International Association of Hydrogeologists

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Well Logging in Groundwater Development

By
H. REPSOLD

The author is a member of the committee of experts "Geohydrology" of the 'Deutscher Verein des Gas- und Wasserfaches' (DVGW) (German Gas and Water Experts Association).

Chapters 1 to 4 of this book are based for the most part on the elaborations of this committee of experts for instruction booklet W 110: " Investigations in boreholes and wells for groundwater development, a compilation of methods". Apart from the author, the members of the committee of experts have also contributed to this work. The author takes this opportunity to express his thanks for their cooperation.

translated from the German
by Mr. Vincent W. Battersby

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Well Logging in Groundwater Development

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1 Introduction

The so often tried and trusted geophysical well logging methods that have been used for over 50 years in the field of oil exploration, have provided this industry with an aid without which, the constantly increasing production figures for oil and natural gas would be unthinkable.

Although the problems with oil and natural gas prospection are different (and generally more complicated), a large number of these methods can nevertheless be used in the search for water and provide information which reduces the costs of exploration and can be of assistance for a practical use of the occurrence.

This book is intended to show which measurements are possible in boreholes and wells that are sunk for the development or observation of groundwater and what one can deduce from them, as far as well logging methods with depth-related, continuous recording of measuring values are concerned (with the exception of the sampler tool and the optical methods). These are the actual well logging methods.

Other methods of measurement such as single and multiple borehole methods for determining the groundwater flow (horizontal flowmeter, tracer methods etc.) as well as pump tests and other methods for determining the hydraulic conductivity are not dealt with, as this would greatly exceed the scope of this book.

The text concentrates more on the practical applications of methods than on the physical principles. However, importance was placed on consideration of many though not all of the methods possible in water wells. For this reason, relatively unusual methods like Neutron, Sonic, Microlog and Dipmeter are also presented; in some cases, particularly in consolidated rock, these methods can also be used and provide results of hydrogeological importance.

Three tables serve for orientation in the selection of methods.

Table 1	shows the possible applications of the methods in open and cased drillholes in unconsolidated and consolidated rock.
Table 2	lists the directly measured value, the corrected measured value and the investigation purpose for each method.
Table 3	divides the methods according to groups of purposes.

Following this, the individual well logging methods are described under the headings below:

. 1	Principles
. 2	Purpose of the measurement
. 3	Disturbing influences
. 4	Technical data
. 5	Possible combinations with other methods
. 6	Presentation of logs
. 7	Interpretation.

Two sections follow, the first of which deals in more detail with the quantitative interpretation of well logs in respect of the purposes of hydrogeology (Section 5), the second contains selected presentations concerning basic principles of some of the methods (Section 6).

At the end there is a guide to Log Quality Control for some methods which are frequently used in wells for water development. It is intended to assist the processor to critically assess the technical quality of borehole logs undertaken and where necessary, to supervise perfect execution of such measurements from the beginning.The guide is based on the customary procedure in oil prospection but nevertheless only contains a part of the usual quality controls used there.

2 General remarks

2.1 Technical comments

For oil well logging probes with diameters between 92 mm (3-5/8") and 43 mm (1-11/16") are normally used.

With groundwater development, probes with a diameter of 35 to 50 mm (approx. 1-1/2" to 2") are predominantly used.

The ratio of borehole to probe diameter determines the so-called

b o r e h o l e e f f e c t.

With most logging methods this more or less distorts determination of the desired rock parameters. For a quantitative determination of the rock parameters it must be compensated through the

b o r e h o l e c o r r e c t i o n.

The borehole effect is all the greater, the greater the ratio of the borehole diameter to the probe diameter.

The borehole effect can be kept small in that one measures in the slimmest possible holes; however, an unimpeded moving up and down of the probe in the borehole must be guaranteed.*

For a 92 mm (3-5/8") probe, 150 mm (6") is normally regarded as the minimum borhole diameter and for a 38 mm (1-1/2") probe it is 100 mm (4").

With greater borehole diameters the response of the method to the parameters to be measured worsens, whereby the necessary borehole correction becomes increasingly greater and consequently more problematic. Methods that work with expanding devices touching the borehole wall (caliper, density, etc.) are tied to specific maximum diameters.

The logs should be recorded on paper with a metric grid or on paper with the internationally used API grid (3 tracks to each 63.5 mm (2-1/2"), divided into 10 divisions, metrically or in English feet expressed depth scale).

The "log heading" of the measurement should contain all of the important hole and log data. Examples of metric and API grids as well as for log headings are presented in the log samples at the end of the book.

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* In point of fact, one usually cannot choose borehole diameters and only has a limited choice of probes, so that one must make the best of the situation.

2.2 Designations of methods / List of symbols

The reader will notice that the manner of writing of the various method designations is not uniform; with some methods the measured parameter is quoted (Gamma Ray, Density, Self Potential, Temperature, Caliper, Deviation), with others the measurement method (Neutron, Sonic Log, Electric Log, Induction Log, Microlog), yet again with others the measuring probe (Salinometer, Flowmeter, Dipmeter, Sampler).

Beyond this, the designations are in part English (Gamma Ray, Density, Flowmeter, etc.) in part German (Akustiklog, Elektriklog etc.).

Whoever studies further literature about well logging will encounter still more variations; instead of Electric(al) Log in English the terms in German are Elektriklog or Elektrolog; for focussed resistivity measurements in general the Schlumberger trade name "Laterolog" (now 35 years old) is frequently used; instead of Density (Log) "Formation Density" frequently appears (likewise originally a Schlumberger trade name); instead of Salinometer, Fluid Resistivimeter is the Anglo-Saxon term, instead of Self Potential the French designation Polarisation Spontanee (abbreviation PS) occasionally appears; with the Dresser-Atlas Service Company one will look in vain for the method designations Formation Density and Microlog but here, these methods are referred to as "Densilog " and "Minilog", as the first-named designations were originally trade names of the Schlumberger Company.

This jumble of names prevails through the entire branch. Trade names frequently became general method designations later. Likewise for reasons of copyright, new names were found for already existing methods.
Names and designations from the French, Anglo-Saxon and German language area flowed together and were either directly adopted or slightly altered.

A systematic nomenclature could not and cannot be originated in this manner. Anyone concerned with this specialist subject must accept the "naturally developed" designations with good grace.

An attempt has been made to use only the most common designations, whereby multiple designations have been avoided if possible.

The symbols used hereinafter are listed below.

List of Symbols			Units
API	=	API Gamma Ray Units	API
B_{cp}	=	compaction factor	
CAL	=	caliper	mm;inches
CBL	=	Cement Bond Log	
CCL	=	Casing Collar Locator	
cps	=	counts per second	cps
D, FD	=	Density, Formation Density	cps; g/ccm
d	=	borehole diameter	mm; inches
D_e	=	probe diameter	mm; inches
D_i	=	infiltration diameter	mm; inches
DIP/DV	=	Dipmeter/Deviation	
ES, EL	=	Electrical Survey, Electric Log	ohm.m
FEL, LL	=	Focussed Electric Log, Laterolog	ohm.m
FLOW	=	Flowmeter	revs per s
IES, IEL	=	Induction Electrical Survey, Induction (Electric) Log	mmhos/m
ϕ	=	porosity, total porosity	
ϕ_{cor}	=	shale corrected porosity	
ϕ_e	=	effective porosity, specific yield	
ϕ_f	=	fracture porosity	
ϕ_g	=	intergranular porosity	
ϕ_r	=	specific retention	
ϕ_{sh}	=	porosity of shale	
GR	=	Gamma Ray	cps; API
GR_{max}	=	maximum GR level, mostly level of pure shales	cps; API
GR_{min}	=	minimum GR level, mostly level of clean sands	cps; API
GRI	=	Gamma Ray Index	
K	=	hydrochemical constant	mV
ML, MLL	=	Microlog, Microlaterolog	ohm.m
N	=	Neutron	cps; porosity units
N	=	count rate	cps
OPT	=	optical investigations	
R	=	resistance } in physics	ohm
ρ		resistivity } in physics	ohm.m
R_{ohm}	=	resistance } in well logging	ohm
R	=	resistivity } in well logging	ohm.m
R_a	=	apparent resistivity read from the log	ohm.m
R_i	=	resistivity of mud invaded zone	ohm.m
R_{xo}	=	resistivity of mud flushed zone	ohm.m
R_m	=	mud resistivity	ohm.m
R_{mf}	=	mud filtrate resistivity	ohm.m
R_t	=	true resistivity of rock	ohm.m

ρ	=	density of rock	g/ccm
ρ_b	=	bulk density	g/ccm
ρ_{fl}	=	fluid density	g/ccm
ρ_m	=	mud density	g/ccm
ρ_{ma}	=	density of rock matrix	g/ccm
SAL	=	Salinometer (fluid resistivimeter or conductivimeter)	ohm.m; µmho/cm
SAMP	=	fluid sampler	
SP	=	Self Potential	mV
SV	=	Sonic (Velocity) Log, Akustiklog	µs/m; µs/ft
T	=	temperature of layer investigated (formation temperature)	degr.C;F
TC	=	time constant (damping)	s
TEMP	=	temperature of the borehole fluid	degr.C; F
v	=	cable speed (speed of probe travelling in the borehole)	m/min
v_{cl}	=	clay content	
v_{sh}	=	shale content (content of clay plus silt)	
v_{ma}	=	volume of sand matrix	

3 The tables

3.1 Table 1: The most important methods and their possible applications

3.2 Table 2: Functions of the methods

3.3 Table 3: Grouping of methods according to purpose

To Table 1 the following explanations are given:

● frequently applied methods (standard methods)

+ Measuring possible without limitations
* Measuring possible with limitations

- Measuring either not possible or impracticable

*1) Undesirable damping through casing, completion and large borehole diameter, however, checking of clay sealings possible

*2) Frequently impaired by caving.

*3) Checking of gravel packing of screens possible under favourable circumstances

*4) Only for qualitative correlation purposes, no reliable conversion into porosity values.

*5) Recording of a resistivity profile possible in the screens, however, no quantitatively interpretable resistivity values, depth control of screens possible (8"/32" normals may be more suitable than 16"/64" normals).

*6) Precondition for quantitative interpretation is a shale/sand alternating bedding; frequent disturbances through non-identifiable baseline shifts. In water-filled drill holes in consolidated rock with fracture porosity usually no interpretable SP curve is attained.

*7) As for *5); in certain cases additionally suitable for checking leaking casing collars and other leaks (casing collar locator in steel casings see CCL).

*8) Problematic with so-called "slotted" casings: falsification of results may be considerable due to fluid flow behind the pipes.

*9) Minimum pump rates are to be observed!

*10) In steel cased holes, azimuth measurement is only possible with a gyrocompass.

The most important methods and their possible applications
(For explanations to Table 1 see page 13)

Table 1
Sheet 1

Ser. Nr.	Dry hole	Open hole with mud or water: in unconsolidated rock	Open hole with mud or water: in consolidated rock	Steel cased or screened hole with mud or water: in unconsolidated rock	Steel cased or screened hole with mud or water: in consolidated rock	Plastic or non-metallic cased or screened hole with mud or water: in unconsolidated rock	Plastic or non-metallic cased or screened hole with mud or water: in consolidated rock
1. ● Measurement of natural gamma radiation; Gamma Ray, GR	+	+	+	*1)	*1)	*1)	*1)
2. Measurement of rock density; Density, D, FD	–	*2)	+	*3)	*3)	*3)	*3)
3. Measurement of rock porosity; Neutron, N	–	+	+	*1)	*1)	*1)	*1)
4. Measurement of sonic velocity in rock; Sonic Log, Akustiklog, SV	–	*4)	+	–	–	–	–
5. Checking of cementing; Cement Bond Log, CBL	–	–	–	+	+	–	–
6. ● Measurement of rock resistivity in multiple point array; Electric Log, ES, EL	-	+	+	–	–	*5)	*5)
7. ● Measurement of electric self potential; Self Potential SP	–	*6)	*69)	–	–	-	-
8. Measurement of rock resistivity in focussed array; Focussed Electric Log, Laterolog, FEL, LL	–	+	+	–	–	*7)	*7)
9. Measurement of electric rock conductivity (focussed induction method); Induction Log, IES, IEL	+	+	+	–	–	+	+

The most important methods and their possible applications
(For explanations to Table 1 see page 13)

Table 1
Sheet 2

Ser. Nr.	Dry hole	Open hole with mud or water: in unconsolidated rock	Open hole with mud or water: in consolidated rock	Steel cased or screened hole with mud or water: in unconsolidated rock	Steel cased or screened hole with mud or water: in consolidated rock	Plastic or non-metallic cased or screened hole with mud or water: in unconsolidated rock	Plastic or non-metallic cased or screened hole with mud or water: in consolidated rock
10. Measurement of resistivity of the hole´s immediate vicinity; Microlog, Microlaterolog, ML, MLL	–	+	+	–	–	–	–
11. Measurement of resistivity (or conductivity) ● of the borehole fluid (water or mud); Salinometer, SAL	–	+	+	+	*8)	+	+
12. Measurement of temperature ● of the borehole fluid (water or muid); Temperature, TEMP	–	+	+	+	*8)	+	+
13. Measurement of borehole or casing diameter Caliper, CAL	+	+	+	+	+	+	+
14. Casing collar locator in steel casings; Casing Collar Locator, CCL	+	–	–	+	+	–	–
15. Measurement of vertical fluid speed ● in a borehole or well; Flowmeter, FLOW (hole must have been developed)	–	–	*9)	*9)	*8)+*9)	*9)	*9)
16. Measurement of borehole deviation; Deviation, DV	+	+	+	*10)	*10)	+	+
17. Measurement of strike and dip; Dipmeter, DIP	–	–	+	–	–	–	–
18. Sampling (water or mud); Sampler, SAMP	–	+	+	+	*8)	+	+
19. Optical investigations; Borehole Camera, TV Camera (only possible in clear water)	+	–	+	+	+	+	+

Table 2 Sheet 1

Funktions of the methods

Short description	Immediate measuring signal	Optimum diameter* recommended max diameter mm (inches)	Corrected measuring signal	Investigation purpose
1. GR	Count rate of natural gamma radiation	100 to 200 (4 to 8) 500 (20)	Natural radio. activity of	Rock structure, shale content
2. D, FD	Count rate of Comton scattered gamma rays	100 to 200 (4 to 8) 500 (20)	Rock density	Porosity, fracturing
3. N	Count rate of secondary neutron-neutron or neutron-gamma rays (NN or NG)	100 to 200 (4 to 8) 300 (12) **		Porosity
4. SONIC, SV	Travel time of seismic waves between transmitter and receiver of the probe	100 to 200 (4 to 8) 300 (12)	Velocity of seismic waves in rock	Porosity fracturing
5. CBL	Amplitude of the seismic waves recorded by the receiver	100 to 200 (4 to 8) 300 (12)		Cementation quality
6. ES, EL	Apparent resistivity (non-focussed multiple electrode method)	100 to 200 (4 to 8) 500 (20)	True resistivity of rock	
7. SP	Potential difference between borehole electrode and surface electrode	100 to 200 (4 to 8) 500 (20)	Potential difference between sands and shales	
8. FEL, LL	Apparent resistivity (focussed multiple electrode method)	100 to 200 (4 to 8) 500 (20)	True resistivity of rock	
9. IES, IEL	Apparent Conductivity (focussed multiple coil induction method)	100 to 200 (4 to 8) 500 (20)	True conductivity, true resistivity of rock	
10. ML, MLL	Apparent resistivity (unfocussed and focussed resistivity methods: contact device)	100 to 200 (4 to 8) tool-dependent	True resistivity in the hole´s immediate vicinity	Delineation of thin layers
11. SAL	Resistivity (or conductivity) of the borehole fluid			Total salt content of borehole fluid
12. TEMP	Temperature ofe the borehole fluid			Geothermic gradient
13. CAL	Borehole diameter	tool-dependent		Correction value for other methods
14. CCL	Induction impulse (flux variation) of an open electromagnet array			Location of casing collars of steel casings

* Minimum diameter tool-dependent (see 2.1: technical comments)

** Maximum diameter with the sidewall probes also tool-dependent

Table 2 Sheet 2

Short description	Immediate measuring signal	Optimum diameter* recommended max diameter mm (inches)	Corrected measuring signal	Investigation purpose
15.FLOW	Revolutions of a spinner (impeller)	***	Velocity of fluid flow in the borehole or well	Determination of the water inflow and outflow
16.DV	Pendulum and compass signals		Inclination and azimuth	Spatial course of the borehole
17.DIP	3 or 4 MLL signals + pendulum and compass signals	>150 (>6) tool-dependent	3 or 4 MLL signals, inclination and orientation of the borehole	Dip and strike of penetratedl layers, fractures and fissures
18.SAMP				Water samples defined depths
19.OPT		tool-dependent		Photographic and TV pictures

*** Dependent on probe sensitivity and velocity of flow.

Grouping of methods according to purposes **Table 3**

The listing follows the sequence given in Table 1, i.e. it is not an order of precedence

Methods in uncompleted test and exploratory boreholes				Methods of checking completions and establishing operating data and age phenomena			
Unconsolidated rock		Consolidated rock		Unconsolidated and consolidated rock			
Rock structure	Water quality	rock structure Fracturing Water inflow	Water quality	Completion	Water inflow	Water quality	Checking operations Ageing
GR	ES	D	SAL	GR	FEL	SAL	SAL
D	SP	SONIC	TEMP	D	SAL	TEMP	CAL
N	FEL	ES	SAMP	CBL	TEMP	SAMP	FLOW
SONIC	IES	FEL		ES	FLOW		OPT
ES		IES		FEL	SAMP		
FEL		ML/MLL		CAL	OPT		
IES		SAL		CCL			
		TEMP		DV			
		CAL					
		FLOW					
		DIP					

4 The methods of measurement

4.1 Measurement of the natural gamma radiation; Gamma Ray, GR

4.1.1 Principles

The natural gamma radiation measured with the Gamma Ray Probe originates from the potassium 40 isotope and from the isotopes of the uranium and thorium decay series. These isotopes are essential components of clay minerals, whereby they usually stand in a fixed ratio of quantities.
Clay minerals are in turn essential components of shales, therefore in the normal case, the Gammma Ray measurement permits differentiation of shale and sand layers and estimation of the shale content in the case of more or less shaly sediments.

Other radioactive minerals, like e.g. glauconite and glimmer, are noticeable in the log in the same manner as shales. For this reason, they can only be recognized with the assistance of additional geological or minerological information.

Uranium ores, which compared with shales occur extremely rarely, cause distinct peaks with high count rates in the Gamma Ray Log, an unequivocal decision about the material quality can, however, only be made here with a Gamma Ray Spectrometer Probe.

The natural gamma radiation can be measured with a Geiger-Müller Counter (ionisation tube with a length of at least 10 to 50 cm, vertical resolution therefore is not too good) or with a scintillation counter (length of the detector 5 to 10 cm) (see Fig. 1).
The latter method is in general use today due to the good vertical resolution. Geiger-Müller tubes are only used now in high temperture probes in which a scintillation counting device would no longer function.

The count rate measured with a Gamma Ray Probe is dependent on:

- the radioactivity of the surrounding rock formation
- the size of the scintillation crystal
- the borehole diameter
- the type of mud
- the type and thickness of the casing
- the position of the probe in the borehole (centred or not centred).

A quantitative and reproducible conclusion from the count rate to the radioactivity of the rock under investigation is therefore not readily possible. For this, a borehole correction and checking of the Gamma Ray Probe with a calibration source are necessary.

A qualitative interpretation of the Gamma Ray curve with the aim of differentiating between shaly and non-shaly layers is, however, generally possible.

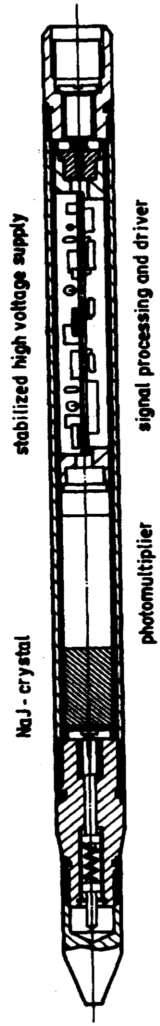

Fig. 1 Gamma Ray Probe

Gamma rays produce light flashes (scintillations) in the scintillation crystal (usually NaJ). The light flashes activate the photocathode of a photomultiplier.
The amplified photocurrents (electron showers) arriving at the anode release electrical impulses, which further amplified and shaped and transmitted to the surface via the cable, are summed up in the measuring apparatus and displayed as a "count rate".

4.1.2 Purpose of the measurement

Determination of layer boundaries, differentiation of shaly and non-shaly rocks, determination or estimation of the shale content with shaly sediments. Identification of radioactive precipitations in joints in consolidated rock

4.1.3 Disturbing influences

The sensitivity of the Gamma Ray measurement deteriorates all the more

- the more unsensitive the probe, i.e. the smaller the scintillation crystal is (the size of which is mainly determined by the probe diameter) – low count rates mean a high level of statistics and thus an unfavourable signal-to-noise ratio:

  p r o b e p a r t of the borehole correction;

- the larger the borehole diameter is – with very large diameters (>1m) the sensitivity with the excentral probe is practically halved, in the case of a centred probe and fluid-filled borehole it is reduced to almost zero:

  g e o m e t r i c p a r t of the borehole correction;

- the more casings that are installed and the thicker these and/or possible cementations are present in the logged borehole – due to this, an undesirable additional damping of the gamma radiation from the surrounding rock is effected:

  d a m p i n g p a r t of the borehole correction.

  A Gamma Ray measurement is generally no longer purposeful with more than one cemented or two uncemented steel casings.

4.1.4 Technical data

The measurement signal of the Gamma Ray Probe is an impulse count rate. The usual units are cps (counts per second) for measurements with an uncalibrated probe, API* -units for measurements with a calibrated probe. Calibration in API units applies for Gamma Ray measurements in shaly-sandy sediments: with a probe in a 5" borehole with fresh water mud pure sands yield about 10-20 API, compact shales about 140-160 API (see also 6.1).

Calibration is effected before and after a measurement with the aid of a radioactive source ("field standard"). It makes the gamma ray signal probe-independent, i.e. independent of the type of probe construction, the size and ageing state of the scintillation crystal, but not borehole-independent.

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* API - American Petroleum Institute, Houston/Texas, that functions as the standards institution in the USA for the oil sector.

The Gamma Ray signal becomes borehole-independent in that it is corrected through the so-called b o r e h o l e c o r r e c t i o n (compensation of the borehole effect) to s t a n d a r d c o n d i t i o n s.

In oil-well drillings the following standard conditions apply:

200 mm (8") well, 92 mm (3-5/8") probe, 1.2 g/ccm (10 lbs/gal) bentonite mud.

For hydrogeological wells in unconsolidated rock, the following are also in use:

125 mm (5"), about 40 mm (1-1/2" to 1-11/16") probe, 1.0 g/ccm (8.3 lbs/gal) fresh water mud.

For a borehole correction to hydro-standard conditions see Fig. 26 and Chart (1).

Calibration and borehole correction are not necessarily connected with one another: neither does a borehole correction require a Gamma Ray measurement with a calibrated probe nor must a measurement with a calibrated probe be necessarily borehole corrected.
A borehole correction is always necessary when a Gamma Ray measurement in a borehole with varying diameter and/or varying completion has to be quantitatively interpreted. A calibration of the probe is necessary for measurements taken at different times in the same borehole (borehole correction is not absolutely necessary) as well as for the comparison of measurements in different boreholes (borehole correction is usually necessary).

A correct Gamma Ray Log only results when the following setting instructions are adhered to:

- The time constant TC (in s) should be set so that TC is > 200/N. Here N is the average Gamma Ray count rate (in cps) of the borehole to be measured. This is the condition why the spontaneous statistical varations of natural gamma radiation, which do not reflect rock characteristics, are confined within a range of about ± 5% of the average count rate N.

- The cable speed v (in m/min) should then be set so that v is < 20/TC; however, 5-6 m/min should not be exceeded. This is the condition why layers of up to approx. 0.5 m thickness can still be resolved in the log, presupposing adequate radiation contrast.

  These somewhat theoretical requirements may be reduced to the setting which in the majority of cases will produce good results, assuming a 1"x 2" scintillation crystal and a "moderate" borehole diameter (i.e. 4"- 8"):

  TC = 4-6 s and v = 4-6 m/min (depending on the facilities provided by the measuring equipment).

- Recordings of the statistical variations in a range with high radiation level and a range with low radiation level should be carried out in each case (measurements with stationary probe, same settings as for the preceding log, duration approx. 2 min.)

4.1.5 Possible combinations with other methods

Gamma radiation measurement is frequently carried out as a single log. Combination with the Casing Collar Locator is possible, with the appropriate probe also a combination with the caliper tool (however, in such case the probe will be centred, which is not desirable with greater borehole diameters, see Section 4.1.3).

A customary combination is e.g.:
Two density measurements (see Section 4.2), a natural Gamma Ray measurement and a one-arm caliper in one probe, with which porosity, shale content and caliper can be simultaneously determined.

Furthermore, the combinations possible with the Gamma Ray method are so varied that in case of doubt, it is necessary to refer to the records of the service companies

4.1.6 Presentation of logs

The Gamma Ray curve should be registered over about 2/3 of the full scale (measuring range). Peaks should not greatly exceed the full scale. Otherwise, reference should be made to the examples given in the log samples.

The log heading should contain precise details about probe diameter and crystal size as well as borehole completion details (diameter, material and thickness of casing). In addition, data concerning the density and composition of the mud.

4.1.7 Interpretation

The interpretation usually takes place on a qualitive basis in connection with interpretation of drilling cores or drilling samples.

With a well, in which pure shales (or clays) and clean sands are encountered and with which a shaleline and a sandline can be clearly established (see also SP), the shale (or clay) content for intermediate layers with thicknesses > 1 m can be roughly determined from the Gamma Ray curve (this is the grain size share < 0.02 mm or < 0.002 mm resp. according to German DIN 4022).

The same applies for alternating beddings in consolidated rock (claystone/sandstone or claystone/limestone).

First of all, the Gamma Ray Index (GRI) of the layer concerned must be determined:

$$GRI = \frac{GR - GR_{min}}{GR_{max} - GR_{min}}$$, wherein

GR = Gamma radiation of the layer concerned

GR_{max} = Gamma radiation of the pure shales

GR_{min} = Gamma radiation of the clean sands

The shale (or clay) content can then be determined through a transfer function from the Gamma Ray Index, the form of which can e.g. be dependent upon the degree of consolidation of the rock and local conditions; a first approximation is an equation of the Gamma Ray Index with the shale content (grain size share < 0.02 mm; see also 5).

The interpretation described presupposes that the borehole diameter and the completion are constant throughout the entire length of the depth interval observed. If this is not the case, a reduction to standard conditions (borehole correction, see Chart (1)) must be undertaken beforehand.

If a Gamma Ray measurement calibrated in API-units is available, one does not necessarily have to depend on the occurrence of pure shales and clean sands in the depth interval to be investigated. In this case (borehole corrected measurement presupposed), an average value of 15 API is applied for the clean sands and one of 150 API for the pure shales, so that for the approximate Gamma Ray Index one obtains:

$$GRI = \frac{GR\,(API) - 15}{135}$$ (see formula above)

4.2 Measurement of rock density; Density, D, FD

4.2.1 Principles

With a linear array gamma source - lead column - detector the density of the surrounding rock can be determined in a borehole, after appropriate calibration.

At the lower end of a probe there is a gamma radiating source (usually 137 Cs) and above this a gamma detector (mostly a scintillation counter), that is shielded against the direct radiation of the radioactive source by a lead column (see Fig. 2). The gamma radiation emanating from the source is scattered on the elctron shells of the atoms composing the rock and more or less absorbed according to their density (Compton effect). A part of the scattered radiation reaches the detector and is recorded there as a gamma-gamma signal.

Strictly speaking, it is not the density of the material but the electron density that is determined which, however, with a constant ratio of the number of electrons to the nuclear mass number (Z) is the same, apart from a factor. This constancy applies (with the exception of $Z = 1$ (hydrogen)) up to the atomic number $Z = 26$ (iron) and is thus given for the most important rock elements.

The volume registered with the measurement is largely dependent on the source-detector distance and the density of the rock. Its horizontal expansion (radius) for the normally applied array (distance source-detector ≈ 40 cm) with a density of 2 g/ccm is roughly 15 to 20 cm.

The error in the density determination under optimum conditions (laboratory) can be kept between 1 - 2%.

In practice, a measurement error that is at least twice as large must generally be taken into account.

4.2.2 Purpose of the measurement

Determination of layer boundaries, differentiation of various rocks according to their density, determination of rock porosity, location of fracture zones in consolidated rock. Checking of gravel packs in wells.

4.2.3 Disturbing influences

Due to the extreme dependence of the gamma-gamma signal on mud and mud cake with freely suspended probes in the borehole, sidewall tools are used exclusively which are pressed against the borehole wall and shielded towards the borehole. In this way the disturbing influence of the mud and the mud cake are largely eliminated.

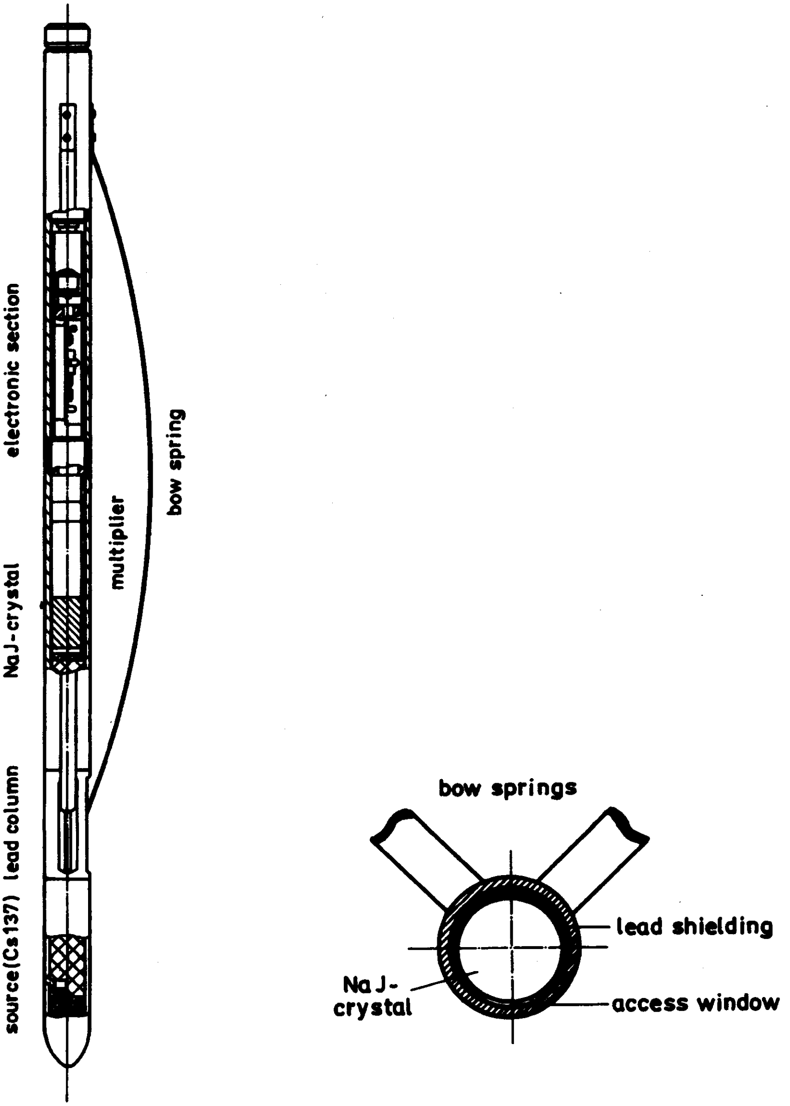

Fig. 2 Gamma-Gamma-Density Probe

The gamma radiation emanating from the radioactive source at the lower end of the probe is scattered on the electron shells of the rock atoms of the formation (Compton effect) and more or less absorbed according to their density. A part of the scattered radiation reaches the detector arranged at a fixed distance above the source. The count rate of this so-called gamma-gamma radiation can be calibrated in rock density.
The probe is pressed against the borehole wall to achieve reduction of the borehole effect.

However, because of insufficient pressure and/or mud cake that is too hard it is possible that the tool does not continuously adhere to the borehole wall. This results in erroneous readings that cannot be identified in all cases by means of caliper measurement.

4.2.4 Technical data

The measurement value of the gamma-gamma density probe is an impulse count rate (units are counts per second (cps) or counts per minute (cpm)). Bulk density (unit g/ccm) is only obtained through calibration of the probe.

Smaller measuring equipments usually record the impulse count rate (direct gamma-gamma signal). Conversion into bulk density follows by means of calibration diagrams or formulae (see Chart (2)). With larger measuring equipments this conversion takes place in the apparatus, so that the bulk density is recorded directly.

4.2.5 Possible combinations with other methods

As the natural gamma radiation and the borehole diameter are required as correction values for conversion of gamma-gamma signals into bulk denstity, one usually combines the Density measurement with Gamma Ray and caliper measurement.

In addition to the normal measuring array, density probes often have a second array with a smaller distance between source and detector for the resolution of thin layers and/or the mud cake correction of the long-spaced-gamma-gamma signal.

4.2.6 Presentation of logs

With the measurement combination described in Section 4.2.5, the natural Gamma Ray signal is usually recorded on the left of the diagram, the density signal to the right of it and the caliper signal on the extreme right trace (see Log Samples).

4.2.7 Interpretation

The interpretation is generally undertaken qualitatively in connection with the interpretation of drilling cores or drilling samples.
With a known matrix density (with sandy aquifers mainly 2.65 g/ccm for SiO_2) and known density of the pore fluid (1.0 g/ccm for water), the gamma-gamma density measurement allows determination of the porosity in accordance with the following easily verifiable formula:

$\rho_b = \varnothing \cdot \rho_{fl} + (1 - \phi) \cdot \rho_{ma}$, from this by conversion:

$$\varnothing = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

Herein the meanings are:

$\varnothing$ = total pore volume in fractions of 1
ρ_b = bulk density, the value taken from the log
ρ_{ma} = matrix density
ρ_{fl} = density of the pore fluid

all density values in g/ccm.

