received with letter dtd. 3/28/92

U.S. DEPARTMENT OF ENERGY

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YUCCA MOUNTAIN

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

MODERN OPEN HOLE GEOPHYSICAL LOGS

A One-Day Survey Course

Presented to

U.S. Department of Energy
Yucca Mountain Site Characterization Project Office

Presented by

Loren E. "bud" Thompson
Science Applications International Corporation

Las Vegas, Nevada
March 28, 1992

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From: John Gilray

ADD: Ken Hooks

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SITE CHARACTERIZATION
PROJECT

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A note from bud:

This one-day survey course has been designed for non-geotechnical personnel who need an introduction to or review of modern wireline geophysical logging tools and techniques. The information presented during the workshop, along with the material contained in this course manual, will enable you to become more knowledgeable about the types of log measurements, the data collection process, and the uses for modern log measurements.

My goal is to provide the background information to bring you "up to speed" so you will be able to appreciate the need for quality log data for site characterization and other purposes.

We will discuss the following salient points throughout the workshop:

- **Why we want to use log data**
- **Generic types of logs**
- **How each type of log makes its measurement**
- **How log data are collected**
- **Information which may be interpreted from logs**
- **Basic pitfalls in using log data**
- **Quality Control and Quality Assurance of log data**

Within the time constraints of a single day-long class, and given the diverse backgrounds of those in attendance, the information presented must be at a basic, near-lay person level in order to bring us all up to a common level of understanding of these topics. At a later date, I can offer a more comprehensive three- to five- day seminar on log analyses or specific applications during which you would have ample opportunity for hands-on problem solving using log and related data.

Part of our time will be spent with lecture presentations and part with video tapes. The tapes have been supplied by a commercial vendor of logging services for training and information purposes. The use of these tapes should not be considered an endorsement of a particular vendor's products.

An additional note regarding this course manual:

Due to several factors, mostly involved with timing, it was not feasible to prepare a concise and typographically uniform manual specifically for this workshop. I elected to gather up relevant material from various sources to provide the information I felt would be of most benefit to you. You will, therefore, find a variety of type faces, formats, page numbers, and references.

These sources are diverse, and include:

> Course manuals I have previously prepared
>
> Articles from a newsletter I published while in private practice
>
> Logging service company literature

In the future, I will be able to reprint all the information in a single format for related courses.

bud Thompson

May 28, 1992

TOPICS WHICH WILL BE COVERED

DRILLING

BOREHOLE ENVIRONMENT

BASICS OF LOGGING

TYPES OF MEASUREMENTS

- Mechanical Measurements
- Measurements of Natural Occurring Energy
- Logs Which Introduce Energy into the Borehole System

PRODUCTION LOGS

BASICS OF LOOKING AT LOGS - Leading to Pitfalls

- Relative Volumes Investigated
- Porosity Determination
- Thin Beds
- Rock Typing
- Bore Hole Size

LOG CALIBRATIONS

LOG QUALITY CONTROL

LOG QUALITY ASSURANCE

LOGGING AT YUCCA MOUNTAIN

LOG TYPE	BOREHOLE APPLICATION			MEASUREMENT OR ESTIMATE	USED FOR DETERMINATION		
	EMPTY	FULL	CASSED		Ø	SW	LITH
ELECTRICAL METHODS							
INDUCTION	✓	✓		CONDUCTIVITY		✓	
LATEROLOG		✓		RESISTIVITY		✓	
DIELECTRIC	✓	✓		DIELECTRIC CONST.		✓	
DENSITY METHODS							
COMPENSATED DENSITY	✓	✓		ROCK DENSITY	✓		✓
GRAVIMETER	✓	✓	✓	ROCK DENSITY	✓		✓
NEUTRON METHODS							
COMPENSATED NEUTRON		✓	✓	HYDROGEN INDEX	✓		
EPITHERMAL/SIDEWALL	✓	✓		HYDROGEN INDEX	✓		
GEOCHEMICAL LOG	✓	✓	✓	12 ELEMENTS			✓
THERMAL DECAY TIME	✓	✓	✓	SIGMA	✓	✓	
ACOUSTIC METHODS							
ACOUSTIC (SONIC)		✓		TRAVEL TIME	✓		
FULL WAVE FORM		✓	✓	TT RELATIONSHIPS	✓		
NATURAL GAMMA METHODS							
GAMMA LOG	✓	✓	✓	API GR			✓
SPECTRAL GAMMA	✓	✓	✓	K, U, Th			✓
CORE ANALYSES		N/A		VARIOUS MEASUREMENTS	✓	✓	✓

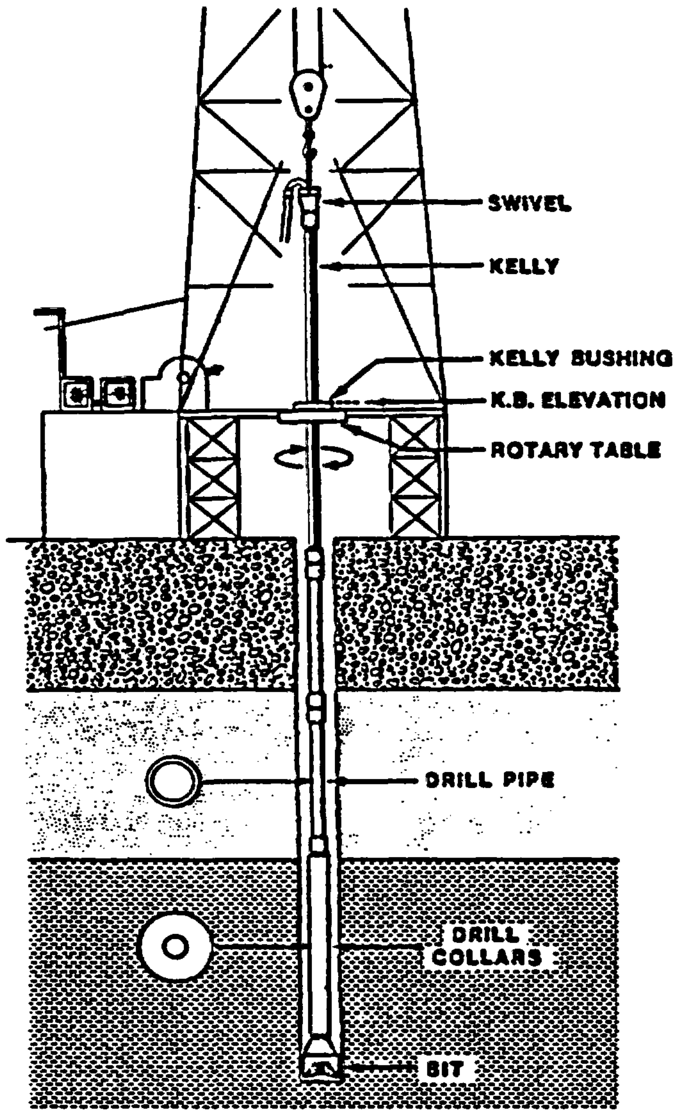
LOGYM1Z.123/3-12-91

DRILLING

AND

BOREHOLE ENVIRONMENT

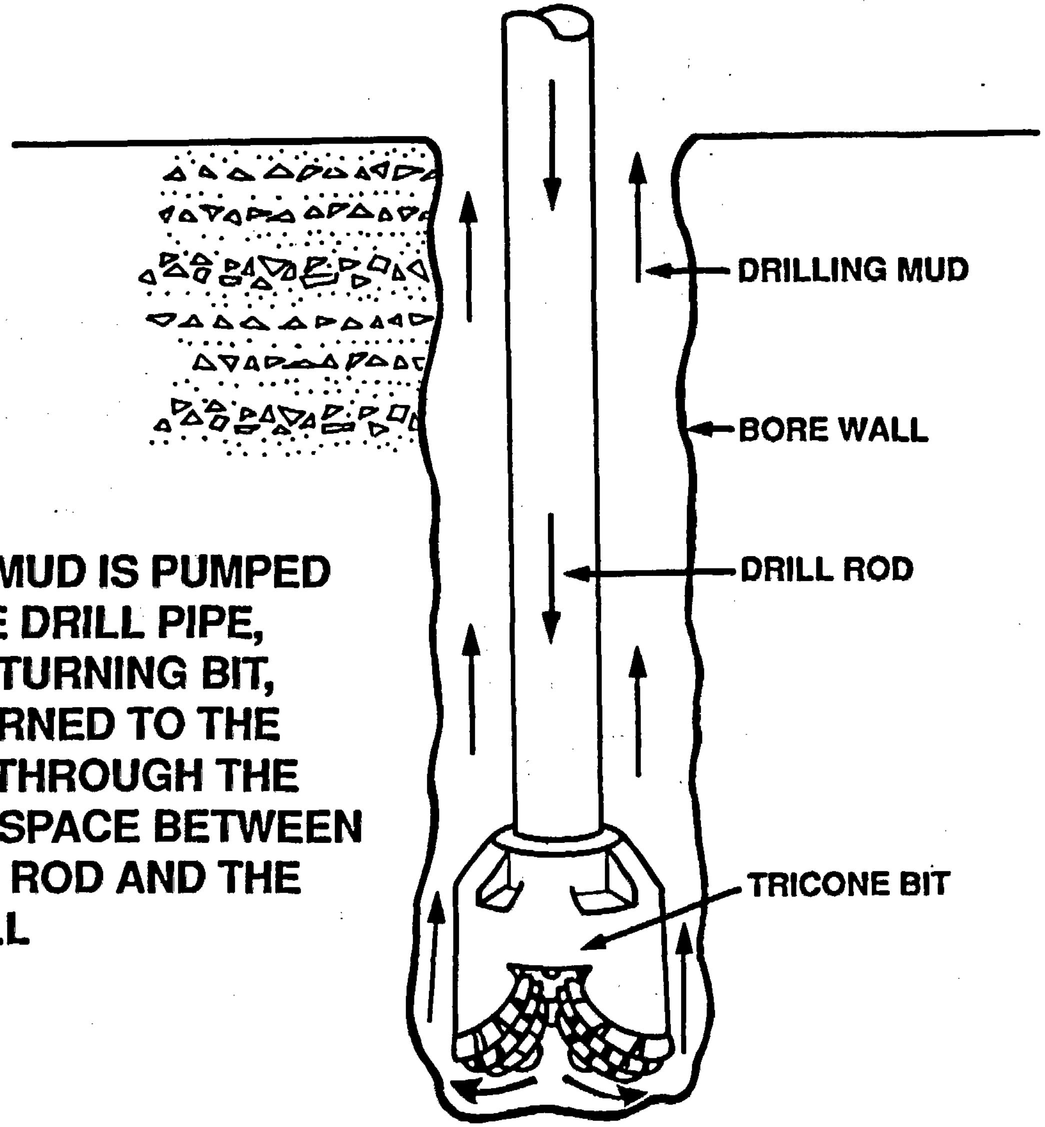
FIGURE I–B
DRILL STRING AND ROTARY BIT



DRILL STRING AND BIT. The figures at bottom left indicate the comparative sizes of the drill pipe and drill collars.

MILLED-TOOTH BIT.
(Photo courtesy of Hughes Tool Co.)

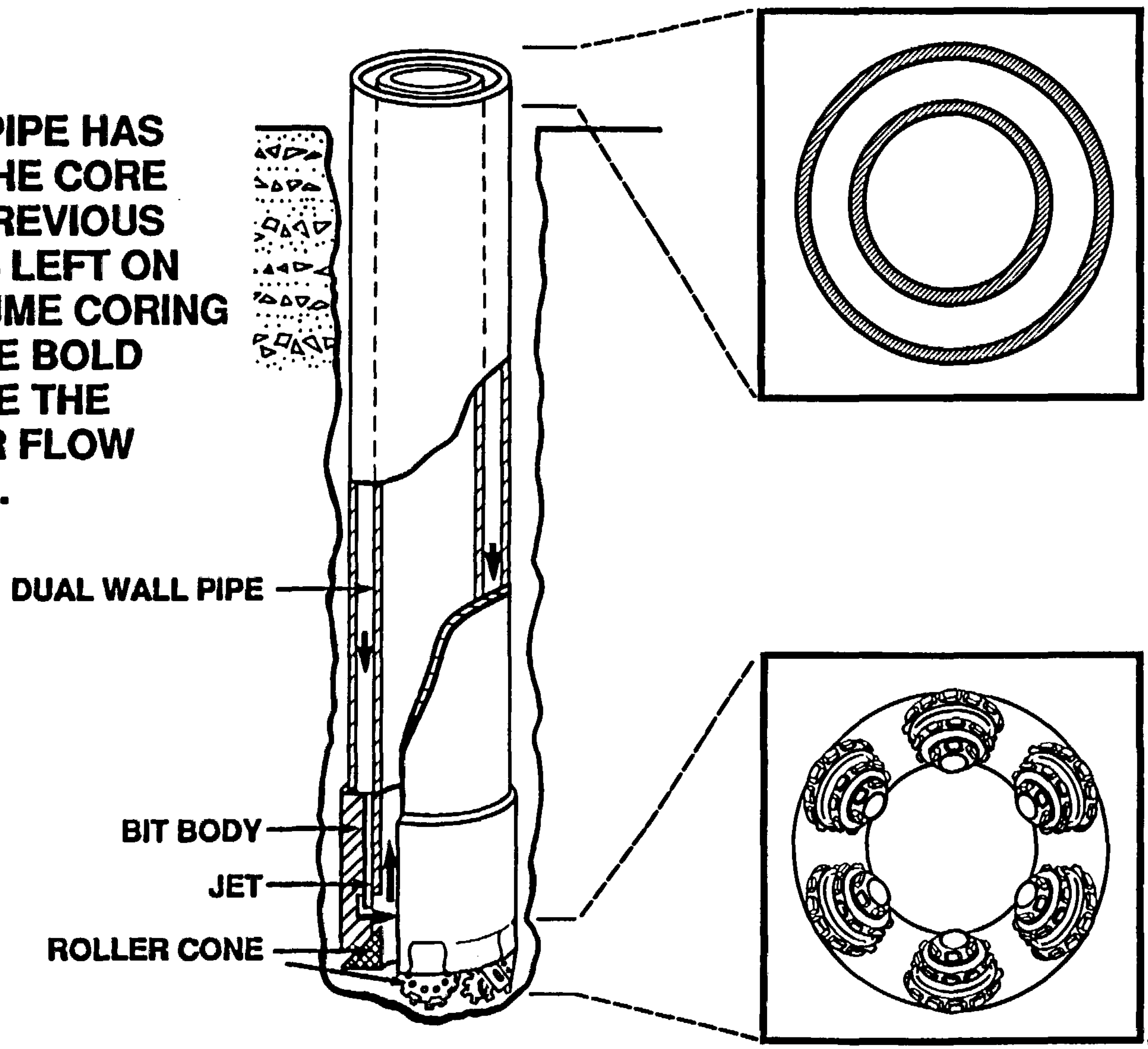
CONVENTIONAL OIL FIELD DRILLING CONFIGURATION



DRILLING MUD IS PUMPED DOWN THE DRILL PIPE, PAST THE TURNING BIT, AND RETURNED TO THE SURFACE THROUGH THE ANNULAR SPACE BETWEEN THE DRILL ROD AND THE BORE WALL

DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO. 1

THE DUAL WALL PIPE HAS REAMED DOWN THE CORE TRACK FROM A PREVIOUS CORE RUN AND IS LEFT ON BOTTOM TO RESUME CORING OPERATIONS. THE BOLD ARROWS INDICATE THE DIRECTION OF AIR FLOW DURING REAMING.



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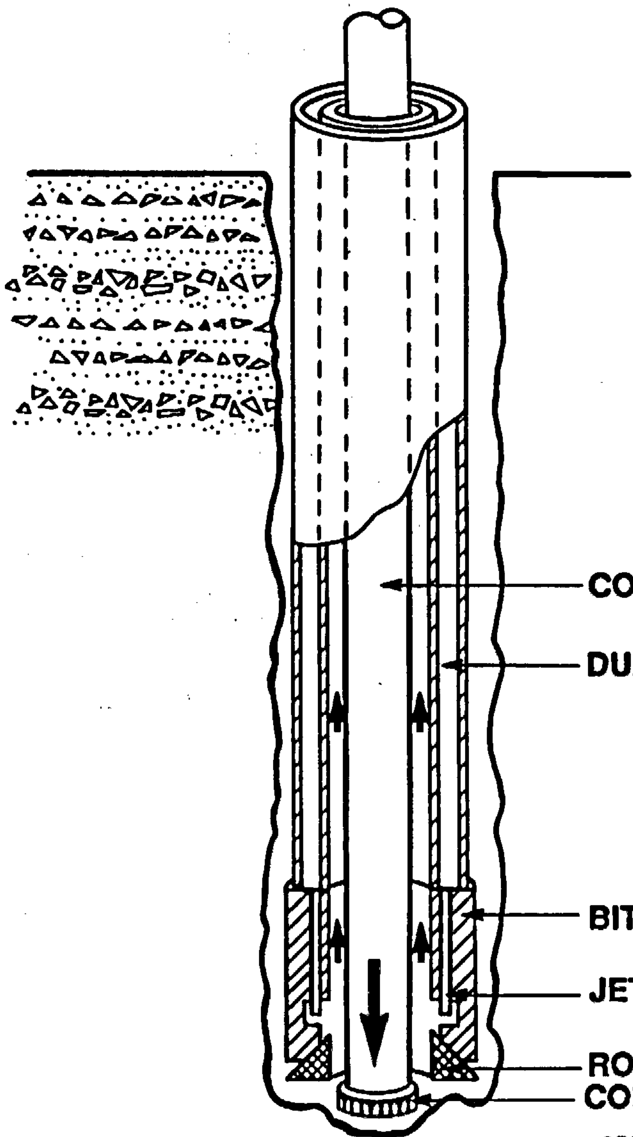
DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO. 2

THE CORE ROD IS RUN IN THE HOLE INSIDE THE DUAL WALL PIPE. THE DRILLPIPE ACTS AS A PROTECTIVE CASING TO PROTECT THE CORE ROD FROM THE FORMATION AND TO PROTECT THE FORMATION FROM THE HIGH PRESSURE AIR AND CUTTINGS PRODUCED BY THE CORING OPERATION. ARROWS INSIDE AND ADJACENT TO CORING ASSEMBLY INDICATE DIRECTION OF AIR FLOW DURING CORING OPERATIONS.



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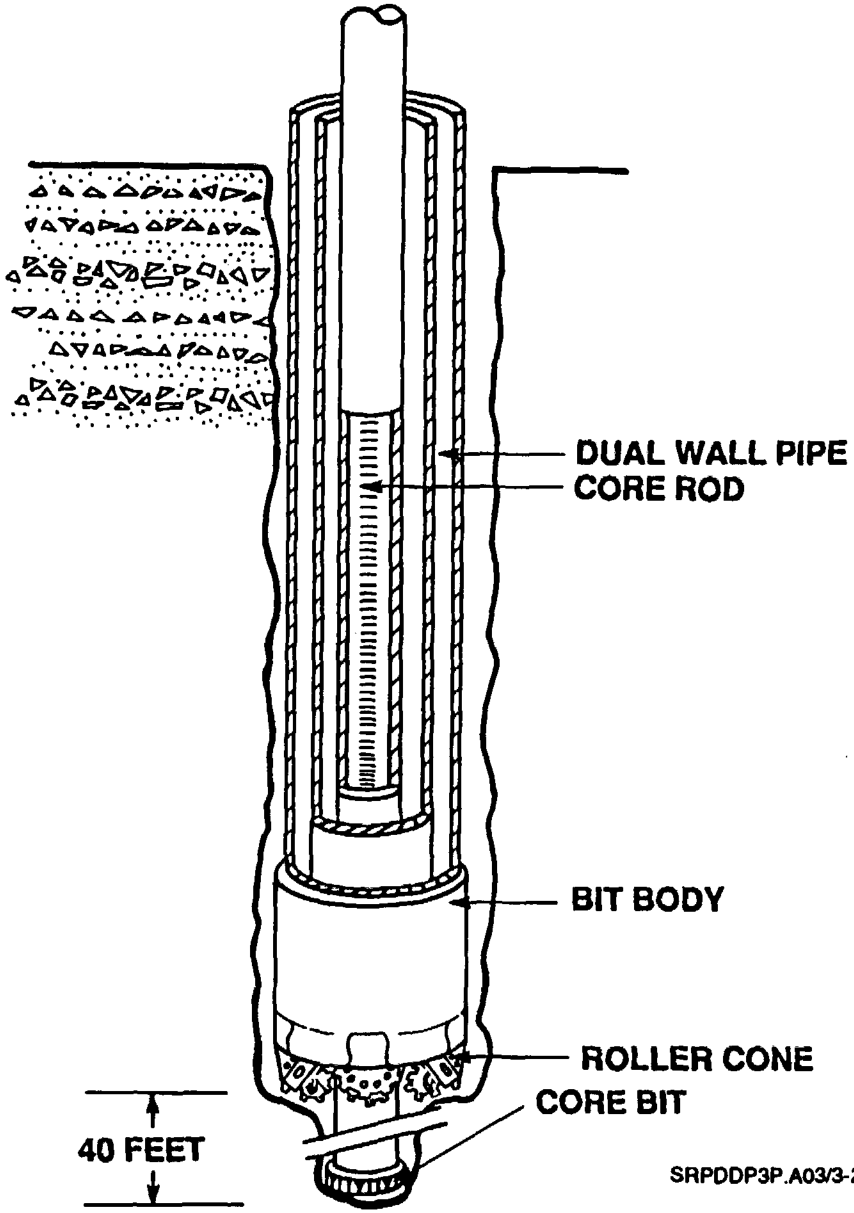
DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO. 3

CORING OPERATIONS ARE COMMENCED AND THE CORE ROD IS ADVANCED 40 FEET AHEAD OF THE DUAL WALL PIPE IN 10 FOOT INCREMENTS (10 FOOT CORES). THE CORES ARE RETRIEVED BY CONVENTIONAL WIRELINE WHILE THE CORE ROD IS LEFT IN THE HOLE FOR THE DURATION OF THE 40 FOOT CORE RUN. THE 40 FOOT LIMIT IS USED TO PREVENT THE MORE FLEXIBLE CORE ROD FROM INITIATING A DEVIATION IN THE BOREHOLE AND CAUSING THE DRILLPIPE TO FOLLOW A DEVIATED PATH RESULTING IN BINDING OF THE DUAL WALL PIPE.



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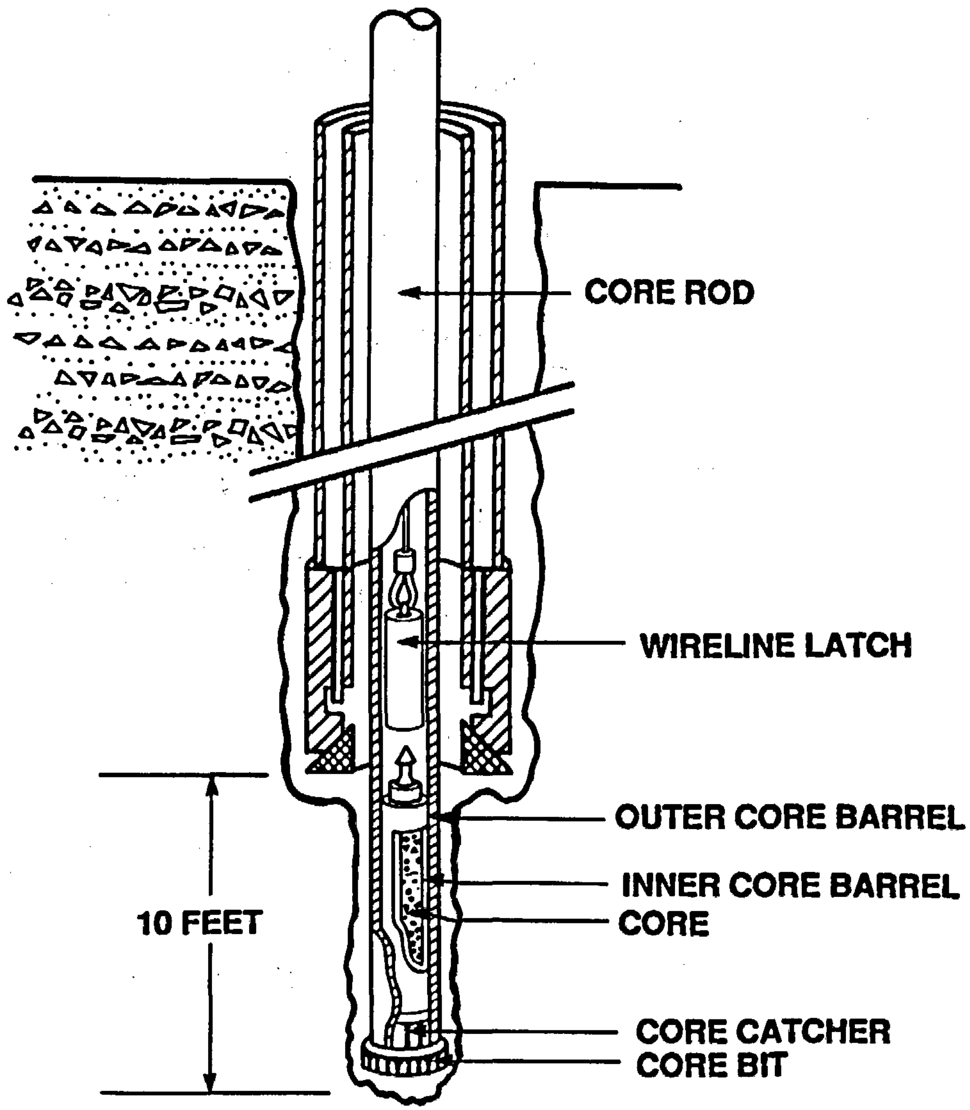
DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO.4

AT THE END OF EACH 10 FOOT CORED INTERVAL THE CORE ROD IS PICKED UP SLIGHTLY AND THE CORE IS BROKEN BY THE CORE CATCHER JUST ABOVE THE CORE BIT. THE CATCHER IS A DEVICE WHICH ALLOWS THE CORE TO ENTER THE INNER BARREL BUT PREVENTS IT FROM BACKING OUT. A WIRELINE LATCH (OVERSHOT) IS THEN RUN INSIDE THE CORE ROD AND THE TOP OF THE INNER BARREL IS "CAUGHT" WITH THE WIRELINE.



