variation.

The borehole was then reamed 14½" diameter (370 mm) before inserting the wellscreen and gravel pack. A 6" (150 mm) stainless steel wellscreen and a 4" (100 mm) thick gravel pack was installed.

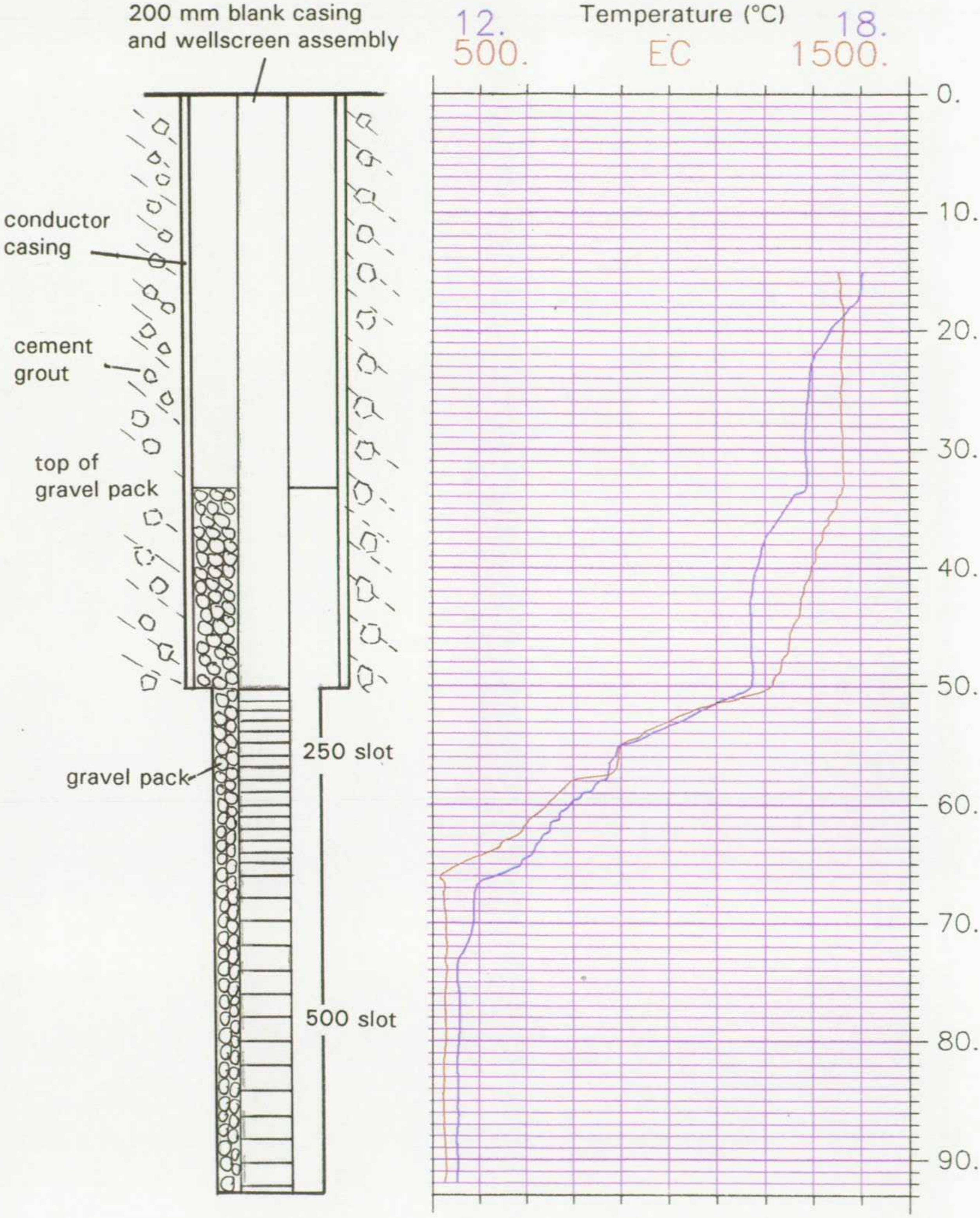


Figure 3.4.7 Effect of cement grout on fluid temperature and fluid conductance.

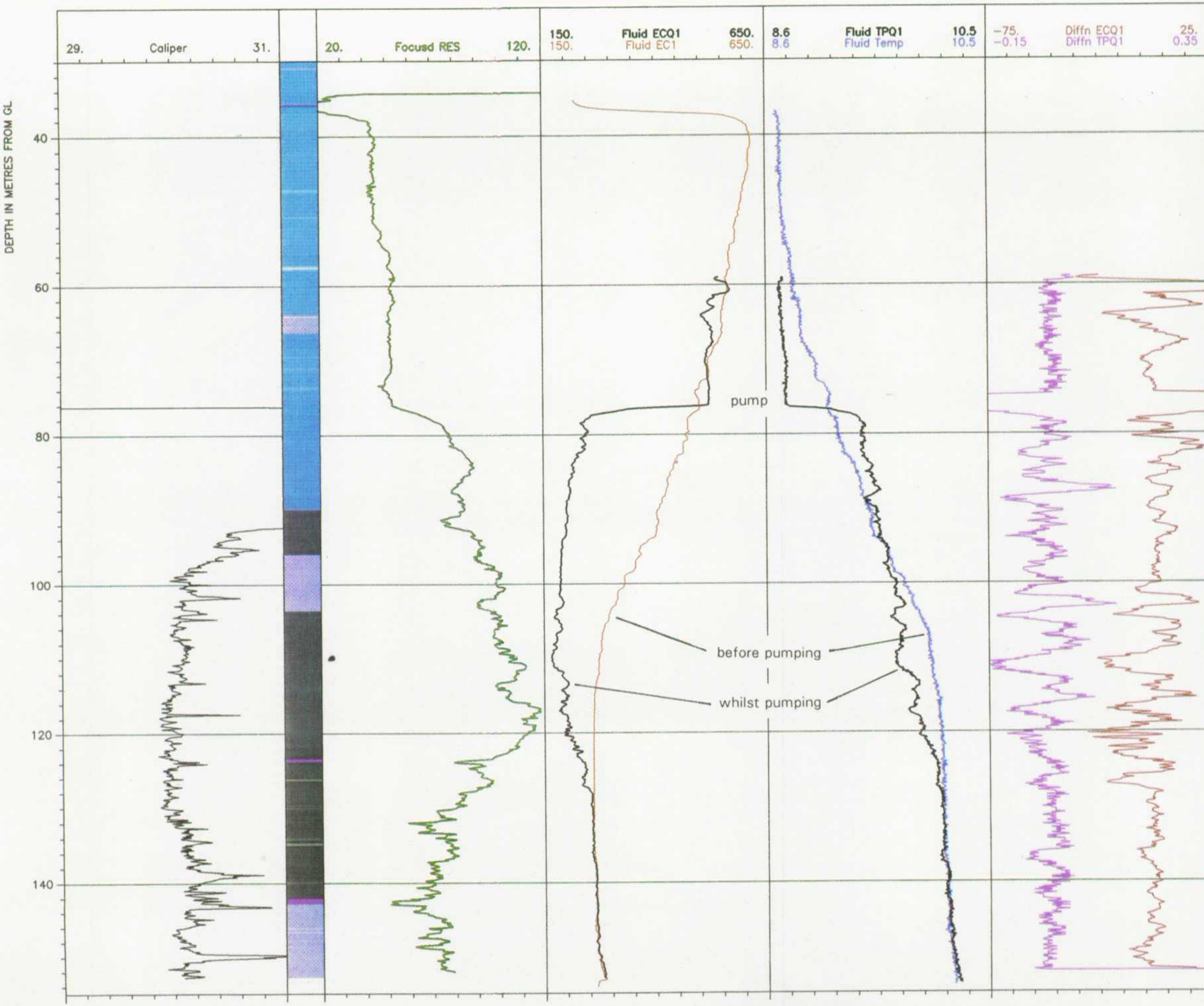


Figure 3.4.8 Overlay plot of fluid temperature and EC logs before and during pumping in large diameter borehole.

The wellscreen assembly comprised sections of 500 micron slot, zero slot (which allows water entry for sampling, open area ~2%) and blank pipe as shown in Figure 3.4.12.