This formula applies for "clean" (shale-free) unconsolidated and consolidated rocks the grain size share < 0.002 mm of which is equating to zero or is negligibly small (grain size classification according to DIN 4022, see 4.1.7)

As only the total porosity can be determined from the Density measurement, with shaly sediments the so-called "fine pore space", i.e. the pore volume of the shale must be determined separately and subtracted from the total porosity.

To begin with one determines the total porosity ϕ in accordance with the above formula and after that, the so-called "shale – corrected porosity" as follows:

ϕ_{cor} = $\phi - v_{sh} \cdot \phi_{sh}$

ϕ_{cor} = Shale-corrected porosity in fractions of 1

ϕ_{sh} = Shale porosity (fine pore space) = $\left(\frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}\right)_{sh}$

v_{sh} = Shale content (share < 0.02 mm incl. fine pore space)

The shale content can be determined from the Gamma Ray curve (see there), the shale porosity from the log value of the bulk density in shale (see also 5).

The graphic representation of this formula can be found in Chart(3).

See also 4.4.8: Assessment of the porosity-sensitive methods Density, Neutron and Sonic.

4.3 Measurement of rock porosity; Neutron, N

4.3.1 Principles

Fast neutrons with an average energy of 4.5 MeV are continuously radiated from a neutron source (mainly americium-beryllium or plutonium-beryllium) in the borehole. On their way they collide with atoms of the surrounding material, whereby they are slowed down and lose more or less energy. If after a certain distance and repeated collisions the neutrons finally achieve the thermic energy level (approx. 0.025 eV), then they are eventually catched by other nuclei which are thereby excited to radiation of a gammaquant of higher energy, so-called capture gamma radiation.

Both the thermic neutrons and the capture gamma radiation can be measured with suitable detectors, which are shielded against the natural gamma radiation. For this reason one differentiates between neutron-neutron or neutron-gamma measurements.

The neutrons experience the greatest loss of energy in collisions with nuclei of identical mass, like e.g. hydrogen. In this case it can amount to 100% with a single collision. However, on average 18 collisions are necessary until the thermic energy level is achieved. On the other hand, with silicon or chlorine 261 or 316 collisions are necessary up till attainment of the thermic energy.

Therefore the Neutron measurement depends largely on the hydrogen content in the vicinity of the probe. As most of the hydrogen in the subsoil is encountered in the form of water and hydrocarbons as pore filling fluids, with corresponding consideration of the disturbing effect of the borehole itself (diameter, mud, mud cake, casing, excentricity of the probe), the Neutron measurement is a good method for determing the rock porosity.

Compensated Neutron probes correct a part of the disturbing borehole influences even during measurement.

4.3.2 Purpose of the measurement

Determination of the rock porosity, determination of the groundwater level in special cases and differentiating between gypsum and anhydrite in combination with other methods.

4.3.3 Disturbing influences

In oil wells the Neutron probes are run against the borehole wall in the same way as the Density probes, in order to keep the influence of the mud-filled hole and mud cake as small as possible (e.g. Schlumberger "Sidewall Neutron Porosity" = SNP and "Compensated Neutron Log" = CNL). However, due to the shielding of the measuring array aginst the borehole this necessitates high source strengths for the neutron sources (up to 15 Ci)*, which creates a need for extensive safety measures during insertion and withdrawal of the

* see footnote next page

probe at the well. With water development these tools can only be used in exceptional cases because the safety measures possible on an oil rig are generally not feasible here. One is therefore compelled to work with smaller source strengths (1 to 5 Ci)*, which makes it necessary to run the probes non-shielded and freely suspended in order to attain the necessary count rates. To be sure, this also requires safety precautions, however, of a type that can be put into effect at well sites for water development.

Although the Neutron method is not diameter-dependent to the same extent as the Density method, a caliper log must be run in order to correct the Neutron values.

4.3.4 Technical data

The measuring value of a Neutron probe is a count-rate. With the large tools employed in oil wells the scale is calibrated in porosity, with smaller, freely suspended tools in counts per second (cps) or simply in "Neutron Units".
The values read from such a scale must be converted into porosity values via correction charts (see Chart 4). There are, however, also small Neutron measuring devices which have a scale calibrated in porosity.

4.3.5 Possible combinations with other methods

In oil well logging the Neutron method is predominantly combined with measurement of the natural gamma radiation (GR) and with measurement of the borehole diameter (CAL). Even more progressive combinations are also possible in this field. Attention is drawn here to the records of the large service companies.

In water development the Neutron Log can e.g. be combined with the Caliper, if the technical equipment of the measuring apparatus provides for this; however, Neutron Logs are also run individually.

4.3.6 Presentation of Logs

Neutron measurements are normally presented in the right part of the log (tracks 2 and 3) with the zero line on the left. Gamma Ray Log and Caliper Log can be recorded on the left (track 1).

4.3.7 Interpretation

As the Neutron method measures directly porosity, no further interpretation of the Neutron Log is necessary. However, from the combination with one or the other two porosity-sensitive methods (Density Log and Sonic Log) further conclusions (amongst others about the lithology) can be drawn but for this, reference should be made to the technical literature.
See also 4.4.8: Assessment of the porosity-sensitive methods Density, Neutron, Sonic.

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* 1 Ci (Curie) = $3.7 \cdot 10^{10}$ Beq (Becqerel)
1 Beq = 1 decay/s

4.4 Measurement of the sonic velocity in rock; Sonic Log, Akustiklog, SV

4.4.1 Principles

The travel time of sonic waves in rock is continuously recorded with the Sonic Velocity Log, mainly referred to as the Sonic Log. The time is measured that the longitudinal waves require in order to cover the distance between transmitter and detector while passing through the rock of the borehole wall.
The velocity of sonic waves in sedimentary rock (and consequently the travel time) is principally dependent on the lithology and the porosity. With knowledge of the matrix velocity and the velocity of the pore fluid one can calcu late the rock porosity from the recorded sonic travel time.

Through extensive laboratory tests, a relation was established between porosity φ and travel time Δt for consolidated shale-free rocks with evenly distributed pore spaces that is formally identical with the relation for determining porosity from the Density measurement (see Section 4.2.7):

$$\Delta t_{log} = \O \cdot \Delta t_{fl} + (1 - \O) \cdot \Delta t_{ma},$$

from this by conversion:

$$\varphi = \frac{\Delta t_{ma} - \Delta t_{log}}{\Delta t_{ma} - \Delta t_{fl}}$$

With less consolidated rocks the obtained porosity values are to be multiplied by an empirically determined correction factor (compaction factor B_{cp}).

In addition, through integration of the measured sonic wave travel times, the travel time over the total measured depth interval can be easily determined. This is important for the calibration of seismic surveys, executed at the surface.

The Sonic Log reacts particularly sensitively to sudden changes in diameter, i.e. cavings and skewing of the probe in the borehole. Through probes with several sonic transmitters and detectors as well as appropriate processing of the travel times measured therewith, these borehole influences can be largely compensated under not too adverse conditions. Most of the sonic probes in use today are of this "Bore Hole Compensated" (BHC) type (see Fig.3).

4.4.2 Purpose of the measurement

Determination of the sonic travel time or the sonic velocity, beyond this determination of rock porosity and fracturing.

4.4.3 Disturbing influences

BHC-Sonic Log tools are largely compensated for borehole influences. The use of Sonic Logs becomes critical with unconsolidated rocks that have low velocities, a frequent occurrence with water development. In this field it is not possible to obtain interpretable results with all tools.

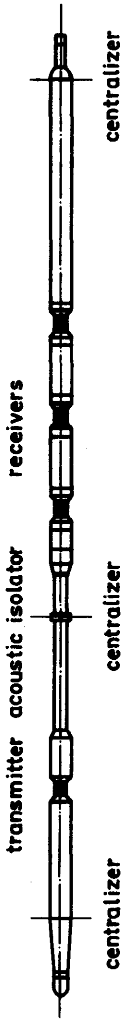

Fig. 3 BHC-Sonic Borehole Probe

Ultrasonic pulses travel from the transmitter on the probe through rocks in the immediate vicinity of the borehole until they reach the detectors fitted to the probe. The porosity can be calculated from the sonic travel time (related to the longitudinal unit), the reciprocal value of the sonic velocity.

However, under favourable conditions a Sonic Log can be recorded that is suitable for correlation purposes; the determination of porosity in unconsolidated rock is doubtful anyway, if not impossible (see also Section 4.4.7, interpretation).

4.4.3 Technical Data

The Sonic probe measures the travel time that the longitudinal sonic waves require in order to pass from the sonic transmitter on the probe through the rock layers in the immediate vicinity of the borehole, until they reach the detector which is likewise fitted to the probe.
Related to the longitudinal unit, this travel time is recorded in microseconds per metre (μs/m) or microseconds per foot (μs/ft) on the log. Although the scale is somewhat misleadingly designated with "interval transit time", this is in fact the reciprocal value of the sonic velocity of the rock.
The Sonic probe does not transmit a continuous sonic signal but rather small sonic explosions in short time intervals (approx. each half or each whole second). This intermittent periodic noise of the probe's sonic transmitter is clearly audible when the probe at the surface is switched on. The function of the sonic transmitter can be acoustically checked in this manner.

4.4.5 Possible combinations with other methods

Combinations with the Sonic Log are not usual in groundwater wells.

4.4.6 Presentation of the log

Recording of the sonic travel time is normally presented in the right part of the log: whereby the zero line is to the right so that increasing travel times (i.e. sonic velocity becoming smaller) mean deflection to the left. Thus the Sonic Log calibrated in sonic travel time can be qualitatively read, so that deflections to the right mean increased sonic velocity in the rock. A calibration of the Sonic Log scale in porosity is not usual.

4.4.7 Interpretation

As the Sonic Log registers sonic travel times, the sonic velocity in rock can be calculated through establishment of the reciprocal value. Nevertheless, the rock porosity is only indirectly determined from the Sonic Log, as with the Density Log (see above and graphic representation in Chart(5)). A knowledge of the sonic velocities of rock matrix and pore fluid are necessary for this.
Although the latter poses no problems with water (its sonic velocity is about 1700 m/s), determination of the matrix velocity with unconsolidated rocks is problematic, if not impossible.
For this reason the method is not suited in this case for quantitative determination of rock porosity.

4.4.8 Assessment of the porosity-sensitive methods

The three methods described above, namely D e n s i t y (D), N e u t r o n (N) and S o n i c (SV) are designated as "porosity-sensitive" methods. In fact, the Neutron Log measures porosity directly, whereas porosity can be calculated from the Density Log and the Sonic Log with the inclusion of addtional parameters.

With regard to the quality of porosity determination from the three methods, the following comments are pertinent:

The N e u t r o n L o g is assessed as the best porosity log. However, this applies to the borehole corrected sidewall tools with strong neutron sources (up to 15 Ci, see footnote, page 30) that are applied in oil well logging and require extensive safety measures. The not excentered Neutron Logs with weaker sources (1 to max. 5 Ci) used in water development are less accurate. Nevertheless these weaker sources still require certain safety measures.

The method is poorly suited for determining fracture zones in consolidated rock.

The S o n i c L o g works without radioactive sources and is thus unproblematic in this context. If the sonic velocity of the matrix is known it provides good porosity values. However, in the case of unconsolidated rocks the matrix velocity cannot be determined with certainty, so that a usable porosity value is unattainable.
On the other hand, the method is suitable for determining fracture zones in consolidated rocks.

The D e n s i t y L o g indeed also works with a radioactive source but with a (less dangerous) gamma ray source of relatively weak strength (50 – 100 mCi).

A risk of losing the source naturally exists here too, safety measures are likewise necessary. However, the Density Log is the only one of the three methods which provides usable porosity values even with unconsolidated rock, that are attainable with justifiable effort and relatively low risk. Knowledge of the matrix density is indeed a prerequisite for this but compared with the problem of matrix velocity with the Sonic Log, does not pose difficulties.

The method is also suitable for determing fracture zones in consolidated rock.

4.5 Monitoring a cementation; Cement Bond Log, CBL

4.5.1 Principles

With a normal Sonic Log tool (see 4.4), one of the sonic detectors is specially calibrated so that it can measure not only the time of arrival of a seismic impulse but also its amplitude. This is a measure for damping of the seismic waves, to which they are subjected on their way between transmitter and detector.

As the main part of the sonic transmission in a cased hole is effected through the steel casing, the quality of the cementation can be directly concluded from the amplitude Log:
The better the cement is bonded to the casing, the more the amplitude of the seismic waves is damped. The amplitude signal of the specially calibrated transmitter is recorded separately as a Cement Bond Log.

4.5.2 Purpose of the measurement

Monitoring the cementation of a casing.

4.5.3 Disturbing influences

With a narrow annulus between casing and rock (thin cement shell) it is possible that the sonic waves do not propagate predominantly in the steel of the casing but rather to a considerable part also in the rock; in such case, the amplitude signal provides no reliable information about the cementation: for a proper Cement Bond reading the additionally recorded interval transmit time must yield the sonic velocity for steel (5000 m/s).

4.5.4 Technical data

See Section 4.4

4.5.5 Possible combinations with other methods

See Section 4.4

4.5.6 Presentation of the log

e.g. interval transit time left (track 1), Cement Bond signal right (track 2, 3), but dependent on the service company concerned.

4.5.7 Interpretation

The CBL recording is directly interpreted into cementation quality.

4.6 Measurement of rock resistivity in multiple point array; Electric Log, ES, EL

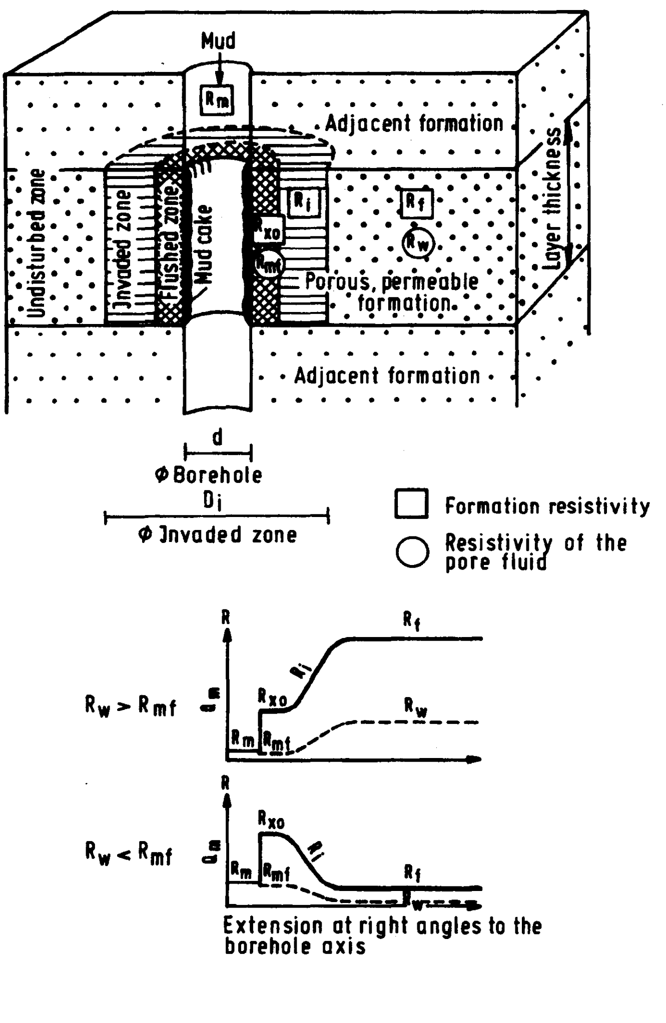

Fig. 4 Distribution of resistivities in the vicinity of a borehole (after SCHLUMBERGER 1979)

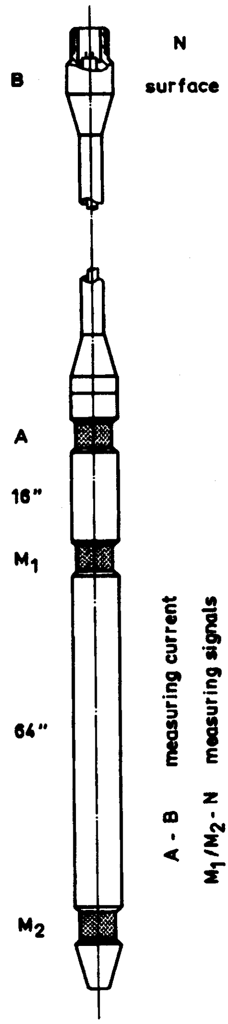

Fig. 5 ES Probe for recording the Electric Log (Electrical Survey):
2 Normals and Self Potential synchronously.

A low frequency square wave alternating current which is automatically kept constant is fed to electrodes A and B, the resistivity signals are taken between M_1 and N and M_2 and N respectively and rectified; the Self Potential, a direct current signal, is recorded simultaneously on one of the M – electrodes.

4.6.1 Principles

A current which is automatically kept constant is passed into the rock over two current electrodes arranged on the borehole probe (or on the borehole cable).
The signal that is recorded between two potential electrodes is proportional to the resistivity and is continuously recorded on a chart (see also 6.2).
This multiple point resistivity method is basically identical with that applied with direct current geoelectrical depth soundings (Wenner or Schlumberger array).

The measured resistivities are not true rock resistivities but rather so-called apparent resistivities (mixed resistivities) because the measurements always take place in a borehole filled with mud or water, the influence of which cannot be ignored (see Fig. 4).

Measurements are normally effected with two different electrode spacings (see Fig. 5).
The 16" normal has a shallow lateral investigation depth and as a result is relatively strongly influenced by the mud and by a perhaps existing mud invaded zone. However, it has a relatively good layer resolution due to its narrow electrode spacing (with satisfactory resistivity contrast down to approx. 0.5 m thickness).

The 64" normal has a greater lateral investigation depth and thus approaches more closely the true rock resistivity with its measuring value. However, the layer resolution is appreciably less than with the 16" normal (only down to about 2 m thickness).

With favourable layer thickness conditions and resistivity contrasts, the true resistivity of the rock can be determined and indications about possible mud invasion can be obtained from the apparent resistivities of both resistivity curves, with the aid of correction diagrams (resistivity departure curves). Knowledge about mud resistivity and the borehole diameter is necessary for this.

4.6.2 Purpose of the measurement

Recording of the resistivity profile of the layer sequence sunk by the well, determination of the true rock resistivity.

4.6.3 Disturbing influences

The position of the reference electrode N, which usually is placed at the surface, may be critical. As a rule it should be buried at an appropriate distance (i.e. at least 30-50m) from borehole and measuring vehicle.
With erroneous recordings, e.g. when parts of the curves run below zero, the grounding of the N electrode must be checked and its position changed if necessary. The placing of the N electrode in the mud pit, as is often carried out by service companies to achieve a low grounding resistance, is not optimum in every case as disturbances can occur in the uppermost part of the borehole.

This method of measurement is usually still analogously transmitted over the cable, in contrast to the methods like GR, CAL and others with which a pulse rate is transmitted. For this reason, proper cable insulation (cable head!) is decisive for faultless recording.

Regular checking of the insulation is consequently necessary.
However, as erroneous cable insulation is not necessarily visibly manifested in the recording, one must rely on correct implementation of the measurement and the necessary cable checks by the service company.

4.6.4 Technical Data

The scale of a multiple point resistivity measurement is calibrated in ohm.m. This is a resistivity and, in this case, a so-called apparent resistivity. It is not identical with the true rock resistivity but is rathermore a mixed resistivity in which apart from the true rock resistivity, the mud resistivity and the resistivity of the invaded zone (if existent) are still included.
The apparent resistivity can only be converted into the true rock resistivity via correction diagrams (resistivity departure curves) with the application of mud resistivity, borehole diameter and infiltration data (see Section 4.6.7).

4.6.5 Possible combinations with other methods

In the normal case, at least 2 electrode spacings will be run simultaneously because a purposeful determination of the true rock resistivity is only possible in this manner. Customary are 16" and 64" in normal arrangement; other spacings are possible and are also used under certain conditions. Measuring in the normal arrangement is usually combined with recording of the Self Potential curve (SP).

Moreover, there are combination probes with which several spacings, measurement of Self Potential and Gamma Ray are combined (Gamma Ray Electric Log Tool).

4.6.6 Presentation of the log

This is normally effected in the form of the classic Electric Log (Electrical Survey): track 1 (left) Self Potential, tracks 2 and 3 (right) 16" and 64" normals.

4.6.7 Interpretation

The curves of the Electric Log can be qualitatively interpreted directly from the log whereby the fact that layer boundaries are not sharply recorded must be considered. Layers with high resistivity (in comparision to the adjacent layers) show too great a thickness whereas those with low resistivity show too small a thickness. The specialist literature should be referred to for the exact delination of layer boundaries with multiple point methods.
One requires 2 curves (usually 16" and 64" normal arrangement) for determining the true rock resistivity and in addition, the mud resistivity and borehole diameter. The true rock resistivity can be determined with these values

by means of correction diagrams (resistivity departure curves; see also Chart (6)).

If mud invasion exists, an additional uncertainty arises when a Microlog or Microlaterolog is not run, which allows determination of the resistivity in the flushed zone (R_{xo}) (See Section 4.10).

Determination of the true rock resistivity from resistivity measurements in the normal arrangement is a special technique that is dealt with adequately in specialist literature. Further details must therefore be obtained from such sources (see e.g. Schlumberger Doc. Nr.3 and Nr.4; Mundry and Repsold).

* See also Section 4.9.8: Principles of the resistivity methods and 4.9.9: Ranges of application of the resistivity method.

4.7 Measurement of the electric self potential; Self Potential, SP

4.7.1 Principles

The Self Potential is not a rock parameter but rather an effect that first originates through the borehole itself, as a result of the interplay of mud filtrate, pore water and shales.

It is not possible to go into the cause of origination of Self Potentials in boreholes at this point as most complex phenomena are involved.
The simplest thing about the Self Potential curve, usually referred to as the SP curve, is its measurement: the natural potential difference (electric voltage) between a single borehole electrode and a reference electrode at the surface is continuously recorded in relation to the depth, usually synchronously with measurement of the rock resistivity in the muliple point array (ES).

4.7.2 Purpose of the measurement

Acquisition of information concering the salinity of the pore water in porous (permeable) rock.

4.7.3 Disturbing influences

That said about critical positioning of the reference electrode N in Section 4.6 applies even more for the SP curve. Should no interpretable recording of the SP curve be obtained, the position of the N electrode must be changed. If too many disturbances (e.g. stray currents) influence the N electrode, it can be placed in the mud pit or even directly connected to the cable armour as an emergency measure.

4.7.4 Technical Data

The scale of the SP curve is calibrated in millivolts (mV) and has a floating zero point. As only sensitive recording of the Self Potential changes are important, the greater part of the voltage actually occurring is compensated by a zero suppression.

A correctly recorded SP Log deflects to the right when the borehole electrode becomes electrically positive in relation to the reference electrode at the surface (N) and vice versa.

4.7.5 Possible combinations with other methods

Usually with measurement of the rock resistivity in the multiple point array (ES).

4.7.6 Presentation of the log

On track 1 (left) of the Electric Log

4.7.7 Interpretation

The very simple method of recording the SP curve contrasts with the considerable difficulty experienced in usefully interpreting an SP curve, especially in the field of water development.

In principle, deflection to the left indicates more saline water and deflection to the right fresher water if at the same time, the shale content does not change (or changes only slightly).

An interpretation of the SP curve with the aim of quantitatively determining the resistivity of the pore water (and thus the total salt content) is a rare occurrence in water development and if at all only possible in broad terms.
The reason is that in such cases, one is frequently involved with fresh water filled unconsolidated sediments, with wich the strong inhomogeneities of the shales make a quantitative interpretation practically impossible.

The basic condition for a quantitative interpretation of the SP curve is in every case, that a clear shale-sand alternate bedding and an obvious difference of salinity between mud filtrate and pore water must exist, so that a shale baseline and a sandline can be determined, the potential difference of which can be used for interpretation purposes. However, so-called baseline shifts of hydrochemical origin, not always recognizable as such in the log, can greatly disturb the course of an SP curve and give rise to misinterpretation.

If consolidated rock is involved and pore water and mud filtrate are predominantly sodium chloride solutions, assuming the above described basic preconditions are fulfilled and the SP curve is not disturbed, then the approach for the quantitative determination of the pore water resistivity is relatively simple (see also Section 5.3):

$$SP = K \cdot {}_{10}\log(R_{mf}/R_w)$$

SP	=	Difference between shale base and sandline in mV
R_{mf}	=	Resistivity of mud filtrate in ohm.m
R_w	=	Pore water resistivity in ohm.m
K	=	65 + 0.24 T in mV
T	=	Temperature of the investigated layer in degr.C

However, this applies only – repeated for the sake of emphasis – for sodium chloride solutions and consolidated rock, conditions that seldom occur in the field of water development. Even small deviations from these ideal conditions can cause considerable uncertainty, so that this method cannot be recommended for determining the salinity of pore water. Here also, reference must be made to the specialist literature for more detail concerning possible problems.

4.8 Measurement of rock resistivity in focussed array; Focussed Electric Log, Laterolog, FEL, LL

4.8.1 Principles

With this method, the current flow of a single borehole electrode is "focussed" to a thin, horizontal disc by means of addtional electrodes placed above and beneath it, through which the vertical resolution and lateral investigation depth are significantly increased compared with the 16"- 64" normal arrangement (see Fig. 6).

With an FEL probe with e.g. a measuring electrode length of 10 cm, a total length of about 2 m and a diameter of 35 mm, the maximum layer resolution (with not too large a borehole diameter and normal resistivity contrast) is about 20 cm and the lateral investigation depth accords roughly to that of a 64" normal.

Fine alternations can be resolved in detail with the FEL Log. With extreme contrasts in resistivity (above all with resistivity minima) the layer resolution can even extend into the centimetre range. It is this which renders the FEL method especially employable under certain conditions for fracture detection in consolidated rock.

The true rock resistivities of the penetrated layers can be determined relatively simply in the $R_t/R_m > 1$ range (rock resistivity greater than the mud resistivity). The pre-condition here is that there is no mud invasion or it is only slight.

The undisputable advantages of the method are opposed by some disadvantages:

With some of the FEL tools, it is not possible to measure resistivities as high as those measured in normal arrangement.

The FEL Log loses layer resolution with larger borehole diameters and the same applies with the presence of mud invasion.

The FEL probe mostly is an "active" device, i.e. it contains electronic modules and consequently requires appropriate servicing.

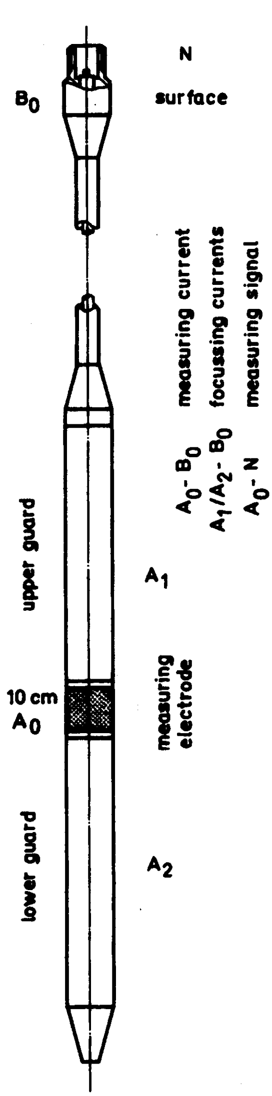

Fig. 6 FEL (Laterolog) Probe

The current emanating from electrode A_0 is focussed by additional bucking currents, emanating from the guard electrodes A_1 and A_2, to a confined "current disc". The two guard electrodes are kept on the same potential with the measuring electrode. A better layer resolution is attained in this way than with the multiple point array

4.8.2 Purpose of the measurement

Resolution of thin layers and alternations, determination of the true rock resistivity in the case of $R_t/R_m > 1$.

4.8.3 Disturbing influences

As with measurement of rock resistivity in the multiple point arrangement (see Section 4.6).

Resistivity measurement in the focussed arrangement is only suitable for qualitative interpretation when $R_t/R_m < 1$. The variations in resistivity shown in this case originate from the immediate surroundings of the borehole, they may be related to geology but must not be over-interpreted.

4.8.4 Technical Data

Like any other resistivity measurement, the Focussed Electric Log measures resistivities in ohm.m. These are apparent resistivities as is the case with measurements in the multiple point arrangement.
Nevertheless, the amount of the borehole correction in most cases is smaller than with these.
The apparent resistivity indicated is in consequence more often closer to the true resistivity of the undisturbed rock. Focussing of the very low measuring current (in the order of 1 mA) is achieved through additional bucking currents, which automatically regulated, are passed into the rock via the guard or focussing electrodes. These currents can achieve strenghts of 1 or 2 A. When an FEL probe is being installed into the borehole, increased caution is essential as with the probe that is switched on, there can be considerable current flow when touching certain electrodes.

4.8.5 Possible combinations with other methods

There are usually no combinations in slim hole logging. However, there are a variety of probe combinations for special tasks in the oil industry which connect several focussing arrays with one another. Reference must be made here to the records of the service companies.

4.8.6 Presentation of the log

Usually on the right side (tracks 2 and 3) of the log. Some equipments allow recording of the resistivity in a logarithmic scale, through which a considerably greater range of resistivity can be covered on the log (e.g. with boreholes that extend from fresh water filled sediments close to the surface through to the salinized zone of a coastal area or down to the caprock of a salt dome).

4.8.7 Interpretation

As the curves of the Focussed Electric Log show a considerably sharper reaction to layer boundaries than the multiple point resistivity curves, they are particularly suitable for delineation of layer boundaries and rock fractures.

Determination of the true rock resistivity in the $R_t/R_m > 1$ range is effected via correction diagrams in which the measured apparent resistivity, the mud resistivity and the borehole diameter are also entered (see Chart (7)). As long as little or no mud invasion is encountered this method poses no problems. Otherwise, determination of the true resistivity is most uncertain. In this respect, an additional measurement in the multiple point array is desirable to support the interpretation of a measurement in focussed array.

* See also Section 4.9.8: Principles of the resistivity method and 4.9.9: Fields of application for resistivity methods.

4.9 Measurement of electric rock conductivity (focussed induction method); Induction Log, IES, IEL

4.9.1 Principles

The rock resistivity can also be determined by measuring rock conductivity.

This is the reciprocal value of the resistivity, the measuring unit is mho per metre (which = 1/ohm.m). However, scales are usually calibrated in mmho/m (milli-mho/m).

The measurement takes place in that electromagnetic waves, mostly with a frequency of about 20 kHz, are transmitted into the surrounding rock from a transmitter coil on the measuring probe. According to the conductivity of the rock, more or less strong eddy currents are thus generated in the rock, the magnetic fields of which induce voltages in a detector coil that is located at some distance (mostly about 1 m) on the measuring probe. The rock conductivity is obtained from the amplitude and phase location of these induced voltages.

Through appropriate positioning of additional transmitting and detector coils, the electromagnetic field is focussed through which greater lateral investigation depth and better layer resolution are achieved.

With larger tools, a 16" normal and SP are usually recorded simultaneously. Moreover for comparison with the 16" normal the conductivity signal is converted into a resistivity signal (reciprocator in the measuring panel), so that altogether 4 curves are recorded: Self Potential, 16" normal, conductivity and resistivity (= reciprocal conductivity).

The main application of the Induction Log is the determination of true rock resistivity R_t in those cases where this becomes smaller than the mud resistivity R_m: $R_t/R_m < 1$. Here, the Induction Log is superior to the resistivity logs (Electric Log and Focussed Electric Log), as through measurement of the conductivity, the signal part of the rock is high compared to that of the mud and the invaded zone.
Under these conditions the reverse applies with the resistivity logs.

The case $R_t/R_m < 1$ can even occur with moderate rock resistivities when poorly conducting mud is used (e.g. surface water); it is almost always the case with pore water that has a high salinity.

A further advantage of the Induction Log is that it requires no galvanicelectrically conducting medium between probe and rock, as do the resistivity methods. Hence the measurement can also be effected in a dry hole. In this case, influencing of the measuring results through the borehole effect is negligible.

As small conductivities are obtained with high rock resistivities, the Induction Log is not suitable for the measurement of high resistivities: conductivities smaller than 10 mmho/m (resistivities above 100 ohm.m) can no longer be adequately read.

Conversions:

resistivity (ohm.m) = 10^3 / conductivity (mmho/m)

= 10^4 / conductivity (μmho/cm)

4.9.2 Purpose of the measurement

Determination of the true rock resistivity from moderate resistivities down to low and very low resistivities ($R_t/R_m << 1$).

4.9.3 Disturbing influences

As the tool operates electromagnetically, possible disturbances are limited to the tool function itself.

4.9.4 Technical data

The Induction Log tool transmits electromagnetic waves into the rock and receives the secondarily induced waves in return, recording a conductivity signal (unit mmho/m). It is focussed by several additional coils. Focussing is not usually as sharp as with Focussed Electric Log tools that have short measuring electrodes.

The Induction Log is a universally applicable resistivity measuring method but is not suitable for high resistivities (see Sections 4.6 and 4.8). However, it can be used in dry holes (i.e. boreholes not containing fluid) and in boreholes with plastic casing.

4.9.5 Possible combinations with other methods

Combinations with other tools are not usual in slim hole logging.

4.9.6 Presentation of the log

The measurement is usually recorded on tracks 2 and 3, i.e. on the right side of the log with the zero line to the right. Rising conductivity causes a deflection to the left. Hence the log can be qualitatively read as a resistivity log with the zero line to the left and rising resistivities to the right.

4.9.7 Interpretation

The true rock resistivity (or true conductivity) is determined via correction diagrams related to the type of tool.

4.9.8 Principles of the resistivity methods

The resistivity methods are grouped into:

– Single Point Method	Single point resistance measurement; Mono -- PR
– Multiple Point Methods	Resistivity measurements in normal (or lateral*) arrangement; Electric Log -- ES, EL
– Focussed Methods	Resistivity measurements in focussed arrangement; Focussed Electric Log, LATEROLOG -- FEL, LL
– Induction Methods	Conductivity measurements in focussed arrangement; Induction Log -- IES, IEL

Single Point Method

This method is still occasionally encountered with small well logging units. It measures the grounding resistance (i.e. a resistance and not a resistivity) of a single borehole electrode.

The resistance that encounters a current emanating from a spherical electrode becomes all the more smaller the greater the cross-section of the current path is. The cross-section is defined by the surface of the sphere $4\pi r^2$, where r is the length of the current path, i.e. it increases with the square of the distance from the electrode centre.

Thus, irrespective of rock composition, even areas relatively close to the electrode have almost no influence on the measured value. This means that the borehole and mud invaded zone have a large share in the measuring result, whereas the true rock resistivity only has a small share or even none at all.

