Logging Fundamentals

A
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for
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Presented
by
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FORMATION EVALUATION - USE OF WELL BORE MEASUREMENT OF ELECTRICAL, NUCLEAR, ACOUSTIC, ETC. PROPERTIES OF ROCKS TO FACILITATE

- SUBSURFACE MAPPING
- DEFINITION OF LITHOLOGY
- LOCATION OF PRODUCTIVE ZONES
- DETERMINATION OF DEPTH AND THICKNESS OF FORMATIONS
- INTERPRETATION OF RESERVOIR CHARACTERISTICS AND CONTENT

PETROPHYSICS

- ROCK TYPES
- RESERVOIR ROCKS
- POROSITY SYSTEMS
- WATER AND HYDROCARBON SATURATION
- PERMEABILITY
- CAPILLARY PRESSURE
- ELECTRICAL PROPERTIES
- NUCLEAR PROPERTIES
- ACOUSTICAL PROPERTIES

ROCK TYPES

ROCK CHEMISTRY CLASSIFICATION

SANDSTONES -- SiO_2

INCLUDE SILT AND CHERT

LIMESTONE -- $CaCO_3$

INCLUDE CHALK

DOLOMITE -- $CaMg(CO_3)_2$

ANHYDRITE -- $CaSO_4$

GYPSUM -- $CaSO_4$ AND CRYSTALLINE WATER

SHALE -- MIXTURE OF CLAY, SILT, AND SAND GRAINS

MAIN TYPES OF CLAY

KAOLINITE

ILLITE

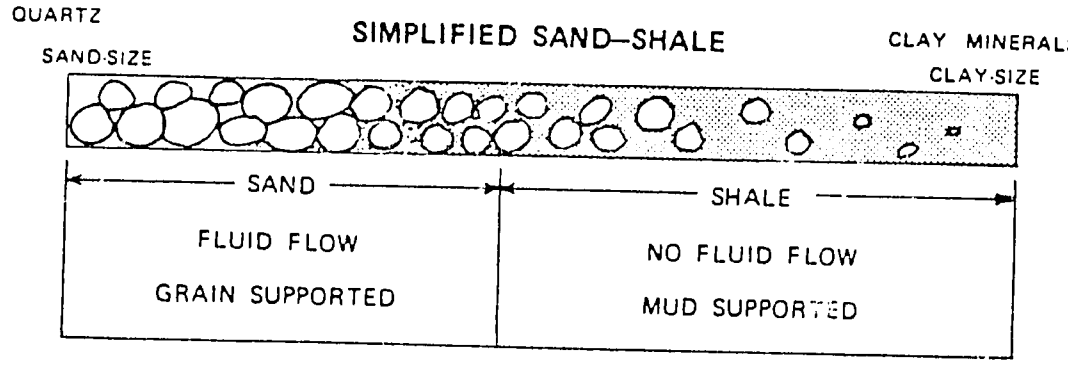
BENTONITE

CLAY DISTRIBUTIONS

ALLOGENIC (DETRITAL ORIGIN)

AUTHIGENIC (DIAGENETIC ORIGIN)

SPWLA SHALY SAND
REPRINT VOLUME
JULY 1982



CLASTIC SEDIMENTARY ROCKS

SEDIMENT	SIZE	ROCK
GRAVEL	2 MM	CONGLOMERATE
SAND	2-1/16 MM	SANDSTONE
SILT	1/16-1/256 MM	SILTSTONE
CLAY	1/256 MM	SHALE

NONCLASTIC SEDIMENTARY ROCKS

ROCK	PHYSICO-CHEMICAL	ORGANIC	SECONDARY
COAL		X	
ROCK SALT	X		
GYPSUM	X		
CHERT	X	X	X
LIMESTONE	X	X	
DOLOMITE	X RARE		X

RESERVOIR ROCKS

NATURE - SOLID ROCK FRAMEWORK
PORE SPACE

HYDROCARBONS ARE FOUND IN

SEDIMENTARY ROCKS - SANDSTONES, LIMESTONES AND DOLOMITES

ONLY RARELY IN SHALES, IGNEOUS AND METAMORPHIC ROCKS

SANDSTONES (CLASTICS)

QUARTZOSE -- LITTLE OR NO SHALE CONTENT -- STABLE MINERALS

GRAYWACKE -- DIRTY SANDSTONE -- CONTAINS SHALE -- STABLE AND UNSTABLE MINERALS

ARKOSE -- DEPOSITION NEAR SOURCE OF ROCKS -- GRANITE WASH

LIMESTONES

ACCRETIONARY -- BIOTHERMS (REEFS) AND BIOSTROMS

CLASTIC -- FROM WEATHERED LIMESTONE LANDMASS

CHEMICAL -- DIRECT PRECIPITATION

DOLOMITE -- MOLECULAR REPLACEMENT OF CALCIUM BY MAGNESIUM

POROSITY SYSTEMS

ABSOLUTE POROSITY -- TOTAL PORE VOLUME -- RESISTIVITY TOOLS

EFFECTIVE POROSITY -- INTERCONNECTED PORE VOLUME -- NEUTRON TOOLS

PRIMARY POROSITY -- DEVELOPED DURING DEPOSITION, COMPACTION AND CEMENTATION -- INTERGRANULAR POROSITY

DEPENDENT ON -

GRAIN SHAPE AND ARRANGEMENT

ANGULARITY AND DISTRIBUTION OF PARTICLE SIZE

AMOUNT OF CLAY AND CEMENTATION

POROSITY INCREASES FOR

- SMALLER GRAIN SIZE AND GREATER ANGULARITY
- DECREASE IN RANGE OF PARTICLE SIZE

POROSITY RANGE -- 10% TO 35%

TEND TO BE LOWER FOR DEEPER AND OLDER ROCKS -- DUE TO WEIGHT OF OVERBURDEN AND CEMENTATION

SHALES FOLLOW SAME TREND EXCEPT WITH LOWER POROSITIES

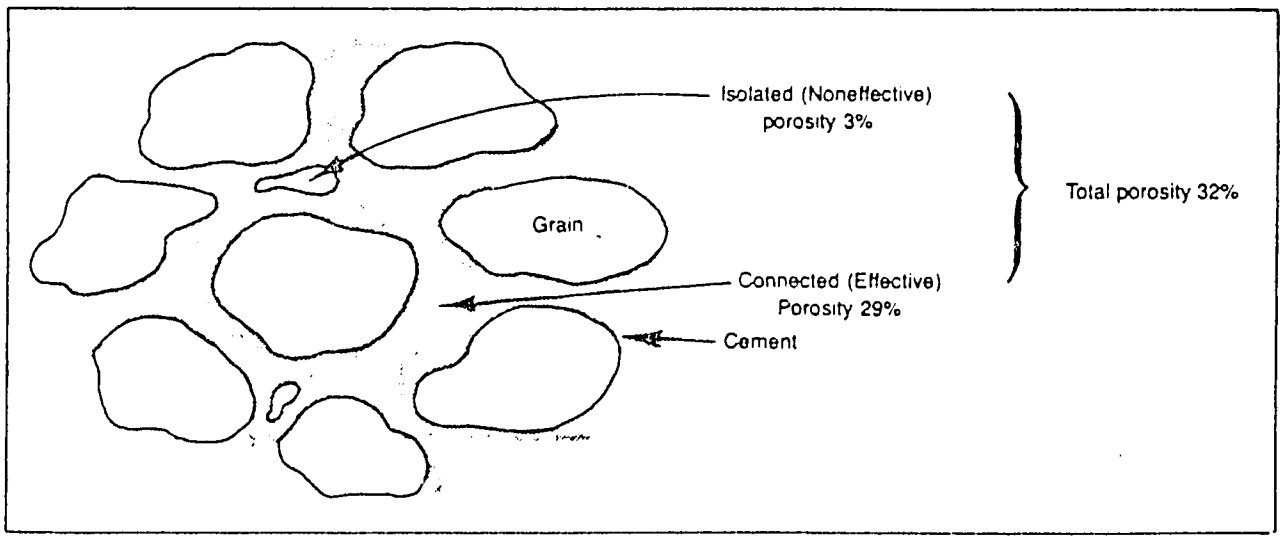
POROSITY SYSTEMS - CONT.

SECONDARY POROSITY

PORE SPACE DEVELOPED AFTER DEPOSITION AND COMPACTION BY LEACHING OR FRACTURING

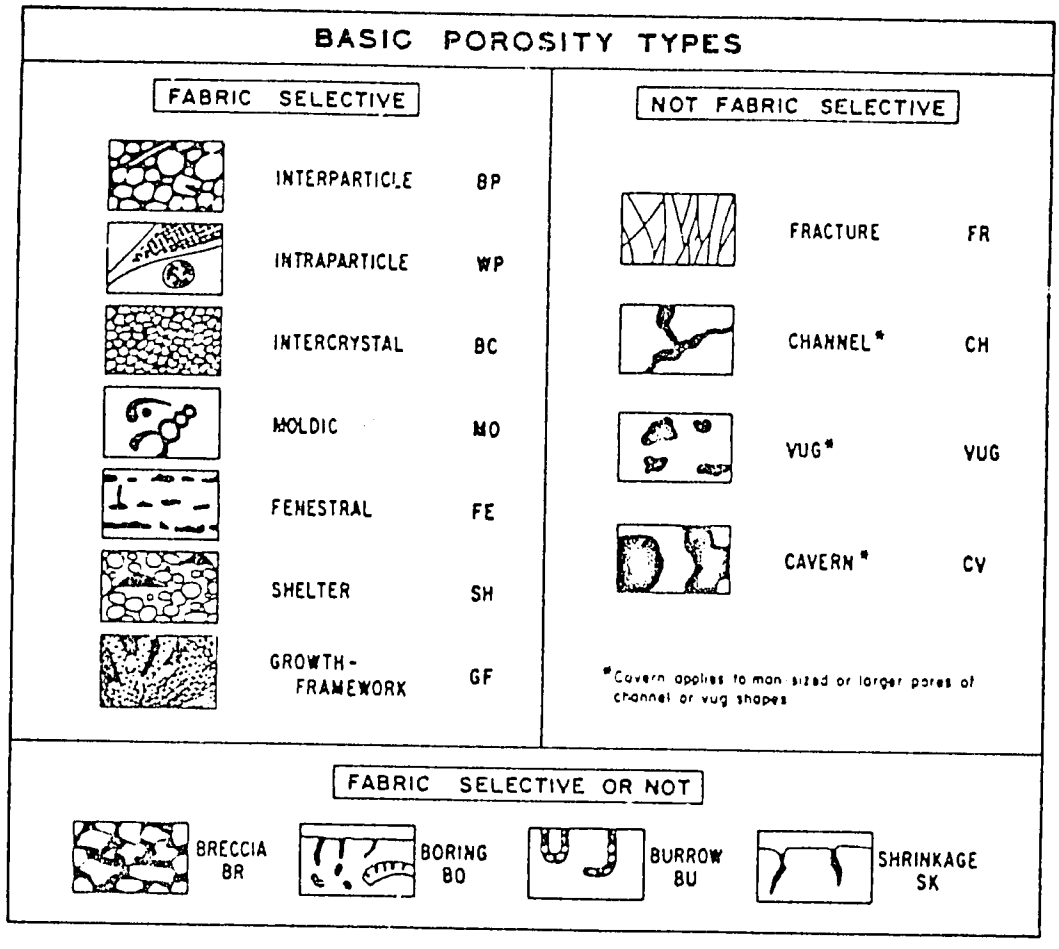
FORMS -- VUGULAR PORE OPENINGS
SOLUTION CAVITIES
FRACTURES

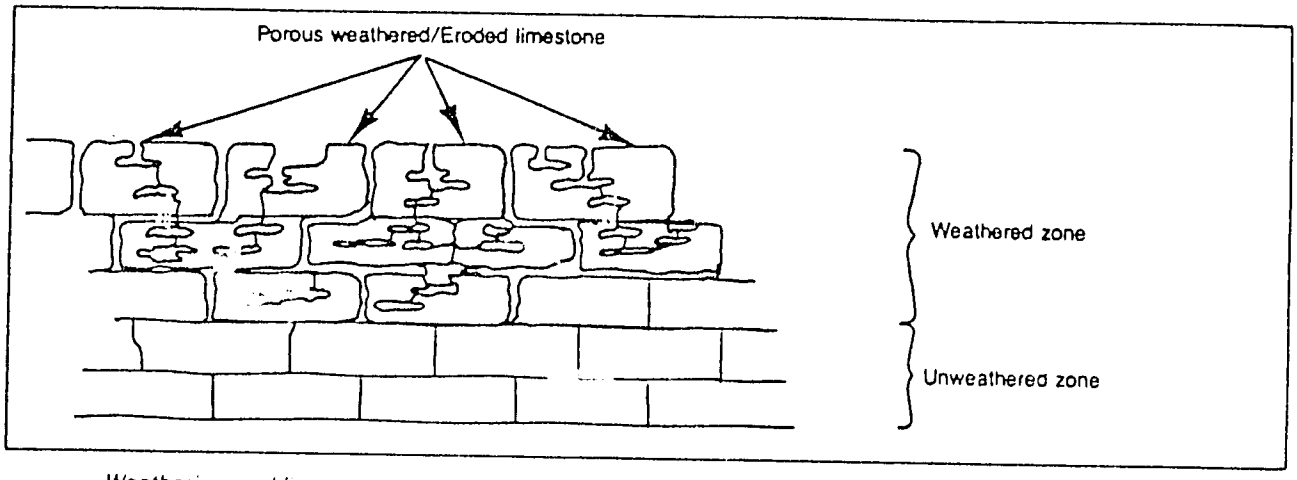
DOLOMITIZATION OF LIMESTONE CAN CAUSE MINERAL SHRINKAGE OF 12%



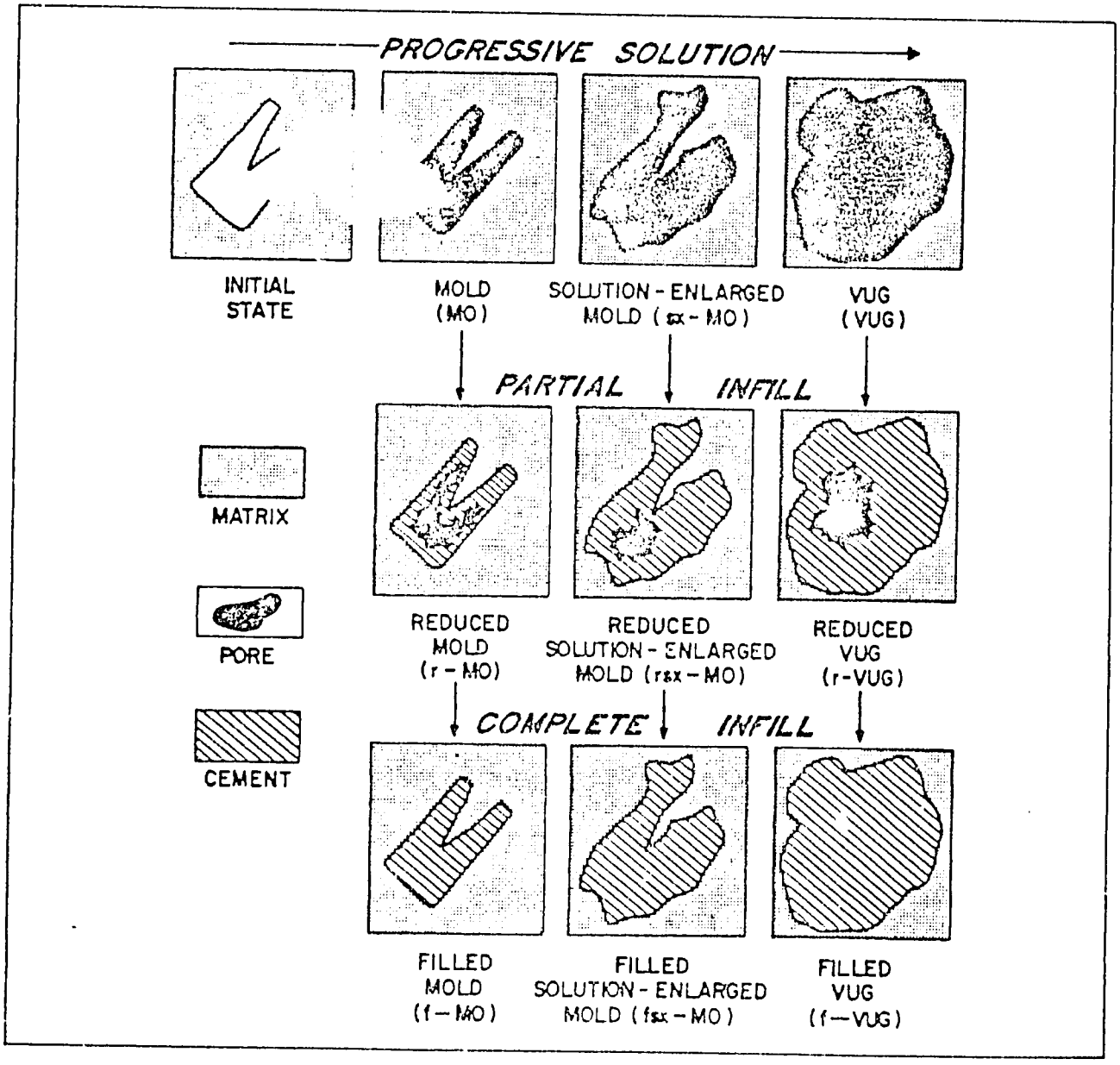
Effective, noneffective, and total porosity

FROM CHOQUETTE AND PRAY,
1970 PERMISSION TO PUBLISH
AAPG





Weathering and limestone porosity



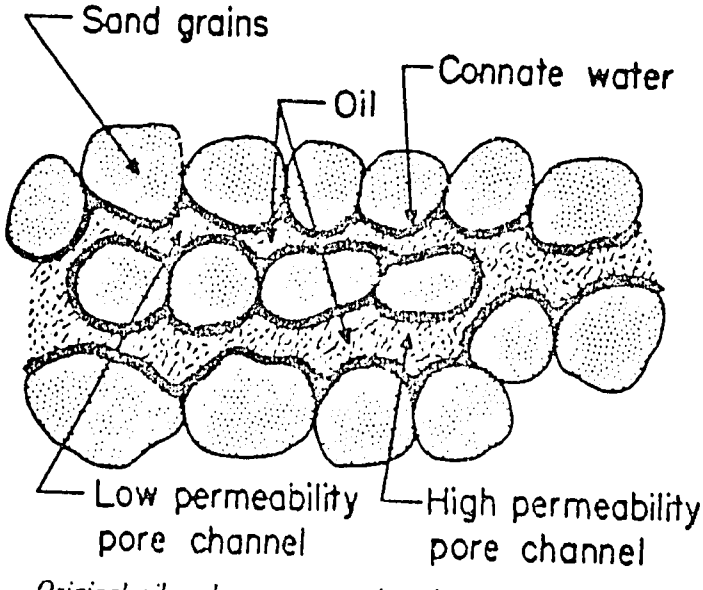
Mo.dic porosity evolution. From Choquette and Pray, 1970. Permission to publish by AAPG.

PORE SPACE SATURATIONS

ROCK PORES ARE FULL OF FLUIDS - WATER, OIL OR GAS

OVER 99% OF POROUS RESERVOIRS CONTAIN 100% WATER

IF YOU CAN'T CALCULATE 100% WATER IN A WATER ZONE - STOP



Original oil and water saturations in pore space at equilibrium.
(Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*

PERMEABILITY -

ABILITY OF ROCK TO PERMIT FLOW OF FLUIDS

PRESENCE OF POROSITY IS NOT ENOUGH - MUST ALSO HAVE PERMEABILITY

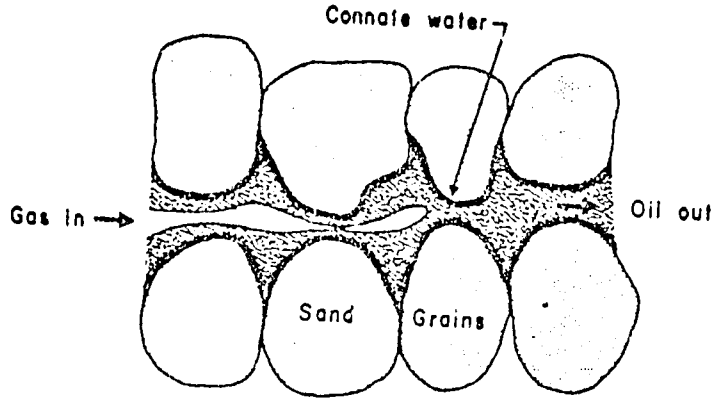
CONTROLLING FACTORS

- SIZE OF PORES NEAR GRAIN CONTACT POINTS
- AVERAGE GRAIN SIZE
- AMOUNT AND DISTRIBUTION OF SHALE
- TYPE OF CLAY
- TYPE AND AMOUNT OF SECONDARY POROSITY

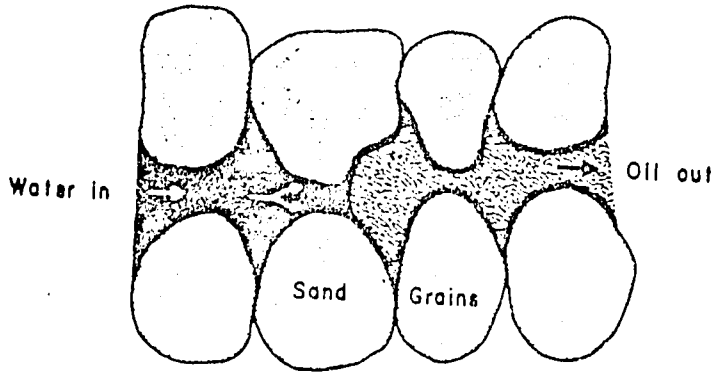
ABSOLUTE PERMEABILITY -- K

EFFECTIVE PERMEABILITY -- K_F

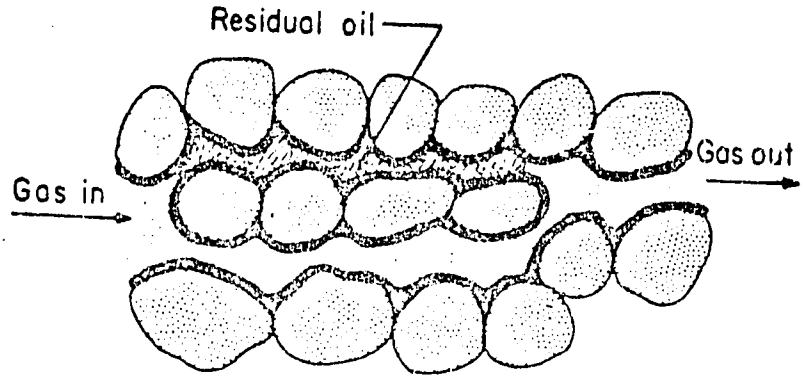
RELATIVE PERMEABILITY -- K_F/K



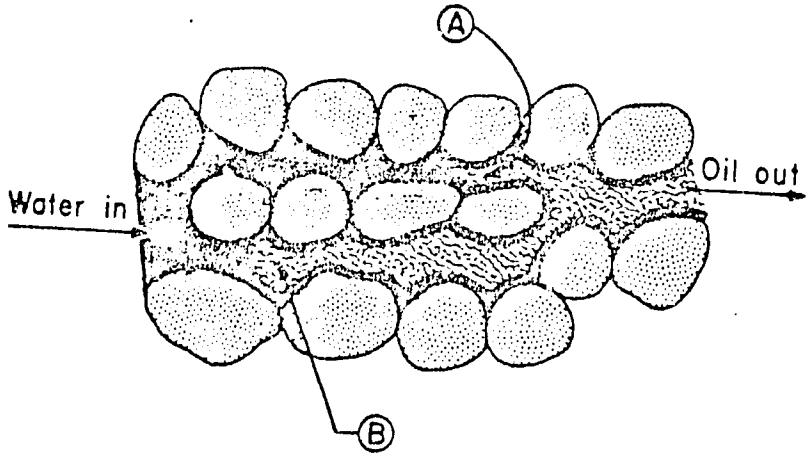
Natural displacement of oil by gas in a single pore channel.
(Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*



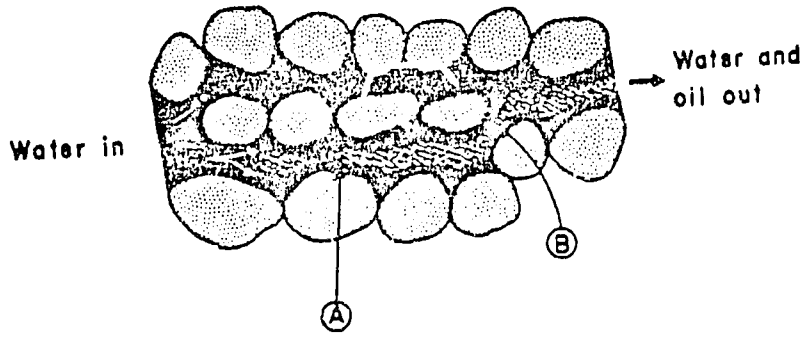
Natural displacement of oil by water in a single pore channel.
(Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*



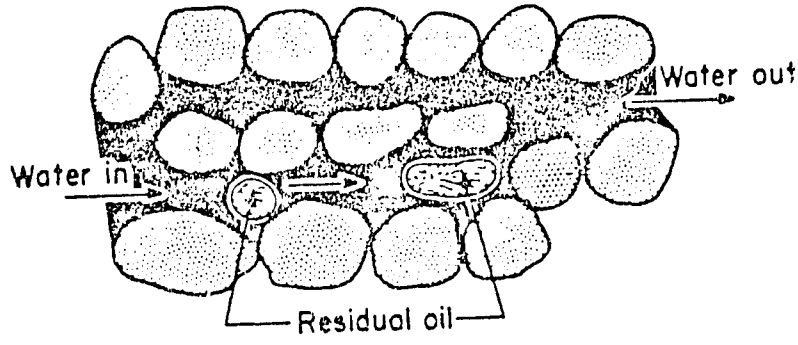
Gas displaces oil first from high permeability pore channels. Residual oil occurs in lower permeability pore channels. (Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*



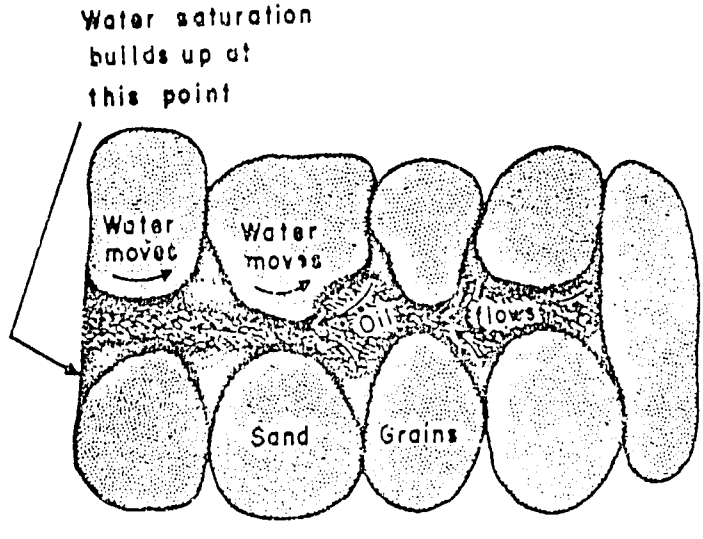
Capillary forces cause water to move ahead faster in low permeability pore channel (A) when water is moving slow through high permeability pore channel (B). (Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*



As thread of oil gets smaller, interfacial tension increases in the film at restricted Points A and B, where film subsequently breaks. (Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*



Water drive leaves residual oil in sand because surface films break at restrictions in sand pore channels. (Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*



Capillary pressure gradient causes oil to move out and water to move into a dead-end pore channel when sand is water-wet. (Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*

ROCK ELECTRICAL PROPERTIES

FORMATION FACTOR -- $F = \frac{R_O}{R_W}$

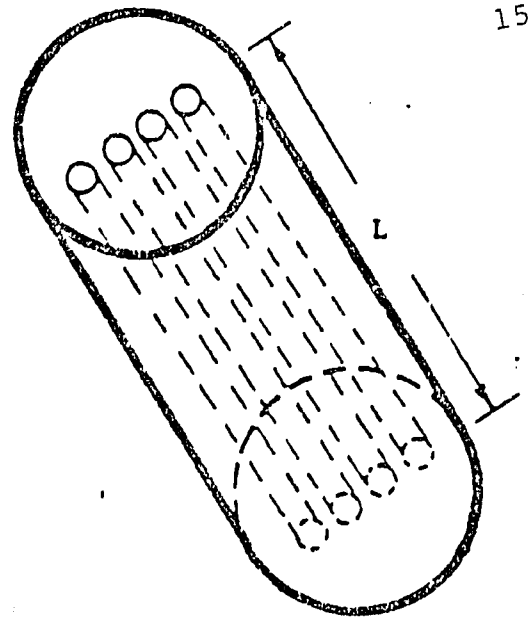


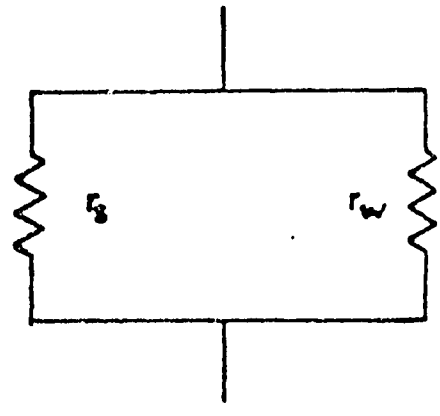
Figure 2
Insulator Core

$$\frac{1}{R_O} = \frac{1}{R_S} + \frac{1}{R_W}$$

R -- RESISTANCE, OHMS
O -- TOTAL SYSTEM
S -- ROCK MATRIX
W -- WATER

SINCE $R_S = \infty$

$R_O = R_W$



RESISTIVITY -- R

$$R \propto \frac{L}{A} \quad \text{OR} \quad R = \frac{RL}{A}$$

SUBSTITUTION ABOVE

$$\frac{R_O L}{A} = \frac{R_W L}{A\phi}$$

Figure 3
Rock Resistance Circuit

THUS

$$\frac{R_O}{R_W} = \frac{AL}{A\phi L} = \frac{\text{BULK VOL.}}{\text{PORE VOL.}} = \frac{1}{\phi} = F$$

FORMATION FACTOR - CONT.

RELATING THE IDEAL SYSTEM TO ACTUAL ROCK SYSTEMS GIVES

$$F = \frac{Ro}{Rw} = \frac{A}{\phi^m}$$

Ro -- ROCK RESISTIVITY WHEN Sw = 100%

Rw -- RESISTIVITY OF SATURATING WATER

A -- CONSTANT

M -- CEMENTATION FACTOR

$$M = F \left\{ \begin{array}{l} \text{ROCK PHYSICAL PROPERTIES} \\ \text{GRAM SIZE} \\ \text{CEMENTATION} \end{array} \right\}$$

<u>WIDELY USED MODELS</u>

$$F = \frac{.62}{\phi^{2.15}}$$ CLEAN SANDSTONES (HUMBLE)

$$F = \frac{1}{\phi^2}$$ CLEAN LIMESTONES (ARCHIE)

FORMATION FACTOR - CONT.

CAROTHERS STUDY (LOG ANALYST, SEPT. - OCT., 1968)

LABORATORY MEASUREMENTS ON 793 SS SAMPLES AND 188 CARBONATES COVERING VARIOUS AGES, FORMATIONS AND AREAS IN USA

$$F = \frac{1.45}{\phi^{1.46}}$$ SANDSTONES

$$F = \frac{0.85}{\phi^{2.14}}$$ LIMESTONES

CAROTHERS AND PORTER STUDY (SPWLA TRANS. 1970)

DENSITY LOG AND RESISTIVITY LOG MEASUREMENTS

$$F = \frac{2.45}{\phi^{1.08}}$$ PLIOCENE SS IN SOUTHERN CALIFORNIA

$$F = \frac{1.97}{\phi^{1.29}}$$ MIOCENE SS IN TEXAS - LA GULF COAST

FORMATION FACTOR - CONT.

WHAT DO THE F VS ϕ STUDIES SHOW?

LITTLE AGREEMENT WITH EACH OTHER OR WITH HUMBLE MODEL

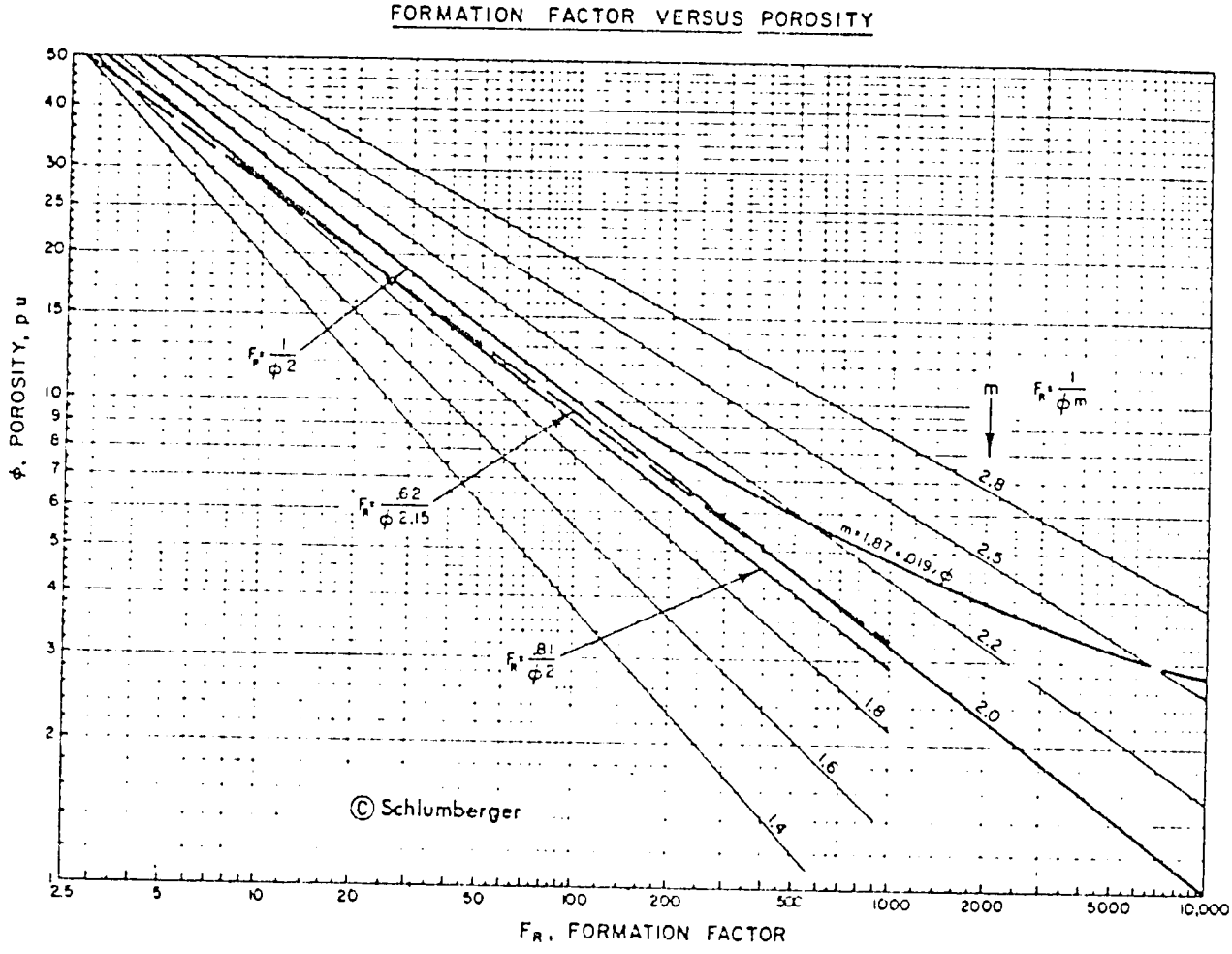
ANY F VS ϕ RELATIONSHIP MAY NOT PERTAIN TO MANY RESERVOIRS

WIDE APPLICATION OF A F VS ϕ RELATIONSHIP CAN CAUSE ERRORS OF 10 TO 20% OR MORE

MOST MODELS WERE DEVELOPED FOR CLEAN ROCKS (LESS THAN 10% SHALE) HAVING PRIMARY POROSITY

SHALES TEND TO INCREASE R_o AND DECREASE R_T

FORMATION FACTOR VERSUS POROSITY



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: $F_R = 1/\phi^m$ $m = 1.87 + 0.019/\phi$

FORMATION FACTOR - CONT.

LABORATORY DETERMINATION

$$E = RI = \frac{L\,R_0}{A}\,I \qquad \text{OHM'S LAW}$$

USE STATISTICAL SAMPLE OF CORE PLUGS

SATURATE EACH PLUG 100% WITH BRINE OF RESISTIVITY R_W

MEASURE E, L, A, I, ϕ AND COMPUTE R_0. THEN

$$\frac{R_0}{R_W} = F = \frac{A}{\phi^M}$$

$$\text{LOG } R_0 = \text{LOG } A - M \text{ LOG } \phi + \text{LOG } R_W$$

PLOT LOG R_0 VS LOG ϕ TO DETERMINE M (SLOPE) OF THE LINEAR PLOT. THEN SELECT ANY POINT ON PLOT AND COMPUTE A.

FORMATION FACTOR - CONT.

DETERMINATION FROM LOG DATA

LET $\frac{R_T}{R_O} = I$ OR $R_T = IR_O = FR_W I$

OR $R_T = \frac{A}{\phi^M} R_W I$

$\text{LOG } R_T = \text{LOG } A - M \text{ LOG } \phi + \text{LOG } R_W + \text{LOG } I$

FOR $S_W = 100\%$ $R_T = R_O$ AND $I = 1.0$

THUS $\text{LOG } R_O = \text{LOG } A - M \text{ LOG } \phi + \text{LOG } R_W$

PICKETT (SPE 1966)

OVER INTERVAL OF INTEREST READ POROSITIES FROM A POROSITY LOG AND CORRESPONDING RESISTIVITIES FROM A RESISTIVITY LOG

PLOT $\phi_{APPT.}$ VS $R_{T\ APPT.}$ ON LOG - LOG GRAPH

DRAW A LINEAR LINE THROUGH DATA FOR $I = 1.0$, $S_W = 100\%$ R_O LINE.

FORMATION FACTOR - CONT.

METHOD ASSUMES

FORMATION INTERVAL OF SINGLE LITHOLOGY

PORTIONS OF INTERVAL CONTAIN S_W = 100%

INTERVAL AND R_O LINE HAVE SAME M, R_W, A AND I

NOTE THAT IN PICKETT METHOD THE SLOPE OF THE R_O LINE IS M

IF THE R_O LINE IS EXTRAPOLATED TO S_W = 100%

$$F = \frac{R_O}{R_W} = \frac{A}{\phi^M} = A = 1.0$$

OR

$$R_O = A\ R_W$$

IF R_W CAN BE OBTAINED FROM AN INDEPENDENT SOURCE, SOLVE FOR "A" OTHERWISE GET $R_W = R_O$ @ ϕ = 100% AND "A" = 1.0

THE LOG ANALYST SEPT. - OCT., 1968

A STATISTICAL STUDY OF THE FORMATION FACTOR RELATION

by
JAMES E. CAROTHERS
Phillips Petroleum Co., Bartlesville, Oklahoma

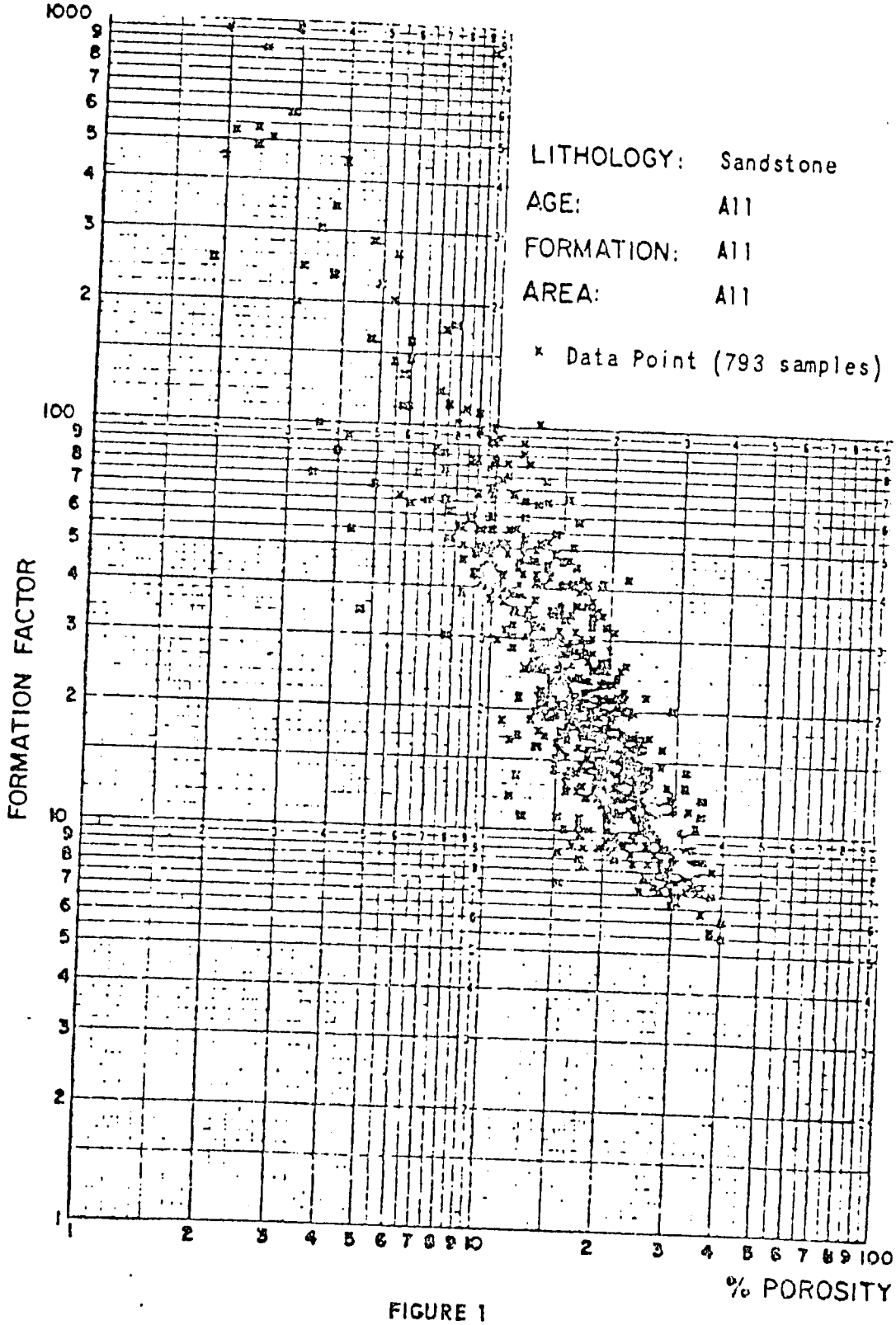
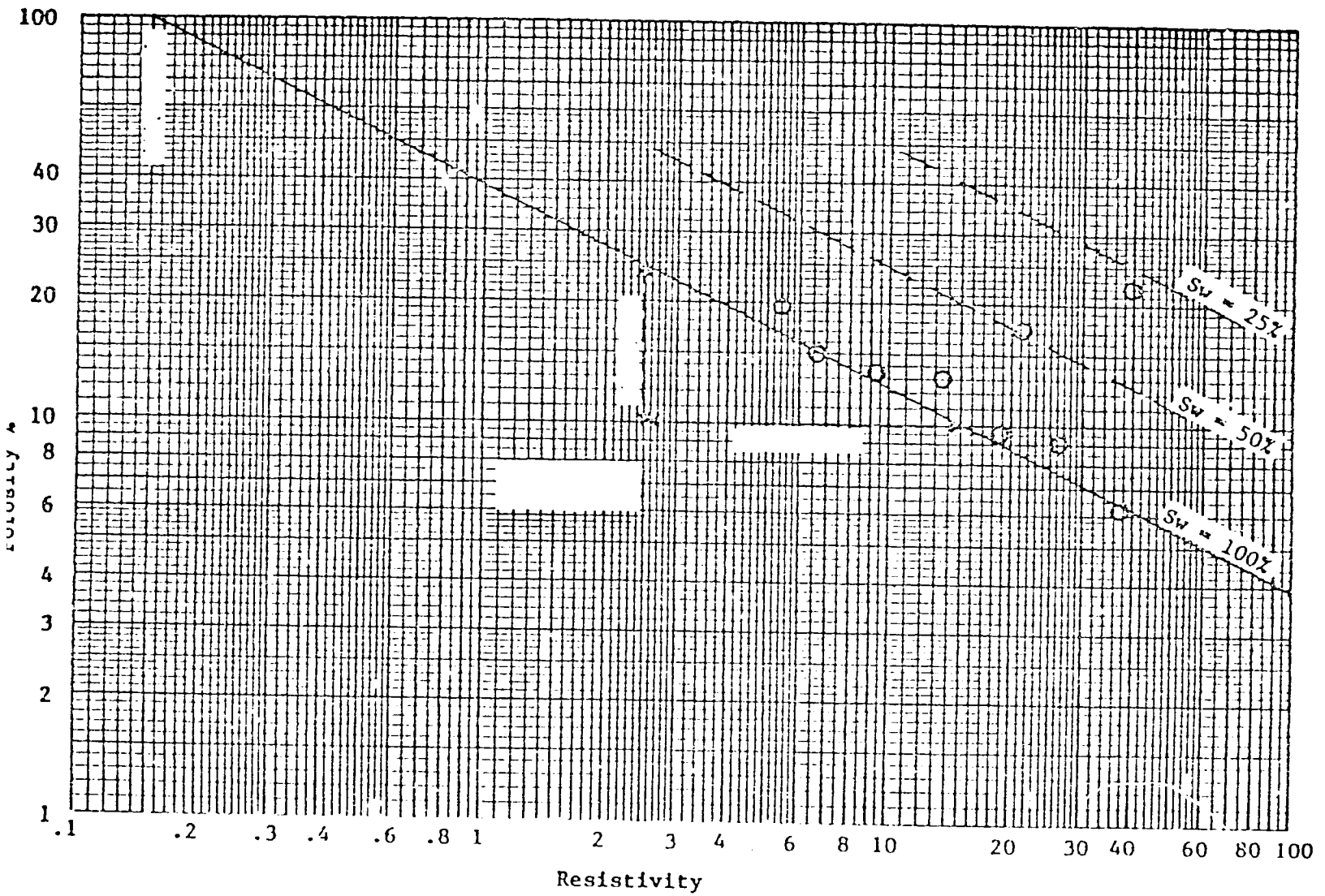


FIGURE 1

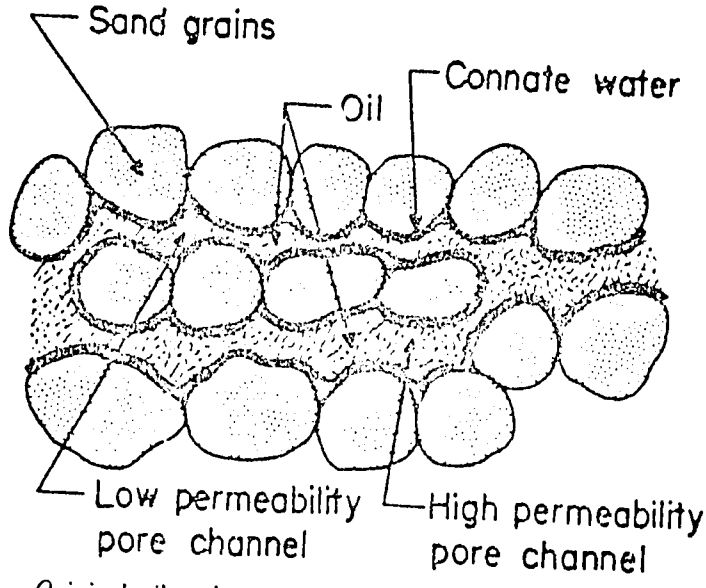
A log-log resistivity-porosity crossplot



ELECTRICAL PROPERTIES

WATER SATURATION

CONSIDER A TWO-PHASE SYSTEM WHERE HYDROCARBONS ARE PRESENT IN THE PORES WITH WATER



Original oil and water saturations in pore space at equilibrium. (Courtesy JOURNAL OF PETROLEUM TECHNOLOGY—*June, 1958.)*

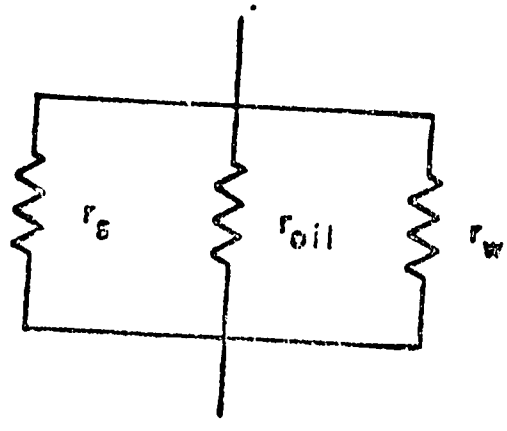


Figure 6
Rock Circuit with Oil and Water

WATER SATURATION - CONT.

$$\frac{1}{R_T} = \frac{1}{R_W} + \frac{1}{R_{HC}} + \frac{1}{R_S}$$

OR $R_T = R_W$

WHERE

$$R_W = \frac{R_W L}{A \; S_W} \qquad \text{AND} \qquad R_T = \frac{R_T L}{A}$$

THUS

$$\frac{R_T L}{A} = \frac{R_W L}{A \cancel{\phi} S_W}$$

FOR IDEAL SYSTEM $F = \frac{1}{\cancel{\phi}}$ AND

$$\frac{R_T}{R_W} = \frac{F}{S_W} \qquad \text{OR}$$

$$S_W = \frac{F \; R_W}{R_T} \qquad \text{FOR IDEAL SYSTEM}$$

WATER SATURATION - CONT.

ARCHIE (TRANS. AIME 1942) DETERMINED EXPERIMENTALLY THAT A BETTER MODEL FOR CLEAN ROCKS WAS

$$S_W = \left(\frac{F\ R_W}{R_T}\right)^{1/N}$$

"N" IS THE SATURATION EXPONENT AND DEPENDS ON

- WETTING MECHANISM
- SURFACE AREA
- TORTUOSITY
- ETC.

VALUES OF "N"

CLEAN ROCKS	$N \approx 2.0$
MODERATELY SHALY ROCKS	$N \approx 1.7$ TO 1.9
VERY SHALY ROCKS	$N \approx 1.5$ TO 1.7

ELECTRICAL PROPERTIES

FORMATION WATERS

ELECTRIC CURRENT FLOW IN --

- METALLIC CONDUCTOR BY ELECTRON FLOW
- AQUEOUS SOLUTION BY MOVEMENT OF IONS

ROCK CONDUCTIVITY IS AFFECTED BY

- POROSITY
- WATER SATURATION
- PPM SALTS IN WATER
- SALT COMPOSITION
- TEMPERATURE
- SHALE CONTENT
- MINERAL CONTENT OF ROCK (CONDUCTIVE SOLIDS - PYRITE AND SULFIDE ORES)

TEMPERATURE EFFECTS ON RESISTIVITY

METALLIC CONDUCTIVITY -- ↗ AS TEMPERATURE ↙

WATER CONDUCTIVITY -- ↗ AS TEMPERATURE ↗

(AS T ↑, μ_W ↓, ION MOVEMENT ↗, DRAG ↙)

Figure 8

VARIATION IN VISCOSITY AND RESISTIVITY WITH TEMPERATURE

(FOR 5000 PPM SOLUTION)

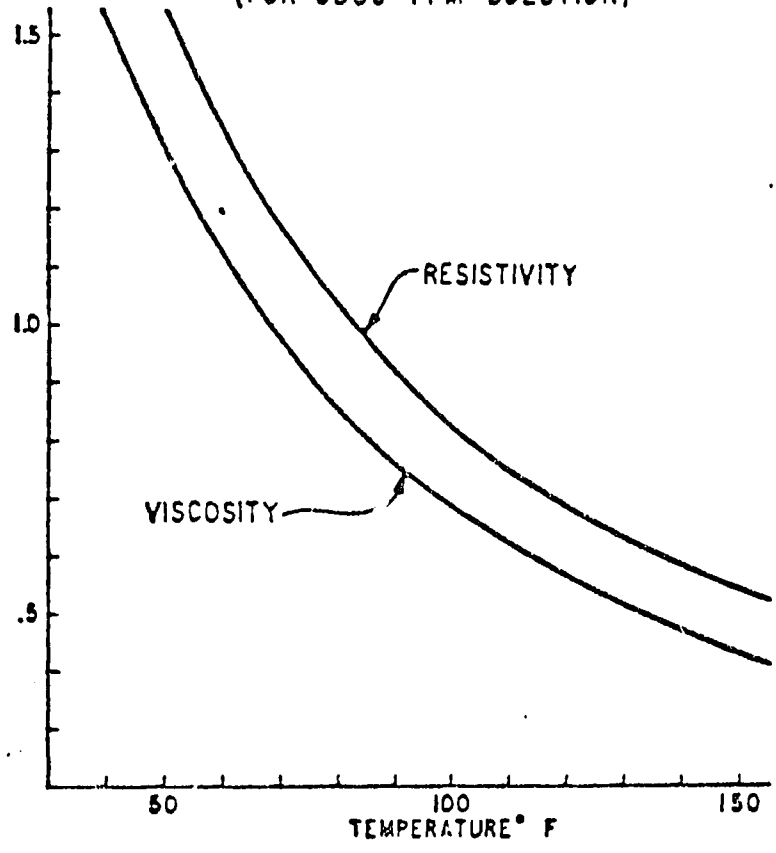
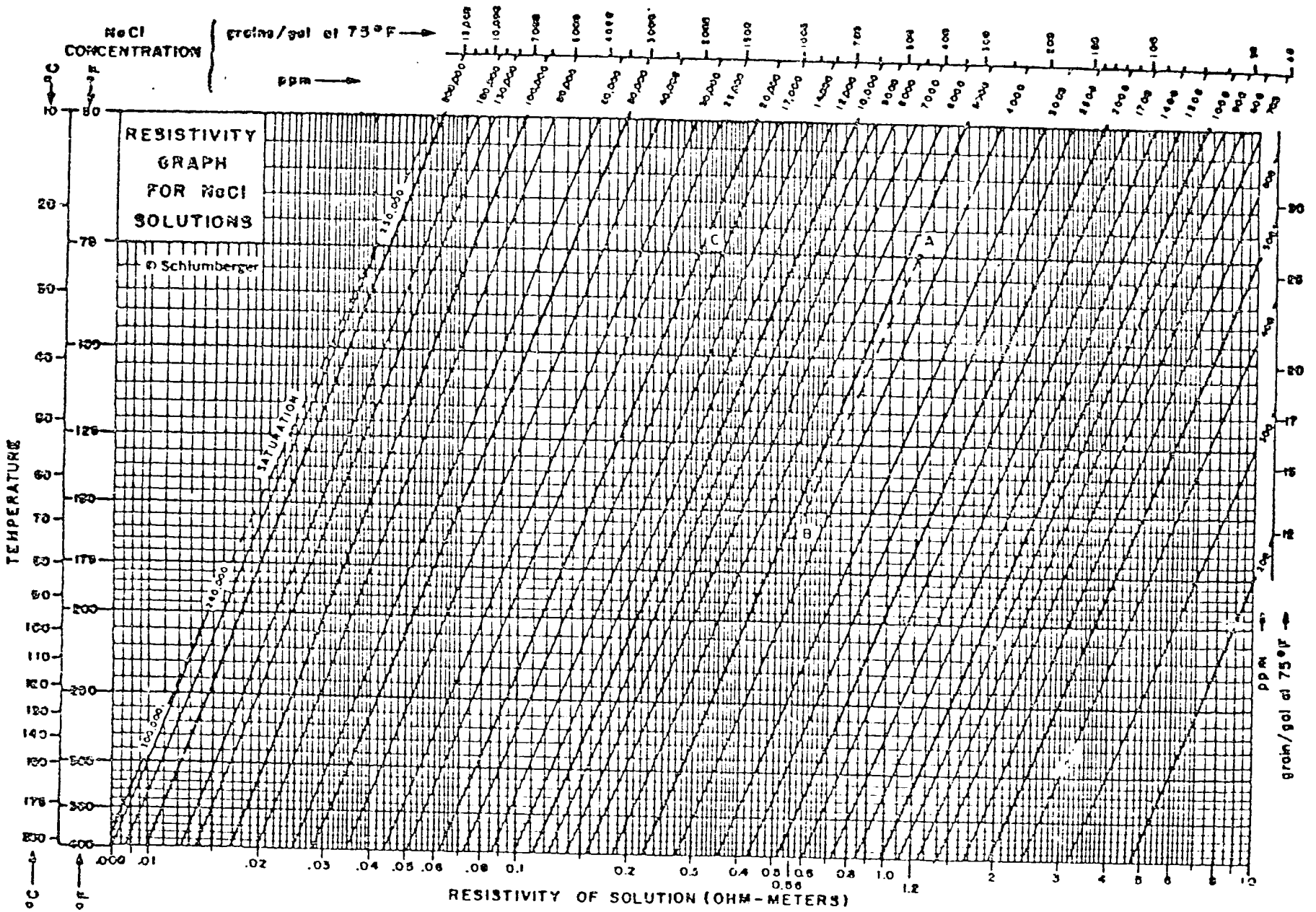
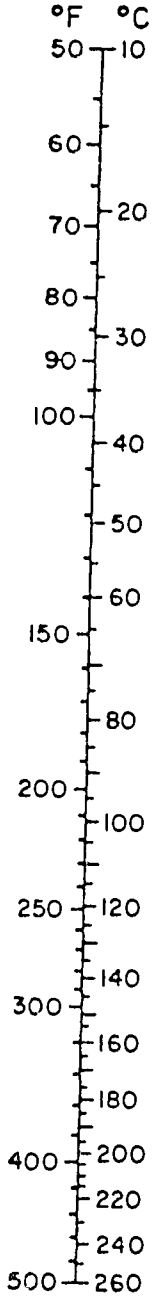


FIGURE 9



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: $R_{FT} = R_{75°} \times (75° + 7)/(FT \text{ (in °F)} + 7)$.

RESISTIVITY NOMOGRAPH FOR NaCl SOLUTIONS

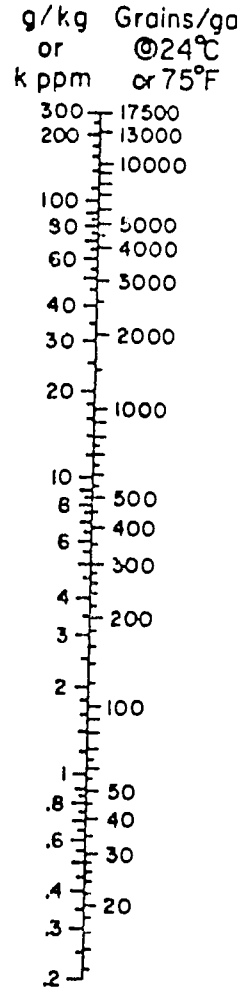


Conversion approximated by:

$$R_2 = R_1\left(\frac{T_1 + 6.77}{T_2 + 6.77}\right)_{(Arps)};\ °F$$

or

$$R_2 = R_1\left(\frac{T_1 + 21.5}{T_2 + 21.5}\right);\ °C$$



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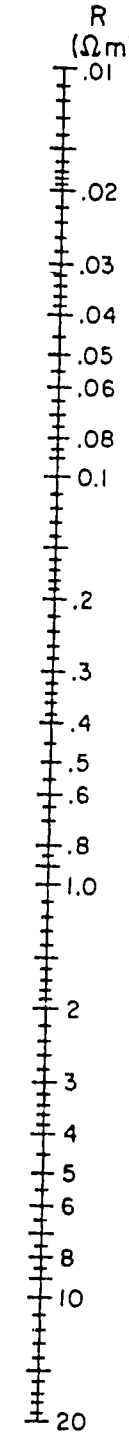


FORMATION WATERS - CONT.

SALINITY AND RESISTIVITY OF
SOME SOLUTIONS @ 70° F

SOLUTION	PPM SALT	RESISTIVITY, OHM M
SEA WATER	30,000 TO 35,000	0.2
SATURATED SALT WATER	250,000	0.04
ROTABLE WATER	500	10
FRESH WATER BASE MUD FILTRATE	1,000 TO 7,000	1 TO 5
SALT BASE MUD FILTRATE	75,000	.L
OIL AND GAS		1×10^{6}

WATER CONDUCTIVITY DUE TO IONIZED SALTS

MOSTLY -- N_A^{+} AND C_L^{-}

ALSO -- K^{+}, HCO_3^{-}, C_A^{++}, M_G^{++}, $CO_3^{-}S^{=}$ AND $SO_4^{=}$

FORMATION WATERS - CONT.

DETERMINATION OF RW

- LABORATORY FROM REPRESENTATIVE SAMPLE
- SP LOG
- R_{WA} LOG
- R_{WA} - SP PLOTS
- RESISTIVITY - POROSITY PLOTS
- R_{xo} AND R_T
- WATER CATALOGS
- CHEMICAL COMPOSITION (CONVERT TO EQUIVALENT NACL)

WATER SAMPLES

USEFUL (POSSIBLY)

- PUMPING WELL WITH HIGH WOR
- FLOWING WELL WITH HIGH WOR
- DRILL STEM TEST

NOT USEFUL

- FLOWING WELL WITH HIGH GOR
- DISTILLATE WELL
- GAS WELL
- WELL @ LEAKY CASING
- TANK BOTTOMS

RESISTIVITIES OF SOLUTIONS[2]

Actual resistivity measurements are always to be preferred, but, if necessary, the resistivity of a water sample can be estimated from its chemical analysis. An equivalent NaCl concentration determined by use of the chart below is entered into Gen-9 to estimate the resistivity of the sample.

The chart is entered n abscissa with the total solids concentration of the sample in ppm (mg/kg) to find weighting multipliers for the various ions present. The concentration of each ion is multiplied by its weighting multiplier and the products for all ions are summed to get equivalent NaCl concentration. Concentrations are expressed in ppm or mg/kg, both by weight. These units are numerically equal.