Several geophysical logs run in the completed borehole are shown to the right of the resistivity track. Logs DEN/DEN2 are formation density logs derived from the short detector (SS) and long detector (LS) count rates. They identify the top of the gravel pack at 53 m. The density logs also identify the different sections of the screen assembly and the joints in the construction at approximately 6 m intervals.

The borehole was subsequently developed by air-lift pumping followed by step-drawdown and constant rate testing. The effect of development was an increase in porosity below 96 m shown by the blue infill between the neutron log curves run before (NN) and after (NN2) development. Associated settlement of the gravel pack is revealed by the density logs.

A test pump was installed at 50 m and fluid EC, temperature and flowmeter logs (FSC) were run whilst pumping (Figure 3.4.13). The fluid temperature log shows an increasing temperature gradient below 98 m signifying little or no fluid movement. Above this depth water moves up to the pump both cooled and increasing in EC, from inflows, e.g. at 98-96 m and 86-78 m. The inflows are observed by the flowmeter downlog (FMD) and stop count log (FSC) as prominent deflections to the right where they are seen to occur alongside the upper part of the 500 slot screen.

Minor peaks present on the flowmeter logs coincide with wellscreen joints at 58 (actually an 'excess velocity' effect), 72, 78, 84 and 90 m. The flowmeter logs reveal approximately 50% of the total production is obtained from the top 3 m of the lower screen and approximately 50% from the top 4-5 m of the upper screened section.

Figure 3.4.11 is an example of flowmeter logging during step-drawdown testing of a borehole in the Netherlands (TNO, 1976). The logs show the relative proportions entering the wellscreen at depth in response to pumping with approximately 50% of the total flow obtained from the top 10 m of screen.

3.4.4 Examination of factors influencing yield

Geophysical logs can also examine factors influencing well yield. These include observing the effects of well development, the removal of fines, sand invasion of the gravel pack, blockage of the gravel pack filter and screen, encrustation or corrosion of the wellscreen slots, and physical damage to the wellscreen. Various logging techniques are used with the borehole either at rest or during pumping.

Well development

The efficiency of well development may be directly assessed by specific capacity testing. The removal of fine material from interparticle pore space responsible for yield improvements can be examined by logging techniques which measure porosity. Hence neutron or density measurements in the wellscreen before and after

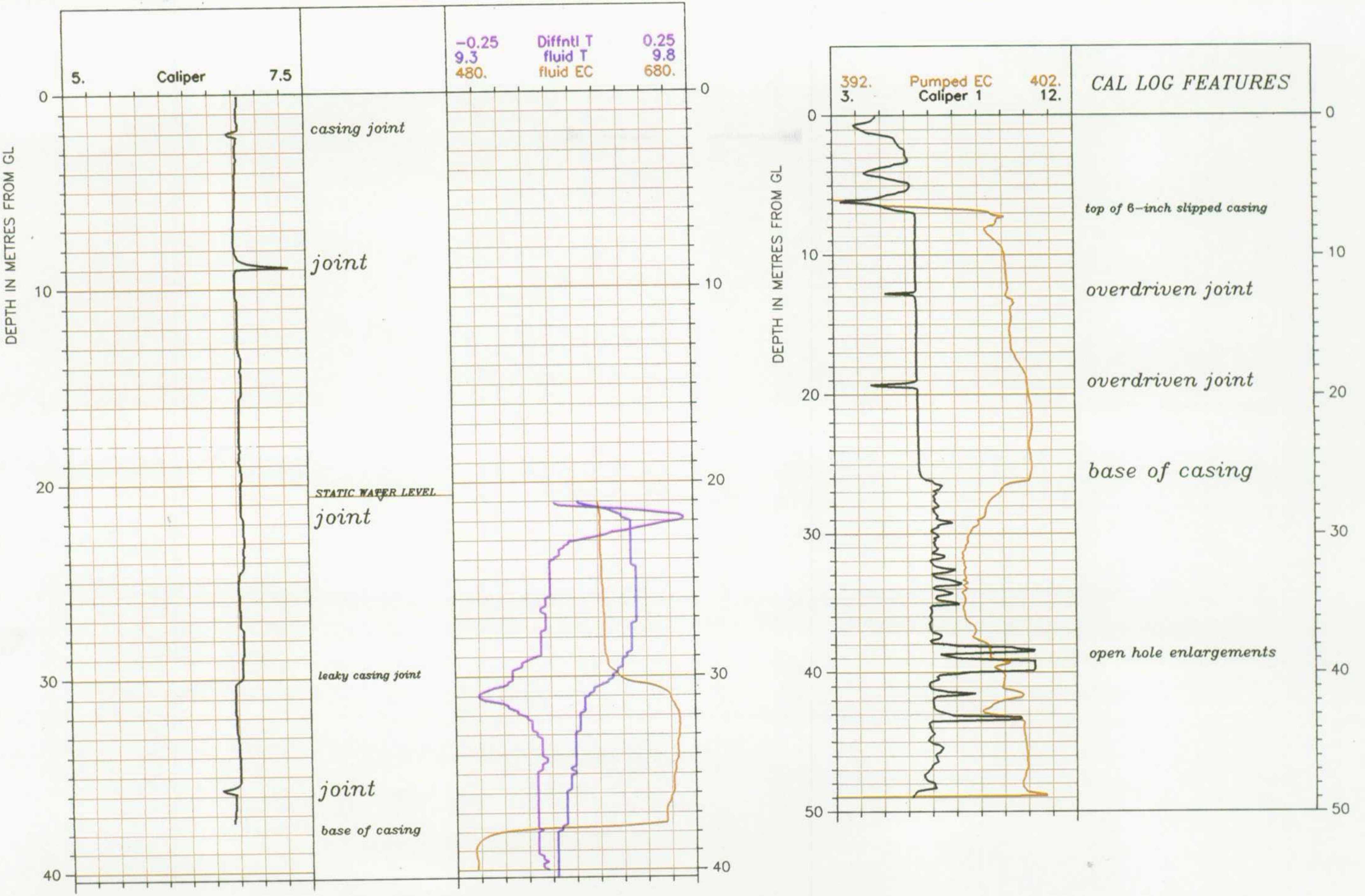
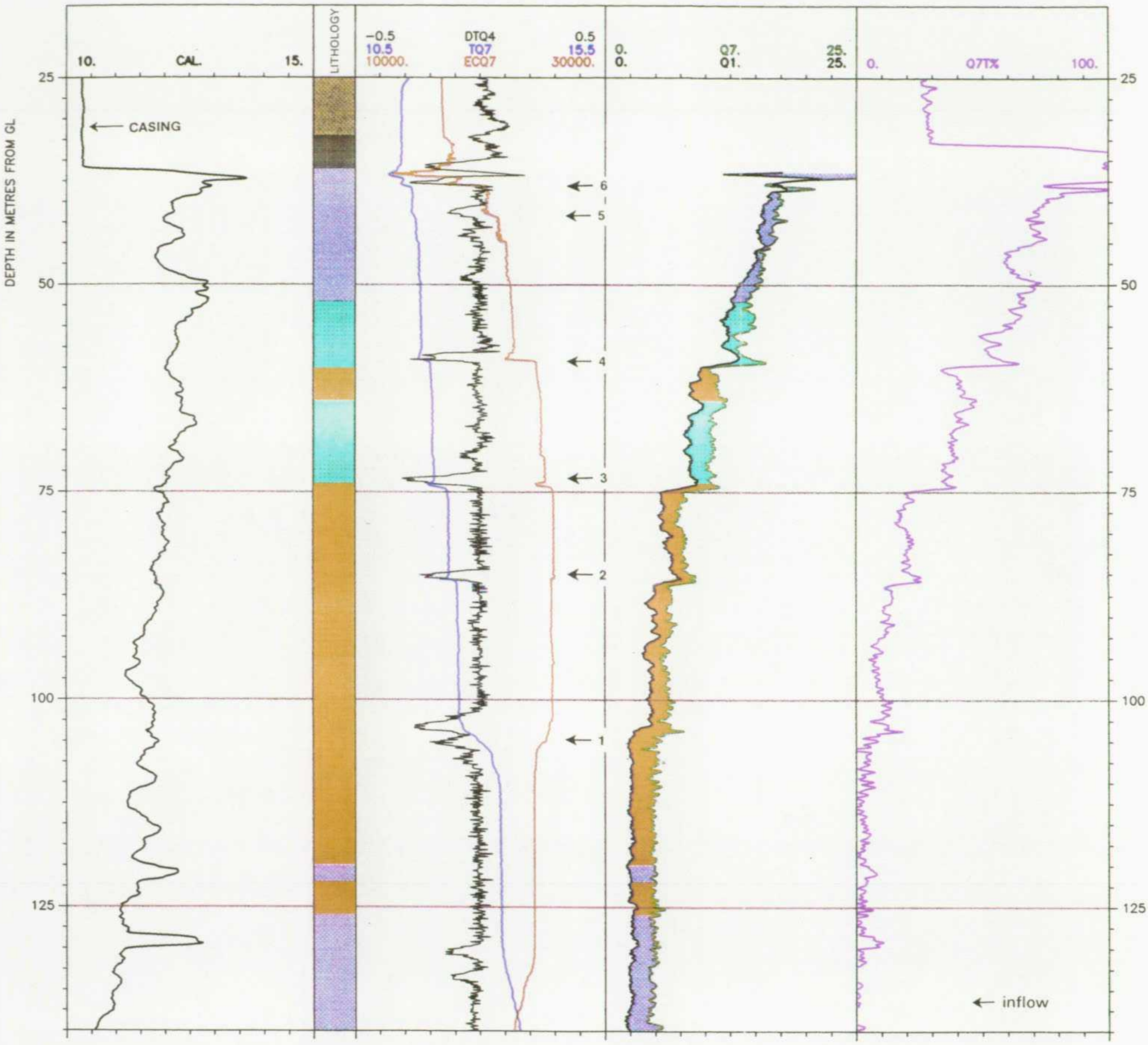