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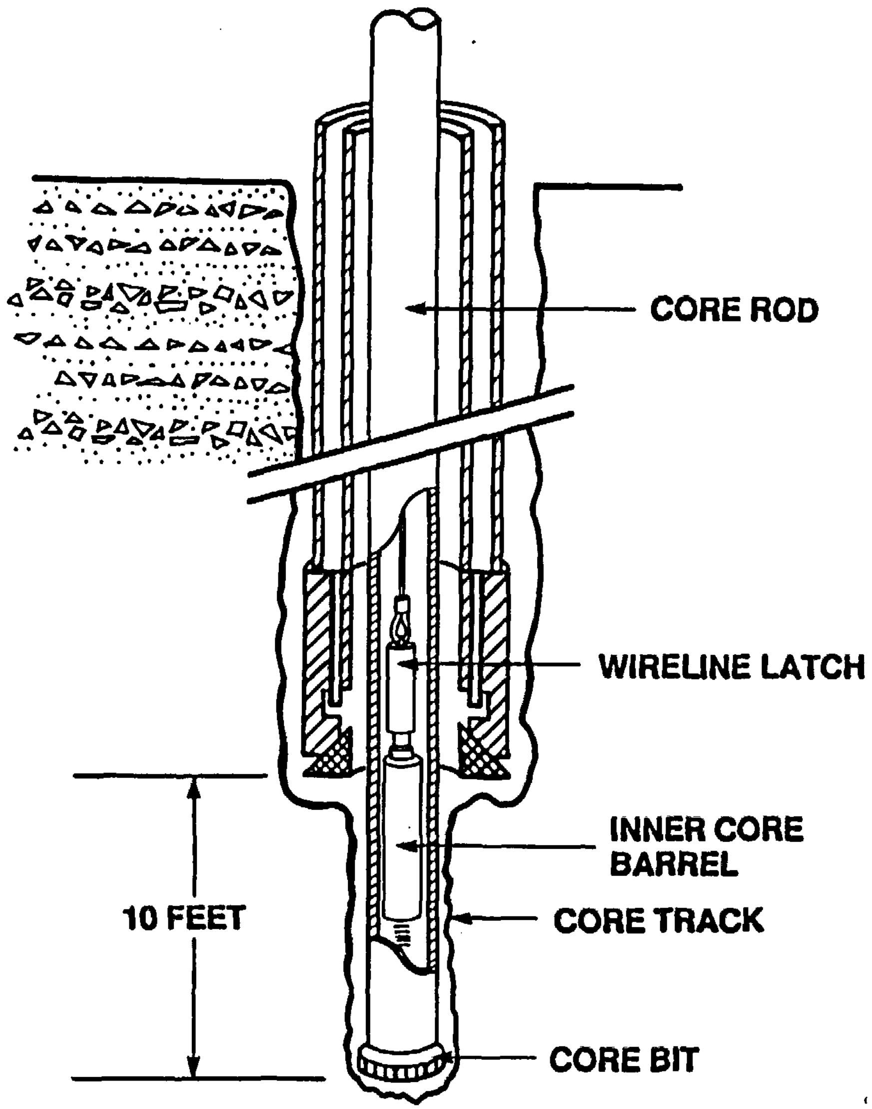
DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO. 5

AFTER THE CORE IS BROKEN, THE INNER BARREL (WITH CORE HELD IN BY THE CORE CATCHER) IS PULLED OUT OF THE HOLE BY WIRELINE. A NEW (EMPTY) INNER BARREL IS THEN RUN IN HOLE, LATCHED INTO THE OUTER BARREL, AND THE WIRELINE IS REMOVED. THIS SEQUENCE IS REPEATED EACH TIME THE CORE TRACK IS ADVANCED 10 FEET.



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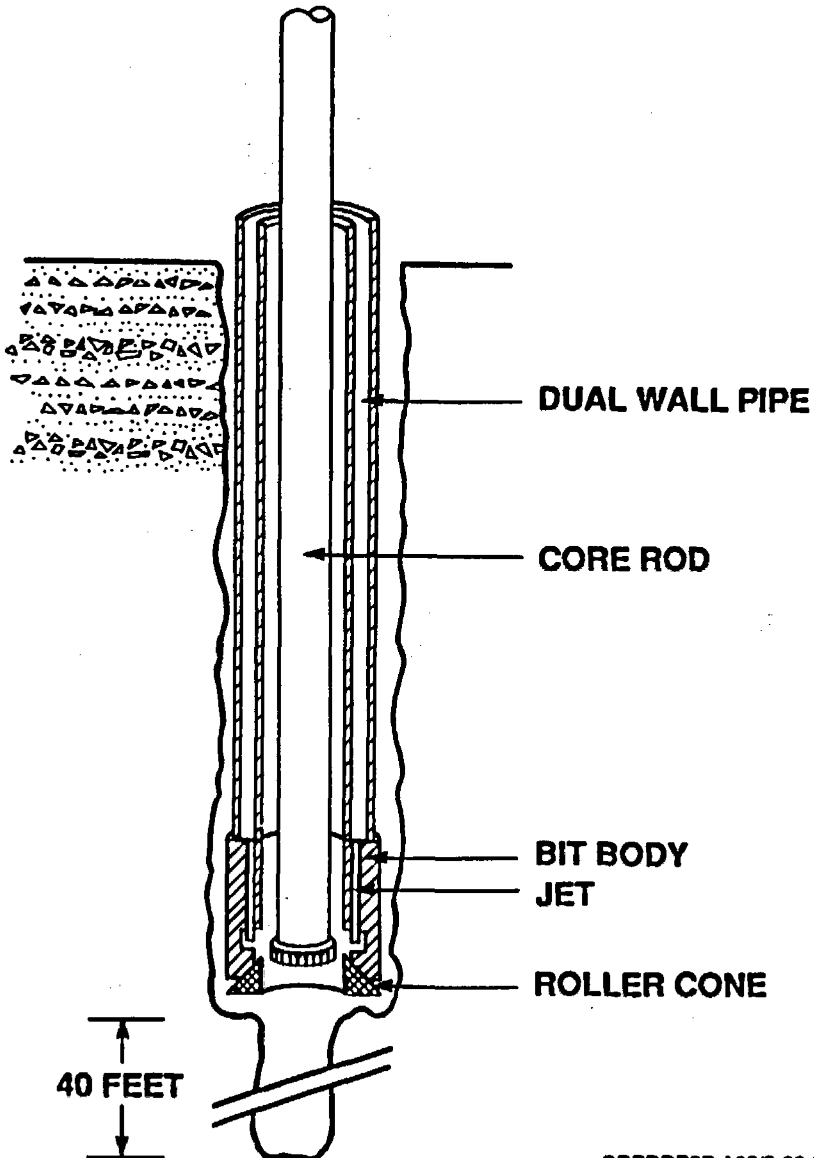
DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO. 6

THE CORING STRING IS PULLED OUT OF THE HOLE AT THE END OF THE 40 FOOT CORE RUN IN PREPARATION FOR REAMING DOWN THE CORE TRACK WITH THE DUAL WALL PIPE.



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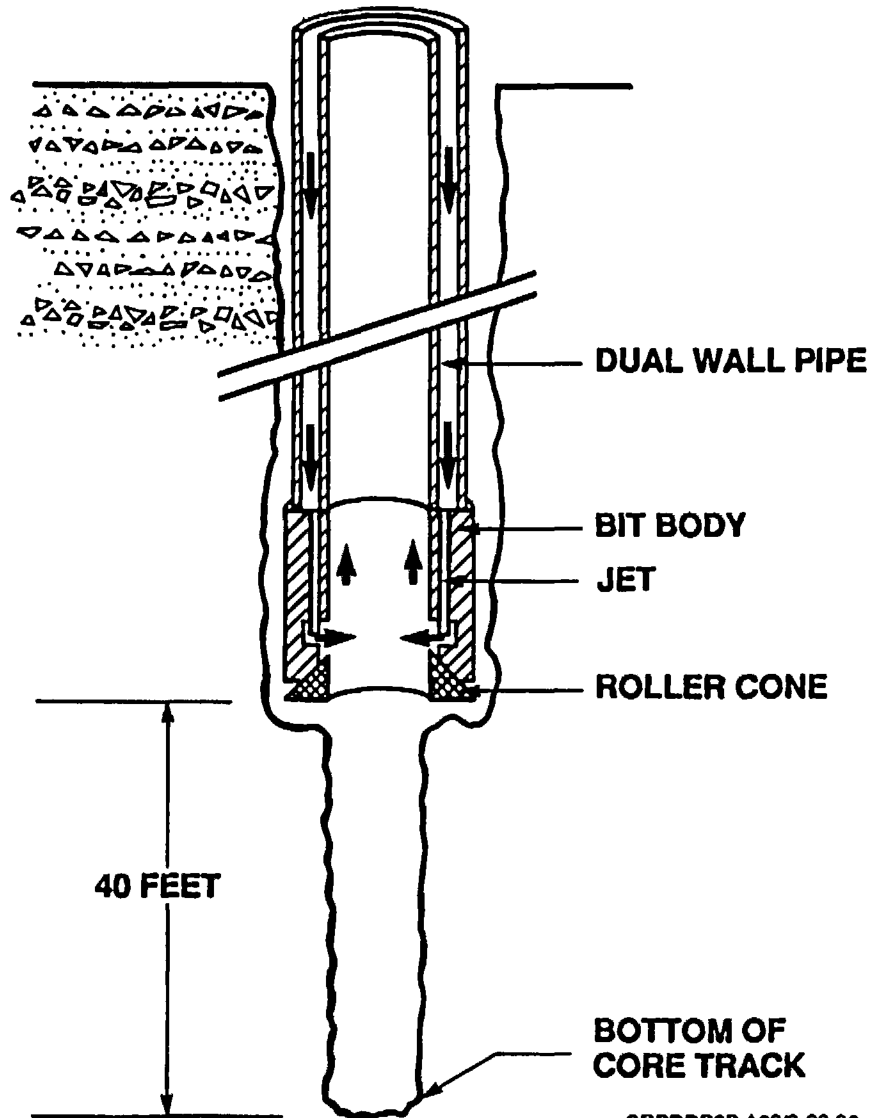
DUAL WALL DRILLING/CORING SYSTEM
DRAWING NO. 7

ONCE THE CORING ASSEMBLY IS OUT OF THE BOREHOLE, IT IS DRILLED/REAMED WITH THE DUAL WALL DRILL STRING TO THE BOTTOM OF THE CORE TRACK. THE FORMATION IS PROTECTED FROM CONTAMINATION NORMALLY ASSOCIATED WITH DRILLING BY CIRCULATING THE CUTTINGS UP THE CENTER OF THE DUAL WALL PIPE. CONTAMINATED FORMATION CAUSED BY THE CORING OPERATION IS REMOVED WHEN THE CORE TRACK IS REAMED DOWN. THE BOLD ARROWS INDICATE THE DIRECTION OF AIR FLOW DURING REAMING.



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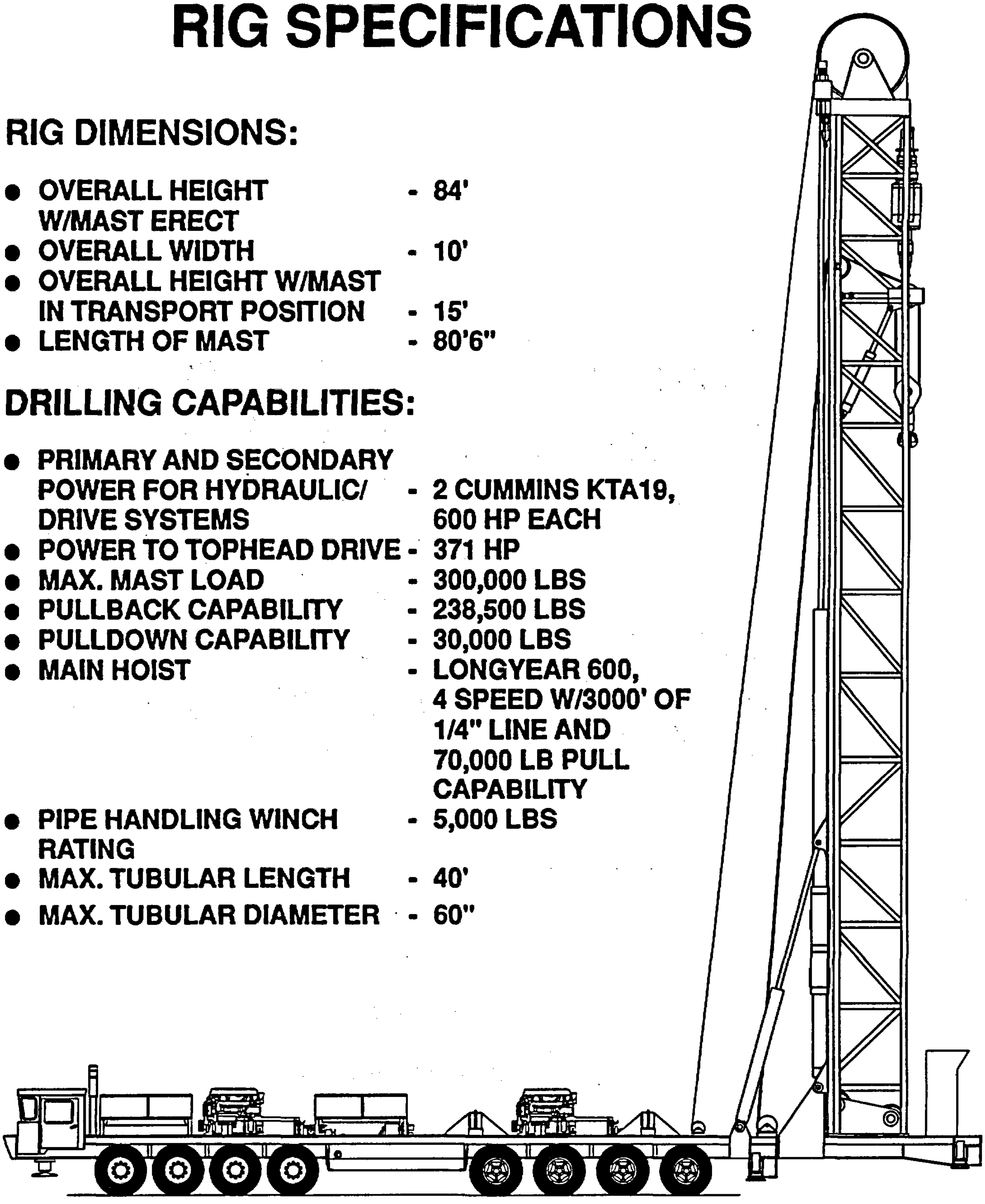
LM-300
RIG SPECIFICATIONS



RIG DIMENSIONS:

- OVERALL HEIGHT W/MAST ERECT - 84'
- OVERALL WIDTH - 10'
- OVERALL HEIGHT W/MAST IN TRANSPORT POSITION - 15'
- LENGTH OF MAST - 80'6"

DRILLING CAPABILITIES:

- PRIMARY AND SECONDARY POWER FOR HYDRAULIC/ DRIVE SYSTEMS - 2 CUMMINS KTA19, 600 HP EACH
- POWER TO TOPHEAD DRIVE - 371 HP
- MAX. MAST LOAD - 300,000 LBS
- PULLBACK CAPABILITY - 238,500 LBS
- PULLDOWN CAPABILITY - 30,000 LBS
- MAIN HOIST - LONGYEAR 600, 4 SPEED W/3000' OF 1/4" LINE AND 70,000 LB PULL CAPABILITY
- PIPE HANDLING WINCH RATING - 5,000 LBS
- MAX. TUBULAR LENGTH - 40'
- MAX. TUBULAR DIAMETER - 60"

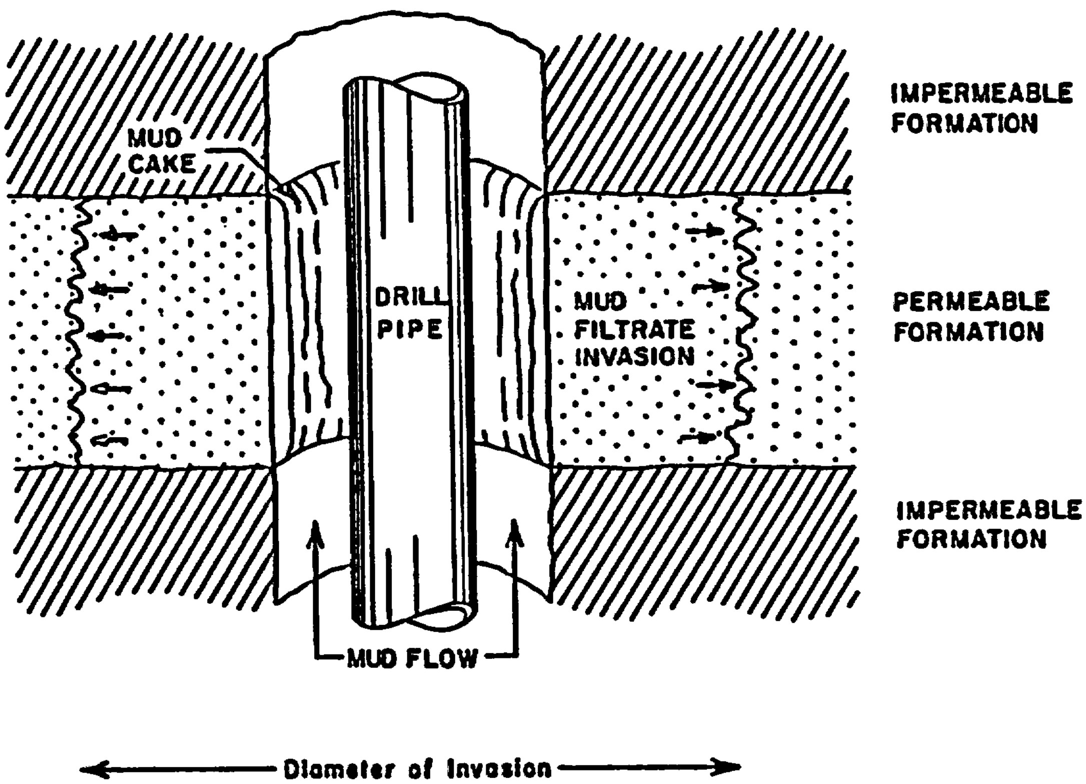


FIGURE I–C

MECHANICS OF INVASION

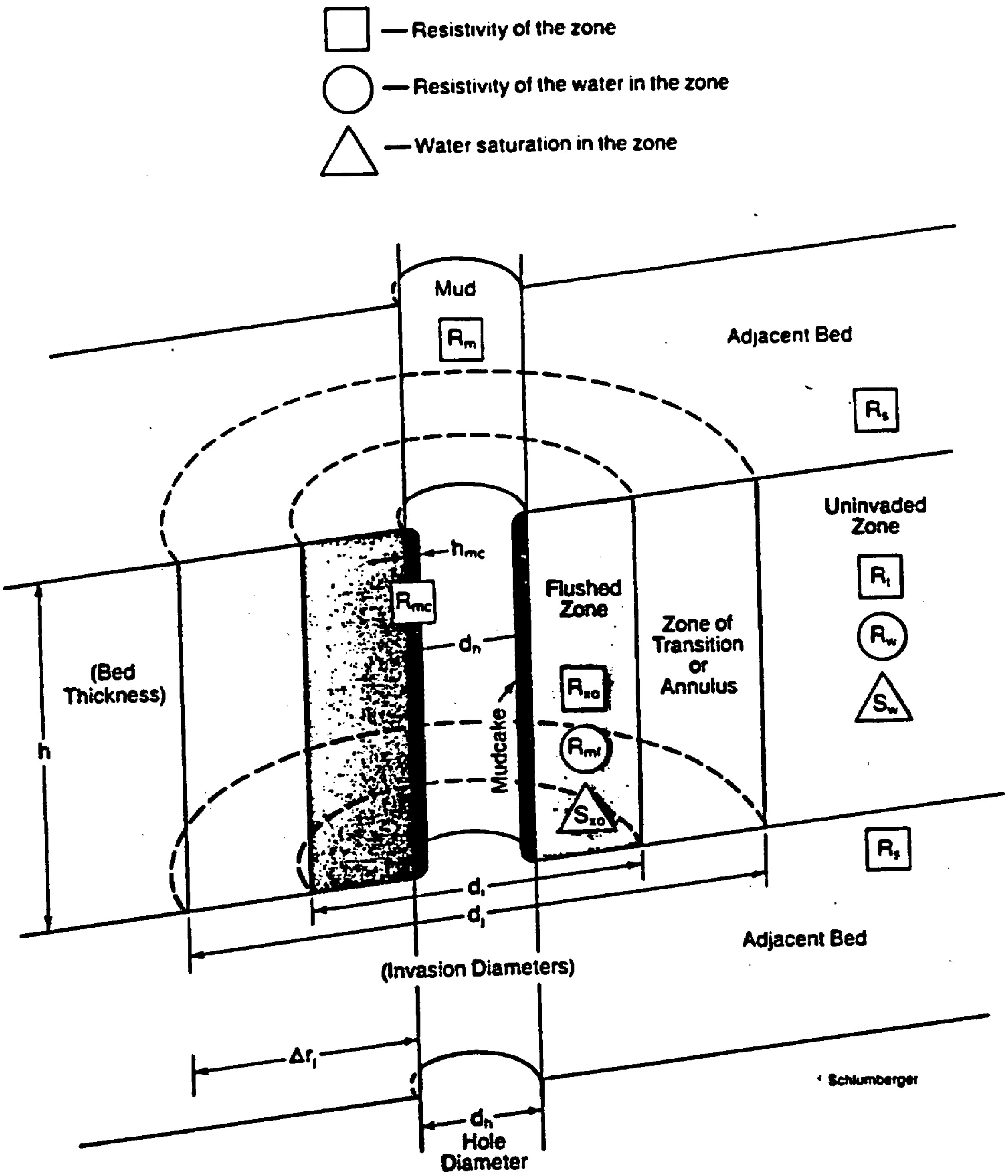


FIGURE I–D

ZONES OF INTEREST SURROUNDING A MUD–DRILLED WELLBORE
(AFTER SCHLUMBERGER)

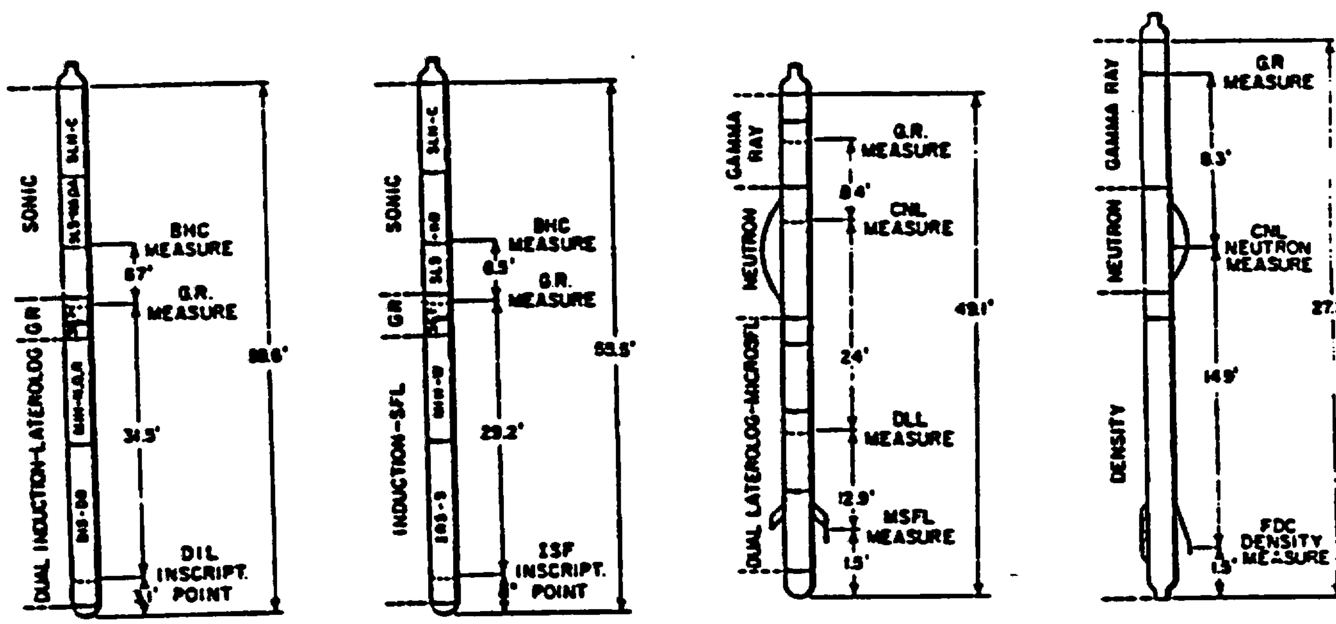


FIGURE II—A

SKETCHES OF LOGGING TOOL ASSEMBLIES
(AFTER SCHLUMBERGER)

BACK TO BASICS

WHAT IS WELL LOGGING?

A well log is a record of a mechanical, electrical, nuclear, or wave energy measurement made in a borehole. When logging measurements are needed the drill pipe must be withdrawn from the borehole. The logging measurements are made by lowering cylindrical tools into the borehole on a wireline, and pulling the tools up the hole while recording the measurements at the surface. In analog form, the log is an x-y chart, where the y axis is depth from the surface, and the x axis is the measurement or response of the rock unit at each depth.

A logging tool is made up of a sonde and a cartridge. The sonde is the portion of the tool which gives off energy or receives energy, or both. The cartridge contains the electrical circuitry to control the downhole equipment, and to transmit and receive data to and from the surface. The wireline supports the weight of the downhole tool, and provides transmission medium for data transfer.

Surface equipment is mounted in a logging truck or van from which all logging operations are controlled. The logging unit contains pulling equipment for lowering and raising the tools in the hole, and electronic equipment for controlling and recording the downhole measurements. Measurements are recorded in two forms: (1) analog, and (2) digital. The analog data may be recorded on photographic film or chart recorder, and are the primary data. The same data are captured in digital form on magnetic tape for later use in computer-aided analysis.

All logging tools and surface equipment must be properly calibrated for the work. Service companies have calibration procedures for all tools, most of which are based on standards established by the American Petroleum Institute (API). Each tool must be calibrated at the surface before placing it in the hole to make measurements, and must pass certain calibrations after the measurements are complete. Some tools also have downhole calibration checks.

After reaching total depth (TD), or some other location of interest in the borehole, measurements are made while pulling the tool upward over several hundred feet of the borehole. This is called the repeat run, and is used to determine the repeatability of the measurements when compared to the main logging pass which follows immediately. After the repeat run is complete, the tool is lowered to TD, and a main logging pass is commenced. During the early portion of these measurements, the responses are compared to those of the repeat run to determine that no instrument drift has occurred.

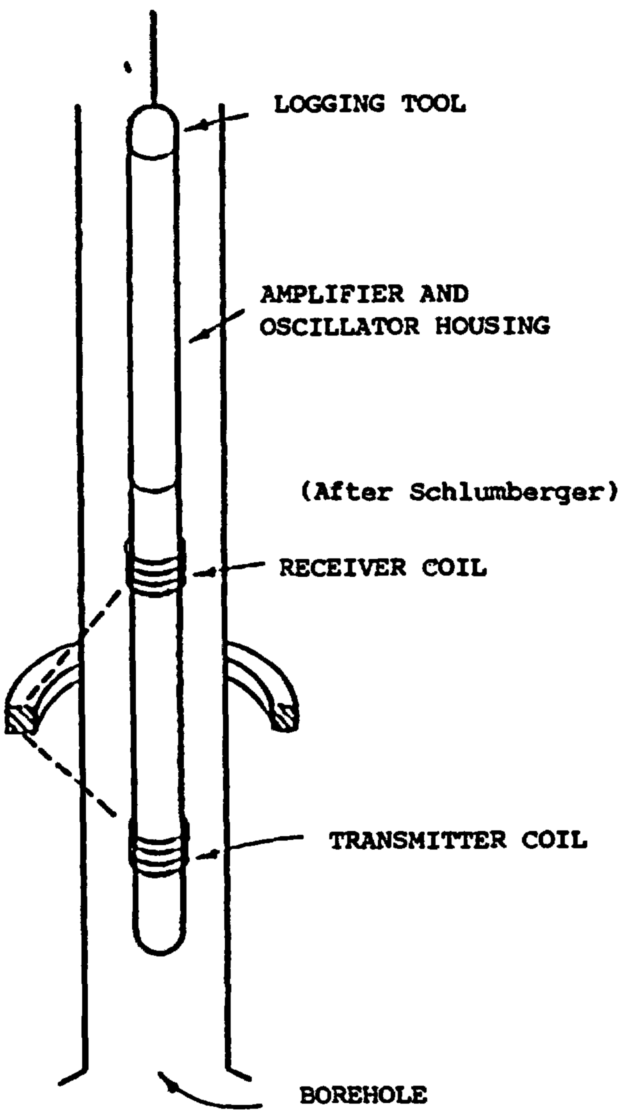
In addition to the actual measurements, the well log record contains information about the logging process which supports use and interpretation of the data. The well name, location, date, surface measurements on the mud system, drill bit size, casing information, and logging equipment data are standard items found on the log heading. Any pertinent information regarding the logging job may be recorded in the remarks section. Results of all field calibration tests and repeats are attached to the bottom of the well log record.