EXAMPLE

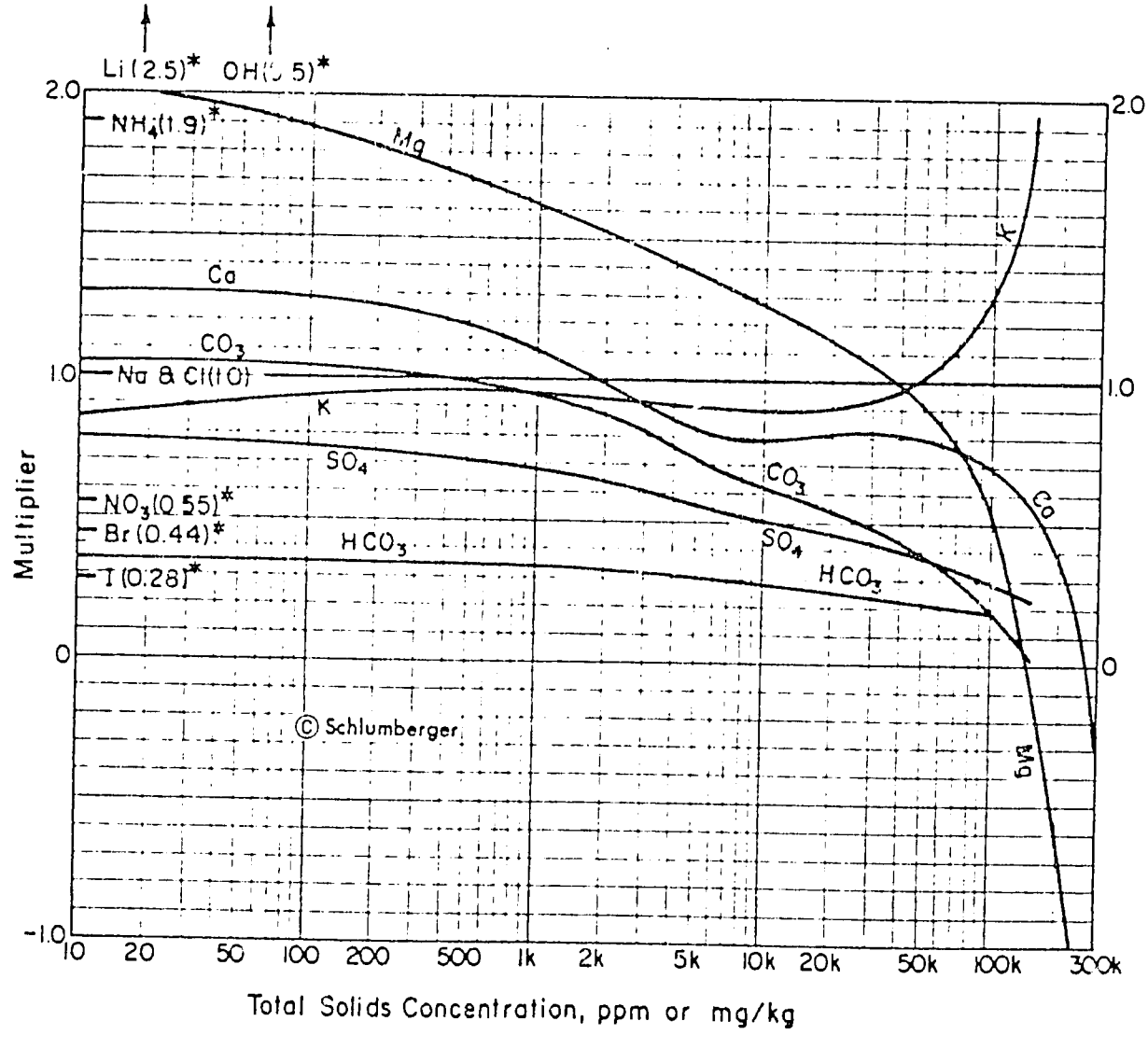
A formation-water-sample analysis shows 460 ppm Ca, 1400 ppm SO_4, and 19,000 ppm Na plus Cl.

Total solids concentration is 460 + 1400 + 19,000 = 20,860 ppm.

Entering the chart below with this total solids concentration, we find 0.81 as the Ca multiplier and 0.45 as the SO_4 multiplier. Multiplying the concentrations by the corresponding multipliers, the equivalent NaCl concentration is found as approximately:

$$460 \times 0.81 + 1400 \times 0.45 + 19{,}000 \times 1 \approx 20{,}000 \text{ ppm.}$$

Entering the NaCl Resistivity-Salinity nomograph (Gen-9) with 20,000 ppm and 75°F (24°C), the resistivity is found to be 0.3 at 75°F.



*Multipliers which do not vary appreciably for low concentrations (less than about 10,000 ppm) are shown at the left margin of the chart.

ELECTRICAL PROPERTIES - CONT.

NATURE OF ROCK AND RESISTIVITY

ROCK MATRICES CONTRIBUTE INDIRECTLY TO CONDUCTIVITY THROUGH

- AMOUNT OF POROSITY
- PRESENCE OF HYDROCARBONS
- WETTABILITY
- INTERNAL FEATURES OF PORES
- TORTUOSITY
- PRESENCE OF SHALES
- PRESENCE OF CONDUCTIVE SOLIDS (PYRITE AND SULFIDE ORES, RARE IN SEDIMENTARY ROCKS)

CLAYS IN SHALES

- ABSORB WATER AND BECOME CONDUCTIVE
- POSITIVE IONS MOVE ABOUT SURFACES OF CLAY PARTICLES
- NEGATIVE IONS ATTRACT POSITIVE IONS AND RESTRICT THEIR MOVEMENT
- EVEN LITTLE MOVEMENT OF POSITIVE IONS CONTRIBUTES TO CONDUCTIVITY

ELECTRICAL PROPERTIES - CONT.

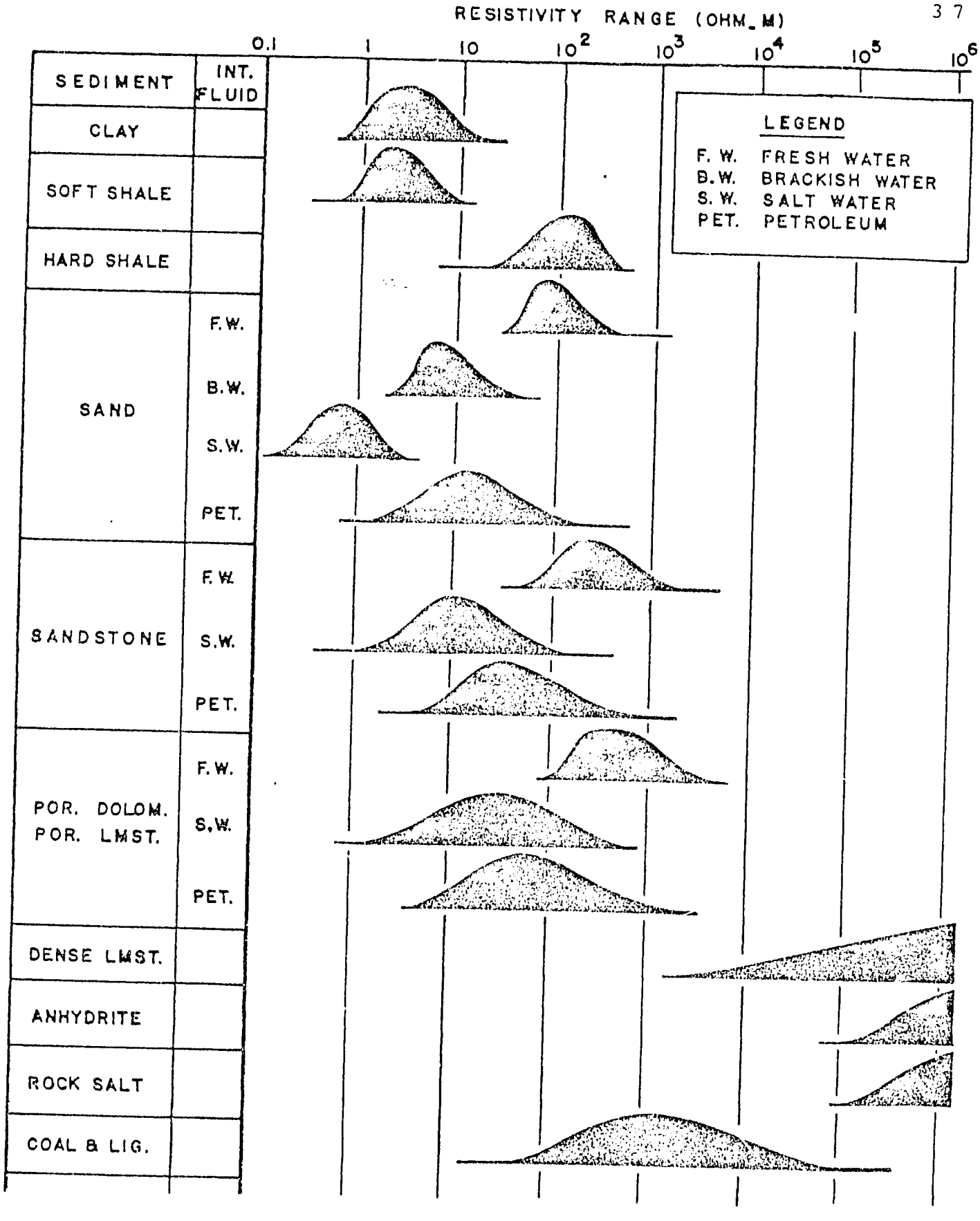
WATER ABSORPTION BY CLAYS IN SHALES IS AFFECTED BY SALINITY OF WATER

FOR PPM $<$ 70,000 ION DISSOLUTION IS IMPORTANT

FOR PPM $>$ 70,000 EFFECTS OF CLAYS ON CONDUCTIVITY IS INCONSEQUENTIAL

EFFECT OF CLAY UPON CONDUCTIVITY DEPENDS ON

- AMOUNT OF CLAY
- AMOUNT OF WATER
- SALINITY OF THE WATER
- TYPE OF CLAY
- DISTRIBUTION OF CLAY



RESISTIVITY RANGE OF COMMON SEDIMENTS

The length of the lines represents the range, while the line thickness indicates approximately the corresponding frequency of occurrence.

GUYOD - ELECTRICAL WELL LOGGING FUNDAMENTALS, 1952

NUCLEAR PROPERTIES OF ROCKS

ATOMIC THEORY REVIEW

RUTHERFORD (1911)

- CONCEIVED FIRST CLASSIC PLANETARY CONCEPT OF ATOMIC STRUCTURE
- NUCLEUS COMPOSED OF PROTONS -- Z POSITIVE PARTICLES

  PROTON MASS = 1836 X ELECTRON MASS

CHADWICK (1931)

- ALL PROTON NUCLEUS CONFLICTED WITH KNOWN ATOMIC WEIGHTS
- DISCOVERED SECOND NUCLEAR PARTICLE, THE NEUTRON @ NO ELECTRIC CHARGE
- NEUTRON IS 0.0023×10^{24} GR HEAVIER THAN PROTON
- NUCLEUS COMPOSED OF NEUTRONS & PROTONS

$$E^{A}_{Z}$$

A -- ATOMIC MASS NUMBER

Z -- ATOMIC NUMBER

A - Z = NUMBER OF NEUTRONS IN NUCLEUS

NUCLEAR PROPERTIES OF ROCKS - CONT.

$^{9}_{4}B$ BERYLLIUM ISOTOPE @

4 PROTONS

5 NEUTRONS

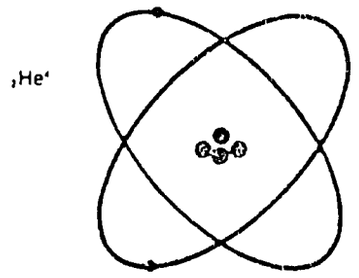
YUKAWA (1935)

- NUCLEUS SHOULD FLY APART -- ALL POSITIVE CHARGES
- WHAT HOLDS PROTONS IN NUCLEUS? -- A NUCLEAR GLUE
- WITHIN 5 YRS. PHYSICISTS CONFIRMED EXISTENCE OF YUKAWA'S NUCLEAR GLUE -- @ DISCOVERY OF MESON GROUP OF PARTICLES
- MESON PARTICLES
  - MASS ABOUT 200 + THAT OF ELECTRON
  - CAN BE POSITIVE, NEGATIVE, OR NEUTRAL
  - BY RAPID EXCHANGE BETWEEN PROTON & NEUTRON -- THEY CREATE PSEUDO - ELECTRO - STATIC EQUILIBRIUM WITHIN NUCLEUS

NUCLEAR PROPERTIES OF ROCKS - CONT.

<u>NUCLIDE</u> - PARTICULAR COMBINATION OF NEUTRONS & PROTONS IDENTIFYING A NUCLEUS

<u>ELEMENTS</u> - IDENTIFIABLE BY UNIQUE NUMBER OF PROTONS IN NUCLEUS -- ORDINARILLY THE SAME AS NUMBER OF ELECTRONS IN SURROUNDING ELECTRON SHELLS



2 PROTONS, 2 NEUTRONS
2 ELECTRONS

Structure of helium atom.

ELEMENTS @ SIMILAR CHEMICAL PROPERTIES CONTAIN SIMILAR NUMBERS OF ELECTRONS -- REGARDLESS OF THE NUMBER & ARRANGEMENT OF THEIR INNER SHELL STRUCTURE.

AN ATOM CAN BE IONIZED BY LOSING ONE OR MORE OF ITS ELECTRONS -- CHEMICAL PROPERTIES CAN CHANGE -- IT BECOMES SENSITIVE TO ELECTRIC FIELDS -- BUT REMAINS THE SAME ELEMENT

NUCLEAR PROPERTIES OF ROCKS - CONT.

ISOTOPES - ATOMS OF ONE ELEMENT THAT CHANGE IN MASS DUE TO VARYING NEUTRON CONTENT

EXAMPLE - NEON GAS AS NATURAL ELEMENT

$$\left.\begin{array}{l} 90.92\% \text{ IS } {}_{10}N^{20} \\ 8.82\% \text{ IS } {}_{10}N^{22} \\ 0.26\% \text{ IS } {}_{10}N^{21} \end{array}\right\} \text{ATOMIC WT. } = 20.183$$

83 OF THE 104 ELEMENTS CONSIST OF A MIXTURE OF TWO OR MORE ISOTOPES

21 ELEMENTS HAVE JUST ONE NUCLEAR FORM

1400 NUCLIDES ARE KNOWN TO EXIST

- 265 ARE STABLE (NOT RADIOACTIVE)
- 1135 ARE UNSTABLE (RADIOACTIVE DECAY TOWARD SOME STABLE STATE)

OF UNSTABLE NUCLIDES ONLY 65 OCCUR IN NATURE -- FOUND PREDOMINANTLY AMONG THE HEAVIEST ELEMENTS

RADIOACTIVE ISOTOPES ARE IMPORTANT BECAUSE THEY EMIT VARIOUS KINDS OF RADIATION, SOME OF WHICH IS DETECTABLE IN A WELL BORE

NUCLEAR PROPERTIES OF ROCKS - CONT.

NATURE OF RADIATION

BECQUEREL (1896) IDENTIFIED ALPHA (α), BETA (β) AND GAMMA (γ) RAYS

ALPHA RAYS

- POSITIVE CHARGE
- COMBINATION OF TWO PROTONS AND TWO NEUTRONS
- IDENTICAL TO NUCLEUS OF HELIUM ATOM, $_2H^4$
- HAVE APPRECIABLE MASS
- EXHIBIT LOW ORDER PENETRATING ABILITY
- WILL NOT EVEN PENETRATE A SHEET OF PAPER
- IMPRACTICAL TO DETECT IN A WELL BORE

BETA RAYS

- ARE ESSENTIALLY A STREAM OF ELECTRONS
- NEGATIVE CHARGE
- GENERATED WHEN A NEUTRON DECAYS INTO A PROTON, AN ELECTRON & A NEUTRINO
- PROTON REMAINS IN NUCLEUS WHILE ELECTRON & NEUTRINO ARE EJECTED
- ELECTRON HAS LOW PENETRATION POWER -- SEVERAL THICKNESSES OF CARDBOARD
- NEUTRINOS ARE EXTREMELY PENETRATING WITH DETECTION IMPOSSIBLE

NUCLEAR PROPERTIES OF ROCKS - CONT.

GAMMA RAYS

- TYPE OF ELECTROMAGNETIC (PHOTON) RADIATION
- OCCURS EITHER INDEPENDENT OR ACCOMPANIES ALPHA OR BETA EMISSIONS
- SIMILAR TO X-RAYS OR RADIO WAVES
- ARE QUITE PENETRATING
- ½ INCH OF LEAD REDUCES INTENSITY BY TWO
- PRACTICAL TO MEASURE ABOVE AND BELOW EARTH'S SURFACE
- MASSLESS QUANTUM OF HIGH FREQUENCY ENERGY SIMILAR TO HEAT AND LIGHT

65 UNSTABLE NUCLIDES EXIST IN NATURE

62 ARE RARE AND CAN BE OMITTED

3 ARE OF SIGNIFICANT ABUNDANCE

URANIUM - RADIUM SERIES

THORIUM SERIES

RADIO - POTASSIUM 40

NUCLEAR PROPERTIES OF ROCKS - CONT.

EMISSION OF GAMMA RAYS IS DISTINCTIVE

POTASSIUM 40 (1 GRAM) EMITS 3.4 PHOTONS/SEC AT 1.46 MEV

THORIUM OR URANIUM (1 GRAM) PRODUCES RESPECTIVELY 12,000 OR 26,000 GAMMA RAYS PER SECOND @ A SPECTRUM OF ENERGIES THAT AVERAGE 0.5 MEV

UCLEAR PROPERTIES OF ROCKS - CONT.

GAMMA RAY - INITIAL ENERGY

- DIMINISHED THROUGH REPEATED ELASTIC COLLISIONS AND BY PAIR PRODUCTION
- AT SOME LOW ENERGY LEVEL IT IS TOTALLY ABSORBED VIA THE PHOTOELECTRIC EFFECT
- SPECTRA OF ENERGIES SENSED IN BOREHOLE IS PARTIALLY DEGRADED BY ROCK BULK DENSITY AND CHEMICAL COMPOSITION

RADIOACTIVITY IN ROCKS

IGNEOUS ROCKS

- SOURCE OF SEDIMENTARY FORMATIONS AFTER EROSION BY MECHANICAL&CHEMICAL FORCES
- CONTAIN A MAJOR PORTION OF EARTH'S POTASSIUM & A LARGE FRACTION OF THE URANIUM & THORIUM
- UPON EROSION RADIOACTIVE ELEMENTS BECOME AVAILABLE FOR SELECTIVE DEPOSITION
- BASIC CONSTITUENTS ARE QUARTZ, FELDSPARS, MICAS & MINOR ACCESSORY MINERALS

RADIOACTIVITY IN ROCKS - CONT.

SANDSTONES

- FORMED BY MECHANICAL EROSION OF QUARTZ
- QUARTZ EXHIBITS STRONTLY BONDED PLANES IN ALL DIRECTIONS
  - CRYSTALLIZES IN PURE FORM
  - TENDS TO EXCLUDE IMPURITIES (RADIOACTIVE ELEMENTS)
- LOW IN RADIOACTIVITY EXCEPT WHEN SHALY

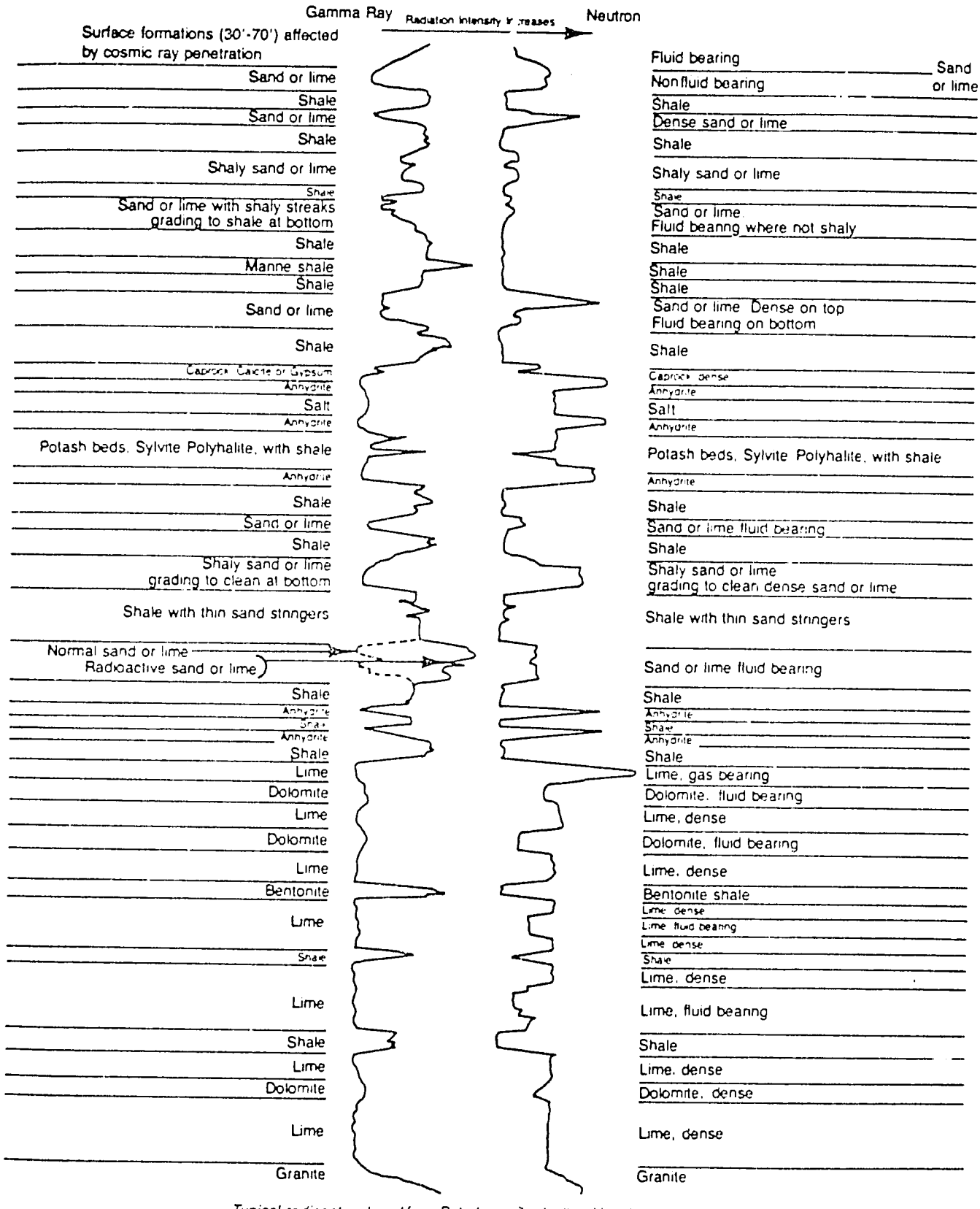
LIMESTONES

- INITIALLY DEVELOPED FROM CALCAREOUS MARINE LIFE
- RADIOACTIVITY ADVERSELY AFFECTS LIVING ORGANISMS
- LITTLE OR NO RADIOACTIVITY FROM BEGINNING
- WHERE MAGNESIUM IONS IN MIGRATING WATERS HAVE CAUSED DOLOMITIZATION, SLIGHTLY HIGHER RADIOACTIVE LEVELS ARE OBSERVED
- LOW IN RADIOACTIVITY EXCEPT WHEN SHALY

RADIOACTIVITY IN ROCKS - CONT.

SHALES

- COMPOSED OF SILT AND CLAYS
- FELDSPARS AND MICAS
  - CONTAIN LARGE SHARE OF EARTH'S POTASSIUM
  - DECOMPOSE RAPIDLY INTO CLAY MINERALS
- CLAYS
  - HAVE OPEN LATTICE & WEAK BONDING
  - HAVE LARGE NUMBER OF BROKEN ION BONDS & UNOCCUPIED ION SITES
  - PERMIT HIGH CAPACITY ION EXCHANGE & ABSORPTION
  - ENCOURAGE INCLUSION OF RADIOACTIVE ELEMENTS
  - ABSORB RADIOACTIVE ELEMENTS FROM MINERALIZED WATER DURING WEATHERING PROCESS
- QUITE RADIOACTIVE BECAUSE CLAY MINERALS ARE PRINCIPAL CONSTITUENTS



Typical radioactive logs (from Petroleum Production Handbook, *1962, © SPE-AIME).*

From 1981 Dresser Atlas Booklet on Gamma Ray Log

ACOUSTIC PROPERTIES OF ROCKS

IN ALL SUBSTANCES -- AN INHERENT FORCE CAUSES RANDOM MOTION OF THE MOLECULES -- FORCE OF ATTRACTION TENDS TO HOLD MOLECULES TOGETHER

RESULTANT OF THESE TWO FORCES -- ELASTICITY -- RESISTS DEFORMATION IN VOLUME OR SHAPE

HOOKE'S LAW -- DESCRIBES BEHAVIOR OF ELASTIC MATERIAL -- RESULTING STRAIN IS PROPORTIONAL TO THE APPLIED STRESS

- STRESS -- EXTERNAL FORCE APPLIED PER UNIT AREA
- STRAIN -- FRACTIONAL DISTORTION

$$\text{MODULUS OF ELASTICITY} = \frac{\text{STRESS}}{\text{STRAIN}}$$

THE ELASTIC MODULI ARE

$$\text{YOUNG'S MODULUS, } Y = \frac{F/A}{DL/L}$$

$$\text{BULK MODULUS, } B = \frac{F/A}{DV/V}$$

$$\text{SHEAR MODULUS, } S = \frac{F/A}{\text{TAN } S}$$

ACOUSTIC PROPERTIES - CONT.

F/A = FORCE/UNIT AREA

DL/L, DV/V, TANS ARE FRACTIONAL STRAINS OF LENGTH, VOLUME AND SHAPE

SEPARATION OF MOLECULES INCREASES IN ORDER FROM SOLIDS TO LIQUIDS TO GASES

SOLIDS HAVE LITTLE COMPRESSIBILITY COMPARED TO LIQUIDS AND GASES

ACOUSTIC WAVE (ELASTIC WAVE) - VIBRATORY STATE GENERATED IN AN ELASTIC MEDIUM

- A DISPLACEMENT TEMPORARILY IMPOSED UPON AN ELASTIC MEDIUM PRODUCES AN OSCILLATING MOTION OF THE PARTICLES
- OSCILLATING MOTION IS TRANSMITTED THROUGH THE MEDIUM OVER LONG DISTANCES FROM THE ORIGIN
- PARTICLES OF THE MEDIUM DO NOT TRAVEL WITH THE WAVE BUT ONLY VIBRATE

ACOUSTIC PROPERTIES - CONT.

ACOUSTIC WAVE TYPES

COMPRESSIONAL WAVES (A LONGITUDINAL WAVE)

- PARTICLE DISPLACEMENT IS PARALLEL TO THE DIRECTION OF PROPAGATION
- PARTICLES ARE DISPLACED CAUSING COMPRESSION -- TEND TO RETURN TO INITIAL POSITION THROUGH ELASTICITY -- IN SO DOING THEY OVERSHOOT AND CAUSE RAREFACTIONS
- CONSIST OF COMPRESSIONS & RAREFACTIONS TRAVELING IN DIRECTION AWAY FROM SOURCE
- CAN BE TRANSMITTED THROUGH SOLIDS, LIQUIDS AND GASES
- A COMPRESSION TOGETHER WITH A RAREFACTION CONSTITUTE A CYCLE
- FREQUENCY IS NUMBER OF CYCLES/UNIT TIME

ACOUSTIC PROPERTIES - CONT.

ACOUSTIC WAVE VELOCITY

- DERIVED USING THEORY OF ELASTICITY WITH NEWTON'S LAW OF MOTION

- COMPRESSIONAL WAVES (P-WAVES) TRAVEL FASTER THAN OTHE WAVES -- FIRST ARRIVAL WAVES

VELOCITY IS A FUNCTION OF DENSITY AND ELASTIC MODULI OF MEDIUM

$$V_c = \left[\frac{B + (4/3)\ S}{\rho}\right]^{\frac{1}{2}}$$

EXAMPLE - FOR A NON-POROUS LIMESTONE

B (BULK MODULUS) = 69×10^{10} DYNES/CM^2

S (SHEAR MODULUS) = 31×10^{10} DYNES/CM^2

ρ_{LMS} (DENSITY) = 2.71 G/CM^3

THUS, THE COMPUSSIONAL WAVE VELOCITY, V_c, IS

$$V_c = \left\{\left[\frac{69 + (1.33)\ (31)}{2.71}\right] 10^{10}\right\}^{\frac{1}{2}} \text{ CM/SEC}$$

= 640,000 CM/SEC OR 21,000 FT/SEC

ACOUSTIC PROPERTIES - CONT.

INTERVAL TRANSIT TIME - ΔT

- IS THE RECIPROCAL OF VELOCITY EXPRESSED IN μSEC/FT

$$\Delta T_{LMS} = \frac{1{,}000{,}000}{21{,}000 \text{ FT/SEC}} = 47.6 \ \frac{\mu\text{SEC}}{\text{FT.}}$$

SHEAR WAVES (A TRANSVERSE WAVE)

- ALSO REFERRED TO AS S WAVES
- DIRECTION OF PROPAGATION IS PERPENDICULAR TO DIRECTION OF PARTICLE DISPLACEMENT
- PARTICLES OF SOLID MEDIA UNDERGO TO AND FRO MOTION IN A DIRECTION PERPENDICULAR TO WAVE TRAVEL
- SOLIDS HAVE A TENDENCY TO OPPOSE SHEARING FORCES, WHICH CAUSE PARTICLES TO SLIDE RELATIVE TO EACH OTHER
- CANNOT BE TRANSMITTED THROUGH LIQUIDS AND GASES WHICH DO NOT POSSESS RIGIDITY

ACOUSTIC PROPERTIES - CONT.

SHEAR WAVE VELOCITY

$$V_S = \left(\frac{S}{\rho}\right)^{\frac{1}{2}}$$

FOR THE NON-POROUS LIMESTONE EXAMPLE, THE SHEAR WAVE VELOCITY, V_S, IS

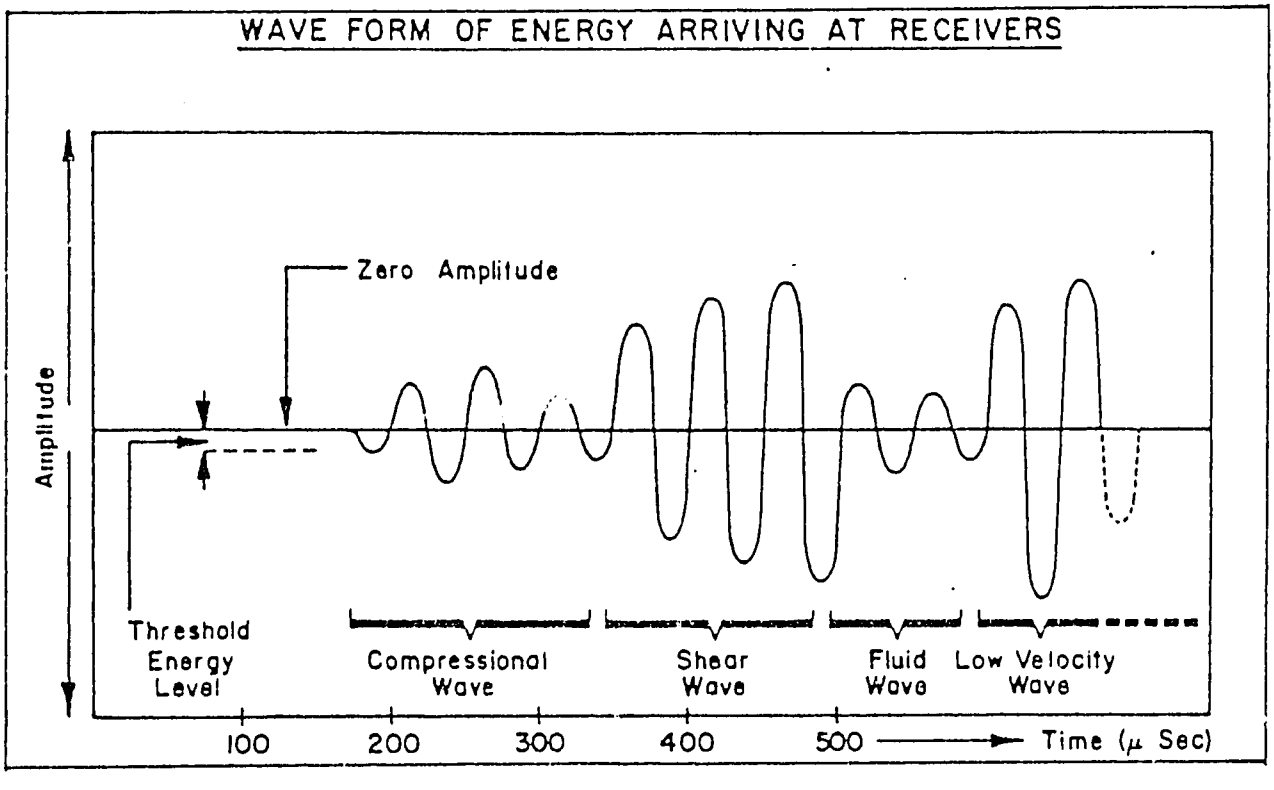
$$V_S = \left[\frac{31}{2.71} \times 10^{10}\right]^{1/2}$$

$$= 338{,}000 \text{ CM/SEC} = 11{,}100 \text{ FT./SEC}$$

AND $\Delta T_{LMS-S} = \dfrac{1{,}000{,}000}{11{,}100} = 90\ \mu\text{SEC/FT.}$

NATURE OF ACOUSTIC PULSES

- FIRST ARRIVAL IS THE COMPRESSIONAL WAVE
- V_S = (0.5 TO 0.7) V_C
- SHEAR WAVES ARE STRONGER AND CAN BE RECOGNIZED
- LATER ARRIVALS OF OTHER WAVE TYPES ARE NOT IMPORTANT - MASKED BY P-WAVE ARRIVALS THROUGH BORE HOLE FLUID
- SHEAR WAVE ARRIVALS ARE OFTEN OUT-OF-PHASE WITH P-WAVE ARRIVALS AND CAN CAUSE INTERFERENCE OF TOTAL WAVE TRAIN


WAVE FORM OF ENERGY ARRIVING AT RECEIVERS
Zero Amplitude
Amplitude
Threshold Energy Level
Compressional Wave
Shear Wave
Fluid Wave
Low Velocity Wave
100
200
300
400
500
Time (μ Sec)

ACOUSTIC VELOCITIES OF SOME MINERALS, ROCKS AND FLUIDS

Formation	V ft/sec	Δt μsec/ft
Sandstone:		
Unconsolidated	17,000 or less	58.8 or more
Semi-consolidated	18,000	55.6
Consolidated	19,000	52.6
Limestone	21,000	47.6
Dolomite	23,000	43.5
Shale	6,000 to 16,000	167 to 62.5
Calcite	22,000	45.5
Anhydrite	20,000	50.0
Granite	20,000	50.0
Gypsum	19,000	52.6
Quartz	18,000	55.6
Salt	15,000	66.7

Fluid	V ft/sec	Δt μsec/ft
Water with 20% NaCl	5,300	189
Water with 15% NaCl	5,000	200
Water with 10% NaCl	4,800	208
Water (pure)	4,600	218
Oil	4,200	238
Methane	1,600	626
Air	1,100	910

From Dresser Atlas 1981 Booklet on Acoustic Logs

FACTORS AFFECTING WELL LOG ANALYSIS

FORMATION TEMPERATURES

- IMPORTANT BECAUSE ALL RESISTIVITY DATA DEPEND ON TEMPERATURE
- HEAT CONDUCTIVITY DECREASES WITH INCREASING TEMPERATURE
- SALT CONCENTRATION HAS LITTLE EFFECT ON THERMAL CONDUCTIVITY OF WATER
- HEAT CONDUCTIVITY IS LITTLE AFFECTED BY LOW POROSITIES BUT FOR HIGH POROSITIES IT VARIES INVERSELY WITH WATER CONTENT
- GEOTHERMAL GRADIENTS
  - ARE HIGH IN OVERPRESSURED BEDS - HIGH ϕ AND WATER CONTENT
  - DEPEND ON LITHOLOGY
  - SELDOM CONSTANT FROM ONE LOCATION TO ANOTHER
- NORMAL INCREASE WITH DEPTH IS GIVEN BY

$$T_F = T_M + \frac{(GG)\ (D)}{100}$$

T_F = FORMATION TEMP., ^oF

D = DEPTH, FT.

GG = GEOTHERMAL GRADIENT, $^oF/100$ FT.

FORMATION TEMPERATURES - CONT.

TABLE 5[11]

Heat Conductivity Values

Material	Approx. Heat Conductivity (Cal. cm^{-2} sec^{-1} $^{o}C^{-1}$)
Gas	0.1
Oil	0.3
Water	1.4
Clay	2.4
Quartzite	6.8-18.9

SUBSURFACE TEMPERATURES GIVEN ON LOGS

- ARE LOWER THAN TRUE FORMATION TEMPERATURE BY 20°F TO 80°F
- CIRCULATION OF MUD PRIOR TO LOGGING REDUCES SUBSURFACE TEMPERATURES
- TEMPERATURE GRADIENTS OF 0.3°F/100 FT. TO 6°F/100 FT. HAVE BEEN ENCOUNTERED. GRADIENTS OF 1°F/100 FT. TO 1.7°F/100 FT. ARE FOUND MOST FREQUENTLY

FACTORS AFFECTING WELL LOG ANALYSIS - CONT.

WELL BORE ENVIRONMENT

- HOLE SIZE, D_H
  - DIAMETER IS GIVEN BY DRILLING BIT SIZE
  - CAN CHANGE DUE TO ----
    - SLOUGHING OF CLAY DUE TO FLOCCULATION
    - COLLAPSE OF POORLY CEMENTED POROUS ROCKS
    - MUD CAKE BUILDUP
  - GENERALLY RANGE FROM 7 7/8" TO 12" IN DIAMETER
  - MOST LOGGING TOOLS REQUIRE LITTLE CORRECTION FOR NORMAL BOREHOLE SIZES

- DRILLING MUD
  - REMOVES ROCK CUTTINGS AND CONTROLS FORMATION FLUID FLOW
  - HYDROSTATIC PRESSURE OF MUD COLUMN MUST EXCEED FORMATION PRESSURES
  - SOME OF DRILLING FLUID INVADES PERMEABLE BEDS
  - DESIGNED TO MINIMIZE FILTRATE INVASION
  - CONTAINS FINE PARTICLES (CLAY MINERALS) CARRIED IN SUSPENSION
  - CLAYS ARE FILTERED OUT ON PERMEABLE BED FACES TO FORM IMPERMEABLE MUD CAKE AND MINIMIZE FILTRATE INVASION

WELLBORE ENVIRONMENT - CONT.

- MUD CAKE
  - THICKNESS RANGES FROM 1/8" TO 1/2"
  - FORMS IN ABOUT 30 MINUTES
  - EFFECTIVENESS IS DETERMINED BY CAKE BUILDING PROPERTIES OF MUD
  - CONSTITUENTS
    - MOSTLY BENTONITE BUT MAY ALSO INCLUDE
    - OIL
    - CELLULOSE
    - LIGNIN
    - TANIN
  - BECOMES IMPERMEABLE BUT CAN BE DAMAGED BY DRILLING, LOGGING OR TESTING TOOLS
  - AFFECTS SEVERAL OF THE SHORT RANGE LOGGING TOOLS
  - ELECTRICAL PROPERTIES (R_{MC}) APPROXIMATE VERY ROUGHLY THOSE OF A SALT SOLUTION
  - BED ϕ AND K HAVE LITTLE INFLUENCE ON ITS SEALING PROPERTIES
  - COMPACTNESS IS RELATED TO ITS THICKNESS, H_{MC}
  - HAS ABOUT SAME H_{MC} AGAINST ALL PERMEABLE ZONES OF A WELL DRILLED WITH ONE TYPE OF MUD

WELL BORE ENVIRONMENT - CONT.

- MUD FILTRATE

  - LIQUID SEPARATED FROM MUD -- WATER
  - ITS RESISTIVITY IS R_{MF}
  - ITS INVASION MODIFIES ORIGINAL DISTRIBUTION OF FLUIDS IN THE ROCK

- BOREHOLE AND FORMATION FLUIDS

  - MUD FILTRATE -- ONLY WATER IN FLUSHED ZONE
  - FORMATION WATER -- ONLY WATER IN VIRGIN ROCK
  - MIXTURE OF MUD FILTRATE AND FORMATION WATER -- WATER IN ZONE BETWEEN FLUSHED AND VIRGIN ROCK
  - RESISTIVITIES ARE R_{xo}, R_w, R_z
  - VARIOUS WATERS BEHAVE LIKE N_A C_L SOLUTIONS

- ZONE OF INVASION - R_I ZONE

  - INVASION FRONT IS UNDOUBTEDLY IRREGULAR AND DEPENDENT ON VARIATION IN PERMEABILITY
  - HORIZONTAL EXTENT IS REFERRED TO AS DIAMETER OF INVASION, D_I
  - SAME VOLUME OF WATER INVADES A LOW ϕ BED AS A HIGH ϕ BED
  - D_I IS HIGHER FOR LOW ϕ THAN FOR HIGH ϕ

WELL BORE ENVIRONMENT - CONT.

'' GENERALLY

$D_I/D = 2$ FOR HIGH ϕ

$D_I/D = 5$ FOR INTERMEDIATE ϕ

$D_I/D = 10$ FOR LOW ϕ

WELL BORE ENVIRONMENT - CONT.

- ESTIMATION OF D_I
  - USE THREE RESISTIVITY LOGS READING SHALLOW (R_{xo}), MEDIUM (R_z) AND DEEP (R_T)
    - IF $R_z \approx R_{xo}$ DEEP INVASION
    - IF $R_z \approx R_T$ SHALLOW INVASION
  - INVASION IS A TIME FUNCTION AND MAY DISAPPEAR IF FORMATION FLUID REINVADES PORES NEAR WELL BORE

- FLUSHED ZONE - R_{xo} ZONE
  - PART OF THE INVADED ZONE
  - INCLUDES THE FIRST 4" FROM BOREHOLE WALL
  - COMPLETELY FLUSHED OF FORMATION WATER FOR MODERATE TO DEEP INVASION
  - IF HYDROCARBONS ARE PRESENT 70 TO 85% ARE USUALLY FLUSHED OUT

WELL BORE ENVIRONMENT - CONT.

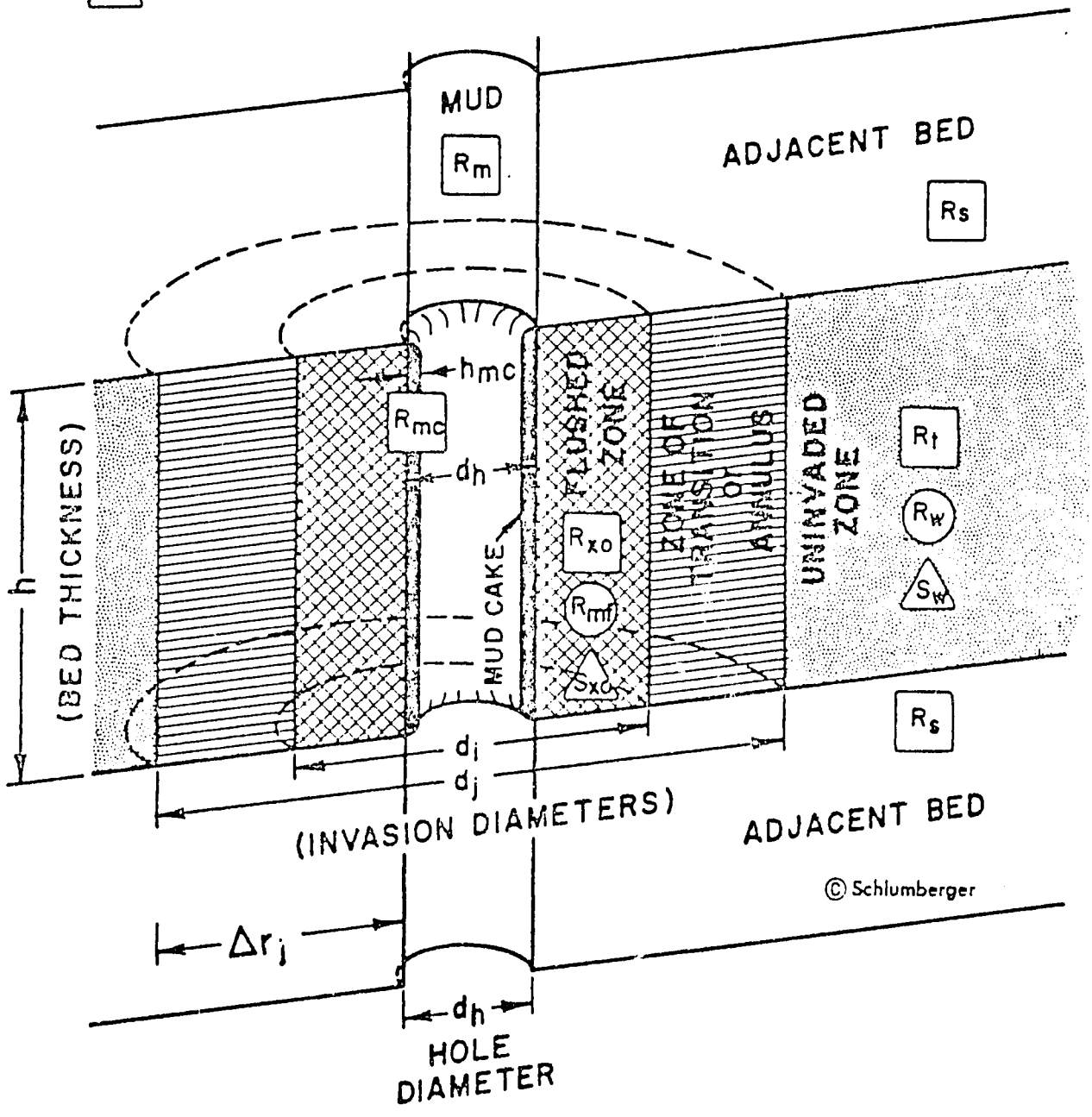
- VIRGIN OR UNDISTURBED ZONE - R_T ZONE
  - LIES BEYOND THE INVADED ZONE
  - PORE SPACES MAY BE SATURATED WITH WATER, WIT WATER AND OIL OR WITH WATER AND GAS
  - WHEN CONTAINING HYDROCARBONS, WATER IS ALSO PRESENT AND PERMITS ELECTRIC CURRENT TO FLO

SYMBOLS USED IN LOG INTERPRETATION
(Schematic)

□ — Resistivity of the zone

○ — Resistivity of the water in the zone

△ — Water saturation in the zone

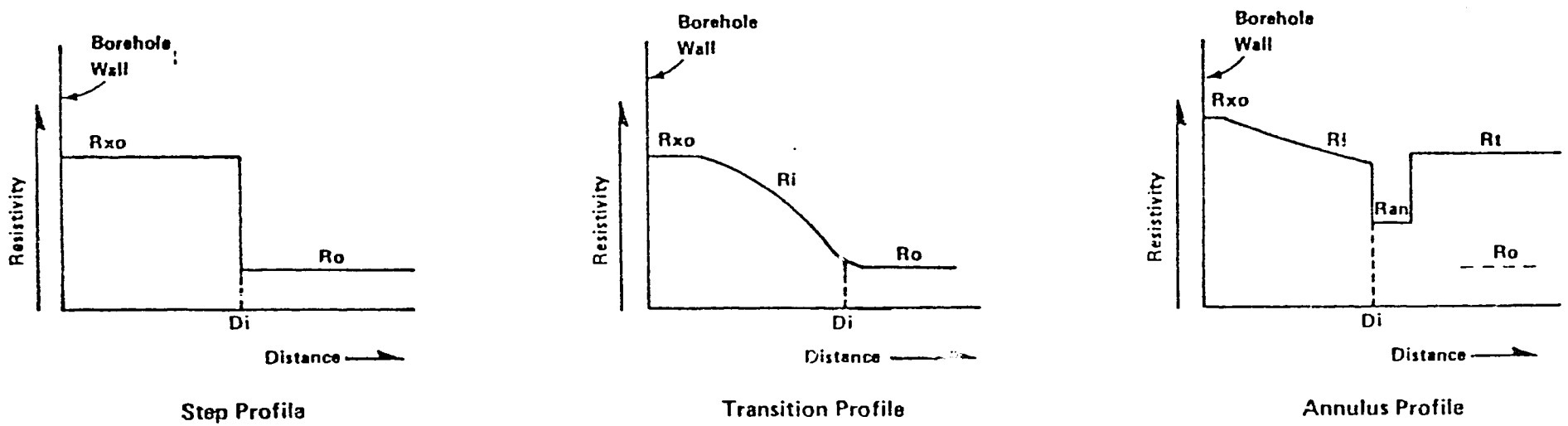


FACTORS AFFECTING WELL LOG ANALYSIS - CONT.

- INVASION PROFILES
  - ARE MATHEMATICAL IDEALIZATIONS NOT LIKELY TO MATCH EXACTLY ACTUAL INVASION
  - APPROXIMATE LABORATORY FINDINGS AND INTERPRETATION EXPERIENCE VERIFIES THEIR ADEQUACY
  - STEP PROFILE
    - CONSISTS OF INVADED AND VIRGIN ZONES
    - SHALLOW RESISTIVITY CURVE READS R_I
    - DEEP RESISTIVITY CURVE READS R_T
    - USED IN COMPUTER INTERPRETATION OF WELL LOGS
  - TRANSITION PROFILE
    - MODELS TRUE BOREHOLE CONDITIONS MORE ACCURATELY
    - USEFUL WHEN THREE OR MORE RESISTIVITY CURVES ARE AVAILABLE TO DEFINE INVASION
    - RELIABLE VALUE OF R_T CAN BE DETERMINED

FACTORS AFFECTING WELL LOG ANALYSIS - CONT.

- ANNULUS PROFILE
  - CHANGES WITH TIME AND USUALLY NOT PRESENT AT TIME OF LOGGING
  - OCCURS ONLY IN OIL OR GAS PRODUCTINE INTERVALS
  - FILTRATE INVASION MOVES HYDROCARBONS FIRST THEN CONNATE WATER WHICH FORMS AN ANNULAR RING AROUND THE BOREHOLE AT THE EDGE OF THE INVADED ZONE
  - AN INDUCTION LOG COULD GET TOO MUCH RESPONSE FROM ANNULUS AND RESULT IN Sw BEING HIGH
  - ANNULAR EFFECT ONLY OCCURS ON INDUCTION LOGS
  - ANNULUS EFFECT DISSIPATES WITHIN A FEW HOURS AND IS NOT CONSIDERED A COMMON OCCURRANCE



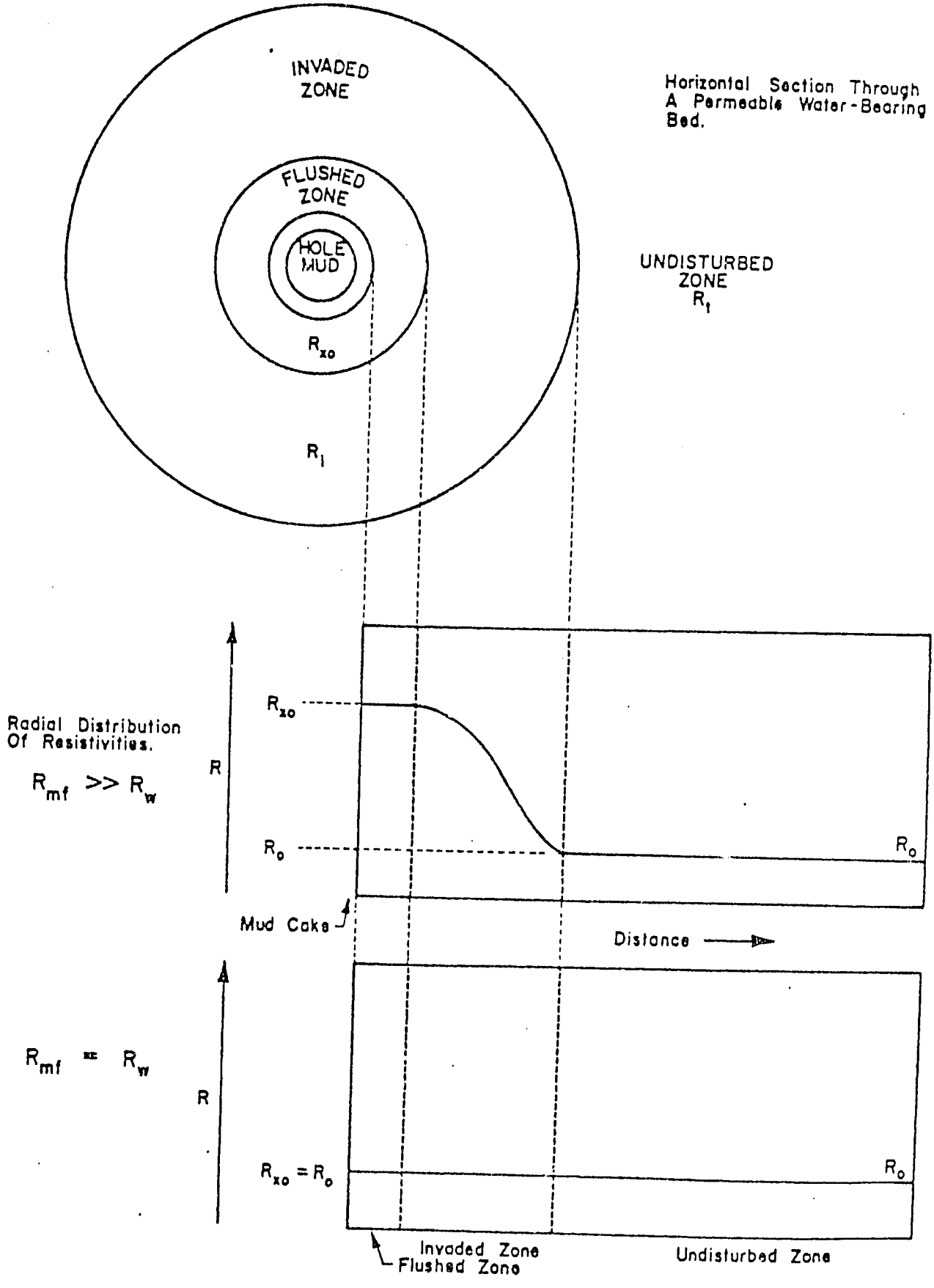
SCHEMATIC ILLUSTRATION OF THE STEP, TRANSITION, AND LOW RESISTIVITY ANNULUS PROFILES OF INVASION

FACTORS AFFECTING WELL LOG ANALYSIS - CONT.

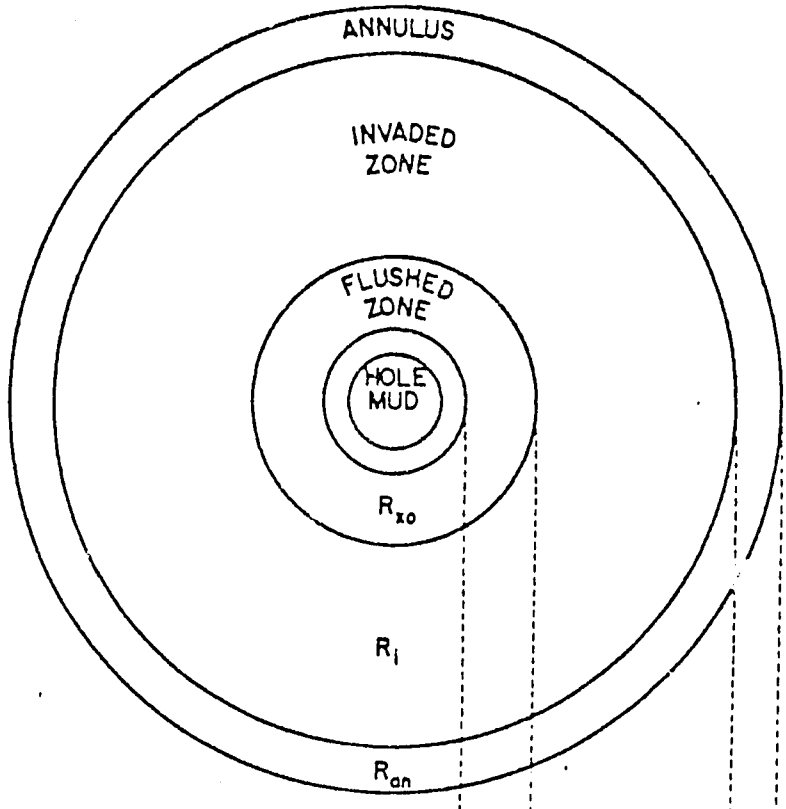
RESISTIVITY PROFILES

- HELPFUL IN JUDGING RELIABILITY OF LOG DATA AND DATA RECORDED ON LOG
- USE SKETCH OF THE RESISTIVITY VALUES OF MUD AND BED UNDER INVESTIGATION
- PLOT R_{xo}, R_I AND R_T VS HORIZONTAL DISTANCE FROM THE BOREHOLE
  - R_I ALWAYS LIES BETWEEN R_{xo} AND R_T
  - R_T MAY BE GREATER, EQUAL OR LESS THAN R_{xo}
- IN AQUIFERS $R_o = F(\phi, R_w)$
- R_T/R_o IS FAIRLY CONSTANT IN A GIVEN BED IF ϕ AND R_w ARE CONSTANT
- REAL VARIABLE IS R_{mf} WHICH CAN CAUSE R_{xo} TO VARY FROM LESS THAN R_o TO GREATER THAN R_T IN AN OIL ZONE
- WATER ZONES CONSIST OF R_{xo}, R_I, R_o
- HYDROCARBON ZONES CONSIST OF R_{xo}, R_I, ANNULUS, R_T
- S_{hc} IN R_{xo} ZONE $\approx$ 15%

RESISTIVITY PROFILE - WATER ZONE



RESISTIVITY PROFILE - OIL ZONE



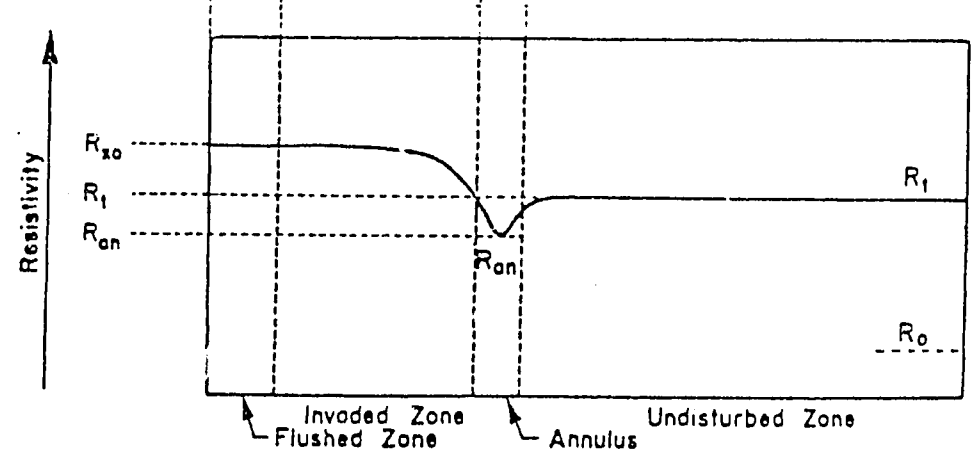
Horizontal Section Through A Permeable Oil-Bearing Bed.

UNDISTURBED ZONE R_t

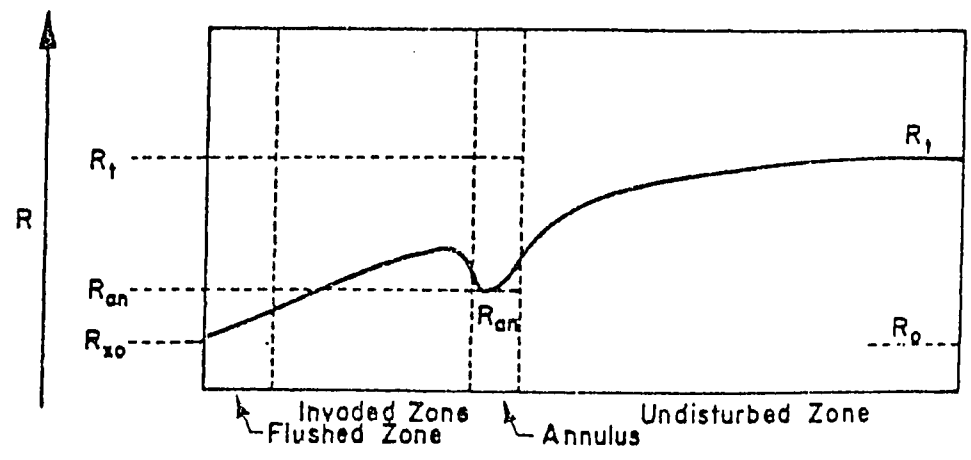
$S_w << 60\%$

Radial Distribution Of Resistivities.

$R_{mf} >> R_w$



$R_{mf} = R_w$



BASIC DATA NECESSARY FOR LOG INTERPRETATION

- LITHOLOGY OF INTERVAL
- TEMPERATURE, T_F
- MUD PROPERTIES, R_M, R_{MF}, H_{MC}
- WATER RESISTIVITY, R_W
- RESIDUAL HYDROCARBON SATURATION, RHS, ROS
  - A FUNCTION OF ϕ, K, FILTRATE VOLUME, μ_{HC}, ^{o}API
  - DETERMINATION
    - RESTORED STATE CORES - PERHAPS MOST RELIABLE
    - $(1-RHS)^2 = \frac{F\ R_{MF}}{R_{XO}} = \frac{R_{XO}\ A_{QUITER}}{R_{XO\ HC}}$
    - LOCAL RULES OF THUMB -- 15% IN MEDIUM POROSITY (15 - 20%) WHERE INVASION IS MODERATE TO DEEP
    - ACCORDING TO FLUID GRAVITY

	^{o}API	RHS %
GAS		5-40
HIGH GRAVITY OIL	40°-50°	5-10
MEDIUM GRAVITY OIL	20°-40°	10-20
LOW GRAVITY OIL	10°-20°	20-30

MEASUREMENTS WHILE DRILLING - MWD LOGS

DRILLING TIME LOG

CONTINUOUS RECORD GIVING RATE-OF-PENETRATION IN TIME PER FOOT OF HOLE OR FEET OF HOLE PER UNIT OF TIME

RIG INSTRUMENTATION

WEIGHT INDICATOR

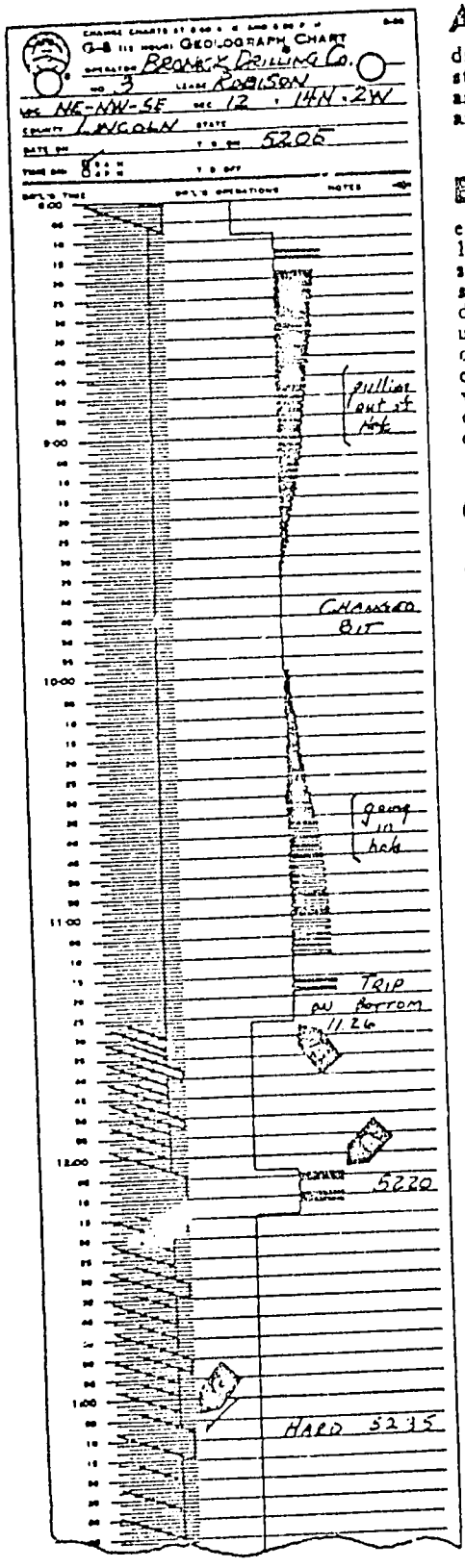
MUD PRESSURE GAUGE

MUD FLOW RATE

ROTARY TORQUE GAUGE

TACHOMETER

RATE OF PENETRATION RECORDER



A Line in drilling operations column moves to the left indicating that driller got on bottom with new bit and started drilling at 11:26. Total trip time, as indicated by "Trip Action", 3 hours and 17 minutes.