Figure 3.4.9 Geophysical logs identifying casing defects in completed wells.



CAL	:	caliper (in)
DTQ4	:	differential temperature (°C)
TQ7	:	fluid temperature (°C)
ECQ7	:	fluid conductivity (µS/cm)
Q1	:	flowmeter (cps)
Q7	:	flowmeter (cps)
Q7%	:	vertical flow (%)

Figure 3.4.10 Geophysical logs showing fluid inflow (consolidated rocks).

development can monitor the removal of fines. Flowmeter logging can be used subsequently to identify any improvement in inflow from the developed horizons.

Sand invasion of the gravel pack and filter blockage

Porosity logs may also indicate a decrease in porosity of the gravel pack when fine sand particles mobilised by pumping invade and block the water-filled pore space of the gravel pack. This can be shown by geophysical logs run in completed boreholesbefore, during and after development.

Figure 3.4.14 shows geophysical logs run in a sand pumping borehole. The borehole had been drilled approximately 30 inch (760 mm) and 20 inch (500 mm) open hole and was completed with 12" (300 mm) diameter plastic wellscreen slotted from 32-87 m with 1000 micron slots. The slotted pipe is wrapped with plastic HYDROTECH* mesh and the annulus is filled with gravel (3-5 mm). No logs had been run in the large diameter open hole.

Although a large diameter hole , the gamma ray log (GR) run in the plastic wellscreen does respond to some of the lithological changes identified during drilling and shown by the lithology column. The density log (DEN) has limited depth of penetration and the log values show that it is essentially a log of the plastic HYDROTECH mesh and surrounding gravel. The top of the gravel pack is revealed by increased density at 29 m above which the low values (1.0-1.3 g/cm^3) are of the plastic base pipe and the water-filled annulus. Above 12 m (SWL) density is <1.0 g/cm^3 on account of the air-filled annulus and low density of the plastic. At joints in the casing the pipe is not slotted, there is no mesh, and the gravel pack comes closer to the base pipe. This effectively increases the density at the joint which is shown by the peaks on the log at approximately 3 m intervals.

The density log in Figure 3.4.14 shows three zones where density increases to 1.5-1.6 g/cm^3 (30-38, 41-49 and 70-78 m) and horizontal comparison with the flowmeter log (FSC) shows that the upper two zones coincide with the main inflow horizons. The implication is that fluid inflow over this interval has mobilised fine sand particles which have invaded the HYDROTECH mesh and increased its density. The density increase at 70-78 m is not however matched by similar evidence of inflow. Test records reveal however that during the initial step-drawdown testing when sand entry was first observed, PWL was 43 m. At that time the upper producing zone and part of the lower zone must have been dewatered so that production must then have come from a deeper horizon. The increase in density of the gravel pack noted on the log at 70-78 m suggests where this water inflow and fine sand invasion of the pack and HYDROTECH mesh took place.

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* Tradename of J Laing Ltd

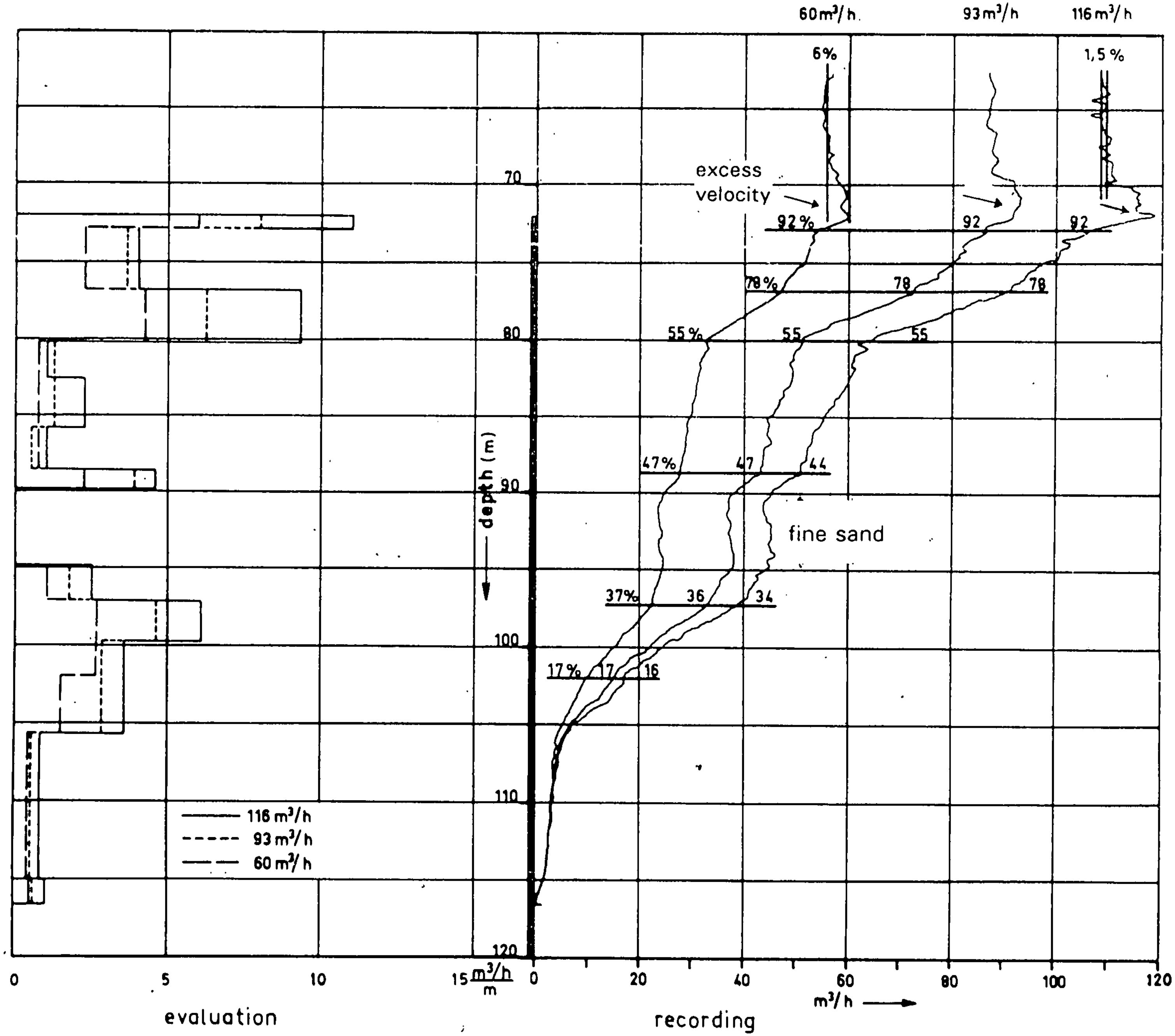
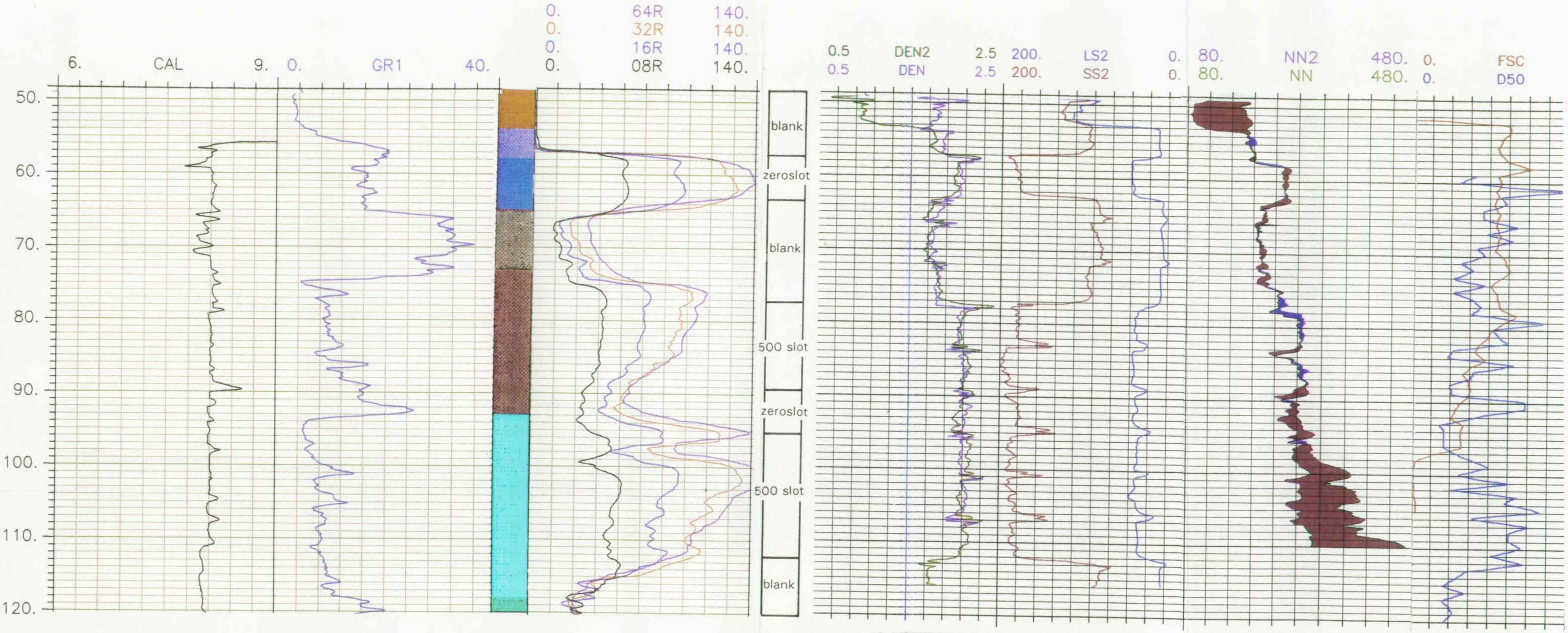