"bud's logging lines" is published monthly by Loren E. "bud" Thompson, Inc.
1858 South Wadsworth, Suite 101, Lakewood, Colorado 80226 303/798-0200

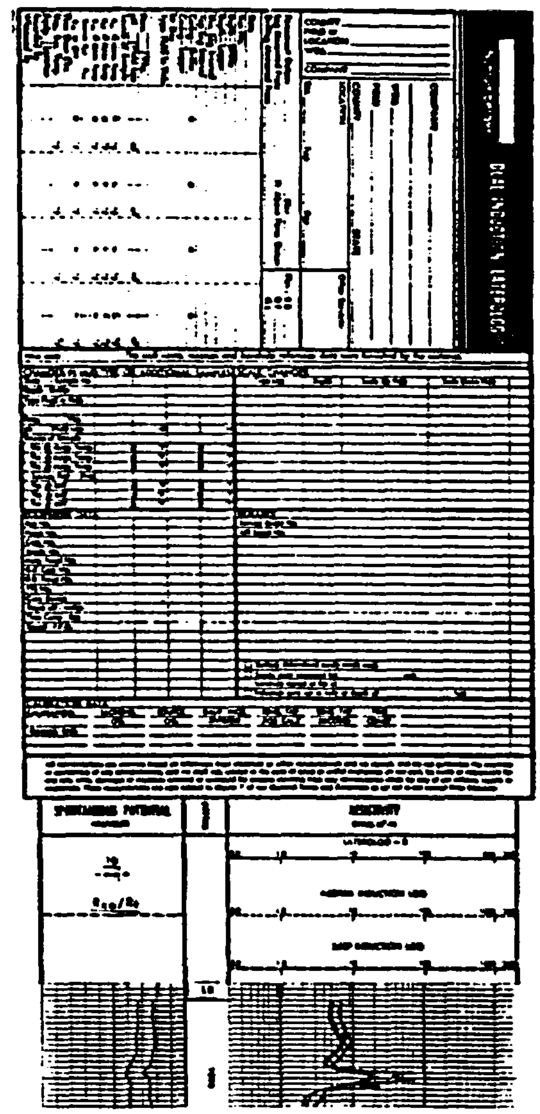
Standard depth (y coordinate) scales used in the U.S. are 5 inches per 100 ft., and half scale 2 inches per 100 ft. International logs may be presented in metric scales of 6 inches per 100 ft. The log response or measurement recorded on the x coordinate is scaled in various units depending upon the type of measurement being made. In analog form, the data are recorded in tracks across the film or paper. A two and one half inch wide track on the left side is called track one, and two similar tracks appear on the right side of the log. Between track one and track two is a narrow open space called the depth track where the depth is recorded.

The quality of the data is paramount to accurate analysis of logs. Since open hole tools cannot make measurements through iron casing, it is imperative that adequate quality control be exercised during the original logging process, while the hole is open and uncassed.

"YOU CANNOT RECALL A LOG FOR REPAIR"



(After Schlumberger)



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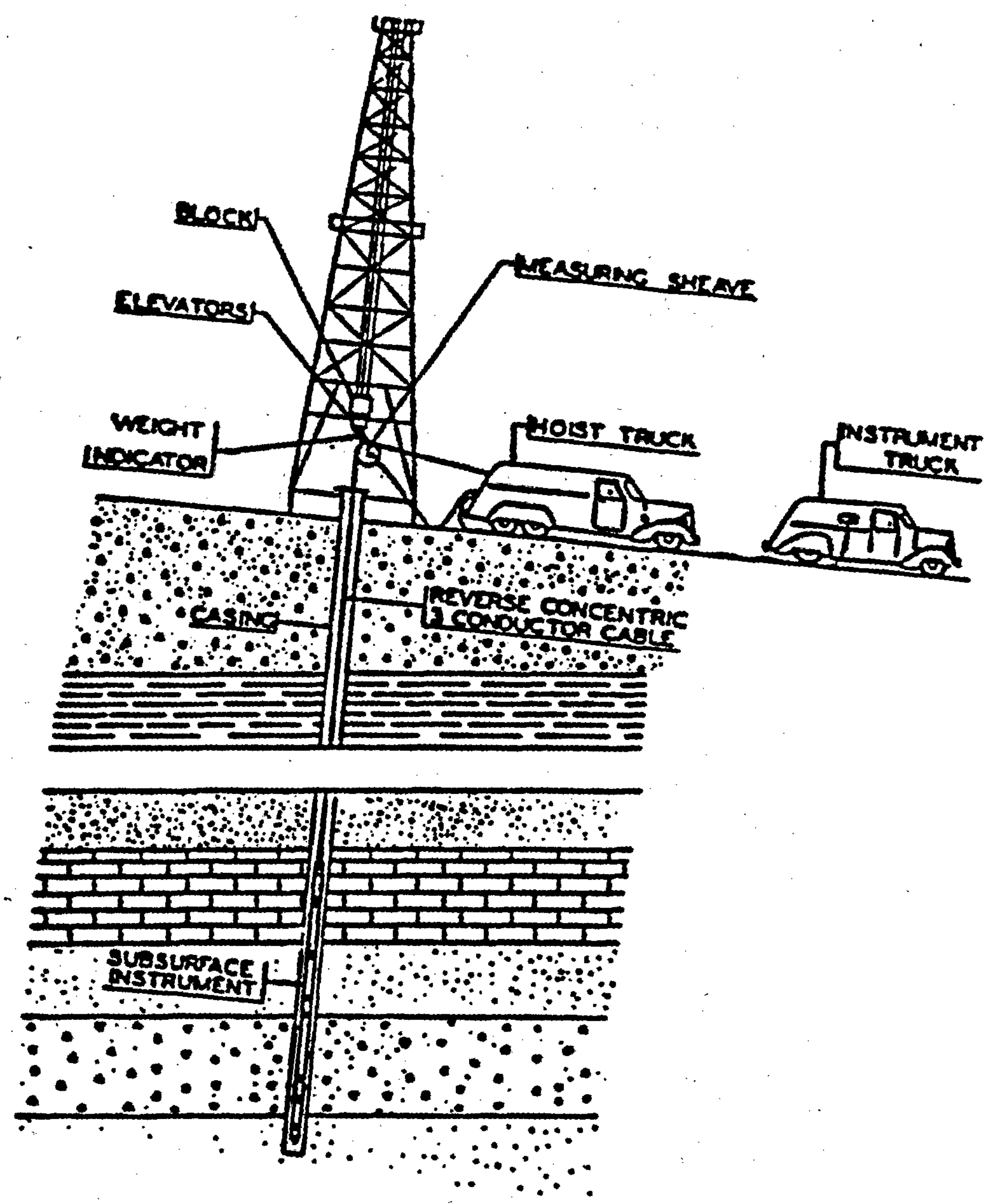

FIGURE II—B

LOGGING OPERATION
(circa 1945)

Schlumberger

SIMULTANEOUS
DUAL LATEROLOG
MICRO-SFL

COMPANY TESTCO

WELL TEST #1

FIELD TEST

COUNTY TEST STATE TEST

COUNTY / FIELD / LOCATION / WELL / COMPANY

LOCATION: NW/SW

API SERIAL NO	SEC	TWP	RANGE
	30	5N	8E.

Other Services:
BHC, WF
LDT/CNL..
HDT, [illegible]
FIL

Permanent Datum: GL ; Elev.: 7240est
Log Measured From KB 15 Ft. Above Perm. Datum
Drilling Measured From KB

Elev.: K.B. 7255
D.F.
G.L. 7240

Date	5/21/83			
Run No.	TWO			
Depth—Driller	7522			
Depth—Logger (Schl.)	7389			
Btm. Log Interval	7364			
Top Log Interval	5944			
Casing—Driller	7" @ 5952	@	@	@
Casing—Logger	59			
Bit Size	6 1/8			
Type Fluid in Hole	SALT KCl			
Dens. | Visc.	9.1 | 47	|	|	|
pH | Fluid Loss	7.4 | 14.4 ml	| ml	| ml	| ml
Source of Sample	FLOW LINE			
Rm @ Meas. Temp.	0.135 @ 59 °F	@ °F	@ °F	@ °F
Rmf @ Meas. Temp.	0.110 @ 59 °F	@ °F	@ °F	@ °F
Rmc @ Meas. Temp.	0.120 @ 59 °F	@ °F	@ °F	@ °F
Source: Rmf | Rmc	M | M	|	|	|
Rm @ BHT	0.07 @ 130 °F	@ °F	@ °F	@ °F
TIME Circulation Stopped	5/20 @ 2200			
TIME Logger on Bottom	5/2 @ 0400			
Max. Rec. Temp.	130 °F	°F	°F	°F
Equip. | Location	8155 | EVSTN	|	|	|
Recorded By	BERLIN			
Witnessed By Mr.	THOMPSON			

FIGURE II—C

EXAMPLE LOG HEADING
(AFTER SCHLUMBERGER)

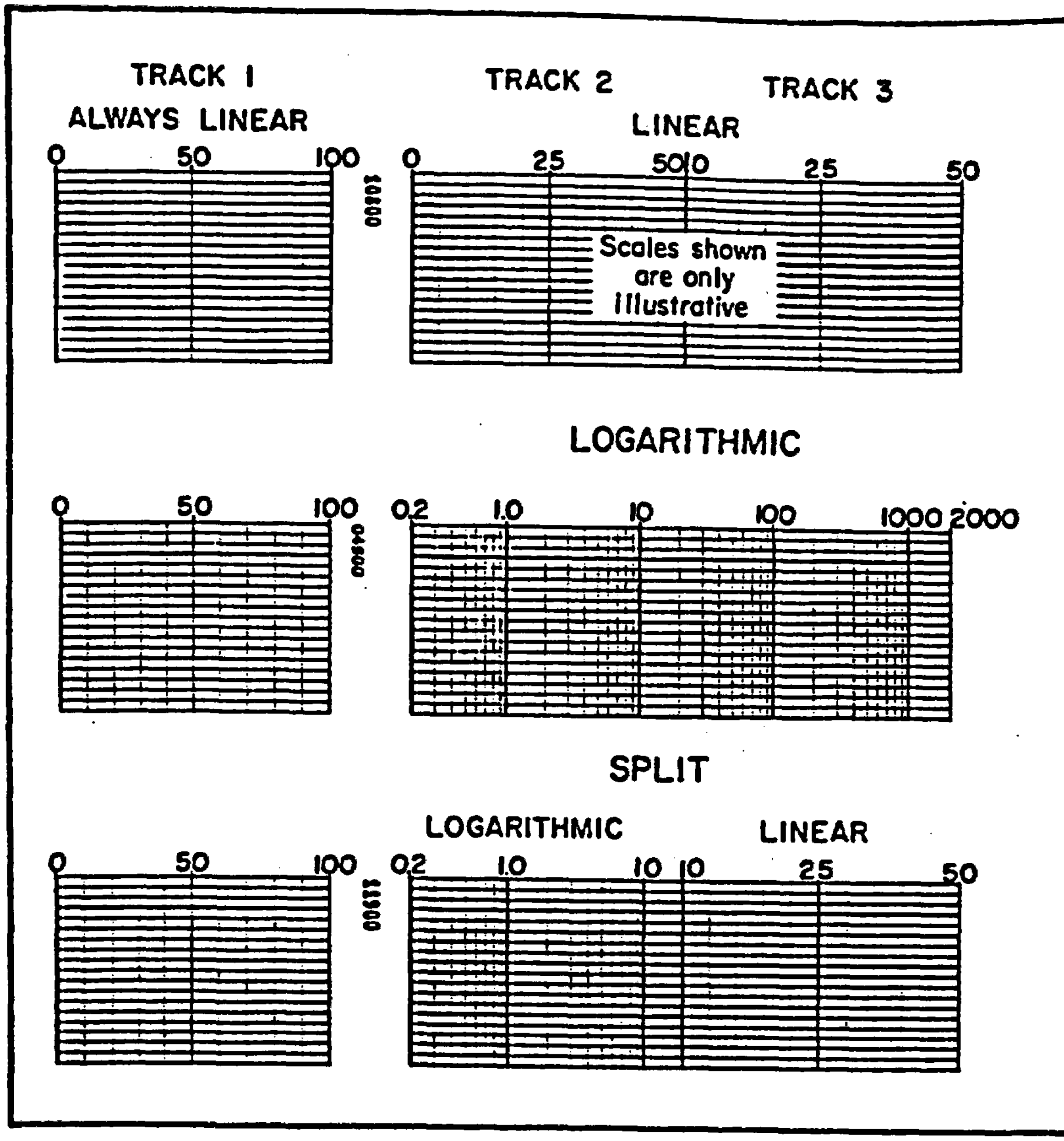

FIGURE II–D

EXAMPLE LOG SCALES

TYPES OF MEASUREMENTS

MECHANICAL MEASUREMENTS

Depth (From the Wireline)

Caliper

MEASUREMENTS OF NATURAL OCCURRING ENERGY

Spontaneous Potential
aka SP

Gamma Ray
aka GR

Spectral Gamma Ray
aka SGR
aka Natural Spectroscopy Logging

Borehole Gravity Meter
aka Borehole Gravimeter
aka BHGM

BACK TO BASICS

MECHANICAL MEASUREMENTS

Two types of mechanical measurements are made during wireline logging work; (1) depth from the surface and (2) diameter of the borehole (caliper).

Depth measurements are made based on the length of the wireline deployed in the borehole at any time. Controls are exercised that provide accurate measurements of depth to any location in the well. As greater amounts of wireline are deployed, and as the weight on the line increases, the line tends to stretch. Several tens of feet of stretch can occur in only a few thousand feet of depth. Check points are established every hundred feet or so in order to compensate for cable stretch. Depth measurements provide spatial data for mapping significant response changes, as well as thickness determinations for volumetric evaluation.

The borehole diameter is measured by a set of spring-loaded or hydraulic arms which continuously conform to the shape of the borewall as the tool is being pulled upward. As the arms move in and out, an electrical signal monitors the distance between the arms. Caliper measurements are very important to the correction of some logging measurements for borehole size. Caliper information is normally recorded in track one. Scales vary, but 6 - 16 inches is the most widely used.

For detailed borehole size and shape, a three or four-arm caliper tool may be employed, such as that used in conjunction with the dipmeter.

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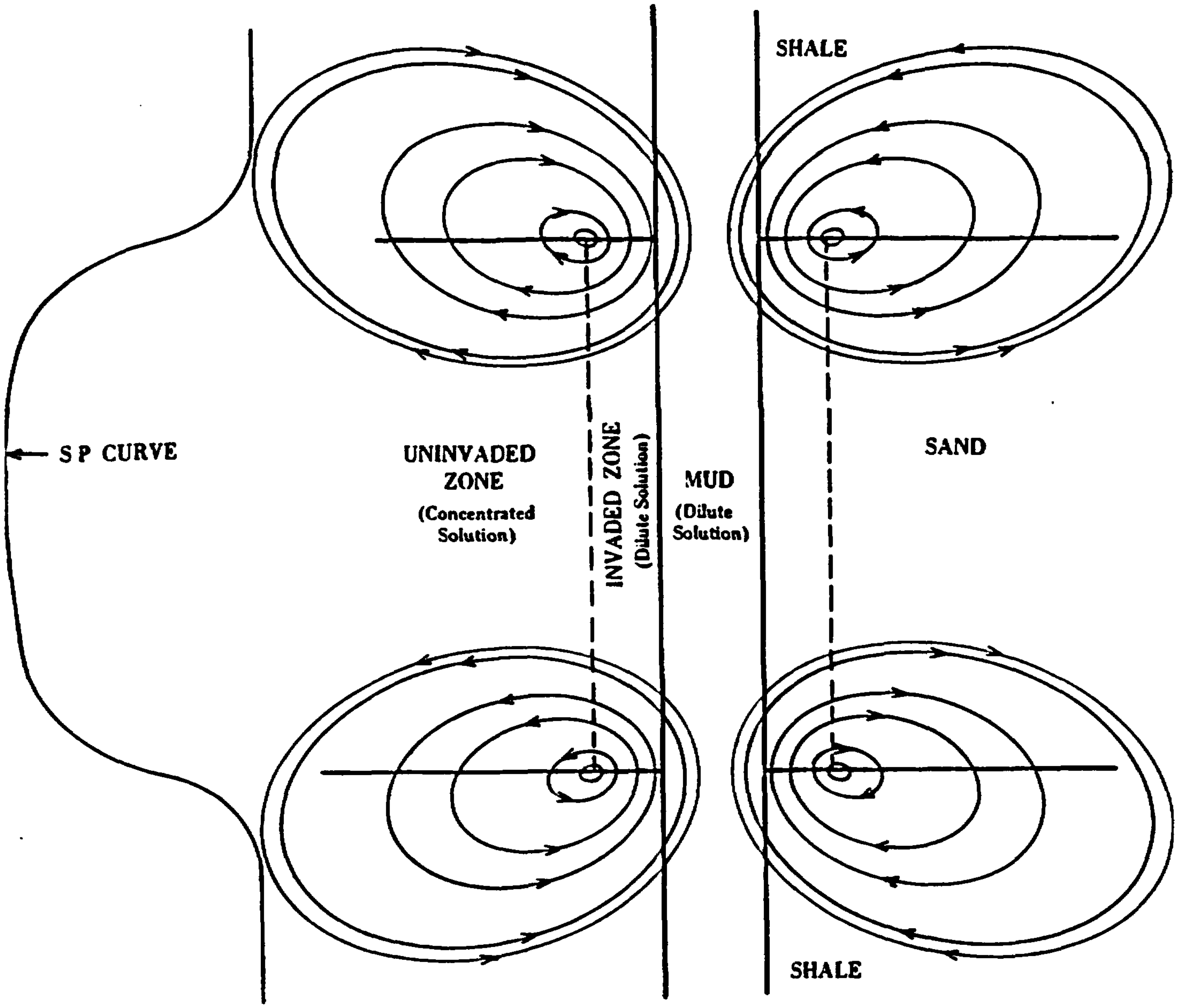

FIGURE III–D

SP CURRENTS IN A LIQUID–FILLED BOREHOLE

(AFTER DRESSER)

BACK TO BASICS

SPONTANEOUS POTENTIAL (SP)

The spontaneous potential (SP) log measures a naturally occurring electromotive force (emf or voltage) that occurs between the mud column in the borehole and the porous and nonporous formations with which it is in contact. At the boundaries between the mud column and such formations, eddy currents exist which can be measured. In general, the amount of SP voltage is dependent on (1) the relative resistivities of the mud and the formation water, and (2) the permeability of the rock unit. The greater the resistivity difference and the higher the permeability, the greater the SP voltage.

Reservoir rock units tend to be more permeable than the surrounding shales, and usually exhibit a larger value of SP. Interpretation is based on the value of the static SP (SSP) in a reservoir unit compared to the value in the surrounding shales, or the SP shale base line.

SP logs are recorded in track one, and are scaled in millivolts (mv), usually 10 to 20 mv per chart division. The SP log is used for (1) discriminating between reservoir and nonreservoir units, (2) estimating the resistivity of the formation water in reservoirs, and (3) estimating the degree of shaliness of the reservoirs.

The SP was the first log run in boreholes in the petroleum industry. The natural battery-like SP voltage developed is very small, and may be interfered with easily. The minute voltage results from the combination of several electromotive forces present in the rock - borehole system. The major contributors are shale potential (membrane potential), and liquid-junction potential.

The shale potential originates at the common boundary between the shale, the invaded reservoir rock, and mud column. The liquid-junction potential stems from the contact between the invaded and uninvaded portion of the reservoir. Together, they form the electrochemical potential which results in the SP voltage. Uses for the SP log include:

- Detection of permeable beds (reservoirs vs. nonreservoirs)
- Correlation of like units from well to well
- Degree of shaliness
- Evaluation of formation water resistivity
- Gross sand counting in a thick section
- Determination of environment of deposition (SP shapes)

The following may affect the SP measurement:

- Mud filtrate resistivity
- Bed thickness
- Volume of shale
- High gas saturation in reservoir
- Depth of invasion
- Bore hole size
- Shale baseline shift
- Highly resistive beds
- Water salinity
- Noise external to the system

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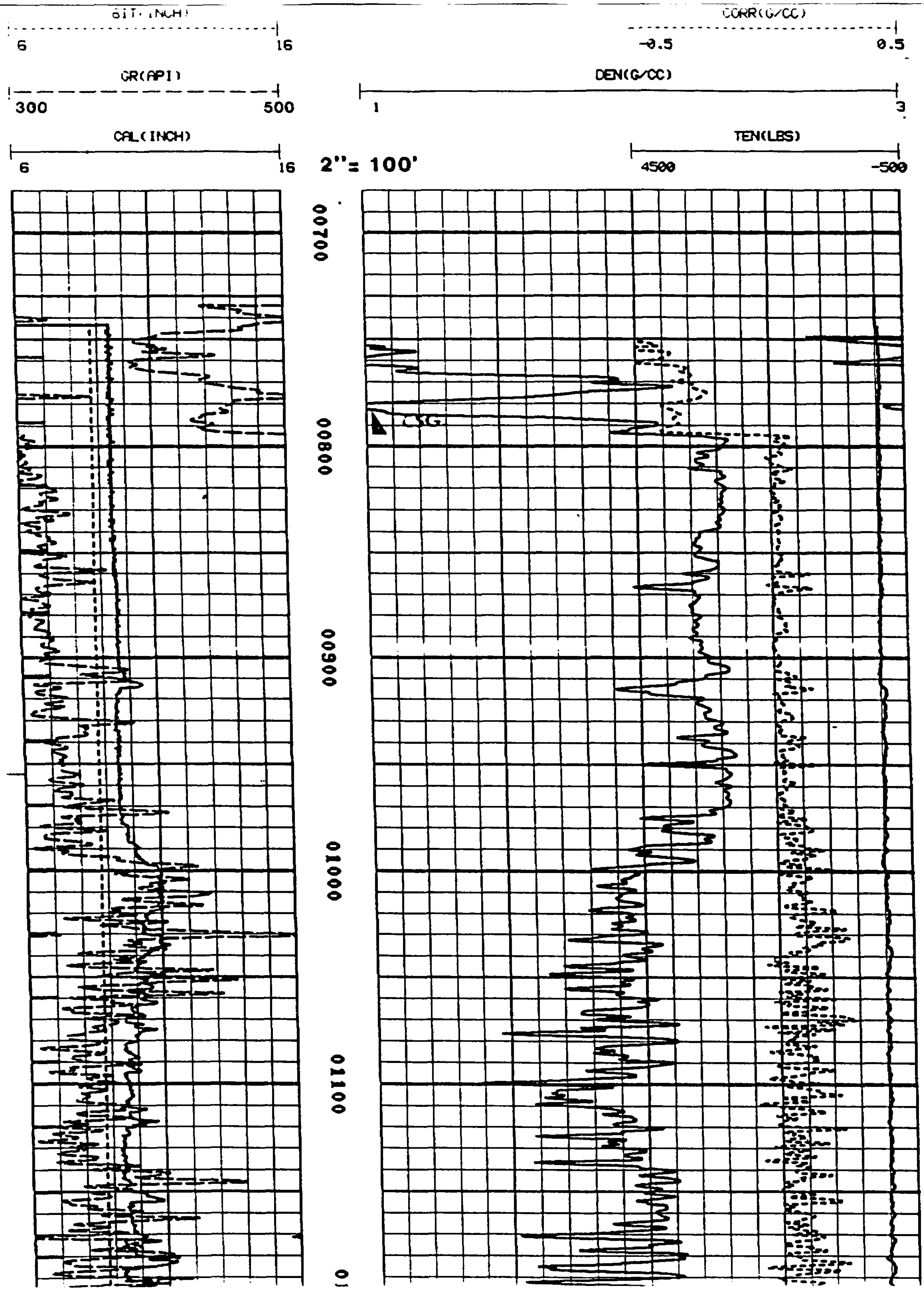
BIT(INCH)
6
16
GR(API)
300
500
CAL(INCH)
6
16
2"= 100'
CORR(G/CC)
-0.5
0.5
DEN(G/CC)
1
3
TEN(LBS)
4500
-500
00700
00800
00900
01000
01100
CSG

BACK TO BASICS

GAMMA RAY MEASUREMENTS

Two measurements of natural occurring earth energy are routinely made in boreholes: (1) gamma ray and (2) spontaneous potential.

The gamma ray log measures the natural occurring radioactivity within the rock units. Most of this radioactivity is produced through the decay of potassium, and some to the decay of thorium and of uranium. The tool contains a detector which is sensitive to all gamma rays, and gives off an electrical signal which is proportional to the level of radioactivity. Gamma ray logs are calibrated in standard API units, and normally scaled from 0-100, 0-150, or 0-200 API units in track one. The greater the API value, the more radioactive the formation. Shales tend to be very radioactive and the sandstone and carbonate reservoirs less radioactive, due to containing less shale material. The gamma ray log is used to (1) differentiate between reservoir and nonreservoir units, and (2) estimate the amount of shale in the reservoirs.

Radioactive isotopes are unstable elemental forms which emit various kinds of radiation as the element decays toward a stable state. Alpha, beta, and gamma rays are emitted but gamma rays are the only energy levels that are detected in a borehole. Alpha and beta rays are slower (weaker) particles, and are readily absorbed by the rockwall and borehole materials. Gamma rays are measured in units of electron volts. The practical unit is million electron volts, or mev. The main isotopic elements found in sedimentary provinces are Uranium-Radium series, Thorium series, and Potassium 40 series.

A recent development in gamma ray logging measures the amount of gamma ray energy within specific energy levels or windows of the electromagnetic spectrum. With these natural spectroscopy tools, the relative amounts of thorium, potassium, and uranium may be determined, allowing a greater discrimination between clean radioactive reservoirs and dirty (shaly) reservoirs. The Schlumberger trade name is NGT for Natural Gamma Tool, and the Dresser tool is called the Spectralog.

Gamma rays are random emissions which vary in quantity with time. Therefore, it is necessary to use averaging techniques for counting in order to establish convenient standards for statistics. Because of these statistical variations, the number of counts per period of time (minute or second) will not be absolutely accurate. A time constant (TC) averaging technique is used for this purpose. Through an appropriate selection of time constant and logging speed, the statistical fluctuations are smoothed out for a better representation of the counts (number of events) at any depth. A time constant is used during logging which provides a practical compromise between logging speed and acceptable statistical quality. All nuclear measurements are statistical in nature, thus this averaging technique applies equally to density and neutron logging practices.

For detailed work, gamma ray logs should be corrected for borehole size, mud weight, bed thickness, and wall rock density.