B This is the way a connection looks on the Geolograph chart. The driller raised the drill pipe from bottom at 12:03, broke out the kelly, picked up a single pipe (adding it to the drilling string), picked up the kelly and resumed drilling. This operation required 11 minutes, and the driller has written the depth of the hole, at that time, on the chart. Thus, every connection is a convenient datum for determining the depth of any drilling or down-time break, either immediately above or below.

C A 4-foot hard streak was encountered at 5,235 feet, as indicated by the increased spacing of the foot marks on this time chart.

D A connection was made at 5,259 feet and a vertical test was run at this point to determine the vertical deviation of the hole. The driller has noted on the chart that the test was actually taken at 5,250 feet and the deviation was ½ degree. The vertical test and connection required 34 minutes.

E Soft bed was drilled from 5,266 to 5,269 feet. Because of the thinness of this bed, no core or drill stem test was attempted.

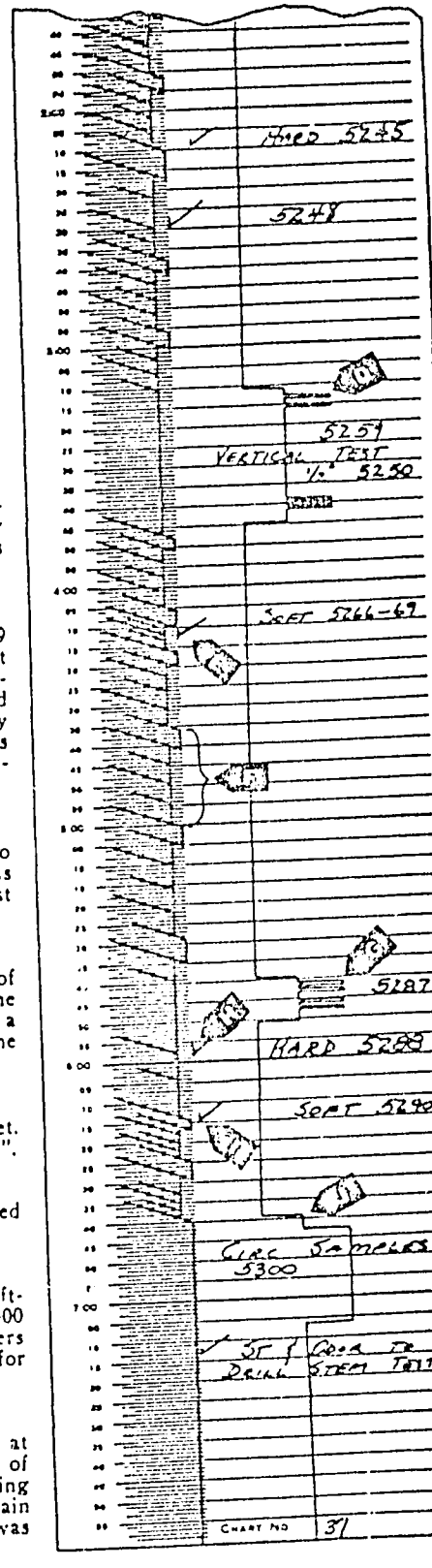
F This section represents 5 feet of drilling. Note that every 5 feet the base line is offset for 1 foot, making a convenient marker for determining the depth of significant drilling changes.

G Connection was made at 5,287 feet. Note similarity to the record at "B".

H A hard streak was encountered from 5,288 to 5,290 feet.

I At 5,290 feet, the formation softened, drilling continued to 5,300 feet where the driller was given orders to cease drilling and circulate for samples.

J Circulating for samples started at 6:39 as indicated by movement of the line to the right. After circulating for 35 minutes, samples showed stain and odor, and a drill stem test was ordered.



Typical mechanical drilling log record. Courtesy Geolograph Mechanical Well Logging Service.

MWD -

CUTTINGS ANALYSIS AND MUD LOGGING

CONTINUOUS INSPECTION OF THE DRILLING MUD AND CUTTINGS FOR TRACES OF OIL AND GAS - IMPORTANT IN EXPLORATORY WELLS

OIL DETECTION - EXPOSURE TO ULTRAVIOLET RADIATION -- ELECTRONIC TRANSITION OF SOME ATOMS TO CAUSE EMISSION OF RADIATION -- FLUORESCENCE -- CAN DETECT AS LITTLE AS 10 PPM

FLUORESCENCE COLOR OF CRUDE OILS

GRAVITY ^{o}API	COLOR OF FLUORESCENCE
BELOW 15	BROWN
15 - 25	ORANGE
25 - 35	YELLOW TO CREAM
35 - 45	WHITE
OVER 45	BLUE-WHITE TO VIOLET

LIMITATIONS

LOW GRAVITY OILS -- FLOURESCE VERY LITTLE

HIGH GRAVITY OILS -- DIFFICULT TO SEE -- ULTRAVIOLET REGION

REFINED RIG OILS -- ALSO FLUORESCE -- WHITE OR BLUE-WHITE

MWD - CUTTINGS ANSLYSIS AND MUD LOGGING - CONT.

ANALYSIS FOR GAS

- HOT-WIRE ANALYZER (WHEATSTONE BRIDGE)

  1.2 VOLTS GIVES 900°C IN AIR -- BURNS ALL GASES

  .65 VOLTS GIVES 550°C IN AIR -- BURNS ALL GASES EXCEPT CH_4

  SENSITIVITY 200 PPM

  LIMITATIONS:

  PRESENCE OF H_2 IN GAS STREAM

  ANALYZER ACTUALLY BURNS COMBUSTIBLE GASES IN THE SAMPLE

- GAS CHROMATOGRAPH -- ABSORPTION AND DESORPTION -- SEPARATES HEAVY TO LIGHT COMPONANTS

- INFRARED ANALYZER - ABSORPTION OF INFRARED ENERGY BY CH_4

- MASS SPECTROGRAPH -- SEPARATES AND DETERMINES RELATIVE AMOUNTS OF VARIOUS IONS ON BASIS OF MASS TO CHANGE RATIO

MWD - CUTTINGS ANALYSIS AND MUD LOGGING - CONT.

DETERMINATION OF LAG TIME

- NECESSARY FOR MEASUREMENTS TO BE CORRELATED WITH DEPTH --- RULE-OF-THUMB - 1 MINUTE / 90' HOLE

- METHODS

  CIRCULATION RATE - SIZE OF MUD PUMP CYLINDERS, NUMBER OF STROKES/MIN. AND PUMP EFFICIENCY (90%)

  TRACERS - PLACED IN PIPE WHEN JOINT IS ADDED -- CELLOPHANE STRIPES, ROLLED OATS, STRAINED CUTTINGS

A. BIT AND CORE RECORDS

B. DRILLING RATE CURVE

C. LITHOLOGY

D. OIL CURVE (MUD)

E. METHANE CURVE (MUD)

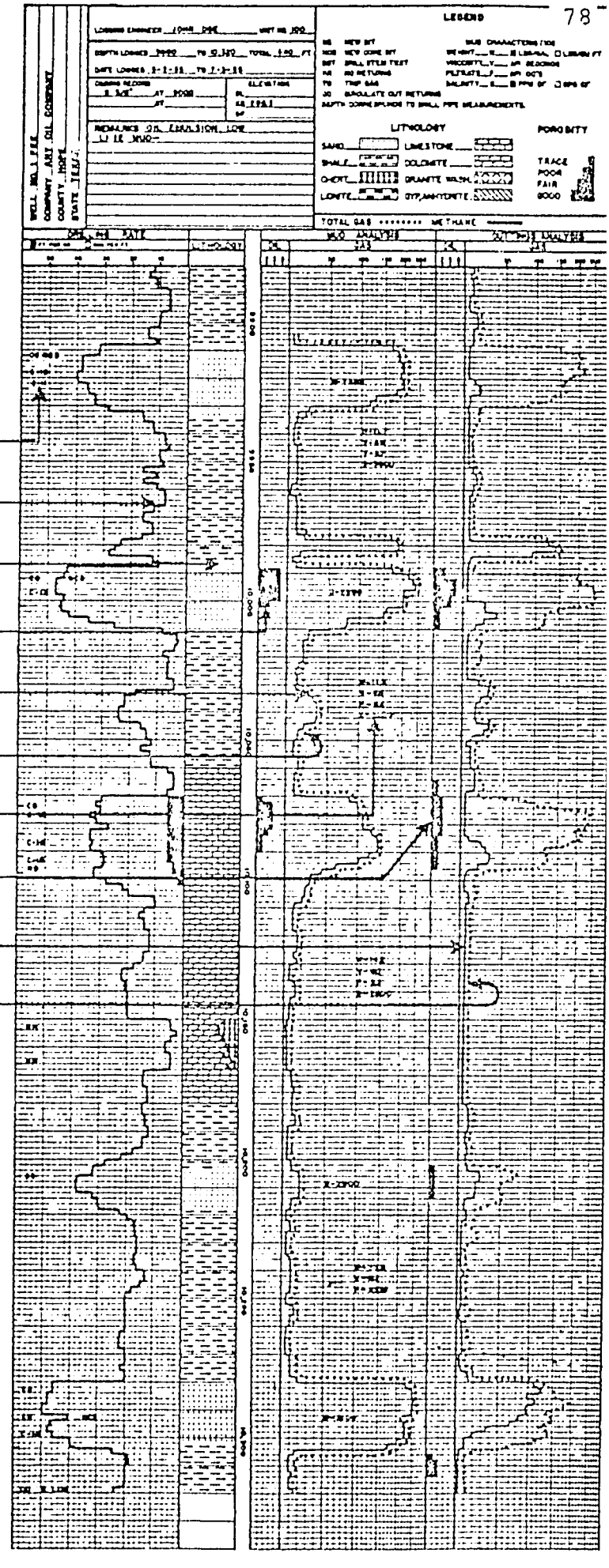
F. TOTAL GAS CURVE (MUD)

G. MUD CHARACTERISTICS

H. OIL CURVE (CUTTINGS)

I. METHANE CURVE (CUTTINGS)

J. TOTAL GAS CURVE (CUTTINGS)



Mud logging report. Courtesy Baroid Sales Division, National Lead Company.

CORE ANALYSIS

- CORING --

  - CONVENTIONAL

    - WILL CUT A LARGE CORE FOR GIVEN SIZE HOLE
    - RECOVERS A LARGE PROPORTION OF CORE CUT
    - CORES RANGE IN SIZE FROM 2 3/8" TO 3 9/16"
    - READILY ADAPTABLE TO MOST FORMATIONS
    - CAN ONLY CUT 20' OF CORE BEFORE HAVING TO PULL DRILL PIPE

  - DIAMOND CORING

    - ESSENTIALLY THE SAME AS CONVENTIONAL CORING EXCEPT CORE BARREL IS FINELY MACHINED
    - DIAMOND CORE BIT IS USED -- TUNGSTEN ALLOY WITH DIAMOND CHIPS
    - NO HAMMERING OR CHIPPING ACTION -- ONLY ABRASIVE ACTION
    - CORES RANGE IN SIZE FROM 2 7/8" TO 4 7/8"
    - CAN CUT UP TO 90' OF CORE BEFORE HAVING TO PULL DRILL PIPE

CORING - CONT.

- WIRELINE CORING

  - DOES NOT REQUIRE ROUND TRIP TO RECOVER CORE
  - INNER CORE BARREL CAN BE RETRIEVED WITH AN OVERSHOT
  - LOWER CORING COSTS ARE INVOLVED BUT

    REQUIRES ADDITIONAL SURFACE EQUIPMENT

    SPECIAL SUBSURFACE EQUIPMENT IS NEEDED

    WORKS WELL IN SOFT FORMATIONS

    CUTS SMALLER CORES -- 1" TO 2 3/16" DIAMETER AND UP TO 20 FT. LONG

- SIDEWALL CORING

  USES SMALL CYLINDERS DISCHARGED INTO SIDES OF BOREHOLE

  ENERGY FROM ELECTRICALLY IGNITED POWDER CHARGES

  UP TO 30 SHOTS CAN BE MADE IN ONE TRIP

  CORE SAMPLES 1¼" DIA. TO 2¼" LONG

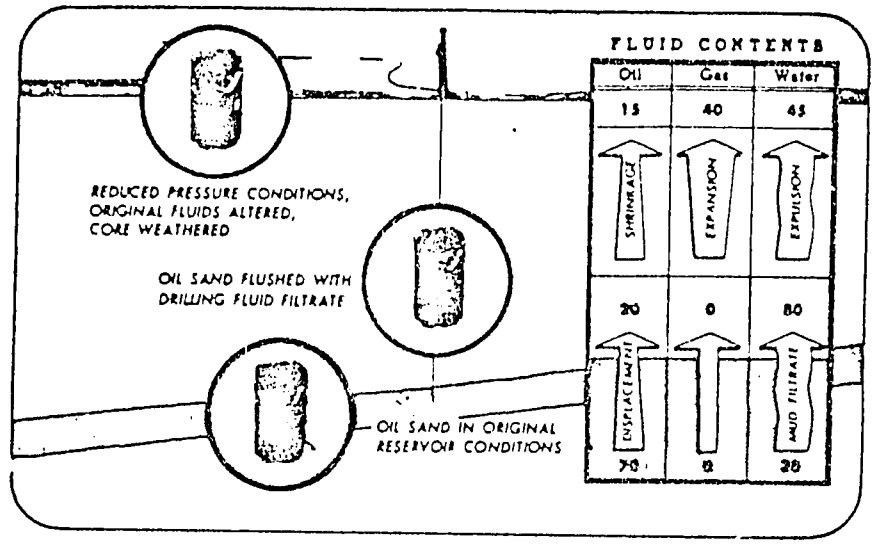


Illustration of changes taking place in a core as it is brought to the surface.

MWD Logs - Coring

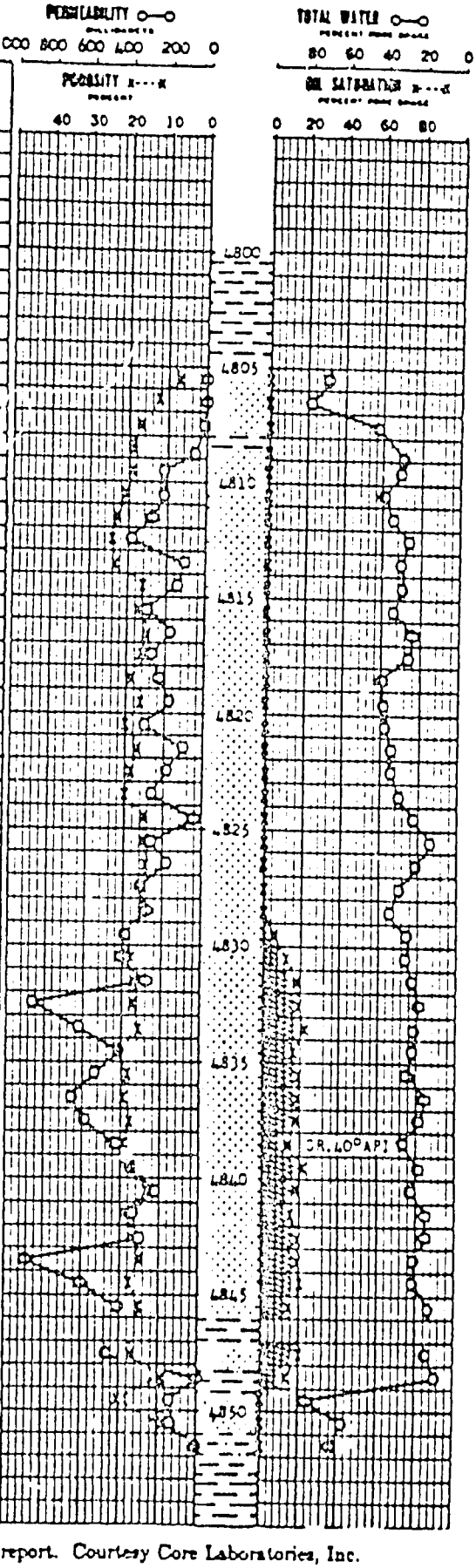
Changes in a Core -- Subsurface to Surface

TABULAR DATA and INTERPRETATION

No Fracture--NF
Vertical Fracture--VF

29	4805.5	0.0	7.5	0.0	68.0	NF
30	06.5	0.0	12.3	0.0	78.0	NF
31	07.5	2.5	17.0	0.0	43.0	NF
32	08.8	59	20.7	0.0	29.0	NF
33	09.5	221	19.1	0.0	31.4	NF
34	10.5	211	20.4	0.0	38.7	VF
35	11.5	275	23.3	0.0	34.7	NF
36	12.5	384	24.0	0.0	26.2	NF
37	13.5	108	23.3	0.0	30.9	NF
38	14.5	147	16.1	0.0	29.2	NF
39	15.5	290	17.2	0.0	34.3	VF
40	16.5	170	15.3	0.0	24.2	NF
41	17.5	278	15.9	0.0	26.4	NF
42	18.5	238	18.6	0.0	39.8	NF
43	19.5	167	16.2	0.0	39.5	VF
44	20.5	304	20.0	0.0	38.0	VF
45	21.5	98	16.9	0.0	34.3	NF
46	22.5	191	18.1	0.0	34.8	VF
47	23.5	266	20.3	0.0	31.1	VF
48	24.5	40	15.3	0.0	22.9	VF
49	25.5	260	15.1	0.0	13.9	VF
50	26.5	179	14.0	0.0	21.4	VF
51	27.5	312	15.6	0.0	28.8	NF
52	28.5	272	15.5	0.0	34.8	VF
53	29.5	395	19.4	6.2	25.3	NF
54	30.5	605	17.5	13.1	25.7	VF
55	31.5	275	16.4	17.7	22.5	NF
56	32.5	852	17.2	19.8	19.2	VF
57	33.5	610	15.5	21.9	21.3	VF
58	34.5	406	20.2	16.3	22.3	VF
59	35.5	535	18.3	19.7	24.6	VF
60	36.5	663	19.6	19.4	16.3	VF
61	37.5	597	17.7	17.5	19.8	VF
62	38.5	434	20.0	14.0	27.5	VF
63	39.5	339	16.9	20.8	19.7	VF
64	40.5	216	13.3	18.1	23.3	VF
65	41.5	332	18.0	15.6	15.6	VF
66	42.5	295	16.1	19.3	15.5	VF
67	43.5	882	15.1	19.2	21.2	NF
68	44.5	600	18.0	20.6	22.2	VF
69	45.5	407	15.7	15.3	13.4	VF
70	4847.5	479	17.8	20.9	14.6	VF
71	48.5	0.0	9.2	14.1	8.7	NF
72	49.5	139	20.5	0.0	77.1	NF
73	50.5	135	8.4	0.0	57.2	NF
74	51.5	0.0	1.1	0.0	53.6	VF

COMPLETION CORELOGRAM



Sample core analysis report. Courtesy Core Laboratories, Inc.

MWD LOGS

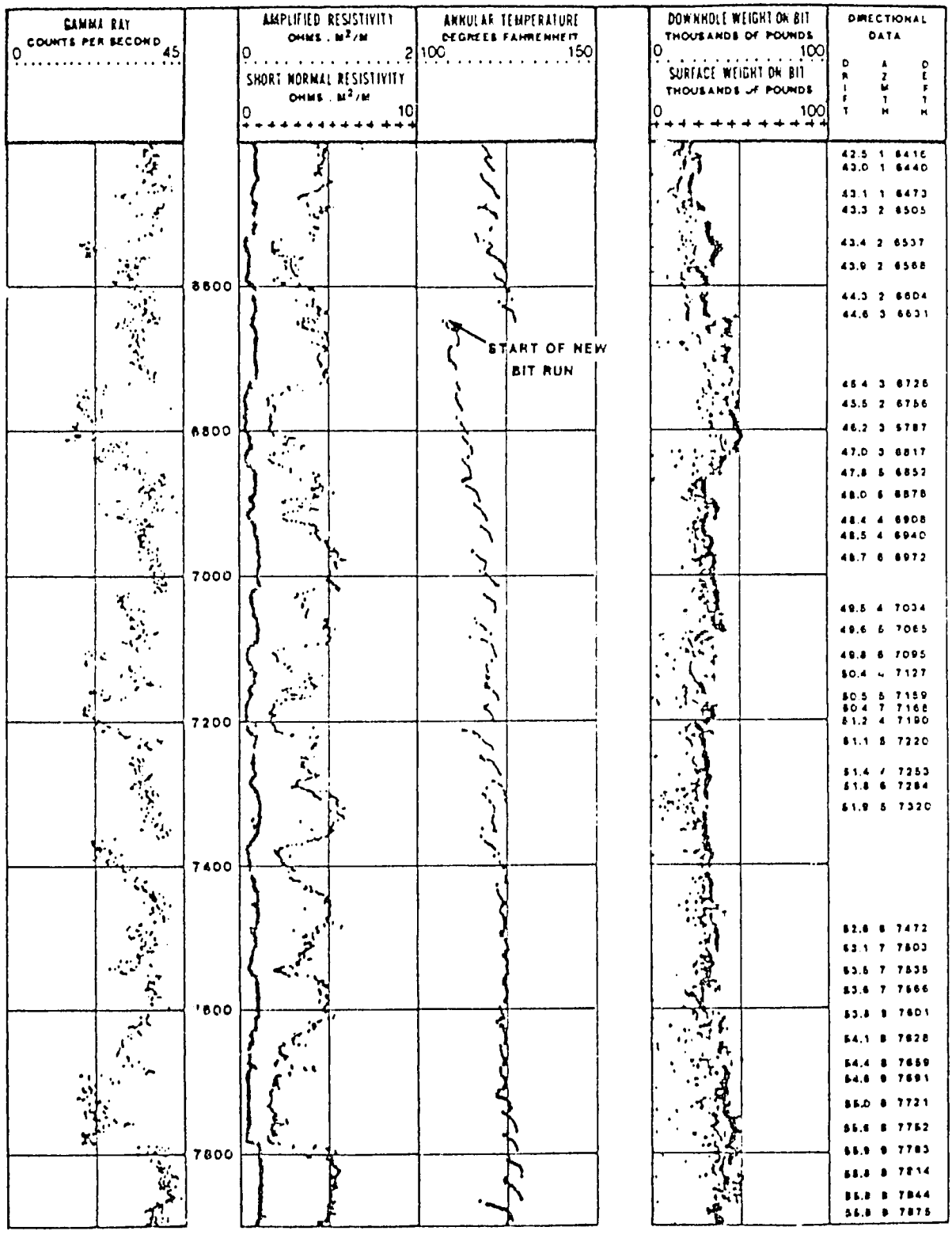
- MODERN MWD SYSTEM
  - MEASUREMENTS CURRENTLY MADE NEAR THE BIT INCLUDE
    - FORMATION RADIOACTIVITY
    - FORMATION RESISTIVITY
    - ANNULAR TEMPERATURE
    - DOWN HOLE WEIGHT ON BIT
    - HOLE DEVIATION
    - AZIMUTH
    - TOOL FACE ANGLE

MODERN MWD SYSTEM - CONT.

- DATA TRANSMISSION
  - VIA CONTINUOUS PRESSURE WAVE THROUGH MUD INSIDE THE DRILL PIPE
  - SIGNALS DETECTED AT THE SURFACE AND PROCESSED BY ON-SITE COMPUTER
  - INFORMATION IS PLOTTED IN REAL TIME ON CONTINUOUS MULTI-SCALE LOGS
  - DATA ALSO AVAILABLE DIGITALLY ON VIDEO DISPLAYS AND STORED ON MAGNETIC TAPE

- USES
  - FORMATION EVALUATION
  - ABNORMAL PRESSURE DETECTION
  - CORRELATION
  - DRILLING CONTROL

MWD ROTARY DRILLING LOG



ELECTRIC LOGGING - THE SP LOG

- WHAT IS IT -- RECORDING VS DEPTH OF THE DIFFERENCE BETWEEN THE POTENTIAL OF A MOVABLE ELECTRODE IN THE BOREHOLE AND THE FIXED POTENTIAL OF A SURFACE ELECTRODE

- IT IS A NATURAL LOG

- USES
  - DETECT PERMEABLE BEDS
  - LOCATE BED BOUNDARIES
  - CORRELATION OF BEDS
  - DETERMINE WATER RESISTIVITY, Rw
  - ESTIMATE BED SHALINESS

THE SP LOG - CONT.

ORIGIN OF SP

MEMBRANE POTENTIAL (SHALE POTENTIAL), E_M

FLOW OF N_A IONS FROM CONNATE WATER THROUGH SHALE TO MUD

C_L IONS ARE RESTRAINED FROM DIFFUSING BY THEIR IONIC BONDS WITH THE SHALE

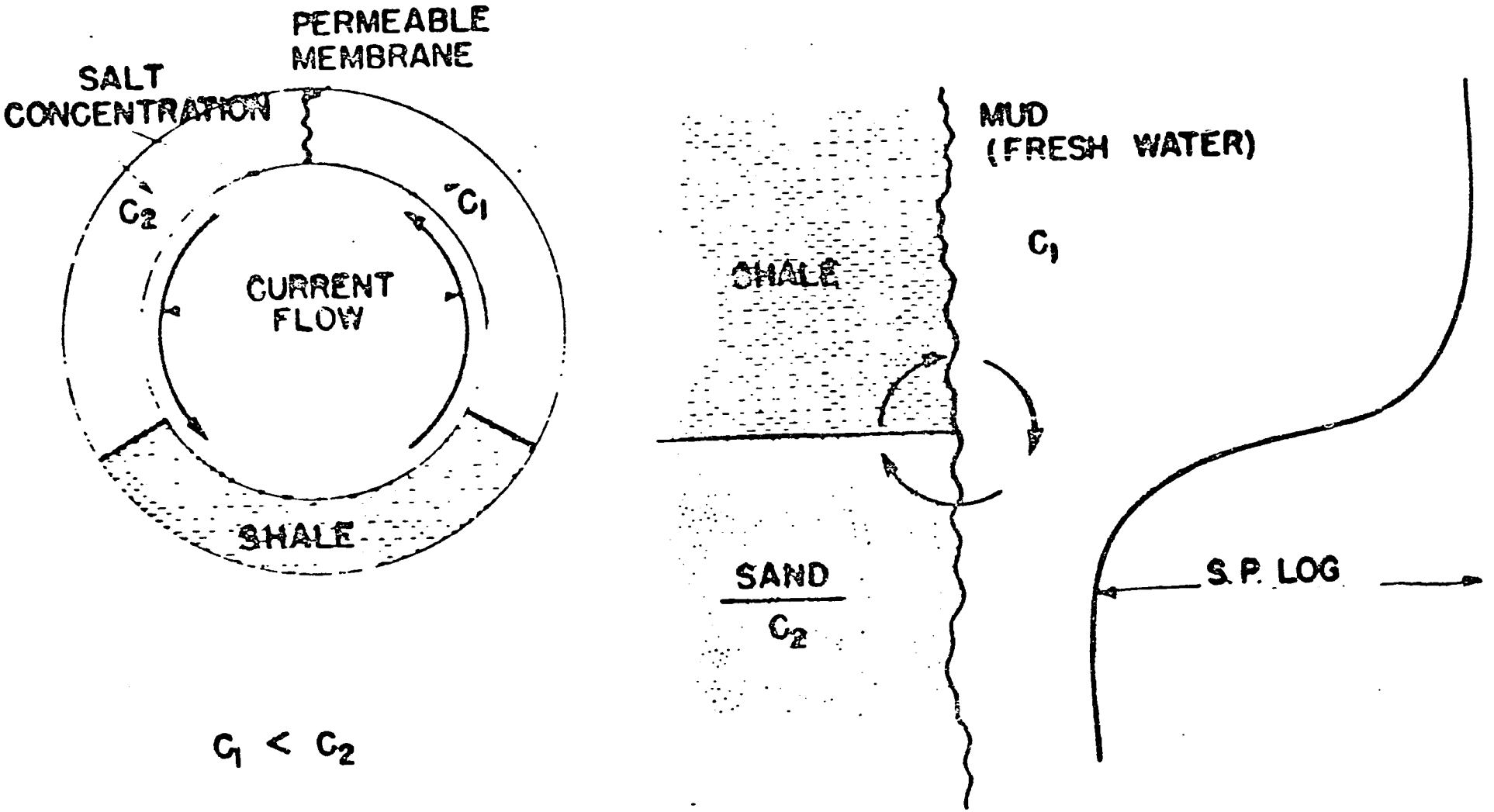
LIQUID JUNCTION POTENTIAL (DIFFUSION POTENTIAL) E_l

DEVELOPED NEAR BOREHOLE WALL AT JUNCTION OF CONNATE WATER AND MUD FILTRATE

C_L IONS DIFFUSE INTO MUD FILTRATE CAUSING ELECTRICAL FLOW IN OPPOSITE DIRECTION

THE SP FORMULA

$$SP = -K \log \frac{A_W}{A_{MF}} = -K \log \frac{R_{MFE}}{R_{WE}}$$



MOUNCE & RUST SHALE CELL

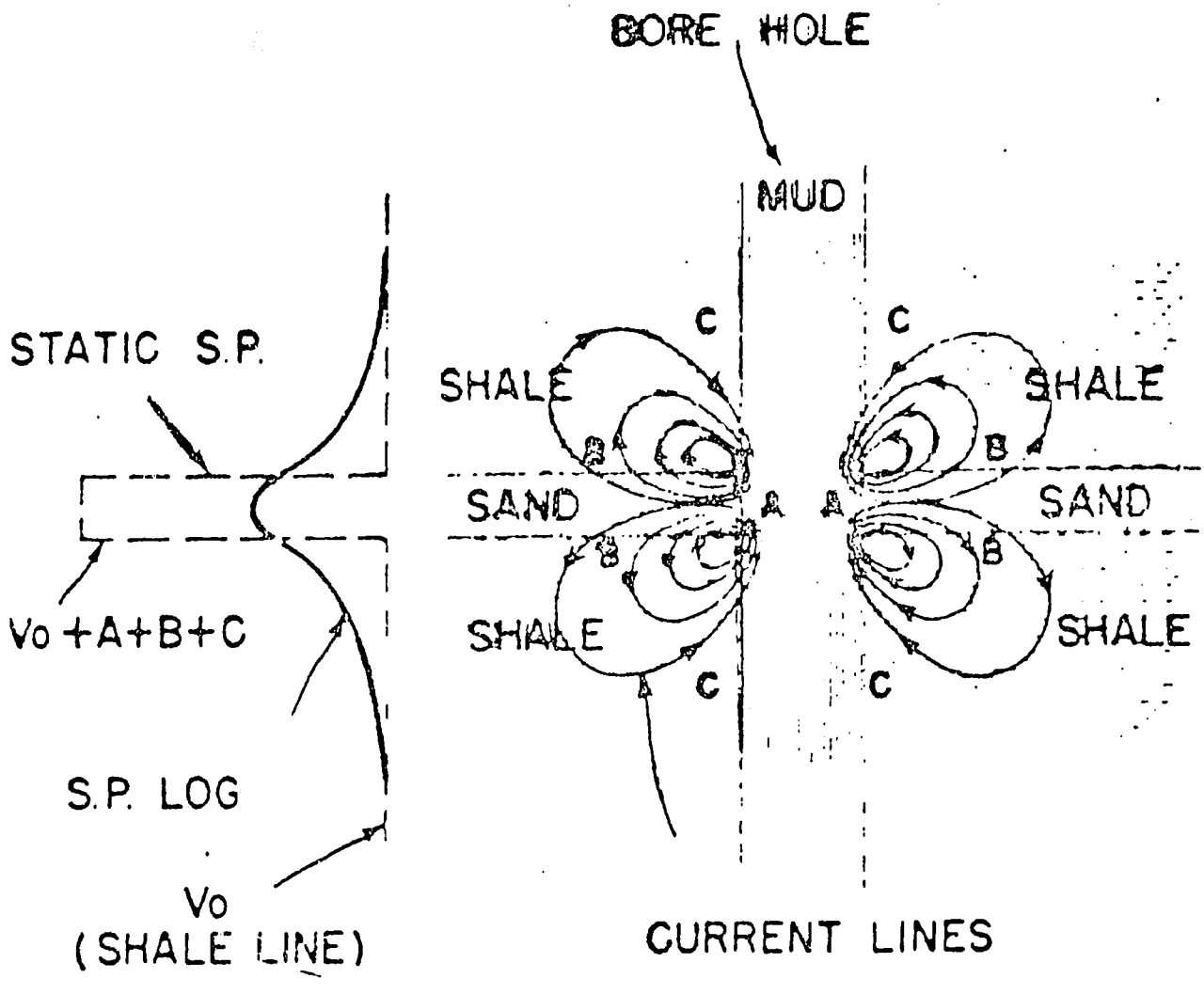
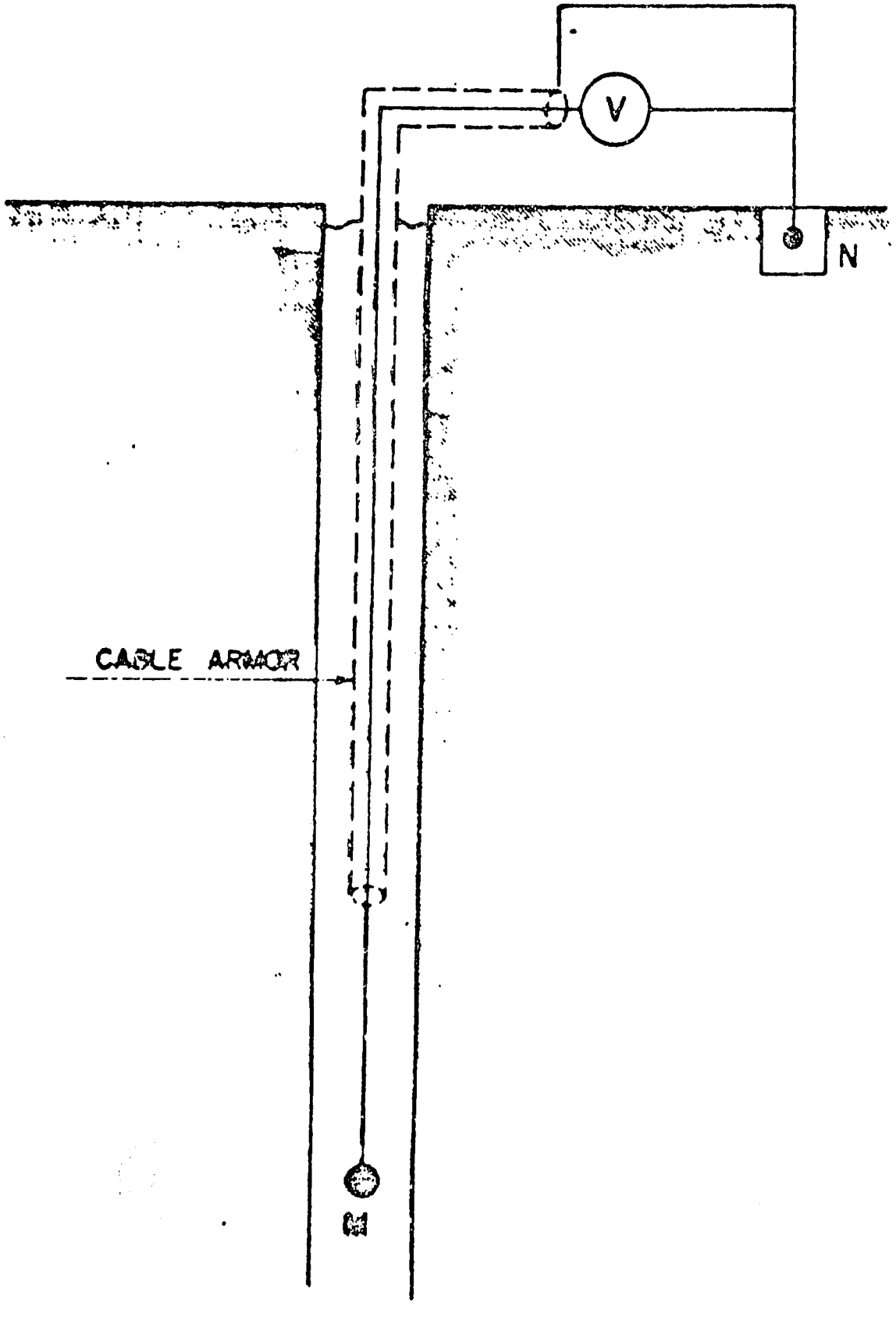
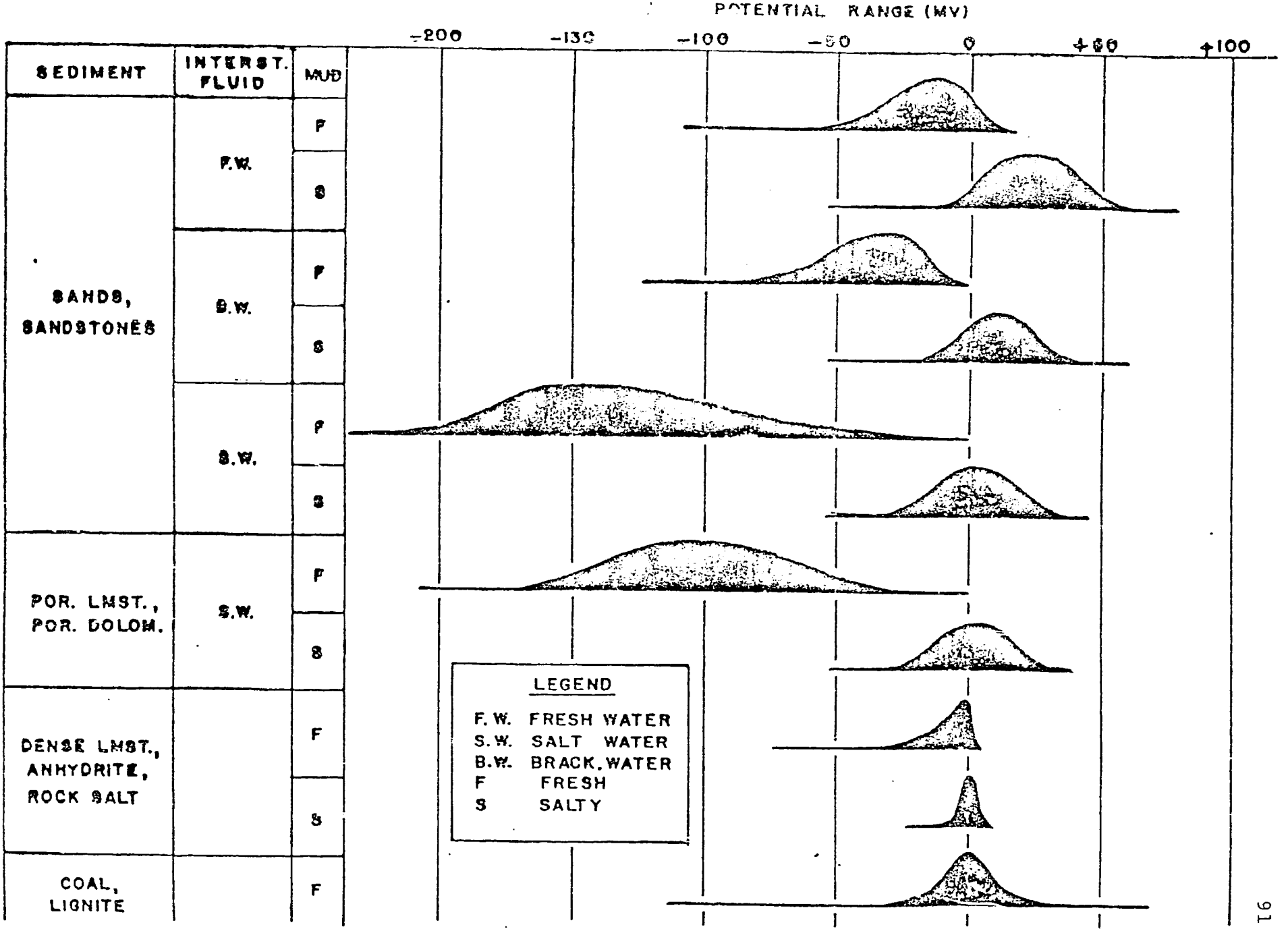


ILLUSTRATION OF THE DYNAMIC S.P.

DIAGRAM OF SIMPLIFIED S. P. CIRCUIT





The length of the lines represents the range, while the line thickness and area approximately the corresponding frequency of occurrence.

POTENTIAL RANGE OF COMMON SEDIMENTS

From Guyod-Electrical Well Logging Fundamentals, 1952

POTENTIAL RANGE OF COMMON SEDIMENTS

ELECTROKINETIC SP (ELECTROFILTRATION POTENTIAL), E_K

PRODUCED BY FLOW OF ELECTROLYTE THROUGH NON-METALLIC POROUS MEDIUM

$$E_K = F\ (\Delta P,\ R_W)$$

MOVEMENT OF MUD FILTRATE THROUGH MUD CAKE IN A PERMEABLE BED

E_K MOSTLY EXISTS ACROSS MUD CAKE BECAUSE ΔP IS ACROSS MUD CAKE

$$E_{K_{MC}} \approx E_{K_{SH}} \qquad \text{OR} \qquad E_{K_{MC}} - E_{K_{SH}} \approx 0$$

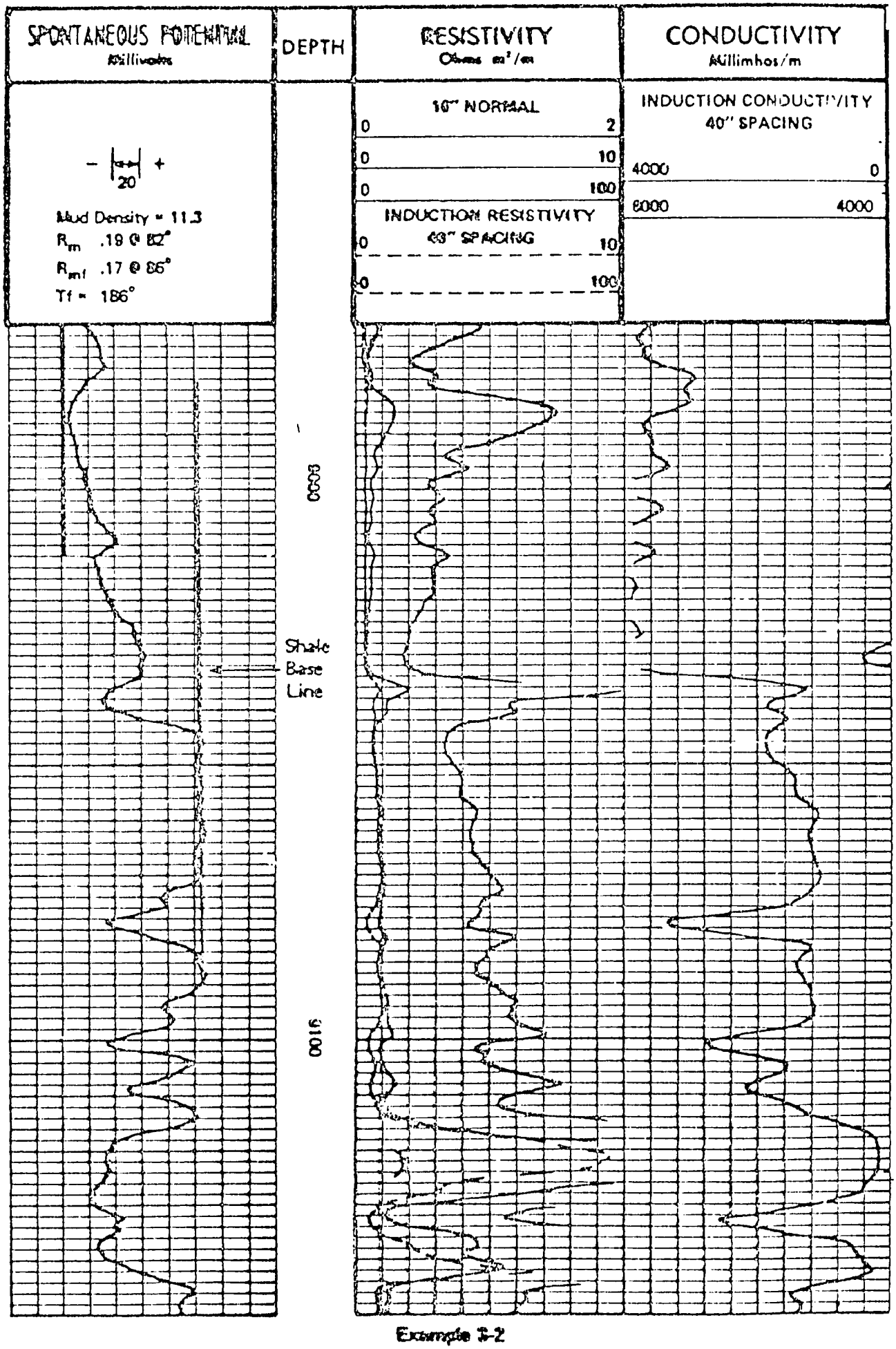
E_K IS IMPORTANT WHEN ----

ΔP IS LARGE (HEAVY MUD) OR RESERVOIR PRESSURE IS LOW

LOW K ($<$ 5 MD) AND LITTLE MUD CAKE IS FORMED AND LOT OF ΔP IS APPLIED TO BED

FORMATION WATER IS BRACKISH AND MUD FILTRATE IS RESISTIVE

PRESENCE OF SIGNIFICANT E_K MAKES THE SP LOG LESS INTERPRETABLE



Example 3-2

Courtesy Dresser Atlas

THE SP LOG - CONT.

SP VS PERMEABILITY AND POROSITY

MUST HAVE SOME K AND ϕ TO HAVE SP BUT

$$SP \neq F\ (K,\ \phi)$$

STATIC SP

SUM OF POTENTIAL DROPS IN BOREHOLE, INVADED ZONE, BED AND SHALE

SP OF THICK ($>16D$) CLEAN BED $\approx$ SSP

SHAPE OF SP CURVE

SLOPE OF SP CURVE IS PROPORTIONAL TO INTENSITY OF SP CURRENTS IN MUD

CURRENT INTENSITY IS A MAXIMUM @ BOUNDARY GIVING MAXIMUM SLOPE (INFLECTION POINT)

SHAPE AND AMPLITUDE OF SP CURVE
DEPENDS ON

BED THICKNESS

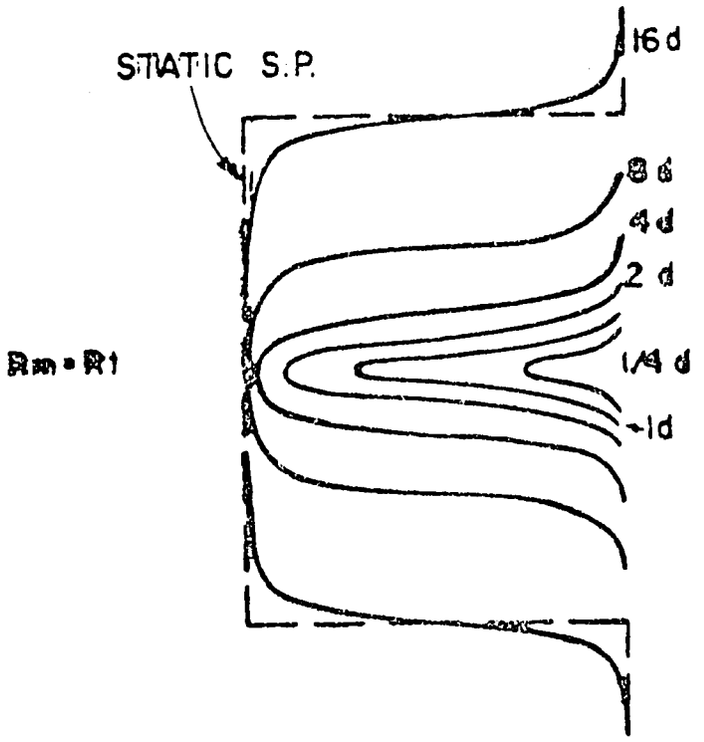
BED RESISTIVITY

CONTRACT OF R_W AND R_{MF}

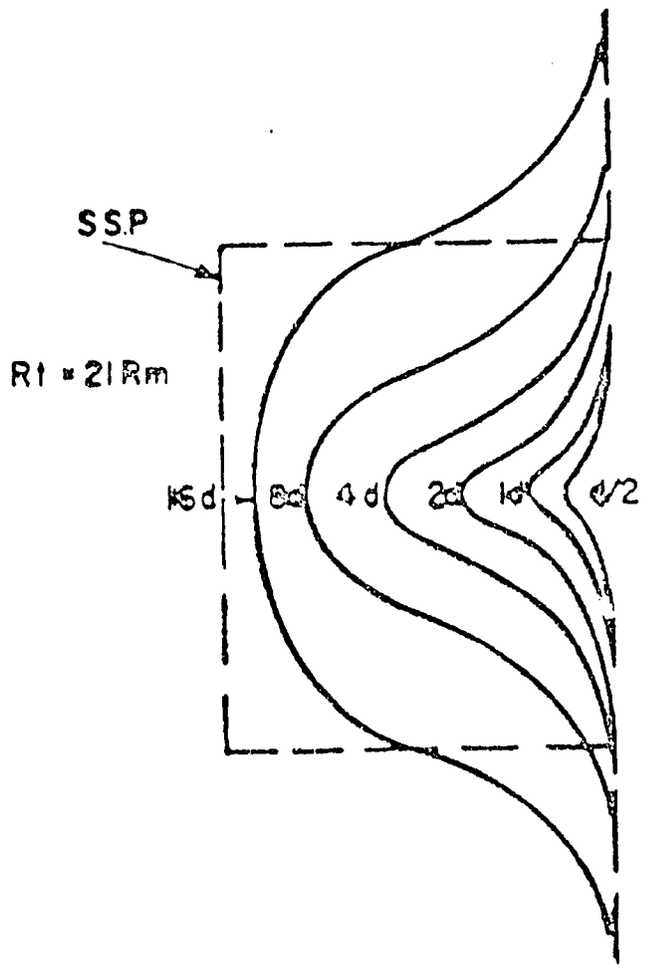
DIAMETER OF INVASION

SHALE RESISTIVITY, R_S

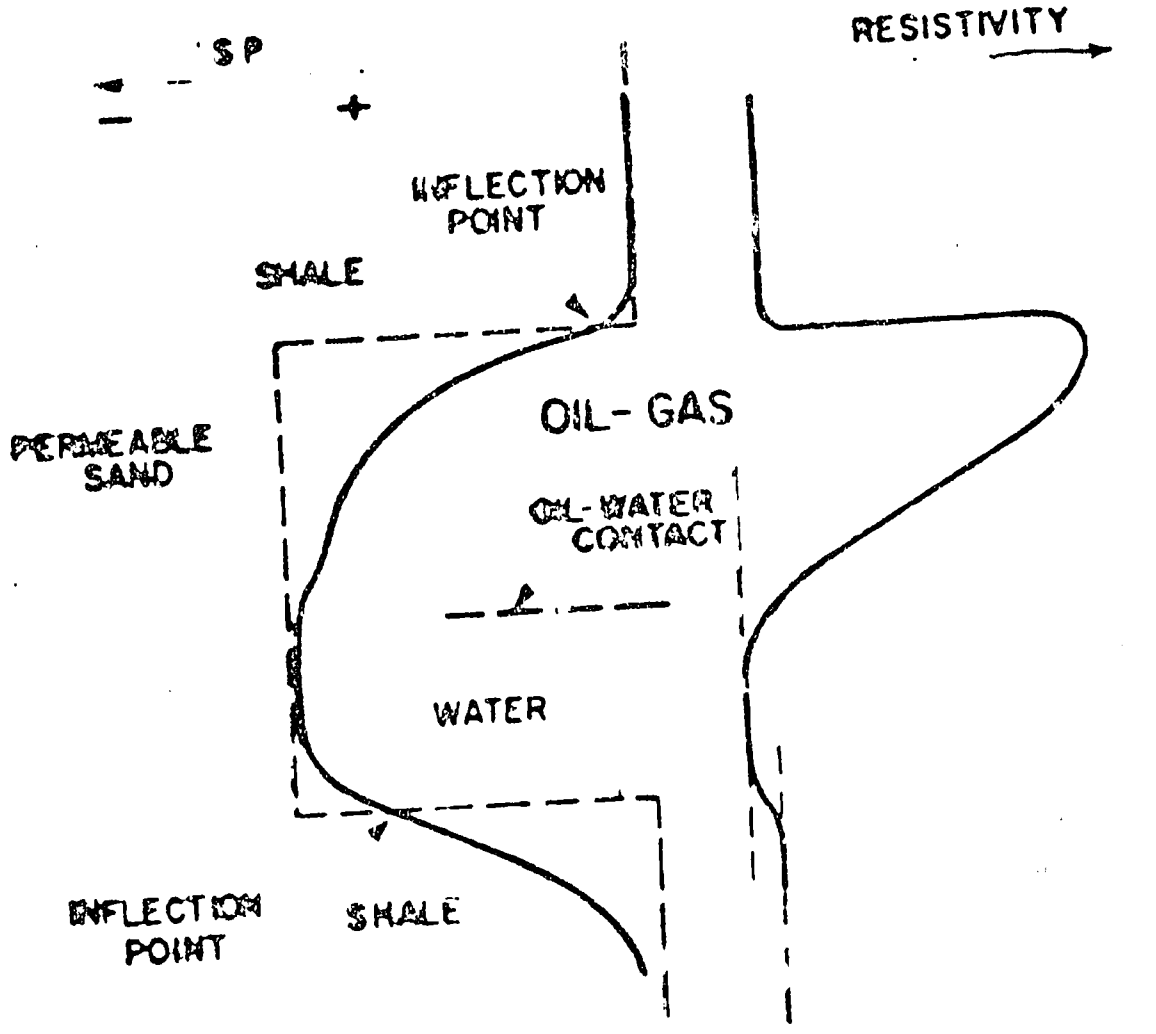
BED SHALINESS, V_{SH}

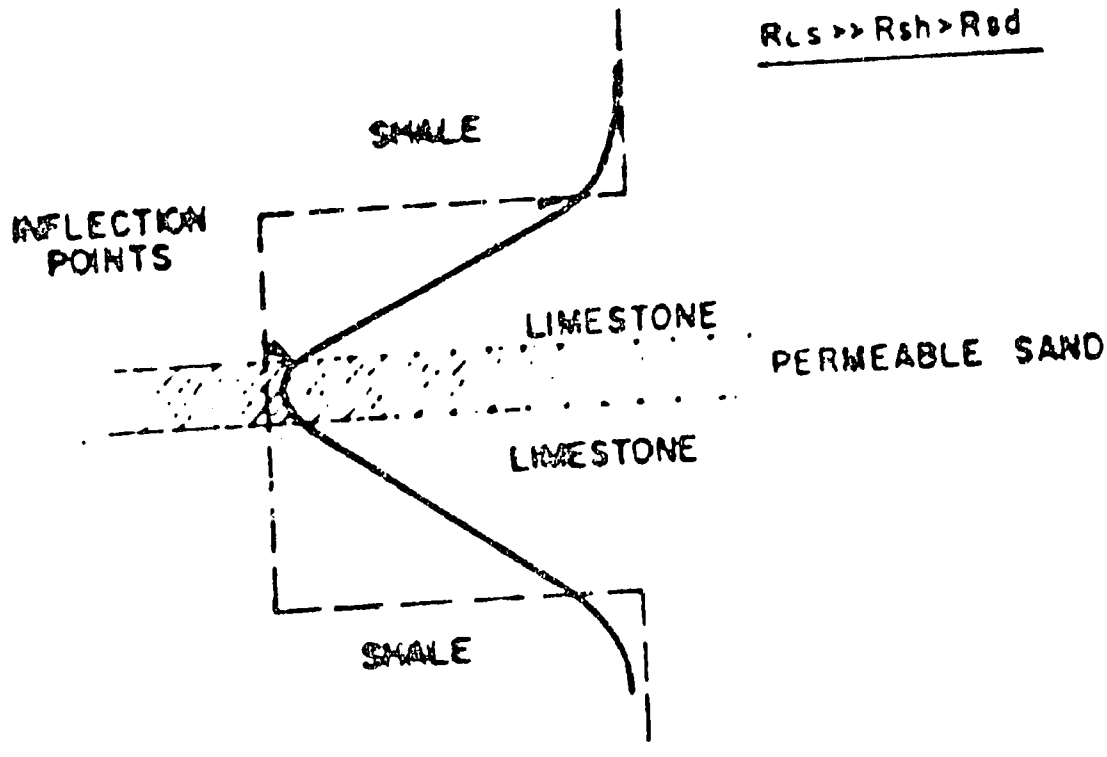


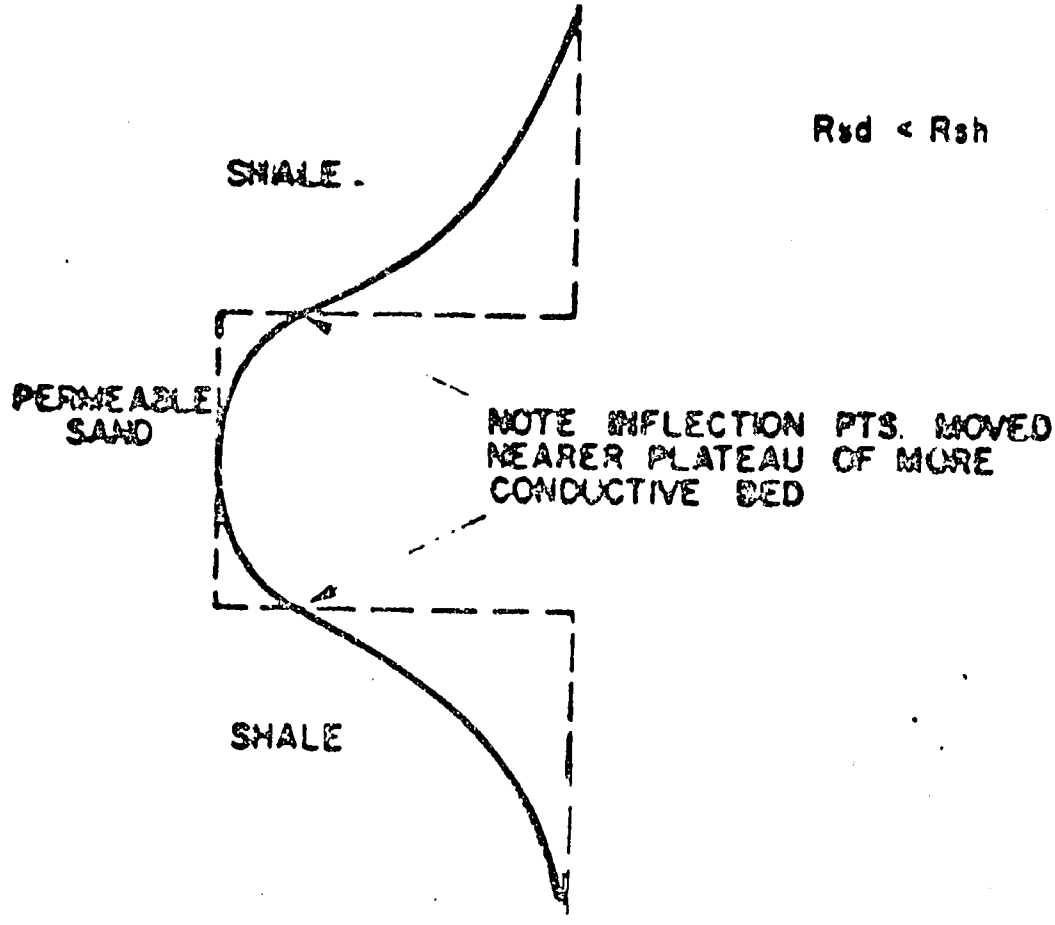
AMPLITUDE OF S.P. AS A FUNCTION OF BED THICKNESS EXPRESSED IN BORE HOLE DIAMETERS

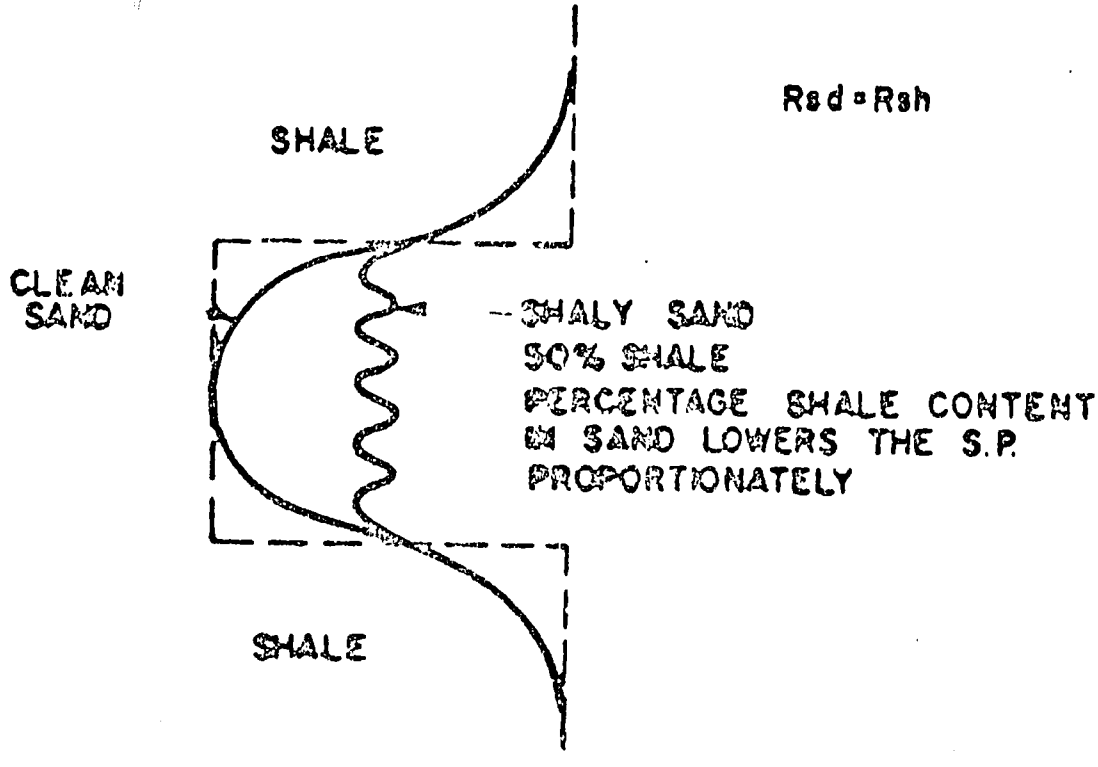


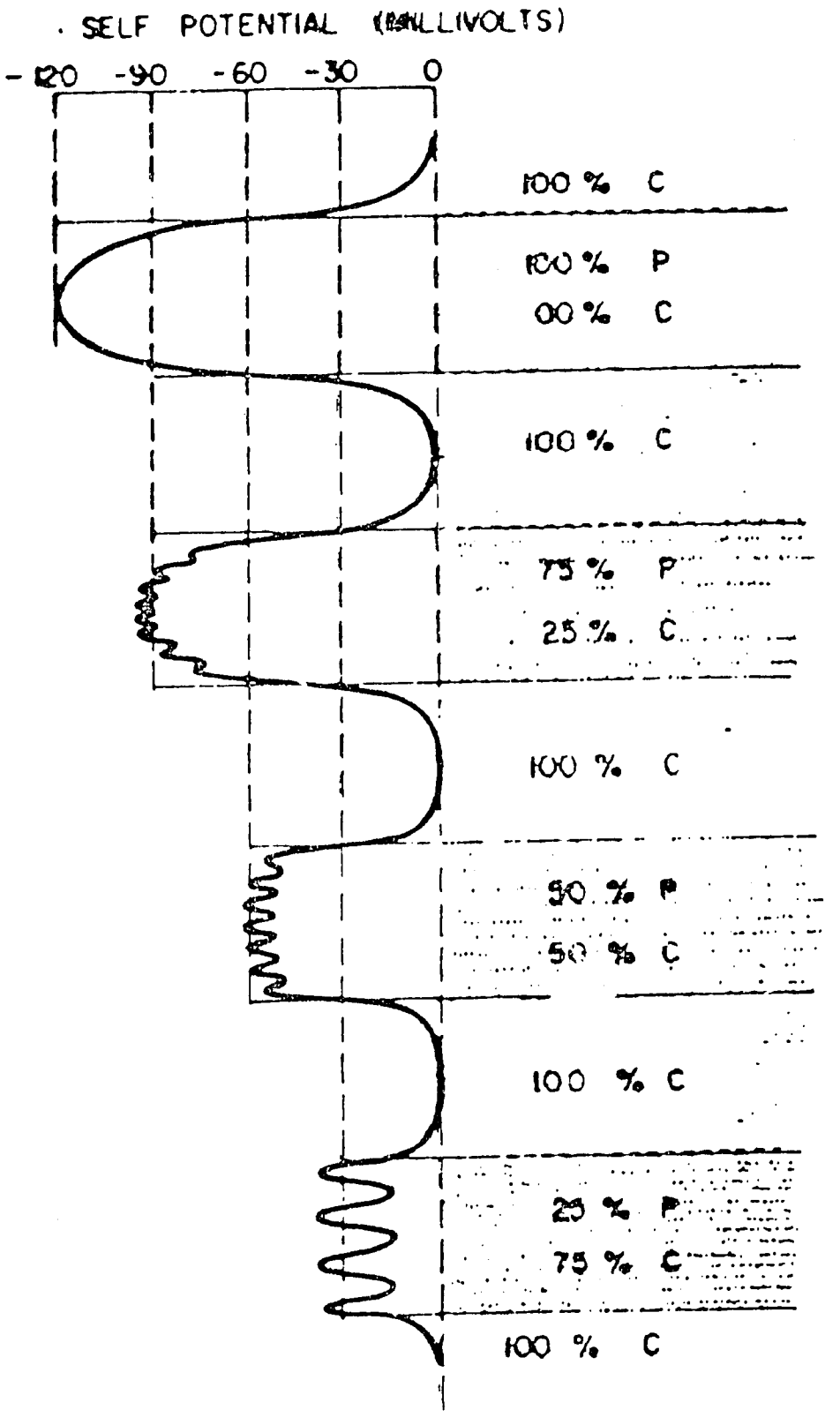
SHOWING DECREASE IN AMPLITUDE AS e→d & ROUNDING OF SP AS R1/Rm INCREASES