Figure 3.4.11 Flowmeter logging in wellscreen during step drawdown testing (from TNO, 1976).



OPEN HOLE LOGS

CAL : Caliper (in)

GR1 : Gamma ray (counts/second)

D50 : median grain size (mm)

08R-64R : 8, 16, 32, 64-inch normal resistivity (ohm/m)

COMPLETED HOLE LOGS

DEN : Density (g/cm^3) before development

DEN2 : Density (g/cm^3) after development

SS2 : short-spacing density (counts/second)

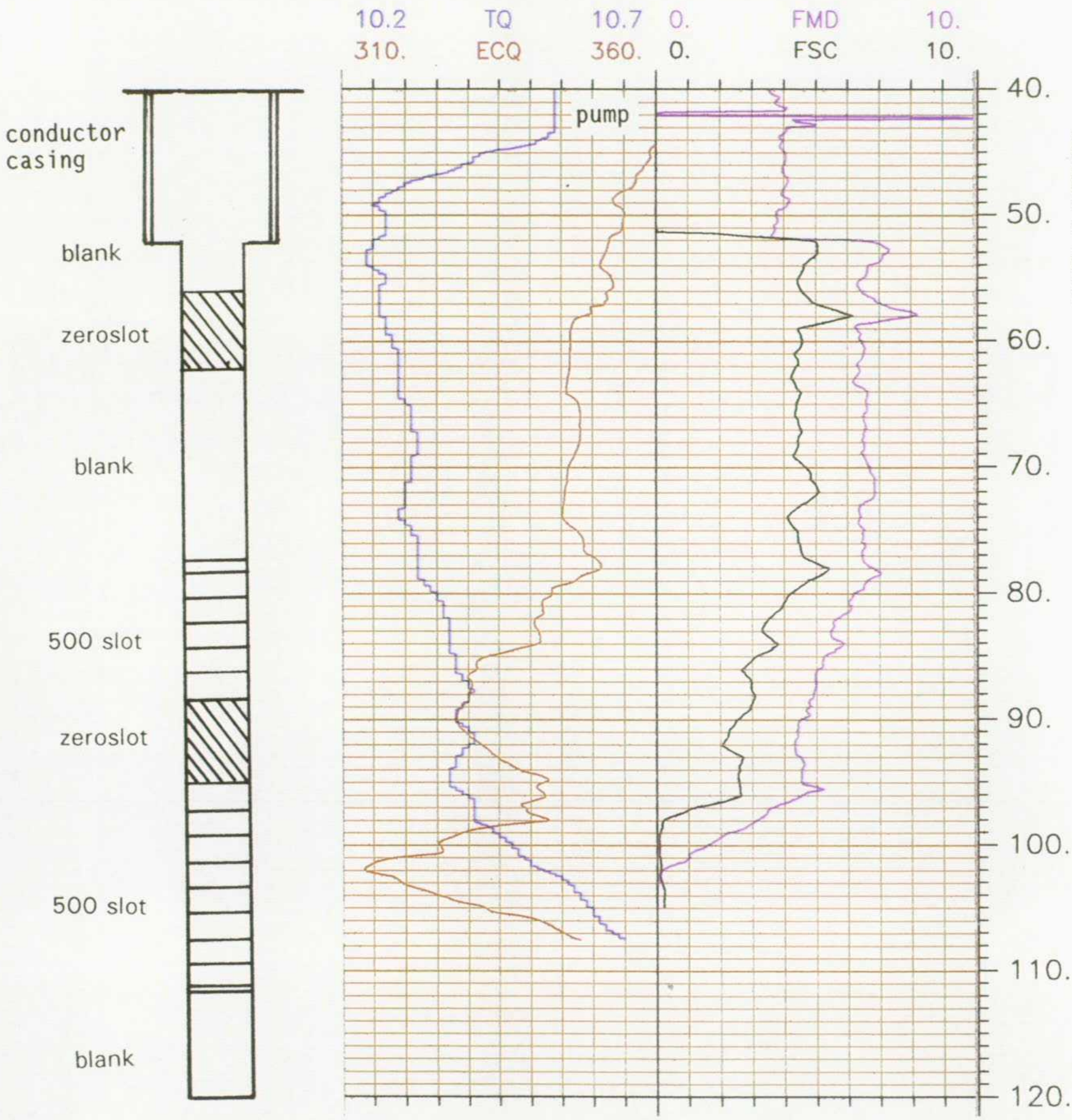
LS2 : long-spacing density (counts/second)

NN : neutron before development (counts/second)

NN2 : neutron after development (counts/second)

FSC : flowmeter stop counts (revs/sec)

Figure 3.4.12 Composite plot of open hole and completed hole logs.



ECQ	- fluid electrical conductivity whilst pumping	µS/cm
TQ	- fluid temperature whilst pumping	°C
FMD	- flowmeter downlog	counts/second
FSC	- flowmeter stop counts	counts/second

Figure 3.4.13 Fluid logs in wellscreen.