The single point method is thus unsuitable for determination of rock resistivity. For this reason it is not dealt with further.

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* obsolete nowadays

Multiple Point Methods

Multiple point methods avoid the disadvantages of the single point resistance method in that voltage measurement is effected over separate electrodes, the immediate vicinity of the current electrodes is therefore avoided. This is purchased through higher technical effort and lower layer resolution but nevertheless permits determination of the rock resistivity with much greater reliability.

The multiple point methods were the standard resistivity determination methods in oil prospection for decades and today, they are still in use in slim hole logging.
In meantime, they have been replaced in oil prospection by an arsenal of various focussed resistivity logs and induction logs; this development is still in the early stages in slim hole logging.

Focussed Methods

The focussed method, also known under the name LATEROLOG that was originally introduced by Schlumberger, has been developed from the single point resistance method through the inclusion of guard or focussing electrodes. It now displays only the advantages and not the disadvantages of the single point method:
Focussed methods have a high layer resolution (according to type into the decimetre or even centimetre range) and great lateral investigation depth.

These measuring systems, of which there are a great variety of types, nevertheless contain a high technical effort, as the bucking currents which focuss the measuring current beam have to be automatically regulated without delay.

Induction Methods

Whereas the methods described above transmit a galvanic current from the probe into the rock and detect its effect with measuring electrodes, whereby the measuring current is usually kept constant and the voltage drop is recorded as a resistivity signal, the Induction Log works according to a fundamentally different principle:

High frequency electromagnetic oscillations (about 20 kHz) transmitted into the rock via transmission coils, induce eddy currents around the borehole, the strengths of which are directly proportional to the conductivity of the rock.
On the other hand, the magnetic fields of the eddy currents induce voltages in detector coils on the probe, the amplitudes of which are likewise proportional to the conductivity of the rock. The Induction Log thus measures a conductivity signal that is mostly converted into a resistivity signal in addition, by means of a reciprocator.

The induction tools of today, in terms of measurement technology, involve even more effort than the focussed resistivity tools and like these, they are also focussed (through additional coils).

Induction Logs are also suited for determining the true rock resistivity in dry holes (medium and low resistivities presupposed).

Technical realization of resistivity measurements

The technical realization of resistivity measurements is such that with the single point and the multiple point methods (16" - 64" normals) as well as with the Laterologs a resistivity signal is recorded. This means, a current which is kept constant is transmitted into the rock and the voltage drop generated on the rock by this is measured: low rock resistivities generate low measuring signals and high resistivities high measuring signals.

However, it is also possible to record a conductivity signal with this method; for this a constant voltage is applied and variation of the current is measured: low rock resistivities then generate high measuring signals and vice versa. This is usually not practical as the methods mentioned are generally applied for measuring moderate to high resistivities, hence only low conductivity values would be obtained.
Nevertheless, tools with this reverse measuring method are employed in special cases (e.g. Schlumberger Conductivity Laterolog), like offshore measurements where low to very low rock resistivities are encountered and accord ingly, conducting muds result.

The Induction Log is bound to measuring a conductivity signal as measurement of a resistivity signal would require sensing devices in the rock.
The response of the measuring method is not affected by technical realization of the measurement (resistivity or conductivity signal), this depends exclusively on the electrode array.
However, the methods with galvanic coupling (single point, 16" - 64" normals and the Laterologs) react differently to the resistivities of the borehole and its surroundings than those methods with inductive coupling (Induction Log). With the resisitivity methods the measuring current "sees" in series mud resistance, resistance of the invaded zone and true rock resistance, which in case of high rock resistivity results in a high part for the latter and vice versa. On the other hand, with the induction methods the induced eddy currents "see" the borehole and mud invaded zone and the undisturbed rock in parallel, which results in a high signal part of the rock with low resistivities and vice versa (see Fig. 7).

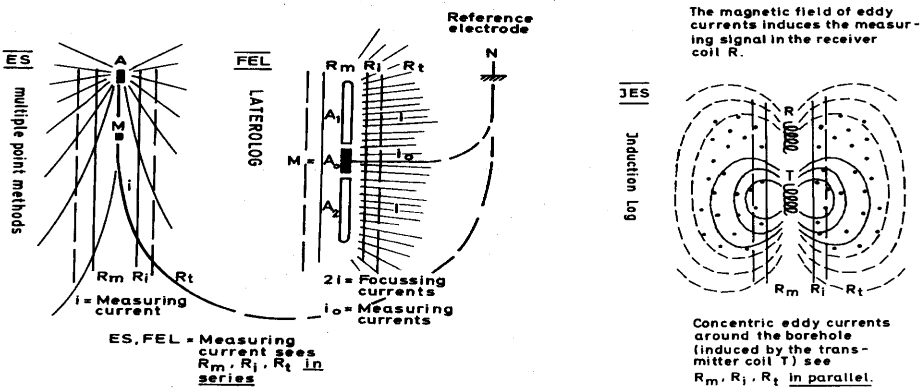

Fig. 7 Comparison of functions of multiple point methods (ES), Laterolog (FEL) and Induction Log (IES)

4.9.9 Fields of application for resistivity methods

The main differentiation criterion for the various fields of application of the three resistivity methods is the ratio of true rock resistivity and mud resistivity R_t/R_m.

(1) Focussed Electric Log, FEL

Without mud invasion well suited in range	$R_t/R_m > 1$
With moderate mud invasion well suited in range	$R_t/R_m > 5$

Below these values, the method is only suitable for recording of resistivity variations in the immediate vicinity of the borehole. Determination of true rock resistivity is no longer possible.
Sensitive detection of layer boundaries and thus a high layer resolution, especially with tools having a short measuring electrode.

(2) Induction Log, IES, IEL

Favoured method for resistivity measurements in the range $R_t/R_m < 1$, as long as 50 ohm.m (20 mmho/m) are not greatly exceeded.
Less sensitive detection of layer boundaries with most tools, therefore moderate layer resolution.

(3) Electric Log, ES, EL

Well suited in range $R_t/R_m > 1$.

Below $R_t/R_m = 1$ the 16" normal is practically influenced only by mud and perhaps infiltration. However, the 64" normal is insensitive to it due to the long electrode spacing. If no great layer resolution and not too great a degree of accuracy are required, the 64" normal can be used instead of the Induction Log for an approximate determination of true rock resistivity.
Less sensitive (rounded) detection of layer boundaries, inferior layer resolution.

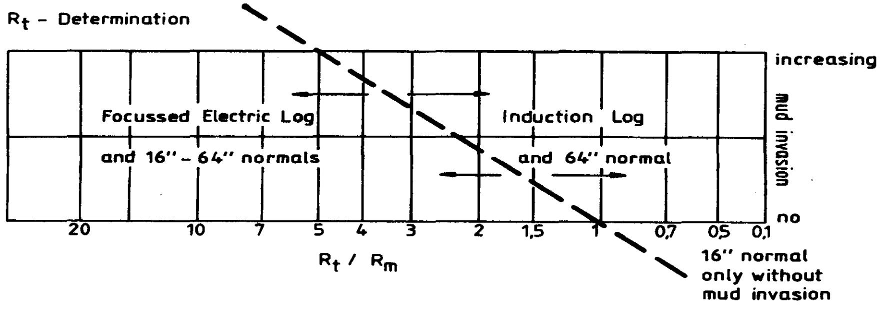

Fig. 8 Fields of application for resistivity methods

4.10 Measurement of resistivity in the borehole vicinity; Microlog, Microlaterolog, ML, MLL

4.10.1 Principles

The method is used to measure the resistivity in the immediate vicinity of the borehole. A small electrode arrangement with electrode spacings of 1-2 inches is installed on a side wall pad that is held against the borehole wall under strong pressure during measuring (see Fig. 9).
The side wall pad adjusts to the borehole wall pressing the mud away so that it does not influence the measurement. The borehole correction is thus obviated.

Several electrode arrangements are in use, the classic unfocussed Microlog and various focussed arrangements that differ from one another through their degree of focussing and hence in their lateral investigation depth. Selection of the method used is dependent on the infiltration conditions in the borehole.

Apart from fine layer resolution, the purpose of a micro-resistivity measurement is determination of resistivity R_{xo} of the "flushed zone", i.e. the annulus around the borehole in which the pore water has been completely replaced by mud filtrate.

Resistance R_{xo} is a correction quantity for the other resistivity measurements, without which determination of the true rock resistivity R_t is uncertain. This mainly concerns consolidated rock.
In boreholes in unconsolidated rock, mud invasion is mostly slight due to the generally high porosity, so that one can usually manage without the microresistivity log with the R_t determination.
In the search for fractures and joints, micro-resistivity arrays can also be of use due to their high layer resolution capacity.

4.10.2 Purpose of the measurement

Resolution of fine layers and alternations, fracture determination and deter mination of resistivity of the mud flushed zone (R_{xo}).

4.10.3 Disturbing influences

These occur mostly when determing the resistivity of the flushed zone (R_{xo}). However, as there are a great variety of micro-arrays reference must be made in individual cases to the records of the service companies.

4.10.4 Technical data

With these methods, resistivity measurements in multiple or focussed array are principally involved (see Sections 4.6 and 4.8). The differences exist simply in the electrode spacings and in positioning of the measuring array directly against the borehole wall.

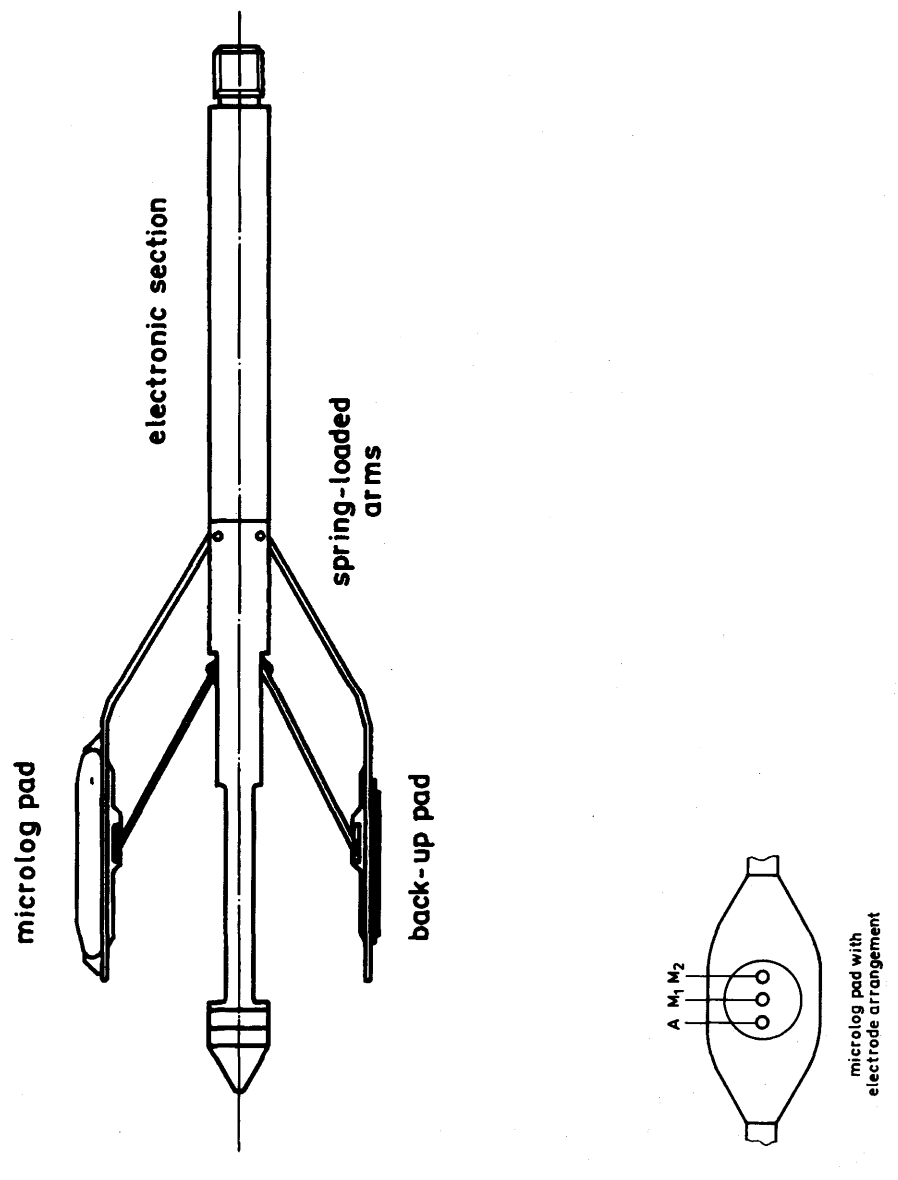

Fig. 9 Microlog Probe

A narrowly spaced electrode arrangement on a side wall pad is pressed aginst the borehole wall. Thus borehole influences are largely eliminated. Resistivities in the borehole vicinity are measured.

4.10.5 Possible combinations with other methods

A combination of two arrays on both pads of one probe is possible; however, due to the great variety reference must also be made here to the records of the service companies.

4.10.6 Presentation of the log

See section 4.6 and 4.8.

4.10.7 Interpretation

The resistivity of the flushed zone must be determined via correction diagrams that are issued by the service companies for the type of probe used.

4.11 Measurement of the resistivity (or conductivity) of the borehole fluid (water or mud); Salinometer, SAL

4.11.1 Principles

The measuring equipment for measurement of resistivity in normal array also permits measuring the resistivity of the borehole fluid. For this another probe, the Salinometer probe, is attached to the borehole cable.
Compared to the 16"- 64" resistivity probe the electrode spacings on this probe are very small (a few cm). Apart from this, the entire electrode array is installed in an internally insultated metallic tube, through which the bore hole fluid can pass. In this way the rock resistivities do not influence the measurement (see Fig. 10).

If the mud or water resistivity has to be measured under undisturbed circumstances, the SAL Log is run first. The measurement is executed during lowering of the probe into the borehole.

Salinometer measurements are mainly used for correction purposes with determination of the true rock resistivity from the 16"- 64" resistivity log or the FEL Log.

In certain circumstances water inflow or outflow can also be detected in completed wells or open holes in consolidated rock.

If the measured resitivity values are to be converted into total salt contents, the Salinometer must be calibrated in the laboratory with standard salt solutions and the temperature of the fluid column in the borehole must be known (see Charts(8) and (9)).

4.11.2 Purpose of the measurement

See 4.11.

4.11.3 Disturbing influences

As a very small electrode array is involved it is necessary to ensure that the electrode carrier is always clean (salinometers must therefore be easy to dismantle). The Salinometer probe must not be run into the borehole sump for the same reason.

4.11.4 Technical Data

In principle, measuring the resistivity of the borehole fluid is effected in accordance with the same method as the resistivity measurement in multiple point array (see Section 4.6).

A resistivity signal is usually measured, with certain types of salinometers a conductivity signal (when water with high salinity is to be investigated): resistivimeter and conductivimeter. The resistivimeter usually measures in ohm.m, the conductivimeter (deviating from the Induction Log) usually in µmho/cm.

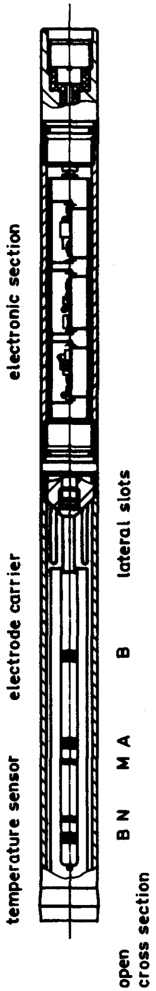

Fig. 10 Combined Salinometer/Temperature Probe

A small electrode array placed in an insultated tube measures the resistivity of the borehole fluid passing through the tool. A thermal detector simultaneously measures the temperature.

Conversion: conductivity (μmho/cm) = 10^4/resistivity (ohm.m) and vice versa.

4.11.5 Possible combinations with other methods

Frequently together with temperature measurement (TEMP), a combination with the Casing Collar Locator (CCL) is also possible.

4.11.6 Presentation of the log

As the measurement is executed while lowering the probe, a representation of Salinometer and Temperature curve with zero on the right is frequently encountered. A simultaneous representation of Salinometer and Temperature together with the resistivity log (ES, FEL or IES) is possible, as the relatively smooth SAL/TEMP curves are easy to separate optically from the most ly oscillating resistivity curves.

4.11.7 Interpretation

The Salinometer directly shows fluid resistivity (or conductivity). A borehole correction is thus obviated. Salinometers have to be calibrated with standard salt solutions. If high accuracy is required an up-to-date calibration curve must be available for the Salinometer used.

4.12 Measurement of the temperature of the borehole fluid (water or mud); Temperature, TEMP

4.12.1 Principles

An electric resistance thermometer is used that records the temperature continuously in relation to the depth.

If the temperature is to be measured in undisturbed conditions, the TEMP Log (often in combination with the SAL Log, see Section 4.11) is run first.The measurement is executed during lowering of the probe into the borehole.

A temperature that is representative for the surrounding rock can usually be measured in the borehole fluid only, as considerable air circulation may take place above the fluid level in the hole. For this reason one mostly observes a temperature step with the entry of the probe into the fluid.

Due to the annual temperature wave the natural temperature increase with depth (geothermal gradient: on average 3 degr. C/100m) can first be observed at a depth of about 20 m. Deviations from the normal temperature rise can indicate vertical water movements in the borehole or well or in the surrounding rock.
The temperature curve frequently displays more or less sharp irregularities at water inflow and outflow points.

If the local temperature rise is to be measured in an undisturbed state, then the temperature disturbances occasioned by the drilling process must indeed have faded beforehand. For this (as an approximate value), one once again assumes the same time that was taken up by the drilling work itself.

4.12.2 Purpose of the measurement

See 4.12

4.12.3 Disturbing influences

None.

4.12.4 Technical data

In principle an electric resistance thermometer is involved (resistance wire with positive - PTC - or negative - NTC - temperature coefficient). Transmission to the surface is usually effected as a pulse rate or as a digital signal. However, the possibilities of constructing a temperature probe are so manifold that one cannot go into detail about them here.

As a general rule, temperature probes can show changes in temperature most accurately, 0.01 degr. C is attainable with the corresponding constructional effort. Absolute values with high accuracy are, however, very much more difficult to realize. Temperature readings with an absolute accuracy of 0.01 degr. C are not attainable.

4.1.2.5 Possible combinations with other methods

With scientific measurements (determination of the local temperature gradient), usually no combination with other tools. Otherwise often combined with the Salinometer.

4.12.6 Presentation of the log

See Section 4.11 Salinometer.

4.12.7 Interpretation

The borehole correction is obviated as the Temperature probe shows the temperature directly in degr. C.

4.13 Measurement of the borehole or casing diameter; Caliper, CAL

4.13.1 Principles

Continuous recording of the borehole diameter provides information about its deviation from the nominal value (bit) diameter.
Here, caving may indicate unconsolidated layers or zones of loose material in fractured (consolidated) rock. One frequently observes borehole narrowing with swelling clays as well as with strong mud cake formation.

The caliper tool usually applied has three spring-loaded arms (umbrella type caliper) which depending on the diameter of the borehole, undergo a corresponding spreading that is recorded in a linear scale in relation to depth (see Fig. 11).

Caliper data can be applied with cementation and filling work as well as completion with casings and filters. Further, they serve for correction purposes with the interpretation of almost all other methods (Gamma Ray, Density, Resistivity, Self Potential, Flowmeter).

4.13.2 Purpose of the measurement

See 4.13

4.13.3 Disturbing influences

With low pressure of the spring arms and and inclined hole it is possible that the caliper tool does not centre perfectly, i.e. that not all arms touch the borehole wall. This' necessarily leads to an incorrect (too small) diameter reading. With some of the caliper tools applied this can even occur with a deviation of the borehole axis from the vertical of only a few degrees. Nevertheless, an incorrect caliper log obtained in this way can be mostly recognized as such due to the irregular course of the caliper curve.

Inclined or horizontal drillings cannot be measured with the usual caliper tools. Special types are required for this purpose which lie against a borehole wall and which sense unsymmetrically in the borehole with one or more arms.

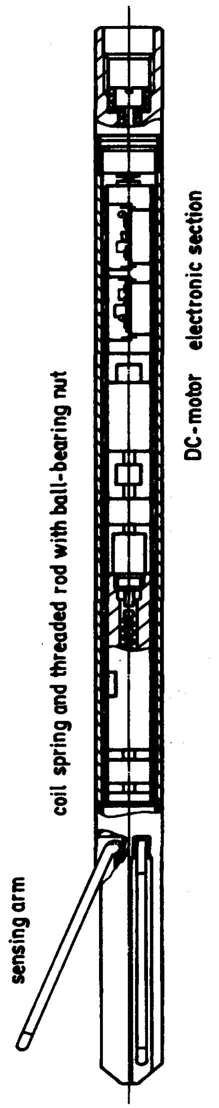

Fig. 11 3 Arm Caliper Probe

3 spring-loaded arms (motor-powered extension and retraction) sense the borehole wall and thus measure the average borehole diameter.

4.13.4 Technical data

The caliper tools in use today are exlusively so-called umbrella calipers. They normally have 3 arms (1 arm in exceptional cases). There are also caliper tools with 4 arms (not to speak about special tools with 8 or even more sensing arms) with which 2 arms each are coupled so that two caliper curves can be recorded and the ellipticity of the borehole cross-section determined.

Older makes of bow spring caliper tools are no longer in use.

All caliper tools are installed in the borehole in the closed state (arms resting on the probe body) and opened (usually by electric motor action) at the lowest point of the section to be measured. The measurement is then executed with the arms riding against the borehole wall. The deflection of the arms is transmitted on a precision potentiometer, usually converted into a pulse rate and passed to the surface over the cable.

The caliper reading on the diagram is not linear with all tools; however, a linearisation of the measuring arms deflection is usually executed in the probe itself by mechanical or electrical means, so that the recording is effected on the diagram in a linear scale.

4.13.5 Possible combinations with other methods

Combinations with several methods are usual: e.g. Gamma Ray, Density, Neutron, Sonic Log, Microlog (or Microlaterolog and other micro-methods), the possiblities are so varied that they cannot be explained in detail here.

4.13.6 Presentation of the log.

The caliper log is presented at various places on the log, frequently on track 1, together with the Gamma Ray Log but also e.g. with the Density Log, on a half track left or right of the actual Density Log with zero left or right or also with suppressed zero, so that only the diameter range in question appears on the diagram.

4.13.7 Interpretation

The measured borehole or well diameter can be obtained directly from the log.

4.14 Casing collar locator in steel casing; Casing Collar Locator, CCL

4.14.1 Principles

The Casing Collar Locator is an open electromagnet (permanent magnet with coil and iron core), the magnet flux of which is changed by variations of the casing wall thicknesses which always occurs with casing collars, so that a voltage is induced in the coil.

The voltage impulse (often several impulses per casing collar), the amplitude of which also depends on the cable speed, is directly displayed on the recorder. The amplitude can be suitably adjusted with a range selector and the position of the CCL Log on the diagram can be optionally selected with a zero point displacement.

Indications of leaking casing collars and other leaks with plastic casings can be obtained with the FEL method, when a tool with a short measuring electrode is used (about 10 - 20 cm, see also Section 4.8 Focussed Electric Log). The accomplishment of this effect has not as yet been fully clarified but is empirically confirmed by a great number of measurements.
The question of the extent to which these CCL-like indications are based on leaks, that can cause a notable inflow of undesired intruding water (e.g. in a groundwater piezometer), must remain open for the time being.

4.14.2 Purpose of the measurement

See 4.14.

4.14.3 Disturbing influences

None.

4.14.4 Technical data

The Casing Collar Locator measures an induction signal from an open elctromagnet caused by material changes in the casing that are generally present with casing collars but also with gaps, eaks and breaks. The signal is dependent on the cable speed, however, its sensitivity can be changed in the measuring panel.

4.14.5 Possible combinations with other methods

With all methods that are measured in steel casings.

4.14.6 Presentation of the log

Usually at the extreme left (further to the left of track 1).

4.14.7 Interpretation

Casing collars or damaged points can be obtained directly from the CCL Log.

See Section 4.14.1 for Casing Collar Locator in plastic casings.

4.15 Measurement of the vertical fluid flow in boreholes or wells; Flowmeter, FLOW

4.15.1 Principles

Before a well is taken into operation or a test well (especially in consolidated rock) is completed, it is necessary to establish from which of the penetrated layers the water flows into the well. As a consequence of differing hydraulic conductivities, this does not normally take place evenly along the entire length of the well.

For this, one uses a Flowmeter that is lowered into the well at a constant speed during pumping and continuously records the vertical velocity of flow of the water in the well.

Whenever the Flowmeter bypasses a "producing" layer on its way down the hole, the revolution count of the spinner decreases by a certain amount because the water flowing into the well from this layer (and drawn upwards from the pump) is no longer registered.

A sort of stepped curve is obtained on the recorder between the maximum reading of the Flowmeter directly beneath the pump and the minimum reading beneath the last water inflow, where the Flowmeter only records its own travel speed in static water (see Fig.12).

The tools usually applied are mechanical-electrical Flowmeters with which the flowing water drives a spinner (impeller), the revolution count of which is transmitted via the borehole cable and is continuously recorded in relation to the depth (see Fig. 13).

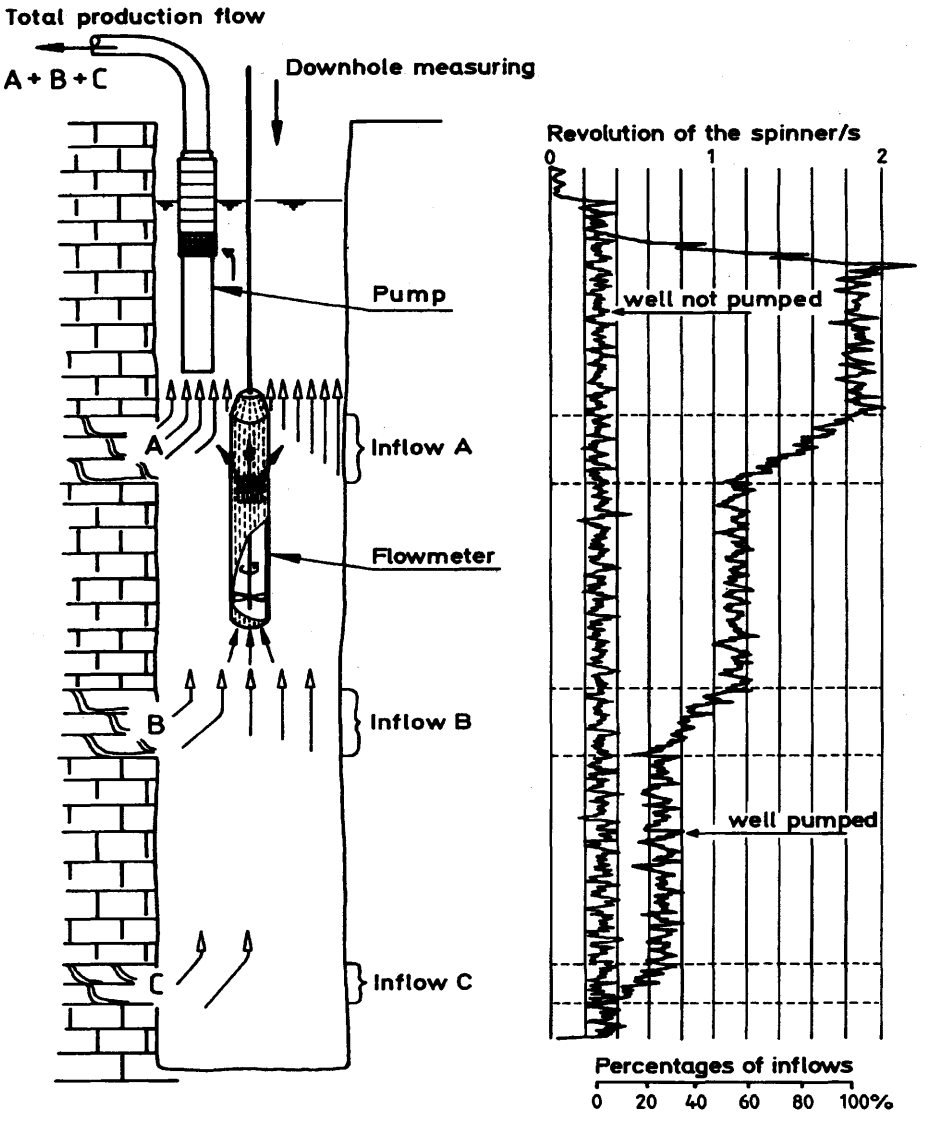

Fig. 12 Function of a Flowmeter (half-open type, measuring downhole, upward fluid flow through the tool); Flowmeter curves with and without pumping.

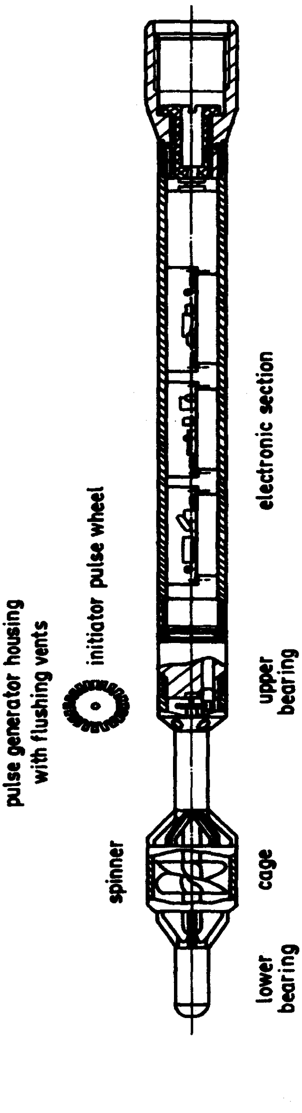

Fig. 13 Flowmeter Probe

Open type, up and down flow through the tool, coding for right and left rotation of the spinner.

Flowmeter measurements are usually carried out in a pumped well or borehole; the measurement should be repeated if possible with altered production rates.

In an artesian well or borehole a Flowmeter measurement can of course be executed without pumping if the fluid speed in the well is sufficiently high (see under 4.15.4: Technical data).

As the velocity of flow of the water and the cable speed of the Flowmeter probe are added in the measuring value of the Flowmeter Log, the share of the latter, the so-called "travel effect", must be determined. This is done by taking a few stand-flow readings (i.e. measurements with the static probe) at selected depths when coming up with the tool after the completed Flowmeter run.

The share in the total production of each individual producing layer is obtained from the Flowmeter reading reduced by the travel effect. In this connection, a negative production can also be involved, i.e. an outflow from the well into the rock. This applies especially in cases of consolidated rock wells and fissured aquifers.

All that is said above is pertinent for boreholes or wells with constant diameters. In wells with a variable diameter (e.g. open holes in consolidated rock) changes in velocity of flow can be brought about also by changes in diameter.
Exact knowledge of the completion data of the well respectively the execution of a caliper measurement is an addtional necessity here as otherwise, a false interpretation is obtained.

4.15.2 Purpose of the measurement

To determine the share of each of the producing layers in the total production of a sequence penetrated by a well or a borehole with a definite pump rate.

4.15.3 Disturbing influences

The following should be observed before executing a measurement:
If a Flowmeter measurement is to be carried out in a pumped well, the pump must be installed just below the maximum drawdown of the water level, never in the lowest depth of the well (close to the well bottom), because Flowmeter measurements alongside the rising pipe are not possible.

For safe lowering of the Flowmeter down to below the pump, a guide tube should be installed between the rising pipe and the wall of the well (this should be arranged beforehand with the commissioning party). Lowering of the Flowmeter alongside the pump equipment without a guide tube (if at all possible) involves considerable risk.

In uncased wells (consolidated rock) a caliper log must be run in addition as otherwise, the Flowmeter diagram cannot be clearly interpreted.

In wells, in which so-called "slotted tubes" without gravel packing (auxiliary casing or filtering) are installed, which is often practised in consolidated rock to secure the stability of the borehole, Flowmeter measurements should only be interpreted with great caution, as due to the usually irregular slotting and hence uncontrollable share of the water flow outside the tubes erroneous results may be obtained.

4.15.4 Technical data

Only vertical velocity of flow can be measured with the Flowmeter.

The Flowmeter is not a flux meter, pumping rates are only obtained by recalculation via the well diameter.

In order to obtain a practically interpretable Flowmeter diagram, three conditions must be observed:

(1) The maximum upwards flow generated by pumping (or the artesian outflow) in the well should be at least as fast as the downward speed of the Flowmeter probe: pump effect $\geqq$ travel effect.

For the resulting minimum pump rates see Chart (10).

(2) On the other hand, the travel speed of the probe must be significantly higher than the speed with which the spinner of the Flowmeter starts to rotate (threshold speed): travel speed approx. 2 x threshold speed is recommended.

With the frequently used small Flowmeters of 35 - 40 mm diameter and half-open type (see below), the threshold speed is about 5 cm/s. Travel speed should therfore be about 10 cm/s = 6 m/min.

(3) A statement of the pump rate(s) is necessary for checking the maximum reading of the flowmeter.

The Flowmeter probe itself represents an interference with the flow conditions in the pumped well:

- The Flowmeter occupies a part of the well cross-section, an increased velocity of flow (for purely geometric reasons) is thus generated in the Flowmeter.
- The two parallel paths "through the Flowmeter probe" and"outside it" have different flow resistances and thus velocities of flow depending on the diameter ratio between probe and well.

The correction resulting form these causes has to be calibrated for each type of probe in a calibrating installation (laboratory, test well). The type curves thus obtained represent the "normal behaviour" of the Flowmeter.

As the actual conditions in a well to be measured (wall friction effects, influence of different types of filters, state of the filters etc.) are not usually identical with those in the calibration installation, type curves should therefore be used with corresponding reserve. Whenever possible, a so-called field calibration should be carried out in the well to be measured. During this, with static water in sections of constant diameter, the Flowmeter is moved up and down at different speeds (see Chart (11)).

In principle, the field calibration curve takes priority over the type curve. In cases where a field calibration is not possible or only a few field calibration points can be determined, work must proceed with the (possibly adjusted) type curves.

With Flowmeter measurements in wells of constant diameter using the type curves can be dispensed with for broad interpretations but not for wells of variable diameter.