SP
RESISTIVITY
INFLECTION POINT
SHALE
PERMEABLE SAND
OIL- GAS
OIL-WATER CONTACT
WATER
INFLECTION POINT
SHALE


Rcs >> Rsh > Rsd
SHALE
INFLECTION POINTS
LIMESTONE
PERMEABLE SAND
LIMESTONE
SHALE


Rsd < Rsh
SHALE
PERMEABLE SAND
NOTE INFLECTION PTS. MOVED NEARER PLATEAU OF MORE CONDUCTIVE BED
SHALE

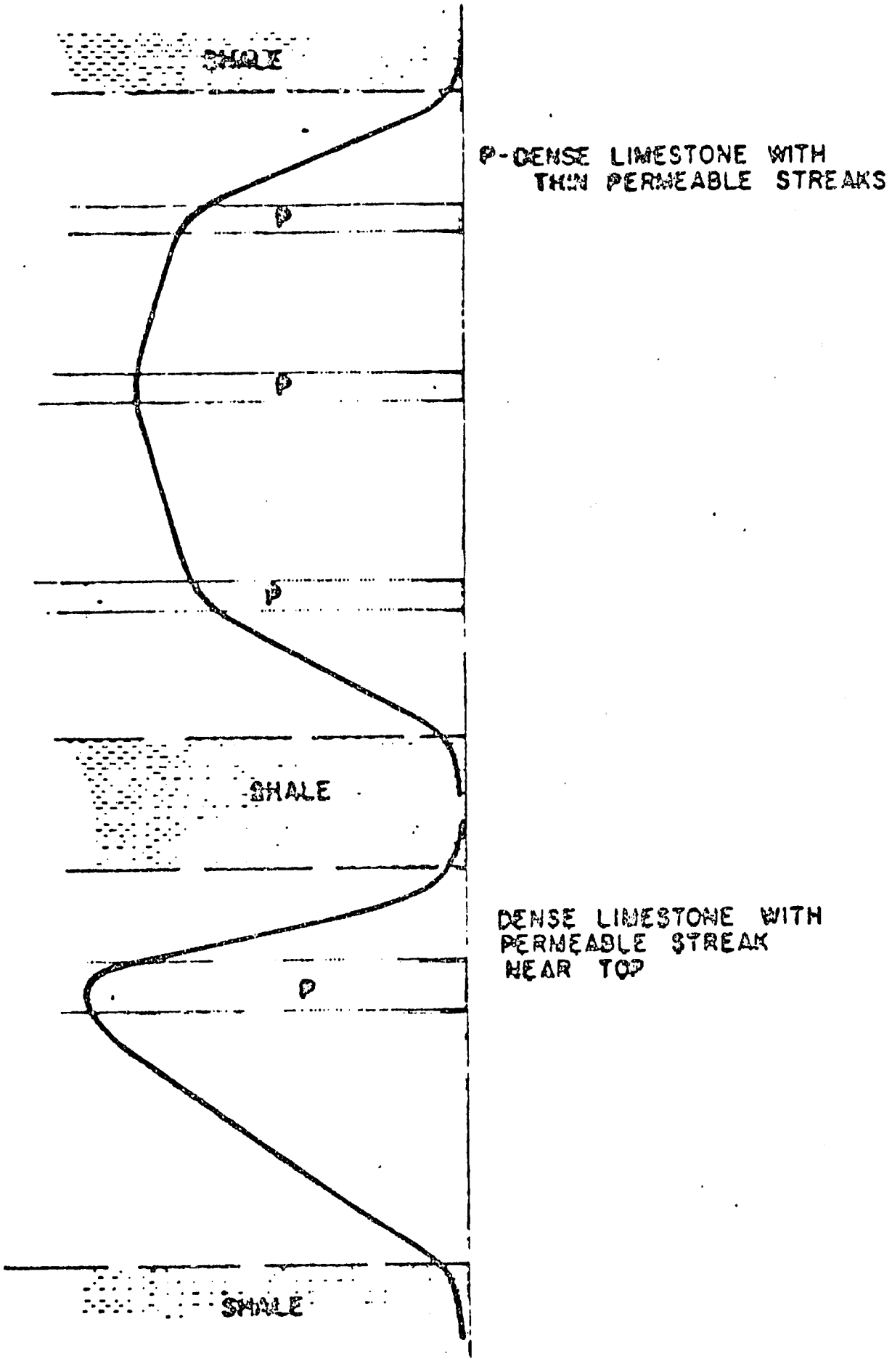

Rsd = Rsh
SHALE
CLEAN SAND
SHALY SAND
50% SHALE
PERCENTAGE SHALE CONTENT IN SAND LOWERS THE S.P. PROPORTIONATELY
SHALE



P = PERMEABLE STRATA

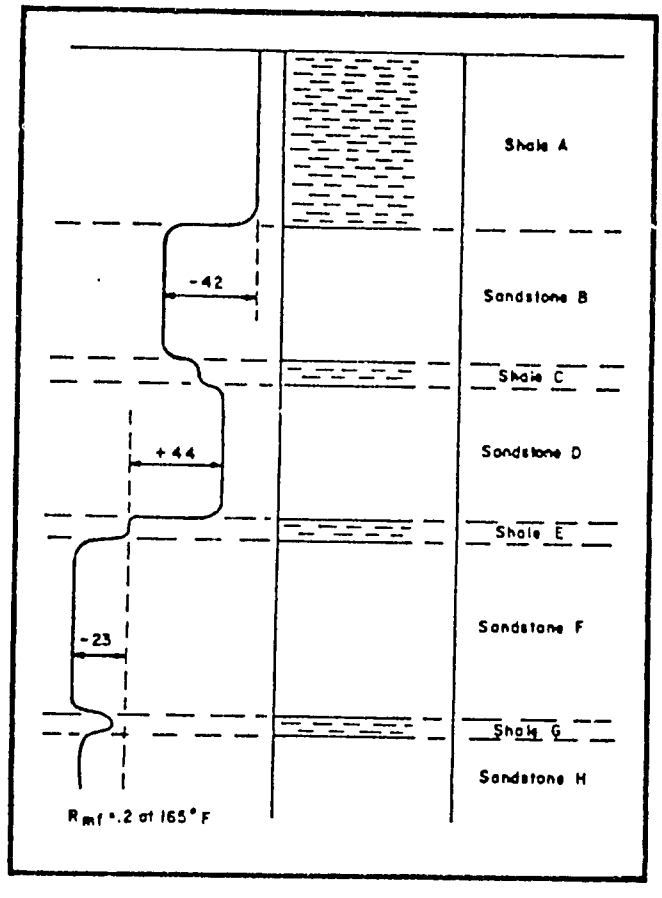
C = IMPERVIOUS & CONDUCTIVE STRATA (SHALE)

% SHALE CONTENT vs. SELF POTENTIAL


SHALE
P-DENSE LIMESTONE WITH
THIN PERMEABLE STREAKS
P
P
P
SHALE
DENSE LIMESTONE WITH
PERMEABLE STREAK
NEAR TOP
P
SHALE

SHALE BASE LINE SHIFTS

OCCUR WHEN BED WATERS OF DIFFERENT SALINITIES ARE SEPARATED BY NON-PERFECT CATIONIC (SHALE) MEMBRANE



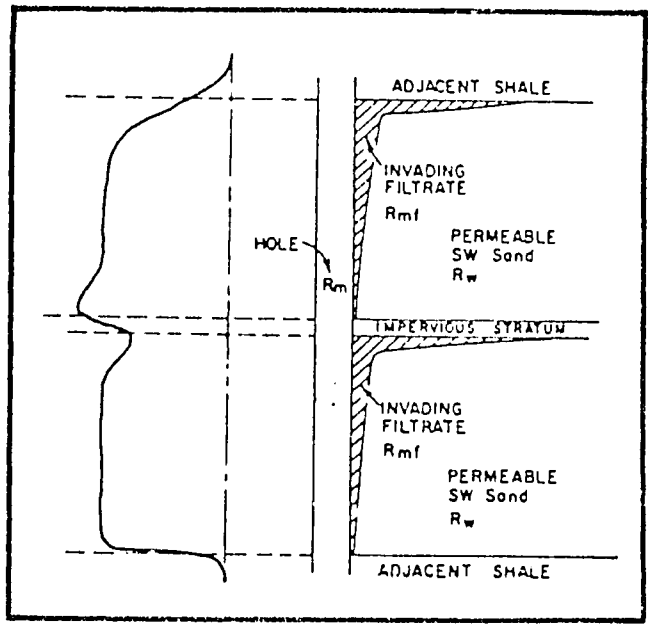
— SP base-line shift.

From Schlumberger's 1972 Principles

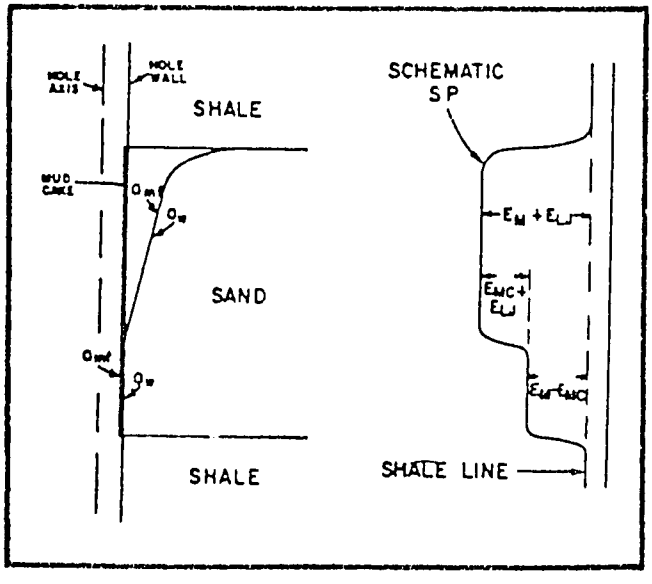
SP ANOMALIES RELATED TO CONDITIONS OF INVASION

OCCUR IN HIGH PERMEABILITY AQUIFERS

MUST HAVE BOTH VERTICAL AND HORIZONTAL PERMEABILITIES



— *Sawtooth SP.*



— *SP reduction by mud-cake membrane emf.*

From Schlumberger's 1972 Log Interpretation - Vol. 1 "Principles"

DETERMINATION OF R_W FROM SP LOG

BASIC ASSUMPTION IS THAT BED IS CLEAN

PROCEDURE

DRAW CLEAN BED AND SHALE BASE LINES ON SP LOG

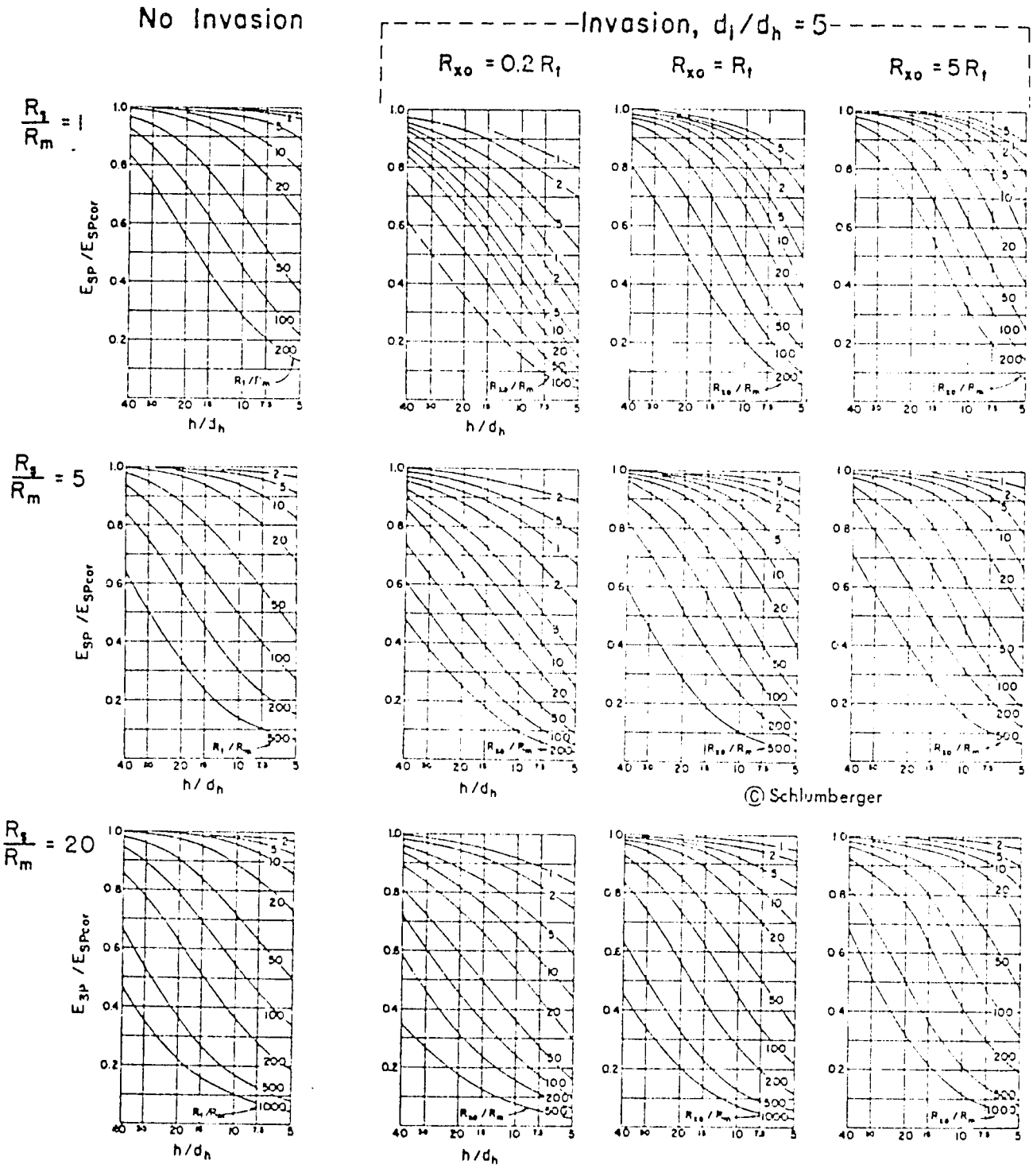
READ SP

CORRECT SP FOR D_I, R_T, R_{XO}, R_S, R_M, H AND D_H USING SP-3 -- GIVES SP_C

OBTAIN R_{WE} FROM SP-1

READ R_W FROM SP-2

SP CORRECTION CHARTS
(FOR REPRESENTATIVE CASES)[4]



© Schlumberger

1. Select row of charts for most appropriate value of R_t/R_m.
2. Select chart for No Invasion or for Invasion of $d_i/d_h = 5$, as more appropriate.
3. Enter abscissa with value of h/d_h (ratio of bed thickness to hole diameter).
4. Go vertically up to curve for appropriate R_t/R_m (for no invasion) or R_{xo}/R_m (for invaded cases), interpolating between curves if necessary.
5. Read E_{SP}/E_{SPcor} in ordinate scale. Calculate $E_{SPcor} = E_{SP}/(E_{SP}/E_{SPcor})$. ($E_{SP}$ is SP from log.)

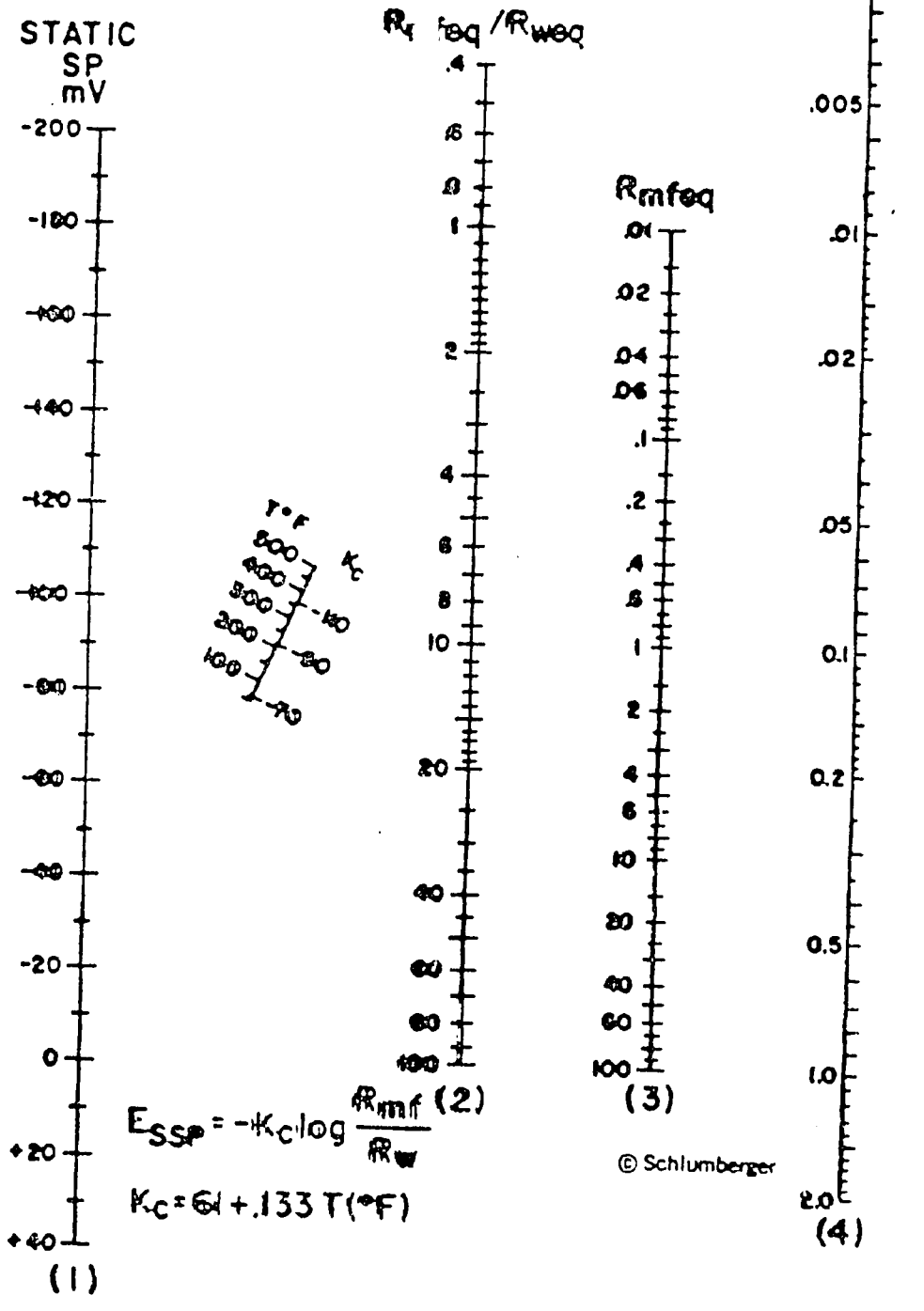
For more detail on SP Corrections see Reference 4.

R_{weq} DETERMINATION FROM THE SSP
(CLEAN FORMATIONS)

For predominantly sodium chloride muds determine R_{weq} as follows:

a. If R_w at 75° is greater than 0.1 ohm-m, correct R_w to formation temperature using Gen-9, and use $R_{weq} = 0.85\ R_w$.

b. If R_w at 75° is less than 0.1 ohm-m, use SP-2 to derive a value of R_{weq} at formation temperature.

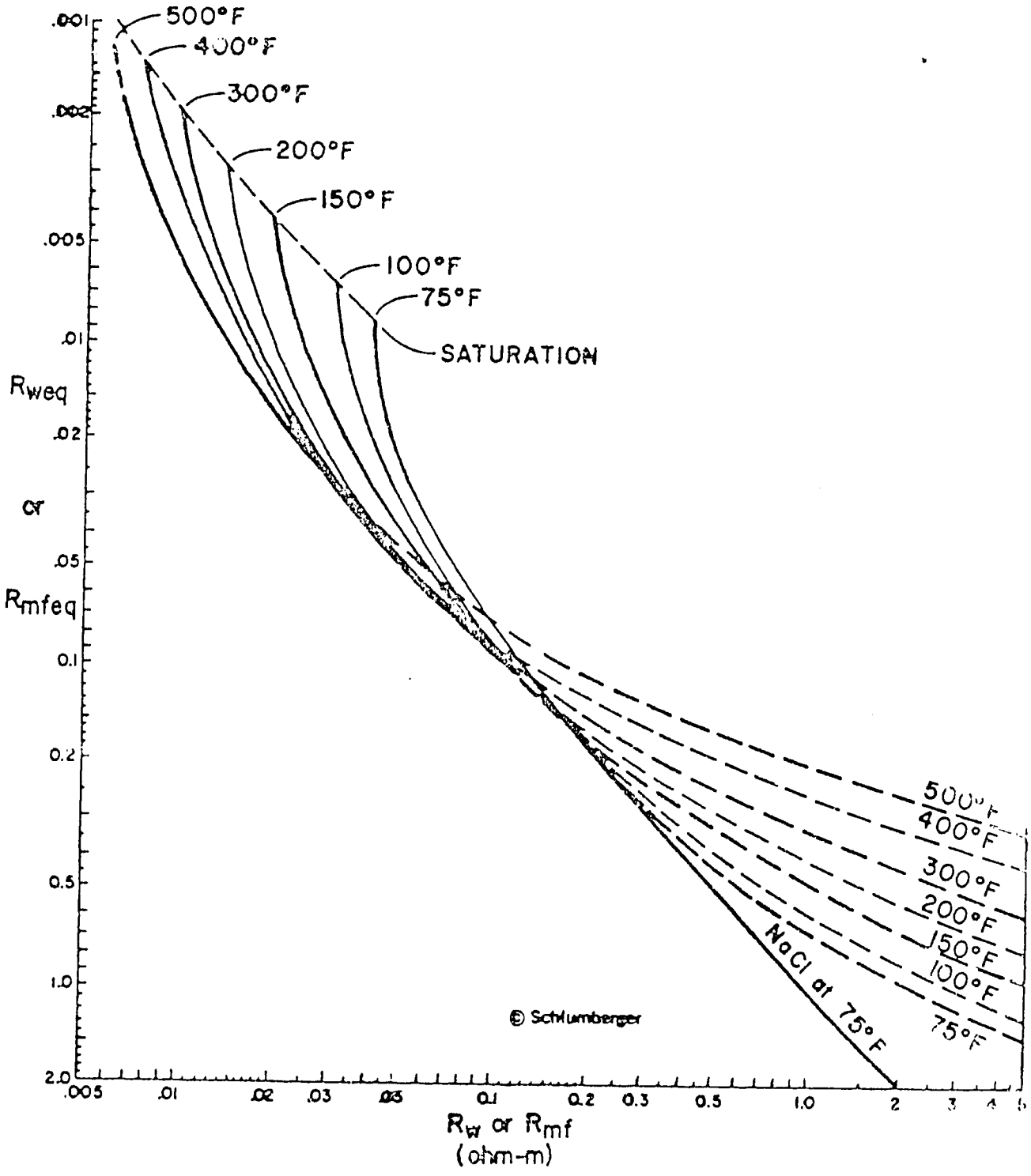


$$E_{SSP} = -K_c \log \frac{R_{mf}}{R_w}$$

$$K_c = 61 + .133\ T(°F)$$

© Schlumberger

R_w VERSUS R_{weq} AND FORMATION TEMPERATURE [3]



Use the solid lines of this chart for predominantly NaCl waters. The dashed lines are approximate for "average" fresh formation waters (where effects of salts other than NaCl become significant). The dashed portions may also be used for gyp-base mud filtrates.

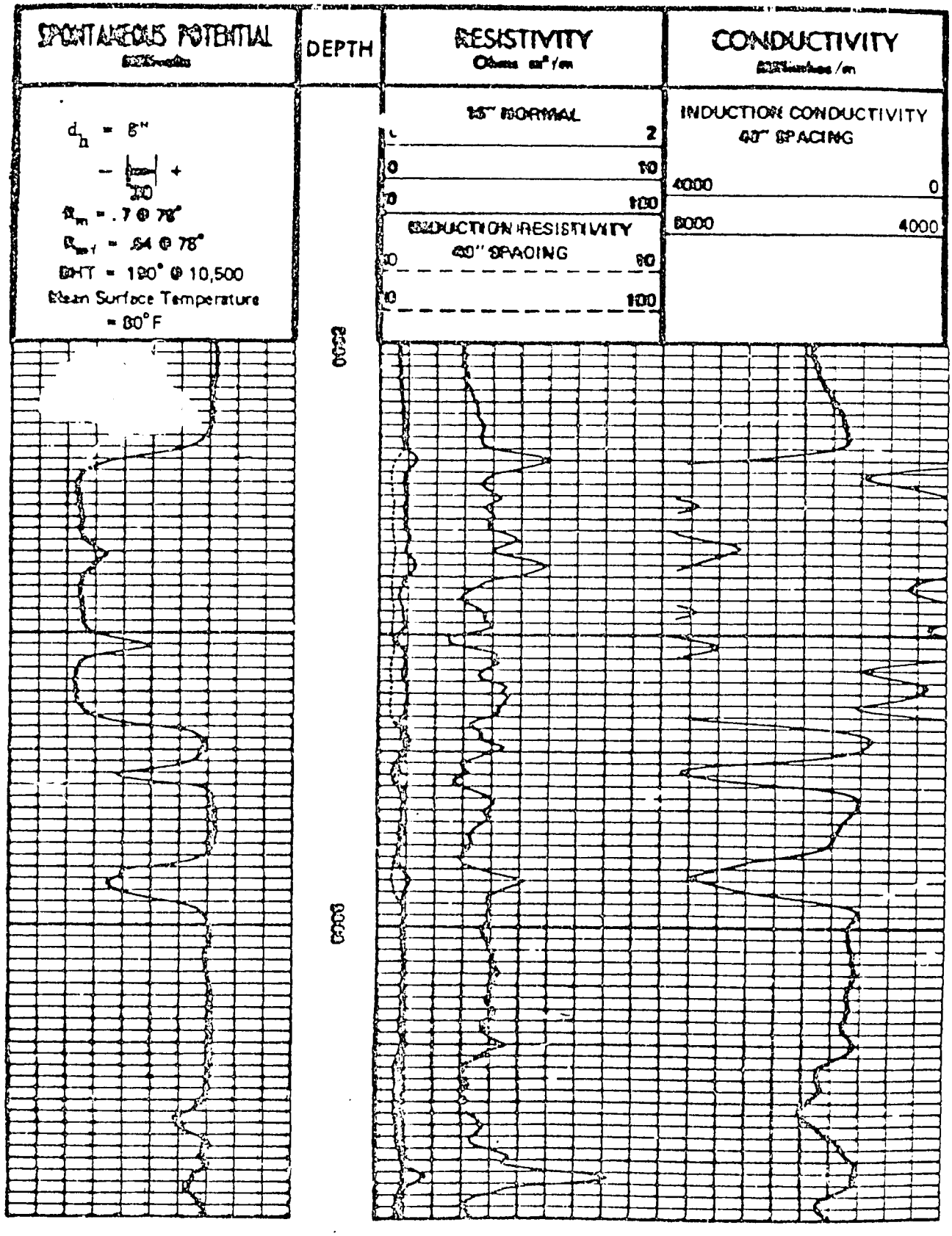
Example: R_{weq} = .025 at 150°F. From chart, R_w = .003

Special procedures for muds containing Ca or Mg in solution are discussed in the reference. Lime base muds usually have a negligible amount of Ca in solution, and may be treated as regular mud types.

R_w from SP Problem

Determine R_w in the interval 8919 - 8951.

PROBLEM



Example 104

From 1975 Log Interpretation Fundamentals - Dresser Atlas

THE GAMMA RAY LOG

- MEASUREMENT OF NATURAL RADIOACTIVITY OF FORMATIONS
- REFLECTS SHALE CONTENT OF BEDS --- RADIOACTIVE ELEMENTS TEND TO CONCENTRATE IN SHALES
- OFTEN REFERRED TO AS THE SHALE LOG
- CLEAN BEDS SHOW LOW LEVEL OF RADIOACTIVITY UNLESS THEY CONTAIN RADIOACTIVE CONTAMINANTS
  - VOLCANIC ASH
  - GRANITE WASH
  - DISSOLVED POTASSIUM SALTS
  - DEPOSITED URANIUM
- CAN BE RECORDED IN CASED AND UNCASED WELLS
- IS A NATURAL LOG

GAMMA RAY LOG USES

- LOCATE WATER ENTRY POINTS IN OLD WELLS
- COMPLETION AND WORKOVER OPERATION
- SUBSTITUTE FOR SP IN
  - VERY RESISTIVE FORMATIONS
  - WELLS DRILLED (W) SALT BASE MUD
  - WELLS DRILLED (W) NON-CONDUCTIVE MUDS
  - EMPTY HOLES
  - CASED HOLES
  - SHALE INDICATOR
  - DETECTION & EVALUATION OF RADIOACTIVE MINERALS (POTASH OR URANIUM ORE)
  - CORRELATION

  TRACER OPERATIONS

GAMMA RAYS

- ARE BURSTS OF HIGH ENERGY ELECTROMAGNETIC WAVES
- ARE EMITTED SPONTANEOUSLY BY RADIOACTIVE ELEMENTS
- IN PASSING THROUGH MATTER, EXPERIENCE SUCCESSIVE CAMPTON SCATTERING COLLISIONS
- LOSE ENERGY AND ARE ABSORBED
- ABSORPTION IS A FUNCTION OF FORMATION DENSITY
  LESS DENSE FORMATION IS MORE RADIOACTIVE

GAMMA RAY LOG RESPONSE

- PROPORTIONAL TO RADIOACTIVE MATERIAL WEIGHT - CONCENTRATION IN THE FORMATION
- AFFECTED BY
  - DENSITY OF FORMATION
  - HOLE DIAMETER
  - MUD WEIGHT
  - CASING
  - CEMENT
- VERTICAL RESOLUTION $\approx$ 2 1/2"
- PENETRATION $\approx$ 6" TO 1"

STATISTICAL VARIATIONS

- RADIOACTIVE EMISSIONS ARE RANDOM IN NATURE
- COUNT RATES FLUCTUATE RAPIDLY WITH TIME
- A TIME AVERAGING PROCEDURE IS ADOPTED TO MINIMIZE STATISTICAL FLUCTUATIONS
- ELECTRICAL PULSES FROM THE DETECTOR OUTPUT ARE COUNTED PER UNIT INTERVAL OF TIME
- COUNT RATE METER IS DESIGNED TO AVERAGE THE RANDOM COUNT RATES OVER A TIME PERIOD PROPORTIONAL TO THE TIME CONSTANT
- SINGLE TIME CONSTANT IS THE RESPONSE TIME IN SECONDS NECESSARY TO RECORD 63% OF THE ULTIMATE THICK BED VALUE.
- SELECTION OF A TIME CONSTANT IS A PRACTICAL COMPROMISE OF LOGGING SPEED AND ACCEPTABLE STATISTICAL QUALITY.

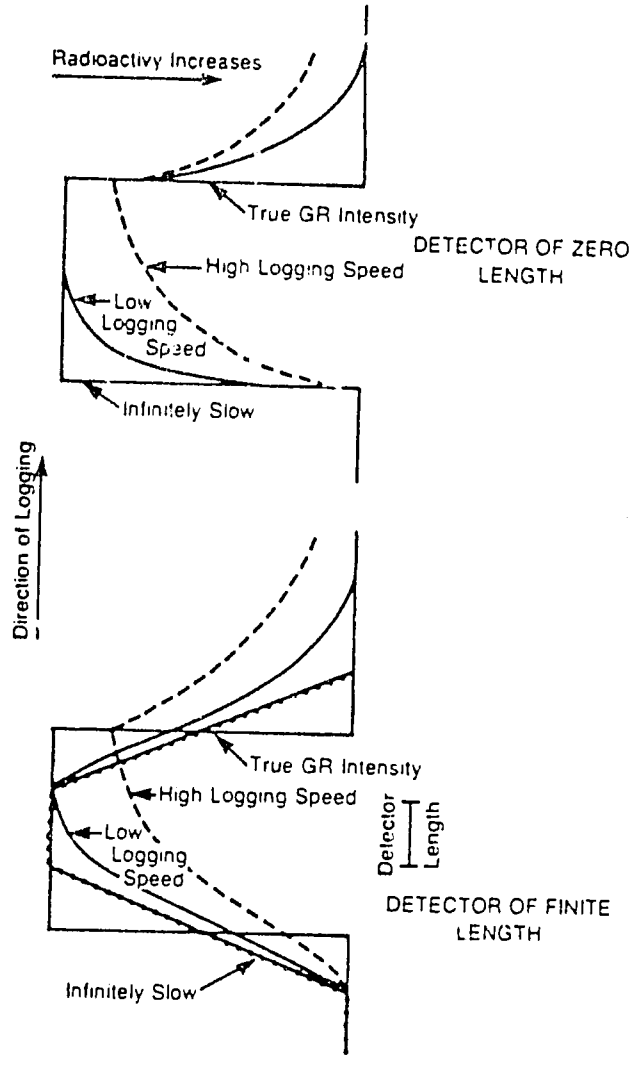


FIGURE 4
Effects of detector length and logging speed on the shape of the Gamma Ray Log (After Ref. 8)

FROM 1981 BOOKLET ON GAMMA RAY LOG
BY: DRESSER ATLAS

GAMMA RAY UNITS

- INCHES OF DEFLECTION FOR A STANDARD RADIATION INTENSITY
- MICROROENTGENS / HR
- MICROGRAM RADIUM EQUIVALENT PER TON
- API UNITS --- TWO SECTIONS OF NEAT CEMENT --
  ONE OF A HIGH & ONE OF A LOW RADIOACTIVITY LEVEL --
  DIFFERENCE IS 200 API UNITS

RADIATION DETECTORS

- IONIZATION CHAMBERS
- GEIGER-MUELLER DETECTORS
- PROPORTIONAL COUNTERS
- SCINTILLATION DETECTORS

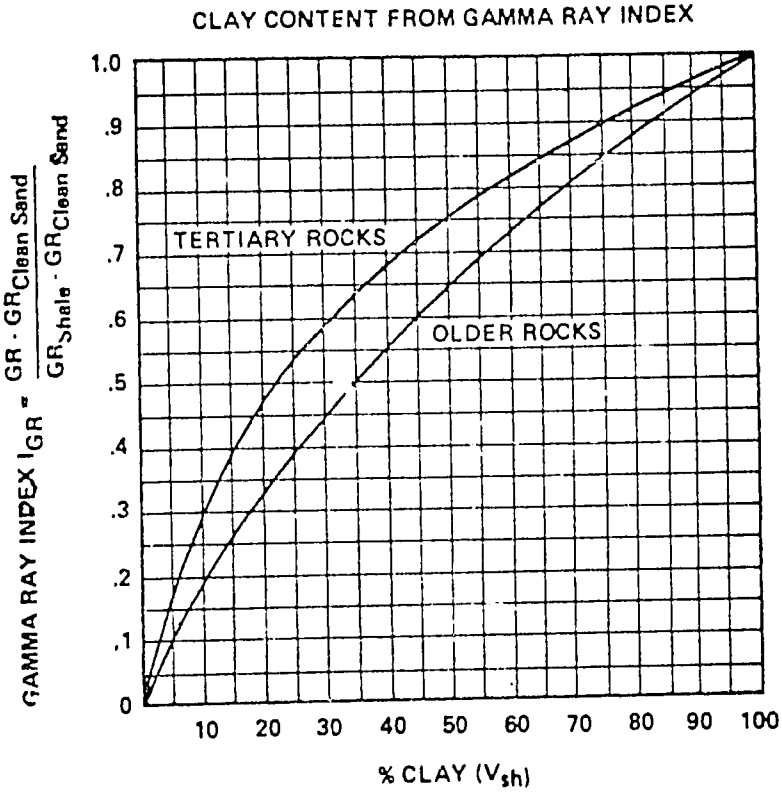
FIRST THREE WORK ON PRINCIPLE OF GAS IONIZATION
& FLOW OF ELECTRONS -- NOT EFFICIENT & LITTLE USED

SCINTILLATION DETECTORS -- GAMMA RAYS PRODUCE TINY
FLASHES OF LIGHT AS THEY EXPEND THEMSELVES ON
CHRYSTALS -- FLASHES ARE CONVERTED TO ELECTRICAL PULSES.

SHALINESS ESTIMATION

GAMMA RAY LOG IS CONSIDERED AN IMPORTANT SHALE INDICATOR

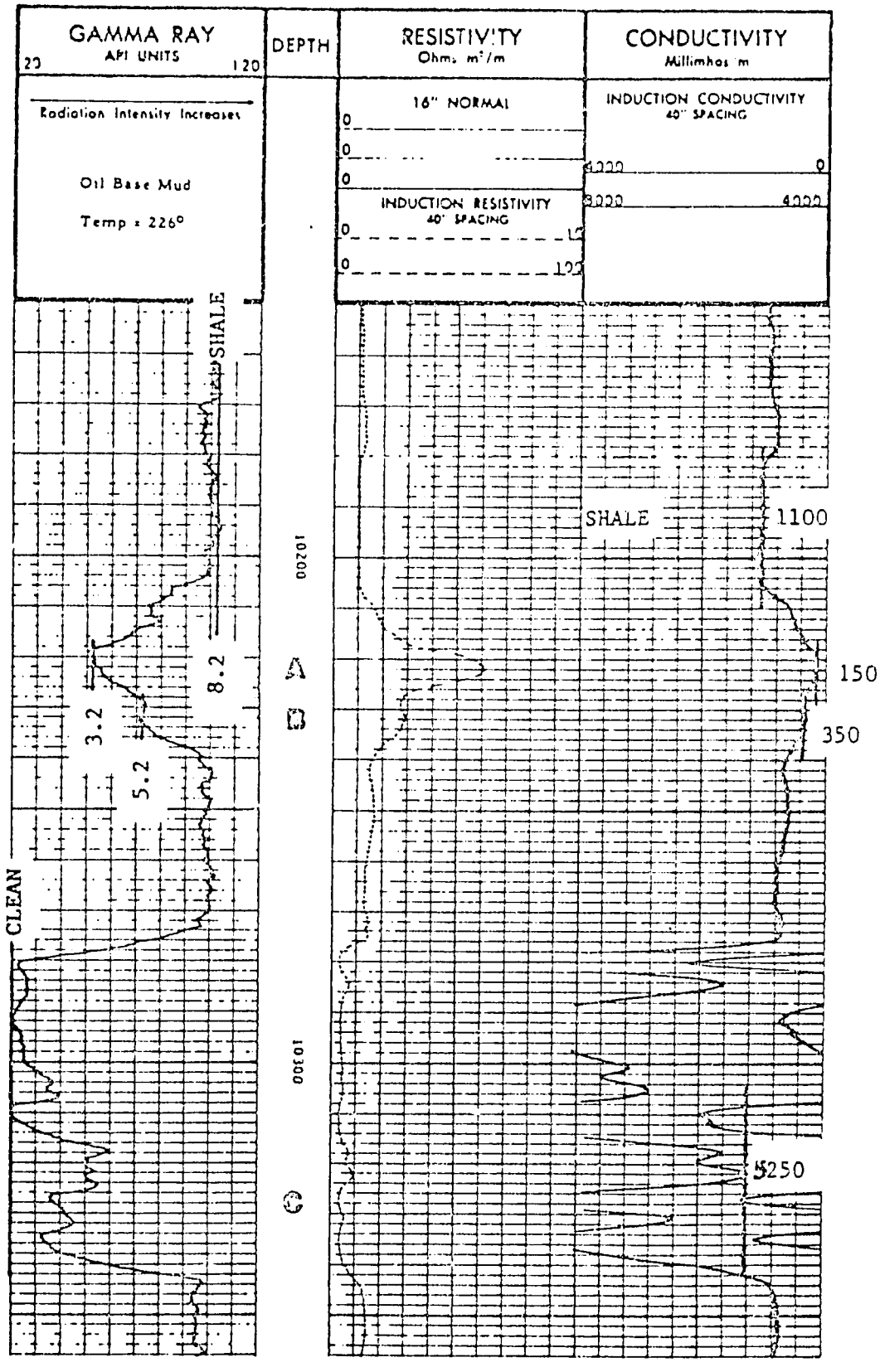
IT IS ASSUMED THAT ALL RADIOACTIVE MINERALS EXIST IN THE SHALES



FROM DRESSER ATLAS

LOG INTERPRETATION FUNDAMENTALS, 1975

A Louisiana Gulf Coast Well (Tertiary sandstones)



From Dresser Atlas 1975 Log Interpretation Fundamentals

NATURAL GAMMA RAY SPECTROSCOPY (SPECTRA LOG)

- DETECTS NATURALLY OCCURING GAMMA RAYS OF VARIOUS ENERGIES EMITTED FROM A FORMATION
- MEASURES --
  - TOTAL GAMMA RAY COUNTS
  - COUNTS EMITTED BY K^{40} @ 1.46 MEV
  - COUNTS BY URANIUM SERIES NUCLIDE BISMUTH, Bi^{214} @ 1.764 MEV
  - THORUIM SERIES THALLIUM, Ti^{208} COUNTS @ 2.624 MEV

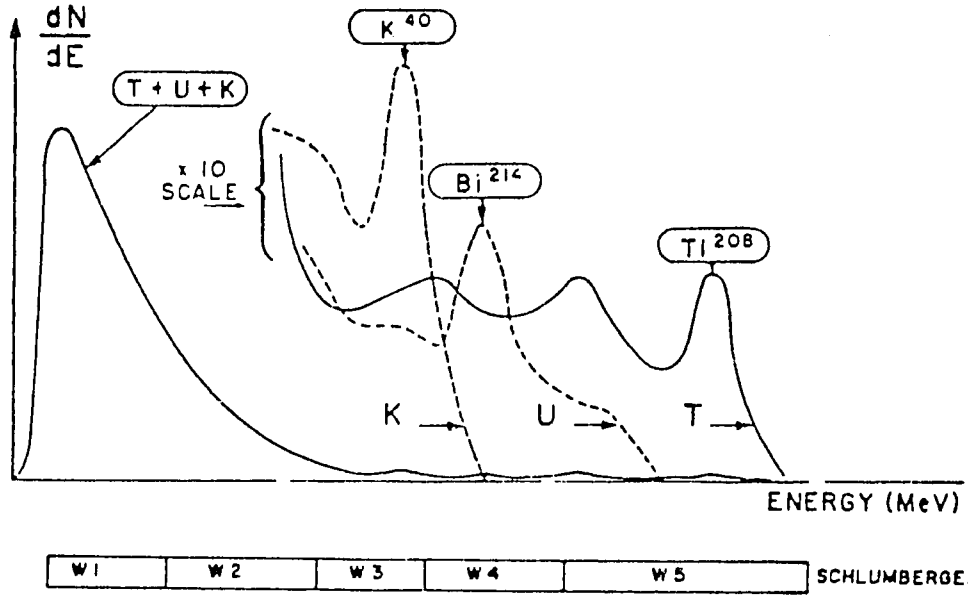


Fig. 3 Potassium, Thorium and Uranium Response Curves (NaI Crystal Detector)

SPECTRA LOG - CONT.'D

- INDIVIDUAL CONTRIBUTIONS OF THE TH, U, K IN RELATION TO TOTAL FORMATION WEIGHT ARE CALCULATED FROM THE ENERGY SPECTRA
- ELEMENTAL CONCENTRATIONS THUS CALCULATED HAVE SHOWN CORRELATION TO
  - DEPOSITIONAL ENVIRONMENT
  - NEOMORPHIC & DIAGENETIC PROCESSES
  - CLAY TYPE
  - CLAY VOLUME
- TOTAL ENERGY RANGE IS RESOLVED INTO FIVE ENERGY INTERVALS OR WINDOWS USING
  - PRINCIPLES OF NATURAL GAMMA RAY SPECTROMETRY
  - STATISTICAL ESTIMATION THEORY
- COMPUTATIONS USING FIVE WINDOWS GIVE GAMMA RAY CONTRIBUTIONS ---

  TH & U IN PPM

  K IN %

SPECTRA LOG TOOL

- PRINCIPAL COMPONENT IS A SCINTILLATION DETECTOR WITH 12" LONG & 1 3/4" DIAMETER SODIUM IODIDE CRYSTAL OPTICALY COUPLED TO A PHOTOMULTIPLIER
- AT SURFACE TRANSMITTED INFORMATION IS DECODED FOR FURTHER DIGITAL PROCESSING

POTASSIUM 40

- ORIGIN -- SILICIC IGNEOUS ROCKS WHERE IT IS PRESENT IN POTASSIUM FIELDSPARS & MICAS -- 2.59% OF EART'S CRUST
- 1/2 LIFE OF 1.2 BILLION YRS. -- 1/16 LEFT ON EARTH
- ALTERATION & WEATHERING CONVERT IT TO CLAY MINERALS -- ILLITE, MONTMORILLONITE, CHLORITE, KAOLINITE
- TRANSPORTATION -- SOMETIMES IN SOLUTION, BUT MOST K^{40} IS ABSORBED BY CLAYS & EXTRACTED FROM WATER BY PLANTS.

THORIUM

- ORIGIN -- SILICIC IGNEOUS ROCKS -- 12 PPM EARTH CRUST CONCENTRATION
- ½ LIFE OF 14 BILLION YRS.
- AVG. CONCENTRATION IN IGNEOUS ROCKS IS 3.5 TO 4 TIMES THAT OF U -- TH/U RATIO IS CONSTANT
- MOST CLAYS TEND TO CONTAIN 8 TO 20 PPM
- ALL OF ITS COMPOUNDS ARE INSOLUBLE
- DURING ALTERATION & WEATHERING IT IS HYDROLYZED & TENDS TO CONCENTRATE IN RESIDUAL MINERALS -- BAUXITE & CLAY MINERALS
- TRANSPORTATION -- ALMOST WHOLLY IN SUSPENSION & CONCENTRATES IN SILTY FRACTIONS OF SHALE --- ASSOCIATED @ MARINE DEPOSITION
- PRESENCE IN CARBONATE ROCKS IS ATTRIBUTED TO SHALINESS
- COMMONLY ASSOCIATED WITH MARINE DEPOSITION

URANIUM

- ORIGIN - SILICIC IGNEOUS ROCK -- EXISTS IN ACCESSORY MINERALS
- 1/2 LIFE OF 4.5 BILLION YRS.
- EARTH'S CRUST CONCENTRATION -- 3 PPM
- EASILY OXIDIZED INTO URANYL ION, UO_2^{2+} BY BACTERIAL ACTION
- VERY SOLUBLE & THEREFORE VERY MOBILE-TRANSPORTED CHIEFLY IN SOLUTION & CAN BE REDEPOSITED.
- UNDER REDUCING CONDITION, UO_2^{2+} FORMS COMPLEXES WITH ORGANIC COMPOUNDS
- IN CLEAN SANDSTONES & CARBONATES THE ONLY RADIOACTIVE ELEMENT WILL BE U .

K^{40}, TH & U COMBINATIONS

EVAPORITES

U & TH USUALLY ABSENT

K^{40} PRESENCE MAY INDICATE POTASH MINERALS

SANDSTONES

TH & K^{40} CONTENT REFLECT CLAY CONTENT & PRESENCE OF MICA & POTASSIUM BY PRODUCTS

U MAY INDICATE

- DEPOSITION FROM SOLUTION
- DEPOSITION IN CALM WATER CONDITIONS -- INDICATIVE OF PALEO ENVIRONMENT & GRAIN SIZES

SHALES

ALL THREE CAN BE PRESENT

TH -- REFLECTS A HIGH CONTENT OF CLAY MINERALS

-- U MAY INDICATE ORGANIC MATERIAL IN THE SHALES

K^{40}-- INDICATES ILLITE - MONTMORILLONITE CLAY MINERALS

Example 2. In the more recent sediments, some apparent shales are, in reality, due to the high Uranium values. This Uranium is concentrated from solutions migrating through the permeable streaks of the formation. The high API value on the log at 570'-80' is caused by a concentration of uranium in the sandstone. This would imply that this 10' zone has a higher permeability than the rest of the formation and was conducive to the transmission of fluids after lithification.

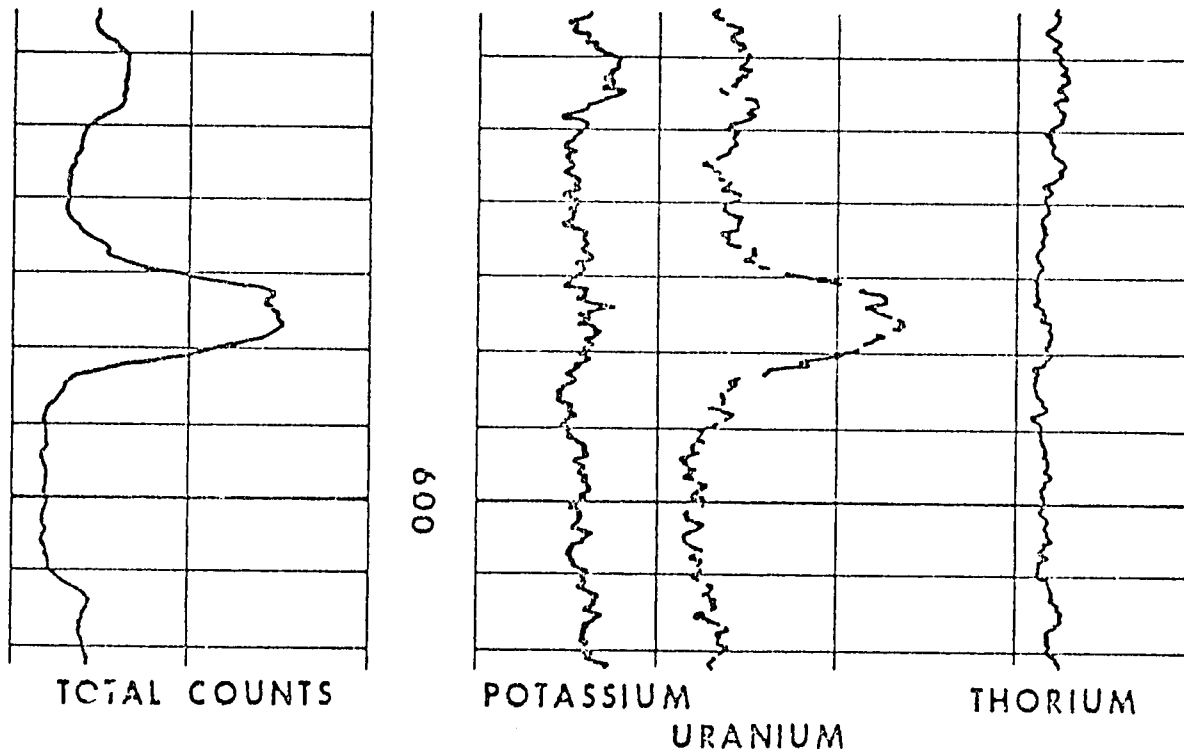


FIGURE 2 – Apparent Shale Caused by High Uranium Streak In Northern California Well

This zone is hydrocarbon productive and wells completed in the "shale" are placed in production without treatment.

THE TRUE RESISTIVITY LOGS

DETERMINATION OF R_T IS ESSENTIAL IN OBTAINING S_W

PRESENCE OF BOREHOLE AND INVADED ZONE MAKE MEASUREMENT OF R_T A COMPLEX PROBLEM

ELECTRICAL LOG SONDES

- ELECTRICAL SURVEY -- (ES) SP, $R_{16''}$, $R_{64''}$, $R_{18'8''}$
- INDUCTION ELECTRICAL SURVEY (I - ES) SP, $R_{16''}$, R_{IL_D}
- DUAL INDUCTION LATEROLOG 8 - LL_8, IL_M, IL_D
- INDUCTION - SPHERICALLY FOCUSED (ISF) -- SP, SFL, IL_D, SONIC LOG
- THE LATEROLOG (LL) - GR, LL_7
- DUAL LATEROLOG - R_{XO} -- LL_8, LL_D, MSFL

MUD SYSTEMS

FRESH WATER BASE MUD -- $R_{MF} > 3\ R_W$

SALT WATER BASE MUD -- $R_{MF} < 3\ R_W$

AN SP CURVE VALUE GREATER THAN 35 mV WOULD INDICATE A FRESH WATER BASE MUD SINCE $R_{MF} \geqslant 3$.