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... OF NGT - DETECTOR LOCATED : 890 FT.. and ______

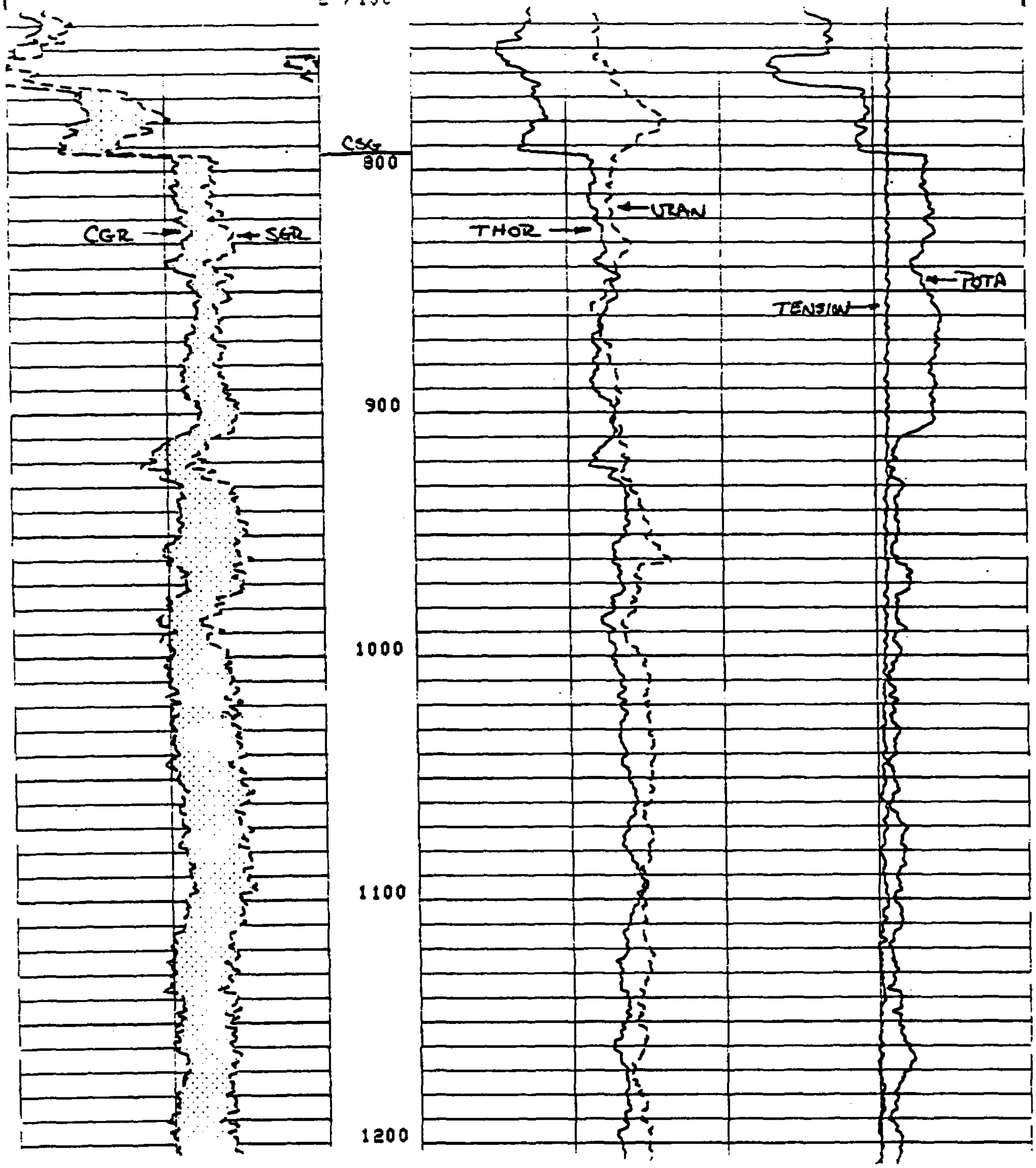
	THOR(PPM)	POTA
	0.0 — 40.000	0.0 — 10000
CGR(GAPI)	TENS(LBF)	
100.00 — 300.00	3000.0 — 0.0	
SGR(GAPI)	URAN(PPM)	
100.00 — 300.00	40.00 — 30.000	

CGR -- SGR

CP 32.4 FILE 1 18-JAN-1991 16:56

17-JAN-1991 21:13

2"/100'



ADVANCED STUFF

NATURAL SPECTROSCOPY LOGGING

The gamma ray log which we are accustomed to having in track one on most of our modern logs is the representation of the total number of natural gamma rays counted at each depth in the borehole. The log is presented in standard API units, where 100 API represents a "standard mid-continent shale'. (See page 3, April, 1983 of Logging Lines).

An advance in recording natural gamma radiation is spectral logging during which specific energy levels or "windows" are monitored, in addition to the the total gamma ray count. Most service companies monitor potassium (K^{40}), near 1.4 mev (million electron volts), the uranium series - 1.76 mev, and thorium near 2.6 mev. The sum total counts of these three radioactive isotopes or series makes most of the contribution to the total gamma ray API on gamma ray logs.

The source of radioactivity (high gamma ray reading) of typical shales is the fine-grained material from the mechanical and chemical weathering of potassium feldspars and micas. At one time we were taught the gamma ray log was a "lithology" log, which we could use to discriminate between the clean reservoirs, sands and carbonates, and the dirty shales. Over the past few years we have learned that many of the dirty or shaly streaks thus identified may really not be so shaly. In fact, many could be potential reservoir materials with significant permeability.

In addition to a three elemental counts presentation, we are provided a comparison of the total gamma counts (e.g. "gamma ray log"), and the counts due only to the potassium plus the thorium detectors. In this way, we often see a significant difference between the standard gamma ray log run with, say the density-neutron combination, and the gamma ray minus the contribution of uranium. In a zone where there is a difference of more than 15 API units, we should not classify the interval as a normal shale, even though the gamma ray log in the zone is reading as high as most of the known shales in the section. Such zones are often uranium-rich due perhaps to the movement of pore fluids through the zone over geologic time, a certain tip off of permeability which should be related to porosity.

Additional information from logs or supporting data should be investigated for complete rock typing. Where we are exploring for oil and gas accumulation, the deep resistivity log should be checked. If the Rt value is not low, as would be expected in a shale, a reservoir type rock, perhaps with hydrocarbon saturation may be indicated. A check of available "porosity logs" should further help in the rock typing exercise.

More advanced work may be done with spectral data, including identification of certain clay types by the relationship of the contributions of the three radioactive isotopes. This leads to the development of more accurate determination of the volume of shale/clay in shaly reservoirs, as well as providing new log-derived information to aid in regional environment of deposition studies. Look for full spectral log data to make an on-going and increasingly significant impact on the accuracy of formation evaluation from logs.

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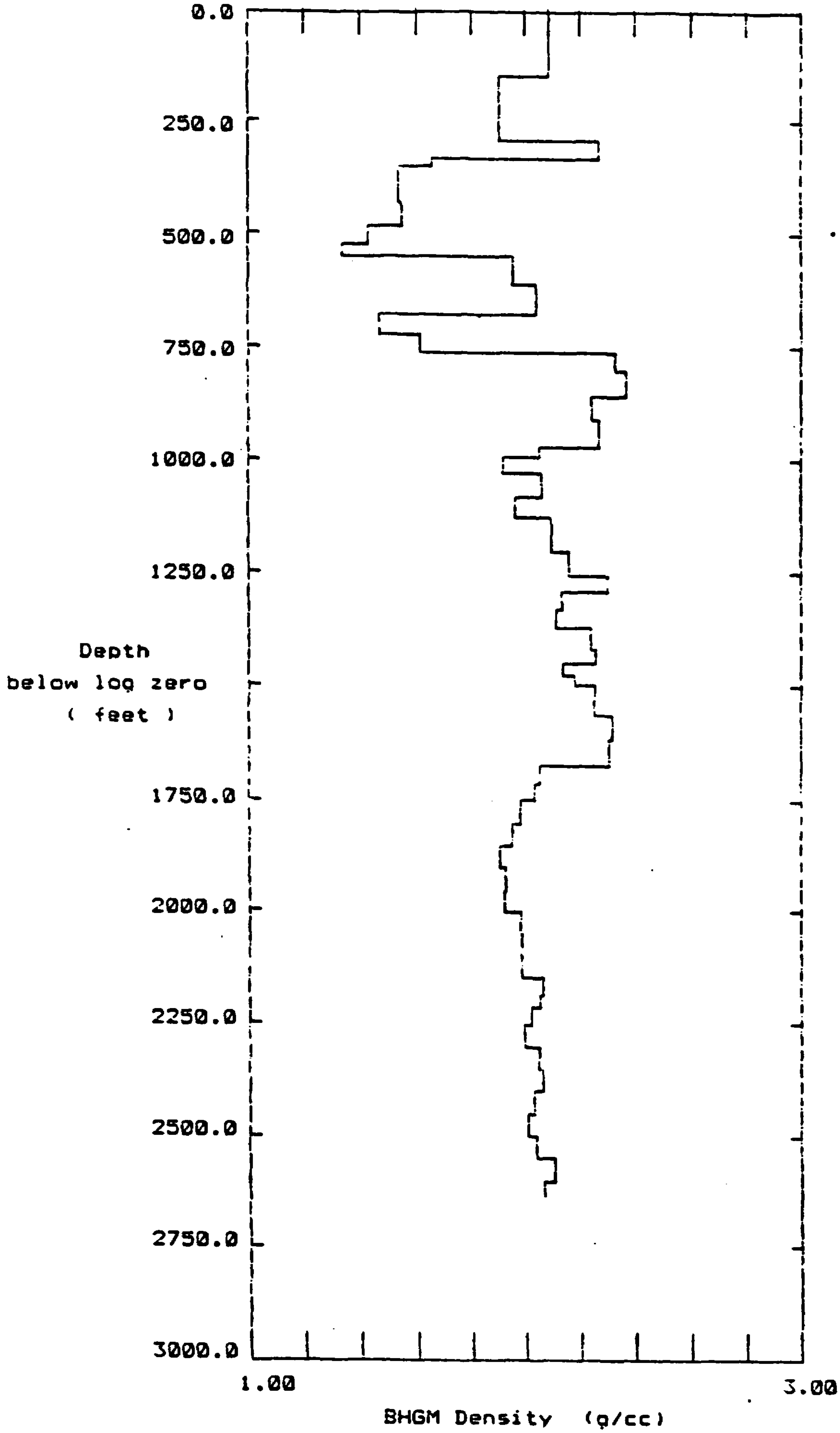
Figure 2.1.2. USW-G2 Density Log



BACK TO BASICS

BOREHOLE GRAVITY LOG

(Note: There are only a few of these instruments in captivity. When I last checked, the USGS had two, and Amoco Production Research had three or four. The only source of commercial borehole gravity services of which I am aware is EDCON in Denver, Colorado. - Ed.)

A measurement of the force of gravity is made using a small, sensitive LaCoste and Romberg Borehole Gravity Meter (BHGM). The basic instrument used and measurement made are the same as for surface gravity surveys. The spring balance equipment is thermostatically controlled, packaged in a Dewar flask, and kept at constant temperature to protect it from wellbore temperature changes. An intricate system of tri-axial drive motors keeps the down hole meter horizontal in deviated holes.

Stationary measurements are made at various depths in the borehole. Typical measurement time is from five to ten minutes for a station. With a value of gravitational attraction for each station, the vertical change in gravity, Δg over a slab thickness, Δz can be determined. The bulk density of the rock between any two measurements may then be calculated, and is virtually unaffected by well casing, washouts, and other near-wellbore considerations. Compared to conventional logging tools, the volume of investigation and subsequent depth of investigation is very large, and may generally be related to station spacing.

The meter is so sensitive that earthquakes and underground nuclear tests have been detected thousands of miles away. Under favorable conditions, rock bulk densities may be determined within 0.01 gm/cc or less over ten foot vertical intervals in the wellbore.

For most applications in petroleum exploration and development, the gravity-derived density is compared to the conventional nuclear type density log made in the open hole. Since the nuclear density log has only several inches of investigation around the wellbore, differences between the density log and BHGM density may be explained by a difference in porosity (or pore fluid composition) away from the borehole. The natural extension of this concept is the detection of fluid-filled fracture systems which do not intersect the borehole, and near-well reef complexes which were missed while drilling. Much success in the latter application has been reported in the Michigan reef plays. If a gas zone is highly invaded and logged with open hole logs prior to dissipation, a subsequent BHGM survey will detect the presence of gas in the uninvaded zone.

BHGM studies have been used for three main purposes: (1) structural mapping, (2) formation evaluation in conjunction with open hole resistivity logs, and (3) reservoir analysis, normally involving the monitoring of residual oil saturation at time intervals during production.

The meter is sensitive to shock, and is usually transported within the passenger compartment of commercial airliners on the way to the location. Because of the replacement costs of new tools, it is preferable to run the surveys in cased holes, but open-hole surveys are made under favorable hole conditions.

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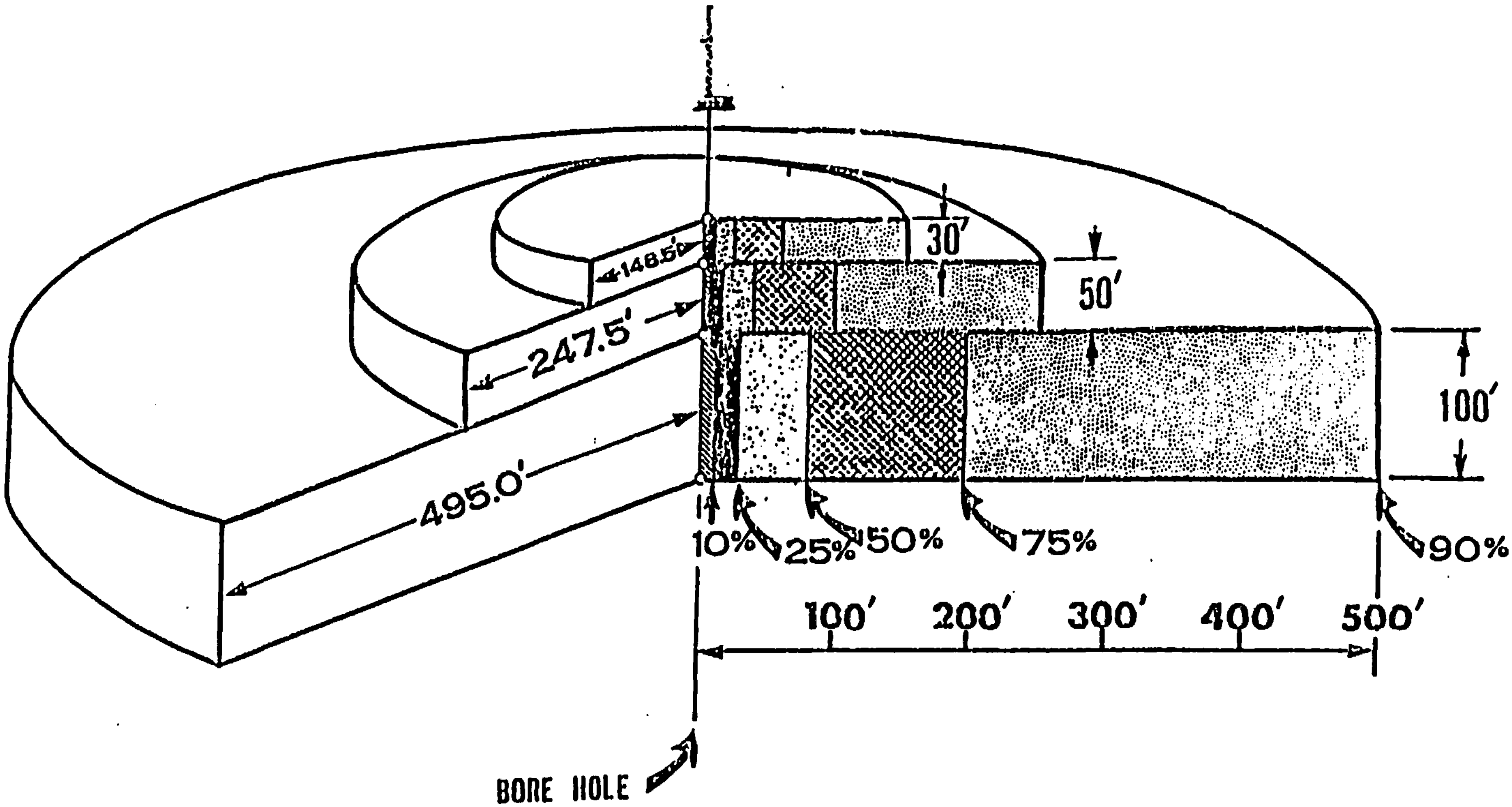
FIGURE 4. ZONES OF CUMULATIVE GRAVITY EFFECT MEASURED BY THE BOREHOLE GRAVIMETER

(FROM McCULLOH)



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TYPES OF MEASUREMENTS

LOGS WHICH INTRODUCE ENERGY INTO BORE HOLE SYSTEM

ELECTRICAL METHODS

Resistivity (Old logs)
aka Normal Array
aka Lateral Array

Laterologs
aka Dual Laterolog (DLL)
aka Guard Logs

Induction Logs
aka Dual Induction Log (DIL)

Micro-resistivity Devices
aka Normals
aka Laterals
aka Spherically Focused Log (SFL)

Special Micro-resistivity Logs
Dipmeter Log (DipLog, HDT,)
Formation Micro Scanner (FMS)

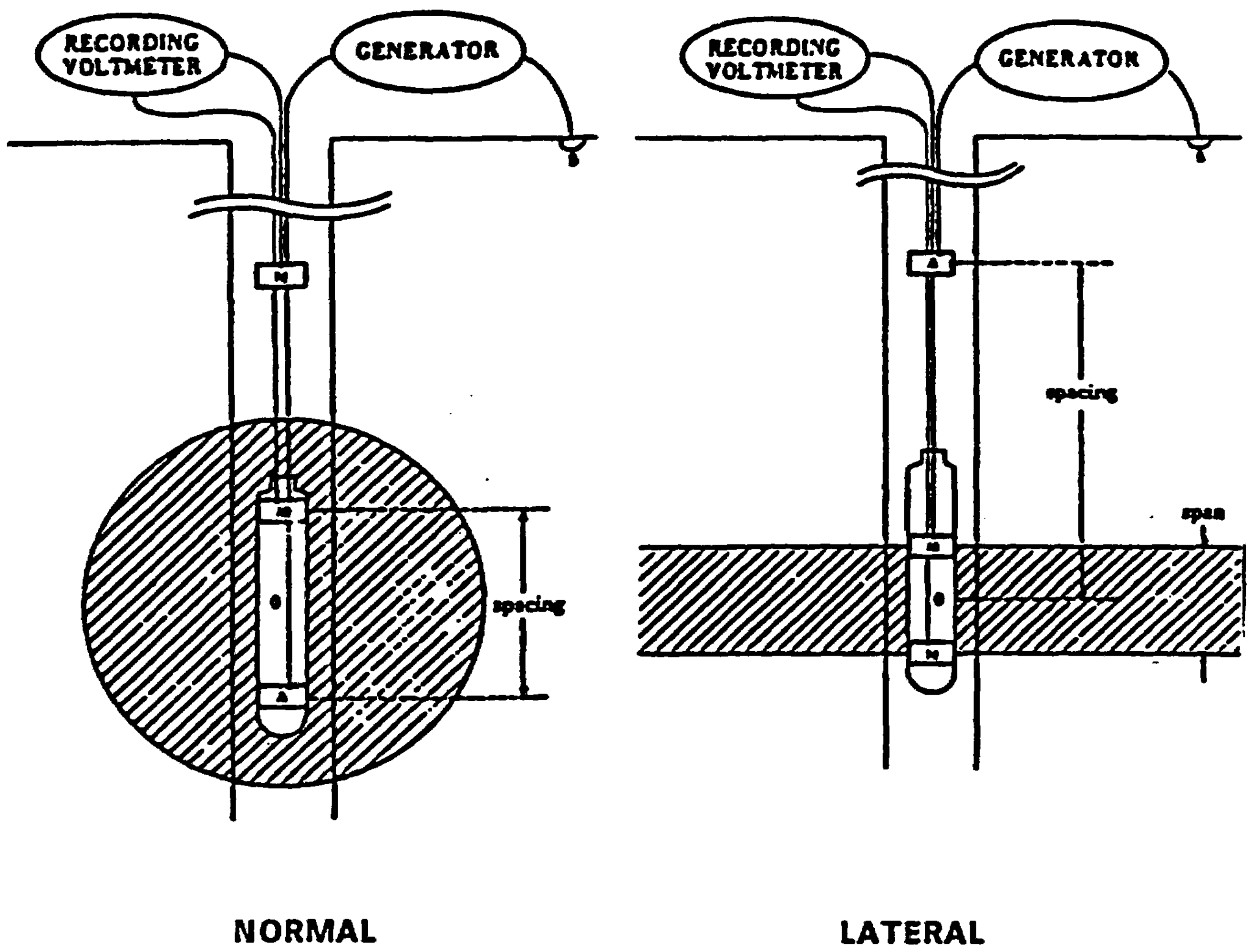

FIGURE III–E

NORMAL AND LATERAL ARRAYS

(AFTER DRESSER)

BACK TO BASICS

RESISTIVITY MEASUREMENTS

Resistivity logs introduce an electric current into the formation from source electrodes and receive a resultant current at receiving electrodes. The original electric logs were configured in the lateral configuration, where a current was applied between a surface electrode and a downhole electrode. The potential difference between two downhole measurement electrodes provided data for calculating the resistivity of the rocks between them. These logs provided nonsymmetrical responses, and allowed the interpretation of a single value of resistivity for each bed or petrophysical zone.

To provide for more symmetrical response, the normal electrode configuration was developed. In the normal configuration, one of the measurement electrodes was moved to the surface. An improvement in symmetry was made, but the measurement still provided only a single value of resistivity for the reservoir. All these older electric logs require significant correction for borehole and bed thickness, and interpretation is mostly art. Refer to figure JN.1 for the electrode arrangements.

Modern day resistivity logs provide symmetrical responses and allow the determination of resistivity values over relatively thin portions of the reservoirs. Modern laterologs provide a focusing system which reduces the borehole effects by forcing the current in narrow sheets into the borewall, thus preventing it from traveling up the mud column to the receiving electrode. The modern induction logs induce a low frequency radio wave-like signal into the borehole system, and do not require the hole to be full of a conductive fluid (mud).

It is valuable to be able to sample the formation resistivity at various distances away from the borehole to evaluate the significance of invasion. A class of micro-resistivity tools is used to measure formation resistivity at only a few inches or a few feet away from the borewall.

When the formation resistivity can be measured at several distances away from the borewall, an interpretation of the degree of invasion may be made. With this determination, the logs can be corrected for geometrical effects, and a more accurate determination of true formation resistivity (Rt) can be made. Such multiple measurements are normally made with a combined set of tools on one trip in the hole.

Resistivity measurements are presented in units of ohm-meters ("ohms"). Most modern petrophysical work is done with the values scaled from .2 to 2,000 ohms logarithmically. Linear scales are used for correlation work to facilitate comparison with the older logs. Resolution of formation resistivity, Rt, is required to calculate water saturation.

Resistivity logs presently in use are the Dual Induction Log (DIL), Dual Laterolog (DLL), Shallow Focused Log, Proximity Log, and Microlaterolog. The latter three are focused microresistivity devices.

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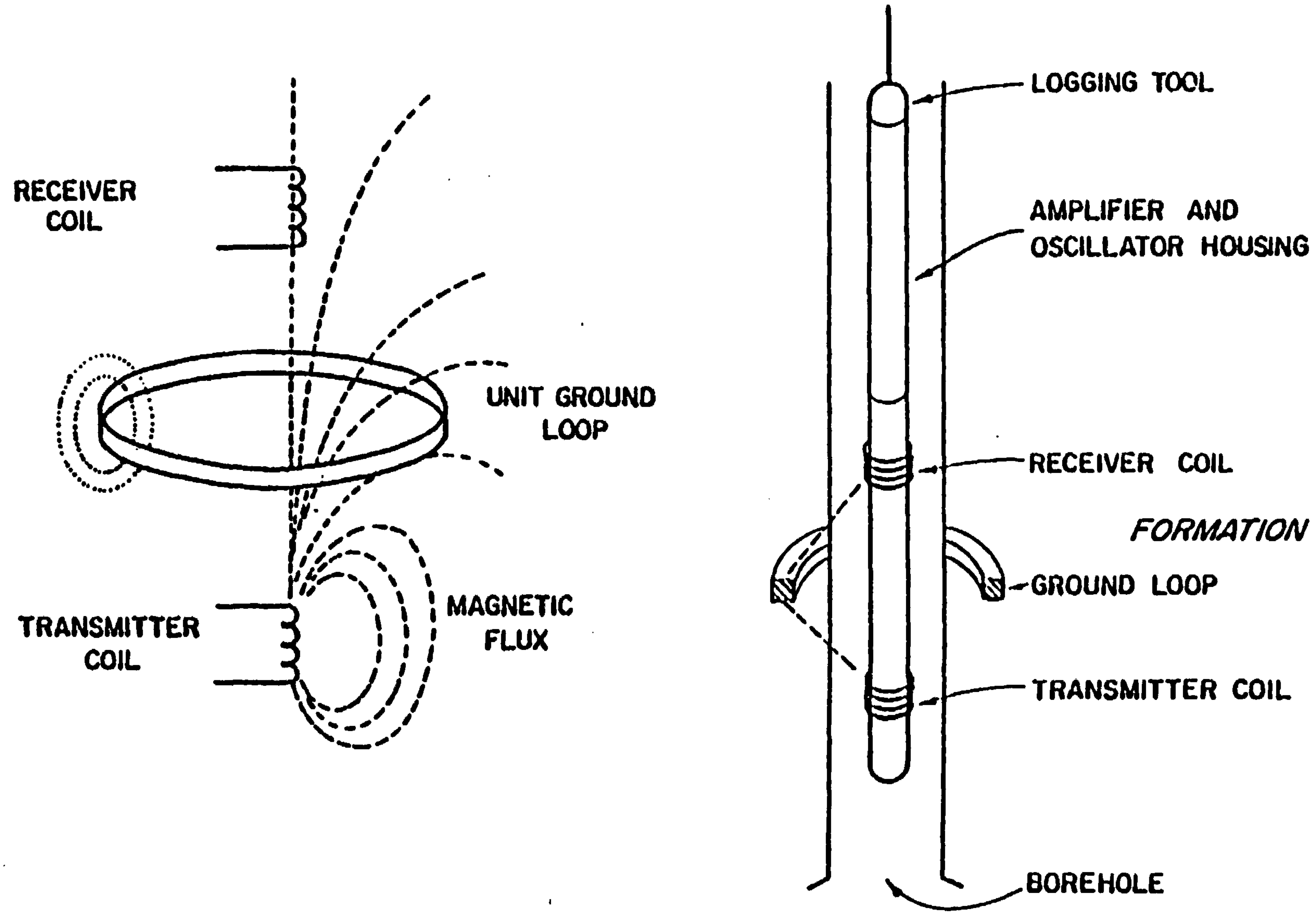


FIGURE III-H

INDUCTION LOG - DIAGRAMMATIC
(AFTER SCHLUMBERGER)