Even with wells of constant diameter, however, the production rate should be checked by means of the type curves: maximum reading of the Flowmeter below the pump intake, converted into velocity of flow via the type curve, converted into volume of water per unit of time via the well diameter.
This value should roughly equal the pump rate measured at the surface. If this is not the case, then either the pump rate has been inaccurately measured (or incorrectly recorded) or water enters the pump from above that is not recorded by the Flowmeter.

There are Flowmeters of both the half-open and open types. With the former the water normally flows from below into the open crossection, drives the spinner and leaves the probe further up through lateral slots. With downwards flow the conditions are reversed but the sensitivity is considerably worse (see Figures 12 and 13).

Flowmeters of the open type are almost equally sensitive to upwards and downwards flow. However, they are certainly more susceptible to dirt, damage to the spinner as well as to becoming caught up at critical points in the well.

The revolution count of the spinner is converted into a periodic pulse rate via a pulse generator (usually with 10 or 20 pulses per spinner revolution) and registered at the surface by means of a rate meter and a recorder.

4.15.5 Possible combinations with other methods

No combinations with other methods (except perhaps with CCL). The desirable combination with the caliper tool with uncased wells in consolidated rock (as the Flowmeter Log is measured while lowering into the hole) would require a special caliper tool with arms extending upwards or with bow springs, which is usually not available.

4.15.6 Presentation of the log

Flowmeter scales are usually calibrated in spinner revolutions per second, occasionally also in pulses/s or pulses/min.

As the Flowmeter is usually measured while lowering, the diagram is frequently presented with zero to the right (spinner revolution count increasing to the left). This is of no consequence for the interpretation.

Flowmeter diagrams for different pump rates should be represented alongside one another wherever possible. The travel speed of the Flowmeter probe must always be recorded.

The extent to which other measurements like CAL, GR, SAL/TEMP, CCL or others are also represented on the Flowmeter diagram, depends on the case in question

4.15.7 Interpretation

Interpretation of a FLOW Log begins with checking the maximum reading of the Flowmeter below the pump (see also 4.15.4: Technical Data above): maximum reading of the Flowmeter (in revs. per s), converted via field calibration curve or type curve into velocity of flow (in cm/s) and into production rate (in m^3/h) via the well diameter.

This value must agree at least approximately with the stated pump rate.

Otherwise an inflow into the well above the pump intake must be taken into account or an erroneous statement of the pump rate must be presumed.

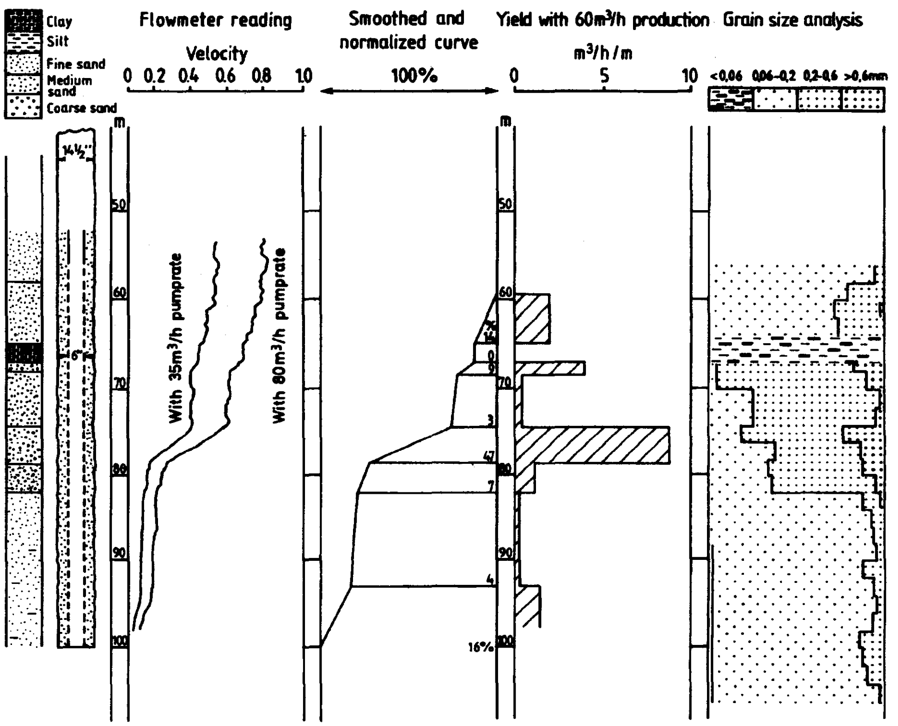

Fig. 14 Example of a quantitative Flowmeter interpretation; normalized curves, yields and grain size data (after RÜLKE 1973)

The simplest case is explained as an example of the actual interpretation (broad interpretation without the use of type curves):

The following steps must be undertaken:

(1) Smoothing of the Flowmeter curve, whereby the characteristic curve composed from vertical and inclined straights, the above-mentioned step curve is attained. Vertical straights mean non-producing and inclined straights producing sections of the well.

(2) Subtraction of the travel effect (obtained by comparison with standflow measurements; all values in revs. per s).

(3) Determination of the thicknesses of the producing sections (depth differences between the ends of the inclined straights) and the "production values" (differences between two adjacent vertical straights in revs. per s).

(4) Determination of the proportional inflows in % of the total production, whereby the maximum reading of the Flowmeter below the pump is assumed = 100%.

An example of such an interpretation is given in Fig. 14.

Varying diameters can make interpretation considerably more difficult, especially with Flowmeter measurements in open consolidated rock wells or with greater requirements for accuracy. The simple method outlined above is no longer adequate in such cases, processing must be left here to an experienced interpreter.

4.16 Determination of the borehole deviation from the vertical; Deviation, DV

4.16.1 Principles

Deviation tools exist in simple form. The so-called "Single-Shot"* tools are dropped into the drilling rods before a bit change, take one value each for inclination and orientation and are finally withdrawn together with the drilling rods. "Multi-Shot"* tools are operated on cable-wire rope or cable and permit taking a sequence of deviation measurements on microfilm in the probe.

However, there are also tools which continuously survey the borehole deviation, like e.g. the deviation section of the Dipmeter probe (inclination and orientation) that can be run separately (see Section 4.17). Such tools provide a so-called Deviation Log (or Directional Survey) that only records the spatial geometry of the well course.

4.16.2 Purpose of the measurement

Determining the deviation of the borehole axis from the vertical and its orientation towards North.

4.16.3 Disturbing influences

Deviation tools with a magnetic compass can only be put to use in open holes or in non-magnetic drilling rods (sinker bars) but not in normal steel casings (see below).

4.16.4 Technical data

The deviation can be measured optically in that a ball in a spheroidal glass in which concentric rings for the well incline are engraved and a compass situated thereunder are jointly photographed.
However, the measurement can also be effected with pendulum and compass, that both work each on a potentiometer with extremely low torque.
Determining the orientation of the deviation with a magnetic compass is of course not possible with ordinary drilling rods (non-magnetic sinker bars must be installed for this). For deviation (orientation) measurements in standard steel casings only gyrocompasses can be used. This is a non-standard application for such an instrument that is only resorted to in exceptional cases.

4.16.5 Possible combinations with other methods

With the 3 or 4 arm micro-resistivity tool to a Dipmeter (see Section 4.17).

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* Trade name of Messrs. Eastman International

4.16.6 Presentation of the log

With photographically operating tools the measuring result is represented by the developed photographs. With electrically operating tools, deviation and orientation are represented directly as curves in the log.

4.16.7 Interpretation

Interpretation of the photographically operating tools takes place in that the film of the camera installed in the probe is developed and then with the aid of a special projector, the position of the ball and the compass needle are interpreted picture by picture and from this, a graphic representation of the borehole deviation and orientation is construed.

In the case of electrically operating tools, this graphic representation is obtained manually or automatically from the log values for deviation and orientation.

4.17 Determination of strike and dip of rock layers; Dipmeter, DIP

4.17.1 Principles

Three or four of the microresistivity arrays on side wall pads (usually Microlaterologs) described in Section 4.10 are placed on a probe in the same way as an umbrella caliper tool (i.e. at the same level). Their signals are sychronously recorded while going up the hole (see Fig. 15).

While passing through a layer the micro-arrays only react simultaneously when the layer boundaries are at right angles to the borehole axis. In all other cases deflections of the microresistivity curves are displaced in terms of depth.

If the borehole axis is vertical, it is relatively simple to calculate the angle of dip from the 3 (or 4) microresistivity curves, using trigonometrical formulae. The layer dip (vertical to the direction of strike), however, takes place on a definite compass bearing and the borehole axis usually deviates more or less from the vertical. Hence an inclination measuring device (pendulum) and a device for measuring orientation (magnetic compass, gyrocompass) are also necessary in the probe. By these means, the values for the angle of dip and direction of dip related to the borehole axis and the arbitrary position of the probe in the borehole are corrected to the actual vertical direction, respectively to geographical North. This so-called deviation cartridge of the probe mostly transmits three signals (probe position towards North, 2 inclination signals of different sensitivity), so that with the actual Dipmeter signals (3 resp. 4 microresistivity curves and caliper) up to 8 signals are recorded simultaneously. Earlier, these signals had to be processed mathematically or graphically in a laborious manner. Today, they are converted by computer means to the desired parameters of angle of dip, direction of dip, borehole diameter, inclination and geographical orientation of the borehole axis and are finally presented in graphic form as a "Dipmeter Log".

Due to the high technical effort involved, the Dipmeter method is on the whole one of the most expensive well logging methods but is nevertheless the only one that permits measurement of the "dip and strike" parameters in a borehole.

Dipmeter measurements can also greatly assist joint and fracture detection (water routing in consolidated rock). In order to obtain sufficient accuracy, borehole diameters of at least 150 mm (6") are necessary for Dipmeter measurements.

The deviation cartridge (inclination and orientation part) of the Dipmeter probe can also be run separately and then provides a so-called Deviation Log that is purely intended for surveying the spatial geometry of the borehole course (see Section 4.16)

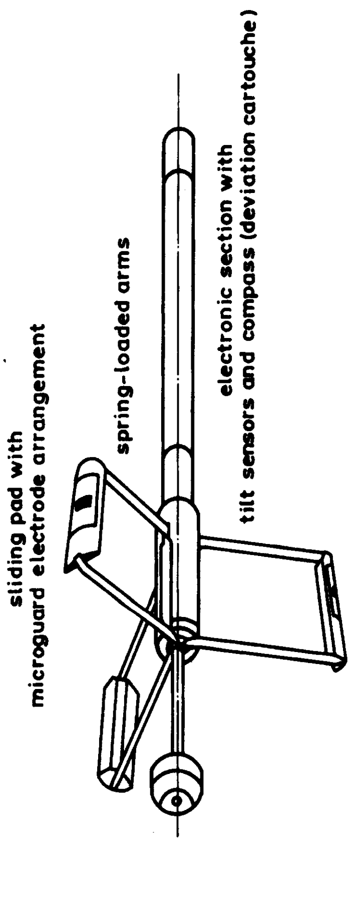

Fig. 15 Dipmeter Probe

3 or 4 microresistivity arrays on side wall pads are placed on a probe like an umbrella caliper tool. Its signals are synchronously recorded while going up the hole.

4.17.2 Purpose of the measurement

Determining strike and dip of the rock layers.

4.17.3 Disturbing influences

Clearly defined changes in resistivity with sufficient contrast are a pre-condition for the proper functioning of a Dipmeter. As this is by no means always the case, the results can be most unsatisfactory, particularly in less consolidated rock

4.17.4 Technical data

The signals of the 3 respectively 4 microresistivity arrays on the arms of the Dipmeter are transmitted to the surface, likewise the signals of the deviation cartridge coupled with the lower part of the Dipmeter. The technique of the microresistivity measurement accords with the method of the Microlaterolog (focussed microresistivity measurement) described in Section 4.10.

4.17.5 Possible combinations with other methods

None. The microresistivity part of the Dipmeter tool is always unavoidably coupled with the deviation part. The deviation cartridge can also be run separately (see Section 4.16).

4.17.6 Presentation of the log

The 3 (or 4) microresistivity signals are usually recorded as curves, the same applies for the borehole inclination, the azimuth angle and the caliper.

The actual representation of "dip" and "strike" appears on the right part of the diagram in the form of "wing direction arrows" (as shown on weather charts). The scale is calibrated in degrees of deviation from the horizontal. Thus the position of the plotted points gives the angle of dip of the layer, the direction of the arrow the orientation of the dip (90^{o} towards the strike), whereby in the conventional manner, top 0^{o} (North) and bottom 180^{o} (South) applies.

4.17.7 Interpretation

Earlier, the representation described above with dots and arrows was carried out manually via interpretation diagrams from the resistivity and deviation logs, whereby certain depth intervals were averaged. Today, this interpretation is executed via computer in the surface unit, so that the presentation of dots and arrows described above appears directly on the Dipmeter Log, without extra work being involved.

However, considerable experience is necessary to quantitatively determine actually existing layer boundaries and their dip and strike from the concentration of indications for certain dip and strike directions.

4.18 Sampling (water or mud); Sampler, SAMP

4.18.1 Principles

With the electromechanical differential pressure sampler it is possible to take a water sample from a precise depth of a borehole or well.

The tool uses the static pressure difference between the groundwater level (atmospheric pressure) and the sampling depth. It has a motor-driven valve that is first opened on reaching the sampling depth, so that only water at the level of the intake can enter the probe. The inflowing water pushes a piston ahead of it which compresses the air behind it that is originally under atmospheric pressure, until an equalisation of pressure prevails at the end of the inflow process.

Before raising, the valve is closed again so that the hermetically sealed sample is brought to the surface. It can then be passed under its original pressure into another sample container through a pressure hose or after releasing the excess pressure behind the piston, it can be drained under atmospheric pressure (see Fig. 16).

The volumetric capacity of the sampling chamber (apart from the geometrical dimensions) is dependent upon the difference in pressure attained; e.g. at 10m below groundwater level the sampling chamber is only half-filled when pressure is equalised (end of the inflow process).

The maximum sampling depth depends on the compressive strength of the sampling chamber; as during raising it must withstand rising pressure from within, one should ensure that the construction of the chamber is designed for the envisaged sampling depth.

Taking a sample is a matter of only a few minutes (apart from travel time).

4.18.2 Purpose of the measurement

Taking samples of the borehole fluid at definite depths.

4.18.3 Disturbing influences

The sealing elements of the intake valve (mostly O-rings) may be damaged by the borehole fluid rushing in at the moment when the valve is just opening. Care should be taken here.

4.18.4 Technical data See Section 4.18.1.

4.18.5 Possible combinations Not applicable

4.18.6 Presentation of the log Not applicable

4.18.7 Interpretation E.g. chemical analysis.

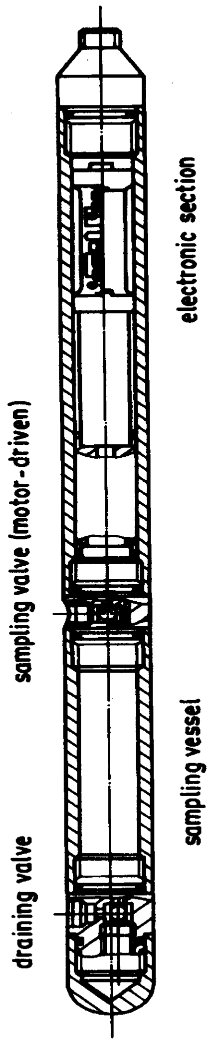

Fig. 16 Sampler Probe

The tool uses the difference in pressure between the groundwater level (atmospheric pressure) and the sampling depth. The electromechanically operated valve is first opened at the sampling depth. Water flows in until pressure equalisation is attained. Before raising the probe the valve is closed, so that the hermetically sealed sample is brought to the surface.

4.19 Optical investigations; Borehole camera, TV Camera, OPT

4.19.1 Principles

Following use from about 1950 of photographic cameras with an electronic flashlight remotely operated from the surface, TV cameras have replaced these in recent years, whereby new developments employ and continually improve colour television technology.

Photographic cameras usually permit the axial view only in which wide angle and extreme wide angle lenses (fish-eye lens) are used. Concentric annular flashlight units or simple flash tubes situated at the side of the lens are employed as illumination devices. The flash units placed at the side of the lens produce pictures with more contrast than the annular flashlight tubes. Forward movement of the film is effected with spring mechanism or electro-motor. Camera and flashlight devices are fitted with a pressure-sealed housing which is lowered into the borehole or well on a cable via depth counter.

Black/white, colour negative or reverse colour film are used according to task requirements.

In the case of TV cameras, equipments are on offer with both radial and axial viewing directions, whereby camera technology is at present constantly experiencing new developments. Black/white television techniques are less important today than colour techniques but they are usually satisfactory for well construction approval or determination of technical defects.

Illumination of the object and image resolution are of decisive importance with colour television systems. Beyond this, it is necessary to ensure that the colours shown on the monitor correspond to those of the object. Colour references which are related to a definite colour temperature (usually 3200 degr. Kelvin), are therefore an absolute necessity. The illumination devices used with black/white techniques (mostly halogen) may be less elaborate.

4.19.2 Purpose of the measurement

Optical borehole investigation methods serve a variety of purposes, like e.g. checking casings and filter sections for defects as well as locating encrustations and other deposits in wells. In open wells in consolidated rock, the methods can e.g. be applied to determine the position of jointed and fractured zones. Fishing operations in particular can also be assisted by the use of a television camera.

4.19.3 Disturbing influences

Both photographic and television cameras can only be used when the water in the well or a borehole is clear and free of suspended material, as otherwise the light of the illumination device is reflected.
Whereas even slight turbidity can make a run ineffective when a flashlight device is used, details on the well wall are still recognizabel with the use of continuous illumination. This is particularly so when a run is made using a radial viewing device and a Zoom fitting.
Optical surveys are always possible above the water level.

4.19.4 Technical data

Due to their design diameters, photographic and colour television cameras are usually only employable with borehole or well diameters greater than 150 or 200 mm. Black/white television cameras can be lowered into boreholes and piezometers with diameters down to 50 mm. Further improvements in the method commensurate with technological progress can be expected.

4.19.5 Possible combinations with other methods

A television camera can be attached to tools for special tasks, e.g. in order to measure the devation (inclination and orientation) of the bore axis (see 4.16)

4.19.6 Presentation of the log

With photographic exposures, representation is in the form of paper picture or slide, depending on the exposure material used.

Television images are viewed on a monitor screen during which, a video recording is made simultaneously. Cross-faded data, such as designation of the well, date, depth and other details permit exact reproduction.

4.19.7 Interpretation

The archived photographic exposures or television images facilitate observation of the well or borehole state at any time, particularly for comparison with previously obtained pictures. For example, the growth of an encrustation can be followed (and compared with Flowmeter measurements). With the aid of pictures taken before and after a regeneration, the success of this measure can likewise be checked. Detected damage can be rationally repaired.
Whereas the colour picture is usually indispensable for detecting encrustations, manganese deposits and other phenomena caused by fungoidal or bacteriological contamination, a run with a black/white TV or photographic camera suffices for the completion approval of a newly completed well.

In low-permeable consolidated formations (as e.g. clays, shales or siltstones), the TV camera can be used for direct detection of water inflows below the water table, when the borehole is pumped out and the camera is run in the dry hole: water producing joints or fractures can be clearly identified and even the production rate of an inflow may be assessed.

5. Quantitative interpretation of borehole logs

One differentiates between "qualitative" and "quantitative" interpretation of well logs. These expressions are "termini technici" that have been adopted from oil well logging.

Under "qualitative interpretation" one understands the qualitative designation of the layers according to the log responses and in addition, the tracing of layer boundaries and thus determination of layer depths and thicknesses (which seen on its own, naturally represents a quantitative determination).

The term "quantitative interpretation" means exclusively the determination of rock parameters by means of mathematically processing one or more well logs.

The hydrogeological parameters, the determination of which is strived for by means of "quantitative interpretation", are the following:

1.) the clay content resp. shale content
2.) the porosity
3.) the quality, i.e. the salinity of the pore water
4.) the hydraulic conductivity.

It goes without saying that all measurements, the zero readings and calibrations must be carefully executed and recorded, so that the errors in the input data are confined to the possible minimum for the calculations that follow.

I wish to thank Dr. K. Fielitz for allowing me to use extracts from his text for the representations under 5.1 and 5.2 which is given in full in the BGR report:"Calculation of depth profiles of clay content and porosity from well logs in unconsolidated sediments", of April 1983 (Archive No. 94447).

5.1 Principles of calculating the clay and shale content

The designations of the German Standard DIN 4022 are used as a basis for defining the terms clay, silt, etc. in the following.*
According to this follows classification of the sediments in respect to grain sizes:

clay	< 2μ
fine silt	2 - 6μ
medium silt	6 - 20μ
coarse silt	20 - 60μ
fine sand	0.06 - 0.2 mm
medium sand	0.2 - 0.6 mm
coarse sand	0.6 - 2 mm

The expression clay primarily designates a grain-size range and only secondarily states something about the mineral content: the material with grain-sizes below 2μ consists for the major part of clay minerals. However, the fine silt (2-6μ) too still contains a considerable amount of clay minerals.
The relative share of volume of a sediment that constitutes the clay is designated as c l a y c o n t e n t V_{cl}. In this share of volume the "clay pore space", i.e. the pore share that is formed by the sedimentation of clay particles is included:

$$V_{cl} = \frac{V_{clma}+V_{clp}}{V_g}$$

V_{clma} = volume of clay particles
V_{clp} = pore space enclosed by clay particles
V_g = total volume of sediment sample.

The s h a l e c o n t e n t V_{sh} is often determined as an alternative to the clay content. It is defined analogously to the clay content but represents a more general parameter, inasmuch as it includes silt shares, whereby the upper grain-size limit is not always clearly fixed. In this manual the upper limit will be assumed at 0.02 mm (i.e. including the fine and medium silt ranges). Shale or clay contents can be determined in a variety of ways from borehole measurements (see e.g. Schlumberger 1972)**. The simplest way is the calculation from the Gamma Ray Log that is also followed here. Gamma radiation from unconsolidated sediments is essentially originated through the potassium content (more exactly K-40) and the radioactive elements of the uranium and thorium decay series. Potassium is a component of clay minerals, alkali feldspars, glimmer and others; uranium and thorium can often occur in elementary form in very small quantities and are p-redominantly deposited in materials with a large internal surface (small grain-size). Both lead to clays and in part silts having a greater gamma activity than sands. It is on this that the method is based for determining the shale, resp. clay content of sediments from the Gamma Ray Log. The method cannot beproperly applied when sands occur which, e.g. contain glimmer minerals (glauconite or others). Such particles must be separated with the aid of the sampling record and excluded from the calculation.

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* identical with the American "Unified Soil Classification System" (USCS).
** Schlumberger Ltd.: The Essentials of Log Interpretation Practice, 1972

For determining the shale, resp. clay content from Gamma Ray Logs, a simple linear relation is applied, the so-called Gamma Ray Index (GRI):

$$\frac{GR - GR_{sd}}{GR_{sh} - GR_{sd}} = GRI \qquad \text{(see 4.1.7)}$$

GR = gamma activity of the material in question

GR_{sd} = gamma activity of a clean sand

GR_{sh} = gamma activity of a shale, resp. clay

The GRI is in turn related to the shale content resp. to the clay content:

$v_{sh/cl} = f(GRI)$.

With Hilchie (1978) one finds a graphic representation of two empirical relations between GRI and shale content for tertiary and older rocks.

Comparisons of grain-size analyses with Gamma Ray Logs (carried out by the author on samples from hose cores in unconsolidated rock) yielded the relations represented in Fig. 18.

Accordingly, the shale content has to be very broadly applied as $v_{sh} \approx GRI$, the clay content to be determined via a function similar to the curve for tertiary rock from Hilchie. However, one sees that the scattering is considerable and the values for shale and clay content determined this way must be treated with due caution, above all when intended for use in further calculations.

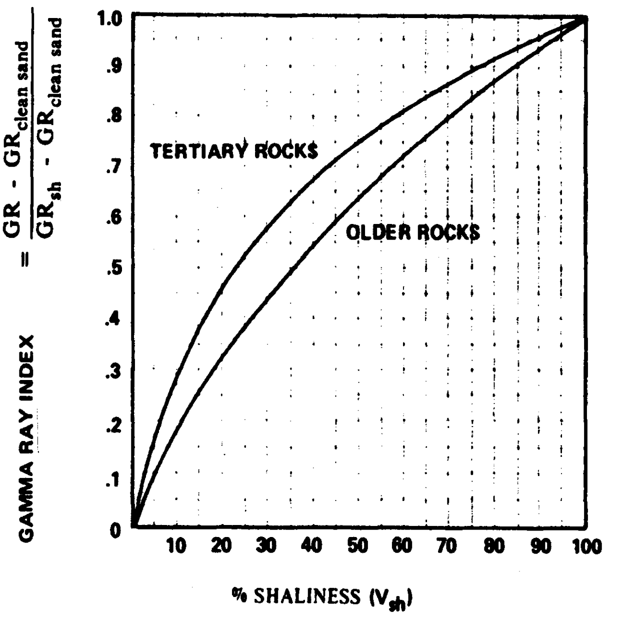

Fig. 17: Shale content in relation to the Gamma Ray Index (after HILCHIE, 1978)

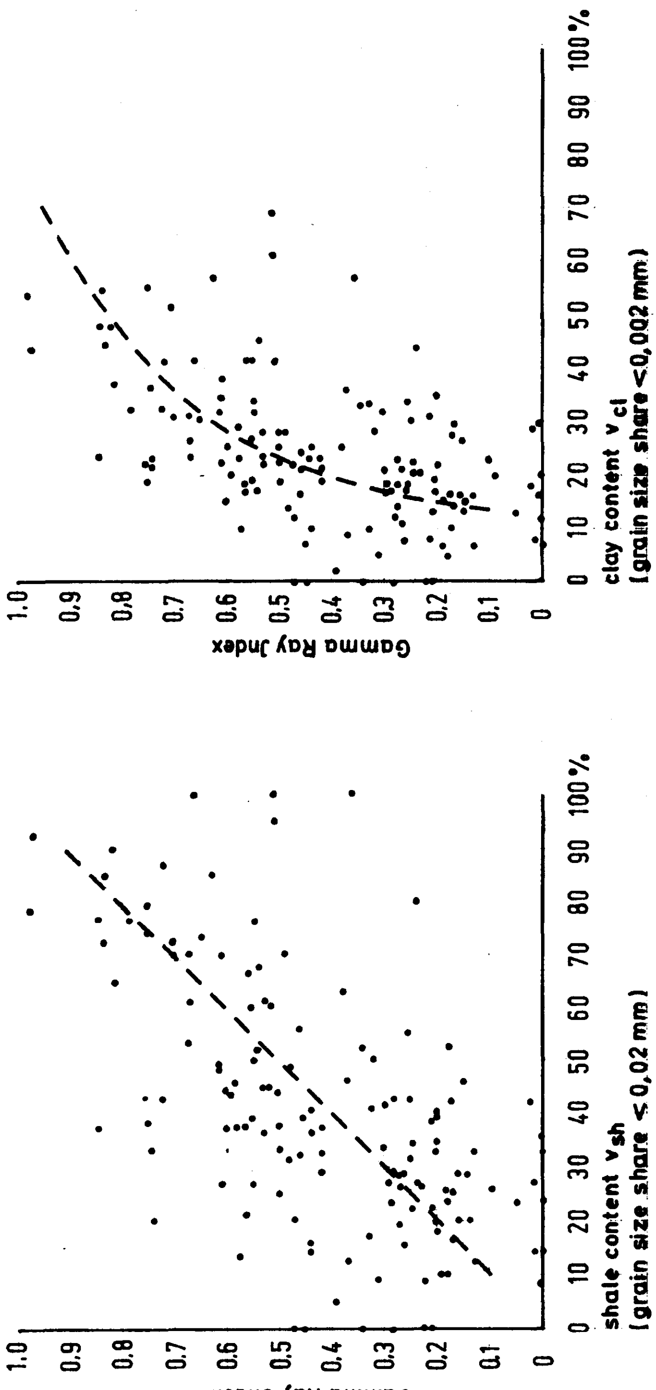

Fig 18: Shale and clay content in relation to the Gamma Ray Index in unconsolidated rock

5.2 Principles of calculating porosity

As porosity can be defined in a variety of ways and the designations are also not uniformly applied, some terms should be clarified to begin with;one differentiates:

total porosity	ϕ	=	$\phi_f + \phi_g + \phi_{sh}$
fracture porosity	ϕ_f		
intergranular porosity	ϕ_g	=	$\phi_e + \phi_r$
effective porosity, specific yield	ϕ_e		
specific retention	ϕ_r		
shale porosity	ϕ_{sh}		

Fracture porosity ϕ_f only occurs in more or less consolidated rock.

Shale porosity ϕ_{sh} is a sealed pore space that mostly contains fossile water bound to the clay. The shale porosity has no direct hydrogeological significance. Intergranular porosity ϕ_g is the interconnected pore space formed by the sand grains of an aquifer.
Considered hydraulically, ϕ_g is a more theoretical quantity because the prime interest is what volume of water can be withdrawn from an aquifer through release of static pressure (pumping). This pore share is referred to as "effective porosity" or "specific yield" ϕ_e. Added together with the "specific retention" ϕ_r, the amount of water that remains in the aquifer, it becomes the intergranular porosity: $\phi_g = \phi_e + \phi_r$.

From the porosity sensitive methods (Density, Neutron and Sonic, see Sections 4.2, 4.3, 4.4), one principally determines the total porosity ϕ . There is no possibility of differentiating between intergranular and fracture porosity, in fact both may exist.

Even in an aquifer with only intergranular porosity, there is no direct access to the "effective porosity" (or "specific yield"). The ratio between "specific yield" and "specific retention" is determined for the most part through the grain-size distribution which cannot be determined from well logs.

There is, however, an indirect way, which is described hereafter. The following porosity terms are used:

ϕ = total porosity (share of the total pore space)

ϕ_e = effective porosity (share of the pore space through which the groundwater flows under normal pressure conditions, i.e. the amount of water that can be removed by pumping)

ϕ_{sh} = shale porosity (total porosity of a layer that contains only clay and silt).

The total porosity can be approximately determined e.g. from the Density Log in accordance with the following relation:

$$\rho_b = \phi \cdot \rho_{fl} + (1 - \phi) \cdot \rho_{ma}$$ (see Section 4.2.7).

This includes ρ_b = bulk density of the rock volume

ρ_{ma} = density of the rock matrix

ρ_{fl} = density of the pore fluid.

The relation assumes complete saturation of the rock with fluid. For the total porosity follows:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

For quartz sands $\rho_{ma} = 2.65$ g/ccm.

If one is not dealing with pure sands only, then for ρ_{ma}, a mean density of the minerals involved must be assumed. The main components of clays and their average densities are:

Montmorillonite	: 2.35 g/ccm
Illite	: 2.75 g/ccm
Kaolinite	: 2.70 g/ccm

As the mean density of a compound of these minerals is probably close to that of quartz density (and an exact value is practically not determinable), the average matrix density ρ_{ma} = 2.65 g/ccm is substituted into the above equation also for shaly sands.

With the aim of obtaining an approximate value for the effective porosity in shaly material, it is customary to calculate the so-called "shale-corrected" porosity ϕ_{cor} (see e.g. Hilchie 1978). The calculation is based on the concept that one can differentiate between the "fine pore space" that is formed through sedimentation of shale particles and the remaining greater pore space. The shale-corrected porosity is obtained in that one subtracts the fine pore space that is contained in the shale volume v_{sh} from the total porosity (see Fig. 19):

$$\phi_{cor} = \phi - v_{sh} \cdot \phi_{sh}$$

This follows under the simplified assumption that the volume share v_{sh} of a shaly sand has the same porosity ϕ_{sh} as a pure shale layer.

The shale-corrected porosity would be equal to the effective porosity if the division into two types of pore space approaches reality and if the fine pore space does not participate in the groundwater flow, whereas the remaining pore space participates fully.

However, in natural sediments with a wide range of grain-sizes division into fine pore space and remaining pore space is over-simplified. Even in a pure sand, not all of the total pore space participates in the groundwater flow whereas on the other hand, in a pure shale not all of the total pore space is excluded from the groundwater flow. From these limitations, it follows that with mainly sandy material

$$\phi_e < \phi_{cor}$$

whereas with predominantly shaly material

$$\phi_e < \phi_{cor}$$

applies.

Fig. 20 shows an example of the dependence of the "specific yield" (or "effective porosity") on the medium grain-size (after DAVIS and De WIEST, 1966).

An example for a (computer-supported) combined Gamma Ray – Formation Density interpretation can be seen in Fig. 21.

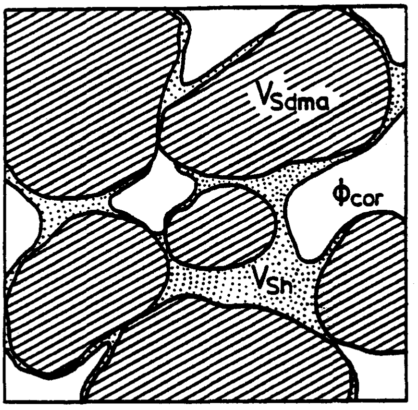

Fig. 19 Schematic section of a shaly sand to explain the terms:

V_{sh} = volume share of shale including the enclosed fine pore space ϕ_{sh}

V_{ma} = volume share of the sand matrix

ϕ_{cor} = shale-corrected porosity

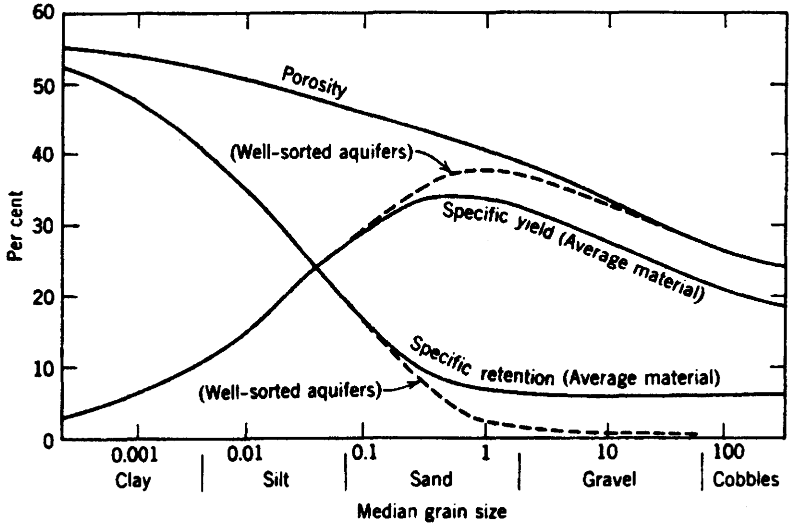

Fig. 20

Relation between medium grain-size and water storage properties of alluvium from large valleys (After DAVIS and De WIEST, 1966).