THE ES SURVEY

' SP, $R_{16''}$, $R_{64''}$, $R_{18'8''}$

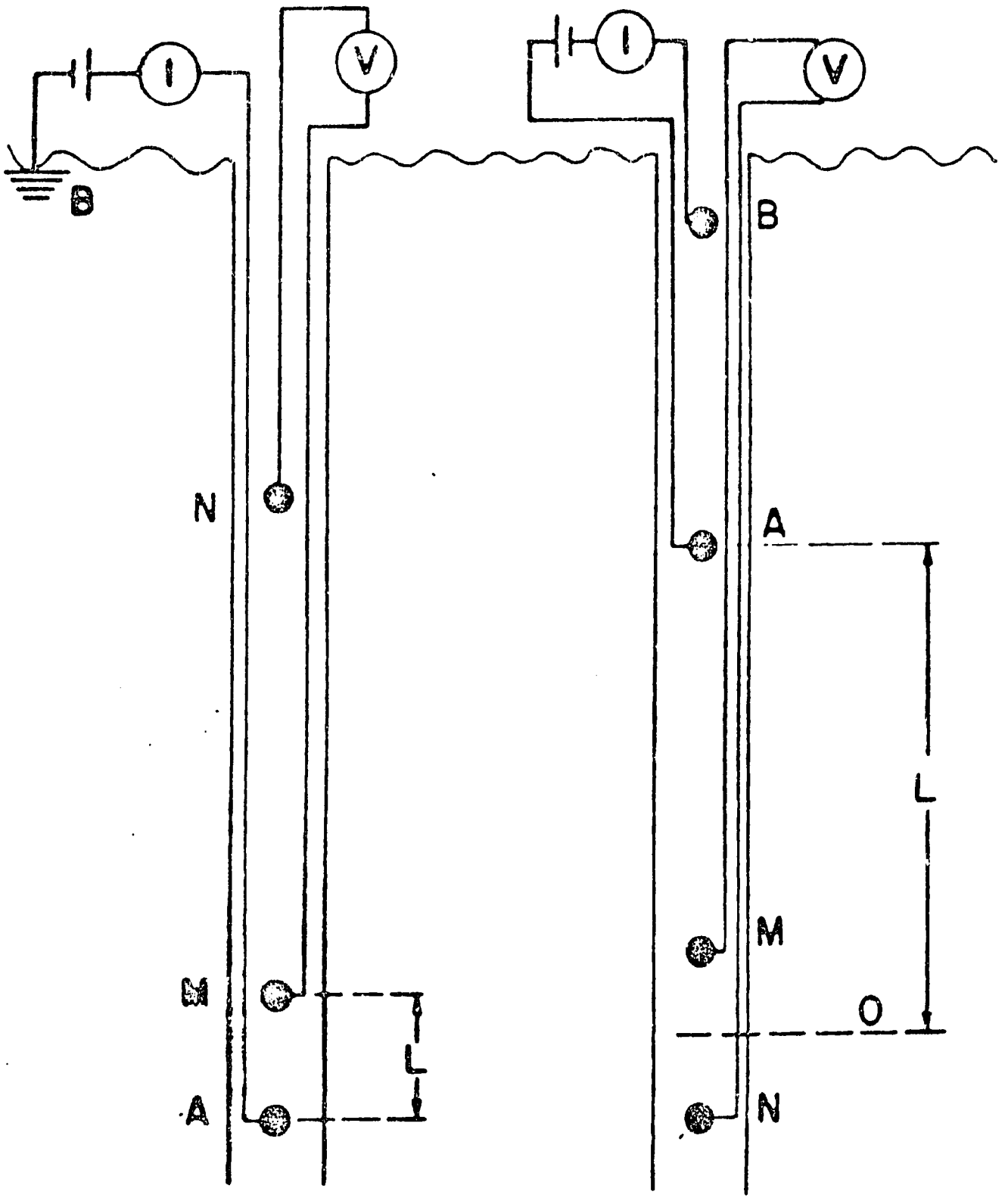
' IMPORTANCE

- ONLY ELECTRIC LOGS RUN FOR 1929 - 56, 27 YRS.
- ALTHOUGH ABSOLETE -- STILL RUN IN MANY PARTS OF WORLD
- NECESSARY IN REINTERPRETATION OF OLD WELLS

' PRINCIPLE

- CURRENTS ARE PASSED THROUGH BEDS VIA CERTAIN ELECTRODES AND VOLTAGES MEASURED BETWEEN OTHER ELECTRODES
- MUD MUST BE CONDUCTIVE
- CURRENT IS EMITTED IN SPHERICAL PATTERN

SCHEMATIC LOGGING DEVICES



NORMAL DEVICE LATERAL DEVICE

' THE NORMAL DEVICES

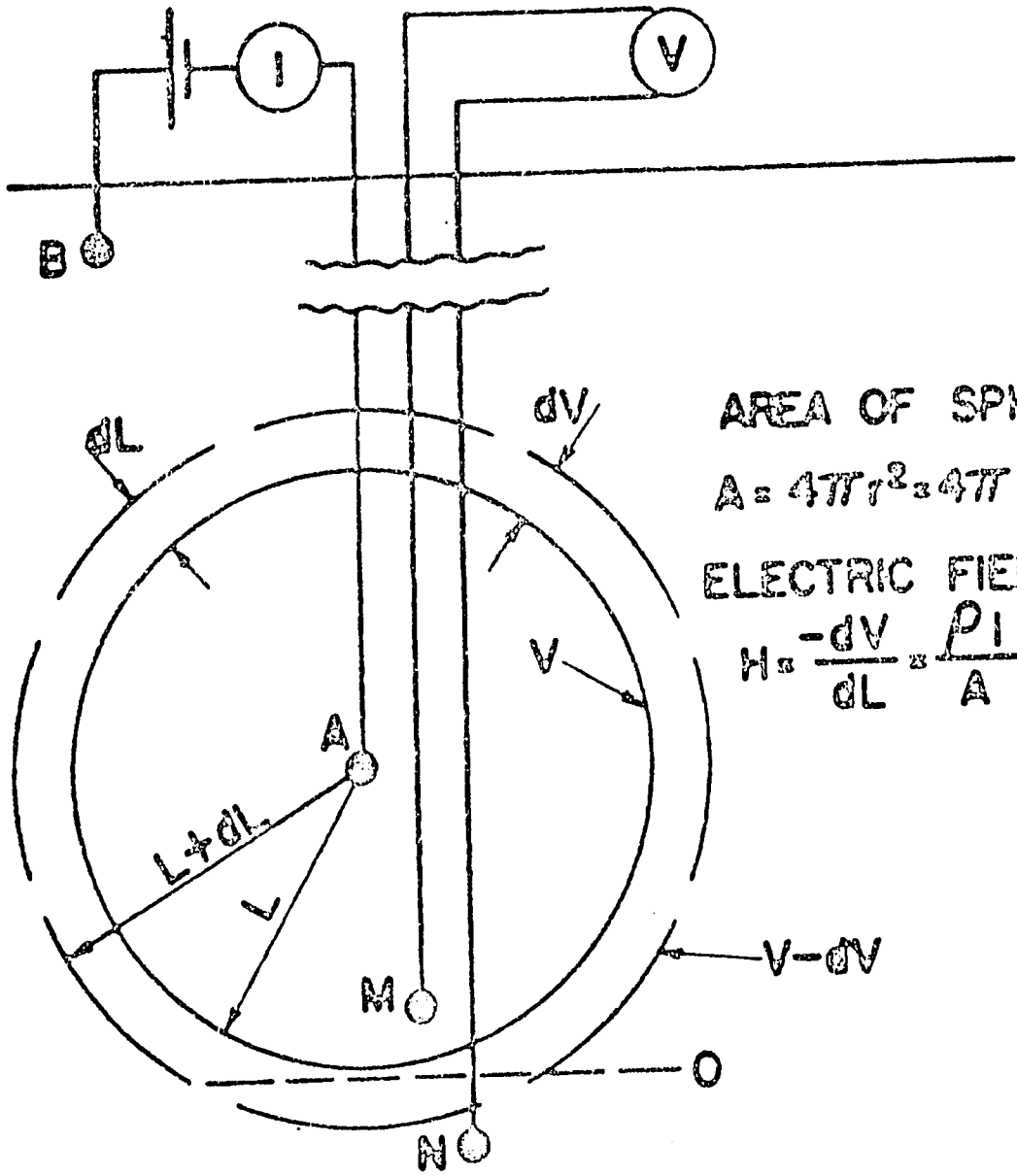
- DESIGN PLACES POTENTIAL ELECTRODE NEAR CURRENT ELECTRODE -- OFTEN POTENTIAL ELECTRODE IS AT INFINITY
- CURRENT IS MAINTAINED AT CONSTANT LEVEL SO THAT R IS DIRECTLY PROPORTIONAL TO THE MEASURED VOLTAGE
- RADIUS OF INVESTIGATION IS FROM ONE TO TWO ELECTRODE SPACING.
- RESISTIVE BED HAS A R GREATER THAN RESISTIVITY OF SURROUNDING BEDS (R_S)
- BED THICKNESS DEFINITIONS
  - '' THICK BED --- $H > 4$ AM
  - '' THIN BED -- $H < 4$ AM
  - '' CRITICAL THICKNESS -- $H \approx$ AM
- SPACING, AM
  - '' 16" NORMAL, $R_{16''}$
  - '' 64" NORMAL, $R_{64''}$

' THE LATERAL DEVICE

- USES TWO CURRENT ELECTRODES (A & B) AND TWO POTENTIAL MEASURING ELECTRODES (M & N)
- MEASURES THE DIFFERENCE IN POTENTIAL BETWEEN TWO EQUI-POTENTIAL SPHERES CENTERED AT A & OF RADII AM & AN
- SPACING IS DITANCE FROM A TO MID POINT "O" BETWEEN POTENTIAL ELECTRODES -- 18'8"
- DISTANCE MN IS 16"
- RADIUS OF INVESTIGATION IS ONE SPACING
- $R_T = F\left[R_T, R_I, D_I, R_M, \text{SPACING}, D_H, H, R_S\right]$

' USES

- LOCATION OF HYDROCARBONS
- CORRELATION
- STRUCTURE & ISOPACH MAPS
- DETERMINATION OF S_W & Ø ESTIMATES



AREA OF SPHERE

$A = 4\pi r^2 = 4\pi L^2$

ELECTRIC FIELD

$H = \frac{-dV}{dL} = \frac{\rho I}{A}$

$R = V/I = \rho L/A$

$V = I\rho L/A = I\rho L/4\pi L^2$

$-dV = \frac{I\rho dL}{4\pi L^2}$; $-\int_0^V dV = \frac{\rho I}{4\pi}\int_\infty^L \frac{dL}{L^2}$

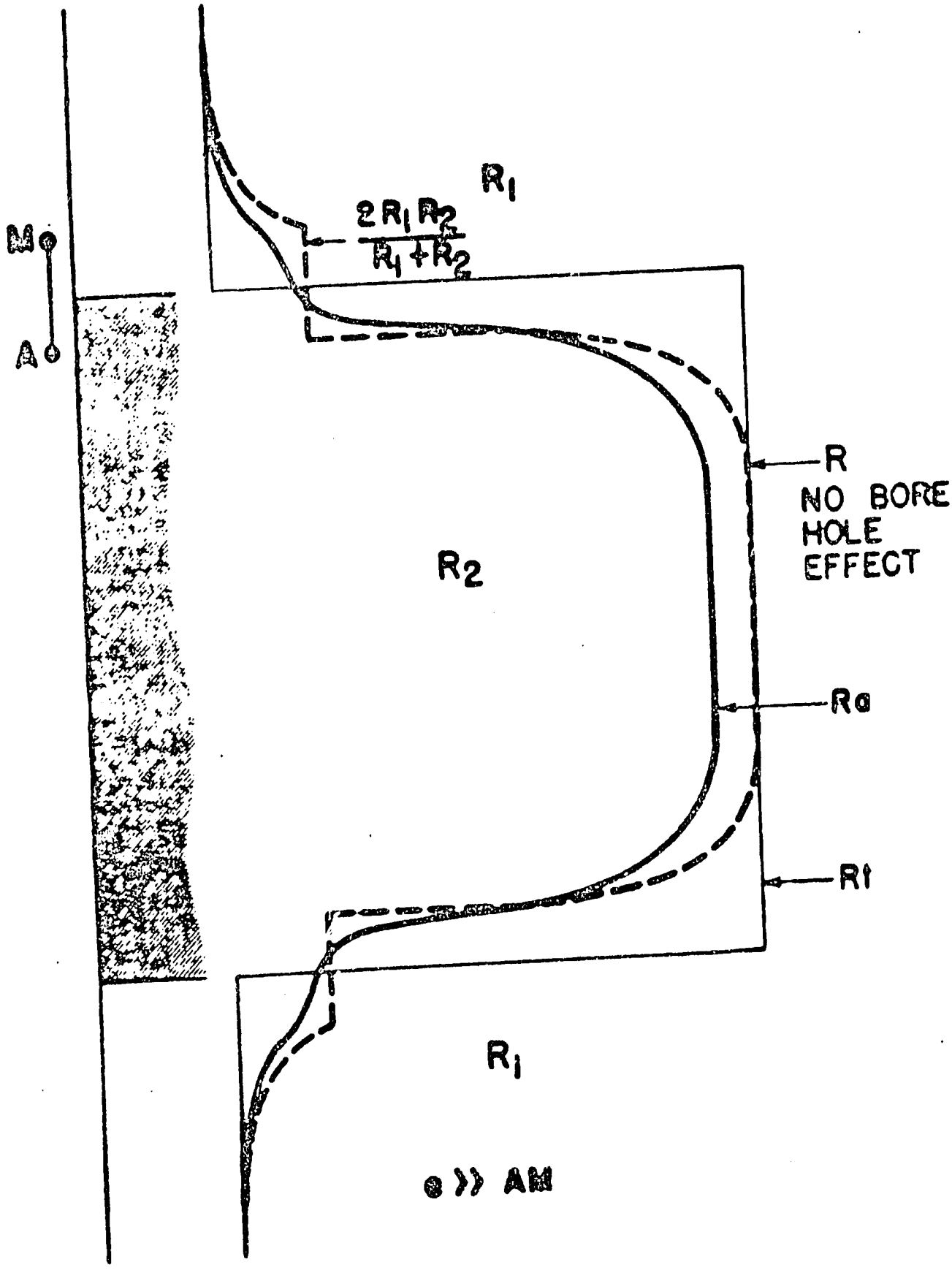
$V = \frac{\rho I}{4\pi L}$; $\rho = 4\pi L V/I$

(2) $\rho = -\frac{dV}{dL}\frac{4\pi L^2}{I} = R$

$R = \frac{4\pi(E_M - E_N)}{i\left(\frac{1}{L_M} - \frac{1}{L_N}\right)}$

RESISTIVITY DERIVATIONS

$R_2/R_1 = 5$



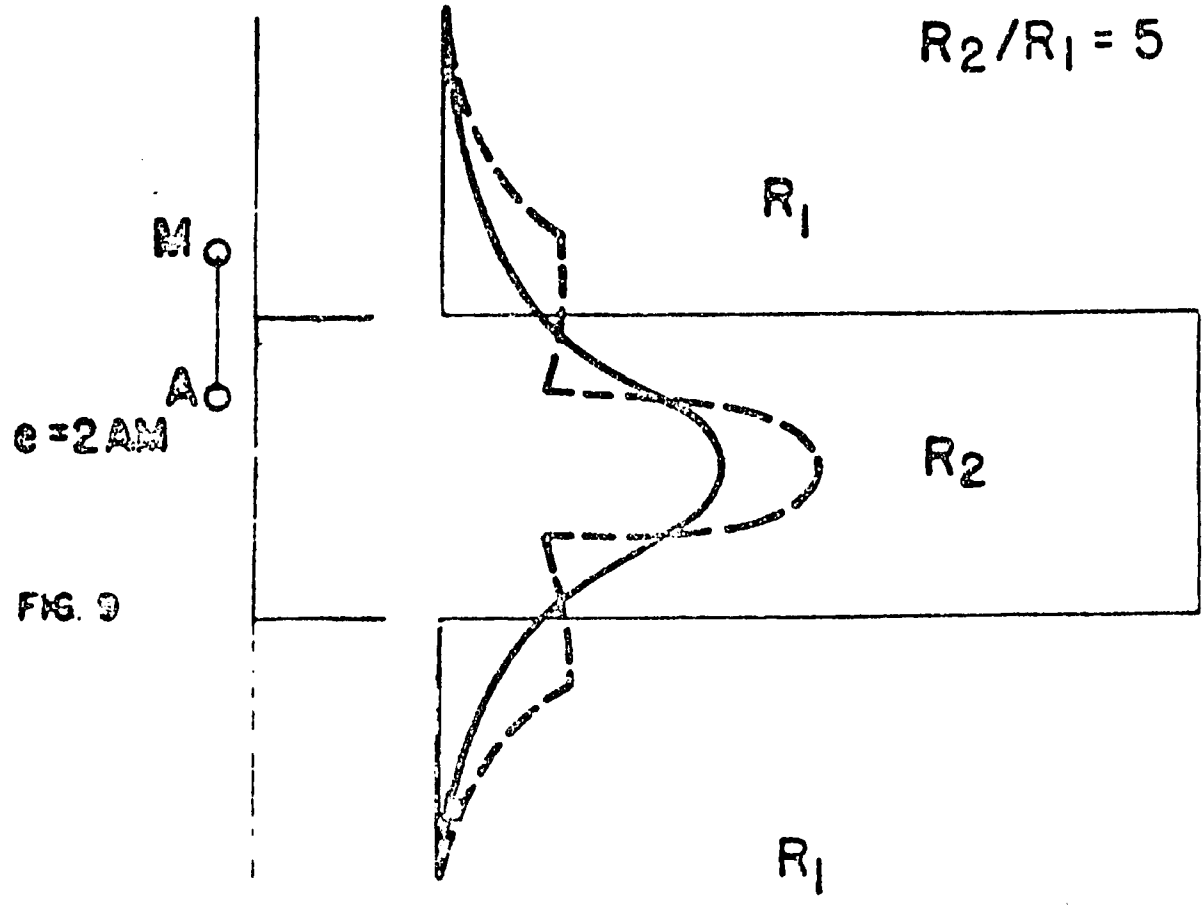


FIG. 9

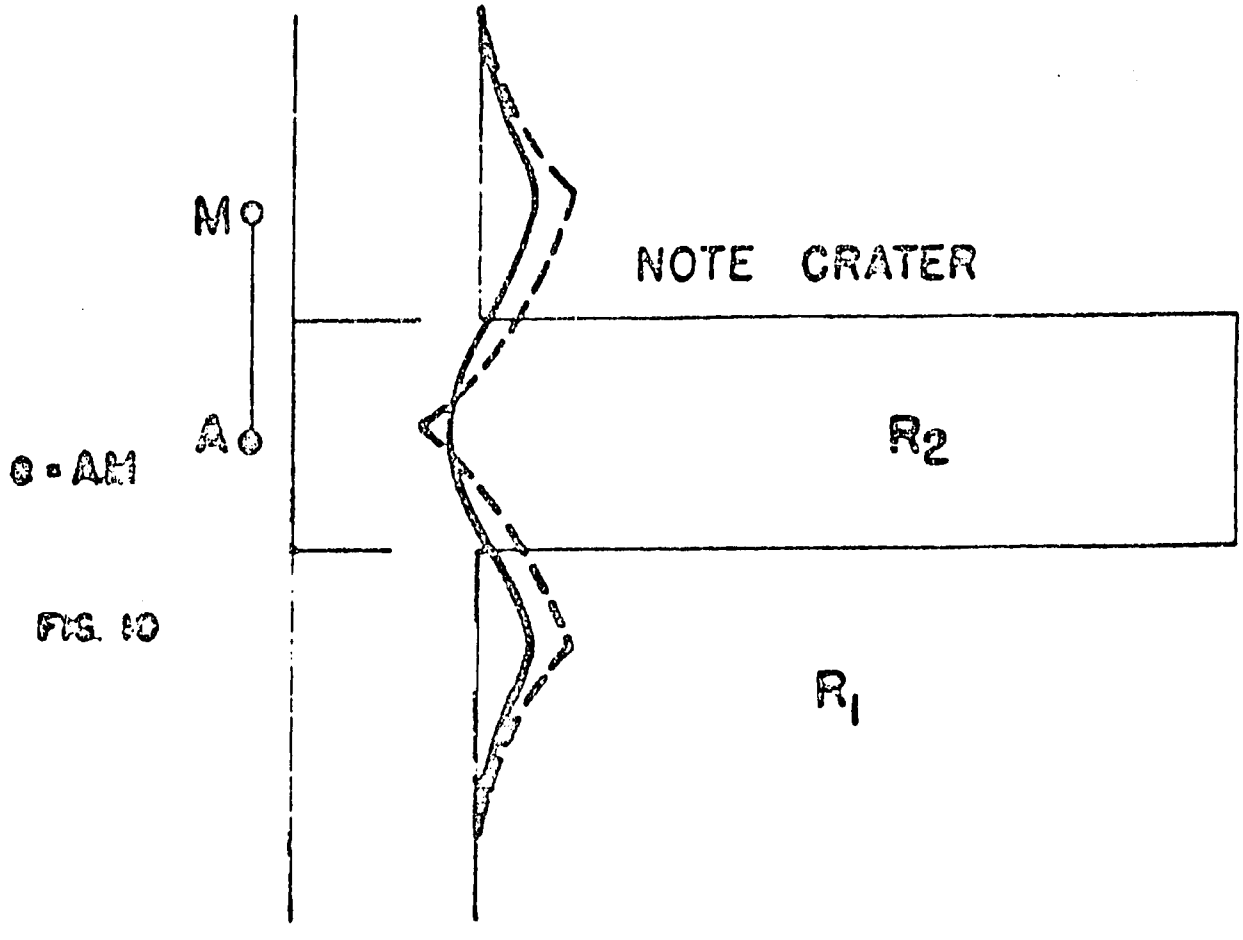
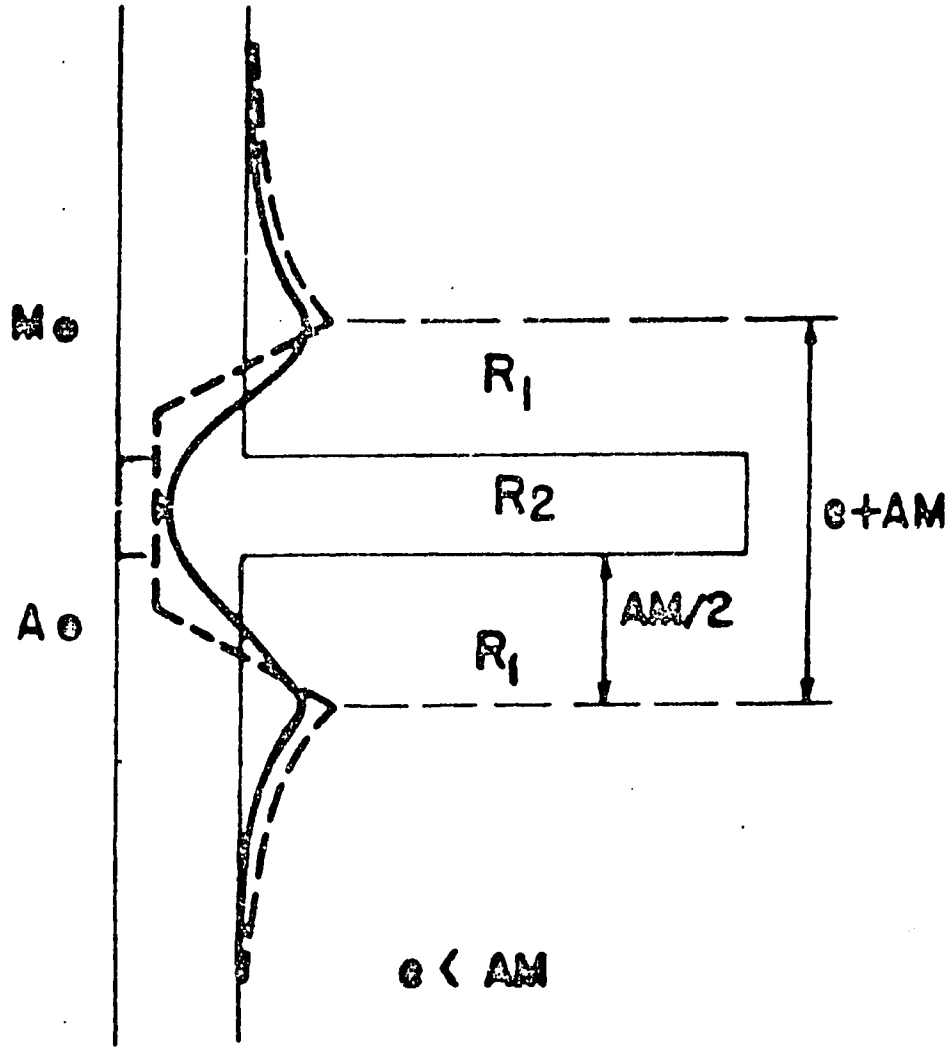
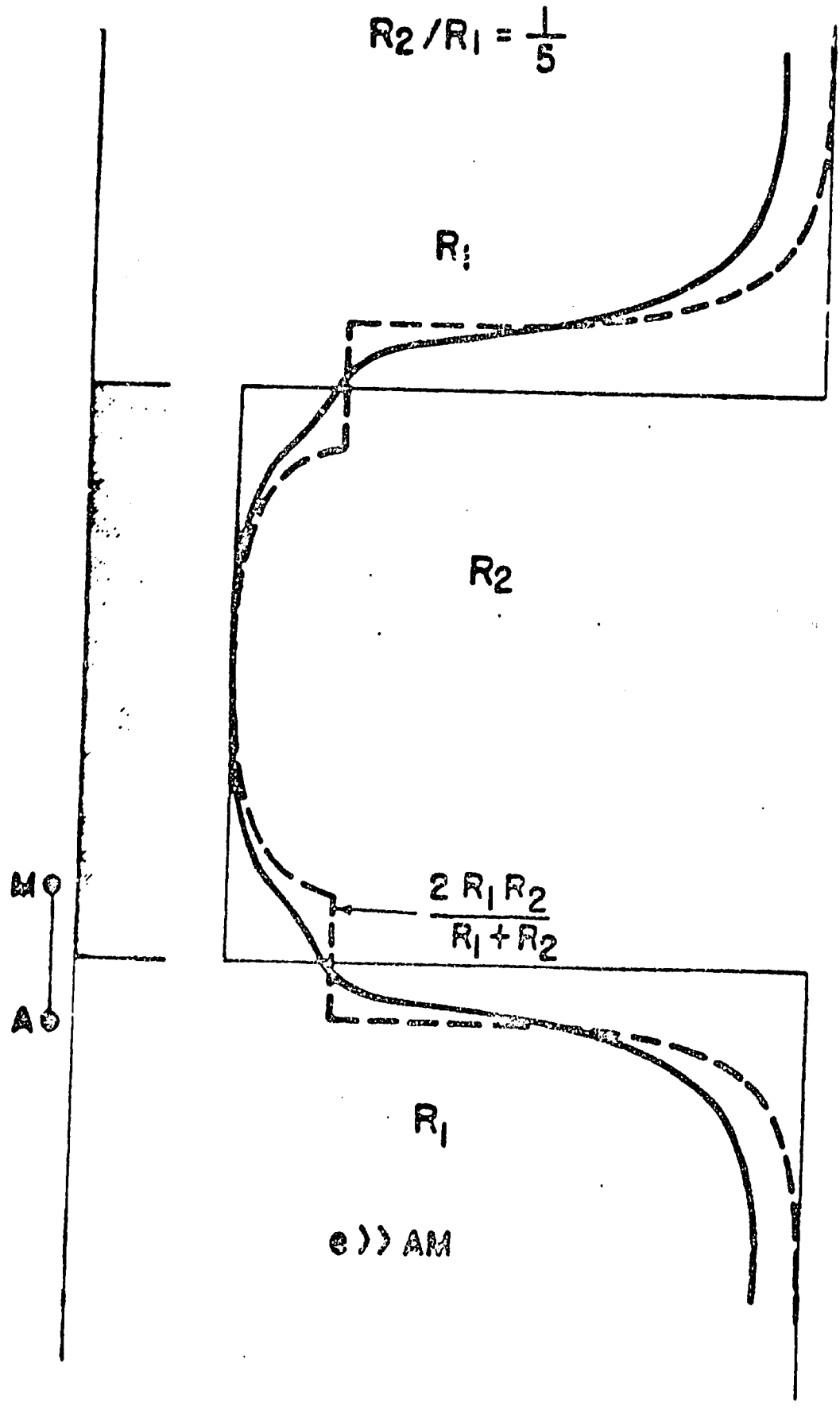
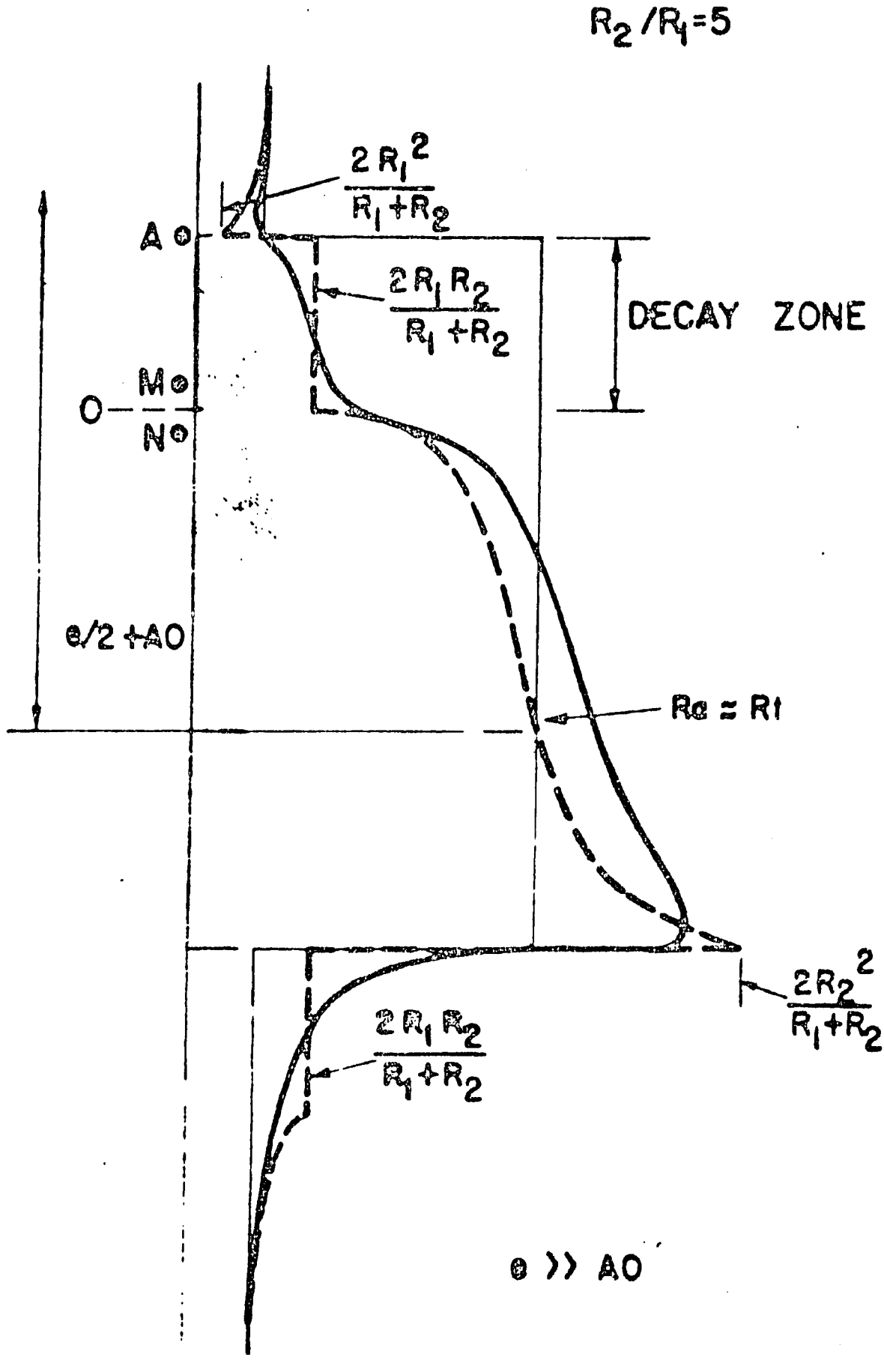


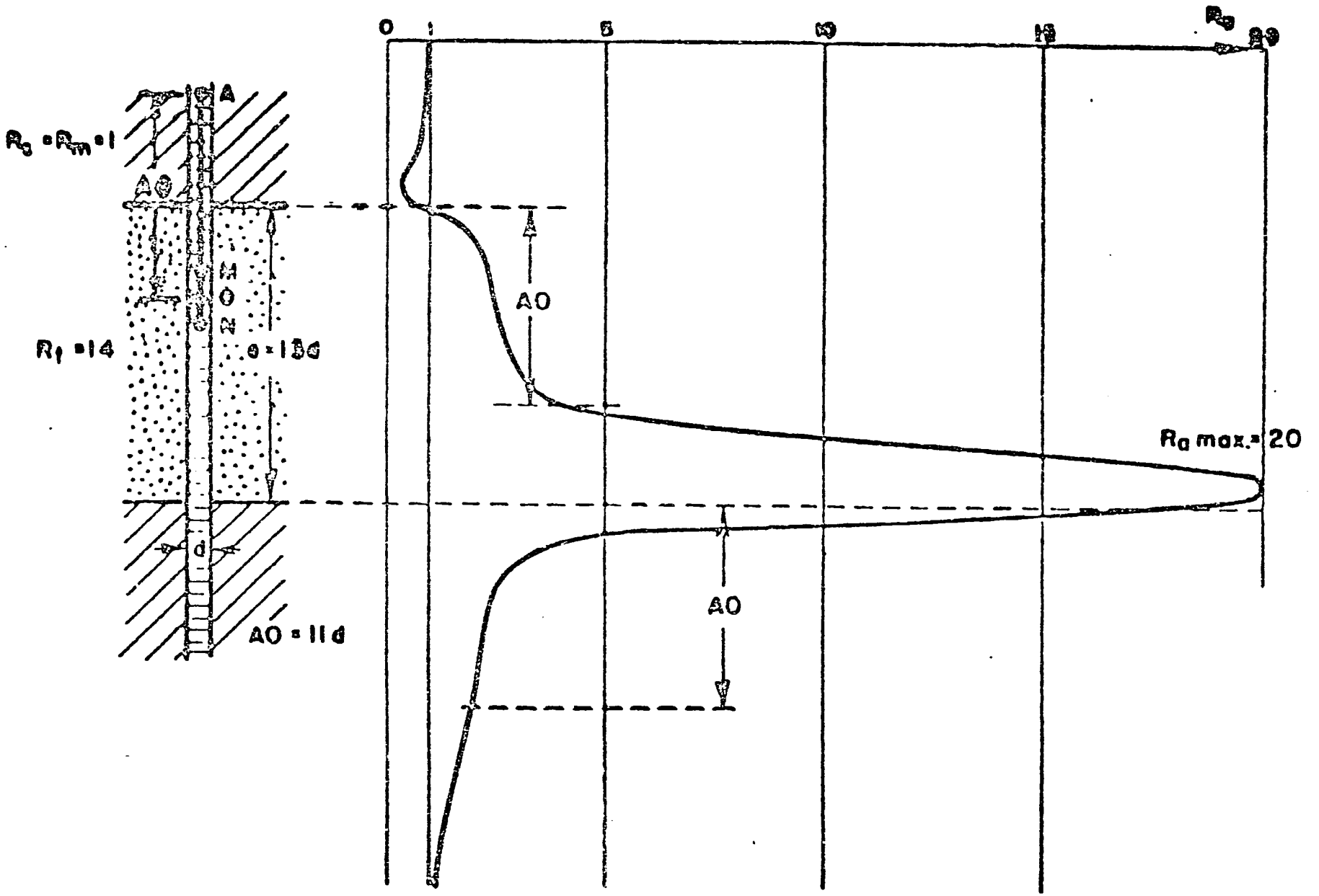
FIG. 10

$R_2/R_1 = 5$

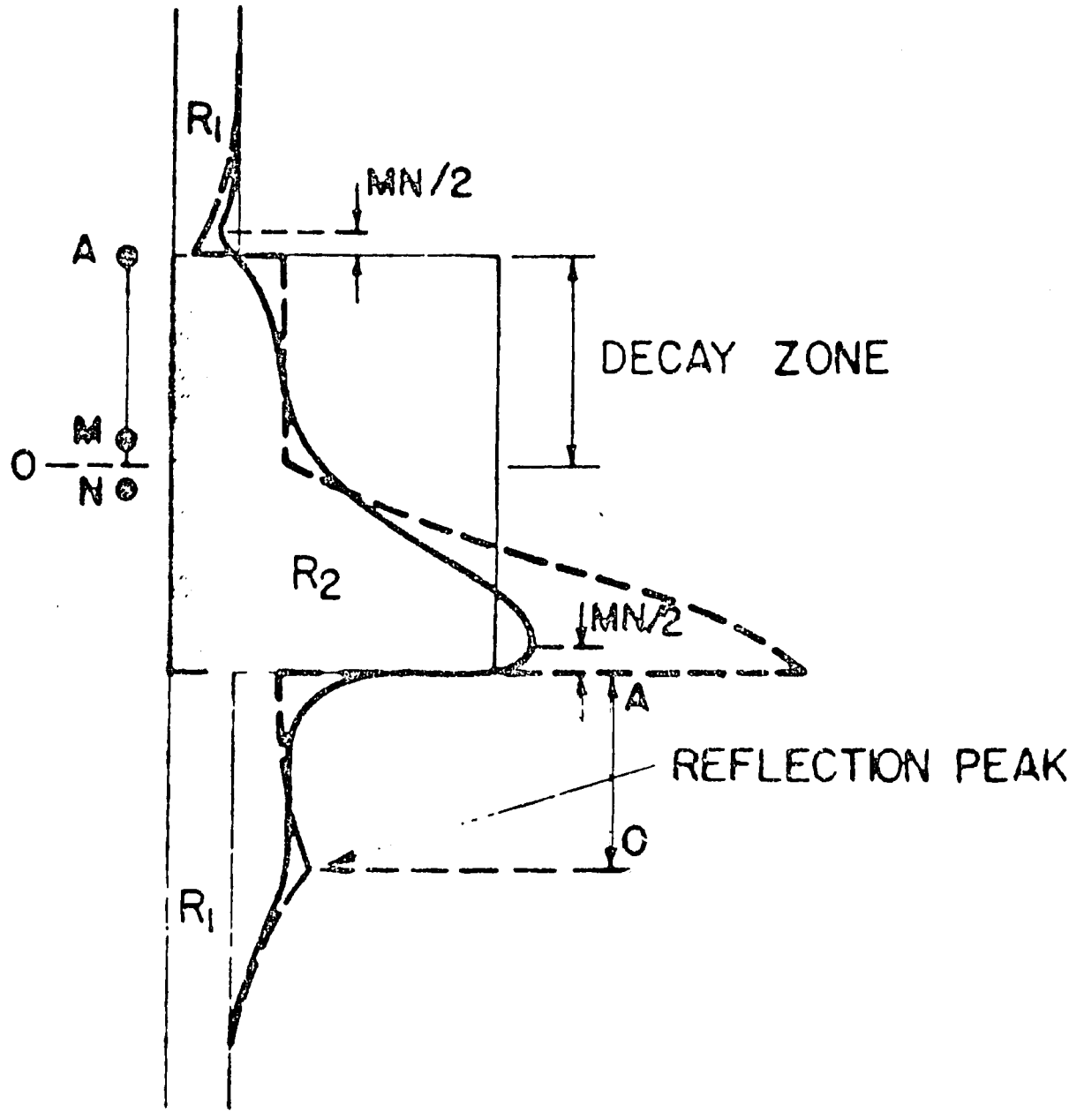



R2/R1 = 1/5
R1
R2
M
A
2 R1 R2 / R1 + R2
R1
e >> AM

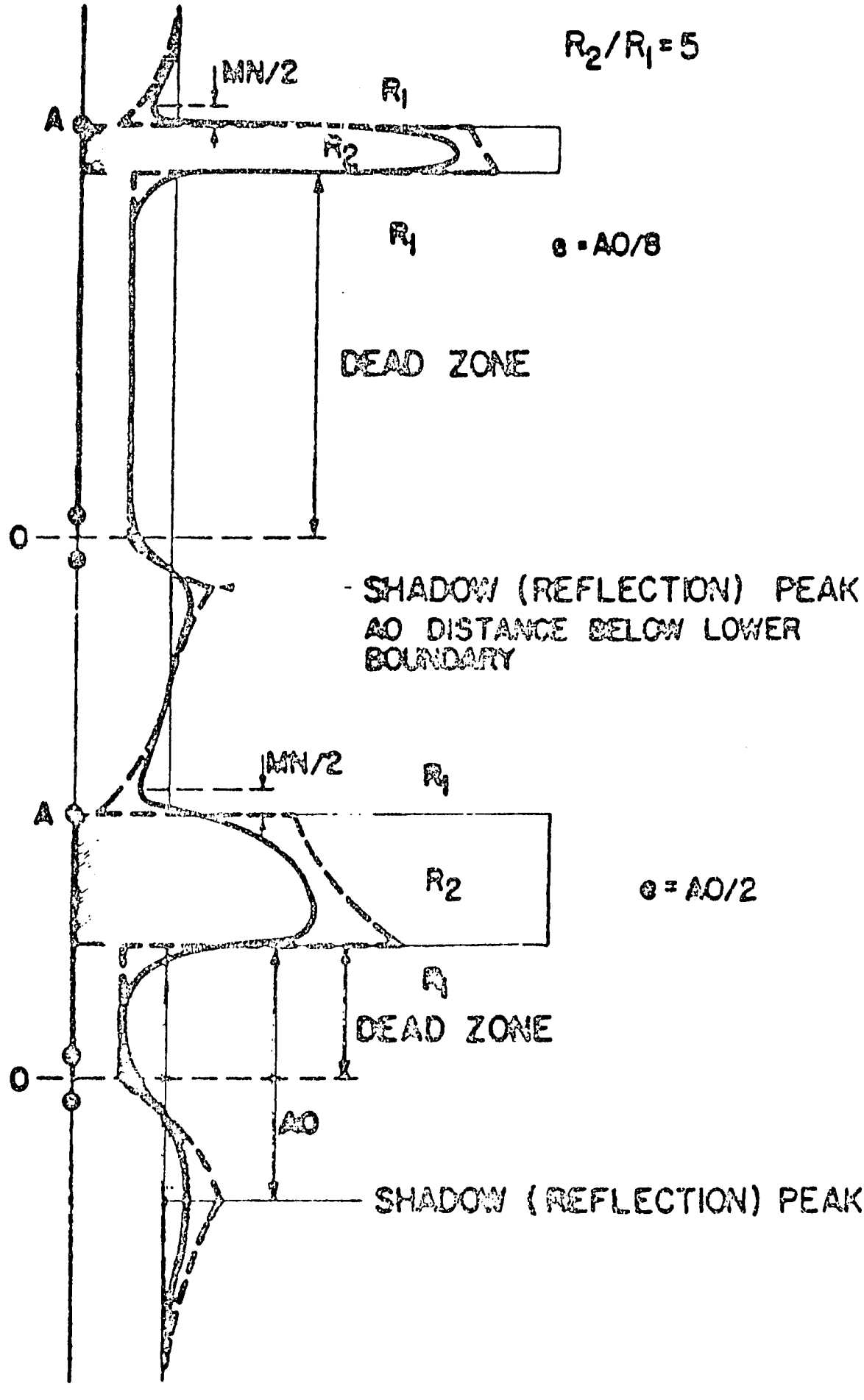

R2 /R1=5
2 R1 2 / R1 +R2
A
2R1 R2 / R1 +R2
DECAY ZONE
O
M
N
e/2 +AO
Re ≈ R1
2R2 2 / R1+R2
2R1 R2 / R1+R2
e >> AO

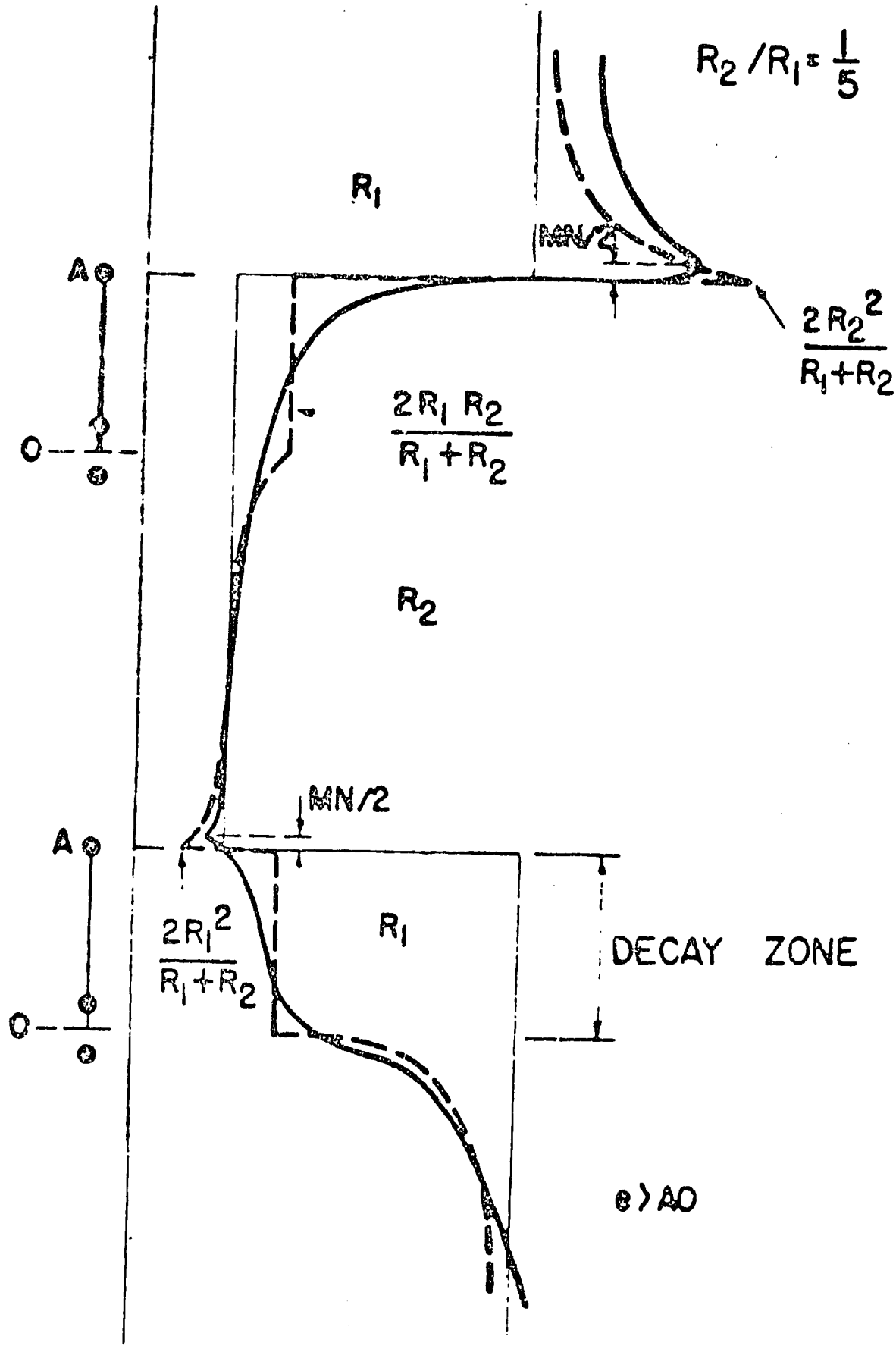

A
$R_0 = R_m = 1$
AO
M
O
N
$R_f = 14$
e = 13d
d
AO = 11d
0
1
5
10
15
20
R_a
AO
AO
R_a max. = 20

$R_2/R_1 = 5$



$e = 2AO$

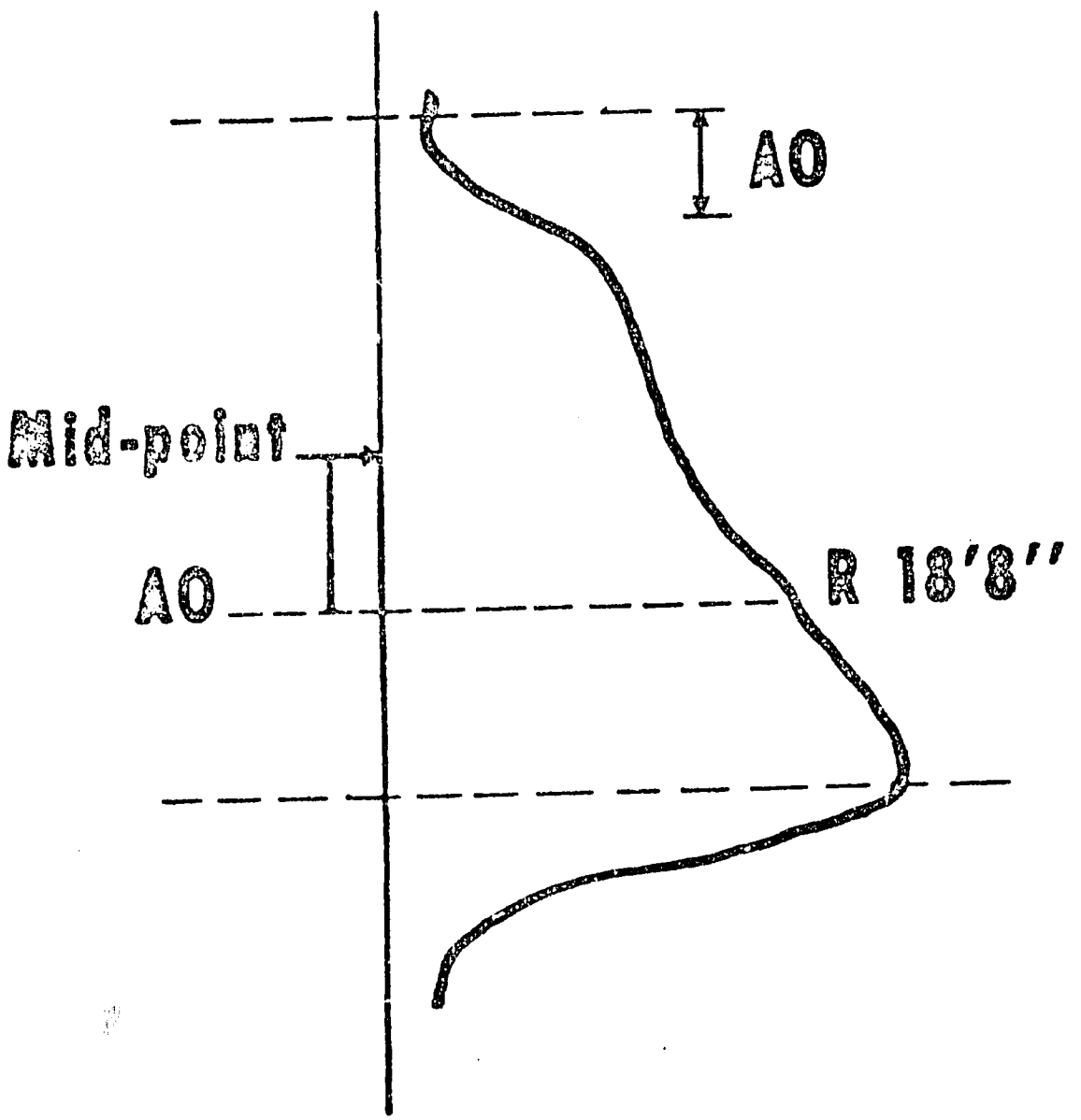

R2/R1 = 5
MN/2
R1
A
R2
R1
e = AO/8
DEAD ZONE
O
SHADOW (REFLECTION) PEAK
AO DISTANCE BELOW LOWER BOUNDARY
MN/2
R1
A
R2
e = AO/2
R1
DEAD ZONE
O
AO
SHADOW (REFLECTION) PEAK


$R_2/R_1 = \frac{1}{5}$
R_1
MN/2
A
O
$\frac{2R_2^2}{R_1+R_2}$
$\frac{2R_1R_2}{R_1+R_2}$
R_2
MN/2
A
O
$\frac{2R_1^2}{R_1+R_2}$
R_1
DECAY ZONE
θ > AO

THE ES SURVEY

- WAS DEVELOPED FOR MODERATE TO LOW R_T BEDS ($R_T < 50$) -- THICK, HOMOGENEOUS, NO INVASION, NO HOLE EFFECT
- SHAPES OF THE CURVES BECOME COMPLICATED & THE LOG CONFUSING IN RESISTIVE FORMATIONS
- DETERMINATION OF R_T
  - ESTIMATION IS POSSIBLE WHEN $R_T < 50$ AND INVASION IS LOW TO MODERATE
  - DEPARTURE CURVES ARE AVAILABLE FOR R_T ESTIMATION
  - ALTHOUGH R_T CAN BE ESTIMATED, IT IS CONSIDERED MUCH LESS RELIABLE THAN THAT OBTAINED FROM A MODERN SUITE OF LOGS.

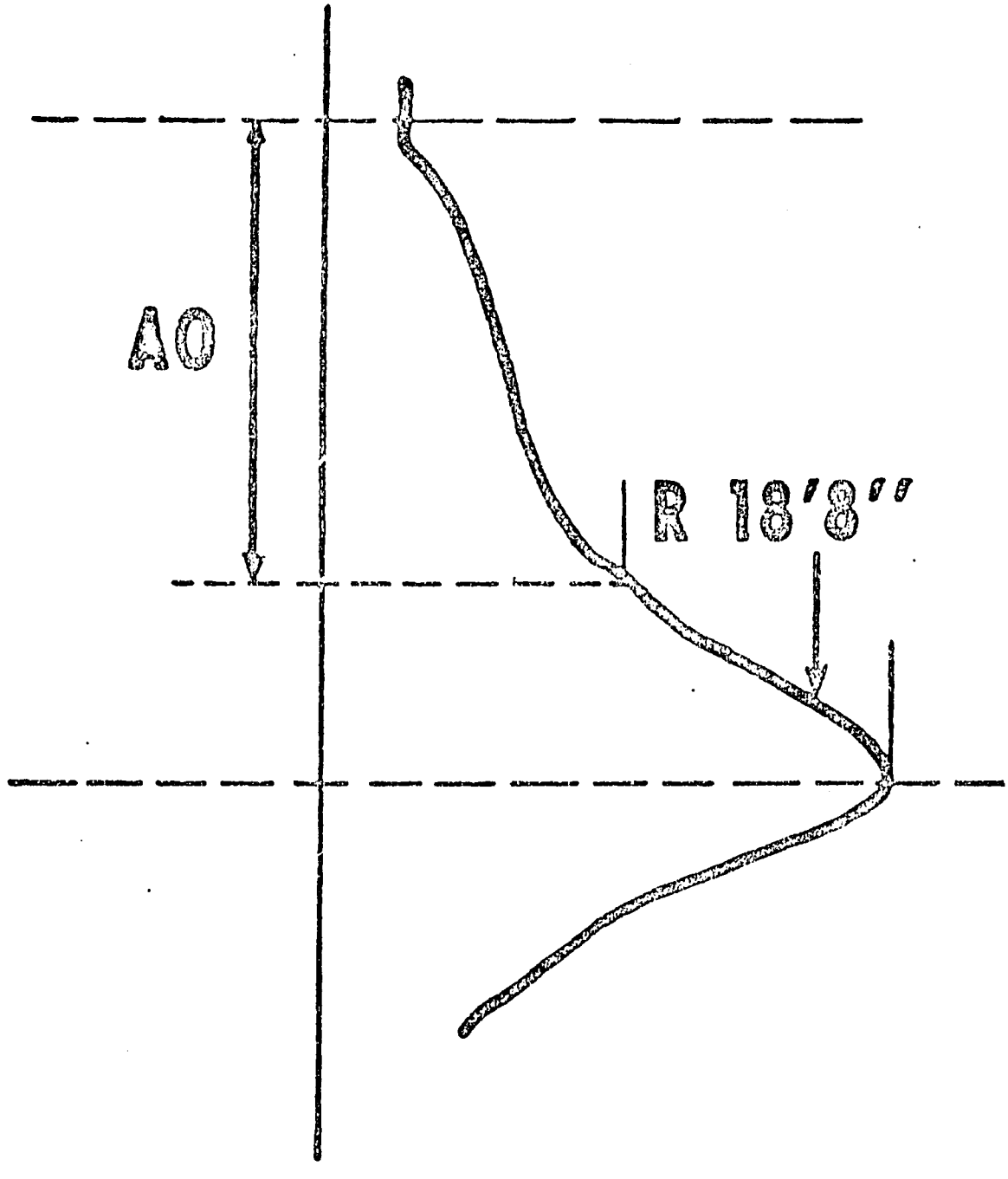
Mid-point Method



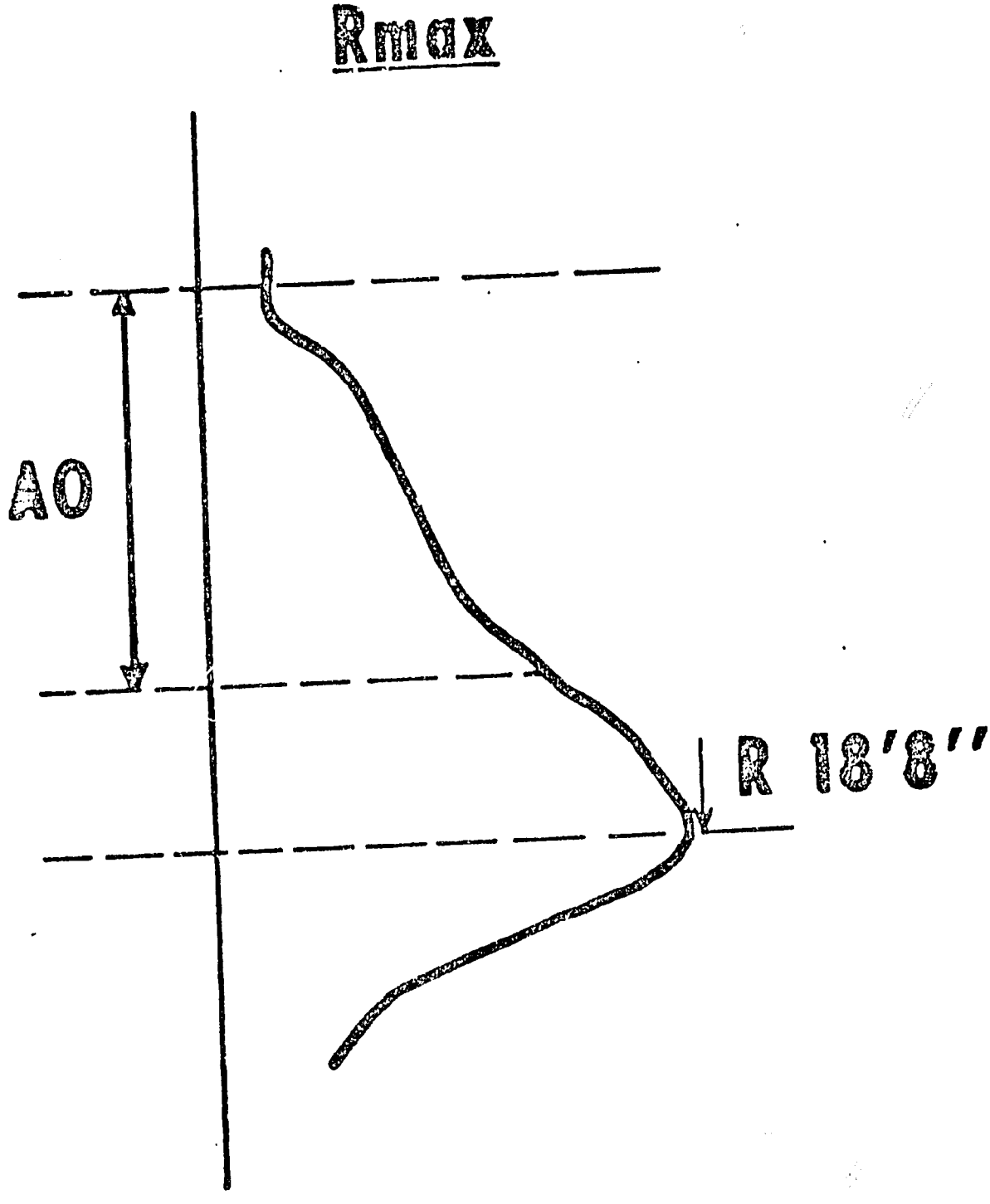
$e > 40' (> 2.0AO)$

RM

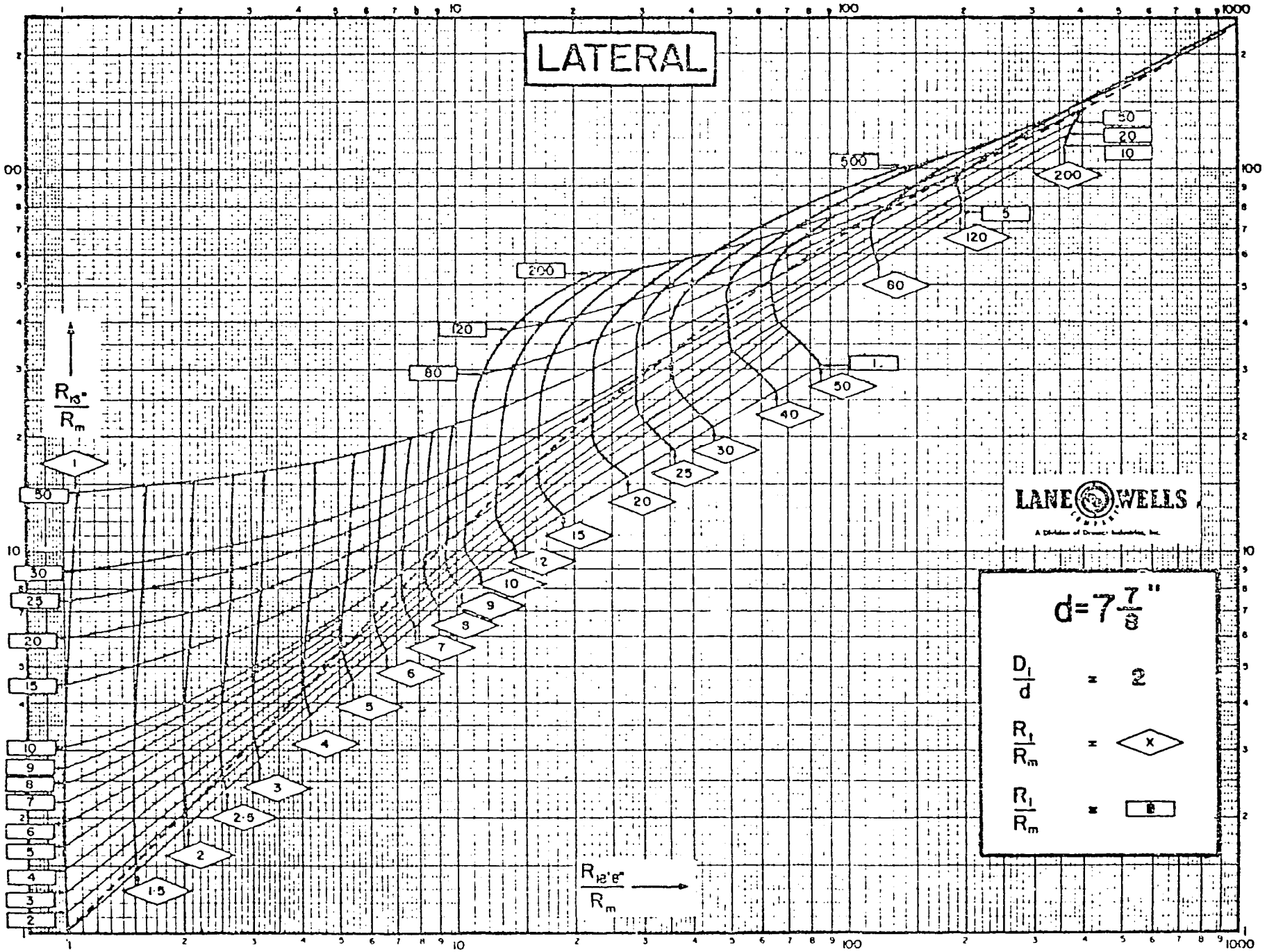
2/3 Rule



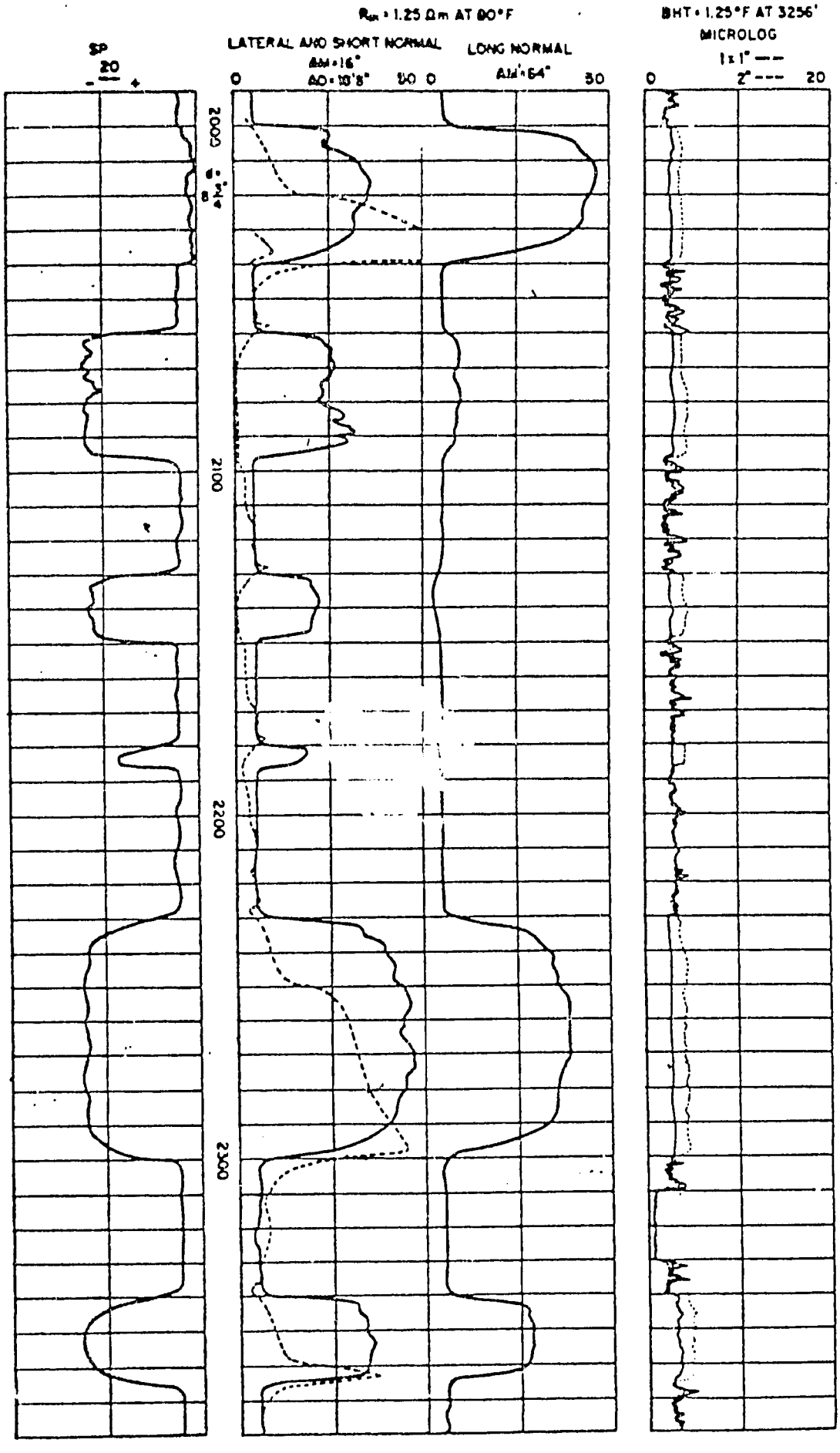
$\theta \simeq 28'$ (= 1.5 AO)



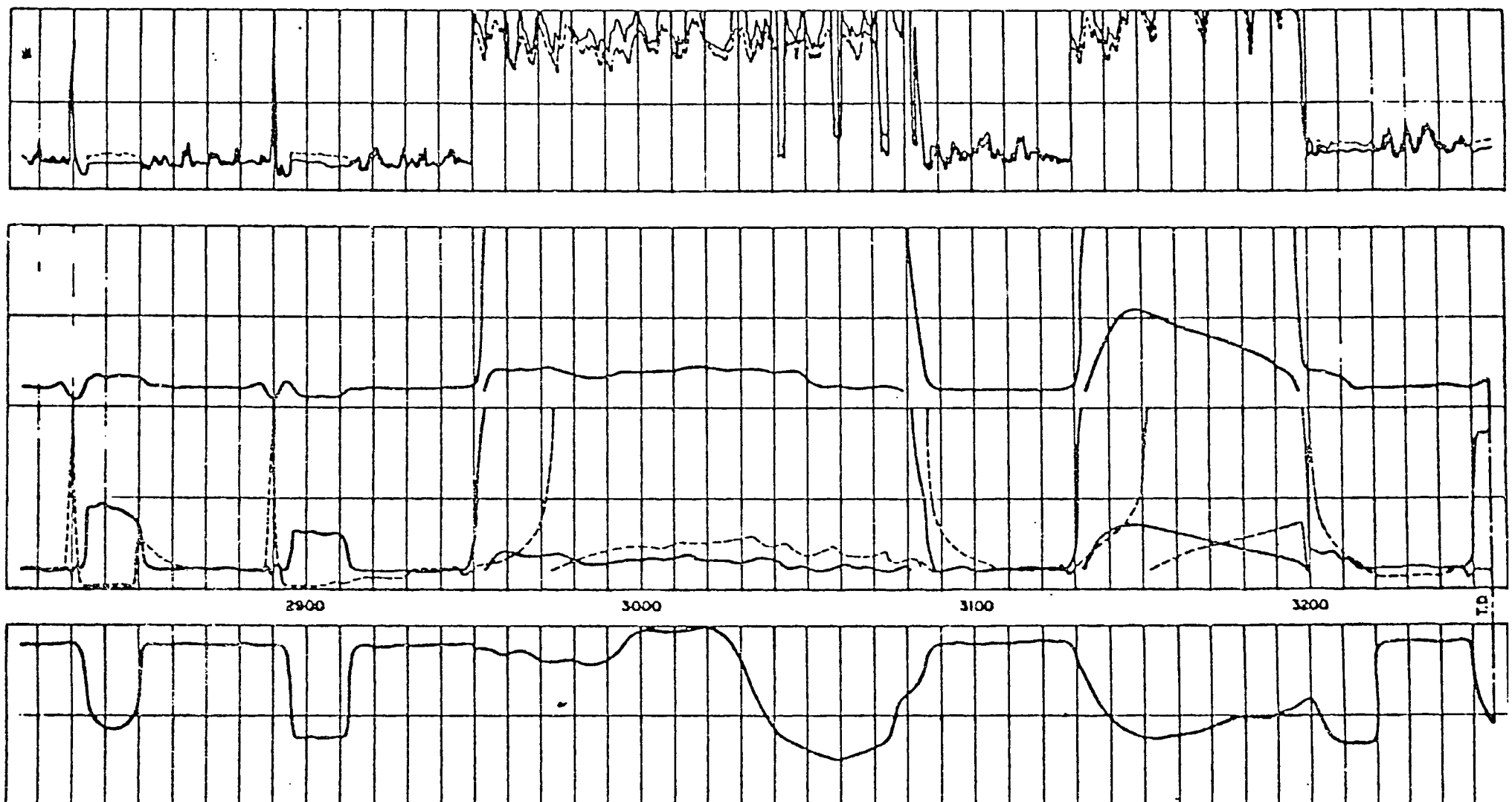
$\theta \simeq 24'(= 1.3\ AO)$

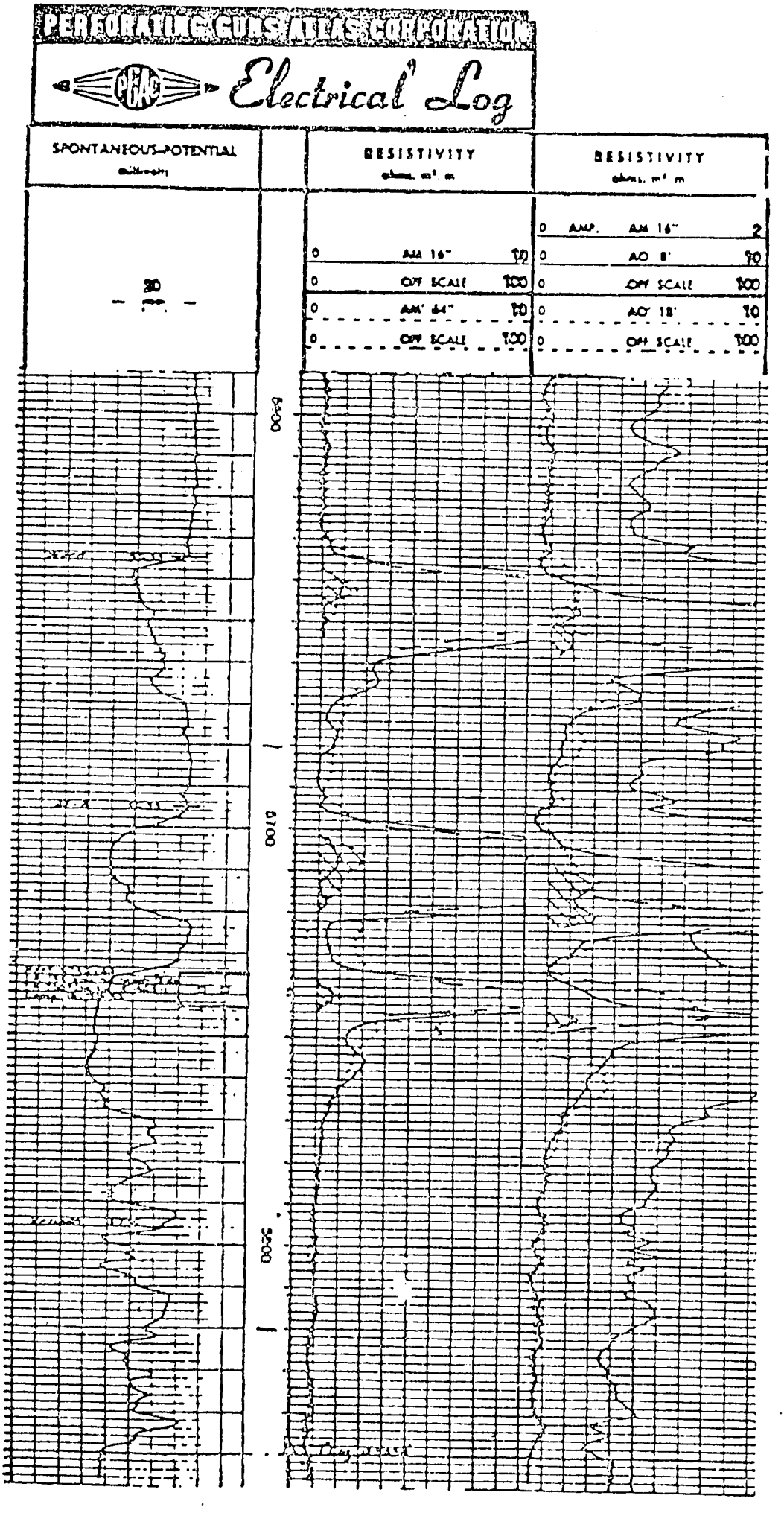


Short normal-lateral interpretation charts for the determination of R_t, D_t, and R_l in a 7⅞ in. bore hole. Reprinted with permission of Lane-Wells Company.