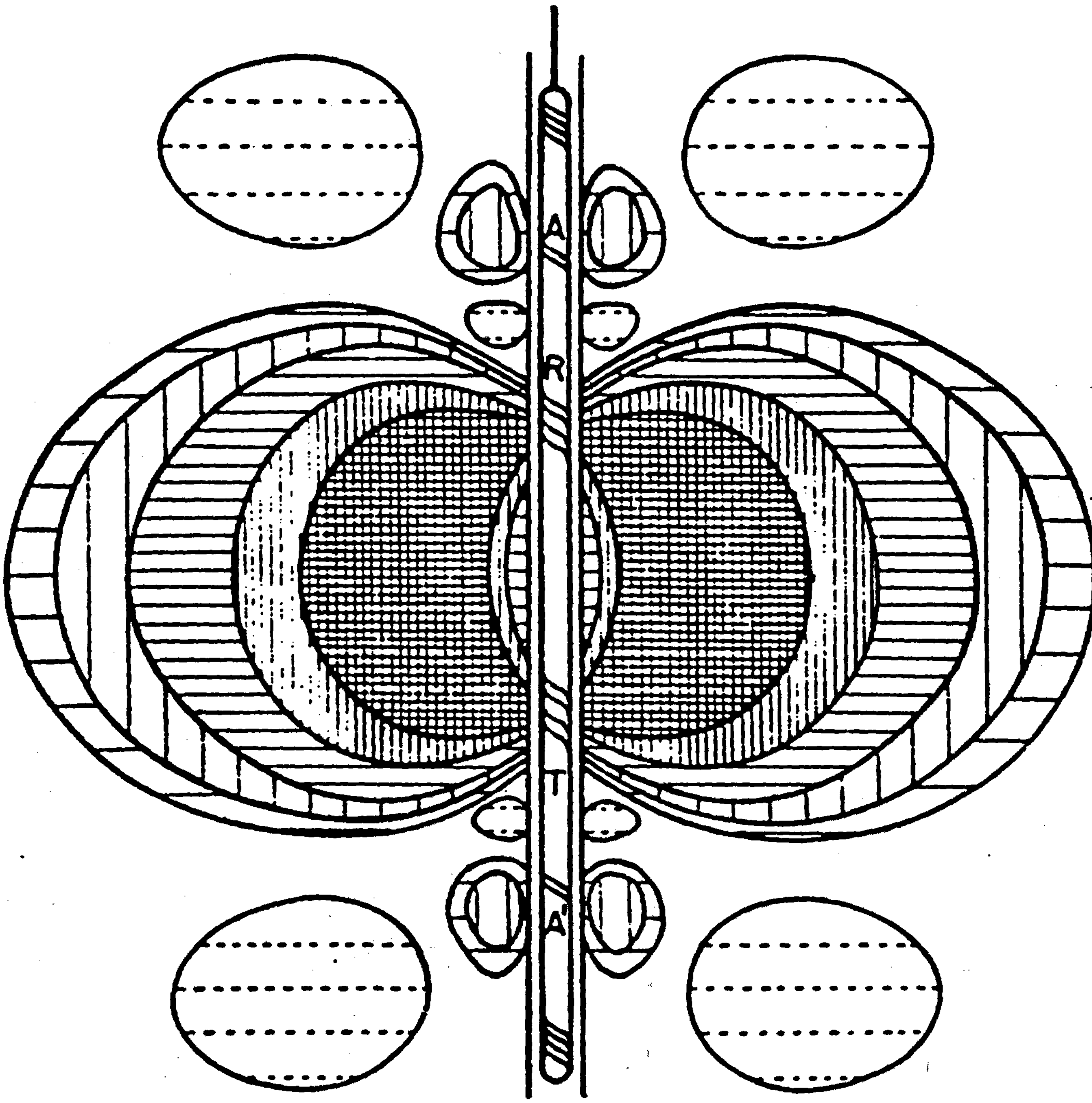
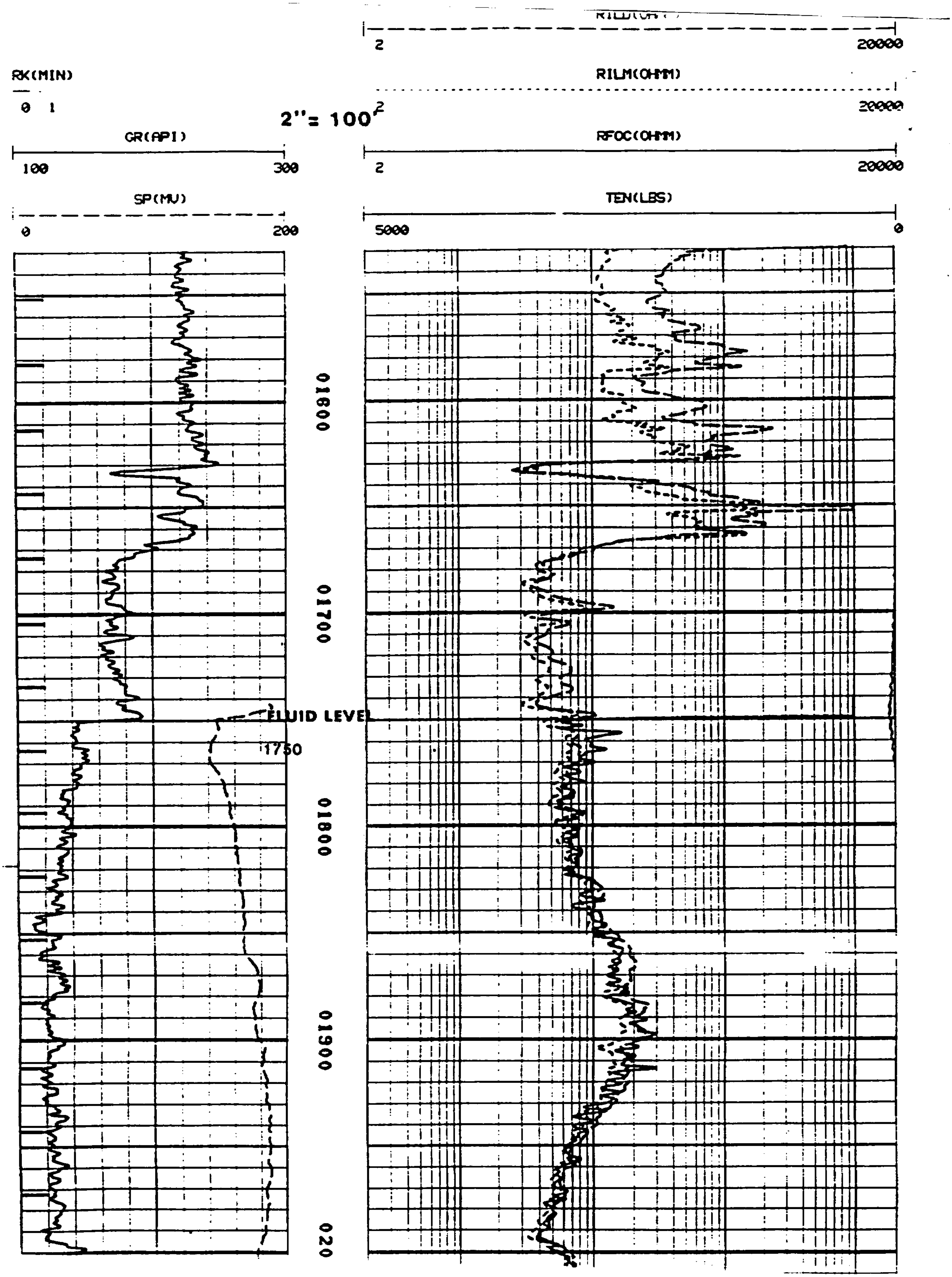


FIGURE III–H

INDUCTION LOG FIELDS – SCHEMATIC

(AFTER SCHLUMBERGER)



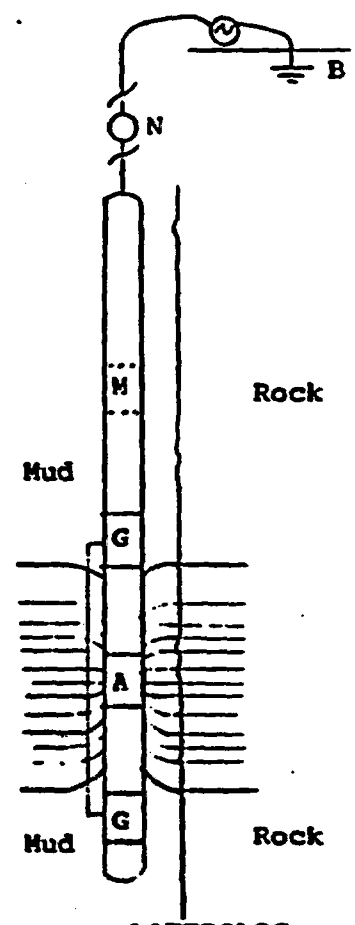
RILD(OHMM)
2
20000
RK(MIN)
0 1
2"= 100'
RILM(OHMM)
2
20000
GR(API)
100
300
RFOC(OHMM)
2
20000
SP(MV)
0
200
TEN(LBS)
5000
0
01600
01700
FLUID LEVEL
1750
01800
01900
020

BACK TO BASICS

BASIC LATEROLOG LOGGING SYSTEMS

Laterologs* measure the resistivity of the rocks surrounding the borehole by using the rock material as a conductor of electric current. Obeying Ohm's law, the current flows more freely through the path of least resistance which in the case of aquifers is through the water in the pore system. Modern laterolog presentations are scaled in ohms logarithmically (usually from 0.2 – 2000) across tracks two and three on the 5 in./100 ft. log. Available presentations are much the same as with modern induction logs (see page 3, May, 1986 Logging Lines – Ed.)

The basic laterolog system is a takeoff on the original "electric log" normal array which was comprised of sonde-mounted current electrode A and voltage electrode M, and distant voltage electrode N (usually on the cable), and return current electrode B at the surface (mud pit). The original electric logs suffer from adverse borehole and near borehole (invaded zone) effects when the salinity of the mud is high. With the original electric logs it is impossible to get adequate resistivity measurements under "salt mud conditions". Where the path of least resistance is through the borehole mud column little or no energy is propagated into the rocks.



LATEROLOG (SCHEMATIC)

To combat the borehole effects, GUARD or bucking electrodes (G in the figure) are placed on the sonde surrounding the A electrode. The guards are connected together (equal potential) and are at the same polarity as the A electrode, thus forcing the electric current away from the guards and into the formation in order to complete the circuit to the return electrode. The current to the guard electrodes is automatically adjusted in response to resistivity changes so that the potential difference between guards and the A electrode is always zero. The applied current is a low frequency pulsating direct current which keeps the down hole electrodes from changing resistivity with use.

The laterolog current is said to be "focused", and is depicted as being propagated in "sheets" perpendicular to the sonde, into the formation, even in highly saline muds. Focusing provides excellent thin bed resolution.

Modern laterologs have many electrodes and various spacings, providing measurements at different depths of investigation away from the borehole. Ensuing measurements are accurate in higher resistivity rocks than those from induction logs. Laterologs are the choice: (1) in low porosity aquifers, and (2) where the ratio Rmf/Rw becomes smaller, such as high salinity muds and/or fresh formation waters.

By understanding how the measurements are made, you will be

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*Not to be confused with lateral, a special array of original electric log.

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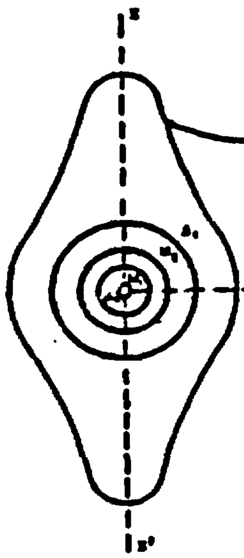
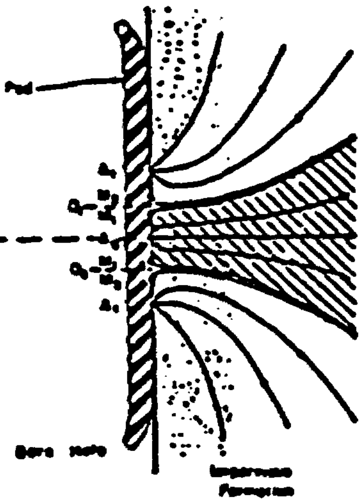
FIGURE III—G
MICRORESISTIVITY TOOLS

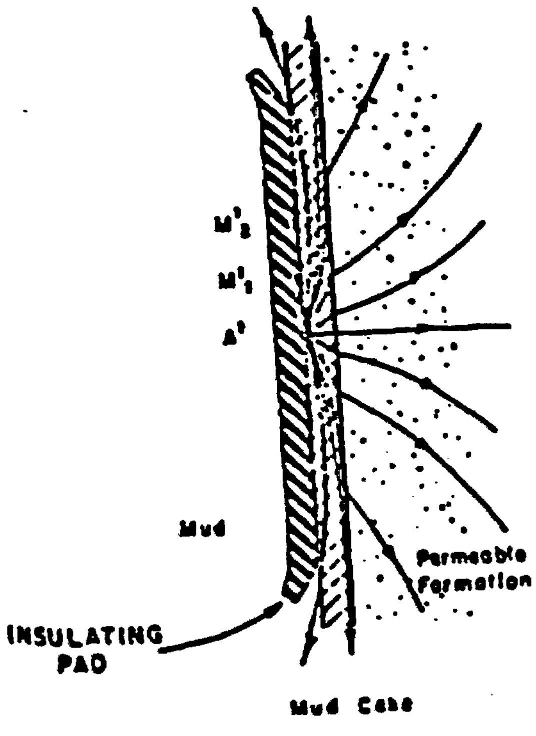
(AFTER SCHLUMBERGER)



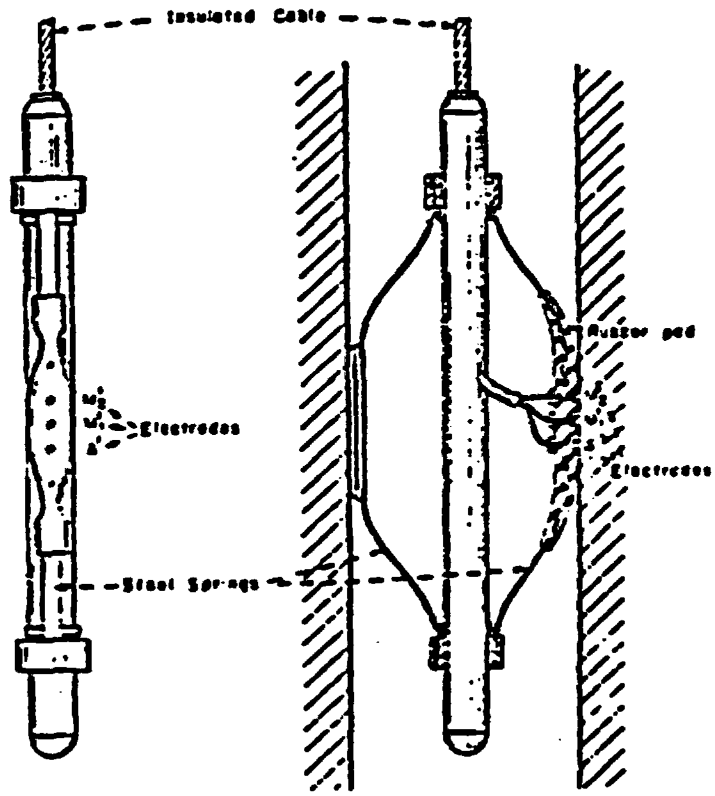
— MICROLATEROLOG DEVICE SHOWING DISTRIBUTION OF ELECTRODES.



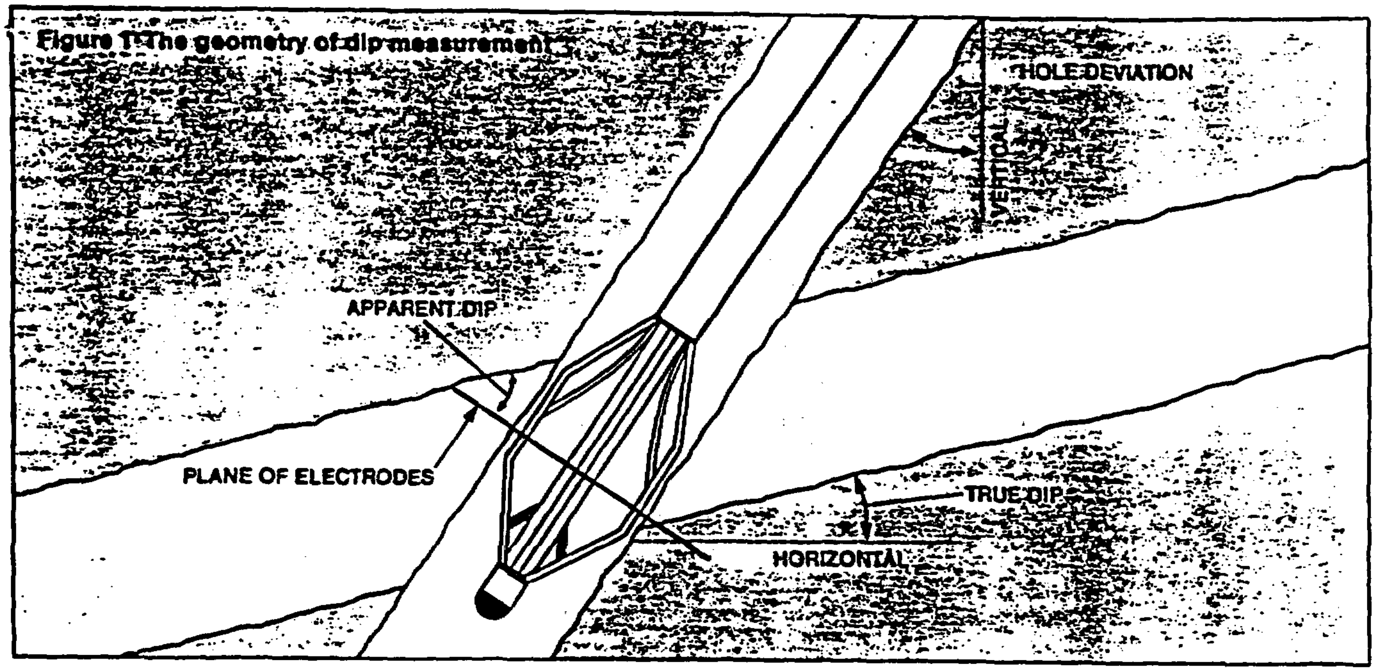
— VERTICAL CROSS SECTION SHOWING THE CURRENT LINES (SCHEMATIC DRAWING).



Microlog



— MICROLOGGING APPARATUS SHOWING DISTRIBUTION OF ELECTRODES



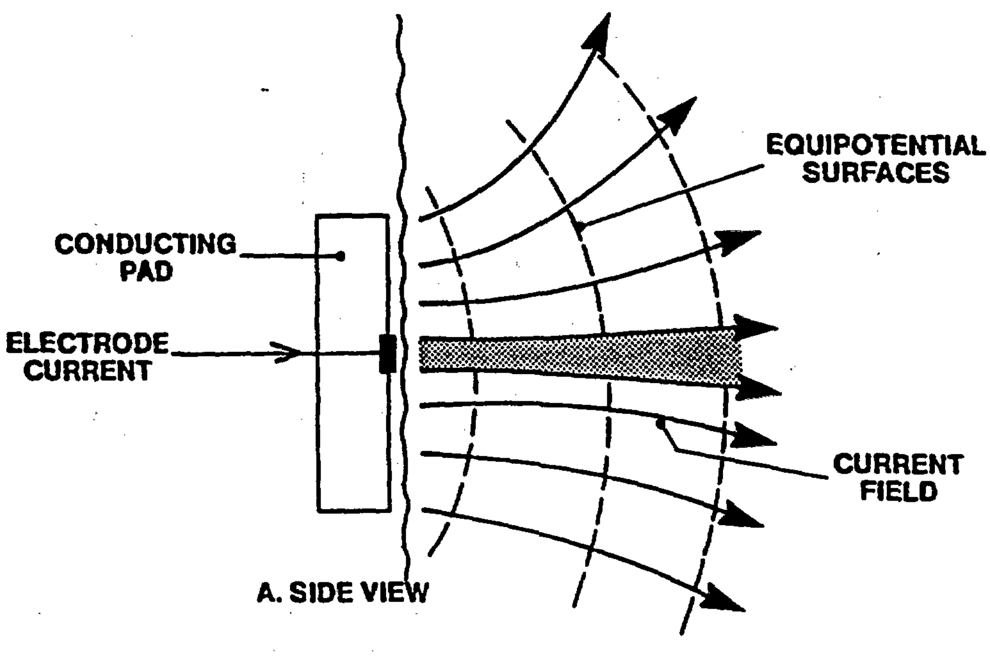


Figure 1. Pad/Electrode Configuration for Microresistivity Measurements.

BB

Figure 11. Fractures, High Dips and Vuggy Porosity in the Monterey Formation.

TYPES OF MEASUREMENTS

LOGS WHICH INTRODUCE ENERGY INTO BORE HOLE SYSTEM

NUCLEAR LOGGING SYSTEMS

Density Logs
aka Gamma-Gamma Density (DL)
aka Compensated Density (FDC)
aka Litho Density Log (LDT)
aka Spectral Density Log (SDL)

Neutron Logs
aka Compensated Neutron Logs
aka Epithermal Neutron Logs
aka Sidewall Neutron Porosity (SNP)

Thermal Decay Time Logs
aka TDT
aka Neutron Lifetime Logs (NLL)
aka Thermal Multigate Decay (TMD)

PE(B/E)
0 20

RK(MIN)
0 1

2"= 100'

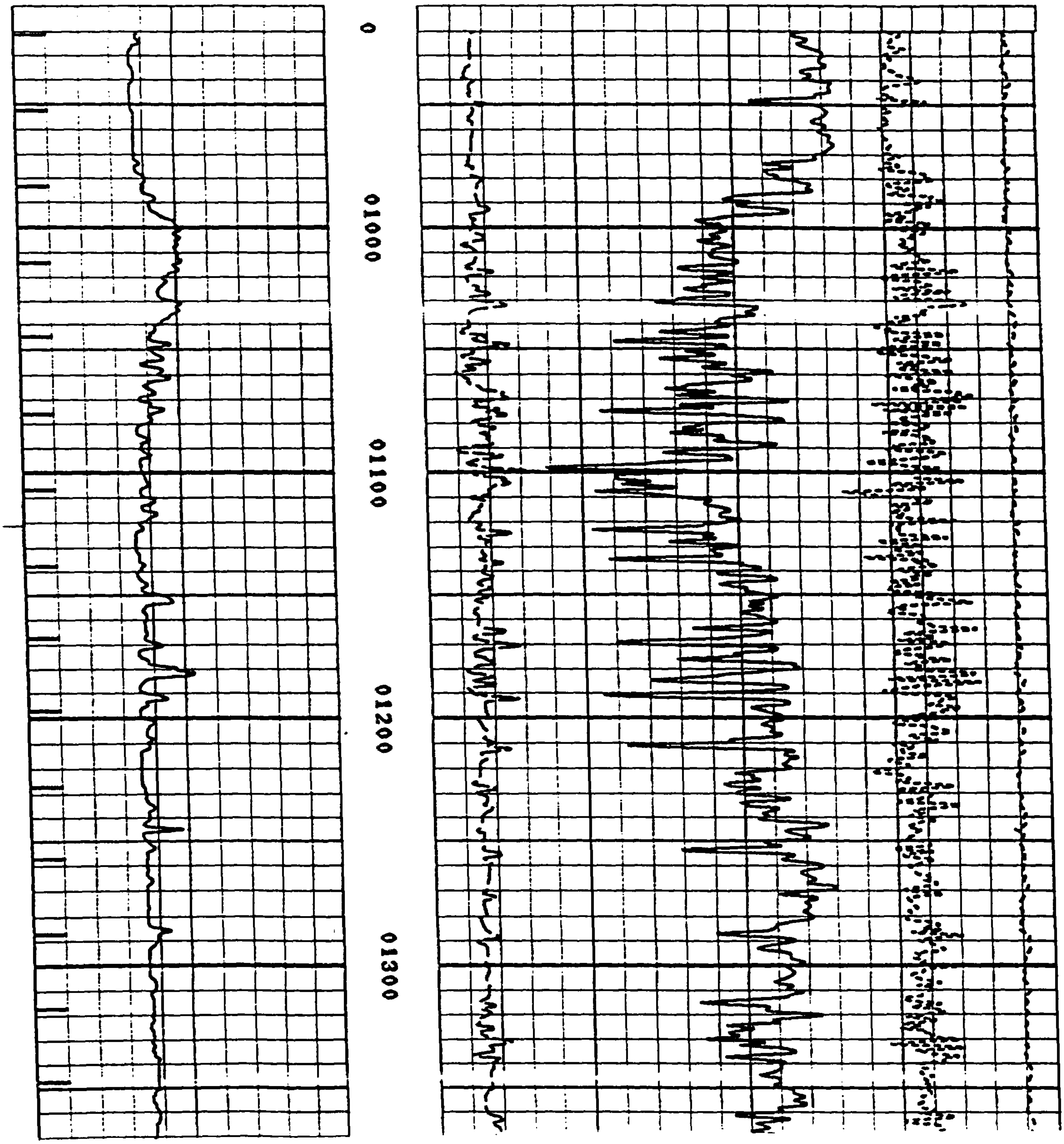
ZCOR(G/CC)
-0.5 0.5

BIT(INCH)
6 16

ZDEN(G/CC)
1 3

CAL(INCH)
6 16

TEN(LBS)
4500 -500

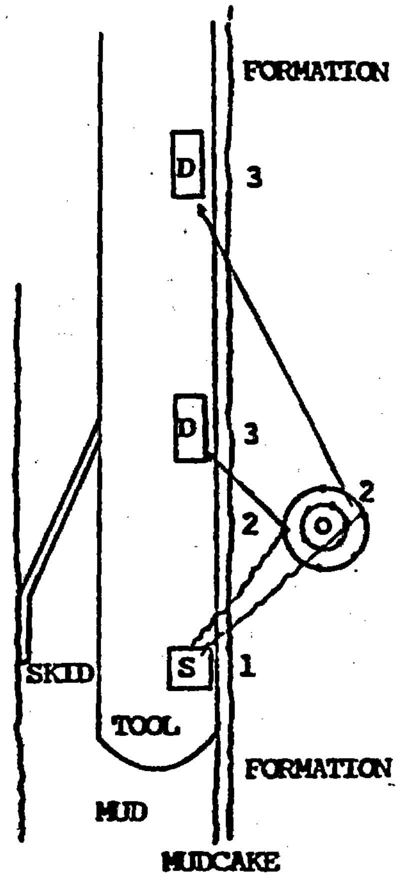


BACK TO BASICS

BASIC DENSITY LOGGING SYSTEMS

1. A radioactive source (usually Cesium 137) emits high energy gamma rays of approximately 1.1 Mev directly into the borewall face.

2. The gamma rays (or photons) react in several ways with atoms in the rock and borehole system. Major reactions include Compton scattering, photoelectric effect, and pair production. Through proper tool design, source-to-detector spacings, and choice of source strength, the basic density tool responds primarily to Compton scattering whereby an incident photon (gamma ray) ejects an electron from its orbit.



3. The scattered gamma rays, having lost some of their initial energy to the ejected electron, are counted by a near- and by a far-spaced detector.

The count rate (number of scattered gamma rays counted per unit of time) at each detector is directly porportional to the electron density of the material between the source and detector(s). Use of two different detector spacings results in compensation for mudcake through a "spline and ribs" computation relating the near and far count rates, and mud cake thickness.

In sedimentary basins logged for water, oil, or gas accumulations the bulk density of the reservoir and source rocks is nearly equal to their respective electron densities. The ratio of atomic number to atomic weight for most of these sedimentary materials is nearly constant ($Z/A = 0.5$). The result, after a slight mathematical correction, is a log of the bulk density of the formation opposite the tool.

The porosity of the rock investigated may be determined from the bulk density if the density of the rock matrix is known. Matrix density is related to the mineral assemblage or lithology of the formation.

In litho density-type systems, the photo electric effect of of the formation is measured, and an estimate of lithology independent of porosity may be determined

The major pitfall in making bulk density measurements is the need for intimate pad contact during logging. Rugose holes often provide inaccurate density readings, tending to be erroneously low, resulting in high apparent porosities.