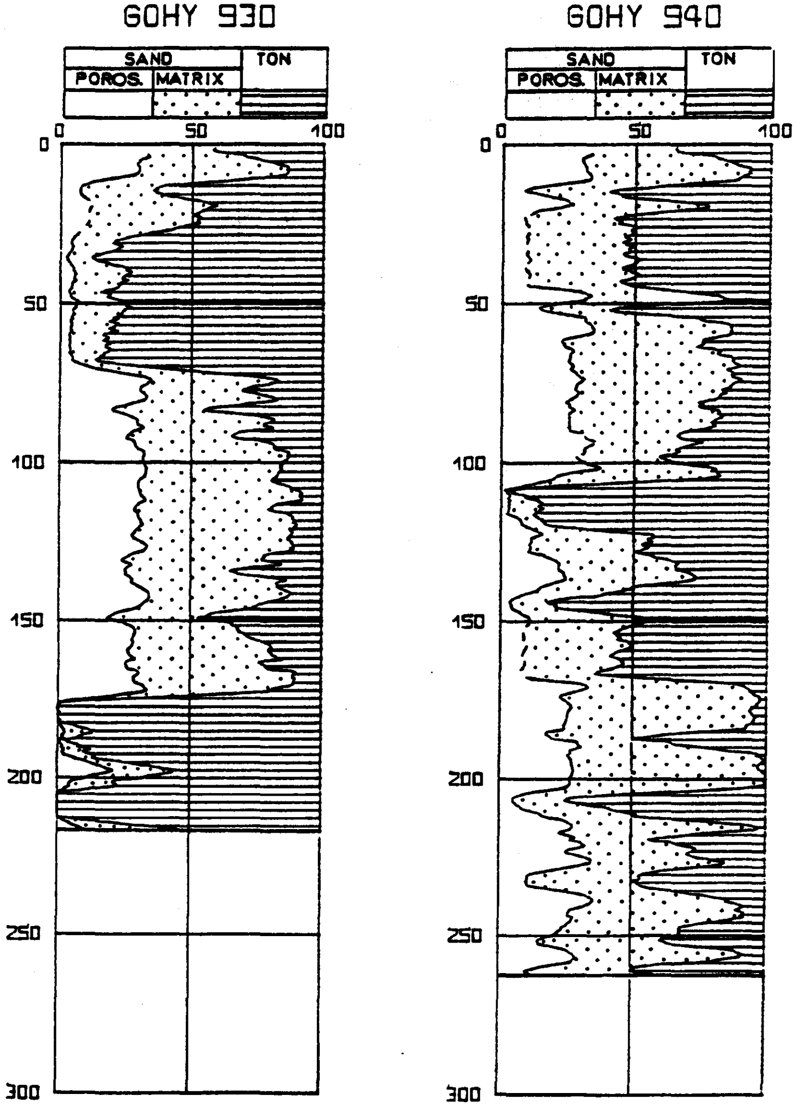

Fig. 21 Combined interpretation of Gamma Ray and Density Logs:

graphic representation of pore volume, matrix and shale content, Gorleben investigation area.

5.3 Determination of pore water salinity

The methods of determining pore water salinity are related exclusively to layers with intergranular porosity, i.e. to layers the porosity of which is formed by the spaces between the individual (consolidated or unconsolidated) particles of the matrix. Layers with joint and fracture porosity do not allow determination of the resistivity of the water they contain. However, under favourable circumstances, Salinometer and Flowmeter measurements, i.e. measurements of properties or behaviour of the fluid column in the well, and the use of sampling tools, may give indications of the resistivity of groundwater in fissured rocks.

The SP curve that is still simultaneously measured as a matter of routine with hydrogeological exploratory wells is time and again a reason for questions from hydrogeologists and other users of well logs as to how one could interpret it with regard to a hydrogeological objective.

Apart from the few opportunities where in a qualitative way, one can obtain change tendencies of the pore water salinity from the SP curve (deflection to the left: "saltier", deflection to the right: "fresher"), under certain conditions the resistivity and thus the total salt content of the pore water can be quantitatively determined.

The methods of SP interpretation are divided into application with "consolidated" and "unconsolidated" sediments. Here, this differentiation means: as "consolidated" sediments one understands those the shales of which are ideal cationic membranes and as "unconsolidated" sediments those with which this is not the case.

Shales first attain the state of the ideal cationic membrane under a certain pressure and at a certain temperature, i.e. usually first at a certain depth. Whether at all or where in the investigation area this is the case cannot be easily forecast. Using tedious processes, shales can be examined in the laboratory to determine their membranous characteristics. However, this is not possible under normal circumstances. Therefore, in case of doubt, one must empirically establish the type of shales concerned.

In general, at least in the North German Plain, one cannot expect that at depths down to 200 or 300 m shales are ideal cationic membranes. However, this must not be so everywhere.

If consolidated sediments in the above sense are concerned and predominantly sodium chloride solutions with pore water and mud filtrate, then one can apply the standard procedure for quantitative SP interpretation (see Wyllie 1949, Hilchie 1978):

$$SP = -K \cdot {}_{10}\log \frac{R_{mf}}{R_w}$$

whereby,

SP = difference between shale baseline and sandline in mV

R_w = pore water resistivity in ohm.m

R_{mf} = mud filtrate resistivity in ohm.m

K = 65 + 0.24 T

T = temperature of layer of interest in degr.C.

However, this case seldom occurs in hydrogeology. One is concerned mainly with fresh water here and frequently with unconsolidated aquifers.
Quantitative interpretation of SP logs is almost impossible in such cases. The then necessary correction for divalent ions in the pore water (and mostly in the mud filtrate too) as well as the non-attainable influence of the imperfect shales confront the interpreter in most cases with insoluble problems (see e.g. Gond., Tixier and Simard, 1957; Repsold, 1989).

With consolidated and unconsolidated sediments, interpretation of the SP curve is subject at any rate to the incalculable factor "mud additives". Through organic additives, e.g. the above mentioned correction to divalent ions in the mud filtrate can be falsified. Looked at in terms of interpretation of the SP curve, managing with as small an amount of mud additives as possible, is highly desirable. However, the question of mud additives is subject of completely different requirements, so that in normal circumstances one cannot exercise influence over them and must tolerate the possible uncertainties.

For these reasons, the SP interpretation method has not been dealt with further here.

Another method of approximately determining the resistivity of the pore water consists of calculating it from the resistivity of the aquifer via the formation factor. However, a reliable resistivity log with the essential data such as mud resistivity and borehole diameter (and perhaps infiltration data) for the determination of the true resistivity is necessary for this. If in addition a usable value for the field formation factor is known, an approximated water resistivity can be simply calculated by division from the aquifer resistivity.

To begin with, however, the term formation factor and its defintion are dealt with briefly.

The formation factor, originally "formation resistivity factor", is defined as the quotient from the resistivity of a 100% water-saturated rock R_t (in oil well logging R_o) and the resisitivity of the pore water R_w:

$$F = R_t/R_w$$

In the case of rocks with intergranular porosity and saline pore water (R_w< 0.1 ohm.m) this quotient is dependent only on the pore volume and the consolidation of the material:

$$F = \frac{a}{\phi^m}$$

a = proportionality factor
ϕ = porosity
m = so-called cementa tion factor

Both relations were formulated in 1942 by ARCHIE.

For the latter relation different versions have been empirically determined for different types of rock. The HUMBLE formula* is that most frequently used for slightly consolidated and unconsolidated sediments:

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

Likewise customary is the very similar formula: $F = \frac{0.81}{\phi^2}$ (see Chart (12)).

One must bear in mind here that these relations were originated by averaging from many, in part widely scattering individual values. Thus they allow an approximation for the porosity from the formation factor and vice versa.

However, prior to the use of such a relation with unconsolidated sediments, one is emphatically warned: there is neither a porosity nor a formation factor obtained via one of the above equations that is suitable for further mathematical processing (see below).

With slightly mineralized (brackish to fresh) pore water the inherent conductivity of the pore matrix becomes increasingly noticeable (PATNODE and WILLIE 1959; SARMA and RAO 1962). The formation factor determined according to the above definition is then reduced compared to that determined with saline pore filling, one speaks (well or ill chosen designations) about "true" or maximum and "apparent" or field formation factor:

True or maximum formation factor: $F = \frac{R_t}{R_w}$ for $R_w \to 0$, in practice: $R_w < 0.1$ ohm.m

Apparent or field formation factor: $F_a = \frac{R_t}{R_w}$ for any $R_w > 0.1$ ohm.m

F is a quantitity that is dependent only on the porosity and the degree of consolidation (see above), F_a on the other hand is still additionally dependent on the water resistivity R_w and on the inherent conductivity of the rock matrix ("excess conductivity") $1/R_{mat}$.

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* From laboratory data determined by WINSAUER et al. from the "Humble Oil and Refining Co."

This effect can be most easily described approximately by the general model of parallel conductivities:

$$\frac{1}{R_t} = \frac{1}{R_{mat}} + \frac{1}{F \cdot R_w} \quad \text{or} \quad \frac{1}{F_a} = \frac{R_w}{R_{mat}} + \frac{1}{F} \quad ,$$

where according to PATNODE and WYLLIE (1950), who introduced this concept into the literature,

$F \cdot R_w$ = resistivity of formation water, 'as distributed in the formation'

R_{mat} = resistivity of conductive solids, 'as distribed in the formation'

One sees that the aquifer resistivity R_t (resp. the apparent or field formation factor F_a) reflects the combined effects of the conductivities of the solid and the fluid phase of the aquifer.

The matrix resistivity can be calculated via the model of parallel conductivities, if true and apparent formation factor and the water resistivity are known.

$$R_{mat} = R_w \frac{F \cdot R_t}{F \cdot R_w - R_t} \quad \text{or} \quad R_{mat} = R_w \frac{F \cdot F_a}{F - F_a}$$

$$R_w = \frac{1}{F} \cdot \frac{R_{mat} \cdot R_t}{R_{mat} - R_t}$$, if F and R_{mat} are known.

On the other hand, the matrix resistivity is related via the internal surface to the hydraulic conductivity, which can be calculated approximately under favourable circumstances via the Kozeny-Carman relation (see Section 5.4).

The model of parallel conductivities can also be applied for calculating water resistivity:

However, it is usually not possible to determine F and R_{mat} in individual cases. One therefore has no choice other than to accept the uncertainty resulting from unawareness of these parameters and to establish an empirical relation from existing values for R_t and R_w, in order to at least "statistically" collect this uncertainty.

Such a relationship is shown in Fig. 22 for the Gorleben investigation area. From the additional curves plotted in accordance with the model of parallel conductivities, one can see that the variations of F and R_{mat} are confined to certain limits: the curves for F = 7 and R_{mat} = 500 ohm.m as well as for F = 4 and R_{mat} = 50 ohm.m can be regarded approximately as upper and lower limitations of the dot cluster.

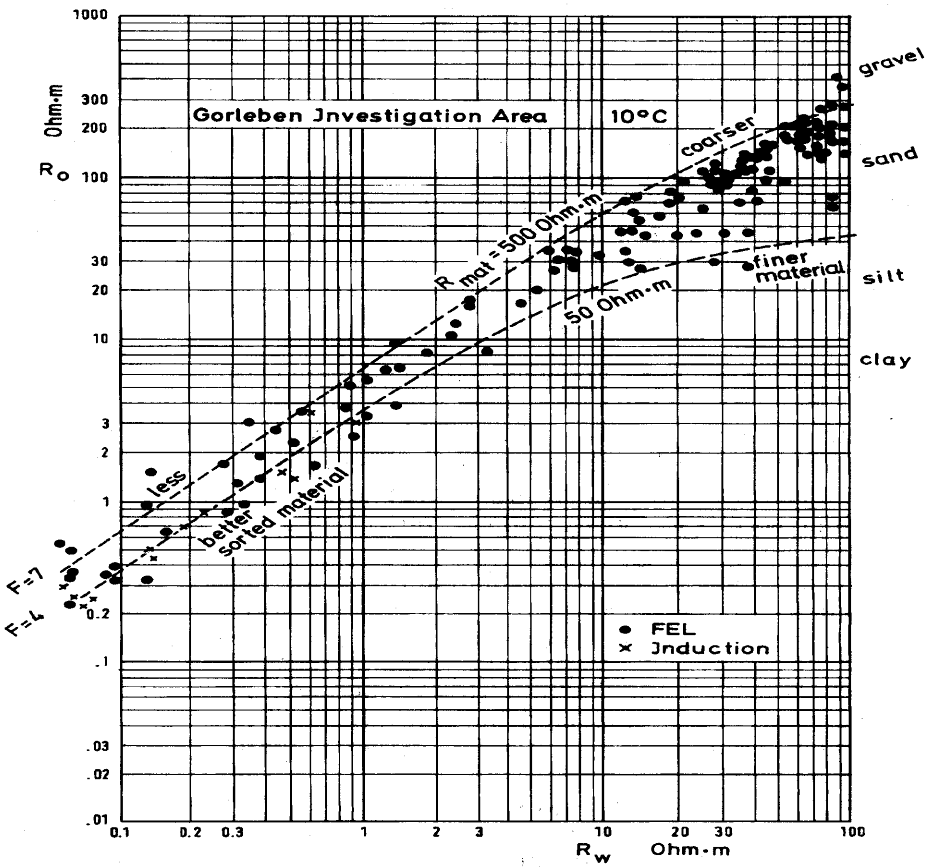

Fig. 22 Relation between pore water resistivity and formation resistivity, Gorleben investigation area

In the Gorleben investigation area, the porosities encountered in the water sands are between 30 and 40%, which is known from interpretation of the Formation Density Logs. According to the Humble formula (see above) these values correspond to maximum (true) formation factors of 8 to 4, which provides a good agreement with the electrical values.

If one considers that higher formation factors indicate lower porosities and therewith usually poorer sorting, on the other hand higher values for R_{mat} correspond with greater grain diameters (lower surface conductivity of the matrix) and vice versa, thus by means of the diagram in Fig. 22 the pore water resistivity can be relatively simply approximated from the aquifer resistivity. Here, with the degree of accuracy attainable with this method it is generally appropriate to differentiate simply between "finer" and "coarser" material (right half of the diagram) respectively between "better" and "worse" sorted material (left half of the diagram).

The following simple rules apply for handling the diagram:

With aquifer resistivities below 10 ohm.m the porosity (resp. the sorting) is to be considered: the higher the porosity (the better the sorting) the further to the right one must enter the diagram to determine the pore water resistivity for a definite aquifer resistivity and vice versa.

With aquifer resistivities above 10 ohm.m the medium grain-size of the material is to be noted ($^1/R_{mat} >> {^1/F} \cdot R_w$ in the above equation): the coarser the material, the further to the left one must enter the diagram and vice versa.

In the central part of the diagram (roughly between 5 and 20 ohm.m), both parameters are to be considered theoretically. However, the method would obviously be overtaxed with such differentiated handling.

The value obtained in this way, disregarding that determination of the true formation resistivity from a resistivity log can also be problematic, may in many cases be more accurate than a water resistivity that was determined from the SP curve (if an SP interpretation is possible at all), above all when unconsolidated rock is involved. Apart from this, an interpretable resistivity curve is more frequently available. Naturally, this method too is subject to considerable scattering so that one should be prepared for surprises; however, the degree of accuracy is probably sufficient for many of the questions that arise.

In order to demonstrate the extent to which the relation represented is valid beyond the Gorleben investigation area, values from other investigation areas were plotted in the same manner (see Fig. 23). One can see that the values more or less lie within the limiting lines for the Gorleben measurements. Only the values of the coarse sands and gravels of the Donauried are above them and those of the shaly silts of the Argentine Pampa (Altos De Chipion) are below. However, limiting lines with F = 15 (ϕ = 25%) and R_{mat} = 1500 ohm.m as well as F = 3 (ϕ = 50%) and R_{mat} = 10 ohm.m also include the values of these areas.

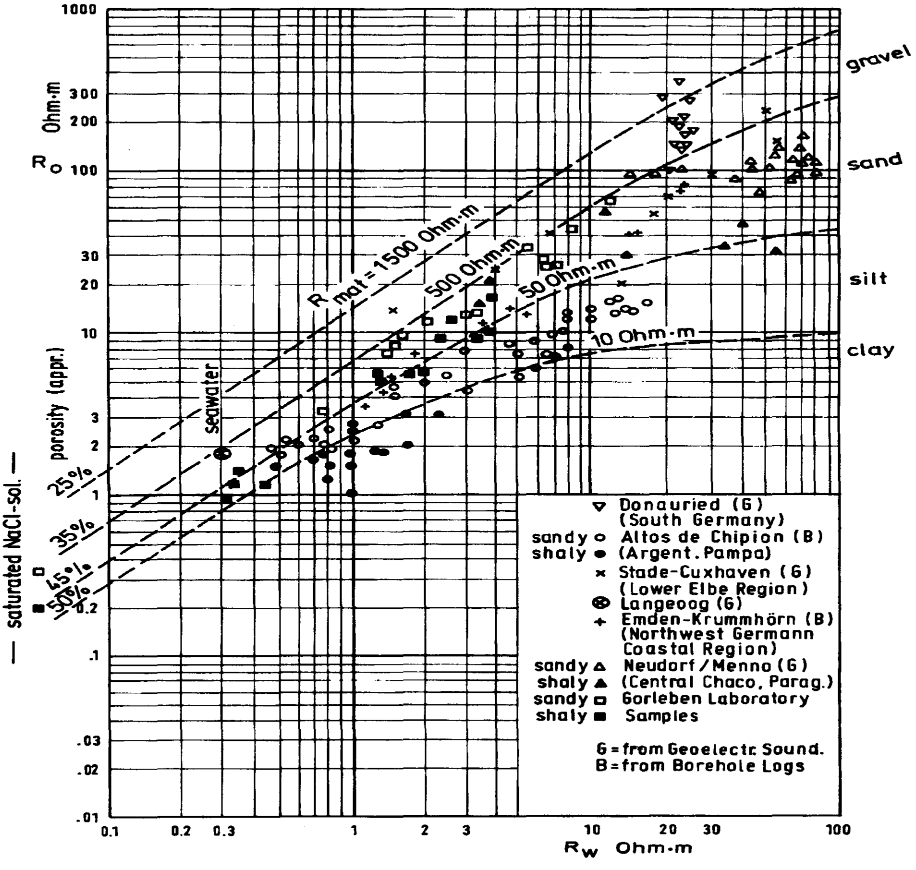

Fig. 23 Relation between porewater resistivity and formation resistivity, Gorleben and other areas

Apart from the laboratory investigations, the aquifer resistivities in this representation originate in part from geoelectrical depth soudings, partly from electrical well logs (as indicated in Fig. 23). The water resistivities were measured in each case from samples that were taken directly by pumping from boreholes or wells.

In cases of doubt and whenever possible, a special relation applicable to the investigation area in question should naturally be established.

5.4 Approaches to hydraulic conductivity

The hydraulic conductivity k_f is defined as the proportionality factor between the specific discharge v_f (measured in $m^3/m^2 \cdot s = m/s$) and the hydraulic gradient $\Delta h/L$ (dimensionless ratio):

$$v_f = k_f \cdot \frac{\Delta h}{L}, \qquad \text{DARCY's Law.}$$

Accordingly, the value k_f has the same dimension as the specific discharge, namely m/s. Specific discharge means volume transport per cross-section normal to the direction of transport per unit of time, this yields the dimension $m^3/m^2 \cdot s$, which reduces to m/s, the dimension of a "simple" velocity.

However, the specific discharge must not be confused with the velocity of groundwater flow v_a in the aquifer, which results only through division of the specific discharge by the effective porosity

$$v_a = \frac{v_f}{\phi_e}.$$

The groundwater flow is thus controlled according to DARCY's Law through the hydraulic gradient (static pressure gradient) and the k_f-value. The latter quantitatively represents the "hydraulic conductivity" or the reciprocal of the "hydraulic resistance" of the aquifer.
The value k_f is influenced by both the porosity and the grain-size or internal surface of the aquifer, its determination from well logs is most problematic but under favourable circumstances, is nevertheless possible using indirect ways.

The Kozeny-Carman relation provides such an indirect way in that it relates hydraulic conductivity, porosity and internal surface:

$$k_f = C \cdot \frac{\phi^3}{(1-\phi)^2} \cdot \frac{1}{s_o^2} = \frac{\phi^3}{s^2} \quad \text{with} \quad s_o = \frac{s_o}{(1-\phi)}$$

including,

k_f	=	hydraulic conductivity
ϕ	=	porosity
C	=	Kozeny constant
s_o	=	specific matrix surface, i.e. internal surface related to matrix volume
s	=	specific bulk surface, i.e. internal surface related to total volume

The relation was established by Kozeny with investigations concerning the irrigation of field, thus for completely unconsolidated sediments. It was later generalized and theoretically supported by CARMAN (s. v. ENGELHARDT 1960) and above all applied in practice, whereby it was established that the range of validity is not confined to unconsolidated sediments (see e.g. MEDER 1966).

Nevertheless, the Kozeny constant is not a universal constant but must rather be determined separately for the respective material (or the material range); moreover, the internal surface of the matrix is a quantity which is not easily obtained.
However, access to the latter is possible via the inherent electrical conductivity of the matrix $1/R_{mat}$ (see also 5.3). The relation between these two parameters is generally of the form $s^a \sim 1/R_{mat}$.

The Kozeny-Carman relation thus becomes

$$k_f = C \cdot \phi^3 \cdot R_{mat}^b,$$

whereby C and b must be known for the materials in question.

It is here that the difficulties begin which make this method appear to be practicable in exceptional cases only. A "calibration" of the Kozeny Carman relation with a vertical sequence of layers consisting of continually changing materials as penetrated by a drillhole, is usually not possible. In addition, calculation of R_{mat} from the model of parallel conductivities (formula in Section 5.3) demands most exact values for F, F_a and R_w, which are not available in most cases. Not forgetting to mention that the porosity, raised to the 3rd power, appears in the equation and accordingly, must likewise be most precisely determined.

Laboratory investigations into sand samples and field investigations into unconsolidated rock aquifers (see the Table, where some data have been compiled) prompt the assumption that the exponent b lies between 1 and 2 with fairly permeable sediments, with an increasing tendency for shaly, i.e. less permeable material. Hence, an approximately linear relationship between matrix resistivity and the hydraulic conductivity k_f can be assumed for sandy aquifers, whereas for increasing shale content a higher order of dependency should be adopted. The latter is also to be expected with consolidated aquifers, as laboratory investigations on drill cores have shown (RINK and SCHOPPER 1974).

Table

ϕ_{Humble}	F	k_f (m/s)	R_{mat} (Ωm)	Measurement objective	Material	Method
20%	20	from 10^{-2} to 10^{-3} $5.5 \cdot 10^{-3}$	1000 100 450 (average)	Donauried at Ulm	poorly sorted unconsolidated river sands and gravels of the Donau, partly shaly	"in situ" GP
28%	10	$5 \cdot 10^{-3}$	500 (average)	Fuhrberg	unconsolidated relatively well-sorted sands, partly shaly	"in situ" GP
28%	10	$5 \cdot 10^{-4}$	100 (average)	Neudorf (Chaco Central)	unconsolidated well-sorted fine sands, partly shaly	"in situ" GP
44%	3.7	$27 \cdot 10^{-3}$	250	River sands (laboratory data Sarma + Rao [1])	loose sands (grated samples) medium to very shaly	Labora-tory
38%	5	$7 \cdot 10^{-3}$	90			
40%	4.5	$1.7 \cdot 10^{-3}$	45			
42%	4	$3 \cdot 10^{-4}$	10 (average)	Altos de Chipion (Argentina)	loosely consolidated well-sorted sands, medium to very shaly	"in situ" BP

1)
(SARMA & RAO 1962)

G = geoelectric depth soundings
P = pumping tests
B = borehole measurements

A different approach to the problem exists in that the hydraulic conductivity k_f is determined from the Gamma Ray Log. This is reasonable, as interpretation of the Gamma Ray curve as a shale indicator equates with an interpretation as a grain-size indicator. Laboratory investigations that the author undertook on hose cores from unconsolidated sediments in Northern Germany (Gorleben investigation area) resulted in a relation of the form

$$k_f = \frac{10^{11}}{GR^{10}} \quad (k_f \text{ in m/s; GR in API units}).$$

On three parallel samples of the same material, porosity and hydraulic conductivity were determined and the natural gamma activity also measured in each case, whereby the latter was "calibrated" with the corresponding log value.

As shown in the graphic representation of the relation in Fig. 24, scattering is considerable. However, this was not unexpected as the determinations of the hydraulic conductivity are necessarily subject to great variations. Moreover, the porosity was not considered as a separate parameter, as only 25 samples were investigated.

For application of the formula, a Gamma Ray measurement calibrated in API units and a borehole correction to hydro-standard conditions (5" borehole, 1.0 g/ccm mud, 1– $^1/_2$" probe) are necessary.
The method is limited to about 30 API, corresponding to 10^{-4} m/s, where the sands no longer contain radiating materials.The application of the given relationship is of course hitherto restricted to material comparable to that from which it was obtained. On the other hand, it should be possible to establish similar relationships for other investigation areas.

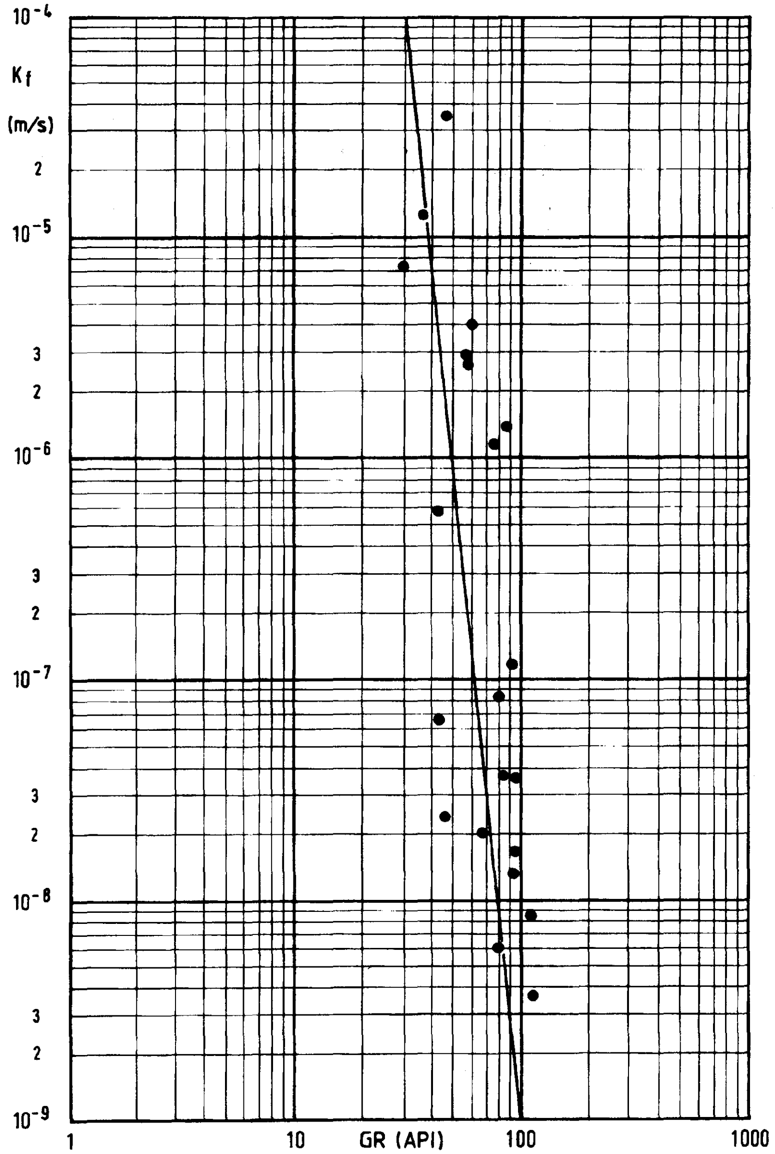

Fig. 24 Relation between natural gamma radiation and hydraulic conductivity

6 Some presentations regarding basic principles of some of the methods

It is not claimed that the following are complete. A calibration procedure for Gamma Ray measurements is dealt with as well as the multiple point resistivity methods and the focussed single electrode method, to intimate what is still available "behind the scenes". Actual involvement in detail with the intricacies of the methods of measurement is naturally only possible through reference to the special literature.

6.1 Borehole correction and calibration with Gamma Ray measurements

All borehole probes must be calibrated so that the measurement parameter can be otained from the original measurement signal. Calibration can be relatively simple: conversion of electric signals (voltages) of a resistivity probe, a resistance thermometer and a caliper tool into resistivities, temperatures and borehole diameters. Other methods are considerably more elaborate, like e.g. the transformation of Neutron count rates into porosities and of gamma-gamma count rates into bulk densities.
Here, calibration in API units of the measurement of the natural gamma radiation, in short Gamma Ray measurement, is to be described as an example which is of equal importance for measurements in hydrocarbon exploration and in hydrogeology. The Gamma Ray measuring signal is a count rate. The gamma quants reaching the detector (mostly a scintillation crystal) are counted and related to the unit of time. The count rate is dependent on several other quantities, apart from the radioactivity of the rock: detector size and state, borehole diameter, mud, casing(s), probe position in the borehole (see Section 4.1). In order to be independent of these latter quantities, two measures are necessary: 1) reduction to constant borehole conditions, the so-called borehole correction and 2) calibration of the probe, i.e. "levelling" the count rate to a "standard value" by means of a calibration standard (e.g. a radioactive source or an appropriate discontinuity of activity in a test well).

The borehole correction makes the count rate independent of the different borehole parameters, the relation to the calibration standard (the actual "calibration"), from the size and efficiency of the detector (with scintillation crystals a question of age amongst other things) and the type of probe. It is only by means of calibrated and borehole corrected Gamma Ray measurements that the radiation level of different layers resp. measurements taken at different times in the same layer can be compared with one another. Such a calibrated and borehole corrected Gamma Ray count rate is indeed borehole- and probe- independent. However, a direct quantitative conclusion from the count rate to a rock parameter is not yet possible. A further step is necessary for this which relates the calibration standard to the rock parameter concerned.

From the Gamma Ray measurement e.g., one can determine the uranium content of a rock. However, this affects the field of uranium ore prospection where gamma probes are simultaneously borehole-corrected and calibrated in a laborious procedure in % uranium oxide per unit of volume. In the following, calibration in API units* is described with which the natural gamma count rate is put into relation with the shale content (resp. to the clay content). In a "test pit" (calibration well), situated in the grounds of Houston University, Texas, a concrete layer with artificially added radioactive material is installed, the gamma activity of which accords to twice the value of a North American "average mid-continent shale" (Fig. 25). The borehole conditions of this test pit (5-$^1/_2$" steel cased borehole filled with water) are equivalent to the standard conditions applied in oil: 8" open hole, bentonite mud (1.2 g/ccm).

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* To be correct: API Gamma Ray Units.

This test and calibration facility was established in 1959 by the "American Petroleum Institute", in order to put an end to the variety of Gamma Ray Units that were difficult to compare one with another (e.g. 7 different units were used by 9 different logging companies). In the future, all Gamma Ray probes should be calibrated in this test pit and thus, Gamma Ray measurements be directly comparable with one another and related to the shale content.
The procedure adopted was as follows (Belknap and others, 1959): more than 200 shales were analysed in the laboratory and spectrometrically investigated. One found that the radioactive radiation originates almost exclusively from the decay products of uranium and thorium and from the potassium 40 radioisotope. An "average mid-continent shale" contains some 6 ppm uranium, 12 ppm thorium and 2% potassium 40*. However, as uranium has a gamma ray activity of

$A_u = 2.8 \cdot 10^4$ photons/s, gU

and thorium one of

$A_{th} = 1.0 \cdot 10^4$ photons/s, gTh,

whereas potassium 40 only has an activity of

$A_p = 3.4$ photons/s, gP,

the "weights" of radioactive radiation of a shale are almost evenly distributed on potassium and the uranium and thorium series. As the gamma ray spectrum usually does not change considerably from one geological formation to another, one can conclude the shale content from the total gamma radiation.

A concrete mixture was used for completion of the test pit the radioactive substance content of which corresponds to twice that of the "average shale", that is 12 ppm uranium, 24 ppm thorium and 4% potassium. The gamma activity observed in this test layer was divided into 200 "API units" **, through which the gamma activity of the "average shale" is defined to 100 API units.

For calibrating, a Gamma Ray probe must be lowered into the test pit and the count rate must be adjusted to 200 units opposite the test layer. After the measurement, the calibration defleclection must be reproduced at the surface with a radioactive test source, so that the calibration can be repeated at any time (for this, the test source is positioned at a distance from the detector that yields the same count rate or a fraction thereof, as in the test layer) ***.

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* Spectrometer measurements on shales from the North German region provided comparable results.

** Strictly speaking, the difference in activity between the test layer and the adjacent "barren zones" is divided into 200 units.

*** In accordance with a recommendation of the IAEA, Vienna, the lower threshold of the gamma count equipment should be adjusted to an energy level of about 400 keV, so that on the one hand dependence on rock matrix is avoided (not to speak about the "low energy noise" below 100 keV) and on the other, the Cs-137 peak (at 662 keV) is properly registered.

A Gamma Ray probe thus calibrated in API units therefore allows a direct conclusion of the avarage shale content (definition see Section 5) of a rock. Here, 10 API indicate the background radiation of a clean sand and 100 API that of a pure shale, presupposing reduction to oil standard conditions (200 mm borehole, 1.2 g/ccm mud, 92 mm probe).
Intermediate values designate rocks containing more or less shaly components.
Hereby the relation between API units resp. Gamma Ray Index and the desired grain-size fraction of the shale (e.g. < 0.002 mm for clay, < 0.02 for clay plus silt = shale) must be empirically determined in the individual case (see Sections 4.1.7 and 5.1).

For a Gamma Ray measurement reduced to hydro-standard conditions (125 mm borehole, 1.0 g/ccm mud, 40 mm probe) other values apply. 15 API indicate the clean sands, 150 API the pure shales. The conversion factor between oil and hydro-standard conditions is thus 1.5 .