SP
20
LATERAL AND SHORT NORMAL
LONG NORMAL
0
50
0
30
MICROLOG
0
20
2000
2100
2200
2300

2400
2500
2600
2700
2800


2900
3000
3100
3200
T.D.



EXAMPLE NO: 154

LOCATION: WEST RANCH, JACKSON CO., TEXAS

RUN NO: ONE

T.D.: 5850'

BHT: 138° F

MUD: WATERBASE

MUD RESISTIVITY: 1.3 @ 85°F

BIT SIZE: 9-7/8"

PROBLEM: DETERMINE Rt USING TWO NORMAL CURVES.

ESTIMATE Rt USING LATERALS

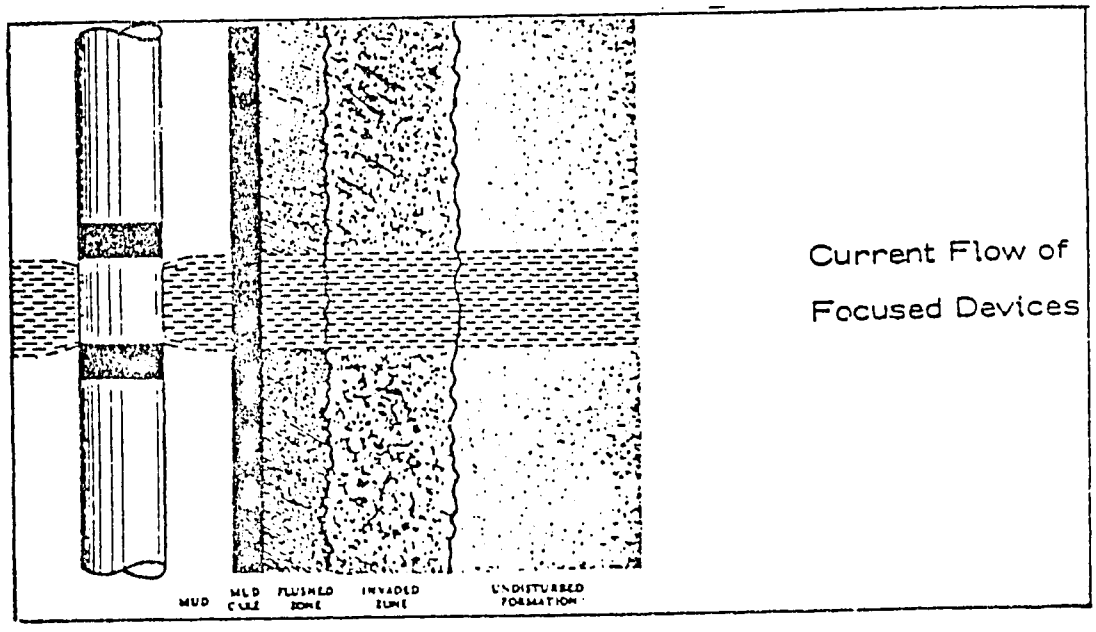
FOCUSING ELECTRODE LOGS - THE LATEROLOGS

- WHEN DRILLING WITH SALT BASE MUDS
  - E.S. SURVEY CURRENTS TEND TO FLOW UP & DOWN THE MUD COLUMN
  - LITTLE CURRENT PENETRATES BEDS
  - INDUCTION LOGS ARE ALSO AFFECTED ADVERSELY

- LATEROLOGS
  - ARE FOCUSED DEVICES
  - CURRENT PATH IS A SERIES CIRCUIT

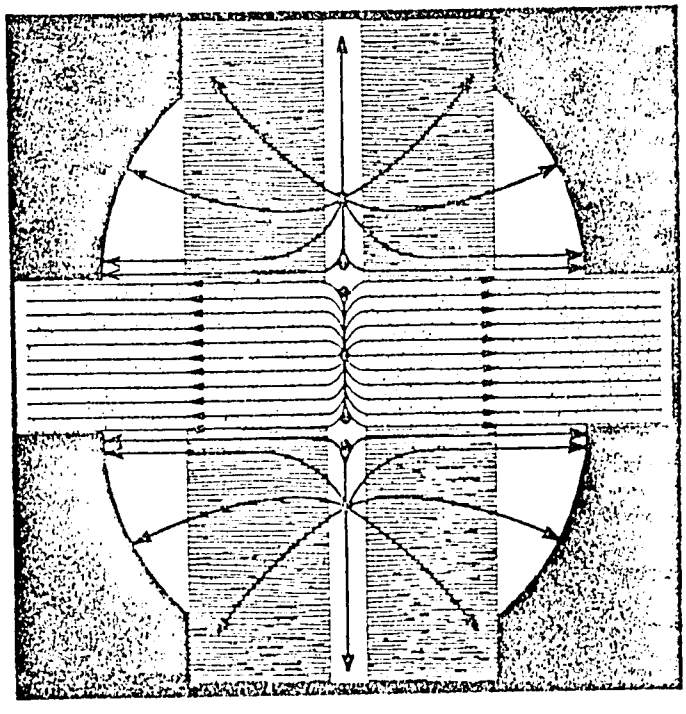
$$V_{TOTAL} = IR_{MUD} + IR_{\substack{INVADED\\ZONE}} + IR_{\substack{UNDISTURBED\\ZONE}}$$

TO GET $R_{LL} \approx R_T$ WE MUST REDUCE R_I AND R_M -- SALT BASE MUD

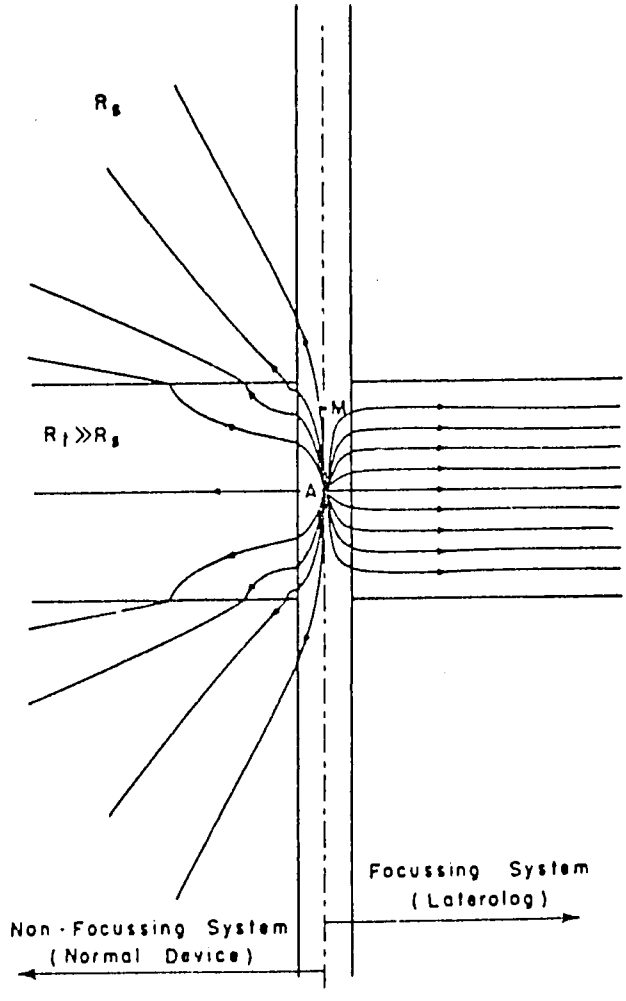


R_t : Resistivity of bed
R_s : Resistivity of adjacent formation
R_m : Resistivity of mud

$R_m \simeq R_s$



Measuring and bucking current distribution around the Laterolog 7 tool. Reprinted with permission of Schlumberger Well Surveying Corporation.



Comparison of current line distribution when logging a thin resistive formation by the short normal and by the Laterolog 7 devices. Reprinted with permission of Schlumberger Well Surveying Corporation.

LATEROLOGS- CONT'D.

- SUPERIOR TO E.S. SURVEY & INDUCTION LOGS
  - FOR LARGE R_T/R_M -- SALT MUDS AND RESISTIVE BEDS ($R_T > 100$)
  - FOR LARGE RESISTIVITY CONTRASTS WITH ADJACENT BEDS, R_T/R_S OR R_S/R_T.
    - RESISTIVE BEDS SURROUNDED BY SHALES
    - SOLID ROCK WITH POROUS STREAKS

- USES
  - R_T DETERMINATION
  - THICKNESS OF THIN BEDS
  - LOCATE HYDROCARBONS
  - CORRELATION

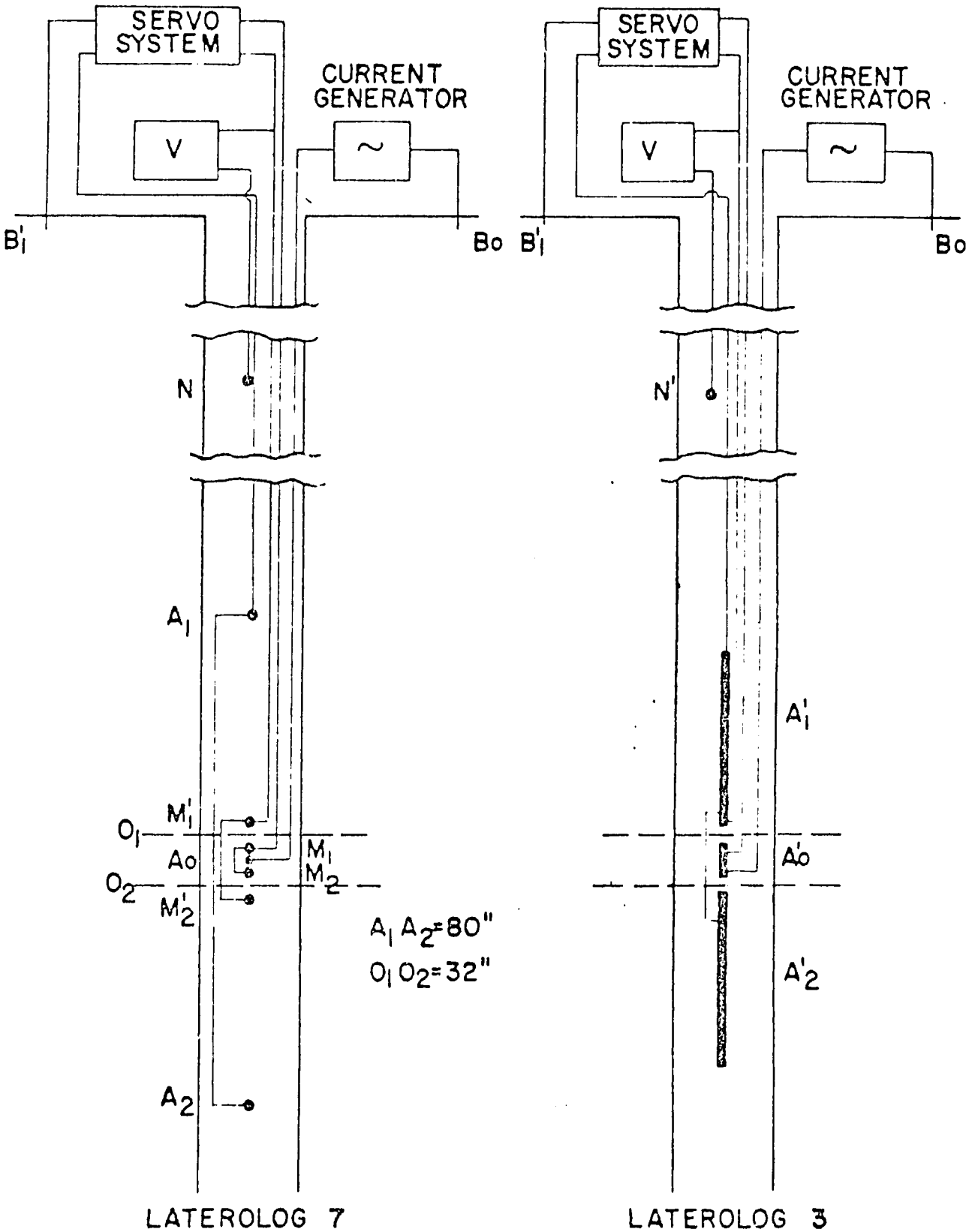
- PRINCIPLE OF OPERATION (LATEROLOG 7)
  - USES A CENTER ELECTRODE A_0 & THREE PAIRS OF ELECTRODES M_1 & M_2, M_1^1 & M_2^1, A_1 & A_2.
  - A CONSTANT DC CURRENT IS SENT THROUGH A_0
  - D C CURRENTS ARE SENT THROUGH A_1 & A_2 TO MAINTAIN EQUAL POTENTIALS AT M_1 & M_2 AND M_1^1 & M_2^1.
  - ΔE IS MEASURED BETWEEN ONE OF THE MONITORING ELECTRODES AND AN ELECTRODE AT THE SURFACE.
  - WITH A CONSTANT I_0, ΔE VARIES DIRECTLY WITH FORMATION R

- DEVICES

  R_T TYPE = LL_7, LL_3, LL_D

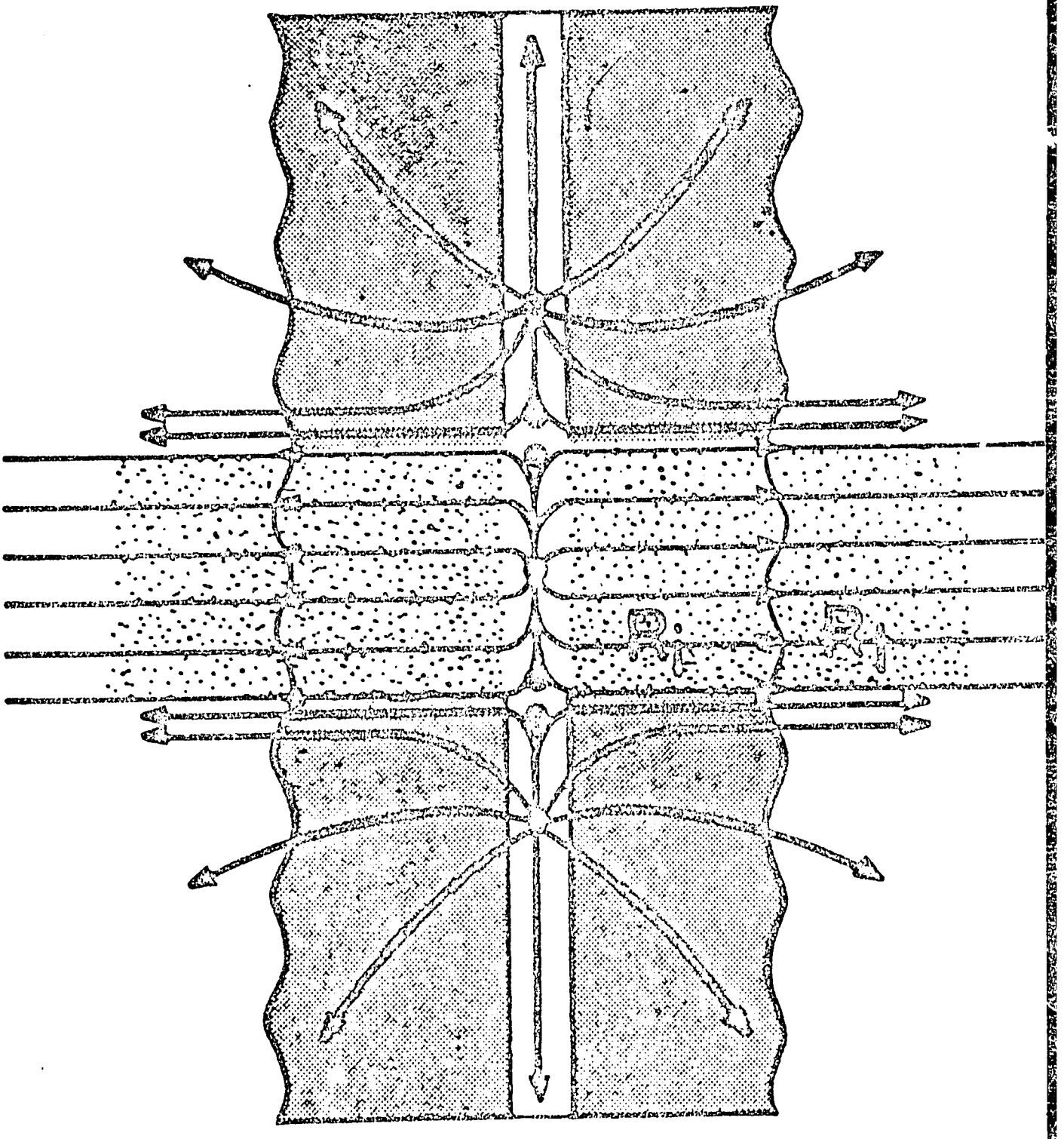
  R_I TYPE - LL_S

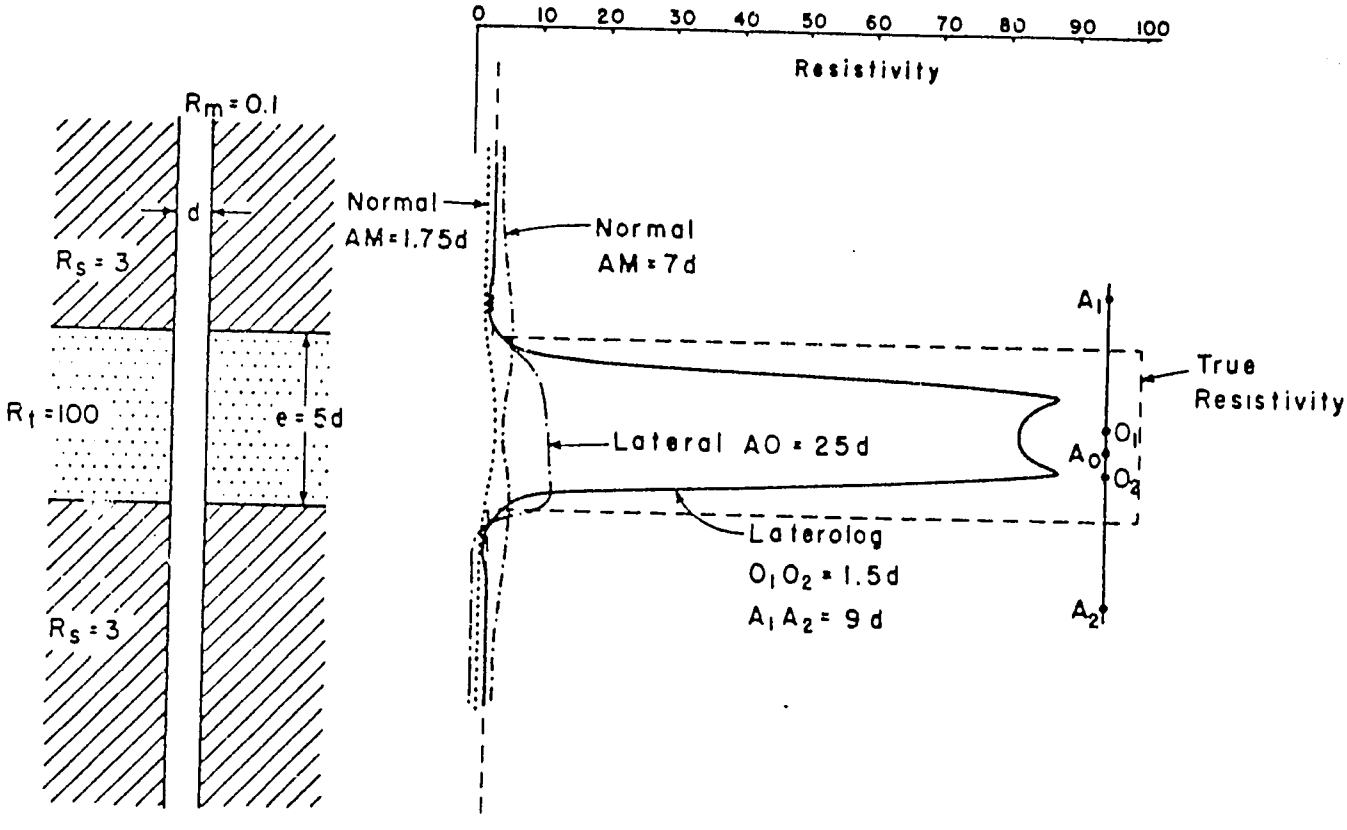
  R_{XO} TYPE - LL_8, SFL



SIMPLIFIED LATEROLOG SCHEMATICS

LATEROLOG





Response of Laterolog 7 and conventional log opposite a thin resistive bed, noninvaded, with salt-mud in the well. Reprinted with permission of Schlumberger Well Surveying Corporation.

LATEROLOGS (CONT'D)

LATEROLOG CHARACTERISTICS

LOG	BEAM WIDTH	VERTICAL RESOLUTION	RADIUS INVESTIGATION
LL_7	32"	32"	≈ 10'
LL_3	12"	12"	≈ 15'
LL_D	24"	24"	> 15'
LL_S	24"	24"	≈ 5'
LL_8	14"	14"	≈ 3'
SFL		<14"	< 3'

SONDES

LL_7 + SP OR GR

LL_3 + SP

LL_3 + SP OR GR + NEUTRON

LL_8 + IL_D + 1 L_M + SP

LL_D + LL_S + GR OR SP

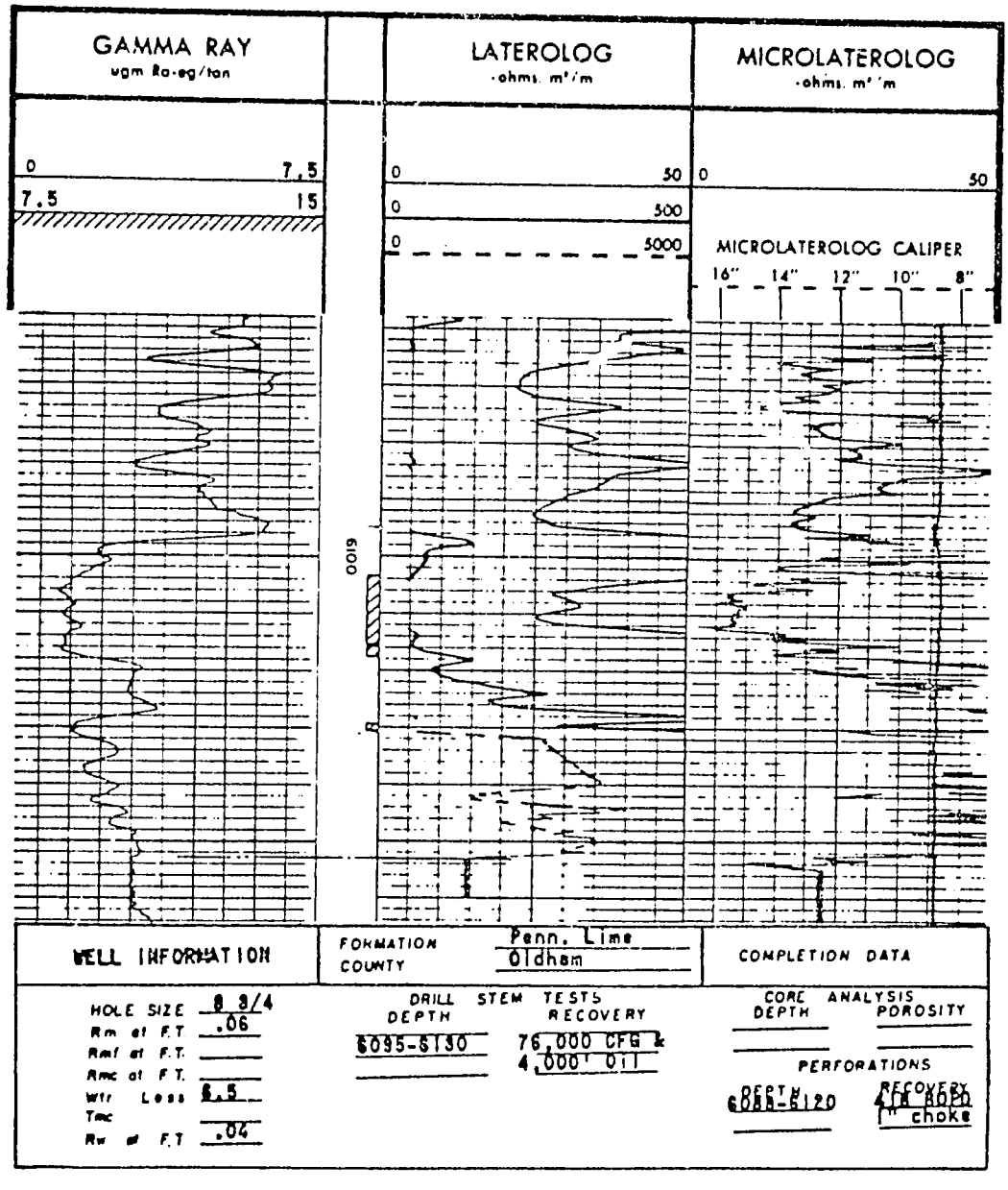
LL_D + LL_S + SFL + GR OR SP

IL_D + SFL + SP OR GR + BHC_{SONIC}

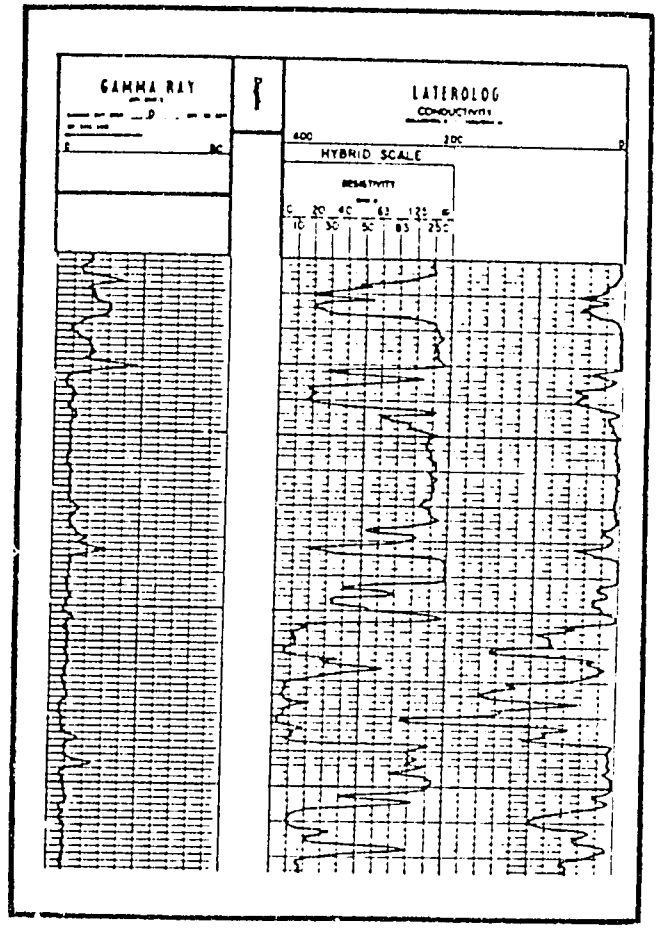
LATEROLOGS (CONT'D)

RECORDING SCALES

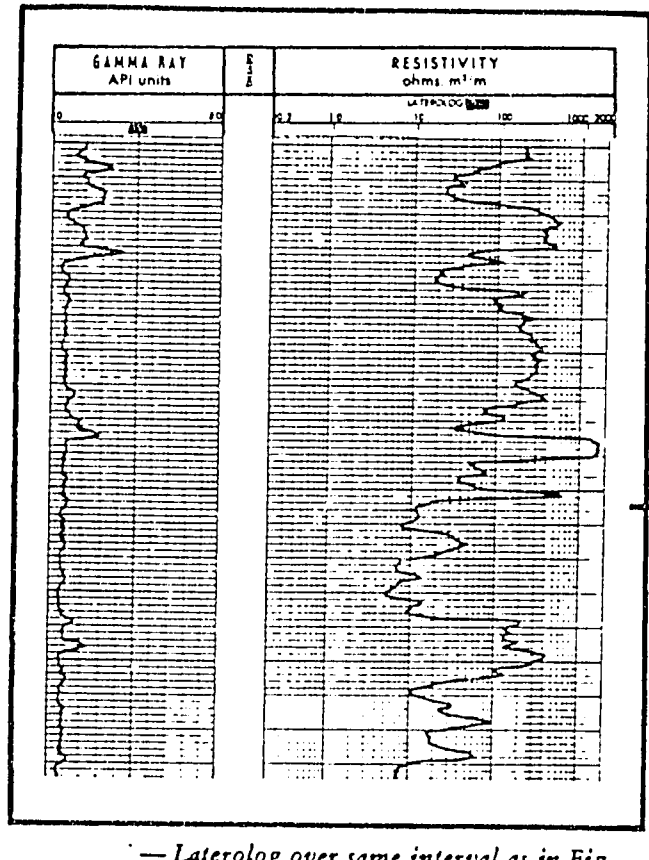
- LINEAR
  - 0-50, 0-500, 0-5000
- HYBRID
  - LINEAR ON FIRST 1/2 OF TRACK
  - LINEAR CONDUCTIVITY ON SECOND 1/2 OF TRACK
- LOGARITHMIC
  - SPLIT 4-CYCLE LOGARITHMIC



Example of Laterolog 7 in salt-mud survey. Reprinted with permission of Schlumberger Well Surveying Corporation.



— *Laterolog recorded on hybrid scale.*



— *Laterolog over same interval as in Fig. 4-4, recorded on logarithmic scale.*

From Schlumberger's 1972 Log Interpretation Principles

LATEROLOGS (CONT'D)

. EFFECT OF BED THICKNESS & ADJACENT BEDS

- FOR RESISTIVE BED WHERE H < CURRENT DISC THICKNESS, CURRENT IS DIVIDED BETWEEN MAIN BED AND ADJACENT BEDS
  - .. AMOUNT OF CURRENT FLOWING IN EACH MEDIUM DEPENDS ON H, R_T AND R_S
  - .. WHEN $R_S < R_T$ $R_{LL} < R_T$
  - .. AS H DECREASES $R_{LL} << R_T$
- FOR A THIN CONDUCTIVE BED WHERE H < CURRENT DISC THICKNESS AND $R_T < R_S$
  - .. $R_{LL} > R_T$
  - .. CURRENT TRIES TO AVOID ADJACENT BEDS AND FLOW IN CONDUCTIVE BED
  - .. CROSS-SECTIONAL AREA OF CURRENT DISC IS REDUCED CAUSING AN INCREASE IN RESISTANCE
  - .. THE SMALLER R_T/R_S & THE THINNER THE BED, THE GREATER THE INCREASE IN R_{LL}
- IN ACTUAL LOG ANALYSIS
  - .. THE FEWER CORRECTIONS MADE TO BASIC DATA, THE LESS CHANCE FOR ERROR IN THE FINAL CALCULATION
  - .. RESTRICT ANALYSIS TO INTERVALS WHERE H IS GREATER THAN RESOLUTION OF DEVICES
  - .. FOR THIN BED ANALYSIS APPROXIMATE CORRECTIONS ARE AVAILABLE

LATEROLOGS (CONT'D)

- EFFECT OF BOREHOLE CONDITIONS
  - NEGLIGIBLE FOR REASONABLE D_H
  - IMPORTANT WHEN $R_T >> R_M$ AND $D_H >> D_E$
    - -- CURRENT DISC TRIES TO AVOID PENETRATING RESISTIVE BED
    - -- D_H BEING LARGE ALLOWS CURRENT DISC TO FLARE & SPREAD WITHIN THE BOREHOLE
    - -- FLARING INCREASES CROSS-SECTIONAL AREA OF CURRENT DISC AND REDUCES RESISTIVITY

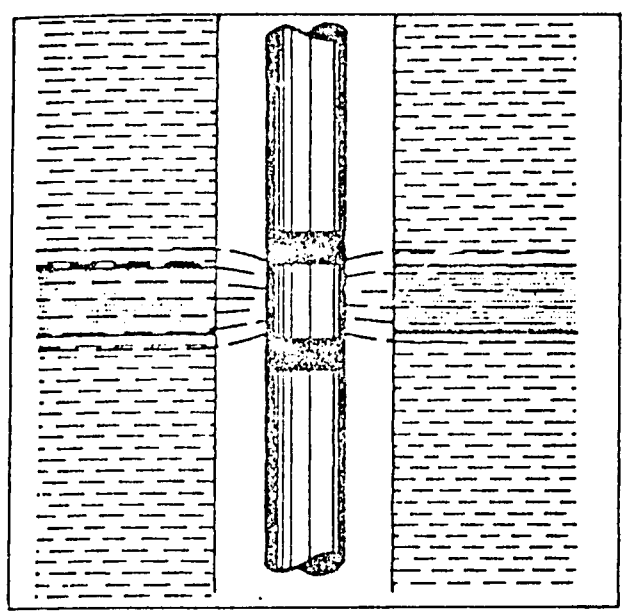
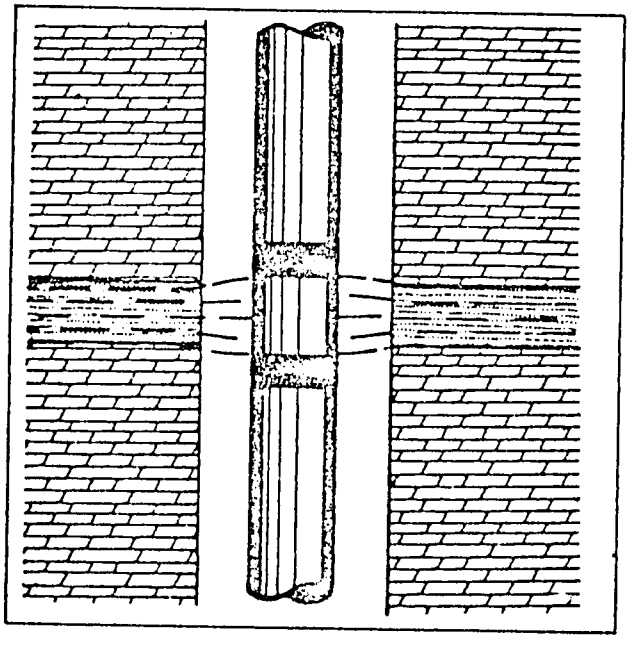
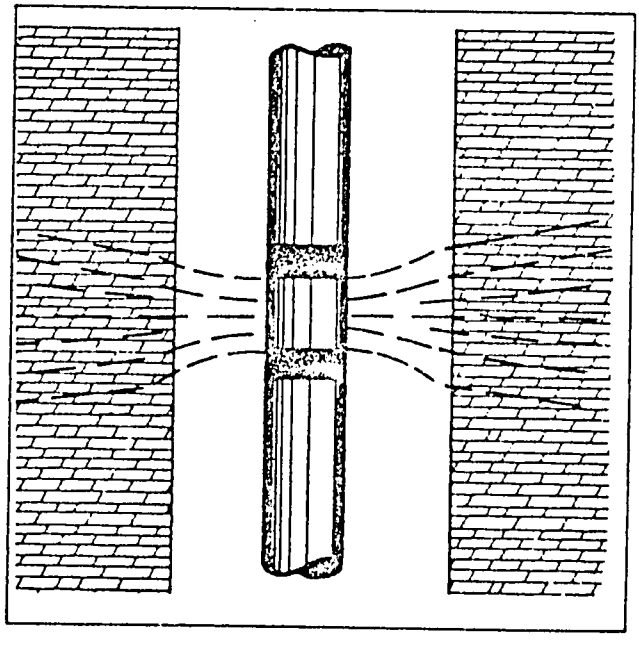


Figure 11

THIN BED & $R_S < R_T$ THEN $R_{LL} < R_T$

FROM DRESSER ATLAS LOG REVIEW 1, 1974



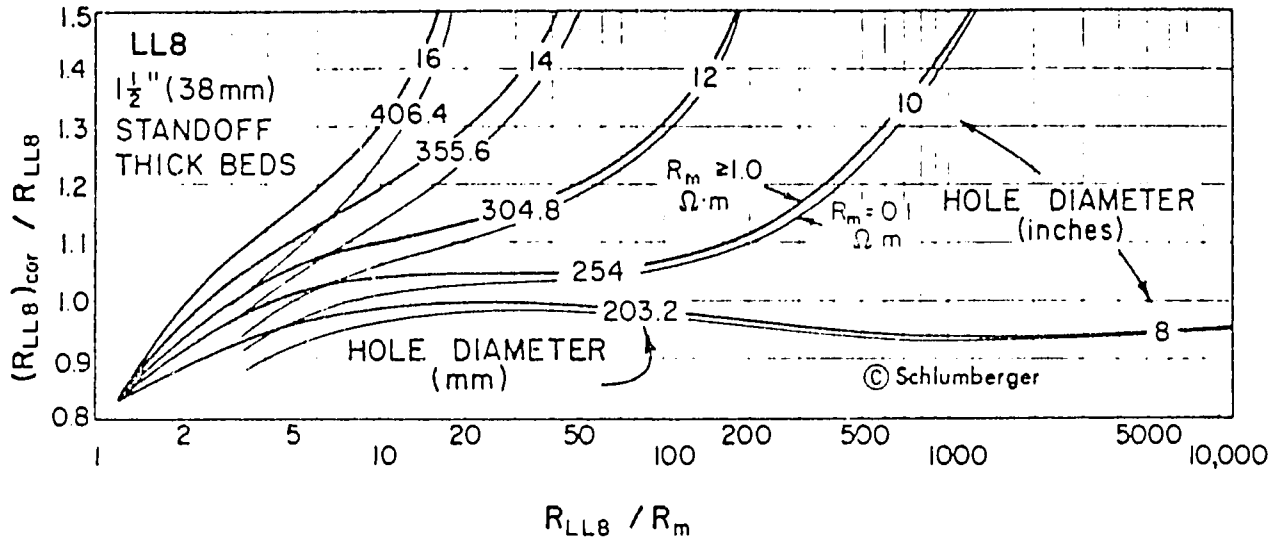


THIN BED & $R_S > R_T$
THEN $R_{LL} > R_T$

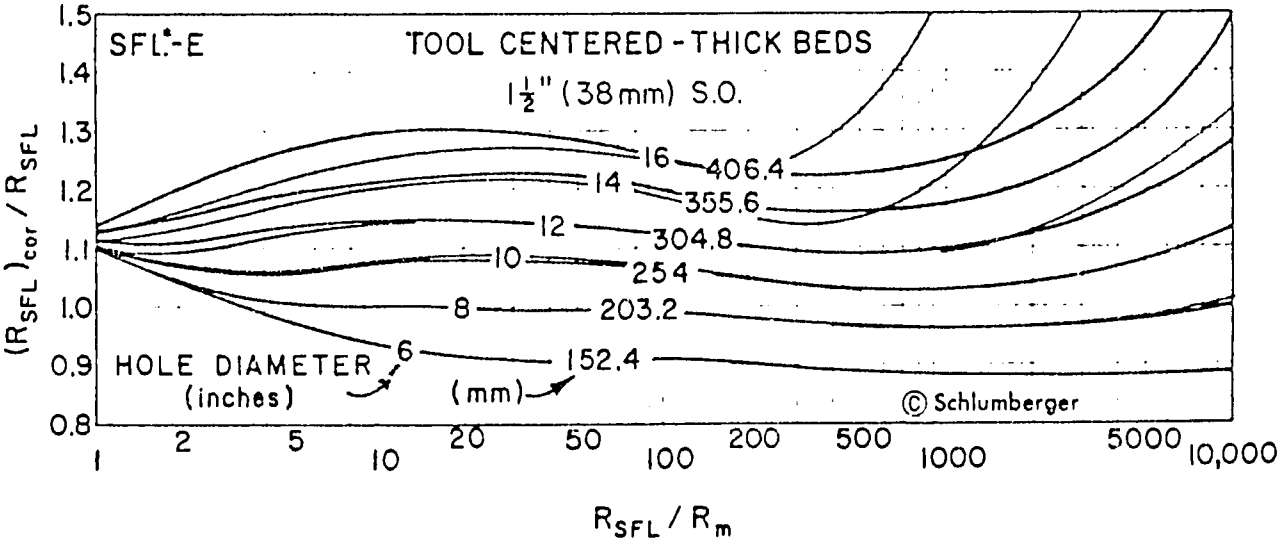
$R_T >> R_m$ & D_h/D_e IS HIGH
THEN $R_{LL} < R_T$

FROM DRESSER ATLAS LOG REVIEW 1, 1974

LATEROLOG*-8 BOREHOLE CORRECTION



SFL* BOREHOLE CORRECTION

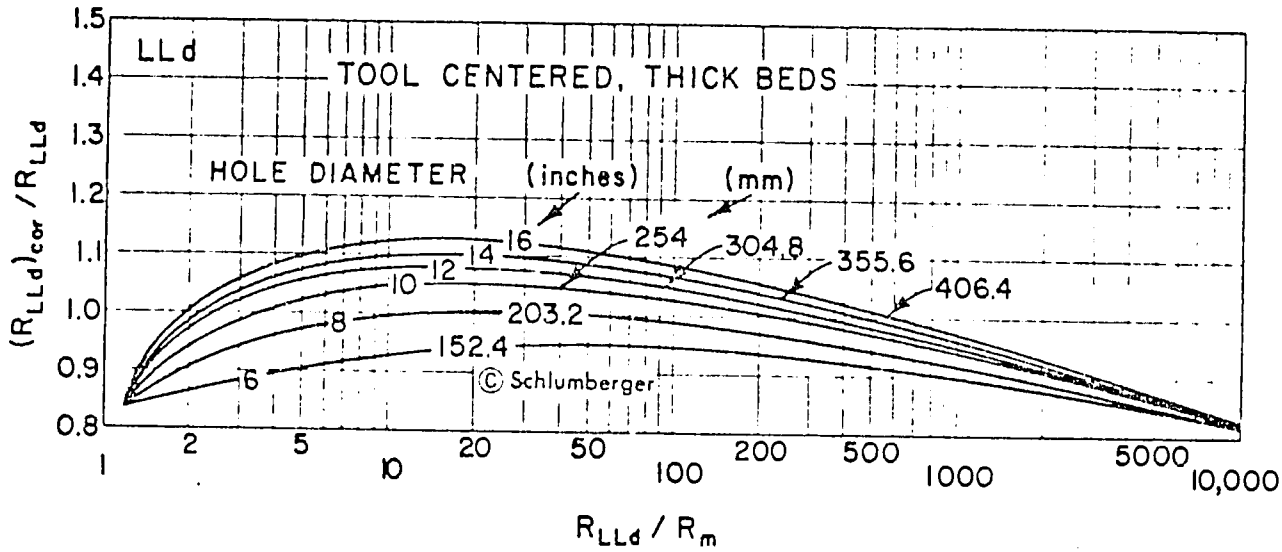


*Mark of Schlumberger

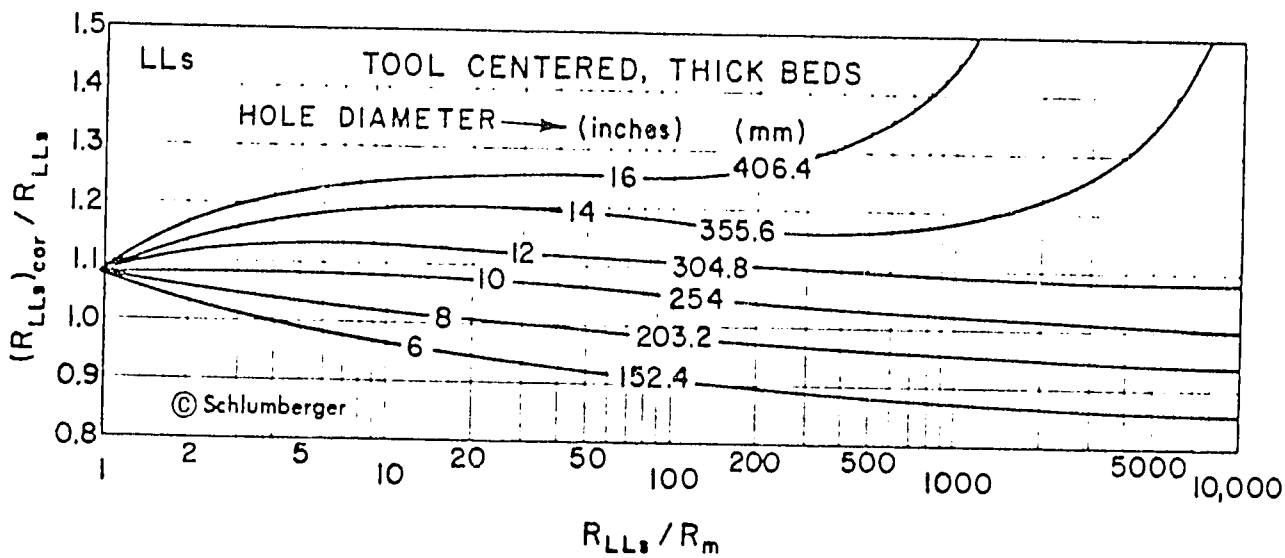
DUAL LATEROLOG* CORRECTION CHARTS

SONDE CENTERED

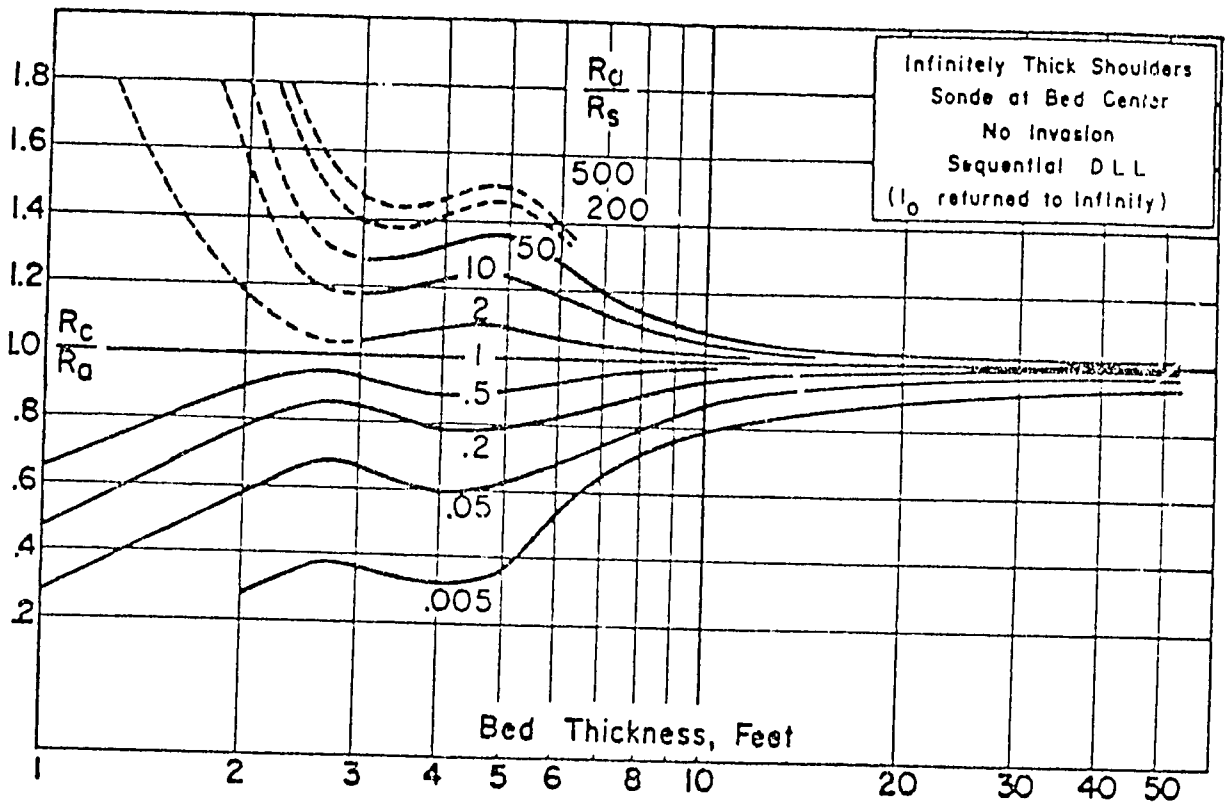
DEEP LATEROLOG* BOREHOLE CORRECTION



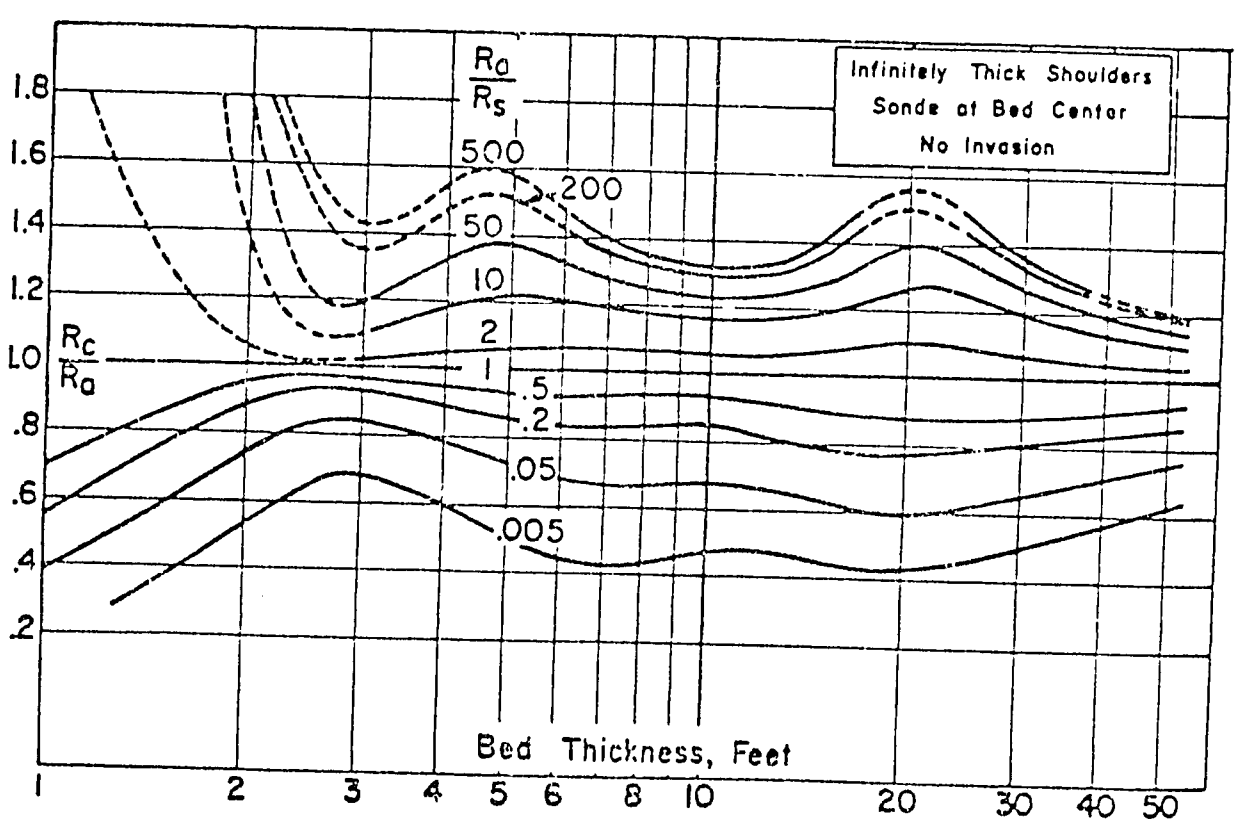
SHALLOW LATEROLOG* BOREHOLE CORRECTION

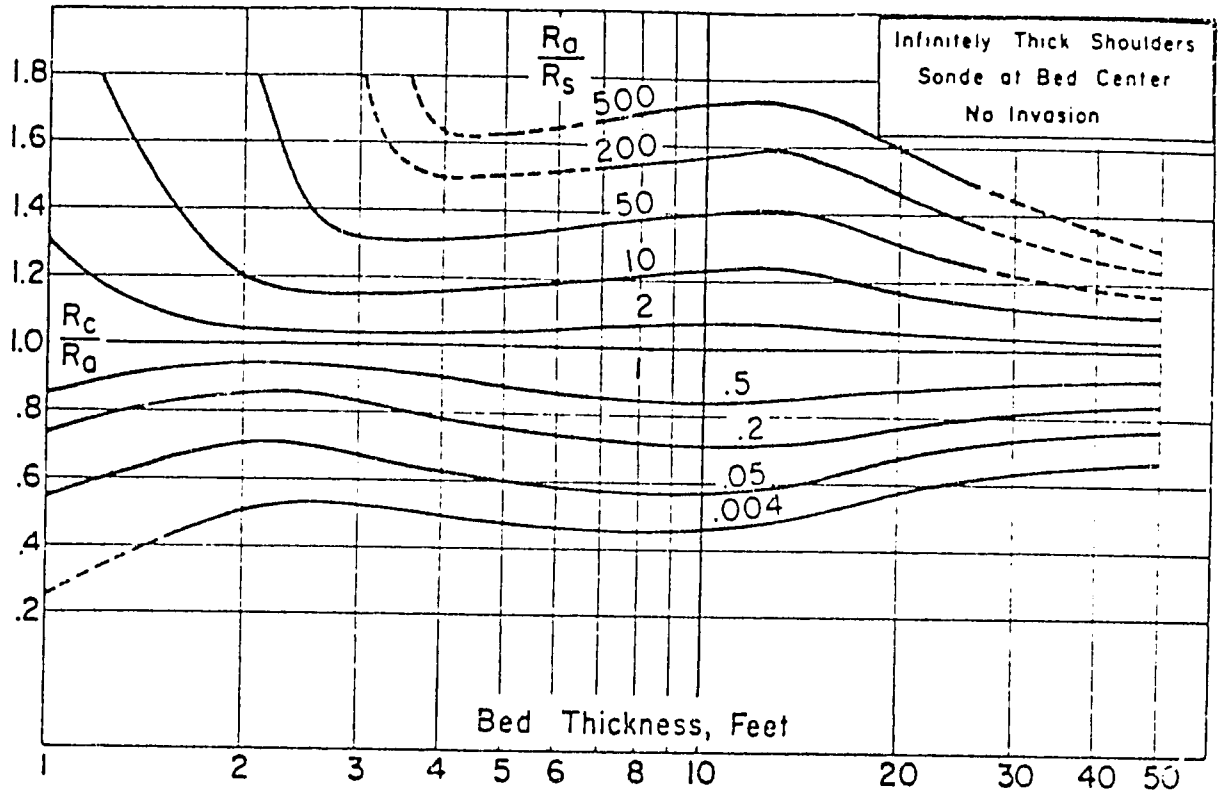


*Mark of Schlumberger



— *Shoulder-bed corrections, LLs (top) and LLd (bottom).*





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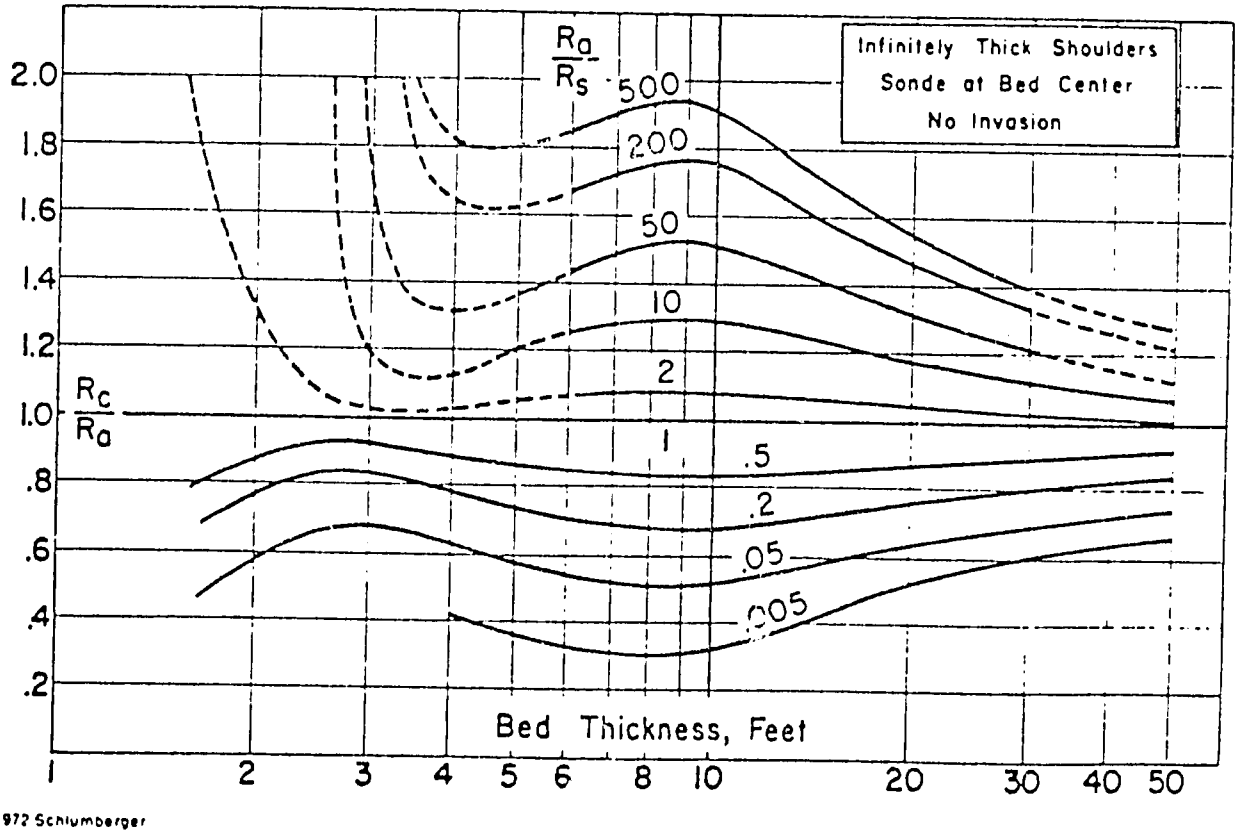
— *Shoulder-bed corrections, 1.1.3 (top) and 1.1.7 (bottom).*



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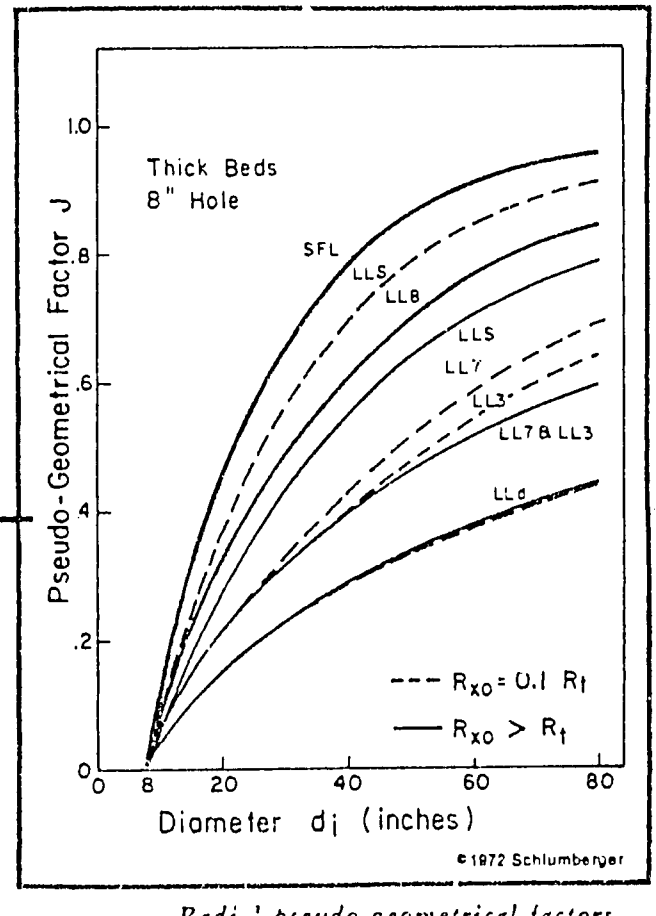
LATEROLOGS(CONT'D)

- EFFECT OF INVASION
  - APPARENT RESISTIVITY MEASURED, R_{LL}, IN A THICK BED IS GIVEN APPROXIMATELY BY

$$R_{LL} = R_{XO} \cdot J_{DI} + R_T \cdot (1-J_{DI})$$

WHERE J_{DI} = PSEUDO-GEOMETRICAL FACTOR GIVING THE FRACTION OF THE TOTAL SIGNAL THAT ORIGINATES FROM A VOLUME HAVING A SPECIFIC GEOMETRICAL ORIENTATION WITH THE SONDE IN AN INFINITE HOMOGENEOUS MEDIUM



— Radial pseudo-geometrical factors, fresh muds (solid) and salty muds (dashed).