By understanding how the measurements are made, you will be

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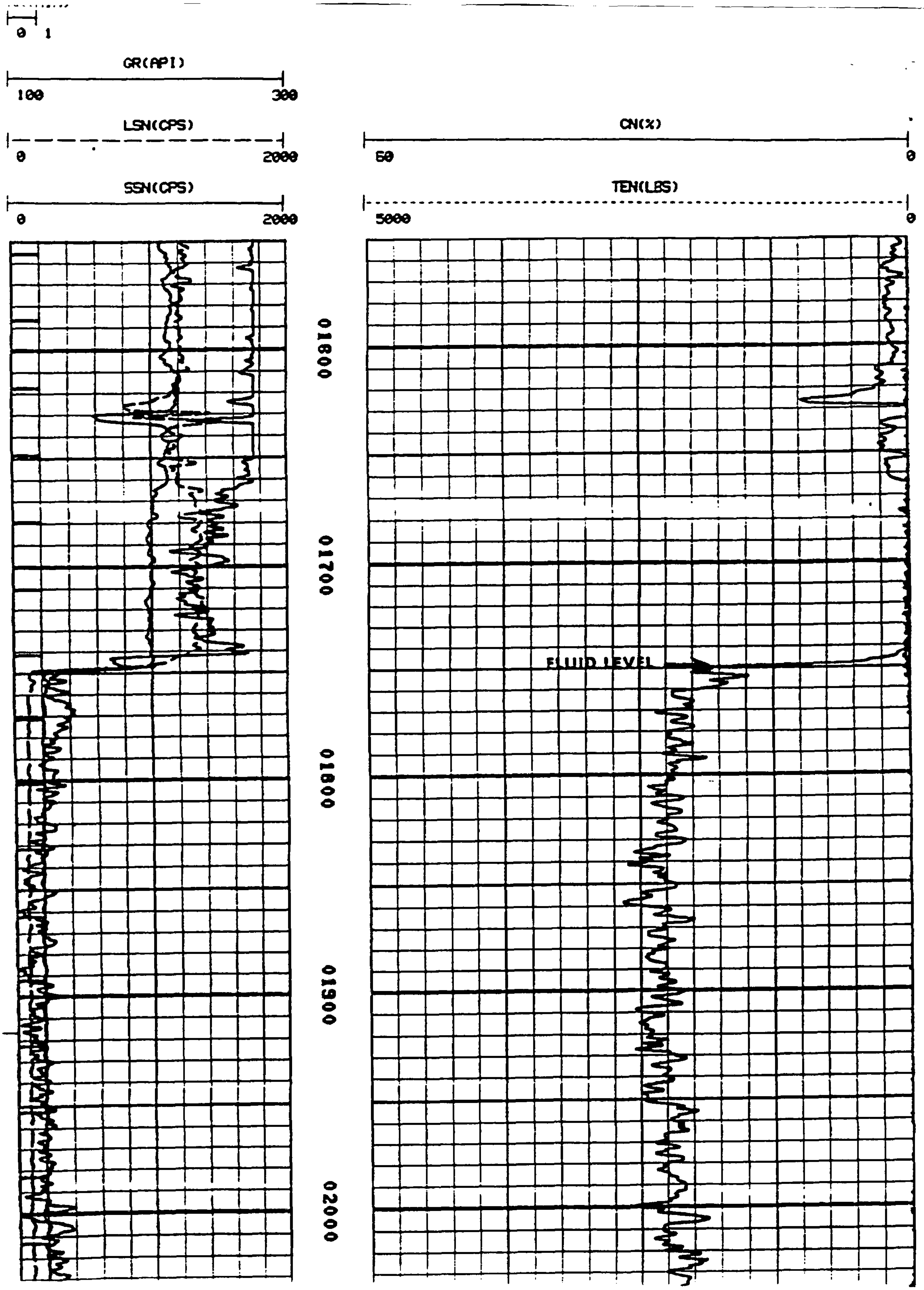


0 1
GR(API)
100 300
LSN(CPS)
0 2000
CN(%)
60 0
SSN(CPS)
0 2000
TEN(LBS)
5000 0
01800
01700
01800
01900
02000
FLUID LEVEL

BACK TO BASICS

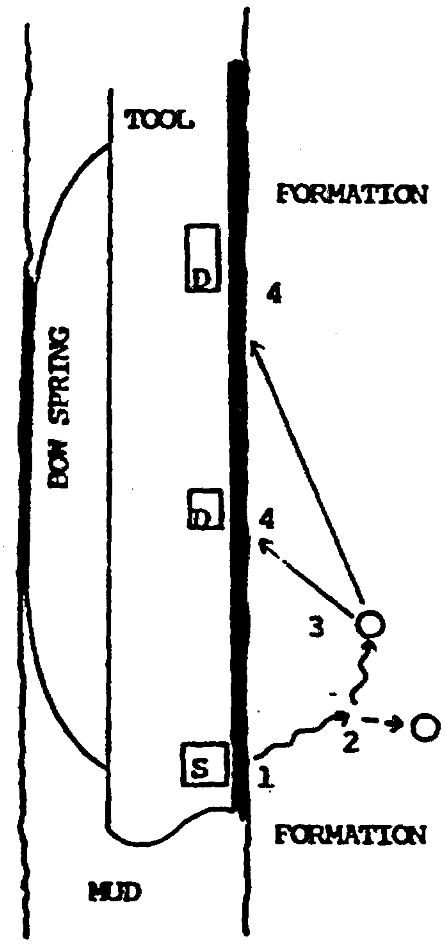
BASIC NEUTRON LOGGING SYSTEMS

1. A radioactive source (PuBe, or AmBe) bombards the formation near the borewall with high energy (high–speed) neutrons.

2. The neutrons are slowed down through billiard ball–like collisions with borehole and rock system atoms, most notably hydrogen.

3. Once the neutrons are slowed to thermal velocities, or "thermalized", some are captured by the hydrogen atoms, while others permeate through the system.

4. In some systems, detectors count the remaining thermal neutrons, and in others gamma rays which are emitted as a result of the capturing process are counted. Through tool design and dual detector spacing, borehole compensation may be affected.



Hydrogen occurs in the pores of rocks in water, oil, and gas. Thermalization takes place closer to the source (farther from the detectors) in high–porosity rocks (high hydrogen content). Where thermalization takes place close to the detectors (low–porosity rocks) count rates are higher (less absorption). Regardless of detector type, counting rates are inversely proportional to the amount of hydrogen encountered due to absorption.

Service companies calibrate their neutron systems to a standard set by the API and maintained at the University of Houston. Development tools are calibrated in the test pit which contains limestone of known porosity values and range. Hence the industry has adopted a primary standard based on limestone porosity units. Hydrogen index may be related to limestone porosity through these calibration standards.

A major pitfall when using the older neutron logs is the significant borehole effect which can distort the data. Large or irregular boreholes result in abnormally high apparent neutron porosity due to the presence of mud near the source. Where mud interferes with the source thermalization takes place close to the source, resulting in low count rates at the detectors. The rule of thumb is – if you do not know the borehole size, you do not know the porosity with an older neutron log. Remember – though related, bit size and borehole size may not be the same.

Pad–type epithermal (SNP) and modern compensated (CNL) logs are run eccentered with real–time caliper data being available for hole size correction.

Neutron logging provides a measure of the hydrogen index of the materials investigated which, through appropriate computation and calibration, may be related to lithology–dependent porosity. By understanding how the measurements are made, you will be

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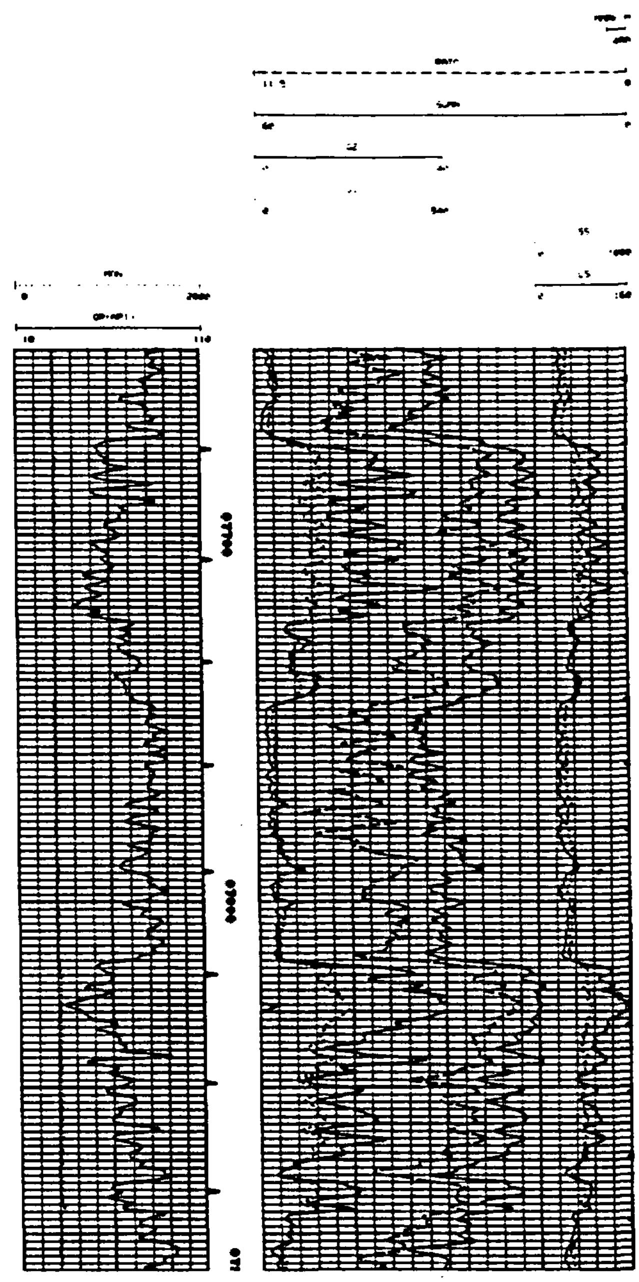
Dual Detector Neutron Lifetime Log® (DNLL)

The Dual Detector Neutron Lifetime Log® measures the macroscopic thermal neutron absorption cross section, Sigma (Σ), of the bulk formation. Sigma is primarily a function of the porosity, of formation water salinity, of quantity and type of hydrocarbon in the pore spaces, and of the type of rock matrix. Sigma decreases with increasing hydrocarbon content, but increases with increasing porosity and with increasing water salinity.

In cased holes, the DNLL can be used to discriminate between gas, oil and saltwater bearing formations. The measurements are not, however, restricted to cased holes. Valuable reservoir data can also be obtained from the DNLL in open hole environments.



APPLICATIONS:

- ❑ Correlate with open and cased hole logs
- ❑ Determine stratigraphy
- ❑ Determine hydrocarbon saturation behind casing
- ❑ Semi-quantitatively determine porosity
- ❑ Locate gas and gas-liquid contacts

SPECIFICATIONS:

Length (W/CCL) (ft)	(m)	Diameter (in.)	(mm)	Max. Temp. (°F)	(°C)	Max. Pressure (psi)	(MPa)
12'3"	3.73	3-5/8	92.1	350	177	20,000	137.9
19'11"	6.07	1-11/16	42.9	300	149	20,000	137.9

TYPES OF MEASUREMENTS

LOGS WHICH INTRODUCE ENERGY INTO THE BORE HOLE SYSTEM

WAVE ENERGY DEVICES

Acoustic Logs
aka Sonic

Full Wave Form Acoustic Logs
aka FWFAL
aka FWAL
aka Cement Bond Log (CBL)

Dielectric Constant Logs
aka DEL
aka Electromagnetic Propagation Tool (EPT)

Bore Hole Televiewer
aka BHTV

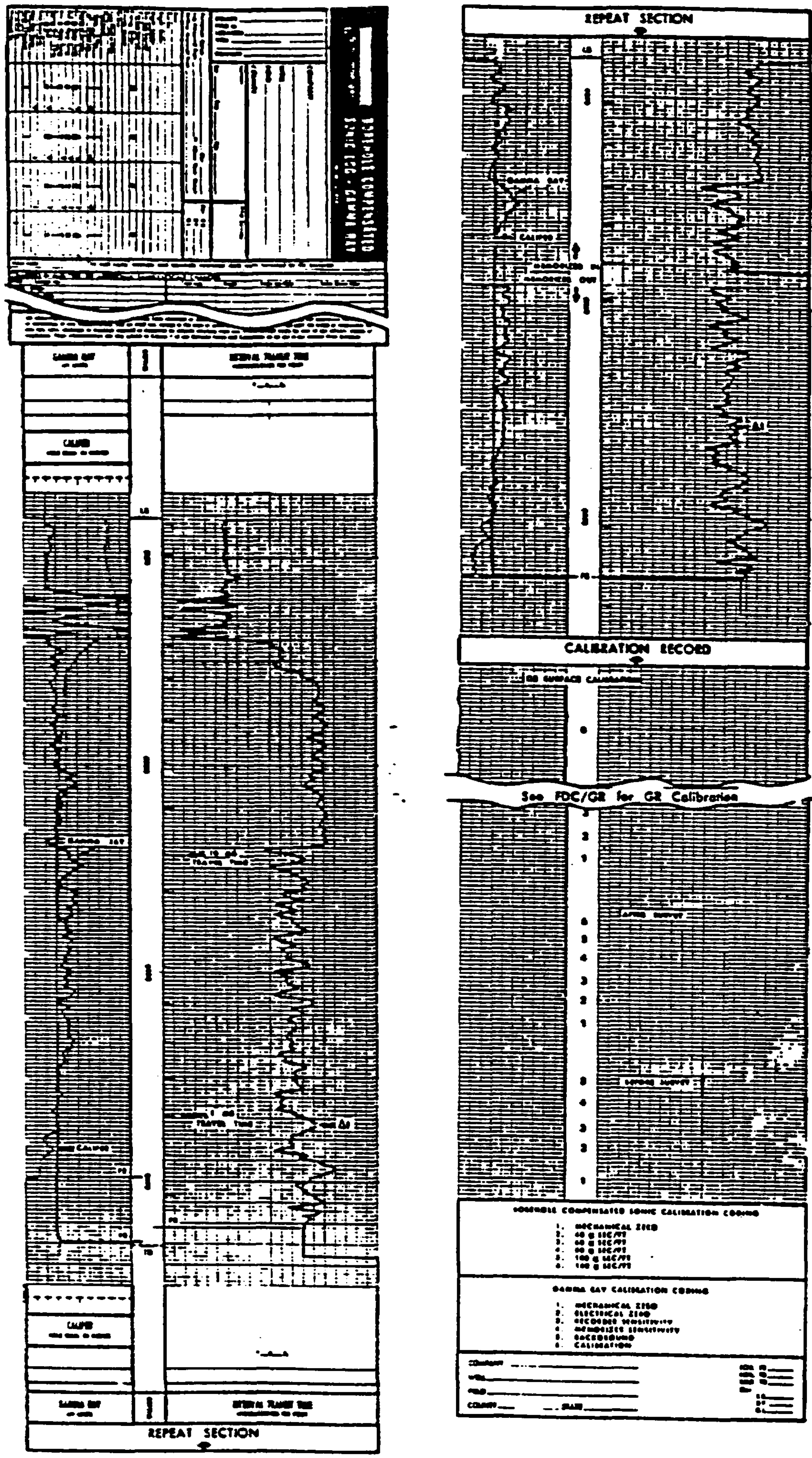


FIGURE III-

SCHLUMBERGE
BHC SONIC LC

BACK TO BASICS

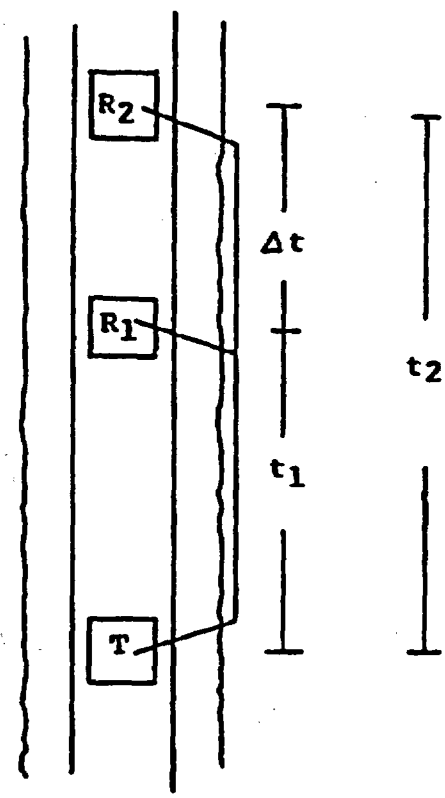
BASIC ACOUSTIC LOGGING SYSTEMS

An array of transducers is mounted on a centralized borehole sonde. The basic array consists of a transmitting transducer and two receiving transducers. The sonde is milled in a maze—like pattern creating a long path for sound waves, effectively decoupling it from the transducers.

Each transducer is composed of pizeoelectric material which, when subjected to pressure, emits an emf (voltage). Alternatively, when a voltage is applied to a transducer, it changes volume. When an alternating voltage is used, a pressure pulse with frequency content is transmitted away from the device. (Remember the stone thrown in the quiescent lake and the resultant ripples?)

A pulse wavelet (usually 20 khz) excites the transmitter (T) at time T_O , and the resultant pressure wave travels through the mud at the velocity of the mud, enters the borewall material, and travels along the borewall at the faster rock velocity. A complex acoustic wave is generated at the mud—rock interface, but it is the compressional mode (earliest or fastest) which is of primary interest in basic systems.

The wave leaves the rock, travels back through the mud, and is detected as a pressure pulse by the receivers (R_1, R_2) which register a voltage change. The total time required from transmitter to each receiver (t_1 and t_2) is measured and through simple trigonometry, the time (Δ_t) required to travel through the rock portion of the path is determined. The standard system of presentation is travel time (Δ_t) in microseconds (1/1000 sec), or µsec per foot. The velocity of the rock, V_R, in feet per second $= 10^6/(\text{usec/ft})$.



BASIC ACOUSTIC LOGGING TOOL
(SCHEMATIC)

In practice, the borehole array consists of two transmitters and four receivers, arranged such that several measurements of travel time are made for each evaluation. Using averages and simple math, the effects of the mud path, borehole irregularities, and sonde tilt are eliminated, resulting in a borehole compensated measurement of travel time. Depth of investigation is less than two inches, and is radial around the borehole.

The porosity of the rock material near the borewall may be estimated if the matrix travel time ($\Delta_t$ma) of the rock is known or assumed. Acoustic porosities are reliable over the range of .06 — .25 p.u. Acoustic tools are calibrated to measure the travel time of a water—filled aluminum tube. In the hole, an acoustic log should be checked by measuring the travel time in free (unbonded) pipe or surface casing (Δ_t pipe ≈ 57.5 usec/ft.)

More advanced tools have arrays with multiple T—R spacings, including long spacings to help separate out the various component modes of the complex wave. Such long—spaced tools are used for rock typing (lithology identification), and research into the nature of the total acoustic wave. By understanding how the measurements are made, you will be

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ADVANCED STUFF

LONG SPACED ACOUSTIC MEASUREMENTS

A review of basic acoustic measurements in boreholes reveals a system of pizeoelectric transducers in an array of transmitters and receivers. A pressure pulse is transmitted through the mud, along the borewall/mud interface, and is received at a receiver a distance away. (See page 2, March, 1983 Logging Lines for a basic explanation of acoustic borehole measurements.)

The accompanying figure is a diagrammatic sketch of an acoustic wave train as received in the borehole over different path lengths. Note the various parts or modes of propegation. Acoustic theory indicates that much valuable petrophysical information is locked up in these complex waves, awaiting to be deciphered.

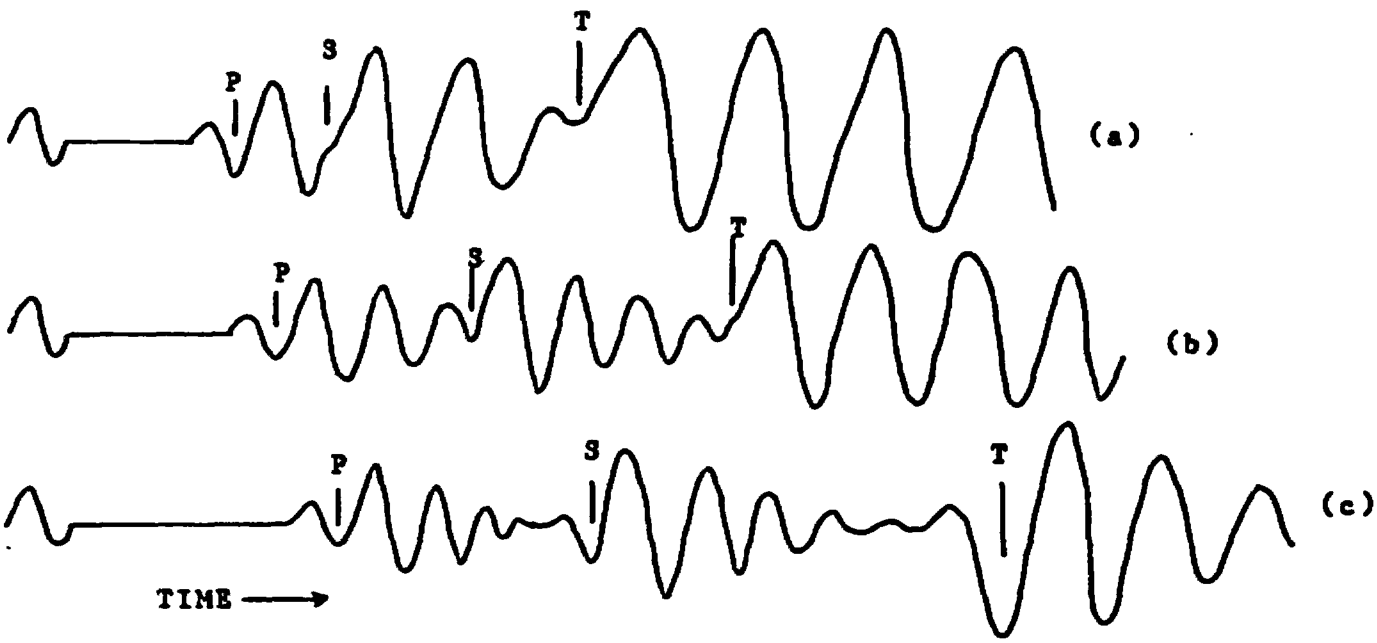

FIGURE N.1 - Acoustic Wave Trains (Schematic)

$$T\text{-}R_a < T\text{-}R_b < T\text{-}R_c$$

While the acoustic wave train is very complex, the basic acoustic or "sonic" log measures only the P wave (compressional) travel time (Δ_{tc}) required for the pulse to go from the transmitter to the receiver. Common borehole compensated acoustic systems have 3, 5, and 6-foot transmitter-receiver (T-R) spacings.

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Where it is desirable to measure S wave (shear) mode travel times, or investigate phase or group velocities, special equipment is often employed. Tools with T-R spacings in excess of 8 feet have become common over the past five years. Modern long spaced tools have T-R spacings of 20 feet and more.

The main reason for increased T-R spacing is to spread out the acoustic wave train so the individual modes or packets are separated and thus easier to observe and digitize. With proper T-R spacing, the damped compressional wave will loose sufficient energy so it does not interfere with the onset of the later shear arrival. As the arrival time for each successively slower mode is increased, the wave train is elongated, and the individual modes become more discernable. Figures N.1 a, b, and c are schematic representations of wave trains from respectively increased T-R spacings.

In addition to more accurate raw compressional and shear travel times (Δ_T) for porosity estimates, other attributes of the propagation of acoustic energy through porous media may now be studied. Investigators are able to tell us more about the rock fabric and contained fluids by cataloging the frequency, energy, and spectral composition of the acoustic wave train and the various modes.

Of particular interest is the attenuation of the component parts over a specific interval of rock. Mobil[1] reported gratifying results after determining permeability through the investigation of the energy loss of the tube wave. They also indicate a significant correlation between tube wave velocity and permeability.

Not all advances are due to the increased T-R spacing. Recent improvements in microelectronics, including signal-to noise ratios, signal detection, analog-to-digital conversion, and digital recording techniques have contributed measureably to our newfound understanding of these complex borehole waves.

[1]SPWLA Transactions, 1984 Paper "T"

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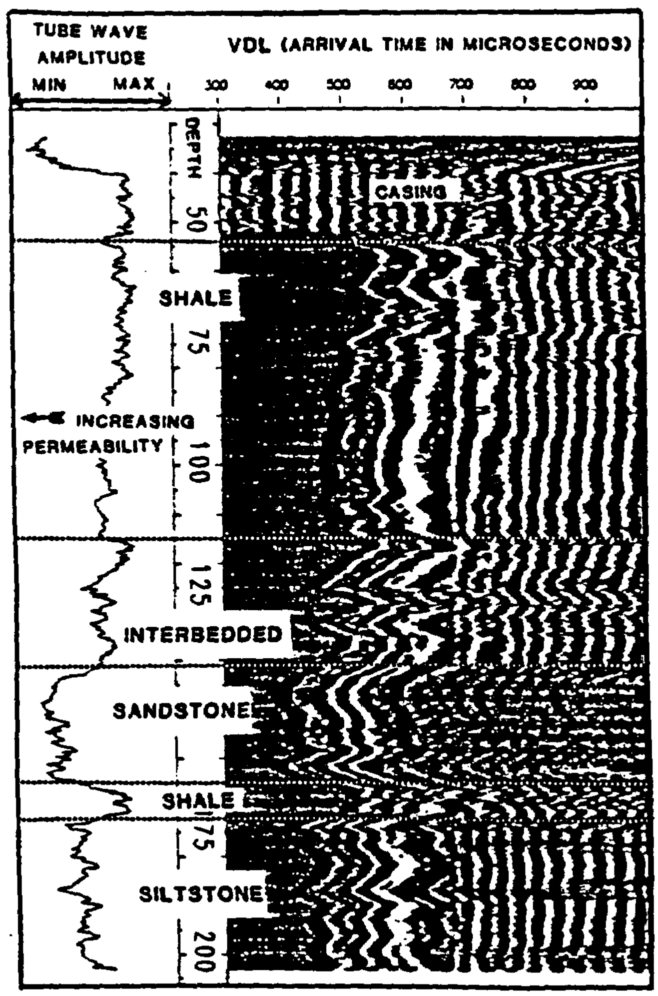


Full waveform logs in Tertiary fluvial sediments, including the tube wave amplitude (left) and the variable density log (VDL, right).

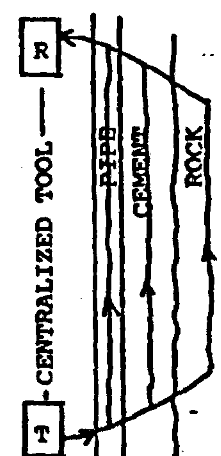
ADVANCED STUFF

ACOUSTIC CEMENT BOND LOGS

(There is much misunderstanding about the Cement Bond Log (CBL). Good luck with this one. - Ed).

Most service companies offering an acoustic cement bond log use their standard multiple-transmitter multiple-receiver acoustic tool. Refer to page 2 of the March, 1983 issue of Logging Lines for an explanation of how the tool works.

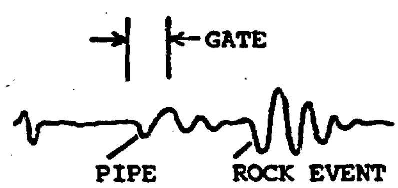
Figure F.1 shows the travel paths of the compressional wave(s) through the system. Figure F.2 illustrates an oscilloscope picture of the wave train as received uphole. In Figure F.2A the unbonded pipe "rings" with a high amplitude, because the pipe is free to move. The energy stays in the pipe since it cannot readily travel through unbonded interfaces. The premise is made that a high pipe signal amplitude is indicative of poor or no bonding. In Figure F.2B a lower amplitude bonded pipe signal is shown. Typically, a time gate is set such that the pipe signal arrival will be discriminated so the amplitude of the signal in the gate may be compared to the calibrated free pipe amplitude. A relationship is determined between the high amplitude in free pipe and the low amplitude in bonded pipe, and a log trace marked "amplitude" or "bonding increases" is presented. Without some calibration in known free pipe, above the cement top, it is impossible to determine bonding in this way. It is a mistake to scale off the amplitude curve directly in percent of bonding, as it only takes a little strip of contiguous bonding vertically for the CBL to "see bonding". (Remember, the acoustic signal is propagated throughout the tubular borehole system, not just along one side as our two dimensional pictures show).