The borehole corrections, based on complicated calculations, are usually represented in graphic form. Such a representation is given in Chart (1) (measurements with a 40 mm probe, reduction to hydro-standard conditions).
Further borehole correction diagrams can be found in the Schlumberger Log Interpretation Charts (reduction of measurements with 92 mm and 43 mm probes to oil standard conditions).
A graphic overview of possible borehole corrections with Gamma Ray measurements is given in Fig. 26.

For the sake of emphasis, the standard borehole conditions for Gamma Ray measurements in use with the oil industry and those applied in water well logging, are repeated here.

Standard borehole conditions used in oil well logging (see Schlumberger Chartbook 1978):

200 mm (8")	borehole diameter
1.2 g/ccm (10 lbs/gal)	density of the borehole fluid (bentonite mud)
92 mm or 86 mm (3-5/8" or 3-3/8")	probe diameter

corresponding to the values occuring in the majority of cases.

The conditions above are not identical with the standard borehole conditions applied in water well logging:

125 (5")	borehole diameter
1.0 g/ccm (8.3 lbs/gal)	density of the borehole fluid (water)
38 to 43 mm (1-1/2" to 1-11/16")	probe diameter

This accords to the bit diameter of 125 mm (5") usually applied in unconsolidated sediments, the water muds normally used (density 1.0 - 1.1 g/ccm) and the customarily employed probes with diameters between 38 and 43 mm (1-1/2" and 1-11/16").

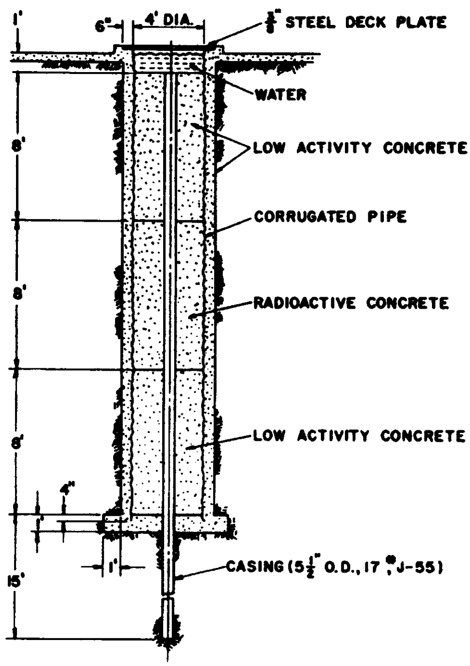


Fig. 25: API Test Pit (after BELKNAP et al. 1960)

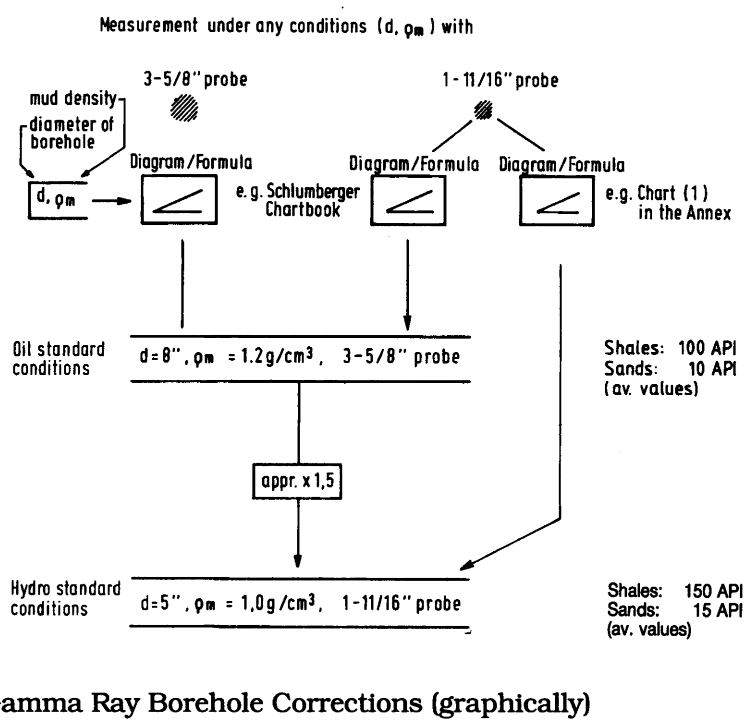


Fig. 26: Gamma Ray Borehole Corrections (graphically)

6.2 General information on the multiple point resistivity method in boreholes.

In the multiple point resistivity method, the electrical field starting at a point electrode is "surveyed" using one or more potential electrodes.

This method can be represented simply for a homogeneous isotropic medium in the following way (see Fig. 27):

A current I spreads with spherical symmetry from a point electrode A in a homogeneous isotropic medium with resistivity. Current return is assumed at infinity; in practice it is usually at the earth's surface or an appropriate distance further up the cable.
The decrease dV_M in potential at M between two closely adjacent concentric spheres (distances r and r+dr from A) generated by a current I_A in a medium with a resistivity according to Ohm's law ($V = I_A \cdot R$) is as follows:

$$(1) \qquad dV_M = \rho \cdot \frac{I_A\, dr}{4\pi r^2}, \quad \text{since} \quad R = \rho \cdot \frac{l}{q} = \rho \cdot \frac{\rho \cdot dr}{4\pi r^2}$$

where $q = 4\pi r^2$ (the surface area of a sphere) and $l = dr$. The absolute value of the potential at M is obtained by adding of all these "decreases in potential" from M to infinity (potential 0). This corresponds to the mathematical integration process:

$$(2) \qquad V_M = \int_M^\infty dV = \rho \cdot \frac{I_A}{4\pi} \int_{r_{AM}}^\infty \frac{dr}{r^2} = \rho \cdot \frac{I_A}{4\pi} \cdot \frac{1}{r_{AM}}$$

where V_M is the potential produced by electrode A at point M (i.e. at a distance of r_{AM} from A).

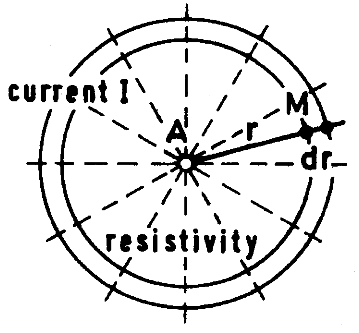


Fig. 27   Current distribution from a point source

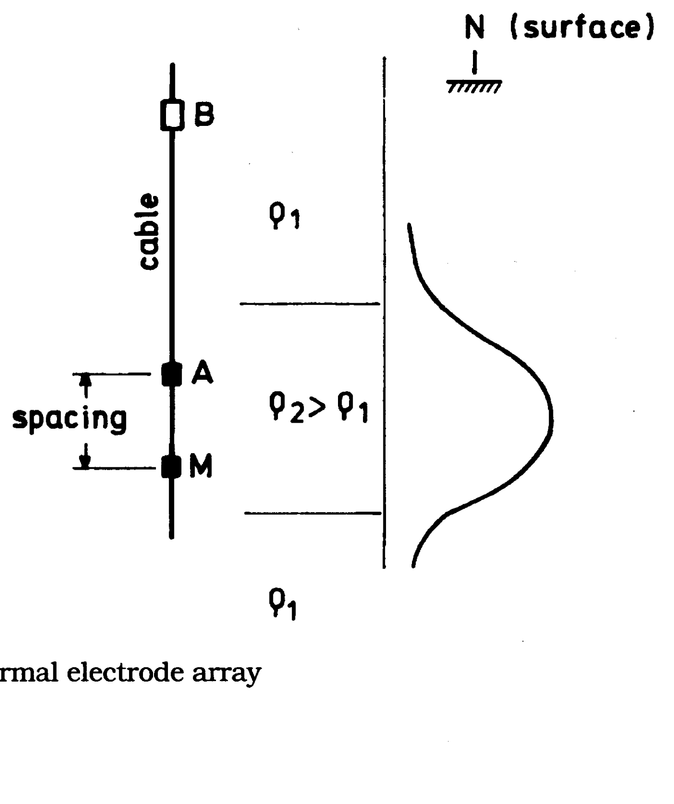


Fig. 28   Normal electrode array

The resistivity ρ of the medium is obtained from Equation (2) as follows:

$$(3) \qquad \rho = 4\pi r_{AM} \cdot \frac{V_M}{I_A} \qquad \text{or} \qquad R = 4\pi AM \cdot \frac{V}{I}$$

where I_A (I) is the current entering the rock from electrode A (current return at B) and V_M (V) the potential at electrode M measured relative to the surface electrode N; (see Fig. 28). The second form of the equation is generally adopted, as the resistivity ρ is usually designated R in the field of borehole logging.

In practice, current I_A is automatically kept constant during the measurement and the potential V_M, with a scale factor 4π AM (the sonde coefficient), is recorded as a resistivity curve.

This arrangement of electrodes is called "n o r m a l a r r a y" (or potential probe or 2-electrode probe). Usually, two resistivity curves are recorded at the same time for two different spacings AM: 16" (0.4 m) and 64" (1.6 m) arrays are generally used. The necessity of recording several (at least two) resistivity curves with different electrode spacings originates from the fact that the resistivity obtained using a normal array is the true resistivity only if the me-dium is homogeneous and isotropic (i.e. absolutely uniform).

In reality, a homogeneous isotropic medium almost never occurs; this ideal condition may only be approximately attained by pure chance. A borehole filled with drilling mud, entry of the drilling mud into the annular space around the borehole (invasion) and the resistivity layering of the rock sequence produce a considerably inhomogeneous and anisotropic "make up" of the resistivities surrounding the measuring array. The recorded resistivity, which is called an "apparent " resistivity, is consequently a mixture of the resistivities involved (mud resistivity, invaded zone resistivity, adjacent bed resistivities, resistivity of the bed of interest), the shares of which, however, are not directly determinable.

This is only possible by use of interpretation curves (so-called resistivity departure curves), which are theoretically calculated for a wide variety of borehole diameters, infiltration and bedding conditions.
With several restrictions, the true resistivity (R_t) of the bed of interest may be finally determined.
For this, it is necessary to have at least two resistivity curves with different electrode spacings since the lateral detection depth increases with electrode spacing AM (which results in a decrease in bed resolution), changing the response to borehole, infiltration, and bedding conditions. Thus, several equations are obtained for determining the infiltration diameter (D_i), the resistivity of the invaded zone (R_i), and the true rock resistivity (R_t) of a layer.

The generally used combination of 16" and 64" normal arrays is a compromise:

The 16" normal array has a small lateral detection depth and, therefore, is strongly influenced by the mud column and possible infiltration of the mud into the rock, but it has, because of its small electrode spacing, relatively good bed resolution (with sufficient resistivity contrast of down to 0.75 m for resistive beds and considerably for conductive beds).

The 64" normal array has a greater lateral detection depth and therefore a closer approximation of the true rock resistivity is obtained. But bed resolution is considerably less than with the 16" normal array (only about 3 m for resistive beds).

The minimum thickness of a bed necessary to be able to measure its apparent resistivity must be taken into consideration: This is about 5 m for the 16" normal array and about 10 m for the 64" array *. Special interpretation curves, which also take into consideration the reduction of the resistivity signal with decreasing thickness of beds, are to be used for thinner beds. This considerably complicates the determination of the true resistivity of the rock.

If the potential of electrode A at M is not measured with respect to infinity, but with respect to another electrode N set relatively close to M on the probe itself, the following expression is obtained (see (2)):

$$V_M = \rho \frac{I_A}{4\pi} \cdot \frac{1}{r_{AM}} \qquad \text{and} \qquad V_N = \rho \frac{I_A}{4\pi} \cdot \frac{1}{r_{AN}}$$

where V_M and V_N are the potentials of electorde A measured with respect to infinity at M and N, respectively. By subtracting these two equations,

$$\text{(4)} \qquad \Delta V_{MN} = V_M - V_N = \rho \cdot \frac{I_A}{4\pi} \cdot \left(\frac{1}{r_{AM}} - \frac{1}{r_{AN}} \right)$$

where V_{MN} is the potential difference between M and N. The resistivity of the medium is then as follows:

$$\text{(5)} \qquad \rho = \frac{4\pi r_{AM} \cdot r_{AN}}{r_{AN} - r_{AM}} \cdot \frac{\Delta V_{MN}}{I_A} \qquad \text{or} \qquad \rho = \frac{4\pi\, AM.AN}{AN - AM} \cdot \frac{V}{I}$$

----

* Presupposing that the current return electrode (B) and the potential reference electrode (N) are both far away from the measuring array (theoretically at "infinity"); if not, other minimum bed thicknesses have to be observed depending on the electrode arrangement actually used.

The electrode arrangement (see Fig. 29) for this resistivity method is called a "l a t e r a l a r r a y" or "inverse array" (also gradient probe or 3-electrode probe). In contrast to the normal array, the response of the lateral array as it is lowered past a bed is not symmetrical, which complicates the reading of the resistivity values from the recordings but does show the location of one boundary of a layer quite distinctly ("leading array" or "trailing array", depending on the arrangement of the electrodes on the probe).
The lateral array is usally obtained by changing the way the electrodes for the normal arrays are connected (a higher current is necessary for this array).

The lateral array used to be part of the Schlumberger Electric Log (ES, systeme chronologique): 16"- 64" normal arrays, 18'8" lateral array and SP. Today, it is of little or no importance (although some ES measuring equipment permits the recording of laterals) since its main advantage of showing the boundary of a bed distinctly was taken over long ago by the laterologs, which react symmetrically to the beds.

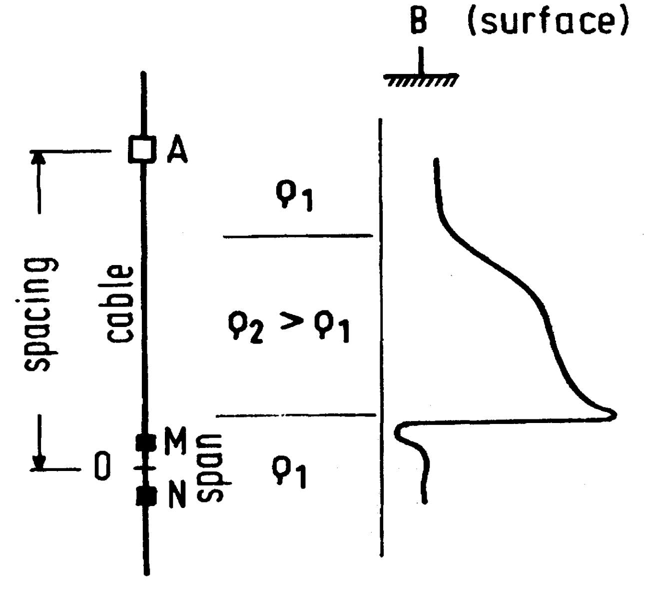


Fig. 29 Latereal electrode array

6.3 FEL measurement principles

The concept of the Focussed Electric Log (Guard Electrode Log, Guard Log, LATEROLOG) presumably originated from observation of the current line pattern of a cylinder electrode (Fig. 30): If it were possible to separate the central disc of the current lines and to operate it independently of the other currents above and below, one would have an improved monoelectrode with sharp layer response and satisfactory horizontal investigation depth (so that determination of rock resistivities would be possible). The technically simple, ordinary monoelectrode offers only the former, the more laborious multiple point resistivity method, only the latter.

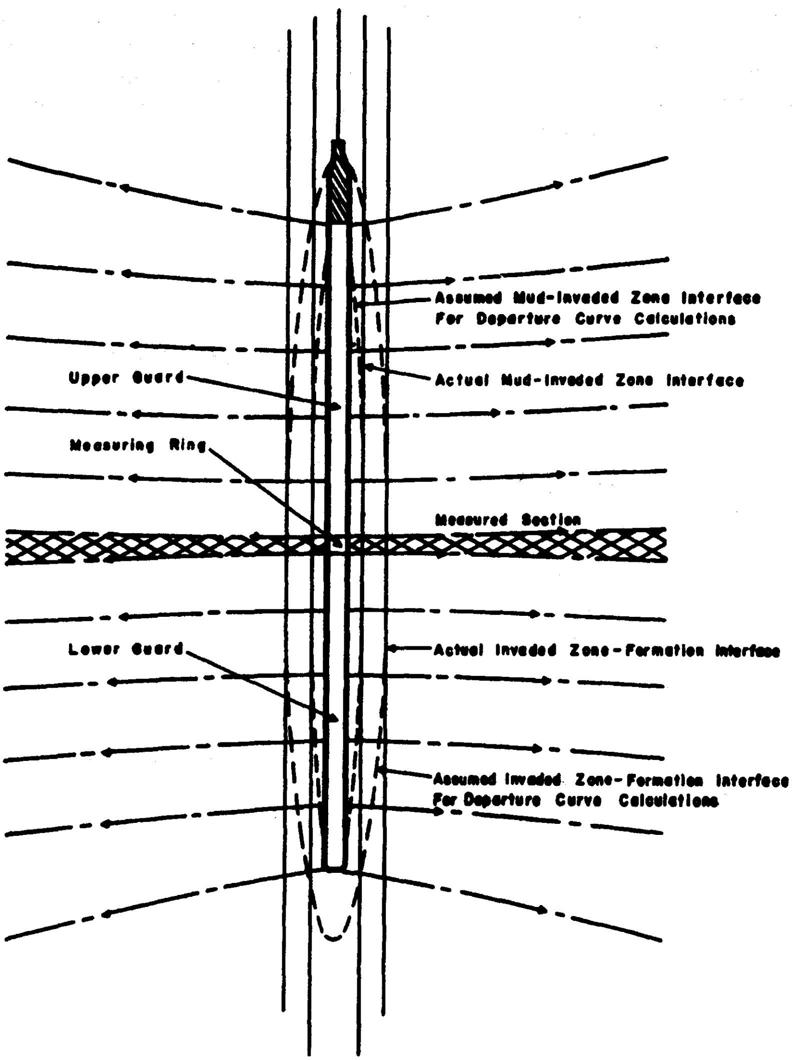


Fig. 30 Guard-Electrode probe and ellipsoid of rotation (after DACHNOW)

The problem in this case is not to subdivide the cylinder electrode and to supply the parts via several cable conductors but rather to supply them in such a way that the current line pattern of the cylinder electrode remains unaltered. The precondition for this is that all 3 electrode parts A_0, G_1, G_2 are maintained at the same potential.

If this is achieved, one can measure over the centre electrode A_0 as with an ordinary monoelectrode. However, the measuring signal reflects the improved response of the focussed centre electrode, that is the LATEROLOG response. The condition that all 3 electrodes must be maintained at the same potential can be realized in two different ways:

A) All 3 electrodes are supplied in parallel over one line (cable conductor) and are thus automatically of the same potential. The centre electrode A_0 is, however, not directly parallel (a slight deviation from the basic principle) but is rather supplied over a very low precision resistor R_x (see Fig. 31). As a result, it is indeed no longer exactly on the same potential as the outer or guard electrodes but still almost on the same, so that the current line pattern of the cylinder elctrode and hence the desired focussed response is not essentially changed.
The voltage drop via the precision resistor is measured from which the current i_0 transmitted via the centre electrode into the rock is obtained. The potential U of the centre electrode towards infinite is likewise measured, the value for the resistivity is obtained through division by i_0 and multiplication with the geometric factor:

$$R_L = k \cdot \frac{U}{I_0}$$

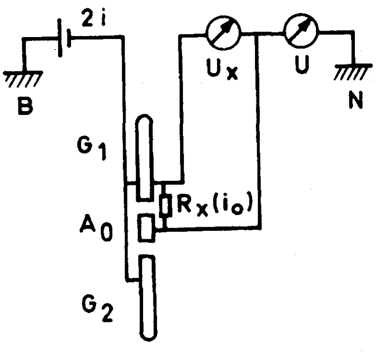


Fig. 31 FEL, version A

This array had already been applied in 1927 in Pechelbronn by the brothers C. and M. Schlumberger (simultaneously with testing of the multiple point resistivity method in the normal and lateral arrays); the measurements were executed intermittently (as static measurements), a continuous measurement is not possible in this simple form. However, the further developed and perfected tools permit a recording of the resistivity signal as a continuous log. For this, the current i_0 via R_x and the voltage U between A_0 and the reference electrode N are measured continuously, usually in the probe, and the quotient is formed. This value is mostly converted to a frequency signal and transmitted to the surface via the cable. Here it is again decoded into an analogous signal and, multiplied with the geometric factor, is recorded as a resistivity.

B) The centre electrode is supplied with a constant current i_o (as is usually the case with the multiple point resistivity method), the guards are always fed in such a way with additional currents over a separate but phase-coherent current supply (at the surface or in the probe) that all 3 electrodes are always maintained at the same potential. Hence, the current line pattern of the cylinder electrode is retained. The exact dosage of the bucking current 2i is automatically regulated via a continuous responder between the centre and guard electrodes. The potential U of the centre electrode is continually measured and as the measuring current i_o is kept constant, can be recorded, multiplied with the geometric factor, as a resistivity (Fig. 32).

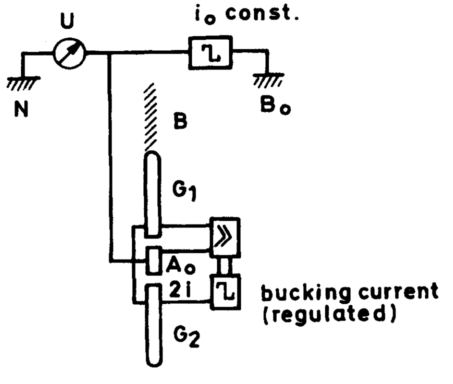


Fig. 31 FEL, version B

This array was used in the first generation of the Schlumberger LATEROLOGS, in those days still with mechanical servomotor regulation of the focussing current at the surface. Modern tools work with electronic regulation in the probe.

With variation B), the callup for potential uniformity can be effected either in the probe or externally over additional sensing electrodes. In the latter case, not the current line pattern of the cylinder electrode will be maintained, that is indeed already somewhat "fanned" when entering a well with conductive mud and hence loses sharpness of response but rather the thickness of the "current disc" (the focussed current line bundle of the centre electrode) is kept constant. However, this ultimately means no significant difference. The borehole corrections must in any case be calculated for the tool in question in order to take the special response into consideration.

For calculation of the geometric factor of an FEL probe, the cylindrical probe is approximated by an ellipsoid of rotation (see GUYOD 1951, OWEN and GREER 1951, DACHNOW 1959, KELLER and FRISCHKNECHT 1966, Fig. 30 from DACHNOW).

$$K_{FEL} = \frac{2\pi \cdot H \cdot \sqrt{L_e^2 - 1}}{L_e \cdot l_n (L_e + \sqrt{L_e^2 - 1})} = \frac{2\pi \cdot H}{l_n 2L_e} \quad \text{for large } L_e$$

whereby,

H = length of the centre electrode (measuring electrode) A_o
L = total lenght of the probe
D_e = diameter of the probe
L_e = L/D_e

For comparison, the geometric factor of a multiple point normal array

$$K_{ES} = 4\pi \cdot AM$$

where,

AM = distance between current and potential electrode.

Thus the apparent resistivity measured with an FEL probe results in:

$$R_{FEL}\,(\text{ohm.m}) = K_{FEL}\,(\text{m}) \cdot \frac{U_{A_0N}}{i_o}\,(\text{ohm})$$

Here, U_{A_0N} is the difference in potential measured between measuring electrode A_o and reference electrode N, i_o the measuring current transmitted into the rock via A_o.

The bucking currents 2i do not occur in the formula for the geometric factor as they only serve to maintain the geometry of the central "focussed" current bundle under the changing borehole and rock conditions.
The latter is the prerequisite that the current flow from an FEL probe can be approximated via an ellipsoid of rotation and all calculations be carried out according to this model.

The measuring current emanating from an electric resistivity probe must first of all pass through the mud and the mud invaded zone that may be present, before reaching the undisturbed rock, the resistivity of which is to be measured. The voltage drop that occurs on this part of its way falsifies measurement of the true rock resistivity and must be compensated by the so-called borehole correction (see above).

The formula for the borehole correction with the FEL method, basing on the approximation through an ellipsoid of rotation, in the most general form, i.e. for a borehole with mud invasion, is:

$$R = \frac{R_{FEL}}{K_{FEL}} = R_m \cdot \int_{\frac{De}{2}}^{\frac{d}{2}} \frac{dr}{2\pi \cdot H \cdot r \sqrt{\frac{4r^2}{B^2}+1}} + R_i \cdot \int_{\frac{d}{2}}^{\frac{Di}{2}} \frac{dr}{2\pi \cdot H \cdot r \sqrt{\frac{4r^2}{B^2}+1}} +$$

$$R_t \cdot \int_{\frac{Di}{2}}^{\infty} \frac{dr}{2\pi \cdot H \cdot r \sqrt{\frac{4r^2}{B^2}+1}}$$

with $B^2 = L^2 - D_e^2 - H^2$

Here:

$R = \frac{R_{FEL}}{K_{FEL}} = \frac{U}{I}$ = sum of the resistances (quotient from voltage and current of the probe), that the measuring current must overcome on its way between probe and remote current return electrode

R_{FEL}	=	apparent resistivity, measured with the FEL probe
R_m, R_i, R_t	=	resistivities of mud, invaded zone and the undisturbed rock.
D_i	=	invasion diameter
d	=	borehole diameter
K_{FEL}	=	geometric factor of the FEL probe

Correction diagrams (resistivity departure curves) can easily be calculated for the tool in use by applying the above formula, so that "apperant" FEL-resistivities may be transformed into true rock resistivities, if the necessary borehole and infiltration data are available.

See Chart(7) for an example of resistivity departure curves calculated according to this approach.

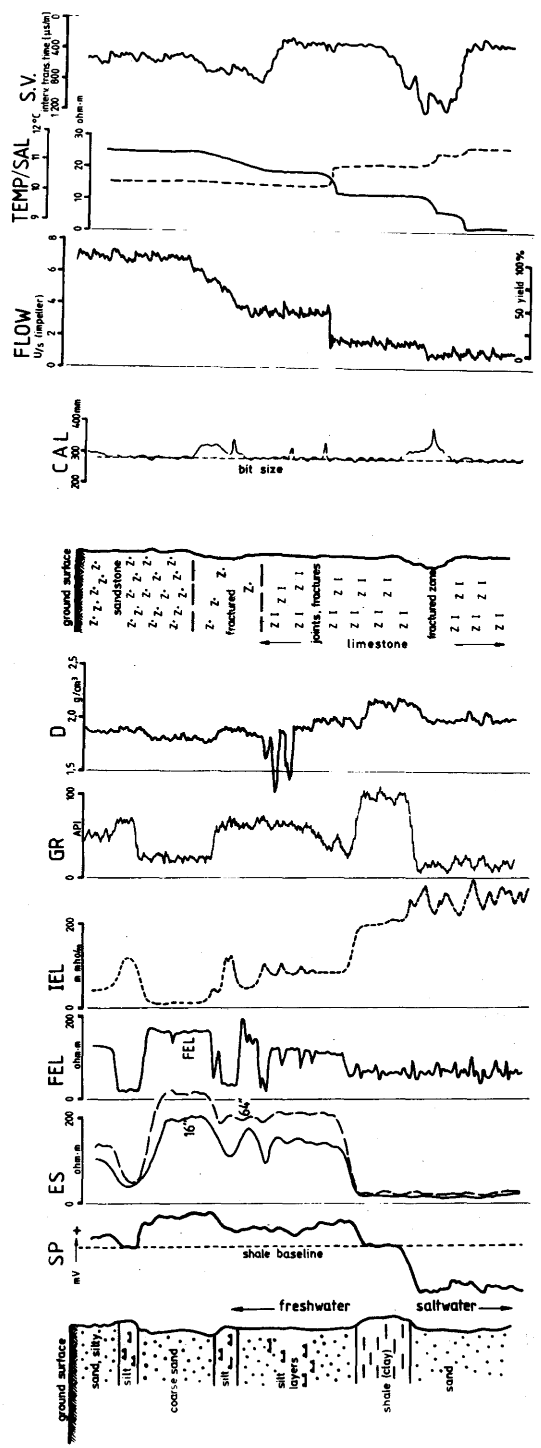


Fig. 33 Schematic represantations of borehole logs (after REPSOLD and SCHNEIDER 1988)

7. Log quality control

Well logs that have to be quantitatively interpreted must have a definite technical measurement standard.

Well logs are usually ordered because they are regarded as necessary for clarifying a particular question. It must therefore also be considered necessary that they be carried out as accurately as possible.

Should a log not meet the requirements imposed (whatever the reason may be) its repetition must be insisted upon, if it can be brought to the required standard as a result.

In general: ensure that you acquire all data which are easy to obtain at the drilling site but which could be difficult to acquire later:

- bottom hole depth, fluid level (water/mud)
- bit size
- completion data: material, wall thicknesses, filter/casing sections, clay sealings
- time since last mud circulation
- mud sample (taken from the last circulation!), mud composition
- depth reference point (if not otherwise agreed: ground surface)
- well head above surface
- grid reference, height a.m.s.l., topographical map number
- drilling data, drilling firm, drilling equipment, drilling method, tool pusher, period of execution, commissioning party.

If exact depth determination is required (core drillings, fracture determination), ensure that you carefully note the depth reference point referred to in each case. Later discussion about, what was when and by whom related to which depth reference point is mostly futile. Wherever possible, you must fix an unchangeable depth reference point from the beginning (upper end stand pipe e.g. can prove to be misleading, if the stand pipe slips downwards during later work on the drilling or is replaced by another).

Questioning the accuracy of the depth counter can also be pertinent in certain cases.

Measuring ranges should be selected so that they best serve the question involved. When necessary, have repetitions executed with altered ranges (sensitivities).

That which otherwise concerns the points which effect the measurement or the measuring equipment itself, the operator must naturally not be made to feel that you are telling him how to do the job: he should rather be pleasantly surprised to find he is daeling with a well informed commissioning party.

In the following, some examples are given although it is not claimed that these "check lists" are complete; one should proceed analogously with the other methods.

Measurement of the natural gamma radiation, GR

- damping (time constant) and cable speed corresponding NT greater 200, v smaller 20/T selected? (N = count rate in cps, T = time constant in s, v = cable speed in m/min)
- mud density?
- mud level?
- borehole diameter, completion (wall thicknesses)?
- statistical records?
- zero, span, calibration of the probe?
- probe diameter, size of scintillator crystal?
- all data entered in the log heading?

Measurement of rock resistivity, ES/EL

- position of the reference electrode N?
- mud resistivity/temperature?
- mud sample from the last circulation?
- mud composition?
- time since last mud circulation?
- borehole diameter, completion?
- all resistivity measurements in the same scale? (mandatory with 16"/64" normals!)
- zero, span?
- with presence of a steel stand pipe: at least 5 m recorded within the pipes?
- position of the current return electrode B?
- cable speed? (An ES measuring equipment usually also has a time constant); also applicable here: v smaller 20/T - however, speed should generally not exceed 10m/min.
- repeat runs in a more sensitive range?
- all data entered in the log heading?

Measurement of the electric self potential, SP

- reference electrode N earthed at an appropriate distance from the well and the measuring truck (minimum 30 to 50 m)? Only in the mud pit in an emergency!
- mud sample from the last circulation?
- mud composition?
- time since last mud circulation?
- measuring range: normally 100 mV or 50 mV on 10 divisions!
- zero and span?
- superimposed sinus wave? = magnetized cable drum.
- strong drift? Try repetition with changed position of the reference electrode N.
- all data entered in the log heading?

Measurement of rock density, D, FD

- "spacing" (distance source-detector)?
- probe position (freely suspended, centred, side wall)?
- caliper recorded simultaneously (distance to density reference point on the probe)?
- natural gamma ray (distance to density reference point)?
- zero and calibrations?
- correction tables (mud and diameter corrections)?
- normal Density Log or FDC ("Formation Density Compensated")?
- mud density?
- all data entered in the log heading?

Measurement of the vertical fluid flow, FLOW

- precise completion data of the borehole or well? – extreme CAUTION with measurements in "slotted" tubes!
- accurate data of the Flowmeter used? type (open, half-open), intake cross section, spinner (diameter, elevation angle, pulses per revolution, coding for right/left rotation)
- Flowmeter centred, freely suspended, stand-off device?
- type curves and/or field calibration (Flowmeter reading vs. velocity of flow and borehole diameter)?.
- production data (pump rate, artesian outflow)?
- minimum pump rate (see 4.15.4) achieved? – if not, Flowmeter measurement is pointless in most cases!
- stand flow measurements?
- measuring with different pump rates?
- reproduction runs (if possible, each measurement duplicated)?
- before and after each measurement: spinner freewheeling?
- all data entered in log heading?