- DETERMINATION OF R_T - LL_3, LL_7
  - CORRECTION FACTORS RELATIVE TO INVASION ARE ONLY APPROXIMATIONS
  - ADDITION OF R_{XO} DEVICE (MLL, PL) AIDS IN THE EVALUATION OF R_T

POROSITY	D_I	R_{LL7} =	R_{LL3} =
5% - 10%	80"	$0.6R_{XO}+0.4R_T$	$0.75R_{XO}+0.5R_T$
10% - 15%	40"	$0.4R_{XO}+0.6R_T$	$0.5R_{XO}+0.5R_T$
15% - 20%	20"	$0.2R_{XO}+0.8R_T$	$0.25R_{XO}+0.75R_T$

  - R_{LL7} & R_{LL3} ARE CORRECTED FOR BOREHOLE AND BED THICKNESS BEFORE USING ABOVE.
  - FOR DEEP INVASION ACCURATE VALUES OF R_{XO} ARE IMPORTANT
  - AS D_I DECREASES INCREASING ERRORS IN R_{XO} CAN BE ACCOMODATED

- DETERMINATION OF R_T - THE DUAL LATERLOG
  - MODERN LATEROLOG SONDE
  - COMBINED WITH AN R_{XO} DEVICE, FIGURES D_I AND R_T
  - CORRECT R_{LL_D} & R_{LL_S} FOR BOREHOLE BEFORE ENTERING DUAL LATEROLOG-R_{XO} CHART

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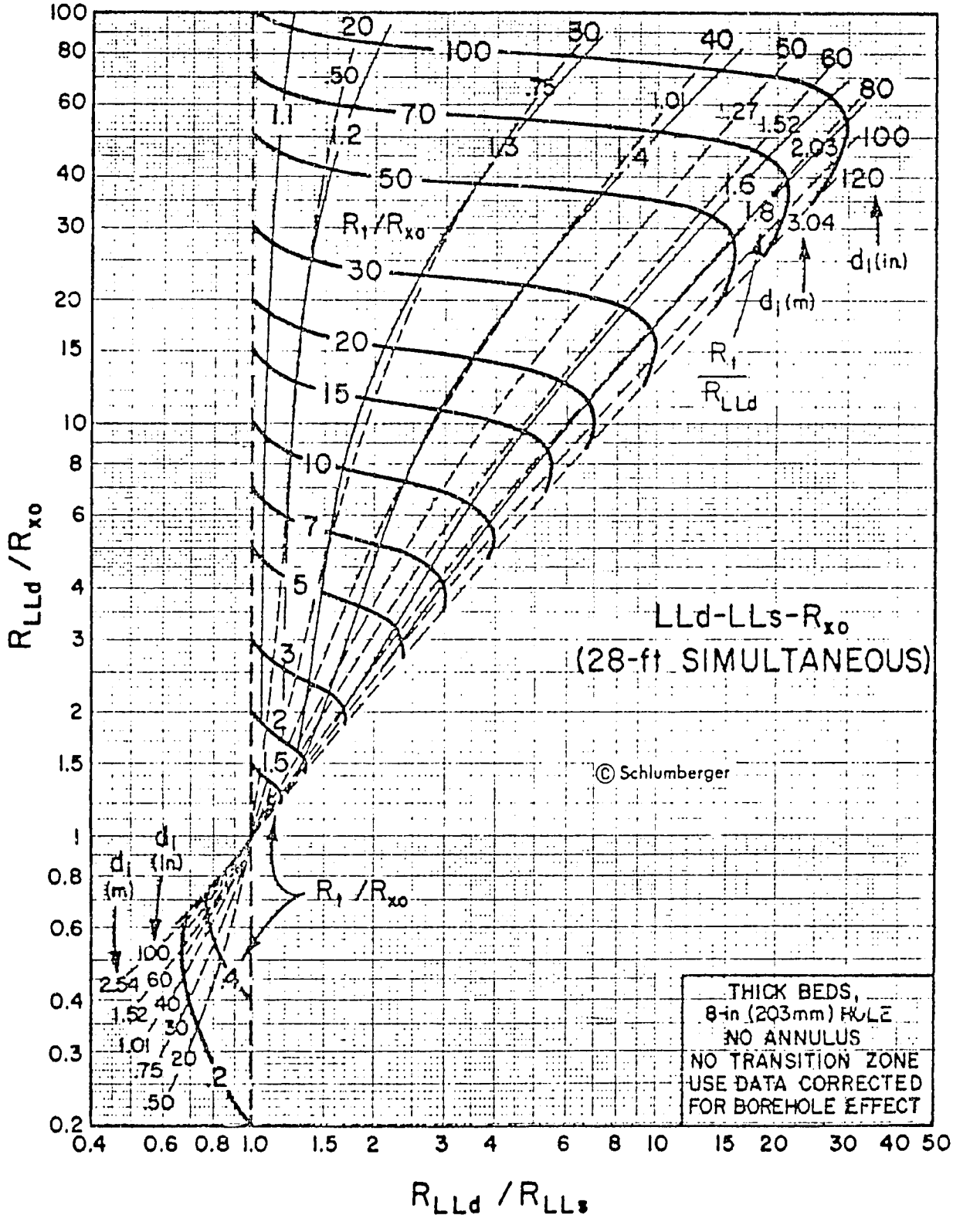
DUAL LATEROLOG* – R_{xo}

LLd — LLs — R_{xo}



*Mark of Schlumberger

DUAL LATEROLOG
(SIMULTANEOUS)

$d_h = 8''$
$R_{mf} = 0.05$ 12"
$R_W = 0.055$
$R_{WS} = 20\%$

GAMMA RAY 100 | 5 INCH | RESISTIVITY 2 1 10 100 1000

Calc: Sw from 2LL-Rxo chart, use 0.5 and m = 2 for Rxo. Calc Sw(Archie)

Graphite

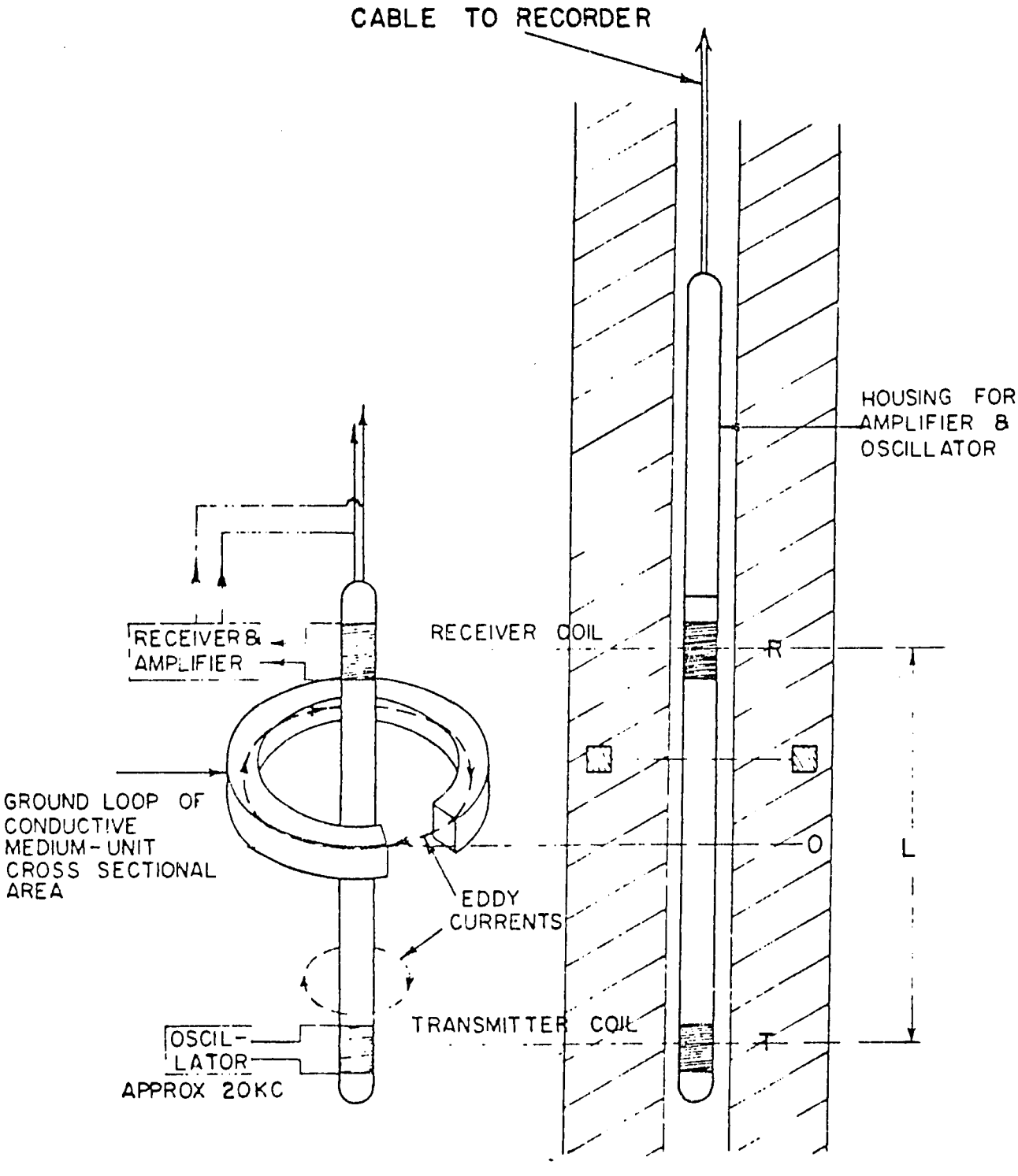
1500

Limestone

INDUCTION LOG

- MAKES USE OF INDUCED MAGNETIC FIELDS TO DETERMINE ROCK RESISTIVITY
  - DETECTION POSSIBLE IN LIQUIDS, SOLIDS & GASES
  - NOT NECESSARY TO HAVE CONDUCTIVE FLUID IN BOREHOLE
  - WORKS WITH BOREHOLE FULL OF GAS, AIR, INVERTED OIL EMULSION MUD, 100% OIL MUD, OR FRESH WATER MUD

- PRINCIPLE
  - HIGH FREQUENCY A C OF CONSTANT INTENSITY IS SENT THROUGH TRANSMITTOR COIL
  - ALTERNATING MAGNETIC FIELD IS CREATED WHICH INDUCES SECONDARY CURRENTS IN ROCKS
  - SECONDARY CURRENTS FLOW IN CIRCULAR GROUND LOOP PATHS CO-AXIAL WITH BOREHOLE
  - SECONDARY MAGNETIC FIELDS ARE CREATED WHICH INDUCE SIGNALS IN THE RECEIVER COILS
  - RECEIVER SIGNALS ARE PROPORTIONAL TO CONDUCTIVITY OF ROCKS



INDUCTION LOGGING TOOL

INDUCTION LOG (CONT'D)

. FEATURES

- DEVELOPED TO MEASURE R_T WHEN USING OIL-BASE MUD OR NO MUD (GAS)
- QUICKLY PROVED SUPERIOR TO E.S. SURVEY WHEN USING FRESH WATER BASE MUDS
- FOCUSED & THUS MINIMIZES EFFECTS OF BOREHOLE & SURROUNDING BEDS
- DEEP INVESTIGATION
- INVADED ZONE EFFECTS MINIMIZED
- SPACING BETWEEN TRANSMITTER AND RECEIVER COILS IN CURRENT TOOLS IS 40"
- DOES NOT REQUIRE A CONDUCTIVE COUPLING BETWEEN TOOL AND FORMATIONS
- PARTICULARLY APPLICABLE WHEN $R_T < 50$
- LOWER LIMIT OF RESISTIVE BED THICKNESS IS ABOUT 4'
- DOES NOT FUNCTION WELL FOR $R_T > 100$ DUE TO BOREHOLE SIGNAL, TEMPERATURE DRIFT, VARIATION IN STAND OFF

. FEATURES - CONT'D

TOOL	VERTICAL RESOLUTION	RADIUS OF INVESTIGATION
6FF40	40"	≈ 10'
6FF28	28"	≈ 5'
$1L_D$	40"	≈ 10'
$1L_M$	40"	≈ 5'

SONDES

6FF40 + 16" N + SP

6FF-28 + 16" N + SP

DIL -- IL_D + $1L_M$ + LL_8 + SP

1SF/Sonic -- 6FF-40 OR $1L_D$ + SFL + SP OR GR + B H C_{SONIC}

- LOG PRESENTATION

  TRACK 1 - - SP

  TRACK 2 - - TWO OR THREE RESISTIVITY LOGS

  TRACK 3 - - DEEP CONDUCTIVITY, $C = \frac{1000}{R}$

- SCALES

  - LINEAR

    .. FIRST USED SCALE

    .. GOOD FOR CORRELATION WITH EARLIER LOGS

    .. NOT USED MUCH ANYMORE - CAN BE DIFFICULT TO READ - - BACKUP TRACES

    .. 1" OR 2" PER 100'

  - SPLIT FOUR-DECADE LOGARARATHMIC

    .. 2" OR 5" PER 100"

    .. HAS GOOD READABILITY @ LOW RESISTIVITIES

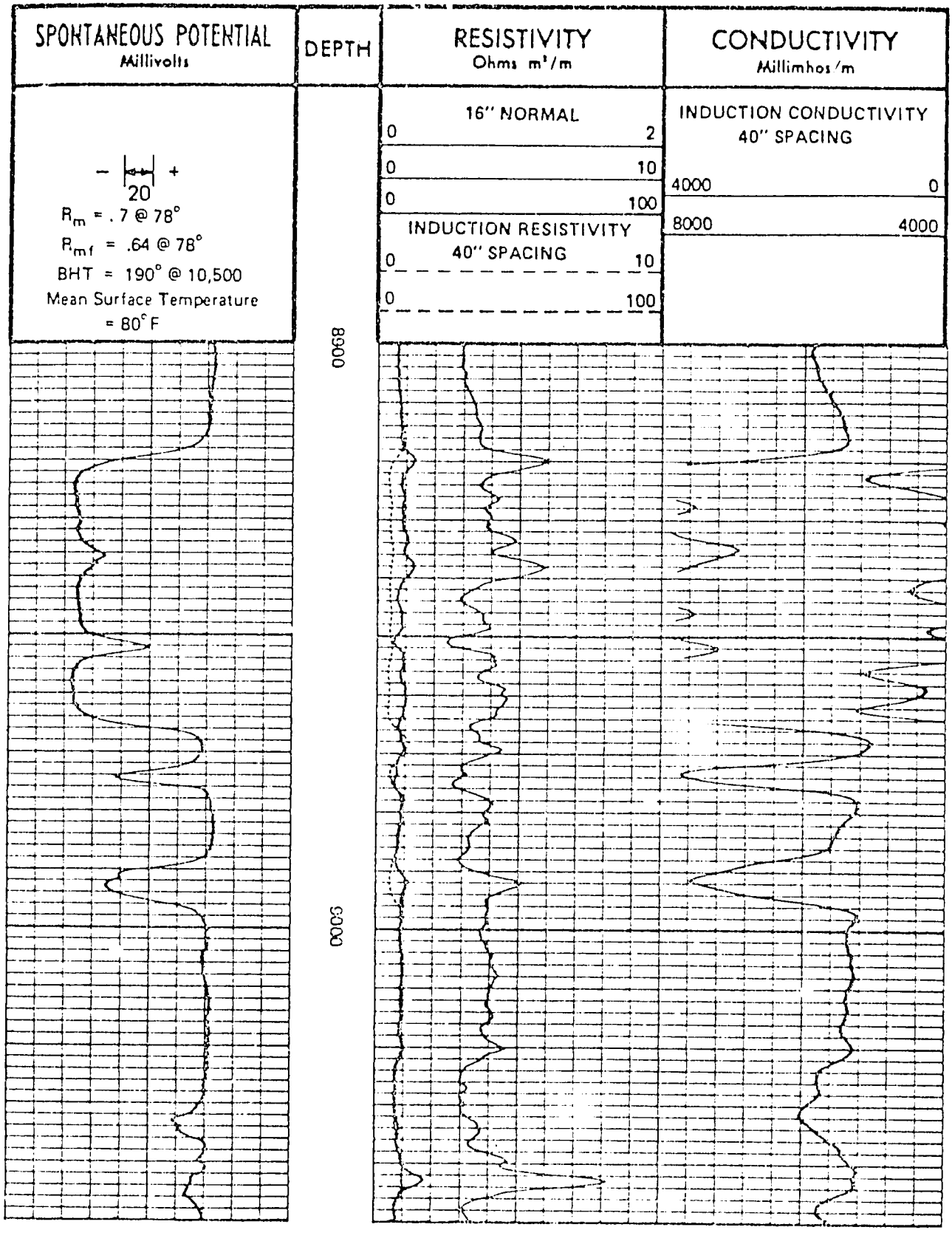
    .. WIDE RANGE WITHOUT BACKUP TRACES

    .. EASE OF READING RESISTIVITY RATIOS DIRECTLY

    .. IS DETAIL LOG FOR ENGINEERING

    .. GOOD READINGS AT HIGHER RESISTIVITIES BY USING CONDUCTIVITIES

PROBLEM



Example 104

From Dresser Atlas 1975 Log Interpretation Fundamentals

- COMPUTATION OF SP LOG - QUICK-LOOK METHOD FOR FINDING HYDRA-CARBONS

$$E_{SP} \approx -K \text{ LOG } \frac{R_{MF}}{R_W}$$

WRITING ARCHIE'S EQUATION

$$S_{XO} = \left(\frac{F\ R_{MF}}{R_{XO}}\right)^{1/2} \qquad \text{FLUSHED ZONE}$$

$$S_W = \left(\frac{F\ R_W}{R_T}\right)^{1/2} \qquad R_T \text{ ZONE}$$

IN AQUIFERS $S_{XO} = S_W = 1.00$ AND $\frac{R_{XO}}{R_T} = \frac{R_{MF}}{R_W}$

THUS FOR AQUIFERS

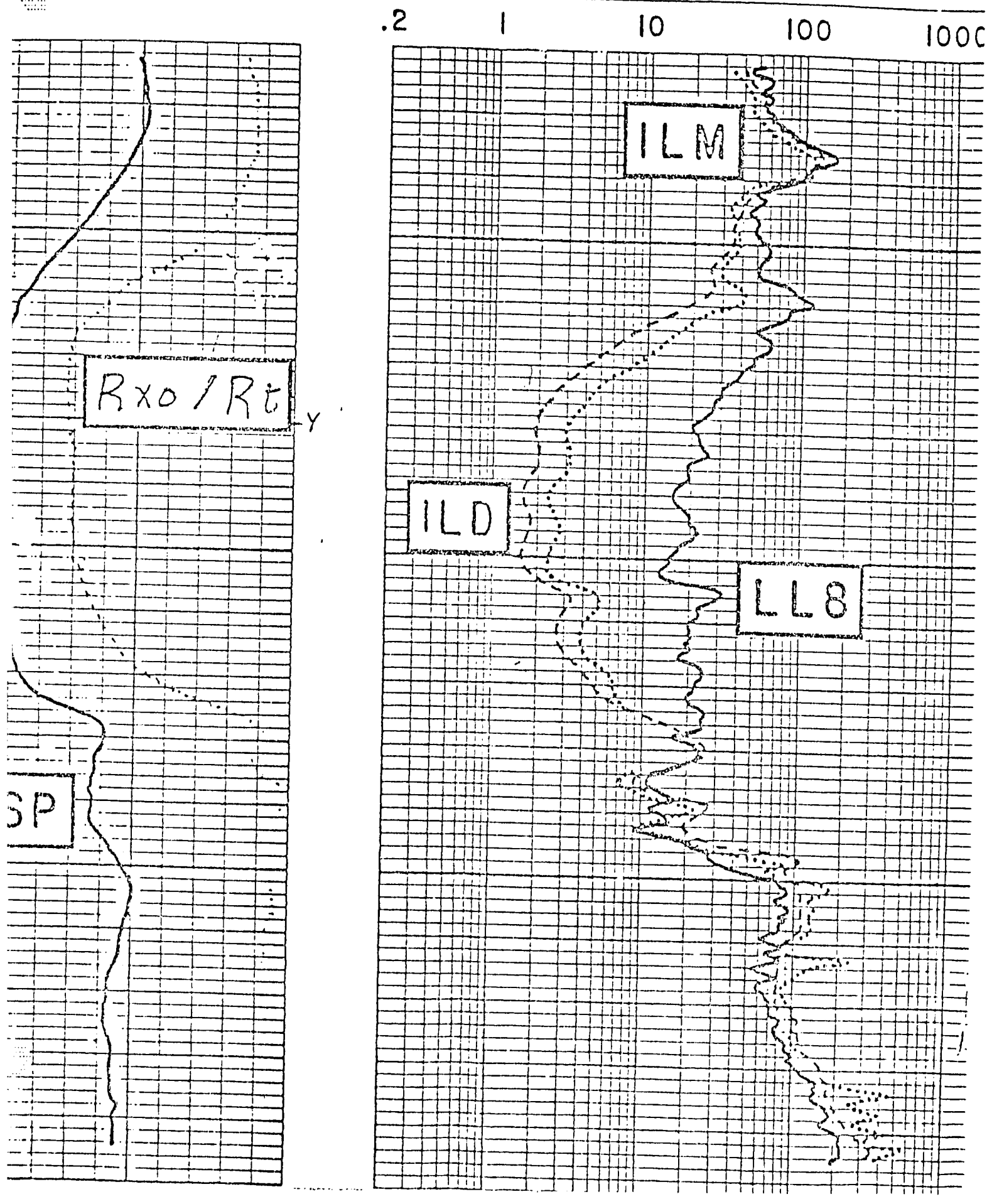
$$E_{SP} \approx -K \text{ LOG } \frac{R_{XO}}{R_T}$$

THUS THE COMPUTED SP CURVE FOLLOWS THE MEASURED SP CURVE WHEN $S_W = 100\%$ AND DEVIATES FROM IT WHEN $S_W \neq 100\%$

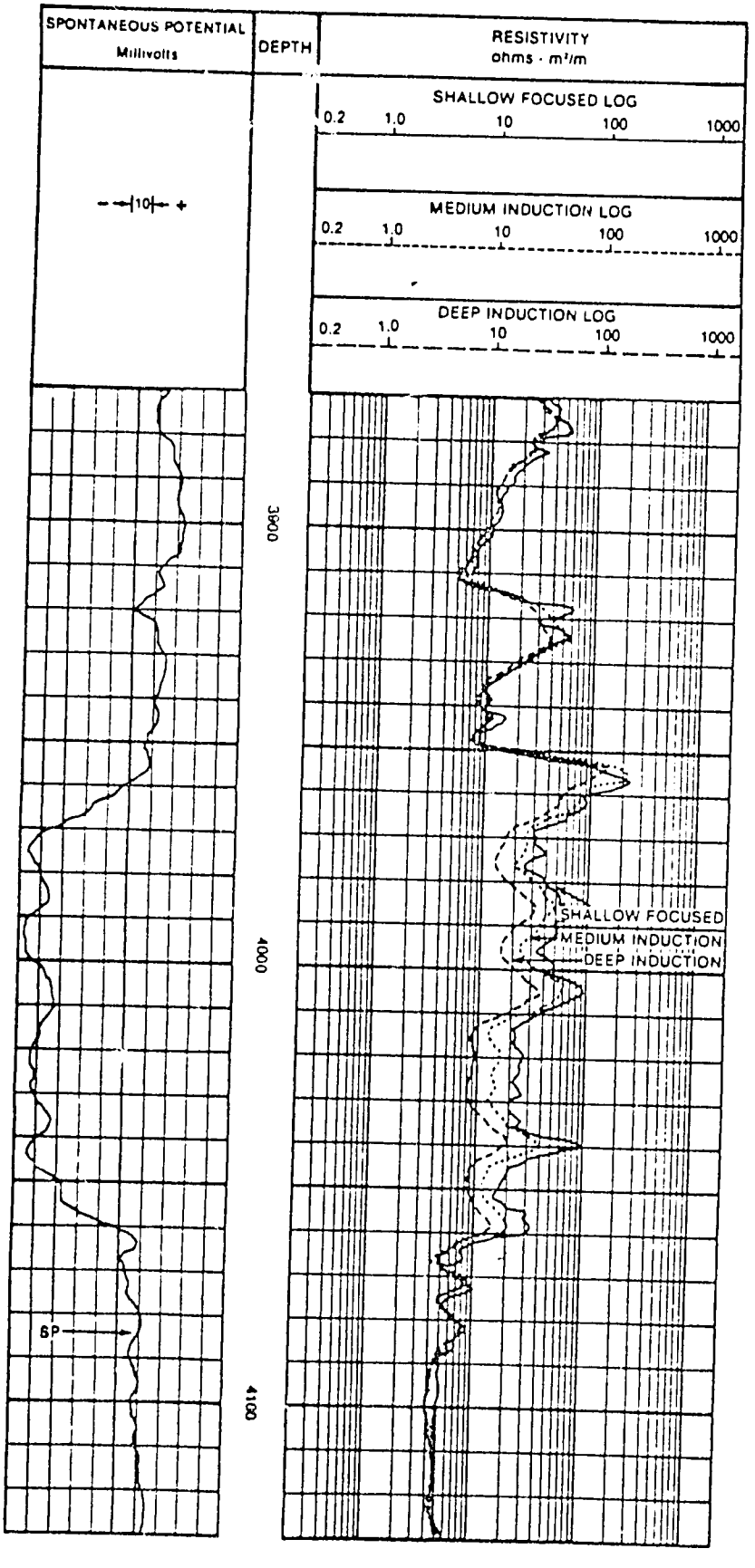
INDUCTION LOG PROBLEM

Log I (a) Determine ϕ, assuming R_{mf} = 0.5 and SP = SSP FT = 200°F R_m=0.7

(b) Compute SP @ point y.



DUAL INDUCTION - FOCUSED LOG



From Dresser Atlas "Well Logging & Interpretation Techniques" 1982

INDUCTION LOGS (CONT'D)

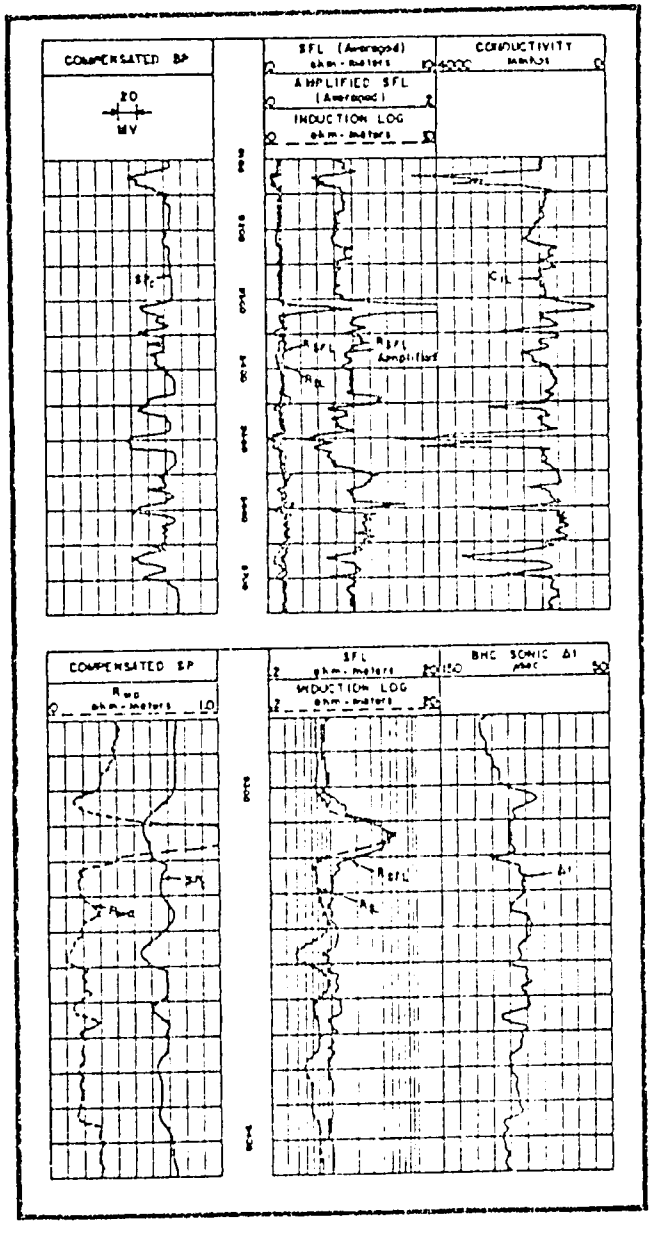
- R_{WA} QUICK-LOOK METHOD FOR FINDING HYDROCARBONS

$$F = \frac{R_O}{R_W} \qquad S_W = \left(\frac{FR_W}{R_T}\right)^{1/2}$$

$$R_W = \frac{R_O}{F} \qquad S_W = \left(\frac{R_W}{R_{WA}}\right)^{1/2}$$

$$R_{WA} = \frac{R_T}{F}$$

THUS $R_{WA} = R_W$ IF $S_W = 100\%$ -- OTHERWISE $R_{WA} \gg R_W$-- HYDROCARBONS



From Schlumberger's 1972 Log Interpretation Principles

- SKIN EFFECT
  - IN VERY CONDUCTIVE FORMATIONS THE INDUCED SECONDARY CURRENTS ARE LARGE
  - THE SECONDARY MAGNETIC FIELDS ARE STRONG AND INDUCE ADDITIONAL EMF'S IN OTHER GROUND LOOPS
  - INTERACTION BETWEEN THE LOOPS CAUSES A REDUCTION OF THE CONDUCTIVITY SIGNAL RECORDED--REFERRED TO AS "SKIN EFFECT"
  - INDUCTION LOGS ARE AUTOMATICALLY CORRECTED FOR "SKIN EFFECT"
  - WHEN MEDIA SURROUNDING SONDE ARE NOT OF UNIFORM CONDUCTIVITY A SECONDARY "SKIN EFFECT" MAY BE REQUIRED -- IS INCORPORATED IN INTERPRETATION CHARTS

INDUCTION LOGS (CONT'D)

. GEOMETRICAL FACTORS

- FRACTION OF THE TOTAL SIGNAL THAT ORIGINATES IN A VOLUME HAVING A SPECIFIC ORIENTATION WITH THE SONDE IN AN INFINITE HOMOGENEOUS MEDIUM
  - .. INTENSITY OF THE CURRENT IN ANY ONE OF THE LOOPS DEPENDS ON ITS LOCATION WITH RESPECT TO THE TRANSMITTING COIL AND ON THE CONDUCTIVITY OF THE FORMATION
  - .. CONTRIBUTION OF A LOOP TO THE RECORDED SIGNAL DEPENDS ALSO ON ITS LOCATION, RELATIVE TO THE RECEIVING COIL
- RESISTIVITY INDICATED BY INDUCTION LOG DEPENDS ON RESISTIVITY OF VARIOUS SECTIONS OF FORMATION & ON THEIR GEOMETRIC FACTORS
  - .. BECAUSE VARIOUS REGIONS ARE AXIALLY SYMMETRICAL, CURRENT INDUCED FLOWS ONLY IN ZONE IN WHICH IT ORIGINATES
  - .. CURRENT WILL NOT ORDINARILY CROSS FROM INVADED TO UNINVADED ZONE, OR FROM ADJACENT BED TO THE OBJECT BED--PROVIDED SONDE IS CENTERED.

INDUCTION LOGS (CONT'D)

- GEOMETRICAL FACTORS
  - THE APPARENT RESISTIVITY IS GIVEN BY

$$\frac{1}{R_A} = \frac{G_M}{R_M} + \frac{G_I}{R_I} + \frac{G_T}{R_T} + \frac{G_S}{R_S}$$

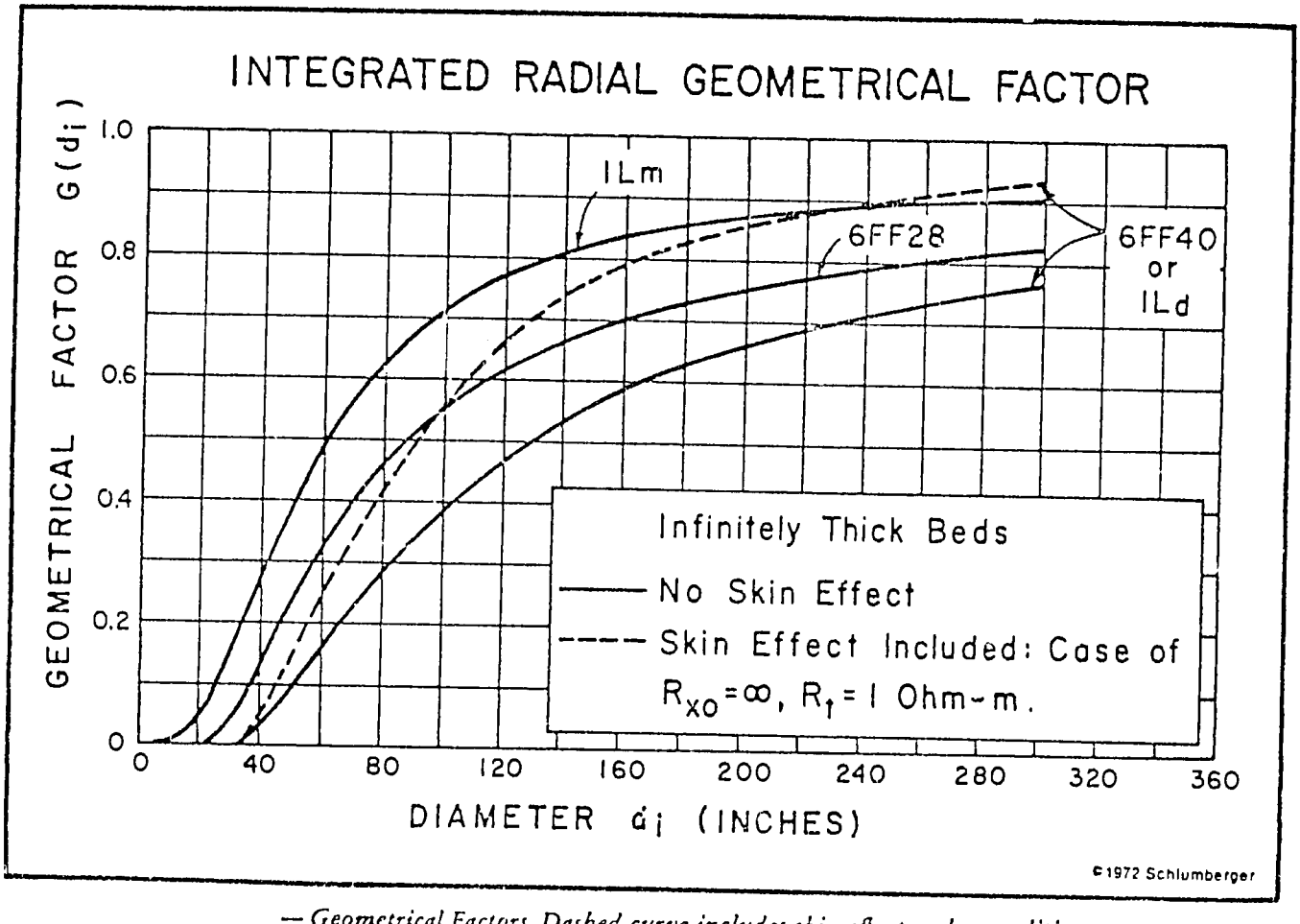
WHERE G'S ARE INTEGRATED GEOMETRIC FACTORS

  - FOR $R_A \approx R_T$ IT IS NECESSARY TO MINIMIZE CONTRIBUTIONS OF MUD COLUMN, INVADED ZONE AND ADJACENT BEDS
  - USE OF A HIGH RESISTIVITY MUD REDUCES

$$\frac{G_M}{R_M} + \frac{G_I}{R_I}$$

$\frac{G_M}{R_M} + \frac{G_I}{R_I} + \frac{G_S}{R_S}$ CAN BE REDUCED BY USING FOCUSING COILS WHICH PROVIDE CANCELING SIGNAL RATHER THAN CONTROL CURRENT DISTRIBUTION AS IN THE LATEROLOGS.

  - SIGNIFICANCE
    - PERMIT CONSTRUCTION OF MATHEMATICALLY SOUND CORRECTION CHARTS TO ACCOUNT FOR EFFECTS OF BOREHOLE, INVADED ZONE, AND ADJACENT BEDS ON R_T

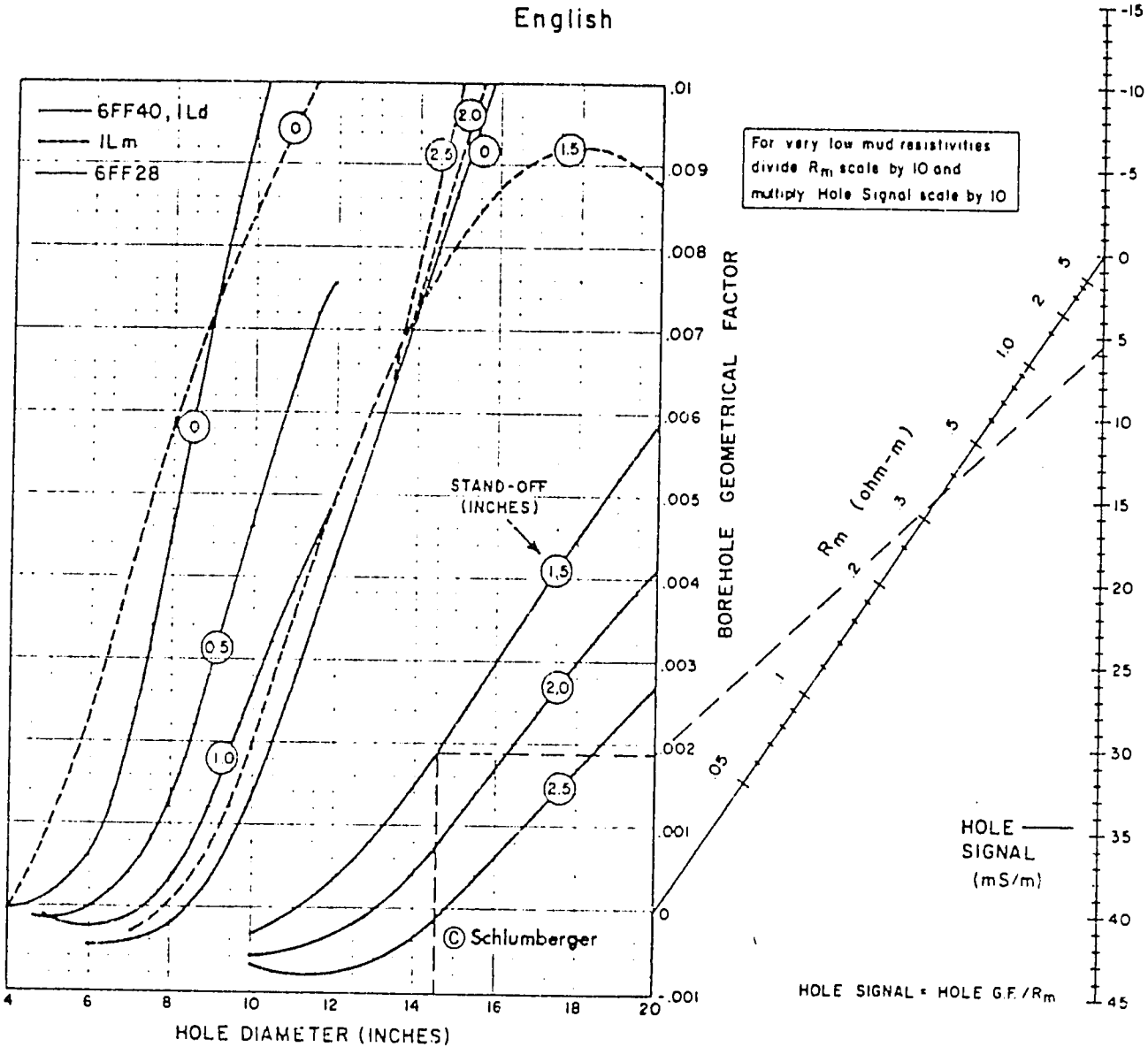


— *Geometrical Factors. Dashed curve includes skin effect under conditions shown, for the 6FF40 or the ILd devices.*

- FACTORS AFFECTING TOOL RESPONSE
  - BOREHOLE CONDITIONS
    - .. BOREHOLE CONDITIONS WHICH AFFECT LOG RESPONSE ARE R_M, R_{MC}, D_H, STAND-OFF
    - .. TOOLS ARE DESIGNED TO REDUCE BOREHOLE SIGNAL TO A MINIMUM
    - .. BOREHOLE CONDUCTIVITY SIGNAL IS SUBTRACTED BEFORE OTHER CORRECTIONS ARE MADE
    - .. BOREHOLE SIGNAL IS REDUCED BY CENTRALIZING THE SONDE
  - ADJACENT BEDS & BED THICKNESS
    - .. ADJACENT BED EFFECTS ARE DIRECTLY RELATED TO BED THICKNESS AND R_S

INDUCTION LOG BOREHOLE CORRECTION

English



The hole-conductivity signal is to be subtracted, where necessary, from the Induction-Log conductivity reading before other corrections are made.* This correction applies to all zones (including shoulder beds) having the same hole size and mud resistivity.

Rcor-4 gives corrections for 6FF40 or ILd, ILm, and 6FF28 for various wall stand-offs. Dashed working lines illustrate use of the chart for the case of a 6FF40 sonde with a 1.5-inch standoff in a 14.6-inch borehole, and $R_m = 0.35\ \Omega\cdot m$. The hole signal is found to be 5.5 mS/m. If the log reads $R_{IL} = 20\ \Omega\cdot m$, C_{IL} (Conductivity) = 50 mS/m. The corrected C_{IL} is then (50 − 5.5) = 44.5 mS/m. $R_{IL} = 1000/44.5 = 22.4\ \Omega\cdot m$.

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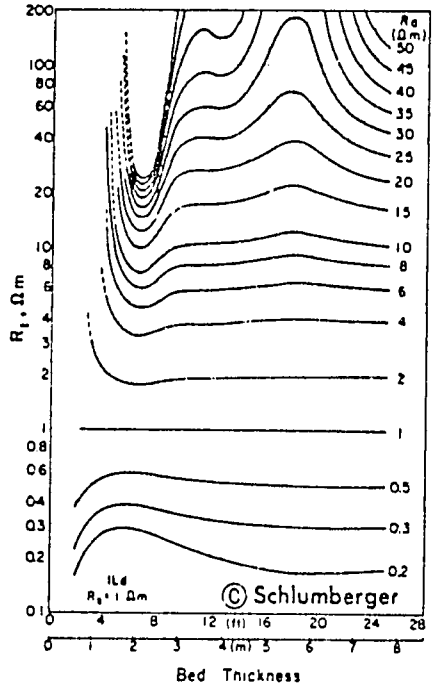
* CAUTION: Some Induction Logs, especially in salty muds, are adjusted so that the hole signal for the nominal hole size is already subtracted out of the recorded curve. Refer to log heading.

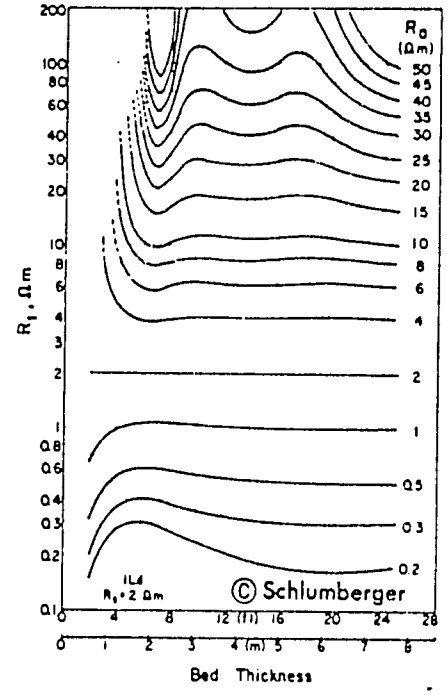
INDUCTION LOG BED THICKNESS CORRECTION

6FF40 or ILd and 6FF28

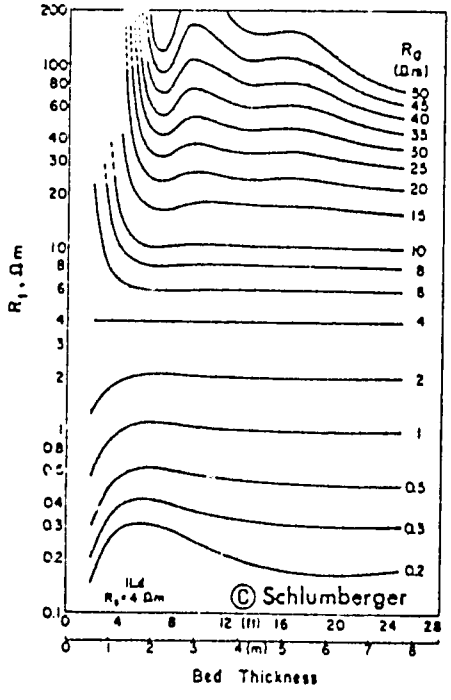
These charts give bed thickness corrections for the 6FF40, ILd, and 6FF28 in beds thicker than 4 feet (1.2 m). A skin-effect* correction is included in these charts. Select appropriate chart for value of adjacent-bed resistivity (R_s). Enter the bed thickness and proceed upward to the proper R_{IL} curve. Read ordinate values of $(R_{IL})_{cor}$.

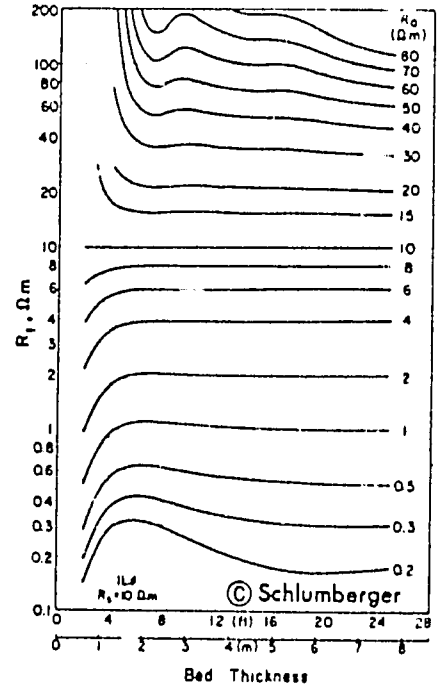
To use these curves for the small-diameter 6FF28, simply multiply the bed thickness by the ratio of the spacings. For a 6FF28 tool reading in a 7-ft bed, the bed thickness used to enter the chart is 40/28 × 7 = 10 ft.





NOTE: These corrections are computed for a shoulder-bed resistivity (SBR) setting of 1Ω·m. Refer to log heading.



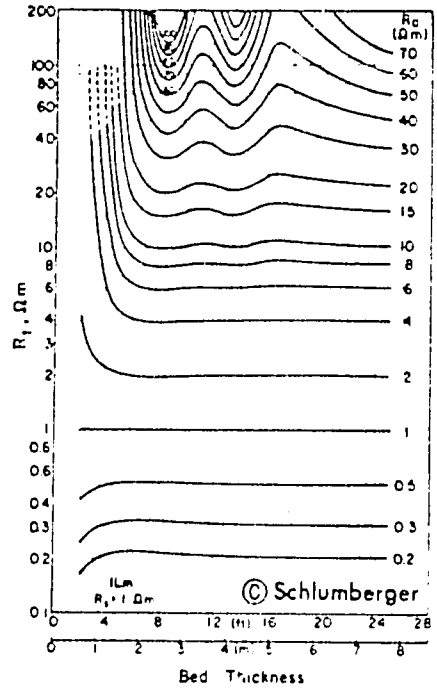


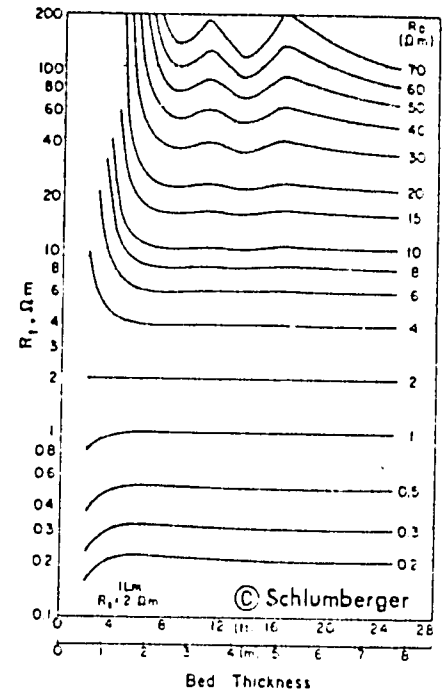
* Skin effect corrections are made automatically by Schlumberger Induction tools. However, these internal corrections are necessarily based on the total conductivity signal measured by the tool, and are therefore correct only in homogeneous, anisotropic beds of considerable extent. In thin beds, adjustments are needed to the corrections made by the tool, and are included in these charts.

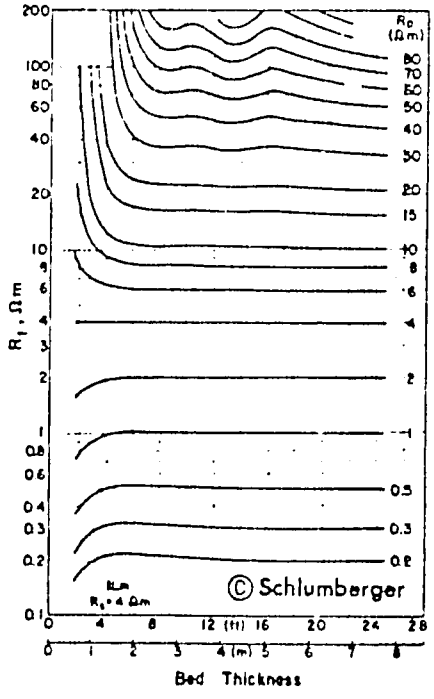
INDUCTION LOG BED THICKNESS CORRECTION

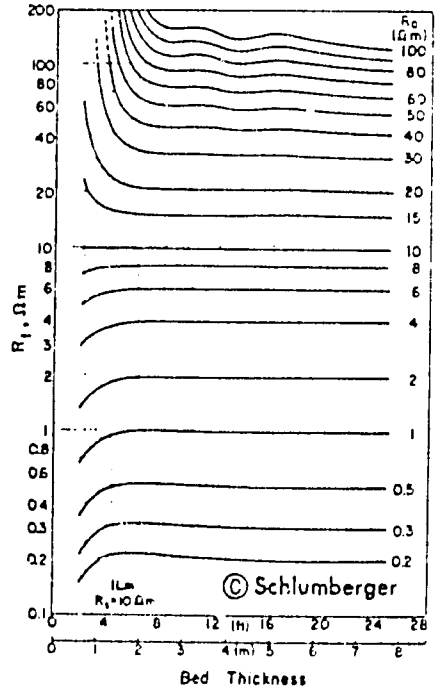
ILm

These charts are for the ILm in beds thicker than 4 feet (1.2 m). A skin-effect* correction is included in these charts. Select appropriate chart for value of adjacent-bed resistivity (R_s). Enter the bed thickness and proceed upward to the proper R_{IL} curve. Read ordinate values of $(R_{IL})_{cor}$.









* Skin effect corrections are made automatically by Schlumberger Induction tools. However, these internal corrections are necessarily based on the total conductivity signal measured by the tool, and are therefore correct only in homogeneous, anisotropic beds of considerable extent. In thin beds, adjustments are needed to the corrections made by the tool, and are included in these charts.

DUAL INDUCTION LOG[9] and LATEROLOG* 8 or SPHERICALLY FOCUSED LOG

The ILd (Deep Induction Log), ILm (Medium Induction Log) and the LL8 (Laterolog 8) or SFL* Spherically Focused Log) are recorded with the Dual Induction equipment. The improved charts on the following pages are used to determine values of R_t, R_{xo}/R_t, and d_i (assuming a step-contact profile of invasion). Skin-effect corrections have been included in the construction of these new charts**.

The Induction Logs are corrected, where necessary, for hole effect and bed thickness using Charts Rcor-4 through Rcor-7. Correct the Laterolog 8 or SFL for hole effect using Rcor-1.

EXAMPLE OF USE:

GIVEN: $R_{LL8} = 25$, $R_{IM} = 5.9$, $R_{ID} = 4.8$, all values previously corrected as noted above:

Entering the $R_{xo}/R_m \approx 100$ chart (Rint-2a) with:	R_{LL8}/R_{ID}	$= 25/4.8 = 5.2$
	R_{IM}/R_{ID}	$= 5.9/4.8 = 1.23$
Read from the solid black curves	R_{xo}/R_t	$= 8$
Read from the dashed curves	d_i	$= 39''$ (1m)
Read from the red curves	R_t/R_{ID}	$= 0.98$

$$R_t = R_{ID} \times (R_t/R_{ID}) = 4.8 \times 0.98 = 4.7$$

SATURATION DETERMINATION (CLEAN FORMATIONS):

The chart-derived values of R_t and R_{xo}/R_t each can be used to find values for S_w. One value, which is designated as S_{wA} (S_w-Archie), is found using the Archie saturation formula (or Chart Sw-1) with the R_t value and known values of F_R and R_w. An alternate S_w value, designated as S_{wR} (S_w-Ratio), is found using R_{xo}/R_t with R_{mf}/R_w as in Chart Sw-2.

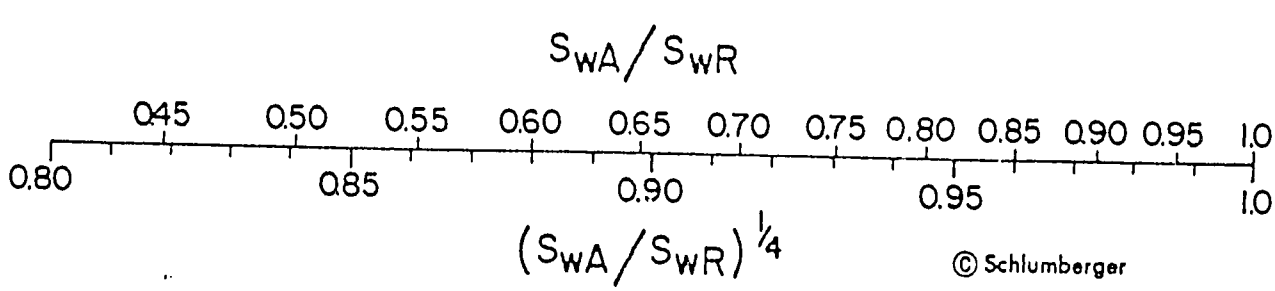
If S_{wA} and S_{wR} are equal, the assumption of a step-contact invasion profile is indicated to be correct, and all values found (S_w, R_t, R_{xo}, d_i) are considered good.

If $S_{wA} > S_{wR}$, either invasion is very shallow or a transition type of invasion profile is indicated; and S_{wA} is considered a good value for S_w.

If $S_{wA} < S_{wR}$, an annulus type of invasion profile may be indicated. In this case a more accurate value of water saturation may be estimated using the relation:

$$(S_w)_{cor} = S_{wA}\left(\frac{S_{wA}}{S_{wR}}\right)^{1/4}$$

The correction factor $(S_{wA}/S_{wR})^{1/4}$ can be found from the scale shown below:



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* Mark of Schlumberger

** Skin effect corrections are made automatically by Schlumberger Induction tools. However, these internal corrections are necessarily based on the total conductivity signal measured by the tool, and are therefore correct only in homogeneous, anisotropic beds of considerable extent. In invaded beds, adjustments a nended to the corrections made by the tool, and are included in these charts.

. CALIBRATION

- THERE IS AN UNCERTAINTY OF ABOUT ± 2 MMHO/M ON THE ZERO OF THE PRESENT SONDES
- RESISTIVITY ERROR MAY BE GREAT AS CONDUCTIVITY APPROACHES ZERO
- TO PRECLUDE AN ERROR OF MORE THAN 20%, THE FORMATION CONDUCTIVITY SHOULD BE GREATER THAN 10 MMHO/M
- PRIMARY CALIBRATION IS PERFORMED BY PLACING A TEST LOOP AROUND THE SONDE--PRODUCES A CERTAIN CONDUCTIVITY SIGNAL

NDUCTION LOGS (CON'T)

INVASION EFFECTS

- INVADED ZONE INCLUDES VOLUMES HAVING SEVERAL CONDUCTIVITIES--
  C_M, C_{XO}, C_I & C_T

  $\therefore C_{LOG} = C_M G_M + C_{XO} G_{XO} + C_I G_I + C_T G_T$ (THICK BED)

- FOR A 6FF40 TOOL, MODERATE HOLE SIZE, A RELATIVELY, FRESH MUD, THE BOREHOLE SIGNAL IS NEGLIGIBLE AND THE C_{XO} & C_I ZONES CAN BE MERGED INTO ONE

  $\therefore C_{LOG} = C_{XO} G_{XO} + C_T G_T$

  FOR $D_I = 65''$ $G_{XO} = .2$ $G_T = .8$

  IF $R_{XO} = 4 R_T$ THEN $C_{XO} = \frac{C_I}{4}$

  THUS $C_{LOG} = \frac{C_I}{4} (.2) + .8C_T = 0.85 C_T$

- FOR THE SAME CONDITIONS BUT USING SALTY MUD SO THAT $R_{XO} = R_T/4$

  $$C_{LOG} = 4 C_T(.2) + .8C_T = 1.6 C_T$$

- THESE EXAMPLES ILLUSTRATE THE "CONDUCTIVITY-SEEKING CHARACTERISTICS OF THE INDUCTION DEVICES--DISCRETION IS REQUIRED FOR THEIR USE IN SALT-MUD ENVIRONMENTS

  RULE-OF-THUMB--$R_T < 2.5 R_{XO}$ & $D_I \leq 100''$ FOR SATISFACTORY R_T DETERMINATION

INDUCTION LOGS (CONT'D)

. THE ANNULUS PROBLEM

- WHEN A FORMATION CONTAINS HYDROCARBONS, THE PROCESS OF INVASION BECOMES COMPLEX
  - .. R_{XO} ZONE IS NOT COMPLETELY FLUSHED
  - .. RESIDUAL HYDROCARBONS AND EVEN SOME CONNATE WATER WILL REMAIN IN R_{XO} ZONE
  - .. R_I ZONE WILL CONTAIN HYDROCARBONS, CONNATE WATER AND MUD FILTRATE
  - .. INVASION WILL BE DEEPER BECAUSE OF S_{OR} IN R_{XO} ZONE
- UNDER CERTAIN CONDITIONS, MUD FILTRATE INVASION OF A HYDROCARBON BEARING FORMATION CREATES A ZONE OF FORMATION WATER--LOW RESISTIVITY ZONE OR ANNULUS
  - .. INDICATIVE OF MOVABLE HYDROCARBONS
  - .. NOT NECESSARILY A CRITERION OF A PRODUCTIVE FORMATION
  - .. ANNULUS IS MORE PRONOUNCED WHEN S_W IS LOW
  - .. ANNULUS THICKNESS INCREASES AS INVASION INCREASES

INDUCTION LOGS - (CONT'D)

. ANNULUS CON'T.

- ANNULUS REPRESENTS AN IDEAL CYLINDER WITHIN WHICH CURRENT CAN FLOW
  - .. ITS EFFECT ON A DEVICE IS DEPENDENT UPON D_I, R_{MF}/R_W, AND HYDROCARBON MOBILITY
  - .. IT DECREASES THE RECORDED RESISTIVITY, R_A AND CAN CAUSE IT TO BE LESS THAN R_{XO} AND R_T
  - .. ITS EFFECT IS MORE MARKED IF THE ANNULUS IS CLOSE TO WELLBORE
  - .. IT DIFFUSES AND DISSIPATES WITH TIME
  - .. IT CAN CAUSE THE INDUCTION LOG TO READ CONSIDERABLY LOWER THAN R_T
- WHEN $R_{XO} > R_T$ $R_A < R_T$ AND THE EFFECTS OF THE TWO TEND TO CANCEL
- ANNULUS HAS MORE EFFECT ON MEDIUM DEVICE, $1L_M$, WHERE $D_I < 5\ D_H$
- ANNULUS IS SEEN WHEN $R_{1L_M} < R_{IL_D}$ & R_{LL_8}

. DIL (LL_8, IL_M, IL_D, GR) IN SALT MUD

- CAN GIVE GOOD RESULTS WITH CERTAIN PROVISIONS
  - .. $\phi \geqslant$ 12 TO 15%
  - .. $D_H \leqslant$ 8" FOR MINIMUM BOREHOLE EFFECT
  - .. $R_{MF} \approx R_W$
  - .. MEDIUM TO SHALLOW INVASION WHEN $R_{XO} < R_T$--FOR DEEP INVASION THE LOW RESISTIVITY R_{XO} ZONE WOULD HAVE A DETRIMENTAL EFFECT ON IL_M & IL_D
  - .. $R_T \leqslant 50$

DUAL INDUCTION LOG*
and
LATEROLOG* 8 or SPHERICALLY FOCUSED LOG

The ILd (Deep Induction Log), ILm (Medium Induction Log) and the LL8 (Laterolog 8) or SFL* Spherically Focused Log) are recorded with the Dual Induction equipment. The improved charts on the following pages are used to determine values of R_t, R_{xo}/R_t, and d_i (assuming a step-contact profile of invasion). Skin-effect corrections have been included in the construction of these new charts**.

The Induction Logs are corrected, where necessary, for hole effect and bed thickness using Charts Rcor-4 through Rcor-7. Correct the Laterolog 8 or SFL for hole effect using Rcor-1.

EXAMPLE OF USE:

GIVEN: $R_{LL8} = 25$, $R_{IM} = 5.9$, $R_{ID} = 4.8$, all values previously corrected as noted above:

Entering the $R_{xo}/R_m \approx 100$ chart (Rint-2a) with: $R_{LL8}/R_{ID} = 25/4.8 = 5.2$

$R_{IM}/R_{ID} = 5.9/4.8 = 1.23$

Read from the solid black curves $R_{xo}/R_t = 8$

Read from the dashed curves $d_i = 39''$ (1m)

Read from the red curves $R_t/R_{ID} = 0.98$

$$R_t = R_{ID} \times (R_t/R_{ID}) = 4.8 \times 0.98 = 4.7$$

SATURATION DETERMINATION (CLEAN FORMATIONS):

The chart-derived values of R_t and R_{xo}/R_t each can be used to find values for S_w. One value, which is designated as S_{wA} (S_w-Archie), is found using the Archie saturation formula (or Chart Sw-1) with the R_t value and known values of F_R and R_w. An alternate S_w value, designated as S_{wR} (S_w-Ratio), is found using R_{xo}/R_t with R_{mf}/R_w as in Chart Sw-2.

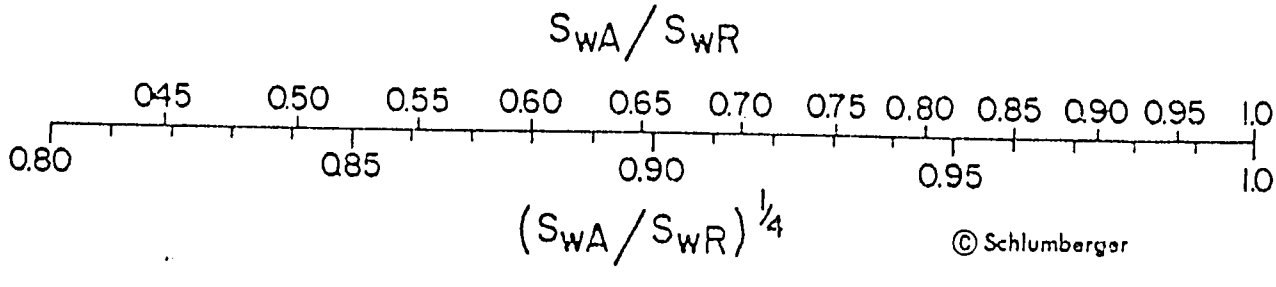
If S_{wA} and S_{wR} are equal, the assumption of a step-contact invasion profile is indicated to be correct, and all values found (S_w, R_t, R_{xo}, d_i) are considered good.