F.1 SIGNAL PATH - BONDED

Proper interpretation is geophysical in nature, and requires the variable density (VDL) or full waveform (FWPAL or signature) presentation. Late events are absent or have very low amplitudes after a ringing pipe signal, indicating that bonding is not adequate. Higher amplitudes following a low amplititude pipe signal usually indicate a solid path from pipe through cured cement, through rock, and back through the cement/pipe complex.

F.2A UNBONDED PIPE SIGNAL



F.2B BONDED SIGNAL

Experience with the VDL or FWPAL presentation allows one to "see" the rocks behind the pipe where bonding is acoustically "sound". Some investigators, including this one, are presently looking at these presentations to detect fractures behind bonded pipe.

RECOMMENDATION: Do not run an acoustic cement bond log without the corresponding VDL or signature presentation. Otherwise it is a waste of money.

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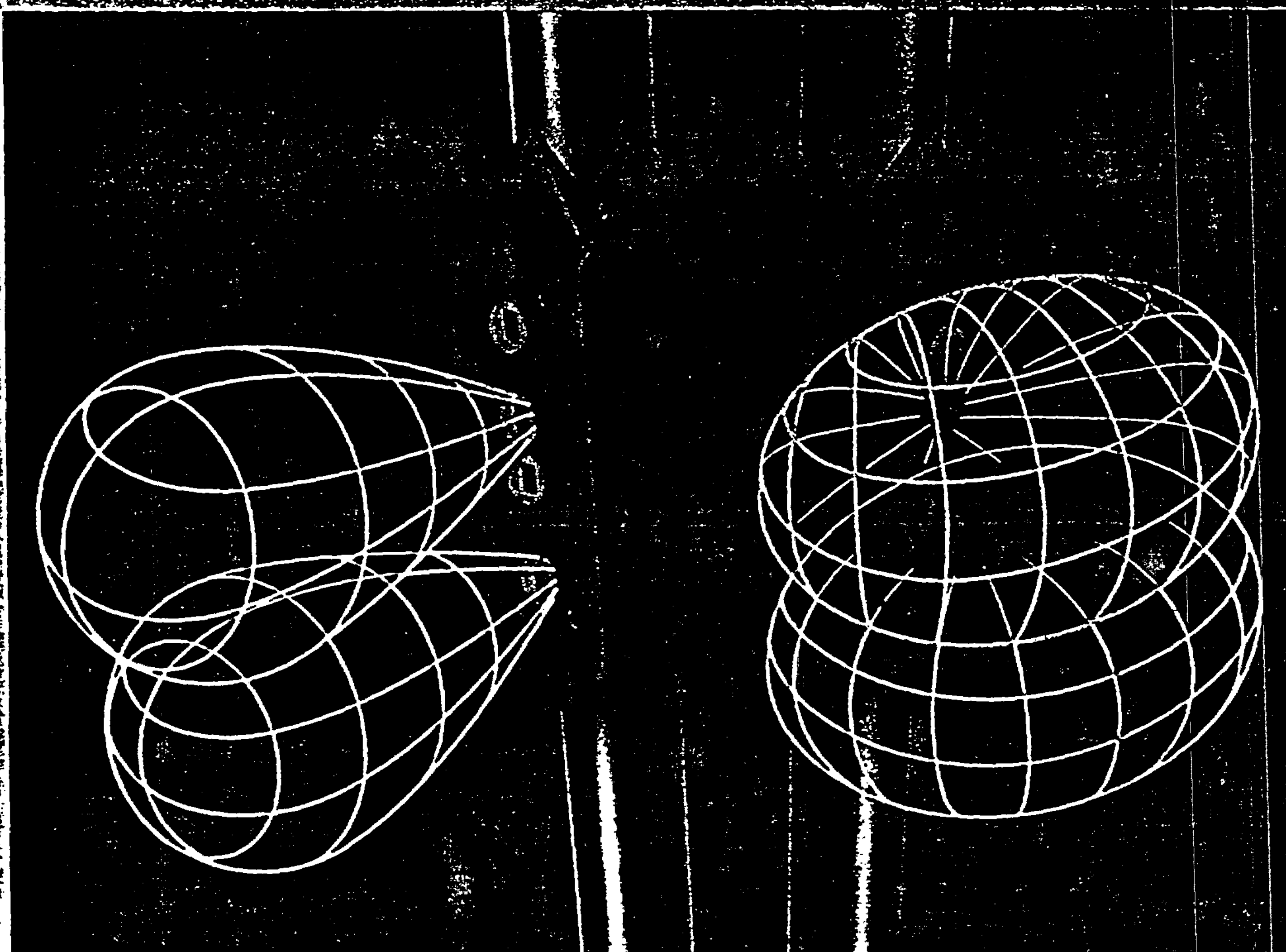
ADEPT Dielectric Tool



Schlumberger

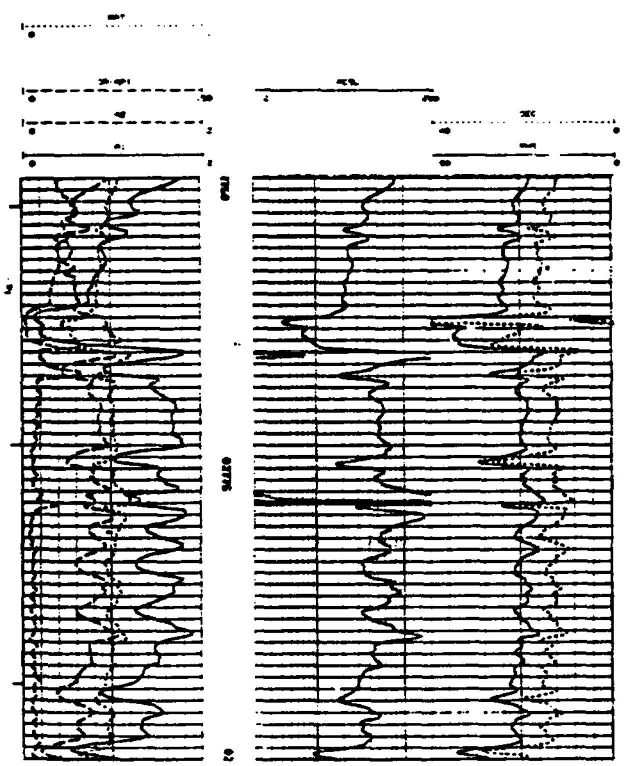
Dielectric Log

The Dielectric logging instrument is used to investigate formation characteristics in areas of brackish or low formation water salinity. Two types of Dielectric logging instruments are available: a 47-MHz instrument that responds to formation properties beyond the invaded zone, and a 200-MHz instrument that investigates the flushed zone. The 47-MHz instrument is a "slick" tool which is operated in a centralized position in the borehole. The 200-MHz instrument is a pad-type which is operated in contact with the formation. The two instruments can be combined to run as a Dual Dielectric Log and to increase wellsite efficiency.

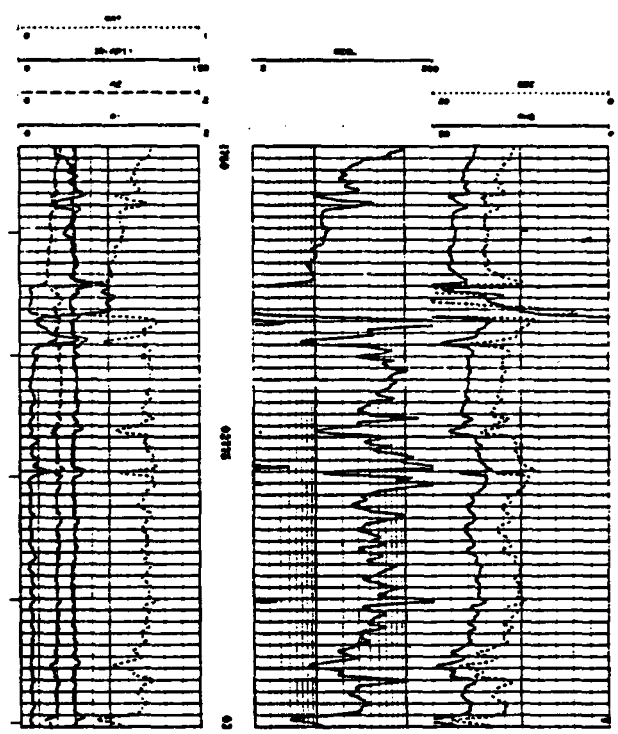
Both tools operate on the same principles, but the different frequencies provide different depths of investigation and different responses according to the characteristics of the formation. The curves of the Dielectric logging instrument are as follows: Amplitude at Receivers 1 and 2 and the ratio of amplitude are presented in track 1. The computed resistivity is presented in track 2. The phase shift (in degrees) and dielectric constants are presented in track 3. The presentation can be changed according to customer request.

APPLICATIONS:

- ❑ Determine flushed and deep water saturations
- ❑ Identify moveable oil
- ❑ Identify shale content
- ❑ Determine sand content (high resolution)
- ❑ Identify Oomoldic and dead-end porosity



47 MHz



200 MHz

SPECIFICATIONS:

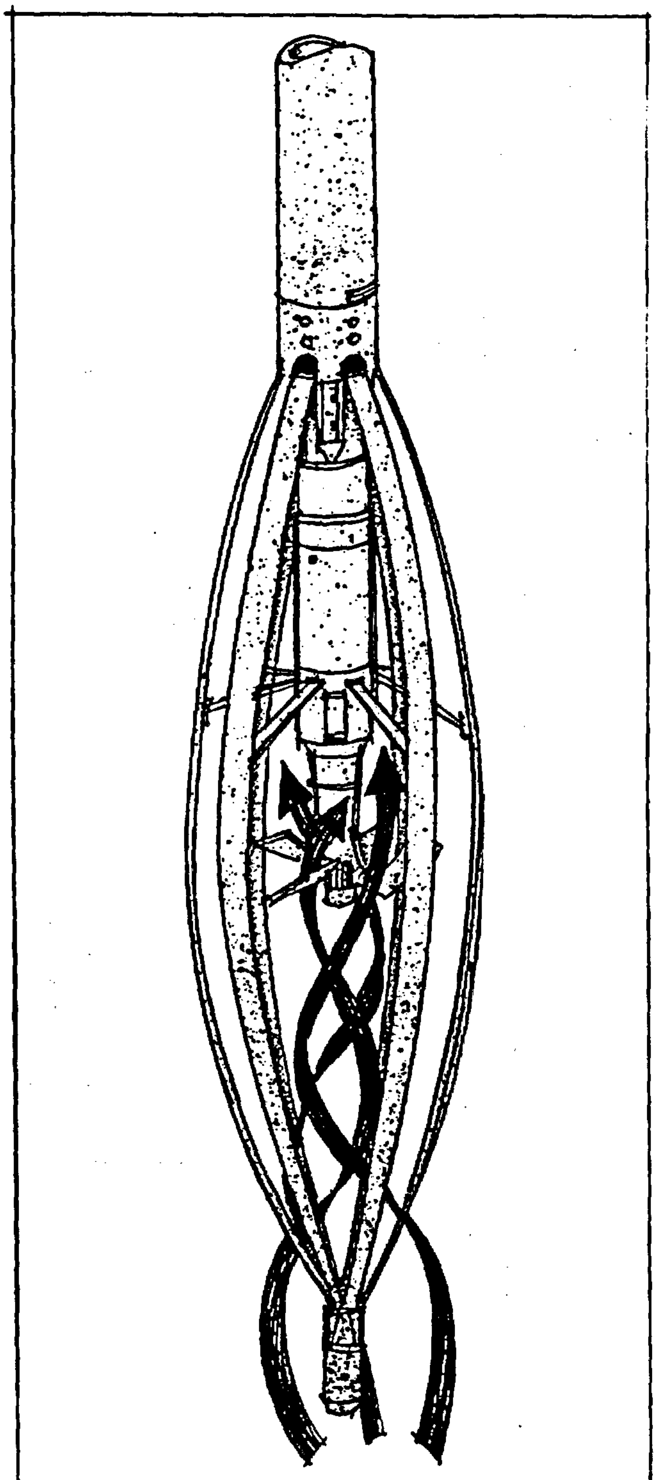
Frequency (MHz)	Length (ft)	Length (m)	Diameter (in.)	Diameter (mm)	Max. Temp. (°F)	Max. Temp. (°C)	Max. Pressure (psi)	Max. Pressure (MPa)
47	11.98	3.65	4-1/8	104.8	400	204	20,000	137.9
200	14.40	4.39	3-3/8	85.9	400	204	20,000	137.9

TYPES OF MEASUREMENTS

PRODUCTION LOGS

- Fullbore Flowmeter
- Continuous Flowmeter
- Radioactive Tracer
- Pressure Gauge (transducer)
- Thermometer (high resolution)
- Manometer
- Gradiomanometer
- Fluid Density Log (radioactive source)
- Bore Hole TV Camera

PLT* Production Logging Tool



The Production Logging tool provides simultaneous measurements from downhole sensors used for the analysis of producing or injection wells. The tool measures fluid entries and exits, standing fluid levels, bottomhole flowing and shut-in pressures, pressure losses in the tubing, and the integrity of the gravel pack and hardware assemblies. Since the measurements are made simultaneously, their correlation is unaffected by any well instability that might cause downhole conditions to vary over a period of time.

Interpretation of the PLT data determines the quantity of unrecovered hydrocarbons, the pressure drop across the reservoir and completion, the permeability of the perforated interval, and skin losses in the completion. In addition, it identifies zones not contributing to production, develops a pressure loss correlation for the tubing string, and compares the actual flow profile to the theoretical flow profile calculated from the Producibility log.

The 1 $^{11}/_{16}$-inch diameter tool can be run through tubing as small as 2 inches in diameter to measure producing or injecting wells under realistic, dynamic conditions. In addition to a casing collar locator and Gamma Ray tool, the PLT tool can be run with the following sensors.

Fullbore Flowmeter–The Fullbore Flowmeter is a spinner-type velocimeter which records production and injection profiles. The tool uses a spinner which nearly covers the casing cross section and therefore is little affected by viscosity changes in multiphase flow. The spinner is collapsed for running in or out of the hole and can work in a pipe range of 3 $^{1}/_{2}$- to 9 $^{5}/_{8}$-inch inside diameter.

Continuous Flowmeter–The Continuous Flowmeter is a spinner tool which records production and injection profiles in high flow rates. It is particularly suitable for logging in gas wells.

Radioactive Tracer–A Dual Radioactive Tracer Ejector tool records flow profiles and detects channels outside the casing. With the dual ejectors it is possible to eject selectively either water-miscible or oil-miscible tracer materials. The tool is particularly applicable for measuring low flowrates.

Pressure Gauge–The Hewlett-Packard precision quartz pressure gauge monitors pressure during a pressure-buildup test. It also can be run continuously to monitor the pressure profile in the well. A temperature measurement is made simultaneously so that a corrected pressure measurement is provided in real time.

Thermometer–A high-resolution thermometer records a temperature profile for the study of temperature anomalies as

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small as 0.5° F. A differential temperature can also be displayed. The principal applications are to locate fluid entries, determine flow behind pipe, detect gas leaks, and correct pressure measurements.

Manometer–The Manometer sensor provides a continuous monitor of the pressure in the well. This pressure profile is a useful aid in interpreting other production logging measurements.

Gradiomanometer*–The Gradiomanometer sensor records a specific gravity profile in the well. The tool is a differential-pressure measuring device with a 2-foot spacing between sensitive membrane-type pressure sensors. The average density of the fluids in the casing between the two sensors is measured. Principal applications are to define fluid contacts, locate gas entries in oil wells, and assist flowmeter interpretation in two-phase flow.

Caliper–The three-arm through-tubing caliper provides a hole-size profile. The measurement is used to interpret flowmeter surveys and to locate casing problems.

Audio* tool–Two types of Audio logs are available for noise detection and analysis. The continuous Audio log is used to detect gas and liquid entries, locate flow behind the casing, and detect leaks. A multifrequency Audio tool for stationary measurements is also available.

Gravel Pack Logging tool–The Gravel Pack Logging tool is a radioactive device that evaluates the condition of the gravel pack. It provides a quantitative analysis of the areas in the pack that need to be replaced before the well is placed on production.

Pressure-Temperature sonde–In some areas, a pressure-temperature sonde is available which provides highly accurate dynamic pressure, temperature, and density measurements. These new PTS sondes replace the standard pressure gauge, thermometer, Manometer, and Gradiomanometer sensors.

	Press. psi	Density g/cc	Temp °F
Resolution	1	0.004	0.01
Accuracy	†10	0.040	1.80

†*with dead weight tester calibration*

Specifications

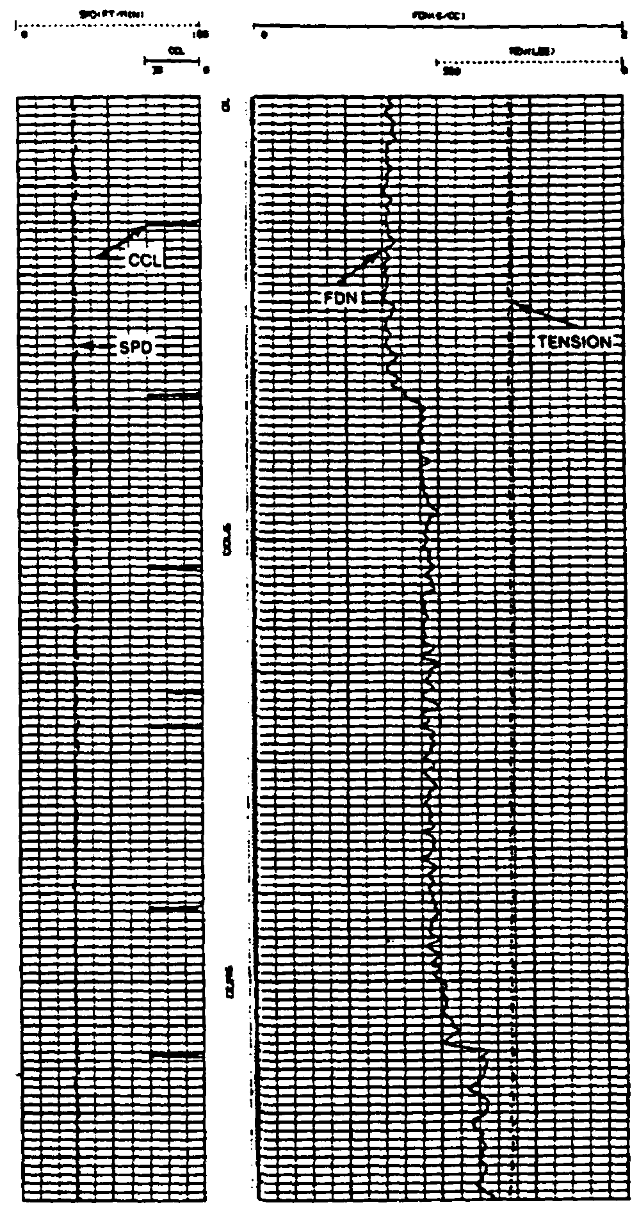
Sensor	Range	Max. Press. psi	Max. Temp °F
Fullbore Flowmeter	50 B/D min	20,000	390
Continuous Flowmeter	400 B/D min	15,000	350
Dual Tracer Ejector	—	17,500	350
Pressure Gauge	0-300° F	12,000	300
Thermometer	0-350° F	15,000	350
Manometer	0-15,000 psi	15,000	350
Gradiomanometer	0-1.6 g/cc	15,000	350
Caliper	2-8 in.	15,000	350
Audio	—	16,500	350
Gravel Pack	—	20,000	350
PTS Sensors			
Temperature	0-350° F	15,000	350
Density	0-2 g/cc	15,000	350
Pressure	0-15,000 psi	15,000	350

*Mark of Schlumberger

Fluid Density Log

The Fluid Density Log is a radioactive log of the gamma-gamma ray type. While the Gamma Ray Log is a measurement of natural gamma rays, the Fluid Density Log data is a record of the density difference between water, oil and gas, and is generated by use of a chemical gamma ray source. The density measurement is made by observing the relative absorption of gamma rays passing through the borehole fluid in a sampling channel. The basic unit of measure is a count of residual gamma rays. This counting rate is inversely proportional to the density of the sample and is a function of the activity of the gamma ray source. The log density data are recorded in grams per cubic centimeter.

The Fluid Density instrument, unaffected by high-angle boreholes, fluid viscosity or fluid velocity, is a good indicator of the type of fluid entering, leaving or present in the borehole.



APPLICATIONS:

- Locate entry of primary and secondary fluids in a 2 or 3-phase production stream
- Provide a density profile in a multi-phase production stream
- Locate borehole fluid contacts in static conditions
- Locate product levels in storage wells
- Locate tubing and casing leaks when the leaks result in multi-phase flow
- Check the operation of gas lift valves

SPECIFICATIONS:

Length (Adapter Only)		Diameter		Max. Temp.		Max. Pressure	
(ft)	(m)	(in.)	(mm)	(°F)	(°C)	(psi)	(MPa)
2'0"	0.61	1-3/4	44.4	400	204	17,000	117.2
2'6"	0.76	1-11/16	42.9	400	204	15,000	103.4

BASICS OF LOOKING AT LOGS
(Leading to Pitfalls)

Relative Volumes of Investigation

Petrophysical Thought Process

- Porosity from Logs
- Picking Values from Logs
  - Log responses
  - Thin beds

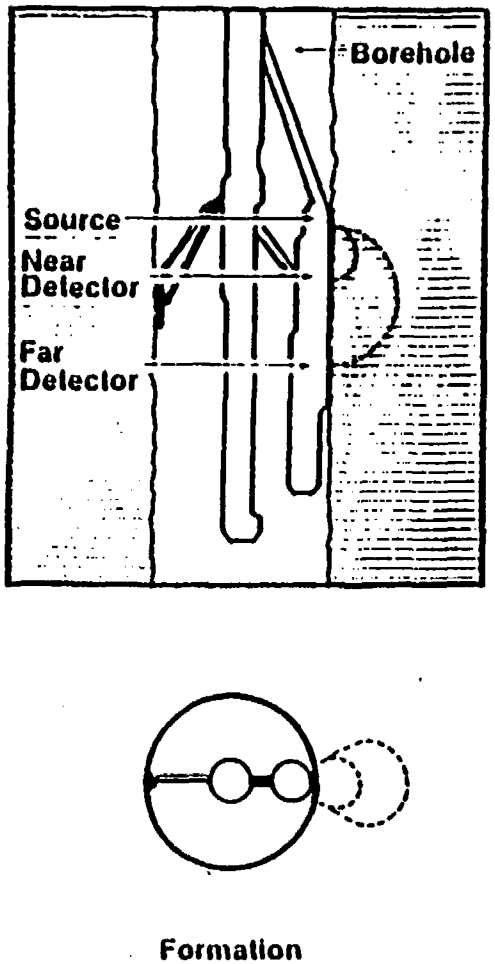
Crossplots

Effects of Borehole Size

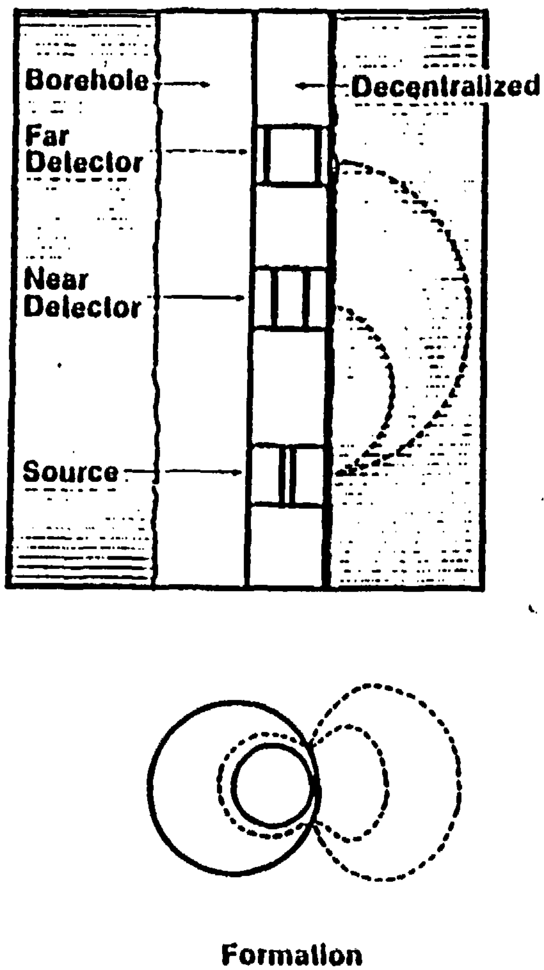
Log Calibrations

Solutions, not Problems

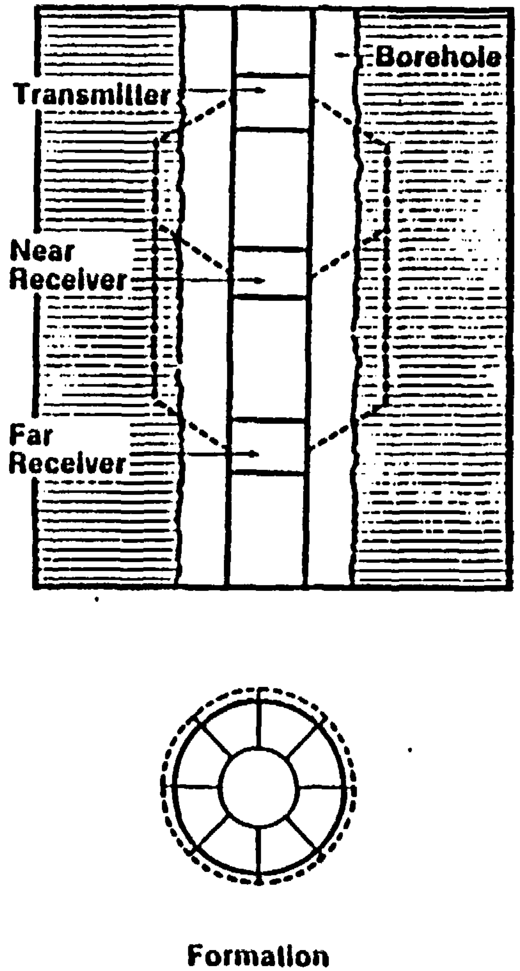
COMPENSATED DENSILOG®



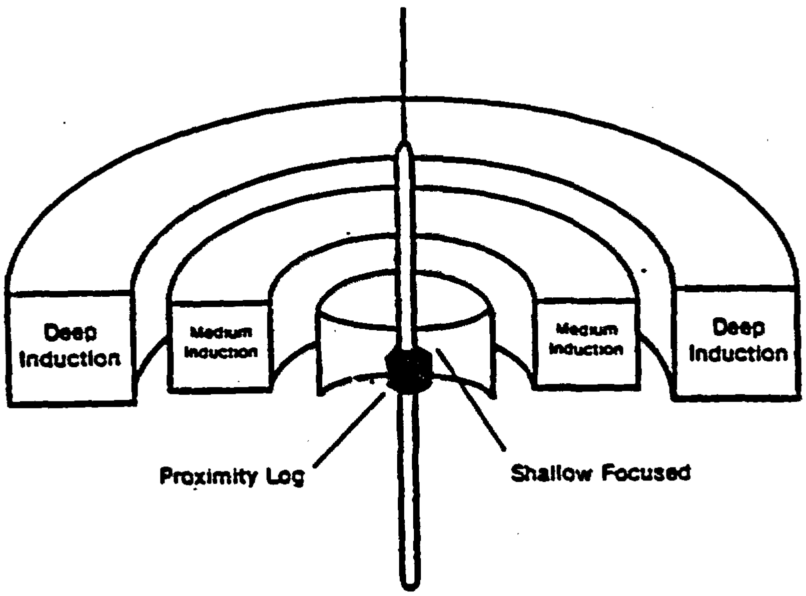
COMPENSATED NEUTRON®



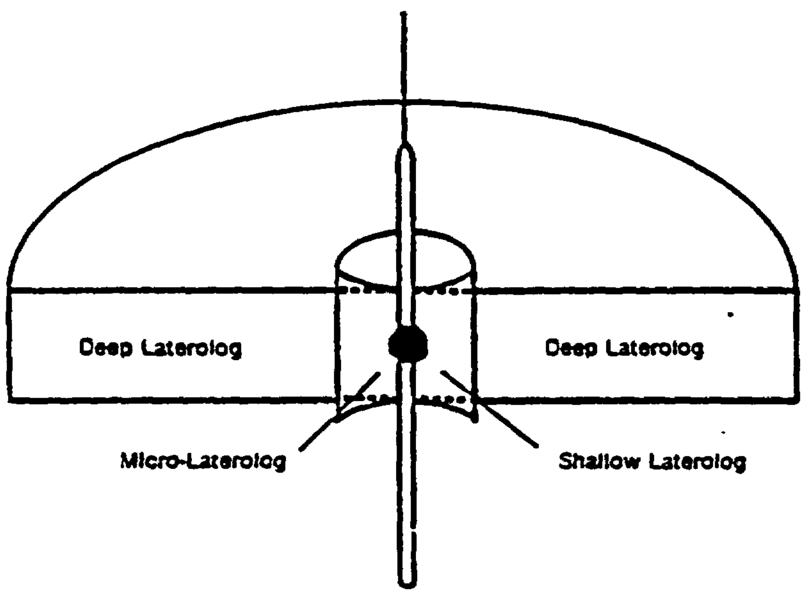
BHC ACOUSTILOG®



Dual Induction Focused Log
Volumes of Investigation



Dual Laterolog
Volumes of Investigation



PETROPHYSICAL THOUGHT PROCESS

The complexity and interdependence of modern open hole wireline log measurements has almost negated the use of "Cook Book" analysis where a number is simply picked from a log and used in a nomograph.