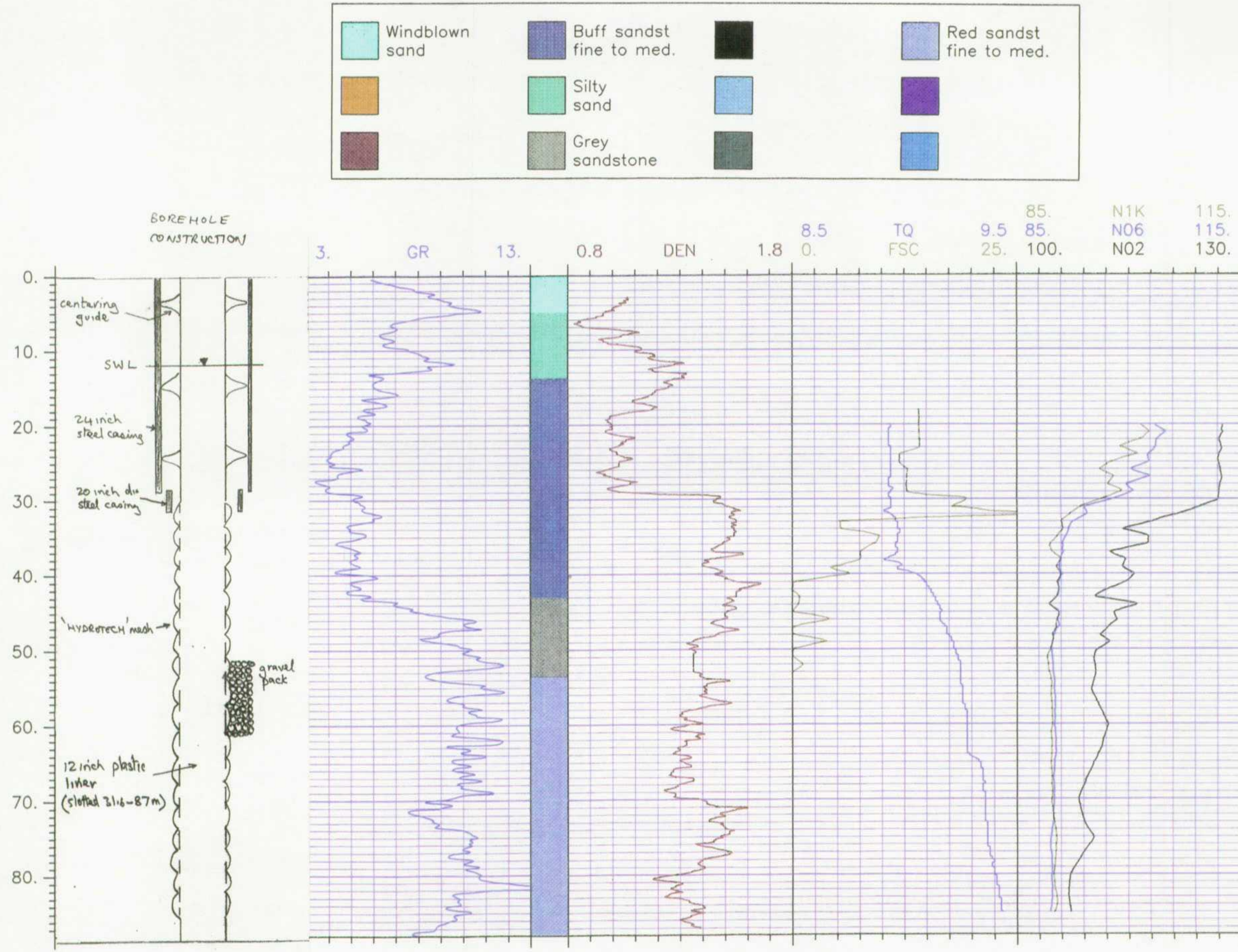


Figure 3.4.14 Geophysical logs in borehole constructed with HYDROTECH plastic mesh liner.

The temperature log (TQ) was run whilst pumping with a small pump placed at 20 m. The changes on the log suggest inflows at 32, 38-40, 45-46, 64-65 and 76 m depth. Below 76 m a geothermal gradient exists suggesting little or no vertical flow. The flowmeter log confirms inflows at 32 m (base of casing), and at 38-40 m, but below 40 m the vertical velocity is less than the threshold velocity of the flowmeter at the available pumping rate.

Figure 3.4.14 also shows noise log curves N02, N06 and N1K. These were recorded with a noise tool designed to examine the acoustic noise of high pressure gas and fluid entry into hydrocarbon boreholes. For the application of noise log measurements in hydrocarbon boreholes see for example Stein et al (1972), McKinley et al (1973), Robinson (1976), and relevant documents of Gearhart-Owen, Dresser Atlas and Schlumberger. The tool contains a piezo-electric crystal sensitive to acoustic energy in the 200 Hz-2 KHz range and the measurements are made with the probe stopped to eliminate any noise due to cable motion. The amplitude and frequency of noise is recorded. It was thought the 'pinging' caused by sand grain entry might be detected. The curves display the acoustic amplitude (in dB) above the frequencies of 200 Hz, 600 Hz and 1 KHz. The 200 Hz curve (N02) shows highest energy because it includes the higher frequencies.

The noise curves do show a general agreement with the flowmeter log and show increased noise energy above 50 m depth relating to the fluid inflows from the higher density sections. Local energy peaks at 60 and 75 m (where fluid velocity is below flowmeter probe threshold) may also signify inflow.

Borehole television video logging may also be used to investigate sand entry through wellscreen slots. The logging may be done with the borehole at rest or during pumping. Broken or damaged screen may be observed directly and slots may be seen to be enlarged due to corrosion. Logging whilst pumping may reveal where sand enters provided this is not from the bottom of the well so that the visibility is all poor. Monitoring of the wellscreen by well logging and television inspection can thus provide valuable information on the condition of the well.

Encrustation of screen

Physical and chemical factors may lead to the deposition of cement-like carbonate scale, the deposition of FeMn oxides or encourage bacterial slime growth on wellscreens which may all reduce well yield. Borehole television inspection can be used to recognise the nature of the encrustation and identify such problems. Resistivity and caliper logging may also be useful in cases of severe encrustation.

Several specialist logging tools are designed specifically for casing inspection. These include a multi-arm casing caliper tool comprising 64 independent arms for detailed measurement of borehole shape and size to detect casing corrosion or damage, and a magnetic flux eddy-current tool to measure casing thickness and corrosion. Details of these tools which are mainly used in petroleum production logging are given by Desbrandes (1985).

Screen damage

Wellscreen damage or breaks of the wellscreen joints or of the seal between wellscreen and blank casing may lead to sand pumping or may allow the gravel pack inside the wellscreen. Borehole television can be used to observe the sand entry or sand infill to the point of damage or failure.

3.4.5 Examination of changes in fluid salinity

Fluid EC and T time-series logging

Change in fluid salinity of a pumped borehole may occur for various reasons including overpumping, failure of blank casing to isolate poorer quality or contaminated water, leakage of joints in the construction and saline intrusion of the aquifer. The relative ease of contamination of unconsolidated aquifers by pollutants from the surface, or by injected wastes at depth means that adequate and satisfactory borehole construction methods must be adopted to exclude poor quality water. Fluid logging alone or in combination with other logs may reveal leakage at joints (Figure 3.4.9), faulty seals, or poor cement grouting in the construction allowing poorer quality water which is often of different temperature, to enter the wellscreen.

Fluid depth sampling

Samples of the borehole fluid may be taken at specific depths using a depth sampler. Some designs of depth-sampler (e.g. mechanical) may accidentally trigger by contact with the wellscreen or obstruction in the well. Motor-driven samplers are more reliable in this respect. It is important to know the location of the fluid sample collected in relation to any fluid movement taking place in the borehole. Fluid depth sampling whilst pumping generally provides more representative samples, especially where natural fluid movement is taking place in the borehole.

4. TOPICS WORTHY OF FURTHER RESEARCH

(1) The close association between sediment grain properties and electrical resistivity measurements and between grain properties and hydraulic conductivity which exist in freshwater-saturated unconsolidated materials, means that a study of log responses and sediment properties and hydraulic conductivity may produce useful relationships.

(2) An examination of diagenetic effects including for example compaction and cementation, and their influence on log responses, in unconsolidated aquifers would be useful. Such features tend to have a disproportionately large influence on groundwater movement and often have great hydrogeological importance.