METRIC CONVERSION TABLE

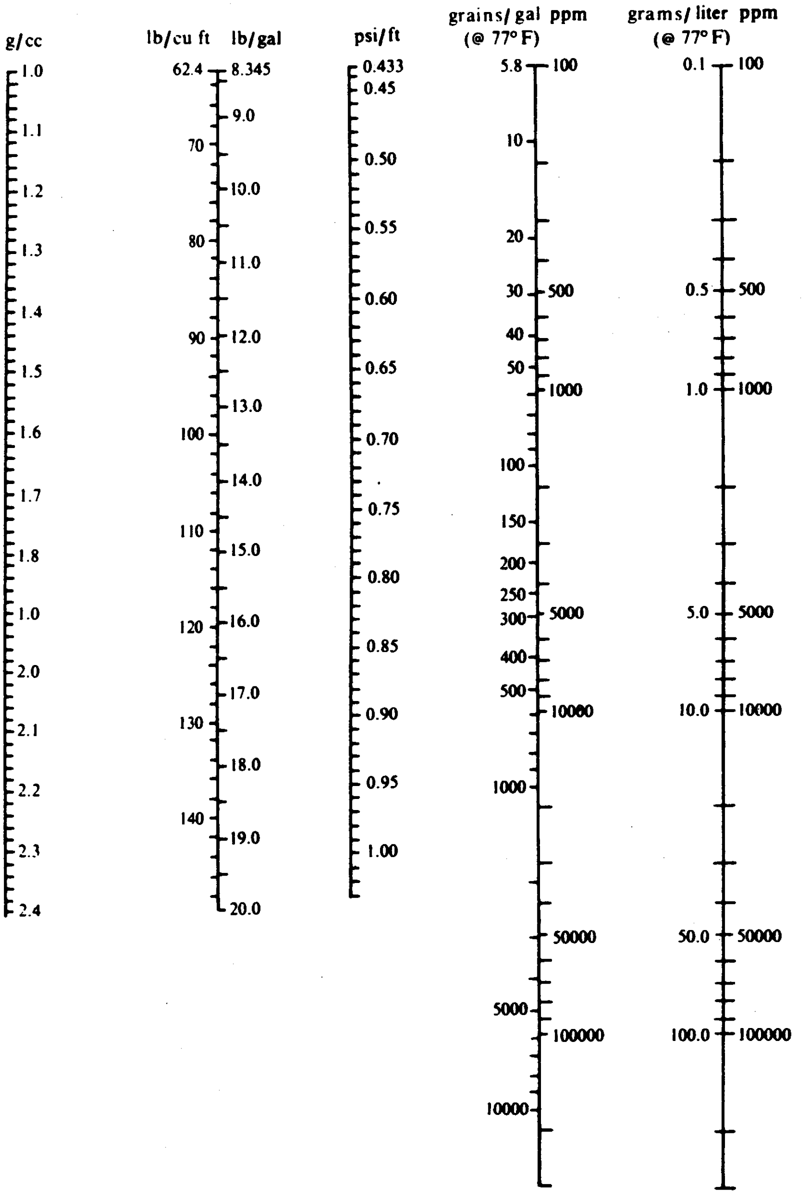
QUANTITY	FROM	TO	MULTIPLY BY
Lengh	inch	millimeter (mm)	25.4
	inch	centimeter (cm)	2.54
	foot	meter (m)	0.3048
	mile	kilometer (km)	1.609
Area	acre	hectare (ha)	0.405
	square mile	square kilometer (km^3)	2.589
Volume	fluid ounce	cubic centimeters (cm^3)	28.41
	gallon (Imperial)	cubic decimeter (dm^3) or liter (l)	4.55
	gallon (U.S.)	cubic decimeter (dm^3) or liter (l)	3.79
Mass	ounce (avdp.)	gram (g)	28.35
	pound (avdp.)	kilogram (kg)	0.454
	ton (short)	kilogram (kg)	907.18
Temperature	Fahrenheit	Celsius (°C)	(°F – 32)/1.8 ≈ °C
Speed	mile/hour	kilometer/hour (km/h)	1.609
Force	pound-force	Newton (N)	4.448
Pressure	pound/square inch	megapascal (MPa)	6.895 E-03

WIRELINE UNITS

QUANTITY	CUSTOMARY UNIT	SI UNIT
Electrode spacing	inch	centimeter (cm)
Depth	foot	meter (m)
Temerature	degree Fahrenheit	degree Celsius (°C)
Pressure	pound/square inch	megapascal (MPa)
Conductivity	mho	millisiemens/meter (mS/m)
Bulk density	gram/cubic centimeter	kilogram/cubic meter
Interval travel time	microsecond/foot	microsecond/meter (μs/m)
Resistivity	ohm meter^2/meter	ohm meter (Ωm)
Velocity of logging run	foot/minute	meter/minute (m/min)
Sonde length	foot	meter (m)
Borehole diameter	inch	millimeter (mm)
Tool diameter	inch	millimeter (mm)
Perforating density	shots/foot	shots/30 cm
Explosive charge mass	gram	gram (g)
Penetration	inch	centimeter (cm)
Density	grams/cubic centimeter	kilogram/cubic meter (kg/m^3)

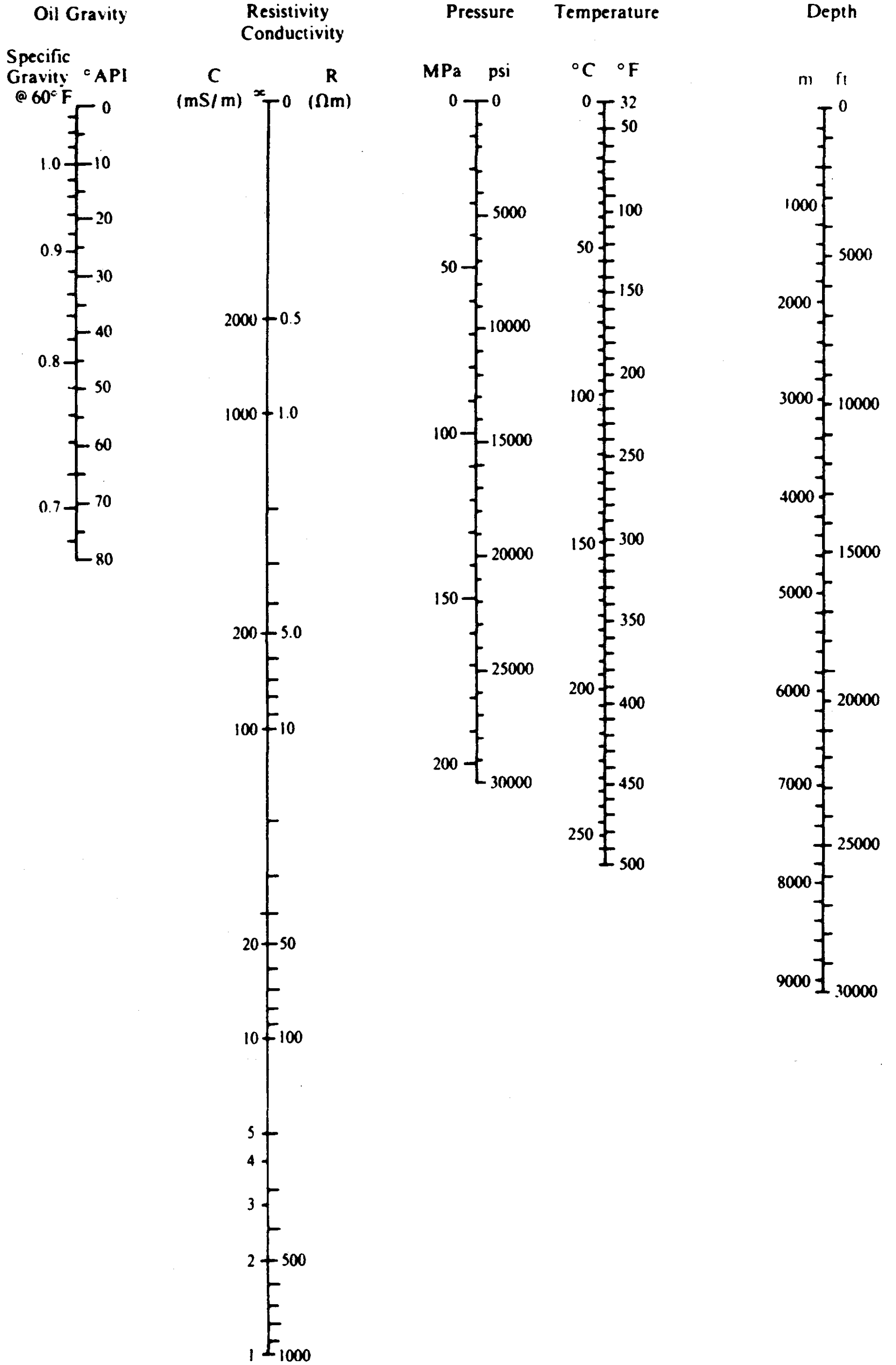
UNIT CONVERSIONS

Mud Weight or Pressure Gradient — NaCl Solution Concentration



Dresser Atlas DRESSER

UNIT CONVERSIONS



9 Explanations to the Log Samples

Log sample (1)

Test well at the BGR location in Hannover. Log (1) was recorded before completion with Gamma Ray (GR), 16"-64" resistivity (ES) and caliper (CAL).

Log (2) in the completed well shows a test run with the 210/35 focussed electric tool (FEL), demonstrating the casing collar locating ability (CCL) of a short spaced guard log tool in plastic tubes (Note, that between 11 m and 52 m casing collar indications are doubled in comparison with the completion data supplied by the drilling company).

Log (3) illustrates Gamma Ray (GR) and Density (FD) measurement in the completed well. The upper part of the hole (from 35 m to the surface) was completed with screens, gravel-packed and fitted with clay sealings as a water well (see completion record on the log), the lower part was completed with screens and casings without gravelpacking.
The Density Log (FD) probably shows irregularities of the annulus zone around the casing due to swelling of the clays or other spontaneous settling processes (compare caliper log (CAL) on log (1)).

Log sample (2)

Hydrogeological research well in the Gorleben investigation area. Bottom hole is reached at about 250 m with resistivities as low as 0.25 ohm.m (caprock region of the Gorleben salt dome). Piezometer wells were sunk a few metres distant from the main well with screens at 37 - 40 m and 110 - 113 m and water samples were pumped. SP and ES interpretations in terms of water resistivity could thus be checked. A positive SP deflection of 12 - 15 mV is observed at the level of the upper screen. Following the standard procedure (see 4.7 and 5.3) which, however, is only valid for NaCl solutions and ideal cationic membrane shales (the first of which at least is not valid, if one refers to the resistivity curves), a water resistivity of approx. 3.5 ohm.m is determined. The pumped sample yields 78 ohm.m. On the one hand, the discrepancy is of course due to the necessary but in this case not applied corrections for divalent ions in pore water and mud filtrate and for non-ideal shale behaviour. On the other hand, the establishment of shale- and sandlines must not be relied on too much. Application of the "formation factor relation" shown in Fig. 22, renders a value which is probably not lower than 50 ohm.m and not higher than 100 ohm.m (aquifer resistivity 200 ohm.m) for the fairly coarse sands encountered. This is within the order of magnitude comparable to the true water resistivity taken from the pumped water sample.

A useful SP deflection is not obtainable at the level of the second screen. Thus the relation in Fig. 22 has to be applied anyway. The result is a water resistivity of approx. 0.7 ohm.m (aquifer resistivity 3.0 ohm.m) for well-sorted sands, which is in good agreement with the "pumped" value of 0.81 ohm.m.

Log sample (3)

Another Gorleben research well, going down to resistivities as low as 0.2 ohm.m or even less in the caprock region. Piezometer screens were set at 133 – 138 m and 215 – 225 m in separate wells close to the main well.

Log (1): At the uppermost screen level the SP curve shows a negative deflection of 15 – 20 mV, which following the standard procedure, yields a water resistivity of 0.3 – 0.4 ohm.m that is not too far from the pumped value of 0.77 ohm.m. Albeit the reliability is questionable as further up the well, a baseline shift (near 110 m) obviously takes place. This result may thus be a coincidence with several errors cancelling each other. An aquifer resistivity cannot be read at this level, so that a "countercheck" is not possible.
In the lowermost screened interval (not shown in the log sample) a negative SP deflection of 20 – 25 mV is recorded. Though pore waters in this region can be assumed as predominantly NaCl solutions, the SP interpretation yields 0.2 – 0.3 ohm.m, which is about 10 times too high, the pumped value being 0.05 ohm.m. Here the non-ideal shales obviously account for the deviation. Application of the diagram in Fig. 22 yields a value of approx. 0.05 ohm.m for well-sorted sands.
The log clearly shows the responses of normal arrays with different spacings (here: 8", 16", 32", 64"). Note the reversal of the sequence of spacings with varying ratio of mud and rock resistivities (easily observable at about 140 m).

Log (2): Density Logs with 2 spacings (48 cm and 15 cm) show a strong dependence on hole diameter, as recognized by comparison with the caliper log. This is despite use of a side wall tool (not of the pad type but the entire probe pressed against the borehole wall). On the other hand, the log indicates a homogeneous behaviour in terms of porosity. The average count rate of 1000 cps, together with a mean diameter of 5 – $^1/_2$", yields a bulk density of approx. 2.15 g/ccm (mud density 1.05 g/ccm assumed). This results in an average porosity of about 45% (matrix density 2.65 g/ccm), a value representative of the fairly-sorted sands encountered in the borehole. The short spaced density log shows a certain affinity with the focussed electric log (FEL, not shown in Log(1)), which is also not regarded as extraordinary as the spacings of both tools are comparable with one another (15 cm and 10 cm) and higher rock densities normally correspond with higher resistivities.

Log sample (4)

Log (1) was recorded in the research well of a "hot dry rock project" in granite rock in Bavaria for exploitation of geothermal energy. The principle aim was the detection of joints and fractures, i.e. finally the permeability of rock. Several logs were run: natural Gamma Ray (GR), a freely suspended (non-directional and non-calibrated) gamma-gamma-log, 16"-64" normal resistivity (ES), focussed resistivity (FEL) and Sonic (SV) (the latter was assembled from single measurements every 1/2 m with the static probe). The wells were core-drilled. Fracture indications shown in the logs are taken from the "fracture catalogue", compiled from the drill cores.

Whereas the Sonic Log (not to speak about the weakly responding gamma-gamma-log) as well as the normal array resistivity curves show little more than the pronounced fracture "zones", whereby the latter still do the "best job", the Focussed Electric Log (FEL) shows extremely clear responses even to single fractures or fissures located close to each other. This is obviously due to the short sensing electrode of only 10 cm.

Log (2) was taken in a well that was drilled horizontally in a mine gallery in Switzerland in diorite rock for research in the field of radioactive waste disposal. The aim was also to obtain information about rock fracturing. The well was core-drilled and the indications shown on the log were taken from the drill cores.

Log sample (5)

Flowmeter measurement in an uncompleted well (i.e. in consolidated rock) (Hessen), showing extraordinarily good agreement of reproduction runs with constant and even with varying pump rates. However, this is often observed also in completed wells in unconsolidated formations and suggests that highly invariable rather than statistically varying flow patterns prevail in a pumped well with turbulent flow.
Pump rates from maximum flow readings taken just below the pump, determined via the field calibration curve, show certain deviations from the pump rates obtained at the surface by a so called "weir": 17.25 m^3/h and 46.5 m^3/h compared to 20 m^3/h and 40 m^3/h. This may be due to the outside temperature, at that time –15 degr.C, which caused considerable handling difficulties throughout the operation.

Interpretation of the Flow Logs for % of the pump rate and flow rates in m^3/h is shown in the diagram.

This compilation is necessarily incomplete. It contains in part works of a general nature as well as papers on special topics. They are not all referred to in the text. The compilation is intended to give the reader an initial introduction to the huge range of publications on the subject. The author specially recommends the two books by Douglas W. Hilchie. These are in fact written for oil well logging analysts but contain an immense amount of practical information, presented in a professionally instructional manner.

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Concluding Remarks

It may be that anyone who reads this manual feels that although it contains a lot of information and recommendations, it does not tell the reader explicitly how to interprete a log in a given situation with a given task. In this context, the author wishes to quote a sentence from the introduction to the book by Scott Keys and MacCary: "One fundamental problem in the application of geophysical logs is that the interpretation of many logs is more of an art than a science".

This is most certainly the case, as the author can confirm from his own experience. Knowing "what to do" comes only with time and increasing "mileage" of logged hole.

Detailed procedures for the interpretation of logs are only rarely given in the manual. This is deliberate, as cookery book instructions of this kind often lead to bitterly disappointing results when applied in practice.

Thus, the well trodden path of initial enchantment via inevitable frustration to final achievement is also unavoidable here.

Annex:

Charts (1) – (12)

Log Samples ① – ⑤

List of Charts

Chart (1)

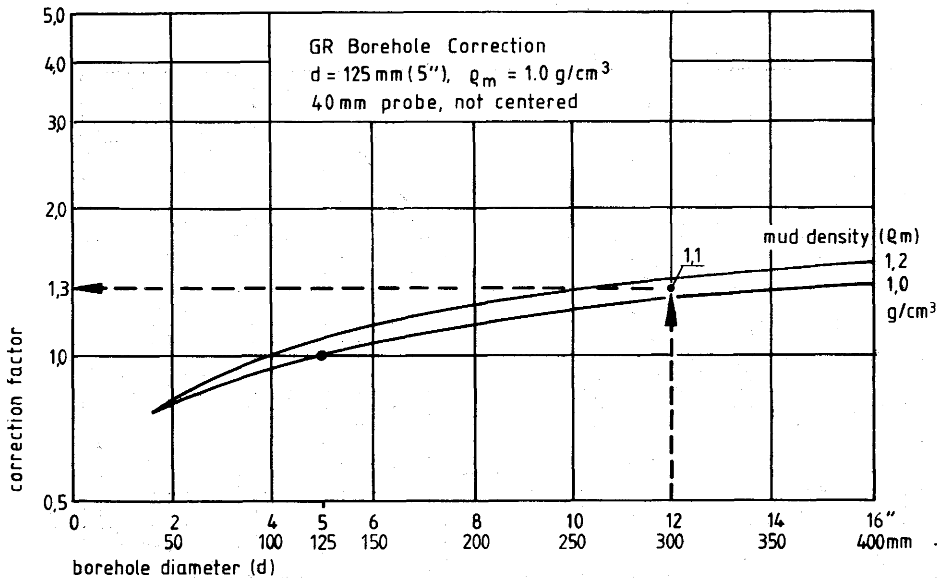
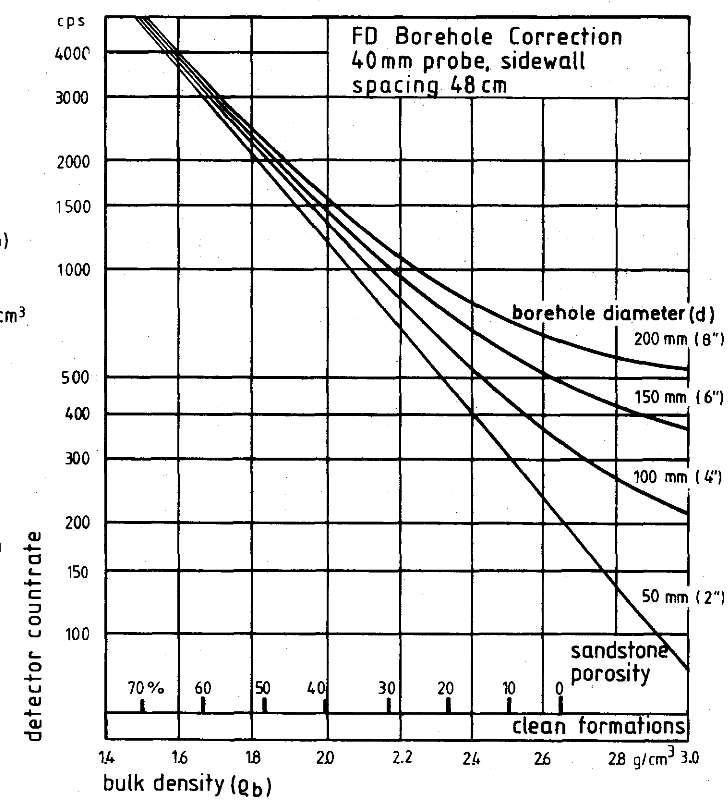
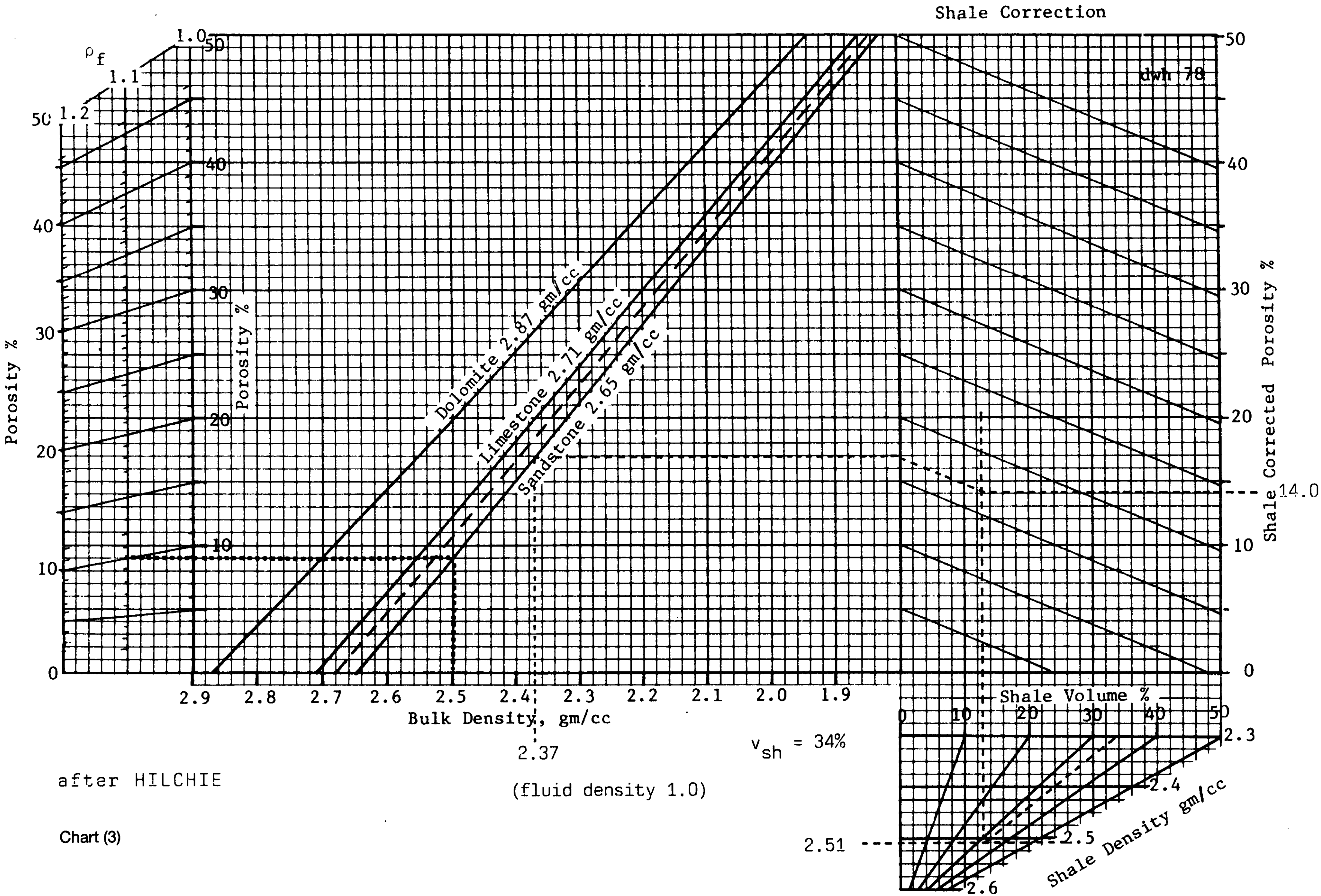


Chart (2)





(fluid density 1.0)

after HILCHIE

Chart (3)

Chart (4)

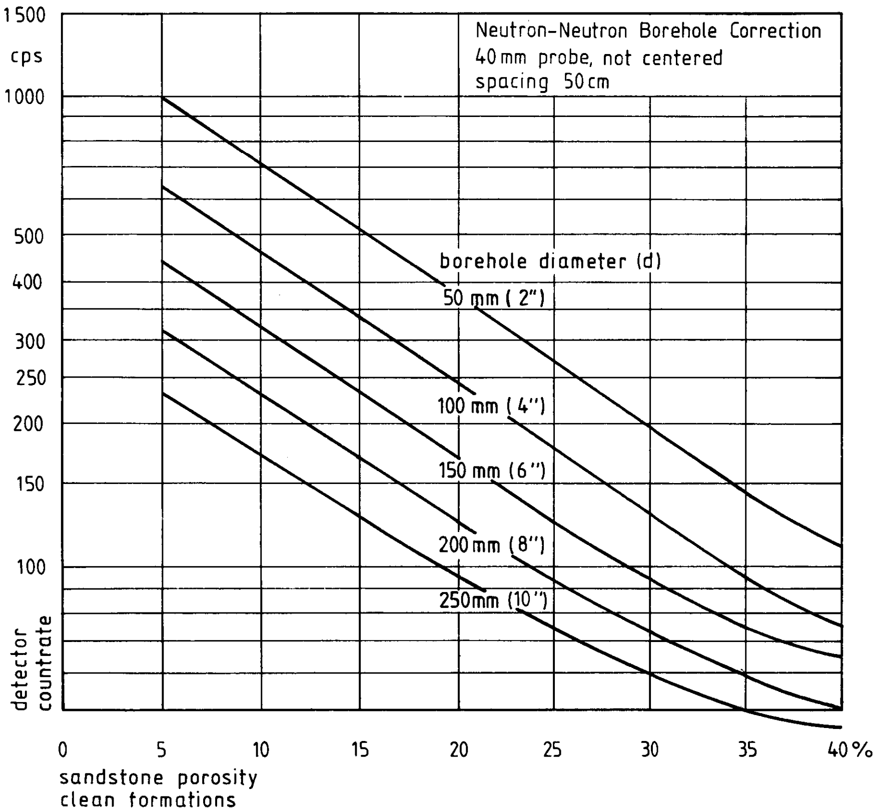
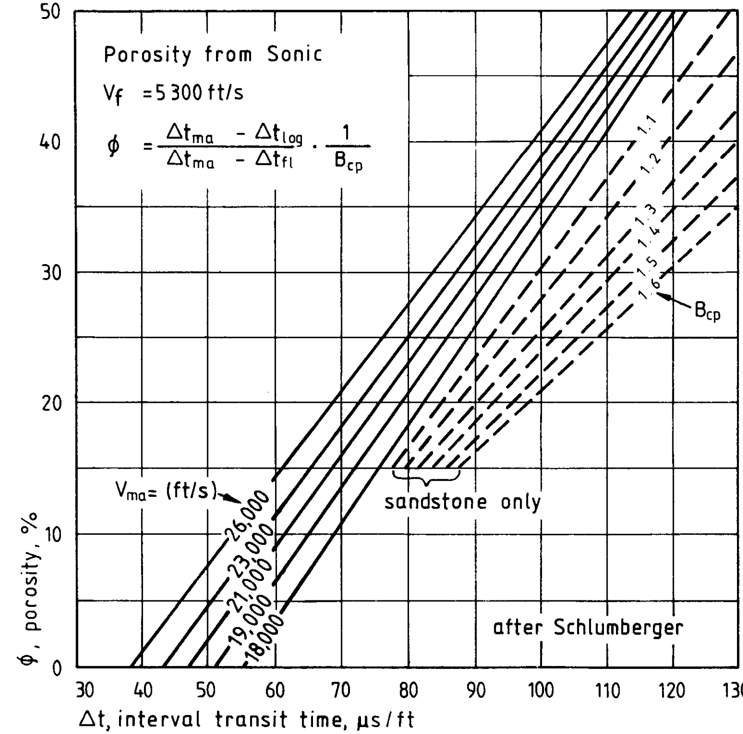
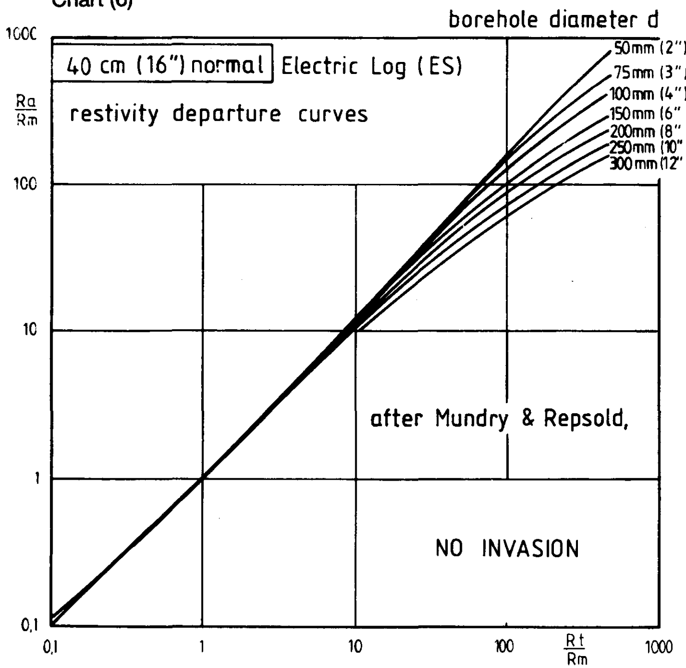


Chart (5)

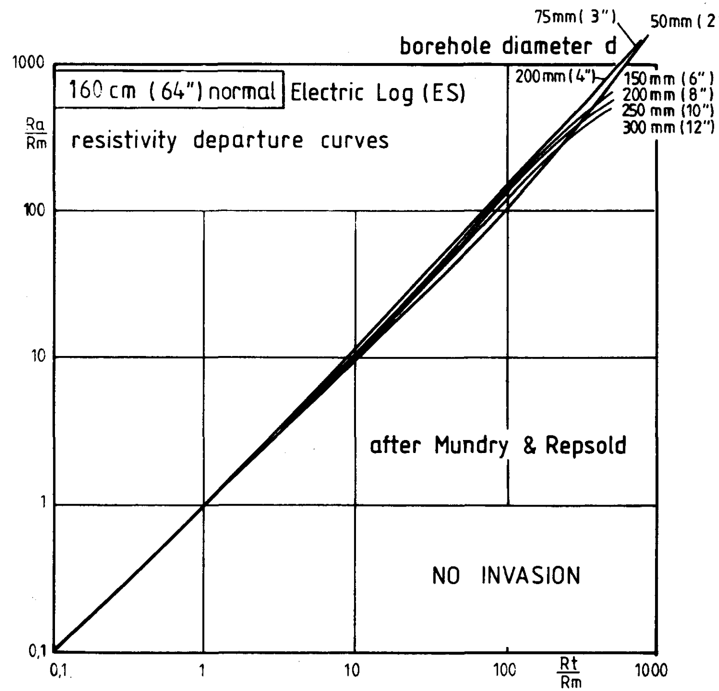


	V_{ma} (ft/s)	Δt (µs/ft)
sandstone	18,000 - 19,500	55,5 - 51,3
limestone	21,000 - 23,000	47,6 - 43,5
dolomite	23,000 - 26,000	43,5 - 38,5

Chart (6)



borehole diameter d
40 cm (16") normal
Electric Log (ES)
restivity departure curves
50mm (2")
75mm (3")
100mm (4")
150mm (6")
200mm (8")
250mm (10")
300mm (12")
Ra/Rm
Rt/Rm
0,1
1
10
100
1000
after Mundry & Repsold,
NO INVASION



75mm (3")
50mm (2")
borehole diameter d
200mm (4")
150 mm (6")
200 mm (8")
250 mm (10")
300 mm (12")
160 cm (64") normal
Electric Log (ES)
resistivity departure curves
Ra/Rm
Rt/Rm
0,1
1
10
100
1000
after Mundry & Repsold
NO INVASION

Chart (7)

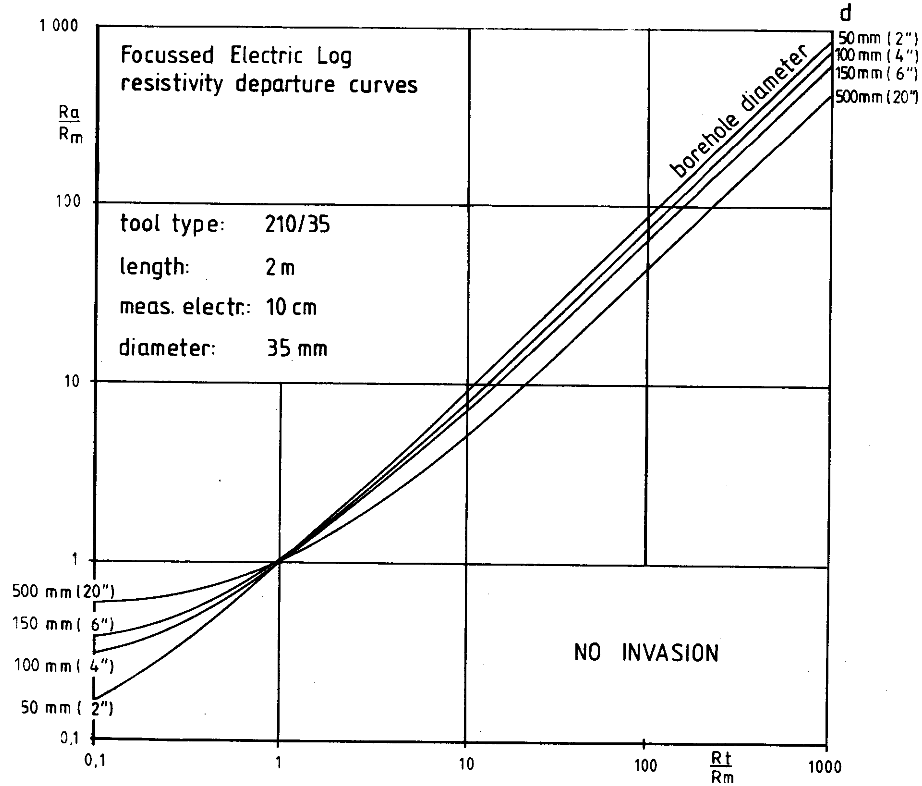
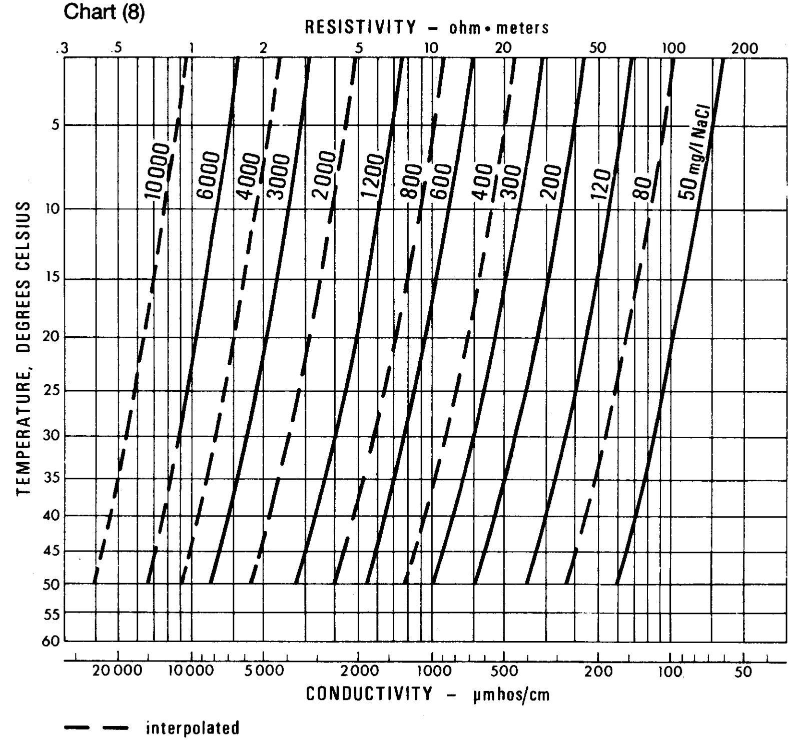
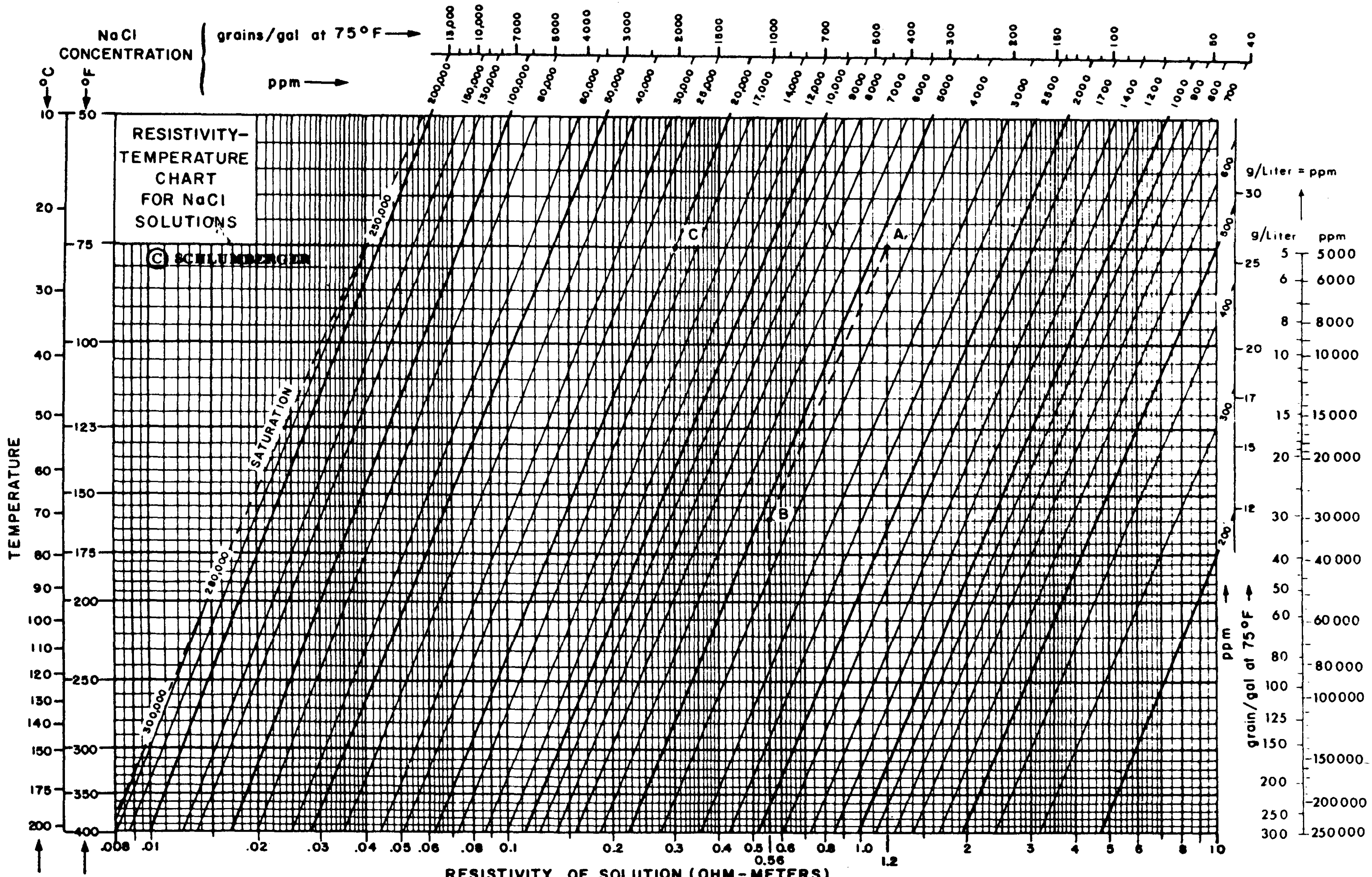


Chart (8)





Example: R_m is 1.2 at 75°F (point A on chart). Follow trend of slanting lines (constant salinities) to find R_m at other temperatures; for example, at Formation Temperature (FT) = 160°F (point B) read $R_m = 0.56$. The conversion shown in this chart is approximated by the Arps formula: $R_{FT} = R_{75°} \times (75° + 7)/(FT\ (\text{in } °F) + 7)$.