The wise modern investigator approaches analysis by asking the question:

"What are these measurements trying to tell me about the materials and fluids near the borewall?"

We now have a better understanding of the various influences that changes in fluid types and saturations, in matrix materials, and borehole size, etc. have on the log responses.

Using the petrophysical thought process, we investigate all possible reasons why a single log measurement may be changing values with depth. (A change in matrix porosity is not the only reason a "porosity" log changes value). By cataloging all possible petrophysical reasons for changes on all measurements in question, it is possible, through a process of elimination, to better interpret what the logs are telling us about their environment.

Using this accumulated information it is possible to group the reservoir materials into petrophysical rock types, i.e., groups of rocks which have similar log responses. In most cases, such groups are coincidental with rock groups for engineering purposes.

An understanding of the two principles presented in the following few pages is the most important difference between an earth scientist who is working with logs, and one who can make logs work for him/her.

POROSITY FROM LOGS

None of the so—called "porosity logs" actually measures reservoir porosity. Each of the three logs, acoustic, density, and neutron makes a determination of a reservoir property that can be related to porosity. When only one porosity log is available, the porosity of a reservoir cannot be determined unless the rock type (lithology) is known, or assumed.

The base line concept for porosity can be applied to all three logs. The matrix base line is the response (x—coordinate) of the log to zero porosity in that specific matrix; that is, where only rock matrix with no porosity exists opposite the tool. Departures from the base line toward positive values of porosity may be interpreted for value only when the tool is opposite the appropriate rock type.

While it certainly does not occur in nature, negative porosity has significance petrophysically. Where a porosity log gives negative numbers, the base line is no longer valid, and must be re—established to determine the porosity. Unfortunately, this is true for some positive log readings where the measurements are being made in a rock type different than the base line assumption. Figure VI—A illustrates this base line principle.

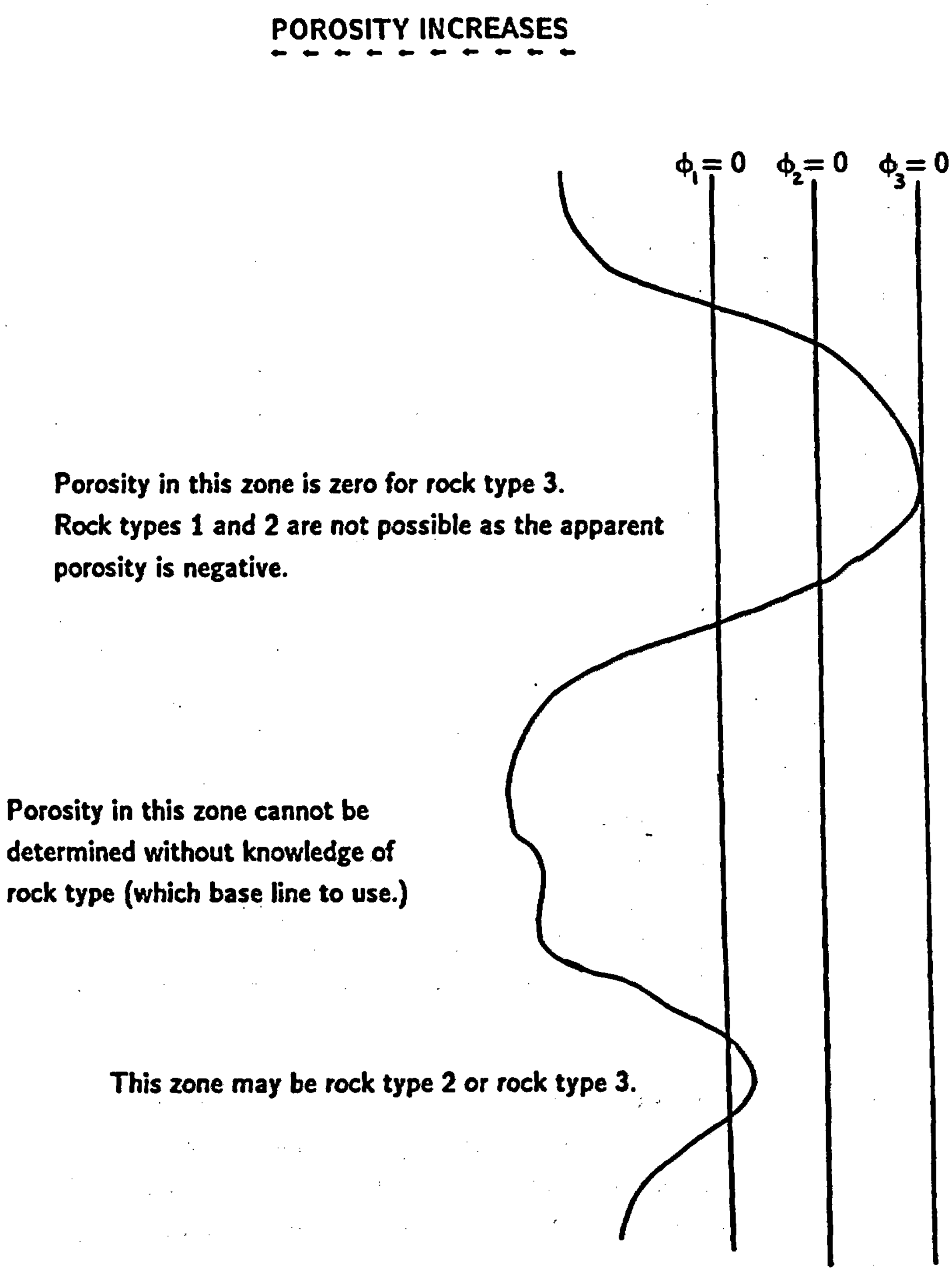


FIGURE VI–A

BASE LINE CONCEPT FOR MODERN POROSITY LOGS

THIN BED EFFECTS AND ZONING LOGS

Apparent log values within thin beds are just that – apparent values. Appropriate corrections may alter the apparent values as much as 50 – 80%, which means if you take the value directly from the log without adequate corrections, you are putting an incorrect value into a computation for porosity, Vsh, Rw, Sw, etc.

Thin bed responses may also alter accurate determination of bed boundaries, thus reducing accuracy for volumetric determinations. Important log values in a reservoir near the boundary with a thin contrasting bed may be masked by the boundary effects.

Figure VI–B is a schematic showing: (1) the ideal response of a tool, and (2) the real world response of the tool as the measurements are made through a series of beds of various thicknesses. The type of tool is not important. The importance is placed on the thickness of the bed relative to the vertical response (generally governed by a T–R spacing and/or source strength) of the tool being used.

In theory, the resultant measurement would yield the actual value in each bed as shown by the solid (squared) line. Because of boundary effects, notice that the actual response in a thin bed is never as much as the actual value – never as low when going toward lower values, and never as high when going toward higher values. Idealized bed thickness corrections would correct the apparent log reading downward or upward accordingly. Near the boundary between contrasting beds, the measurement is adversely affected by averaging over the volume of investigation and the vertical resolution of the tool. This leads to the generalization of picking the mathematical inflection point as the delineation (bed boundary) between two beds. This is satisfactory where each of the beds is a "thick" bed, but the inflection point may not describe the depth of the bed boundary, where one or both of the beds are "thin".

When picking log values "by hand" in a thin bed, it is preferable to pick the peak value (either to the right or to the left), rather than using an eyeball average. Averaging aggravates the situation, yielding an even more incorrect log value. This is the concept of petrophysical zoning, where log values are picked based on the petrophysical response of the tool.

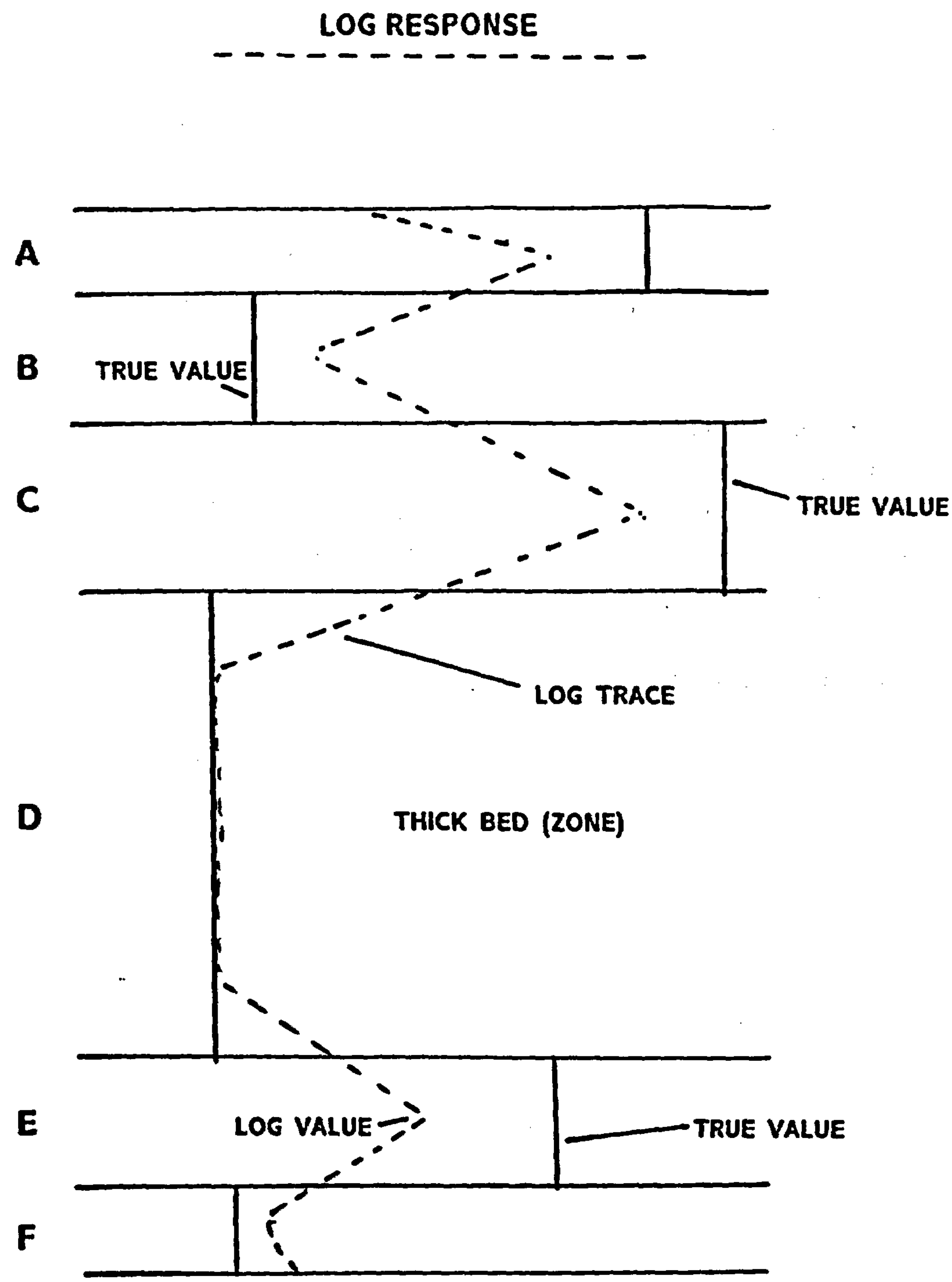


FIGURE VI–B

DIAGRAMMATIC LOG RESPONSE IN THICK AND THIN BEDS

If you have been thinking "bed" as a geologic unit (with several feet of thickness) consider now that the thickest bed on Figure VI–B is only two feet or so thick. In this case, the entire figure may be depicting a single reservoir unit (A to F) from the geologic or engineering viewpoint, but several beds (B,C,D etc.) from the petrophysical response characteristics of the tool. Now the individual changes in log values reflect changes in the petrophysical rock type, such as pore geometry, grain size or distribution, matrix material, degree of shaliness, etc., or saturations. These changes must be recognized to adequately describe the reservoir for accurate formation evaluation from logs.

Adding to the problem is the fact that we use measurements from several tools with vastly different T–R spacings (thus volumes of investigations) for our analysis. Some of these tools average over eight or more feet of material, and others only 15 to 30 inches. We normally take an absolute value for each log as the trace crosses a finite depth marker on the log, and combine the values in our various evaluation algorithms.

This is the way we pick and use log values in the computer, since computers, by definition are very precise. In the future we will have extensive mathematical modeling available via the computer, and will be able to zone reservoirs in a more realistic way.

NOTES

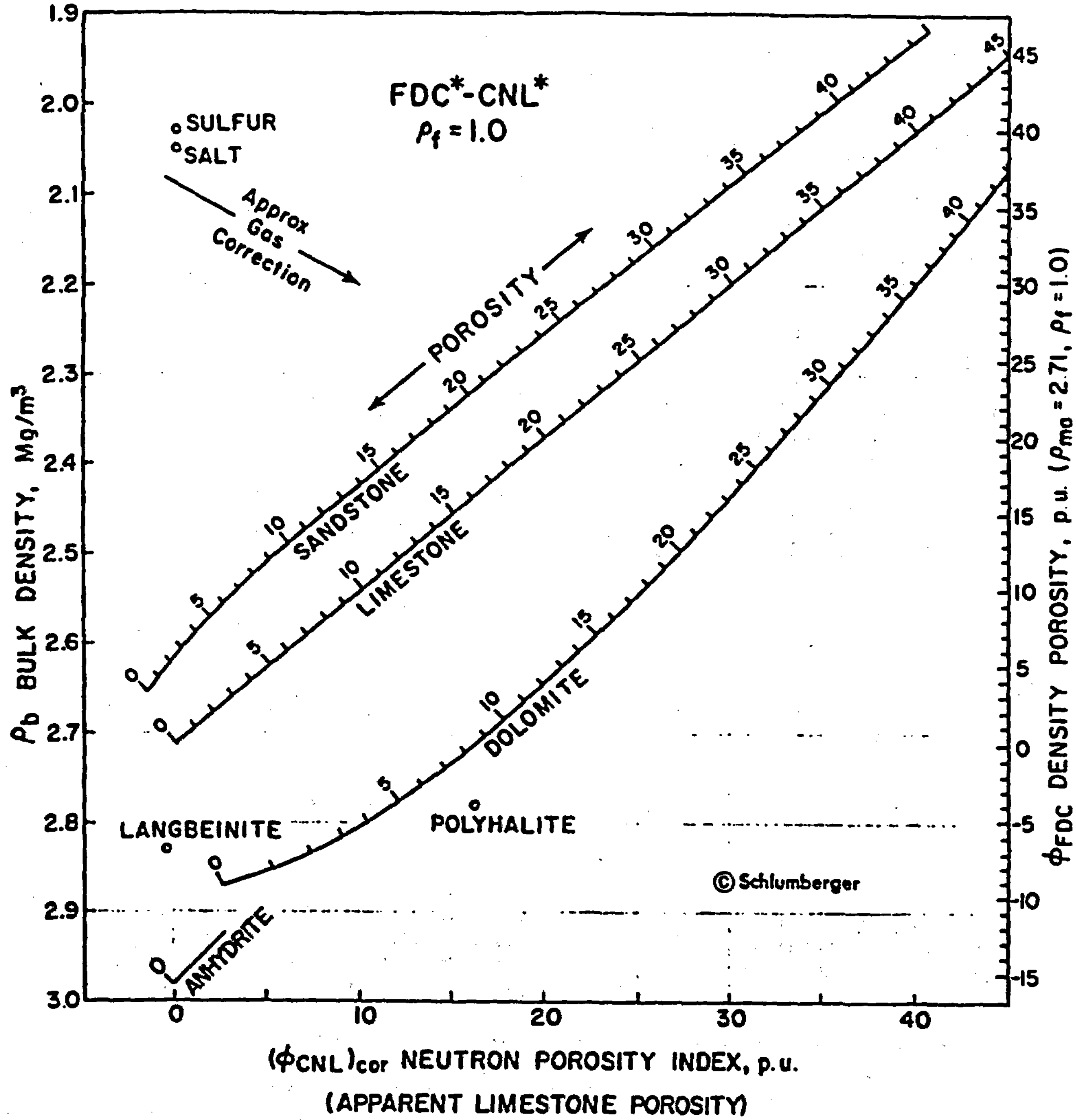


FIGURE V–E

NEUTRON–DENSITY CROSSPLOT

(AFTER SCHLUMBERGER)

BACK TO BASICS

IS THE BOREHOLE TOO BIG FOR THE MEASUREMENTS?

When working with logs one must be cognitive of any zones which may be washed out to the extent that the log measurements are invalid. When planning a prognosis for a new well, consideration should be given to the ultimate size of the borehole during logging, including any possible washouts. If this step is not taken, the result may be log data which are not useable for the desired purpose; formation evaluation, analysis, formation tops, correlation, etc.

The service companies furnish accurate data on how small a wellbore in which each of their tools or combinations will fit, which is primarily a mechanical consideration. Most of the oilfield tools are about the same diameter.

Whether a borehole is too large is highly dependent upon (1) the type of measurement (tool), and (2) specific uses for the data. If the gamma ray has a borehole effect of only 5 percent, it may be used for correlation and volume of shale estimates without correction, but if 80 percent of the signal is coming from the mud column, as in a washout, it should not be used for even the most rudimentary correlation work. Formation tops will not be descernible.

Our first job is to recognize where the data should be totally discarded, then learn how much of the log data should have borehole corrections applied before use. The following rules of thumb may be used:

1. Contact devices, such as compensated density, micro resistivity, dielectric (EPT, ect.) must have intimate pad contact, i.e., a smooth borewall regardless of borehole diameter.

2. Most contact devices start losing required pad pressure as the borehole becomes larger than about 17 inches in diameter.

3. Unless extension arms are used, contact devices should not be trusted in smooth boreholes larger than 18 - 19 inches in diameter. Some tools may be equipped with long arms extending this criterion to 20 - 21 inches.

Density, gamma ray, SP, induction and neutron (including pulsed neutron) tools may suffer significant borehole effects. Service company chartbooks should be consulted for specifics. Corrections are based on (1) actual size of the borehole, and (2) mud properties such as salinity, density, and chemistry.

While the corrections are easily made by computer where a data base has been established, the chartbooks may be used to estimate the amount of correction for work by hand. In most cases, if the chartbook calls for correcting the raw data by more than 20 percent of its value, a serious effort at making the corrections should be made before using the logs in analysis techniques.

It is wise to consider 12-1/2 inches as a maximum bit size for drilling where washouts may be a problem and where accurate log data are required. Reaming may be cheap in the long run. Remember, **YOU CANNOT RECALL A LOG FOR REPAIR.**

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Part One of Two Parts

BACK TO BASICS

LOGS SHOULD BE PART OF THE SOLUTION, NOT PART OF THE PROBLEM[sm]

Open-hole wireline logs have historically been the most universally used tool throughout the oil industry. I know of no other tool available to earth scientists that is used by so many disciplines within our work. Not unlike the old soft drink commercial, logs may also be the "most misunderstood" as well.

How many geologists use decline curves and pressure transient test results in their daily work? Have you seen a geophysicist using Mho's hardness scale or an acid bottle lately? Petroleum engineers rarely calculate acoustic impedance ratios in their daily work. Yet, all these, landmen, promoters, and others invoke logs in support of their efforts which, of itself, does not infer a real understanding of the measurements, applications, or interpretations.

Much has transpired in the field of wireline measurements since the days of normals, laterals, and even the old IES combination. The use of CNT and modern neutron logs together requires a basic understanding of their generic differences. The measurements and the accompanying calibration and recording techniques are totally different than 20 years ago. If we go back 25 years the only two logs being run then which are still being run routinely today are the total gamma ray and the SP. The use of "total gamma ray" in this context is modern and indicative; we now have means to separate out the natural occurring gamma activity into the contribution from several radioactive isotopes.

Within this 20-to 25-year transitory period, many professionals in the industry have worked with both the "old" and the "new" logs, more often than not transgressing interpretation methods. Like rock typing from logs, we cannot mix the old and new logs without definite understanding of the relationships between the measurements used to make each.

What is an "old log"? There is no definite date that can be used for this cutoff. We can, however, make several distinctions for the purpose of using old and new logs as part of our solution, thus keeping them from being part of our problem. These are categorized by the early electrical and nuclear measurements. The nuclear topics will be presented next month.

The old lateral electrode configuration resulted in a nonsymmetrical bed response, i.e., the top and bottom bed signatures were not identical. Consequently, only one value of resistivity for a bed was available. Obtaining a true resistivity, R_t, required the identification of curve shape by use of special diagrams based on the relationships between the conductivities of the target and adjacent beds, hole size, bed thickness, and tool configuration. While the old normal configuration resulted in more symmetrical response, still only one value of resistivity per bed is available.

ELECTRICAL RULE #1: Do not pick resistivity values from old electrical logs on a foot-by-foot basis. ELECTRICAL RULE #2: Do not mix old electrical logs with modern resistivity logs for correlation purposes or picking tops until after you learn how to determine bed boundaries using both types - they are different.

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LOGGING QUALITY CONTROL

LOG CALIBRATIONS

"Open hole wireline logs are calibrated at three times and two places", is how I start off the log calibration session of my Logging Quality Control seminar. The three times are (1) before, (2) during and (3) after the survey, and the two places are at the surface and in the hole.

While somewhat oversimplified it does serve as a beginning of understanding of tool calibrations for those of us who are not involved with the intricacies of tool design, electronics, or neuclear physics.

SURFACE CALIBRATIONS -Logging tools must first meet an industry standard (API) for response to the environment which is being measured - whether that be low energy natural gamma radiation, higher energy induced nuclear activity, or rock resistivity. The purpose is to maintain a standardization so that the gamma ray, bulk density, resistivity measurements, etc. provided by all service companies in the same hole, under the same conditions would be nearly identical. After all, the true resistivity of a given volume of rock is a finite value, as is the bulk density, etc.

Most of the API base standards are located at the University of Houston, and are in the form of test pits. Ideally, when a service company develops a new tool, the prototype is tested in the appropriate test pit, and the instrument response is established on a scale to represent the standard.

For development work some service companies maintain their own standards which have been matched to the API standards. The next level of physical standard, usually located at the service company field office, is used for "shop calibration". Most tools are checked in the shop at least every 30 days, and some each time the truck returns to the shop. The results of shop calibrations should be available on location for client inspection and should be included on the film with the field calibrations.

The final level for calibrating at the surface is well site calibration. Environmental chambers, test jigs, "pills", rings, and other devices are carried on the trucks to establish proper tool operation prior to making a logging run or survey.

Once the logging run is complete and the tool is out of the hole, the field calibrations are again checked to determine if there has been any instrument drift since the before survey calibrations. Once the tool passes the next shop calibrations, the cycle is complete, and you can be assured the tool was functioning properly for your logging job.

Through the sequential series of standardizations carried from the base standard through the service company system to your catwalk, the tools should operate in your well the same as they would in the API test pit. Remember -

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Part Two of Two Parts

BACK TO BASICS

LOGS SHOULD BE PART OF THE SOLUTION, NOT PART OF THE PROBLEM[sm]

(Last month we offered caution when mixing old and new resistivity logs - now a similar concern when using old and new neutron logs is outlined).

"Old" neutron logs come in as many varieties as Heinz products. Neutron logging is where the alphabet soup of mnemonics started in logging, with GNT, GNAM, PuBe, RaBe, etc. being the order of the day.

Except for the caliper, no other open hole measurement, ancient or modern, has such a broad response to the borehole. These older logs were not standardized for source-to-detector spacing, sonde diameter, or whether run centered or ecentered. The number of possible combinations of potential problem areas proliferated with the number of wireline companies offering the service.

The modern counterparts, pad epithermal, SNP (Sidewall Neutron Porosity), and dual-detector compensated, CNL (Compensated Neutron Log), have been designed using more standardized sources, source strengths, and source-to-detector spacings. The sondes are especially shielded to minimize the effects of the mud column behind the source and detectors, and the tools are run with specific relationships to the borewall where possible.

The older logs were run ecentered, sometimes with, but often without a specified standoff, or were run mid-hole by use of centralizers. In most cases a caliper measurement was not made with the run, and frequently no caliper information is available for the hole. A wise old sage once remarked, "A neutron log makes a good caliper log where the porosity is constant". He should know, he helped in the design of the tools.

Both old and new neutron logs provide a measure of the Hydrogen Index, and the intention is to convert this to total porosity of the rock near the borewall. This is done through calibration to the API neutron test pits at the University of Houston. The modern tools are calibrated in limestone porosity units (p.u.), with conversions to other lithologies being available. The older logs were calibrated with a near-logarithmic scale with the highest counts set at a low porosity (.01-.02), and the lowest counts established at .30 to .40 porosity.

NEUTRON RULE #1: Do not use old neutron logs for <u>any purpose</u> including correlation without reference to a caliper log. **NEUTRON RULE #2:** Do not substitute bit size for caliper to make hole size corrections. **NEUTRON RULE #3:** Do not transgress rock types when using an established porosity scale on a neutron log or on any "porosity log".

To make logs part of your solution, it is important to have a basic understanding of the measurements and their petrophysical significance.

Some of the petrophysical misconceptions floating around out there would knock your socks off. They are often so misused that they would make William Sheridan's Mrs. Malaprop blush.

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