(3) An examination of the relationship between magnetic susceptibility measurements, grain properties and hydraulic properties of aquifers could be

useful. Magnetic susceptibility measurements reflect the magnetic mineral composition and grain coating and in principle relate to grain size and surface area, both of which relate strongly to hydraulic conductivity and porosity. An examination of their interaction in log responses could be a potentially useful area of research.

(4) More use should be made of the electromagnetic propagation tool to obtain porosity in unconsolidated materials. Unconsolidated formations are potentially unstable which can be a risk for radioactive neutron and density logging. A low-frequency 25 MHz tool can be used in cemented or uncemented PVC or fibreglass casing.

(5) The spontaneous potential log is often featureless in many hydrogeological applications because of an insufficient salinity contrast between borehole and formation fluid. An assessment could be made of the value or otherwise of artificially stimulating the SP by deliberately altering the borehole fluid salinity to produce SP logs of more character.

(6) Further development of techniques which investigate sand entry and organic chemical presence in boreholes would be valuable. Techniques which examine sand grain entry (e.g. TV, noise) could be applied to study the effect of different pumping rates on sand grain movement into wellscreens and gravel packs of different design. Results could help refine criteria for appropriate wellscreen selection. Borehole television cameras that can operate through standard wireline logging cable are now available and will lead to greater integrated use of the TV data with conventional geophysical log information.

(7) Measurements while drilling (MWD) is a system in use in oilwell exploration boreholes. It comprises log measurements made with a downhole sensor sub placed in the drill string and recorded during drilling. The sensor sub is powered by battery or generator, and sends signals to the surface via telemetry. One system in use employs coded pressure pulses in the drilling fluid to transmit the sensor signals to a receiver at the surface. Many measurements are now made whilst drilling by this method including, torque, weight on bit, fluid pressure, fluid temperature, natural gamma ray activity, formation travel time, formation resistivity, hole azimuth and deviation.

With increased use and reduction in cost this method may come to have an application in open hole water-well drilling. The use of similar downhole sensor subs for storing time-varying log data (e.g. fluid log information) has important applications in several hydrogeological studies.

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Geophysics
IEEE Transactions
Journal of Society of Petroleum Engineers

Applied articles on mainly hydrocarbon logging topics are published in several publications including:

Bulletin of the American Association of Petroleum Geologists
Journal of Petroleum Technology
The Log Analyst
SPWLC Transactions and Conference Proceedings
Oil and Gas Journal
Petroleum Engineer

Articles on logging for non-petroleum purposes are to be found in
Groundwater
Groundwater Monitoring Review
Groundwater Management
Bulletin of the International Association of Hydrological Sciences
Journal of Hydrology
Journal of Contaminant Hydrology
Quarterly Journal of Engineering Geology
International Association of Hydrogoeologists publications

A bibliography of well-logging literature which includes non-petroleum applications is compiled each year by Stephen E Prensky of the USGS and published annually in the November-December edition of Log Analyst. It represents a valuable source of information.

General Texts on Well Logging Theory and Practice

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METHODS SUMMARY: GEOPHYSICAL LOGGING IN BOREHOLES

Geophysical borehole logging is a complex and specialist subject and whilst geophysical logging can be undertaken by hydrogeologists, particularly in consolidated materials, it is recommended geophysical logging of unconsolidated materials should be done by specialists. The additional demands of logging unconsolidated materials in mud-supported holes, or in large diameters, or through wellscreens, with specialised equipment often in a limited time opportunity, and the critical nature of the information obtained regarding the well design, is such that it is best left to experts in log acquisition and log interpretation.

For these reasons, method summary sheets describing how to undertake the geophysical logging techniques, such as those listed in Table 4, for example, are not appropriate. This information is available, however, from publication sources listed in the references and from general logging texts included in the Bibliography (Section 6 of the Companion Review). For those interested in the methodology of geophysical logging the following publications are a selection of several which provide practical information.

1. Methods for geophysical logging of boreholes 1981. International Society for rock mechanics, Commission on Standardisation of Laboratory and Field Tests. Int. Soc. Rock Mech. Min Sci and Geomech Abstr 18, p 67-84.

2. IAEA Borehole logging for uranium exploration: a manual. IAEA, Vienna 1982 280 pp.

3. Repsold H. 1989. Well Logging in Groundwater Development. IAH Int. Contrib. to Hydrogeology Series V.9.

4. BS 7022: 1988, British Standards Guide for geophysical logging of boreholes for hydrogeological purposes. British Standards Institution.

5. Log Interpretation Principles/Applications 1989. Schlumberger Educational Services.

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The following sections give information on the practical minimum logging requirements in unconsolidated aquifers, provide information on several features to consider when logs are run, provide information on log calibration and log quality control to ensure appropriate logs are run and the measurements made are representative and satisfactory.

1. Geophysical Logging Programmes

Ideally as many geophysical logging methods as possible should be run to satisfy the objectives of logging, though it is recognised that for practical reasons a certain minimum number of logs only would be run to provide the information required.

LOG TYPE	Measurement	Units	Dry hole	Open hole ⊗ unconsolidated	Open hole ⊗ consolidated	Steel cased or screened ⊗ unconsolidated	Steel cased or screened ⊗ consolidated	non-metallic cased or screened ⊗ unconsolidated	non-metallic cased or screened ⊗ consolidated	Main purposes
CALIPER •	borehole or casing diameter	mm, inches	✓	✓	✓	✓	✓	✓	✓	Borehole diameter, relative hardness, lithology, confirm construction features, log corrections
GAMMA RAY •	total radiation of gamma rays	cps, API	✓	✓	✓	*(1)	*(1)	*(1)	*(1)	Determine lithology, particularly sand/clay indication, clay content, correlation of strata
SINGLE POINT RESISTANCE •	relative resistance of formations, symmetrical response	ohms	-	✓	✓	-	-	*(2)	*(2)	Determine approximate lithology, sand/clay, correlation of strata
SPONTANEOUS POTENTIAL •	imbalance of ion concentration in borehole fluid	mV	-	✓(3)	✓(3)	-	-	-	-	Porosity and permeability indicator, relative sand/clay indicator, fluid salinity
ELECTRICAL RESISTIVITY •	resistivity of formations near borehole	ohm.m	-	✓	✓	-	-	*(4)	*(4)	Relative lithology indicator, correlation of strata, fluid salinity
(i) 16, 64 inch normal	short to medium penetration, asymmetrical response	ohm.m	-	✓	✓	-	-	*(4)	*(4)	Near to far invaded zone resistivity, lithology indicator, correlation of strata
(ii) focussed resistivity	absolute resistivity of formations, deep penetration, symmetrical response	ohm.m	-	✓	✓	-	-	*(4)	*(4)	Deep reading, true formation resistivity measurement. Lithology indicator, correlation
(iii) micro-resistivity	resistivity of immediate vicinity of borehole using contact pad devices	ohm.m	-	✓	✓	-	-	-	-	Borehole wall and near-invaded zone resistivity measurement, fracture indicator
INDUCTION	measurement of rock conductivity	mS/m	✓	✓	✓	-	-	✓	✓	Determination of true, moderate (<100 ohm.m) to low resistivity in all holes except steel lined
DENSITY	scattered gamma ray population (~ electron density)	cps, g/cm³	-	✓	✓	(5)	*(5)	*(5)	*(5)	Determination of formation bulk density, porosity, lithology
NEUTRON POROSITY	thermal neutron or capture gamma ray population	cps, % matrix porosity	-	✓	✓	*(1)	*(1)	*(1)	*(1)	Determination of porosity lithology, fluid level, position of plastic casing
SONIC VELOCITY	acoustic velocity	m/s, µs/ft	-	*(6)	✓	-	-	-	-	Determination of rock porosity, fracturing and relative lithology
CEMENT BOND LOG	acoustic amplitude	% bond	-	-	-	✓	✓	-	-	Monitoring the intensity of casing cementation
CASING COLLAR LOCATOR	flux variation of an open electromagnetic array		-	-	-	✓	✓	-	-	Location of collars and joints in steel casing and well screen
FLUID CONDUCTIVITY •	resistivity or conductivity of borehole fluid	µS/cm	-	✓	✓	✓(7)	✓(7)	✓(7)	✓(7)	Determination of fluid salinity, identifying fluid inflow and fluid movement
FLUID TEMPERATURE •	temperature of borehole fluid	°C	-	✓	✓	✓*(7)	*(7)	*(7)	*(7)	Determination of geothermal gradient, identifying fluid inflow and fluid movement
FLUID FLOWMETER •	velocity of fluid in the borehole	m/s, mm/s	-	-	✓(8)	*(8,9)	*(8,9)	*(8,9)	*(8,9)	Determination of water inflow and outflow and relative contributions to yield of different layers
FLUID SAMPLER	sampling of fluid at depth	volume	-	-	✓(8)	*(8,9)	*(8,9)	*(8,9)	*(8,9)	Taking water samples from specific depths
INCLINATION	gravitational, magnetic field strengths and directions	tilt and azimuth	✓	✓	✓	-(10)	-(10)	-	-	Determination of spatial position and tilt of borehole
DIPMETER	high resolution micro resistivity	dip and azimuth	-	*(11)	✓	-	-	-	-	Determination of dip and strike of bedding, identifying fractures and fissures
BOREHOLE VIDEO	Optical, borehole television images	-	✓	-	✓(12)	✓(12)	✓(12)	✓(12)	✓(12)	Observe lithology, borehole construction, fluid inflows