Chart (9)

Chart (11)

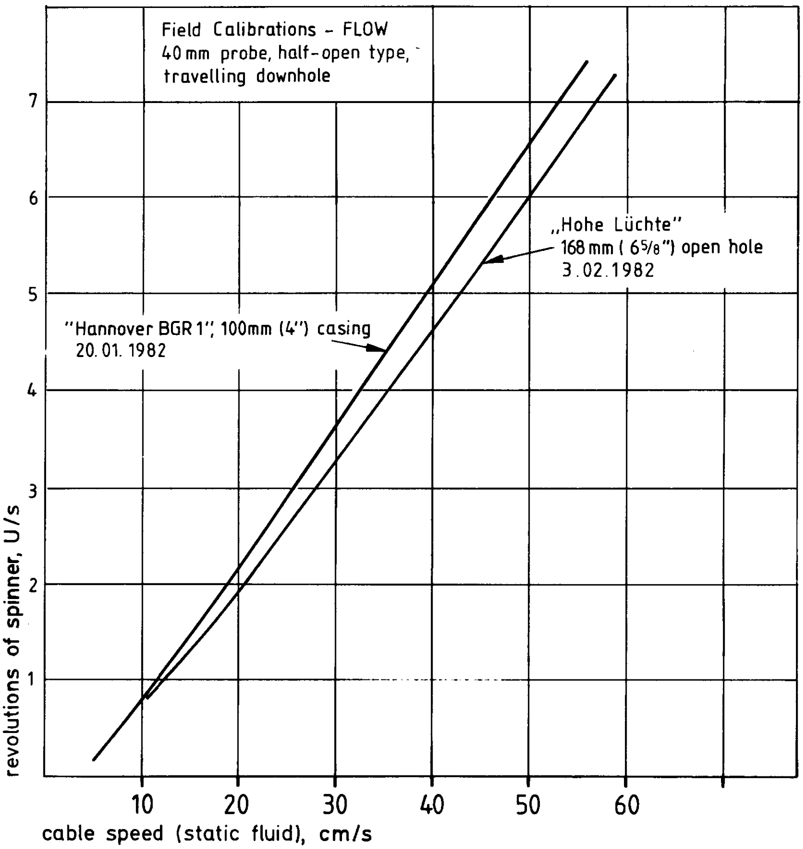
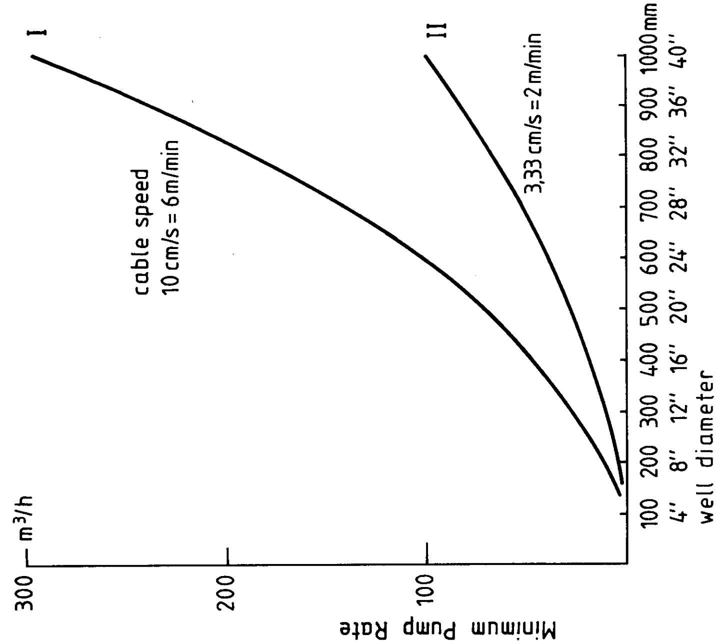
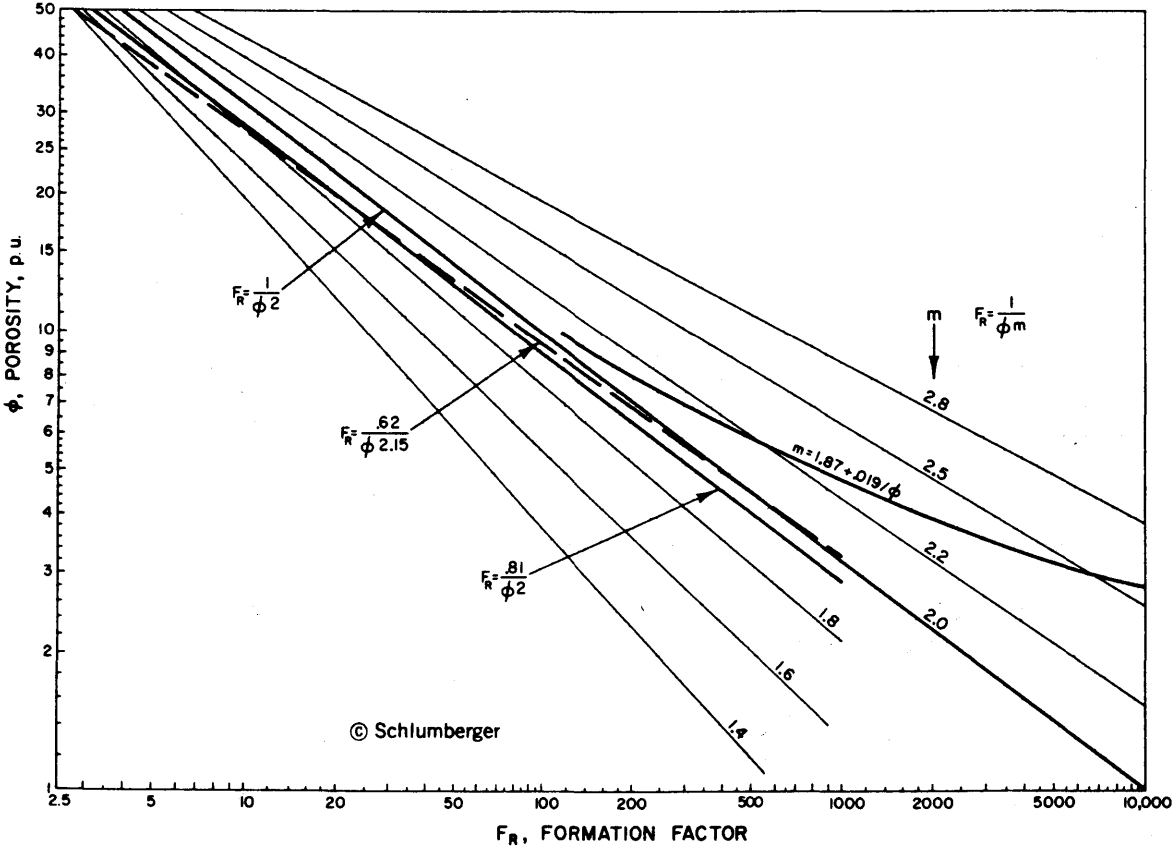


Chart (10)



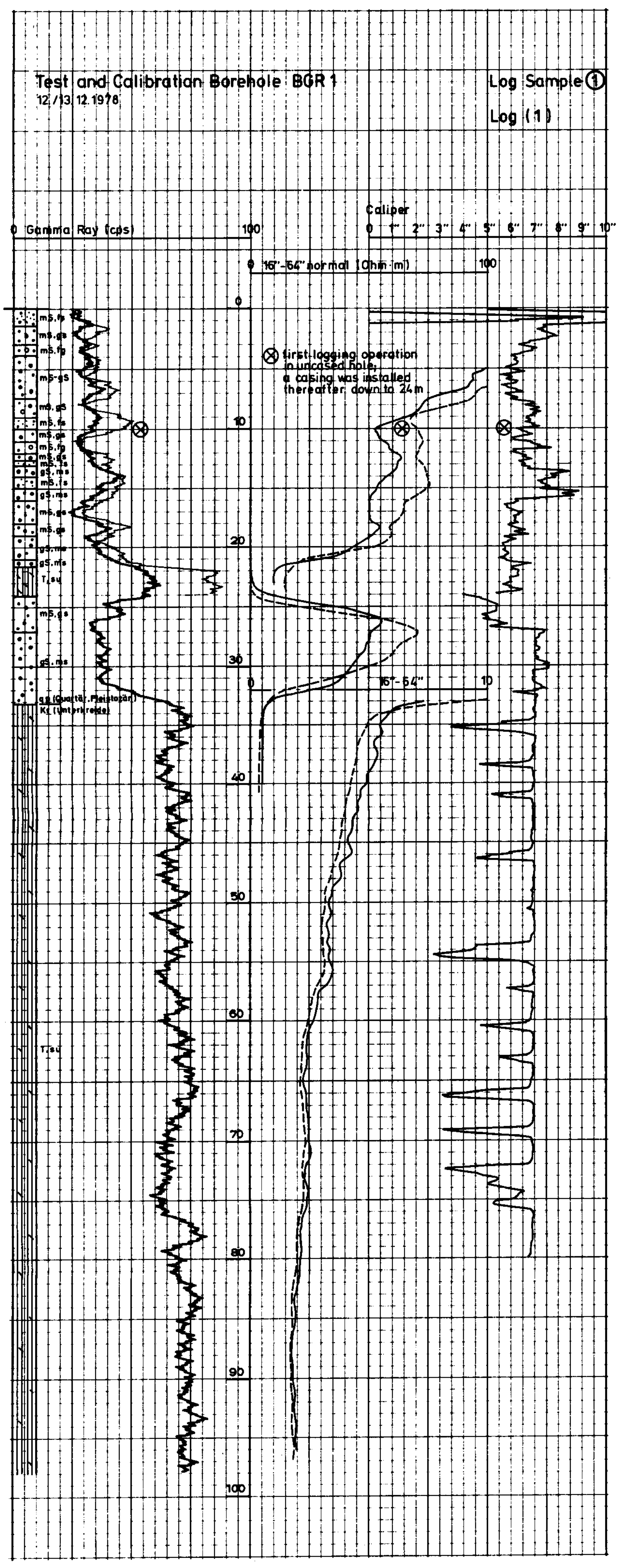
FORMATION FACTOR VERSUS POROSITY

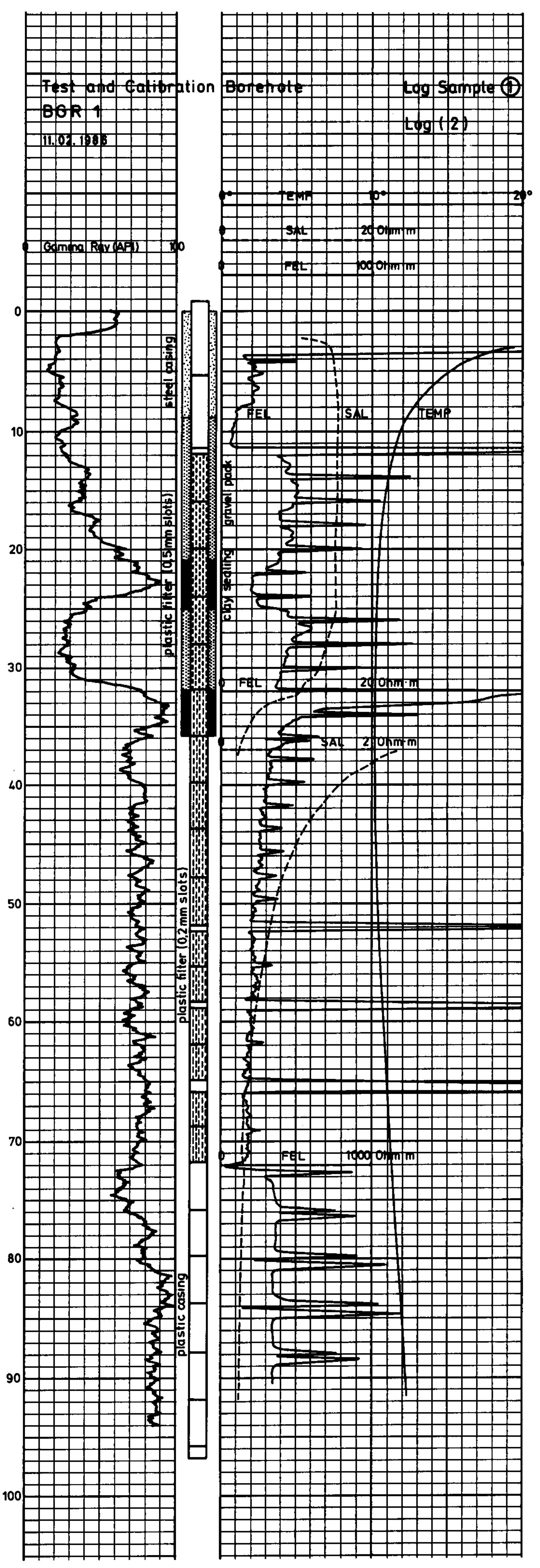
Chart (12)

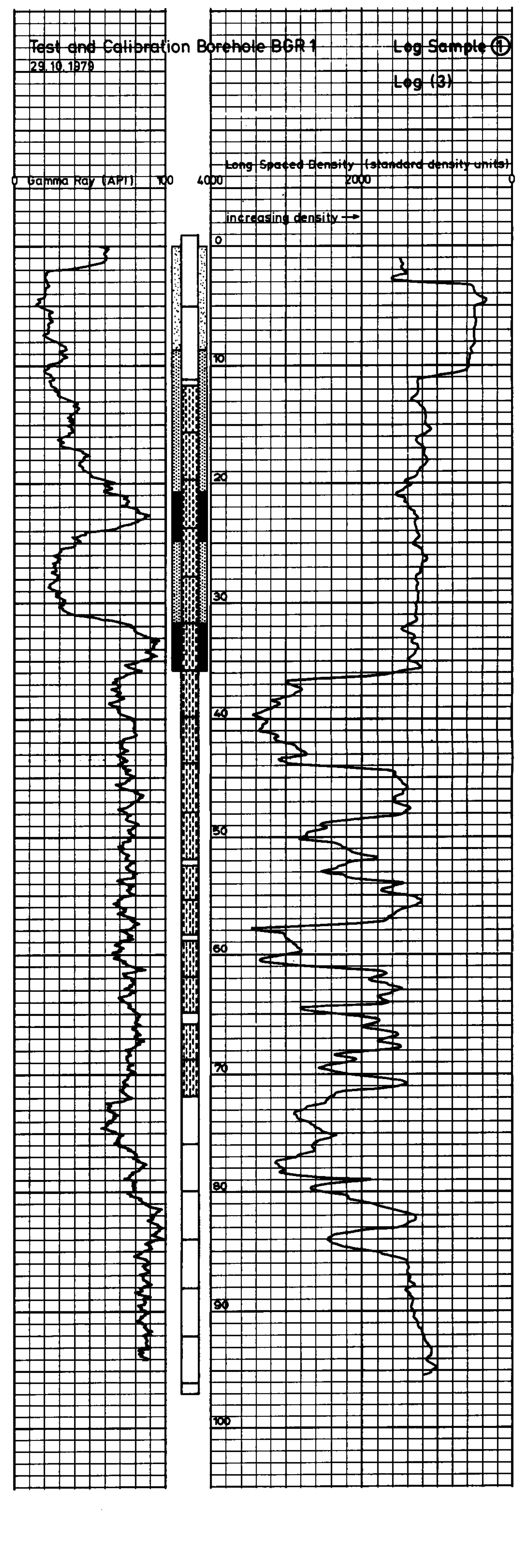


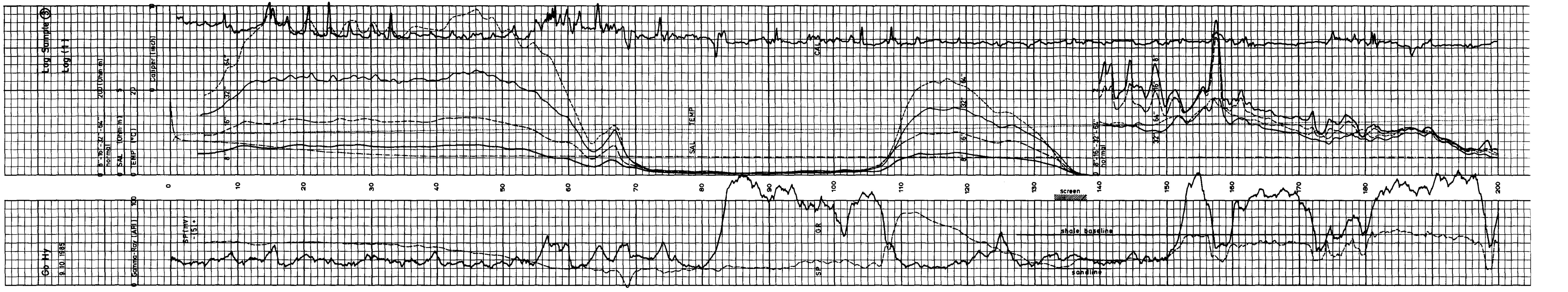
RECOMMENDED F_R-ϕ RELATIONS

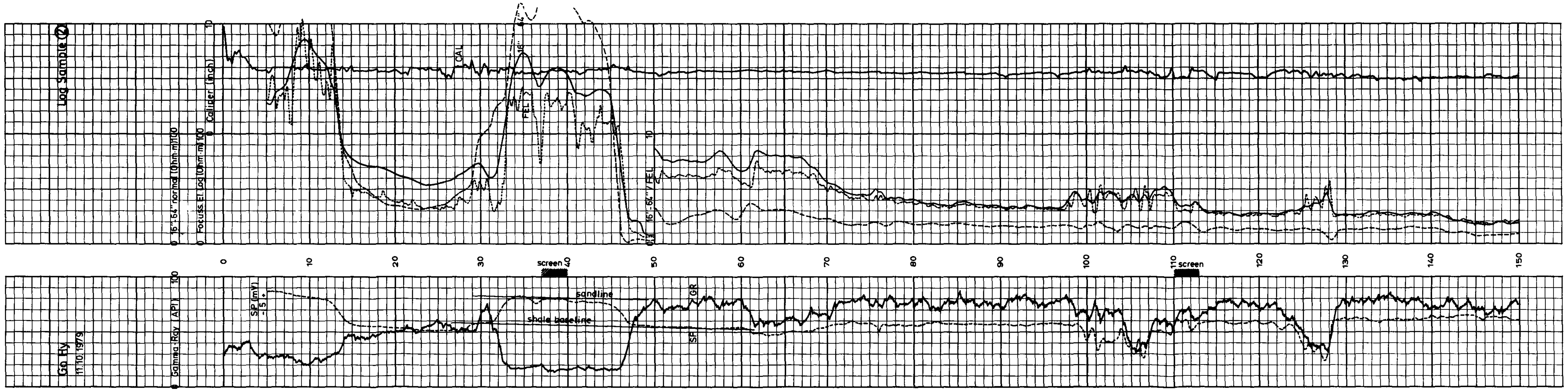
For Soft Formations:	Humble Formula: $F_R = 0.62/\phi^{2.15}$ or $F_R = 0.81/\phi^2$.
For Hard Formations:	$F_R = 1/\phi^m$ with appropriate cementation factor, m.
For Low-ϕ Carbonates (not fractured):	Shell Formula: $F_R = 1/\phi^m$ $m = 1.87 + .019/\phi$


Test and Calibration Borehole BGR 1
12/13.12.1978
Log Sample 1
Log (1)
Gamma Ray (cps)
Caliper
16"-64" normal (Ohm·m)
first logging operation in uncased hole, a casing was installed thereafter down to 24m

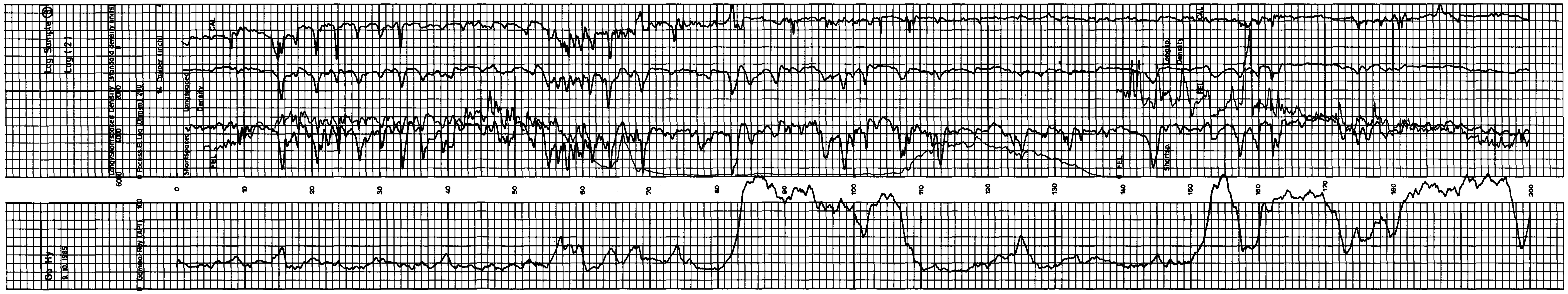

Test and Calibration Borehole
BGR 1
11.02.1988
Log Sample 1
Log (2)
Gamma Ray (API)
TEMP
SAL
FEL
20 Ohm m
100 Ohm m
1000 Ohm m
steel casing
gravel pack
clay sealing
plastic filter (0.5mm slots)
plastic filter (0.2mm slots)
plastic casing


Test and Calibration Borehole BGR 1
29.10.1979
Log Sample 1
Log (3)
Gamma Ray (API)
Long Spaced Density (standard density units)
increasing density →

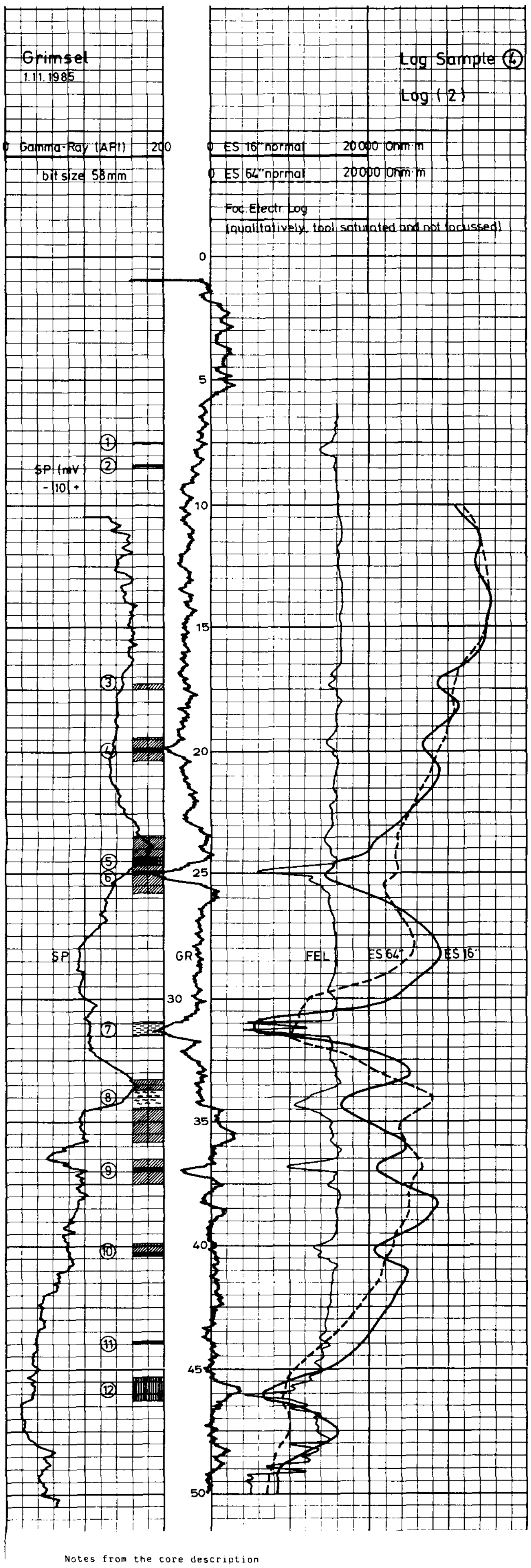

Log Sample 8
Log (1)
Caliper (inch)
SAL (Ohm.m)
TEMP (°C)
CAL
TEMP
SAL
screen
shale baseline
sandline
GR
SP
Gamma-Ray (API)
SP (mV)
Go Hy
9.10.1985


Log Sample 2
Caliper (inch)
Focuss.El.Log (Ohm.m)
CAL
FEL
screen
sandline
shale baseline
GR
SP
Gamma-Ray (API)
SP (mV)
Go Hy
11.10.1979

Log Sample 4
Log (1)
Falkenberg NB 2
Fracture indications from drill cores



Log Sample 5
Log (2)
Gy Hy
9.10.1985



Notes from the core description

(1) Signs of cataclastic deformation

(2) Epidote-filled joint (8mm)

(3) Feldspar porphyroblasts, milky, opaque

(4) Quartz-calcite vein (50mm) in bleached, porous biotite-chlorite Grimsel Granodiorite

(5) Mylonite zone in bleached, porous biotite-chlorite Grimsel Granodiorite

(6) Quartz vein in .... dto.

(7) Biotite schist

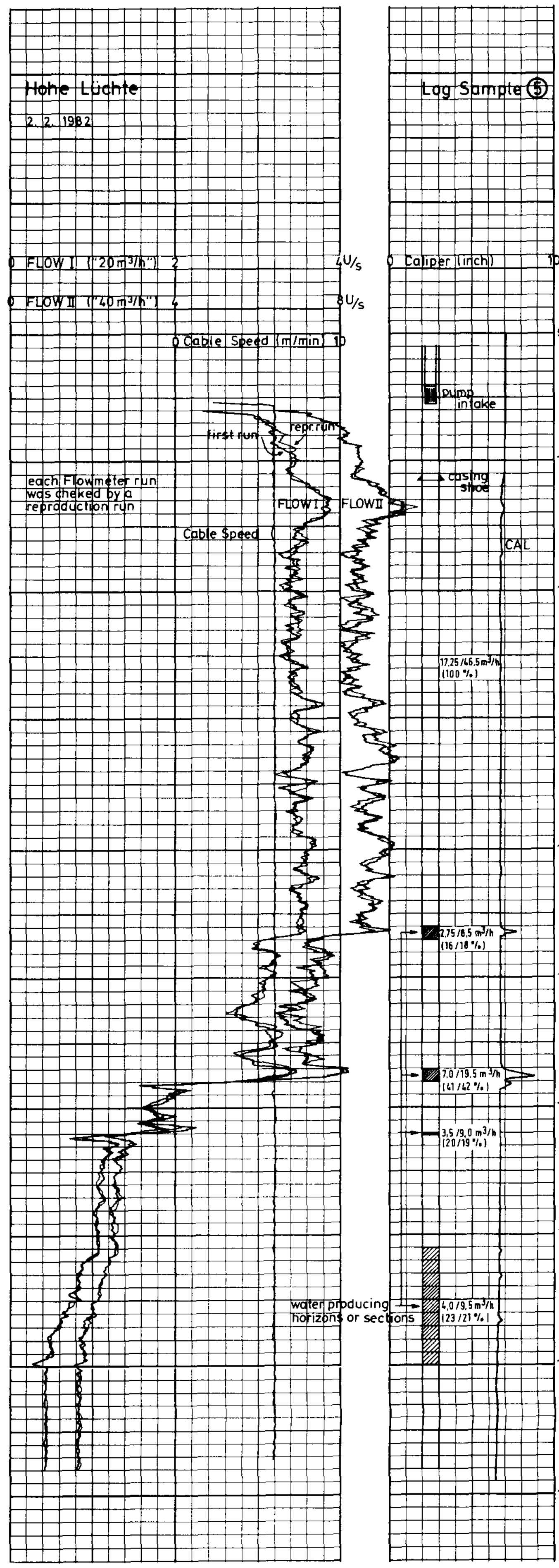
(8) Chlorite, green, earthy texture, in leached, porous Grimsel Granodiorite

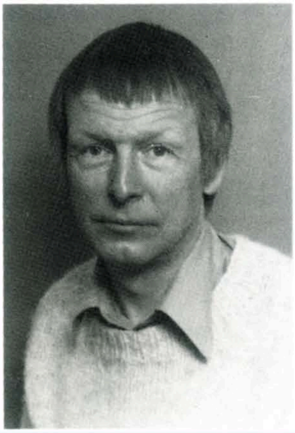
(9) Quartz vein in leached, locally biotite-chlorite-bearing Grimsel Granodiorite

(10) Vein, with quartz and chlorite above it

(11) Epidote-impregnated zone (60mm)

(12) Mylonite zone





HANS REPSOLD

Born 1932, diploma in geophysics from Göttingen University in 1958, with the Geological Survey of Lower Saxony (W.-Germany) since 1959, engaged in geoelectrical depth soundings and later borehole geophysics. Extensive field work in Germany, also in Argentina and Brasil. 1972/73 geophysics expert in a UNDP water resources investigation project in the Central Chaco of Paraguay. Member of the committee of experts „Geohydrology" of the German Gas and Water Experts Association (DVGW) since 1979.

This book is intended to show which logging methods can be applied in boreholes or wells that are sunk for the development or observation of ground water and what can be deduced from them.

The text concentrates more on the practical applications of methods than on the physical principles. Importance was placed on consideration of many (though not all) of the methods possible in water wells.

For this reason, relatively unusual methods like Neutron, Sonic, Microlog or Dipmeter are also presented. In some cases, particularly in consolidated rock, these methods can also be used and provide results of hydrogeological importance.

Three tables in the first section of the book serve for orientation in the selection of methods. Thereafter, the individual well logging methods are described.

Two sections follow, the first of which deals in more detail with the quantitative interpretation of logs in respect of the purposes of hydrogeology, the second contains selected presentations concerning basic principles of some of the methods.

This report is a contribution of the International Association of Hydrogeologists – IAH to UNESCO's International Hydrological Programme – IHP in the framework of IHP III budget 5.3 Application of Geophysical Methods to Groundwater Exploration.

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