⊗ water or mud drilled
• frequently used method
✓ no limitations
* some limitations

cps : counts per second
API : American Petroleum Institute gamma ray unit

(1) - attenuated by high density material, e.g. casing, or large diameter.
(2) - resistance profile possible in plastic screen. Can identify slotted and blank sections.
(3) - SP development requires contrast in salinity between borehole and formation fluids, not always seen in waterwells.
(4) - resistivity profile possible in plastic screen. No quantitative interpretable possible. Includes invaded zone.
(5) - shallow investigation depth may only read properties of the gravel pack.
(6) - matrix velocity uncertain in unconsolidated materials hence porosity estimates poor.
(7) - fluid EC change in borehole fluid may be influenced by screen slot positions.
(8) - natural fluid movement or whilst pumping.
(9) - construction features may give false indication of inflow.
(10) - magnetic measurements not possible in steel cased holes.
(11) - sharp changes in microresistivity not always present.
(12) - requires clear water or empty (dry) holes.

For measurements with omnidirectional tools, optimum hole diameter is 100-200 mm (4-8 inches) and maximum hole diameter is 500 mm (20 inches) except for neutron, density and sonic methods where recommended maximum diameter is 300 mm (12 inches)

TABLE 4. Summary of the main geophysical logging techniques used in hydrogeological studies.

In geophysical logging of unconsolidated formations a clear distinction exists between logging in the open hole during or immediately on completion of the drilling, and production-type logging in the cased and screened borehole after completion. Logging in unconsolidated aquifers can therefore be divided into open hole logging and cased and screened hole logging (Table 5).

2. Factors to Consider when Planning and Running Logs

Planning - decide in advance the purpose of logging the borehole and what information is required. In some circumstances this may influence the manner of construction and the design of the completion (Hodges and Teasdale, 1991). List which logs are necessary to provide this information. Table 4 lists commonly used techniques and outlines some of the main limitations of each method.

- ensure the logging unit has sufficient depth capacity. For mud-supported boreholes, powered winches and logging cable of at least $^{3}/_{16}$ inch diameter and 3300 lb (1500 kg) breaking strength are required to cope with squeezing clays and collapsing sand horizons which may be encountered.

- logging units may be back-pack portable, vehicle or skid-mounted. Consider access and ground conditions for the vehicle type and size chosen.

- consider access to the borehole for logging. In some existing boreholes restricted access may require the use of slim diameter probes.

On site - provide logging personnel with basic data concerning the borehole. This may influence the logs that can or should be run or their order. The borehole information recorded on the log header should include at least the following:

1. Date of logging
2. Borehole identification number, location and grid reference
3. Drilling depth and hole diameters
4. Casing lengths and diameters
5. Screened intervals and types of screen
6. Completion information (casing material, wall thickness, cemented zones, caving zones etc.)
7. Details of drilling method and drilling fluid used.

Specific logging information must be recorded when individual logs are run. Log data recorded on the log header should include:

1. Tool name and serial number.
2. Other curves run.
3. Borehole fluid type, level and resistivity.
4. Depth scale.

OBJECTIVES	GEOPHYSICAL LOGS **	
	Open Hole	Cased Hole
Lithology and bed boundaries	CAL, GR, NN, DEN, RES, IND	GR, NN, DEN, IND*
Identify permeable sands and impermeable clays	GR, RES, CAL	GR, IND*
Porosity and clay content evaluation	NN, DEN, GR	NN, GR
Formation water quality	SPR, RES, SAMP	EC/T, SAMP
Depositional environment	SP, GR, RES	GR
Fluid inflows	-	EC/T, FM
Borehole construction	CAL	CAL, CCL, CBL, GR, VID, NN, DEN
Factors influencing yield	-	GR, DEN, NN, NOISE, VID
Factors influencing fluid salinity	-	EC/T, SP, IND, SAMP

CAL:	caliper	SAMP:	fluid sampler
GR:	gamma ray	SP:	spontaneous potential
NN:	neutron	IND:	induction conductivity
DEN:	density	FM:	flowmeter
RES:	electrical resistivity	CBL:	cement bond log
CCL:	casing collar locator	VID:	television video
NOISE:	noise log		

* in plastic casing ** freshwater or freshwater-mud drilling fluid

Table 5. Typical logging methods used in unconsolidated aquifers.

5. Calibration details.
6. Logging datum, either ground level, top of casing, kelly bushing, etc. and if a temporary datum is used its relationship to a permanent datum.
7. Logged interval.
8. Depth of hole by logger.
9. Logging speed (linespeed).
10. Time constants or filter widths used.
11. Physical details of probes, e.g. types, diameters, spacings, etc.
12. Comments column to record any unusual or unexpected events.
13. Names of logging operator and witness.

Choice of logs and order of log runs

The choice of logs to run depends upon the objectives (Tables 4, 5) and the information desired, but note the borehole construction may influence what can be run. For example electrical resistivity measurements cannot be made where there is steel or plastic casing present, or where there is no fluid in the borehole and sonic logs cannot be run in dry holes. Induction conductivity measurements can produce a resistivity log in dry holes and in plastic cased holes. Gamma ray logs are often the most versatile and if the condition of the hole might curtail logging, a gamma ray log can usually be run inside drillpipe and obtain useful information.

The order the logs are run may also depend upon the types of log. If borehole fluid logs (e.g. fluid temperature, fluid conductivity) are required these should be run first before the fluid is disturbed by logging tool movement. Otherwise it is useful to run a caliper early on to determine the state of the borehole, to evaluate likely borehole effects, and ascertain whether squeezing or caving is likely to be a problem.

In general better logging results will be obtained in freshly drilled formations, and in existing boreholes or boreholes which have stood for a long time be aware that significant fluid invasion may have taken place over an extended period of time. Measurements of fluid conductivity, fluid temperature, water sampling and electrical resistivity of the formation may therefore be affected.

Most log measurements are made coming out of the hole on an uphole run. There are several reasons for this:

1. The position of obstructions, hazards and anomalies have been noted on the run in.
2. The range and optimum scaling for the curves can be judged from the run in.
3. Cable under tension on the uphole trip provides more reliable depth measurements.

However certain logs, e.g. fluid logs, are better recorded on the run in.

Before running the logs the operator should make a note of the depth of possible obstacles noted from the drilling record.

When running in, the operator should monitor the cable tension. If the probe becomes stopped on a "bridge" or obstruction the operator should run in approximately 1 m of slack and lock the winch. The cable should then be lifted by hand and lowered gently to "feel the obstruction". Probes can often be steered around obstructions in this way. The obstruction depth should be noted for future reference.

If line tension is very erratic on the run in or there are repeated hold ups this can indicate unstable borehole walls, squeezing clays or very poor verticality and the operator should decide whether to proceed carefully or withdraw. On approaching the recorded drilled depth the operator should slow the linespeed a few metres before to allow for cavings or depth error. The hole bottom may be hard or soft, and soft mud or slurry may be present for several metres. This can cover the logging tool, and for some tools, (e.g. fluid conductivity, flowmeter, television) may interfere with their measurement.

Before running any radioactive logging tools the operator should be satisfied that the borehole is free of obstructions likely to hinder the passage of the tool and that the walls are stable. Even in fully cased boreholes sections of casing could be damaged so that it is always necessary to run other logging tools, preferably of larger diameter or a caliper to observe unhindered access. If there is any doubt as to the condition of the borehole in relation to free passage, the radioactive logging tools should not be run.

Depth measurements

All log measurements are referred to a depth and should be related to a known start datum. It is essential that the depth measurements are accurate and consistent, and the agreed start datum (casing top, ground level, kelly bushing etc.) is set correctly.

Depth is normally recorded by cable displacement of a calibrated pulley wheel which transmits encoded depth pulses by rotation. In petroleum logging, depth measurement is a sophisticated process involving several measuring wheels and magnetic markers fixed to the logging cable under conditions of known tension and temperature. Because stretch becomes significant at the great depths involved in hydrocarbon logging cable in shallow applications (<500 m) cable stretch is not significant and magnetic marking is not necessary. Slippage of cable on the measuring pulley is more likely to be a source of error so that it is necessary to keep the cable tight and the measuring pulley clean to avoid under-reading errors. Flat-profile measuring pulleys rather than V-profile are preferred for this reason.

Inaccurate depth measurement may arise from wear on the pulley, a build-up of mud on the pulley or cable, or inaccurate initial set up. Depth match can be judged between logs of the same type over repeat sections. Correct depth match between logs of different type requires that tool sensor offsets have been set correctly by the operator before logging.

Repeat runs

It is good practice to run a repeat section over a short interval (at least 10-35 m) to indicate the log repeatability. It is also good practice to run repeats over sections displaying odd or anomalous responses to confirm if these are signal or noise. If random noise or local interference is affecting the log response it is unlikely to be duplicated on a repeat run.

Electrical noise

Electrical 'noise' or interference on the log trace is usually more of a problem on electrical resistivity logs than other measurements. It arises when extraneous electromagnetic signals from overhead cables or ground currents are picked up by the logging cable. The cable run from truck to wellhead can act as a large aerial and oscillation of the logging signal which persists whilst the cable is stationary may be due to the pick up of overhead cable signals or electromagnetic signals. The interference may be minimised and sometimes eliminated by moving the truck position.

Noise on logs which only occurs when the cable is moving is more likely to be magnetic noise. Noise at regular intervals is probably related to a winch rotation or encoder signal, and if it appears more widely spaced at the top of the log than at the bottom is probably related to magnetised cable because at hole top the cable drum diameter is larger. Ground or airborne electrical interference can be distinguished from magnetic noise by the fact that it is often random and does not usually repeat.

Stuck probes

Probes may become stuck on the run in, or more seriously, on the run out of the borehole. Hold-ups on the run in are usually obstructions that can be overcome by raising or lowering the cable by hand to guide the tool past the obstruction. Hold-ups on the run out are always more serious because in applying power to free a stuck probe it can become more firmly wedged with then no means of lowering the probe to steer round the obstruction. Typical hazards encountered in the borehole are cable snagged on base of damaged casing, caliper probe arm wedged in borehole wall fractures, logging cable wrapped around pump or rising main dislodging of blocks from the borehole wall by the logging tool in jointed and blocky formations (consolidated formations) or borehole collapse (unconsolidated formations) around the tool.

In the event of a stuck probe, pulling on the cable will have one of three results:

1. The tool will pull free.
2. The cable will break at an inbuilt weakpoint.
3. The cable will break elsewhere.

If a probe does become stuck on the run out, there are three options to retrieve it:

1. Leave the cable attached to the tool and run a side-door fishing tool.

2. Cut and thread tubing over the cable, try and recover probe inside tubing.

3. Break the weakpoint, recover the cable and fish for the tool with fishing tools or push it to the bottom of the hole with drillpipe and recovering it from the bottom.

3. Log Technical Quality

Many things can adversely affect the technical quality of logs apart from obvious equipment failure. Less obvious causes of poor data include:

- large borehole effect
- adverse condition of borehole, collapse or caving, non-circular shape, washouts
- non-vertical or deviated well causing eccentralisation of logging tools
- inaccurate depth measurement, poor synchronisation, cable slip
- electrical interference 'noise'
- presence of metal junk in borehole
- inappropriate logging tool sensitivity, logging speed or time-constant
- operator error.

Borehole effects

Borehole effects influence log measurements. In particular the shape and dimensions, the manner of drilling and the extent of drilling fluid invasion all distort the log measurements to a greater or lesser degree and need to be taken into account if quantitative analysis is to be undertaken.

To minimise borehole effects the borehole should be ideally just large enough for free passage of the logging probe. However drilled diameter can be a poor guide to actual diameter and a caliper log is essential to record the actual hole size. The effects of poor hole conditions due to caving, collapse, borehole eccentricity etc. are not always removed by applying environmental corrections. Non-centering of the logging probe due to poor verticality may have a variable effect. Some measurements may have inappropriate sensitivity for the environment. Large diameters typically cause problems. Gamma ray measurements may cease to be valid in boreholes >20 inches (500 mm) diameter unless they are pad-contact devices.

Calibration

Calibration is of fundamental importance when making geophysical logs. Calibration is a procedure applied several times in the logging operation. There are various types of calibration that are performed. Most tools have a fundamental or primary calibration which converts the raw response to recognisable physical properties. This is usually referred to as primary calibration and is achieved by establishing the tool response to an artificial formation. Primary calibrations may be established by experimental measurements, by running the tool in test formations under controlled conditions, by scaled experiments or by mathematical modelling. It is normally performed by the manufacturer who then provides appropriate secondary (field) calibration devices so that two or more points of the primary calibration can be reproduced at base, or at the wellhead. Typical field calibrators include gamma ray calibration devices, neutron tube calibration devices, caliper rings etc. Note that an accurate calibration provides consistency but does not guarantee valid measurements. Calibration may introduce a constant systematic error.

Regular calibration of logging tools on the logging system is necessary. This allows for tool to tool differences or compensates for the ageing of radioactive sources, e.g. ^{137}Cs sources of density tools reduce activity by ~0.2%/month. It is useful to have log calibration traceability. That is a record of the calibration which shows the series of steps made in calibration from the primary calibration.

Checks on log quality

In normal circumstances the customer will accept the log run as correct, but how do you determine whether the log values are valid and are representative of the formation? Obvious errors can be identified, for example caliper logs which read incorrect diameters in casing, resistivity logs which read high in steel casing, density logs which read <1.00 g/cm^3. It is more difficult however to recognise if say a gamma ray log response is valid or not.

Repeat running of logs or running of repeat sections of logs is a check on the precision of the measurements though is not necessarily a check of their validity. Properly functioning equipment will normally produce logs which repeat on duplicate runs. Non-repeats can indicate faulty equipment but note that some logs do not repeat. Because of the random nature of radioactive decay, radiation logs (gamma, neutron, density) will not repeat exactly and normal configuration resistivity logs will only repeat on similar direction runs because of asymmetric responses to bed boundaries. Irregular tool movement and different tracking up the borehole wall on repeats may also cause slight differences. Logs which repeat exactly may still not be valid. The measurement system may have a systematic error. That is a reproducible inaccuracy which is present on the repeat runs. For example logs run with a temperature affected gamma ray detector. At high temperatures scintillation crystal gamma ray detectors typically have 30% less light output than at low temperatures. Simply re-running the log with such equipment will reproduce the first invalid measurements at the bottom of the hole.

Repeatability could also be influenced by time-related phenomena. For example changes may occur because of fluid invasion from the drilling process or because of natural flow between formations of different hydraulic head. Such changes can influence repeat run fluid conductivity, fluid resistivity and fluid temperature logs.

Log reproducibility is the difference between logs run in the same borehole under the same conditions with different logging equipment. Logging equipment needs to have good reproducibility. Reproducibility tests are a good means of checking precision, equipment function and identifying depth errors.

Steel casing in a borehole is a useful natural calibrator. It should provide:

- a zero or very low electrical resistivity
- a sonic velocity of 57 microseconds/ft
- a known diameter for caliper logs.

The validity of environmental corrections can be gauged by logging the same formation in different boreholes. In such cases the corrected logs should be similar.