If $S_{wA} > S_{wR}$, either invasion is very shallow or a transition type of invasion profile is indicated; and S_{wA} is considered a good value for S_w.

If $S_{wA} < S_{wR}$, an annulus type of invasion profile may be indicated. In this case a more accurate value of water saturation may be estimated using the relation:

$$(S_w)_{cor} = S_{wA}\left(\frac{S_{wA}}{S_{wR}}\right)^{1/4}$$

The correction factor $(S_{wA}/S_{wR})^{1/4}$ can be found from the scale shown below:

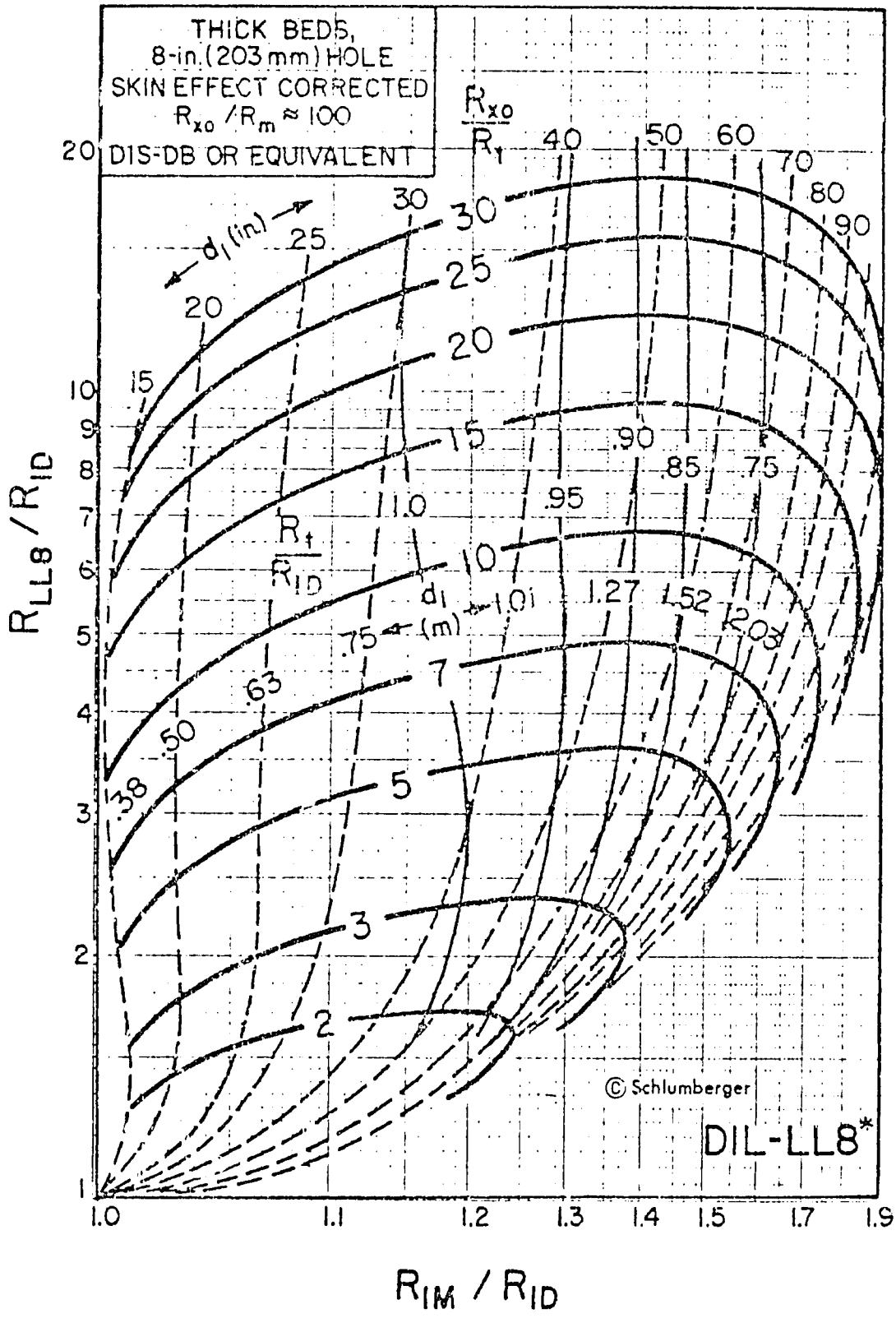


* Mark of Schlumberger

** Skin effect corrections are made automatically by Schlumberger Induction tools. However, these internal corrections are necessarily based on the total conductivity signal measured by the tool, and are therefore correct only in homogeneous, anisotropic beds of considerable extent. In invaded beds, adjustments are needed to the corrections made by the tool, and are included in these charts.

DUAL INDUCTION – LATEROLOG*

ILd — ILm — LL8

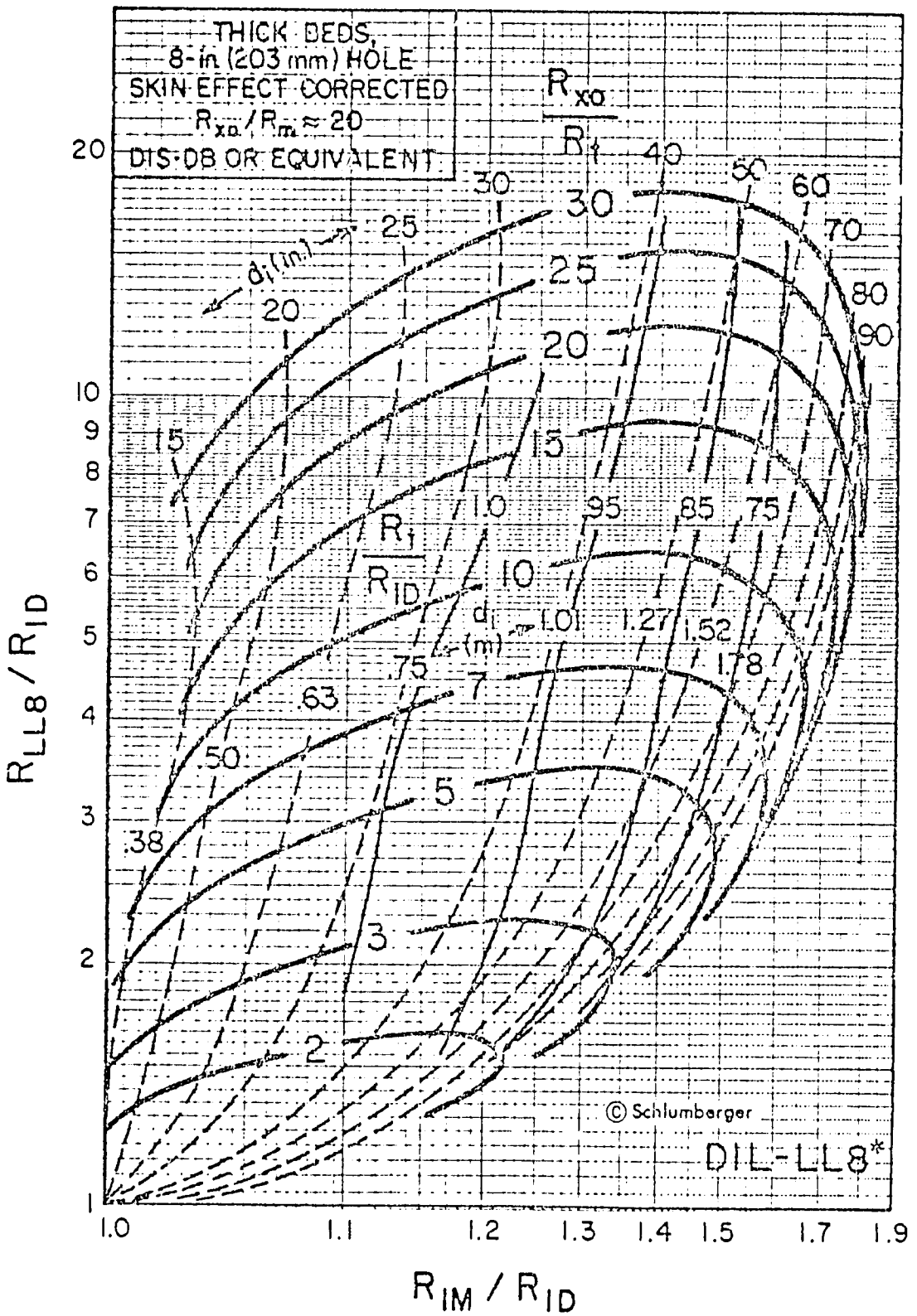


*Mark of Schlumberger

Schlumberger

DUAL INDUCTION – LATEROLOG*

ILd — ILm — LL8

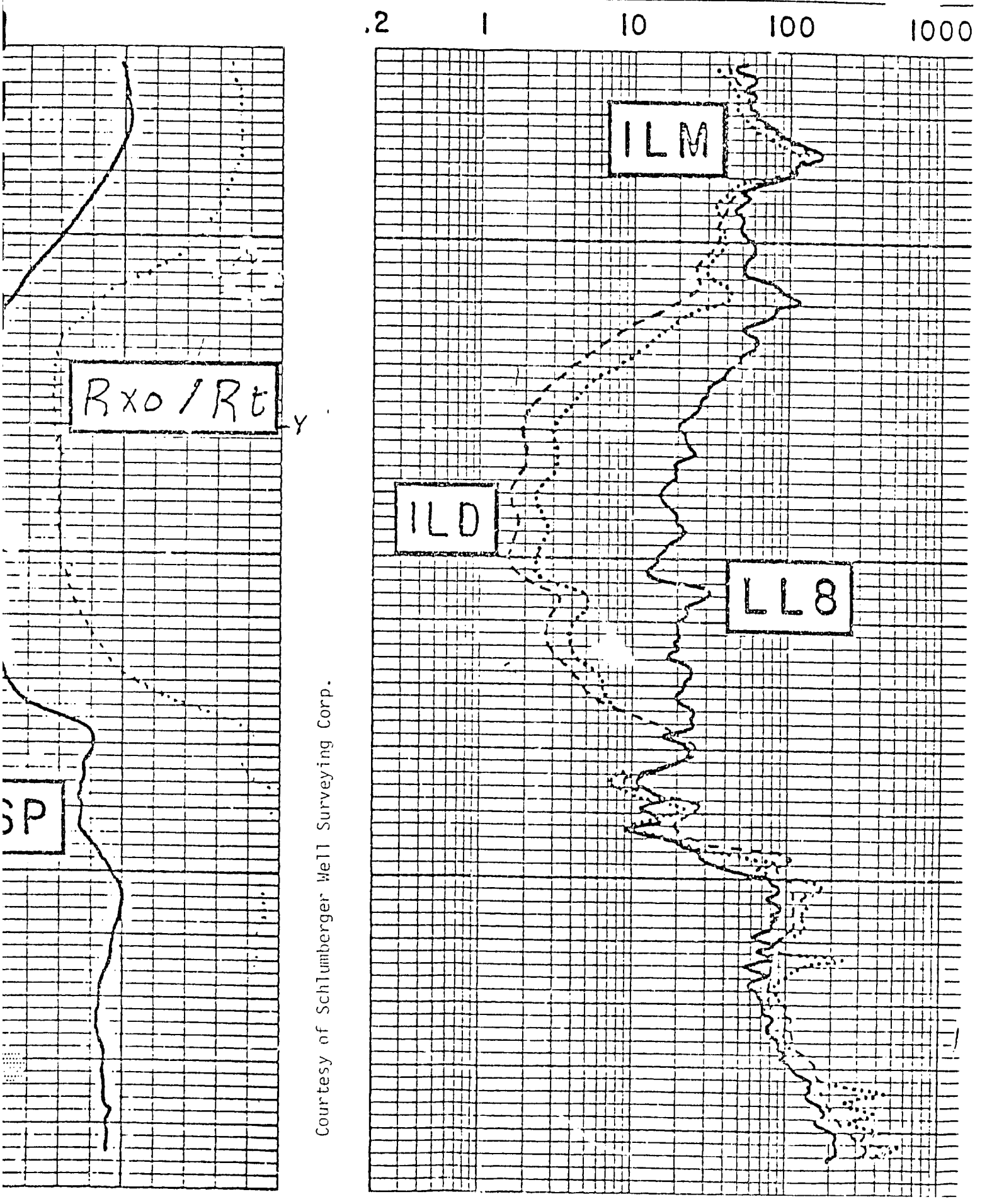


*Mark of Schlumberger

INDUCTION LOG PROBLEM

Log I (a) Determine ϕ, assuming R_{mf} = 0.5 and SP = SSP FT = 200°F R_m=0.7

(b) Compute SP @ point y.

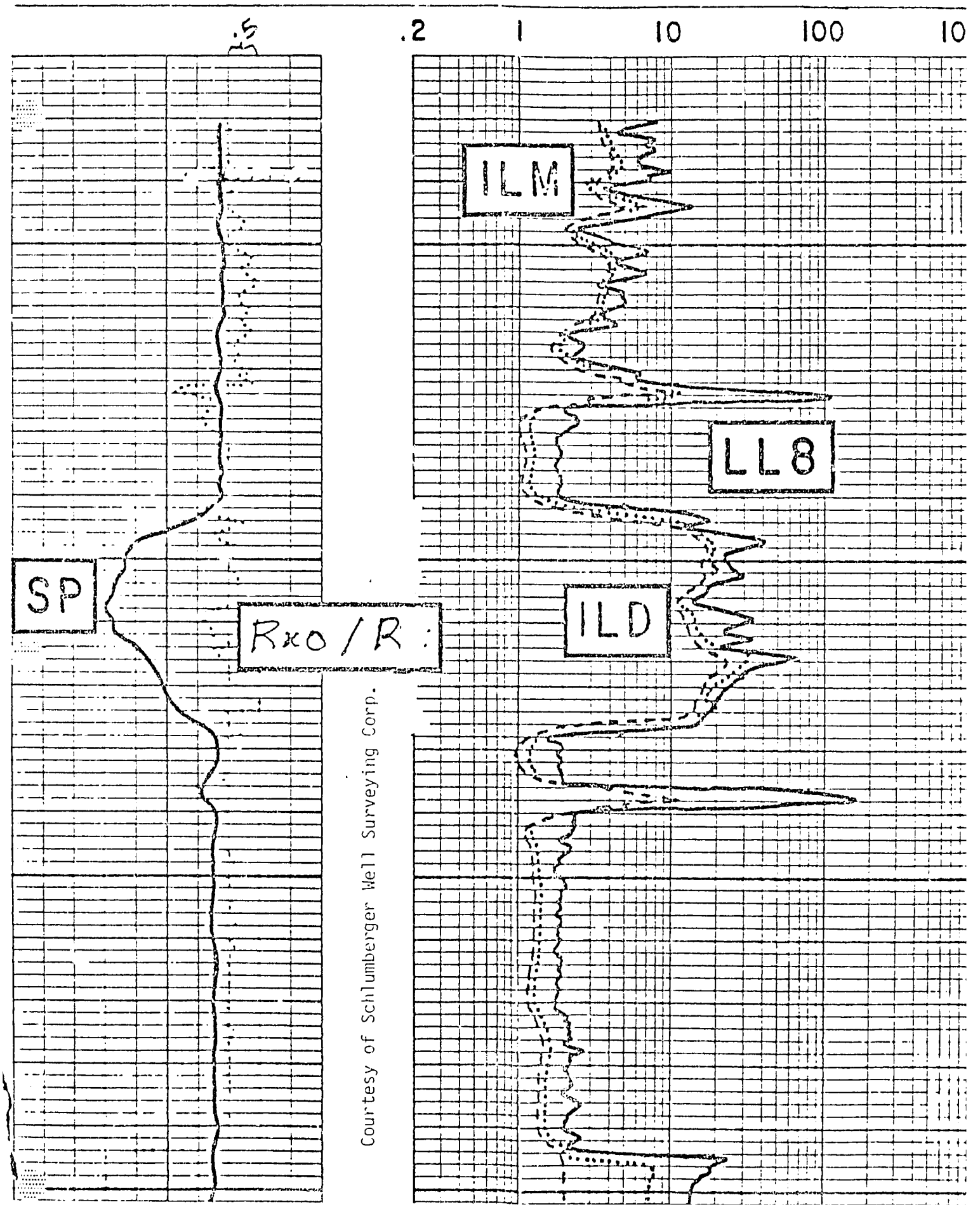


Courtesy of Schlumberger Well Surveying Corp.

INDUCTION LOG PROBLEM

Log II Determine S_w assuming waters in both logs are similar.

d_h = 9" R_{mf} = 0.5 h = 34' R_m = 0.7 @ FT standoff = 1½"



Courtesy of Schlumberger Well Surveying Corp.

- TOOLS
  - MICROLOG
  - MICROLATEROLOG
  - PROXIMITY LOG
  - MICROSPHERICALLY FOCUSED LOG

- CHARACTERISTICS OF TOOLS
  - PRESENT EQUIPMENT INCLUDES A COMBINATION TOOL WITH TWO PADS MOUNTED ON OPPOSITE SIDES
  - ONE IS THE MICROLOG PAD AND THE OTHER MAY BE EITHER THE MICROLATEROLOG OR THE PROXIMITY LOG, AS REQUIRED BY MUD CAKE THICKNESS
  - MICROSFL IS A COMBINATION TOOL THAT CAN BE RUN WITH EITHER F D C OR D L L
  - SONDES NORMALLY INCLUDE THE CALIPER LOG
  - PAD, CARRYING SHORT-SPACING ELECTRODES IS PRESSED AGAINST MUD CAKE, THUS REDUCING THE SHORT CIRCUITING EFFECT OF MUD
  - CURRENTS MUST PASS THROUGH THE MUD CAKE TO REACH THE R_{xo} ZONE
  - SHALLOW INVESTIGATION RESISTIVITY TOOLS

MICRORESISTIVITY DEVICES - THE RESISTIVITY POROSITY LOGS

- USES
  - MEASURE R_{XO}
  - MICROLOG DELINEATES PERMEABLE BEDS BY DETECTING PRESENCE OF MUD CAKE
  - DELINEATE BED BOUNDARIES
  - USEFUL IN NET THICKNESS DETERMINATION
  - HELPFUL TO DETERMINE R_T IN MODERATE TO DEEP INVASION
  - PROVIDES R_{XO}/R_T RATIO IN S_W DETERMINATION
  - PROVIDE ϕ IN CLEAN BEDS WHEN S_{OR} IS KNOWN
  - HELP TO DETERMINE MOVABLE OIL

MICRORESTIVITY LOGS (CONT'D)

. AFFECTED BY
  - MUD CAKE RESISTIVITY, R_{MC}
  - MUD CAKE ANISOTROPY
    .. R_{MC} PARALLEL TO BOREHOLE IS LESS THAN THAT ACROSS THE MUD CAKE
    .. RESULT IS TO MAKE EFFECTIVE OR ELECTRICAL H_{MC} GREATER THAN THAT INDICATED BY A CALIPER
    .. HOLE CAVING OR ROUGHNESS--POUR PAD CONTACT CAN RESULT IN CURREN LEAKAGE--TOOLS INCLUDE TWO-ARM CALIPERS WHICH SHOW THE SIZE AND CONDITION OF BOREHOLE
  - MUD CAKE THICKNESS, H_{MC}

. LOG PRESENTATION
  - MICROLOG--TRACKS 2 & 3 ON LINEAR SCALE WITH CALIPER IN TRACK 1
  - MICROLATEROLOG
    .. LINEAR SCALE EQUAL TO LL SCALE IN TRACK 2 & AN EXPANDED SCALE IN TRACK 3
    .. SPLIT 4-CYCLE LOGARATHMIC SCALE COVERING TRACKS 2 & 3
    .. HYBRID SCALES IN TRACK 2 AND AN EXPANDED LINEAR SCALE ON TRACK 3
  - PROXIMITY LOG--SPLIT 4-CYCLE LOGARITHMIC SCALE IN TRACKS 2 & 3 WITH THE CALIPER IN TRACK 1
  - MICRO SFL -- RECORDED ON SPLIT 4-CYCLE LOGARITHMIC SCALE WITH DUAL LATEROLOG

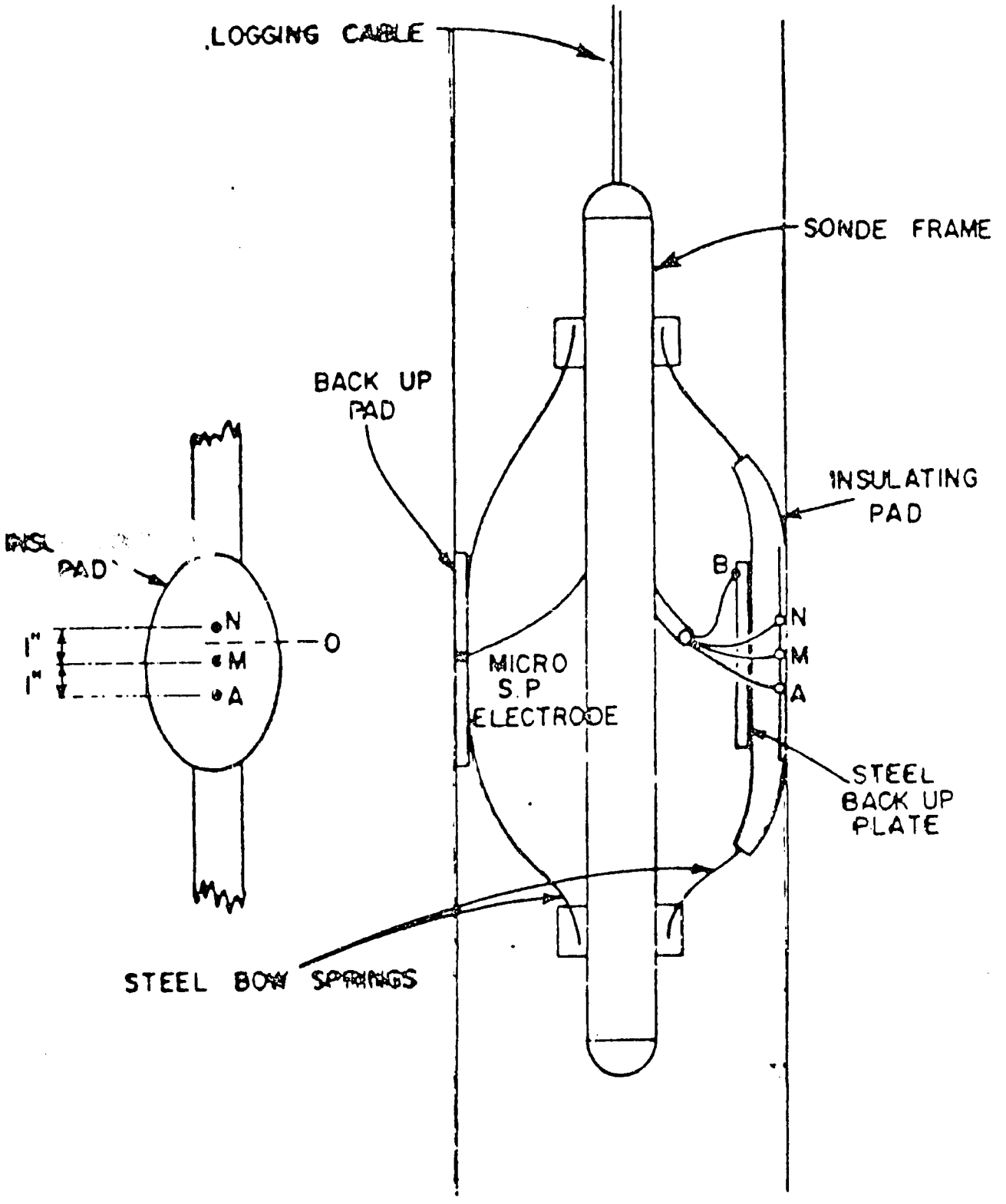
MICRORESISTIVITY LOGS (CONT'D)

- THE MICROLOG (MINILOG, CONTACT LOG)
  - DESIGNED FOR VERY SHORT RANGE OF INVESTIGATION WITHOUT BEING AFFECTED BY MUD
  - WITH ARMS & SPRINGS A RUBBER PAD IS PRESSED AGAINST BOREHOLE WALL
  - PAD CONTAINS THREE SMALL ELECTRODES IN LINE SPACED 1" APART
  - TOOL RECORDS A 2" MICRO NORMAL RESISTIVITY CURVE AND A 1.5" MICRO LATERAL RESISTIVITY CURVE
  - THE MICROLATERAL CURVE PENETRATES 1.5" WHILE THE MICRONORMAL CURVE PENETRATES 4"
  - WHEN $R_{MC} < R_{xo}$ $R_{1.5''} < R_{2''}$
  - PRESENCE OF MUD CAKE CAN BE DETECTED AND THIS, IN TURN, INDICATES PERMEABILITY

MICRORESISTIVITY LOGS (CONT'D)

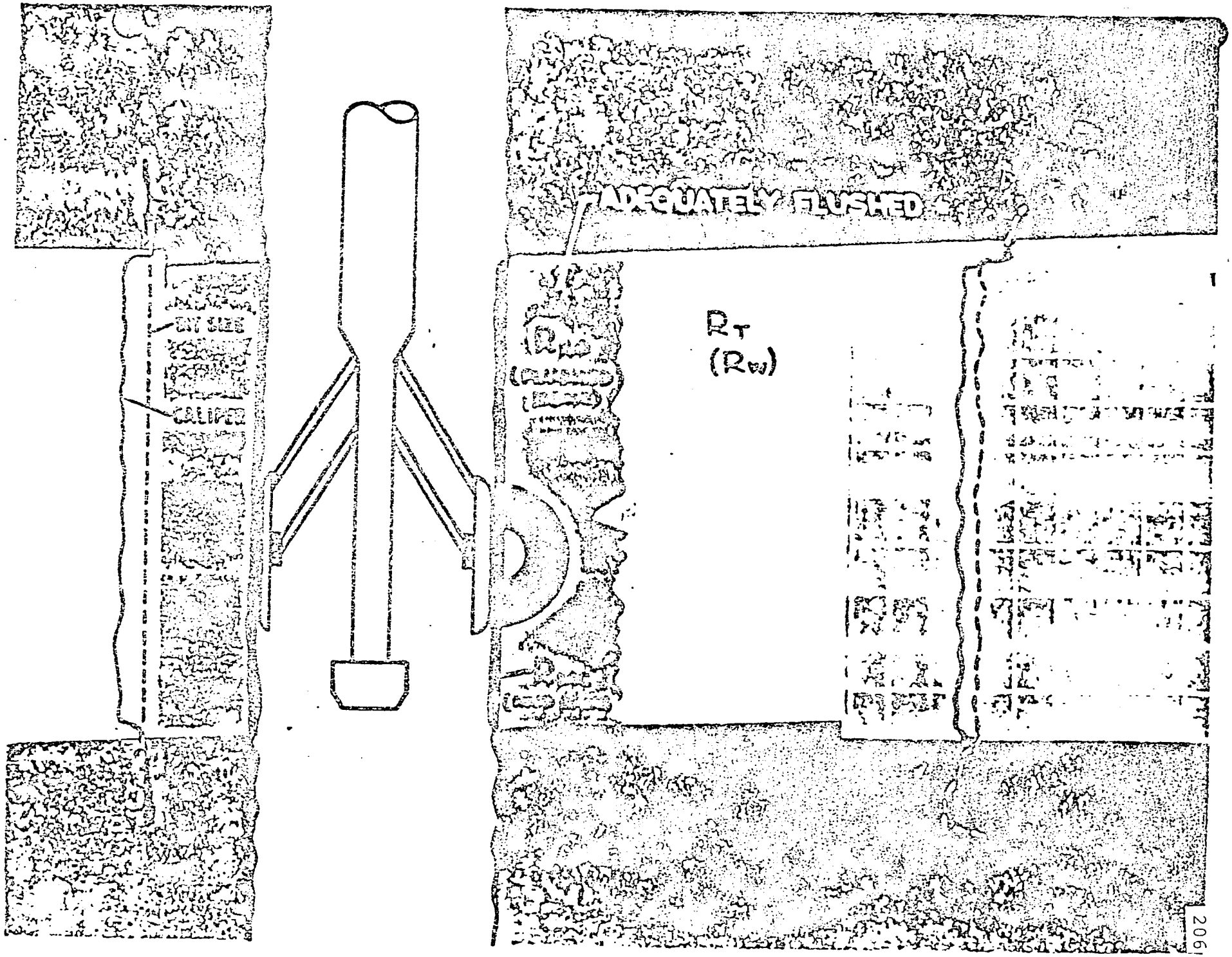
. THE MICROLOG (MINILOG, CONTACT LOG) CONT'D

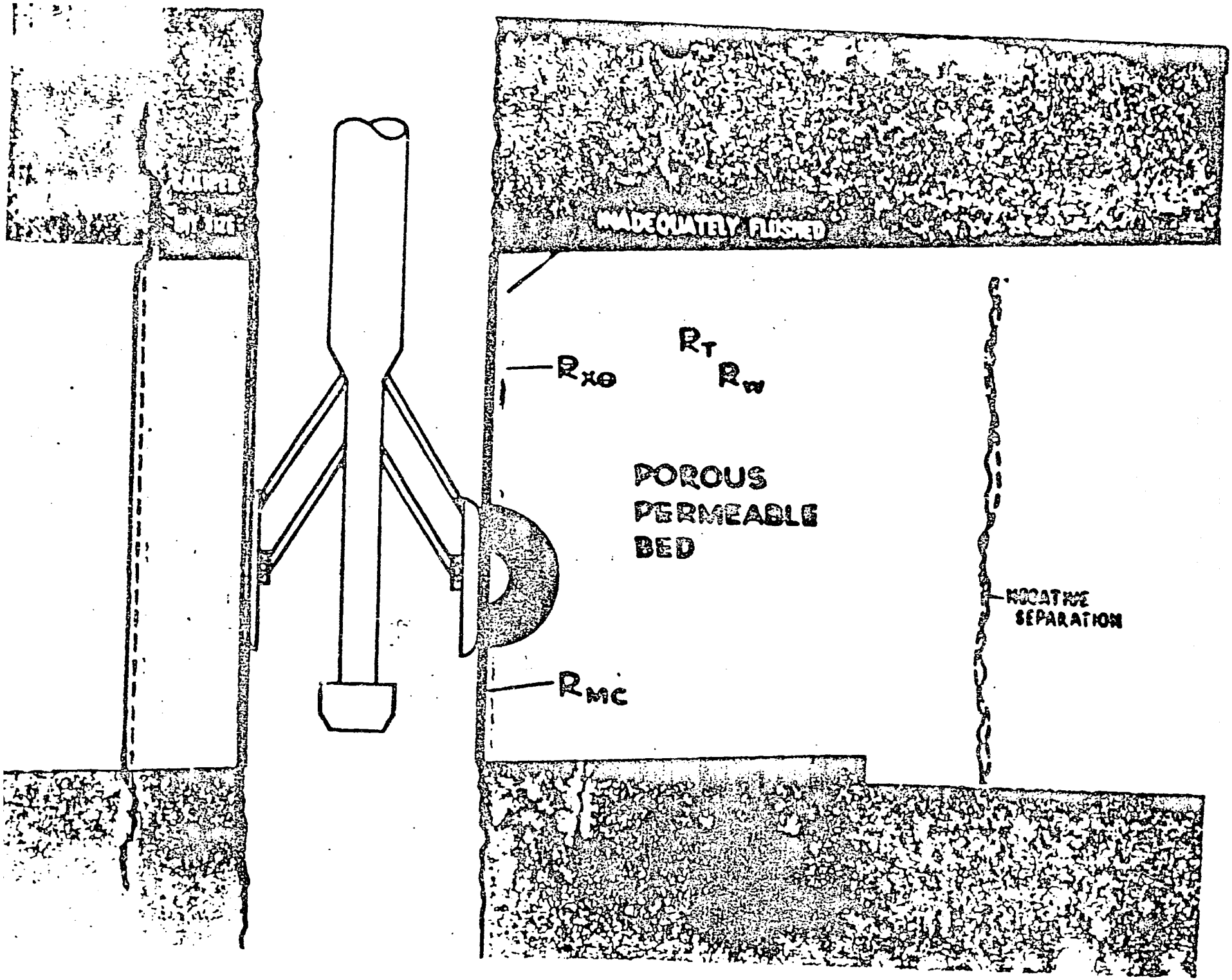
- POSITIVE SEPARATION: $R_{2''} > R_{1.5''}$
- ZERO SEPARATION: $R_{2''} = R_{1.5''}$
- NEGATIVE SEPARATION: $R_{2''} < R_{1.5''}$
- APPLICATION LIMITATIONS
  - .. $R_{XO}/R_{MC} < 15$
  - .. $\phi > 15\ \%$
  - .. $H_{MC} \lesssim 1/2''$
  - .. DEPTH OF INVASION $> 4''$
- THE GREATER R_{XO}/R_{MC}, THE GREATER THE TENDENCY FOR THE CURRENT TO ESCAPE THROUGH THE MUD CAKE

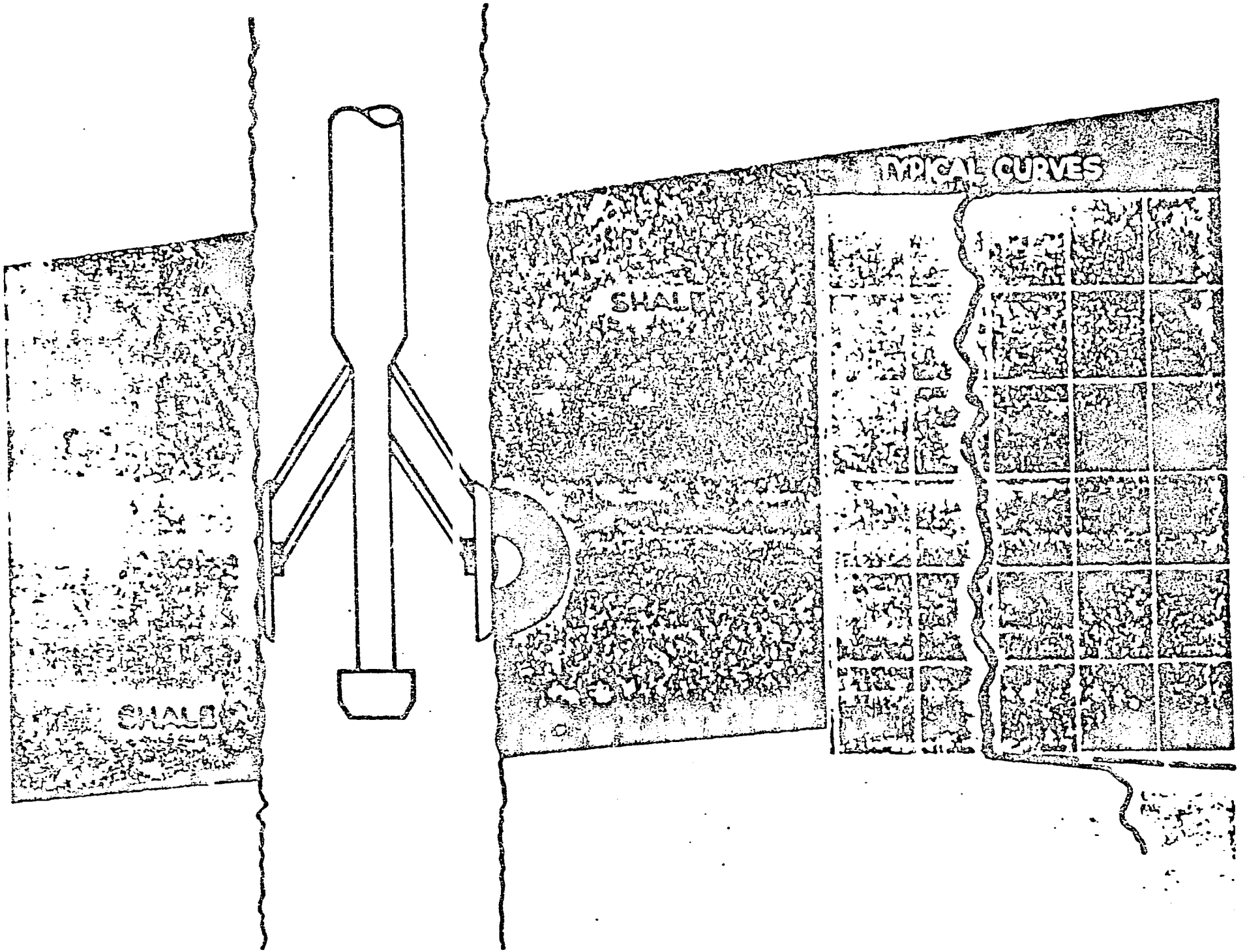


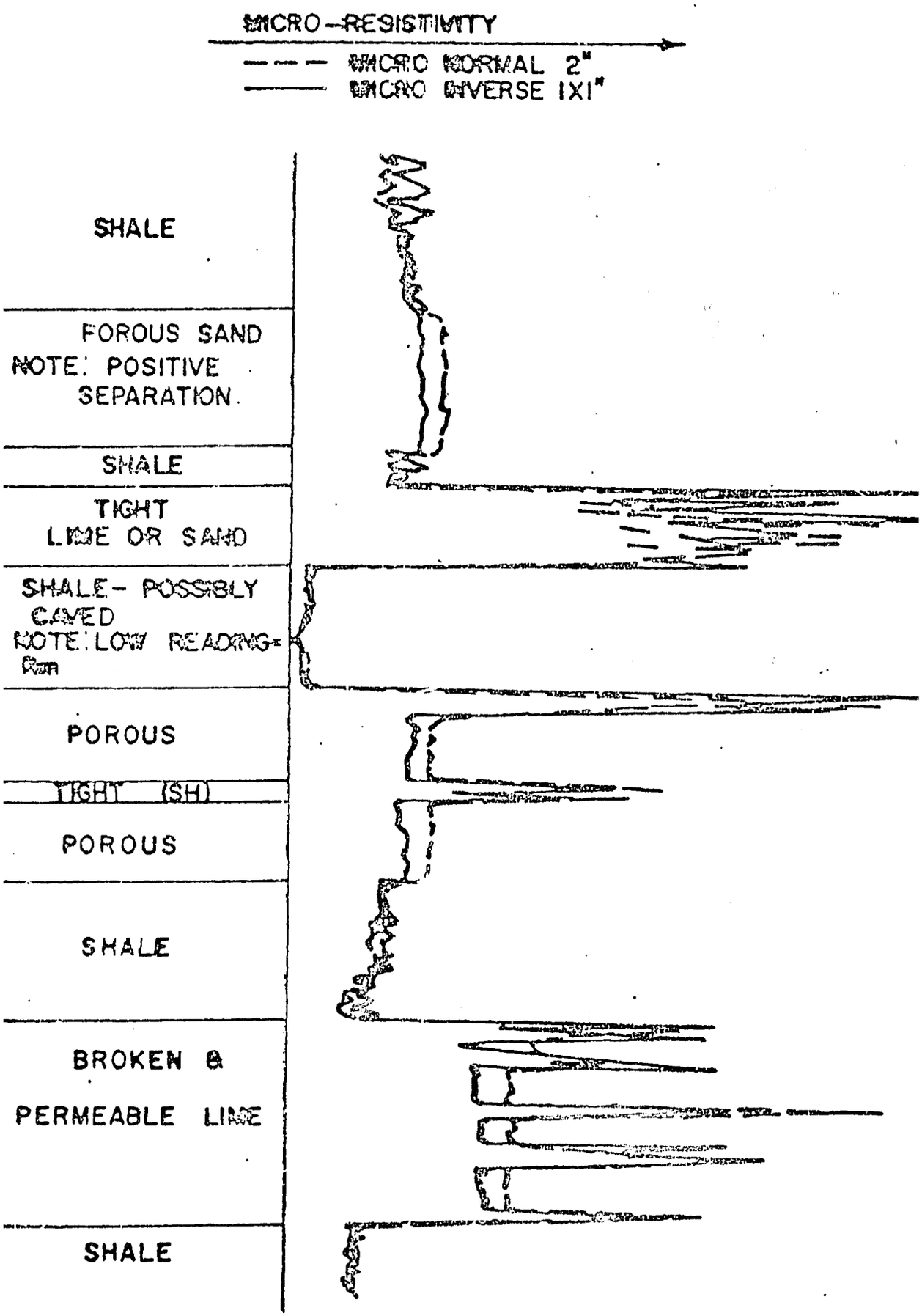
MICROLOGGING TOOL

Courtesy of Schlumberger Well Surveying Corp.


ADEQUATELY FLUSHED
BY SIZE
CALIPER
R_T
(R_w)

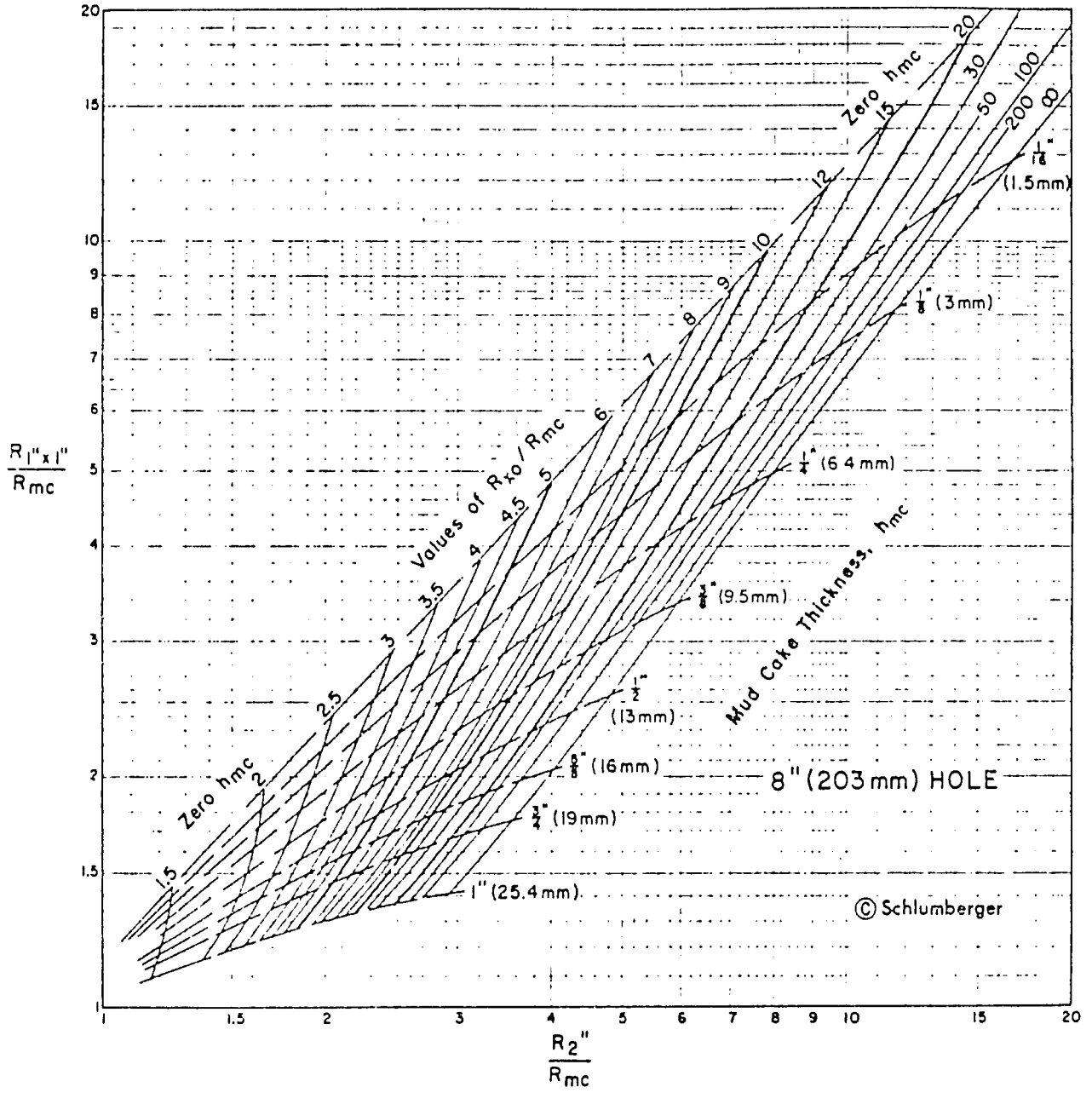

INADEQUATELY FLUSHED
R_{xo}
R_T
R_w
POROUS
PERMEABLE
BED
INDICATIVE
SEPARATION
R_{MC}


SHALE
SHALE
TYPICAL CURVES



SIMPLIFIED ILLUSTRATION OF MICROLOG

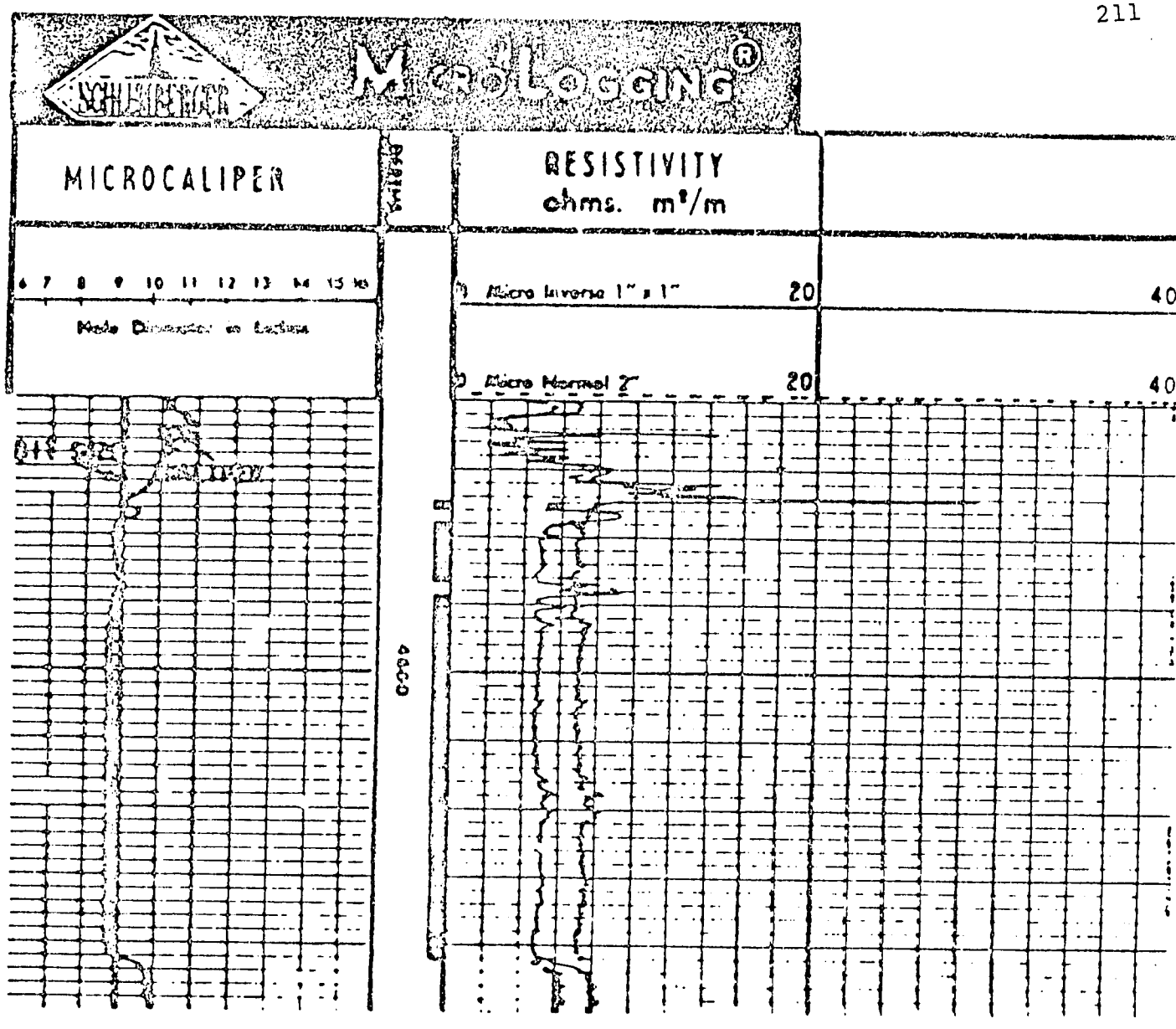
MICROLOG* INTERPRETATION CHART



For hole sizes other than 8 in. (203mm), multiply $R_{1''\times1''}/R_{mc}$ by the following factors before entering the chart: 1.15 for 4¾-in. (120mm) hole, 1.05 for 6-in. (152mm) hole, 0.93 for 10-in. (254mm) hole.

NOTE: An incorrect R_{mc} will displace the points in the chart along a 45° line. In certain cases this can be recognized when the mud-cake thickness is different from direct measurement by the microcaliper. To correct, move the plotted point at 45° to intersect the known h_{mc}. For this new point read R_{xo}/R_{mc} from the chart and $R_{2''}/R_{mc}$ from the bottom scale of the chart. $R_{xo} = R_{xo}/R_{mc} \times R_{mc}$.

*Mark of Schlumberger



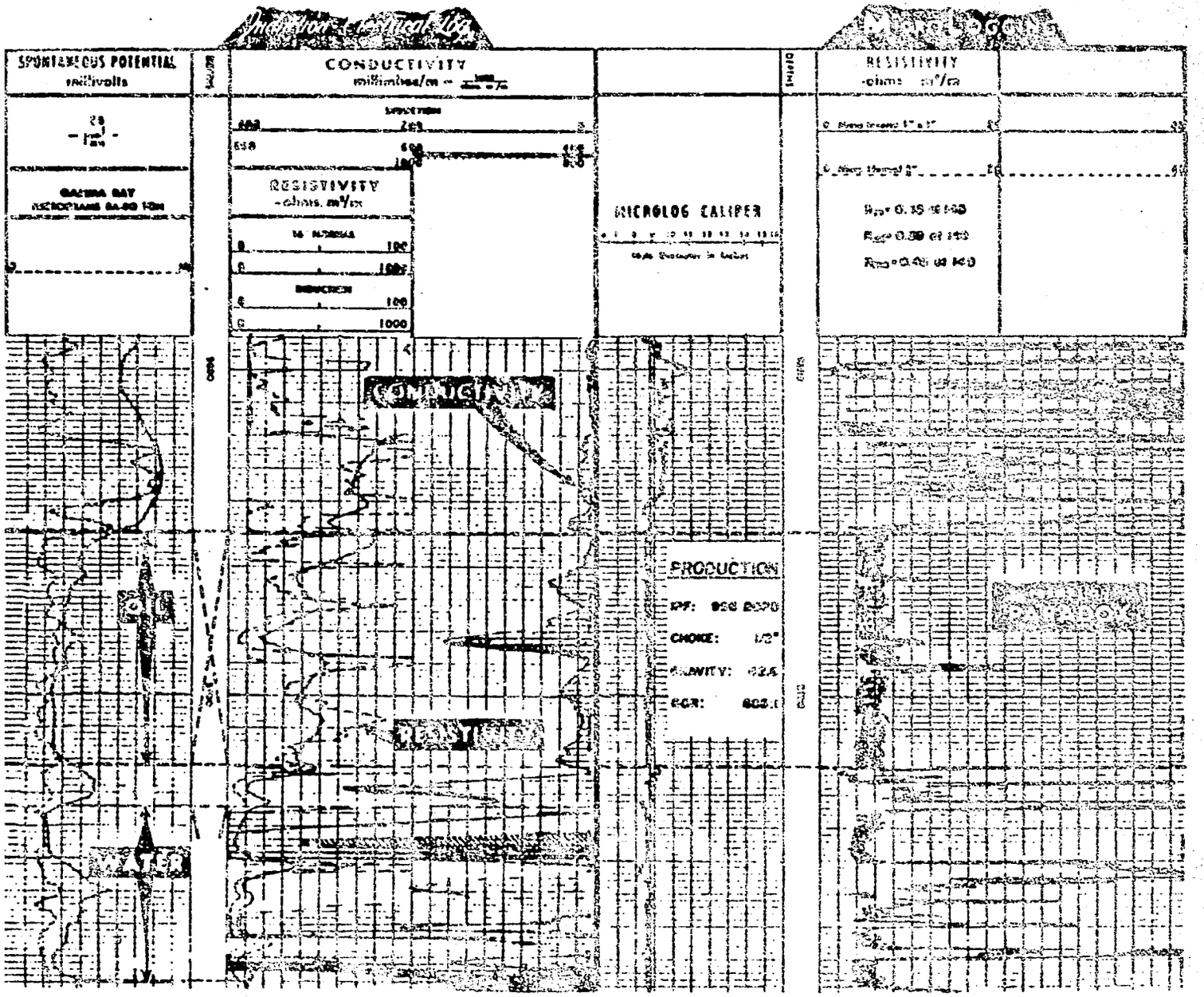
FIELD LOG

ZONE	=	4594-4614
HOLE SIZE	=	9"
R2"	=	7
R1x1	=	4.8
Tmc	=	1/8"
Rm	=	1.12 @ 125
Rmc	=	1.3 @ F.T.
Rmf	=	.80 @ F.T.
R2"/Rmc	=	5.4
R1/1Rmc	=	3.7

POROSITY DETERMINATION FROM CHARTS

Rxo/Rmc	=	26
Rxo	=	35
SXO	=	15%
F	=	29
m	=	2.15
Ø	=	10 1/2%

- Examples of Induction Electrical Log and Micro Log



Example of conventional induction electric log. Reprinted with permission of Schlumberger Well Surveying Corporation.

MICRORESISTIVITY LOGS (CONT'D)

- MICROLOG CONT'D
  - MUD LOG
    - GOTTEN WITH MICROLOG SONDE LOWERED WITH ARMS CLOSED
    - EXCEPT WHEN $D_H < 8''$ PAD WILL FACE AWAY FROM WALL PART OF THE TIME AND READ INSITU R_M
    - USES--CHECK R_M, DETECT MUD SYSTEM CHANGES, IDENTIFY WATER FLOWS

MICRORESISTIVITY LOGS (CONT'D)

. MICROLATEROLOG
  - PRINCIPLE
    .. SMALL ELECTRODE A_0 AND THREE CONCENTRIC ELECTRODES ARE IMBEDDED IN A RUBBER PAD
    .. FOCUSED DEVICE
    .. CURRENT OF CONSTANT INTENSITY IS IMPRESSED ON THE CENTER ELECTRODE
    .. CURRENT OF SIMILAR POLARITY IS IMPRESSED ON OUTER RING ELECTRODE--ITS INTENSITY IS VARIED AUTOMATICALLY TO MAINTAIN A ZERO POTENTIAL DROP IN THE TWO INNER RING ELECTRODES
    .. FOCUSED CURRENT FLOW IN CYLINDRICAL PATTERN FROM CENTER ELECTRODE FOR ABOUT 3" BEYOND WHICH IT FLARES
  - GOOD VERTICAL RESOLUTION--3" TO 6"
  - GOOD FOR SALT BASE MUDS OR WHEN $\frac{R_{XO}}{R_{MC}} > 15$
  - MOST OF RESPONSE COMES FROM MUD CAKE AND THE FLUSHED ZONE

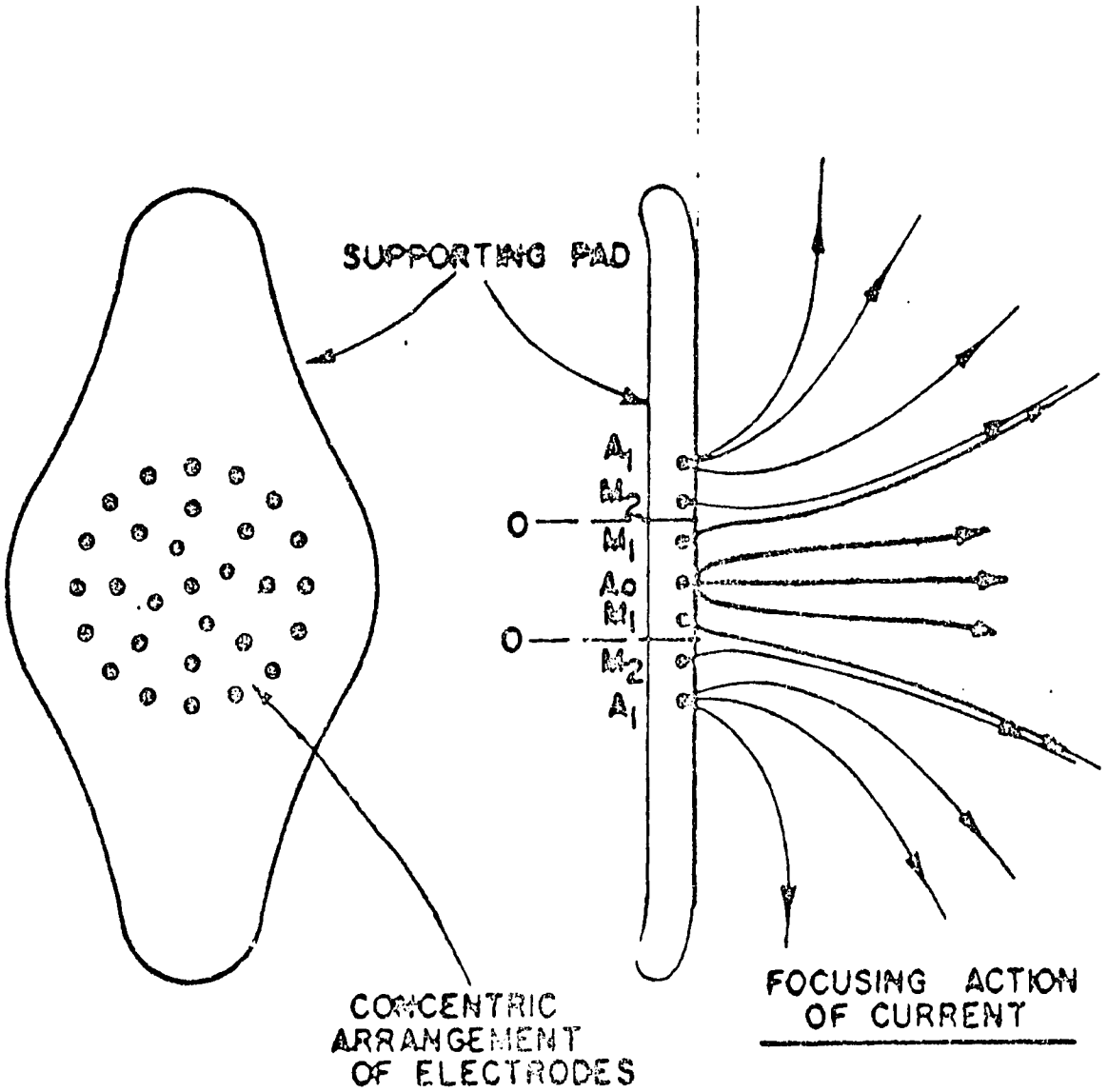
MICRORESISTIVITY LOGS (CONT'D)

- MICROLATEROLOG CONT'D
  - LIMITATIONS
    - .. $H_{MC} \lesssim 3/8''$
    - .. DEPTH OF INVASION $> 3''$ TO $4''$
    - .. FOR $H_{MC} > 3/8''$ TOOL RAPIDLY LOOSES ITS RESOLUTION OF R_{XO}

PROXIMITY LOG

- PRINCIPLE--SIMILAR TO MICROLATEROLOG, BUT USES A WIDER PAD--FOCUSED DEVICE
- MUD CAKE THICKNESSES UP TO 3/4" HAVE LITTLE EFFECT ON THE LOG MEASUREMENTS
- DEPTH OF INVESTIGATION (D_I = 40") MAKES IT ALMOST AN R_I TOOL
- LIMITATIONS
  - .. $H_{MC} \lesssim 3/4''$
  - .. $D_I \gtrsim 40''$

$$R_{PL} = J_{DI} R_{XO} + (1-J_{DI}) R_T$$

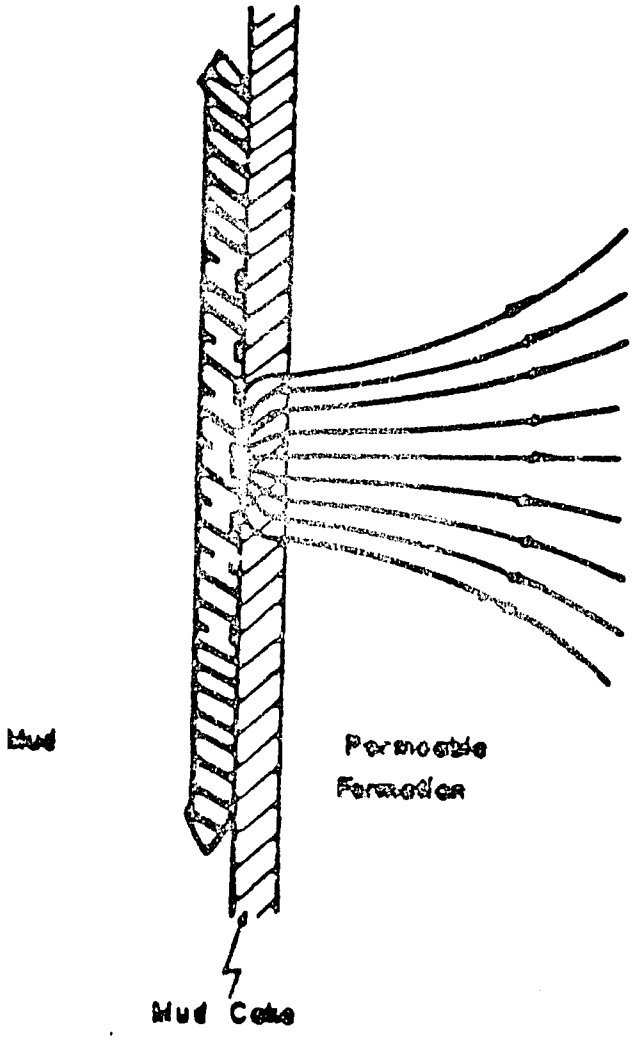


MICROLATEROLOG ELECTRODE ARRANGEMENT

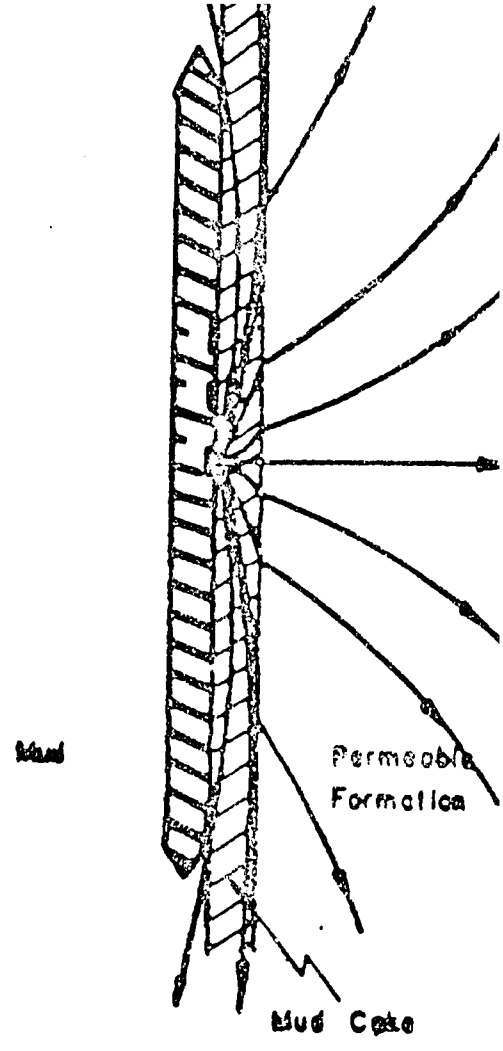
Courtesy of Schlumberger Well Surveying Corp.

COMPARATIVE DISTRIBUTION OF CURRENT LINES

(Formations more resistive than mud cake)



MICROLATERLOG

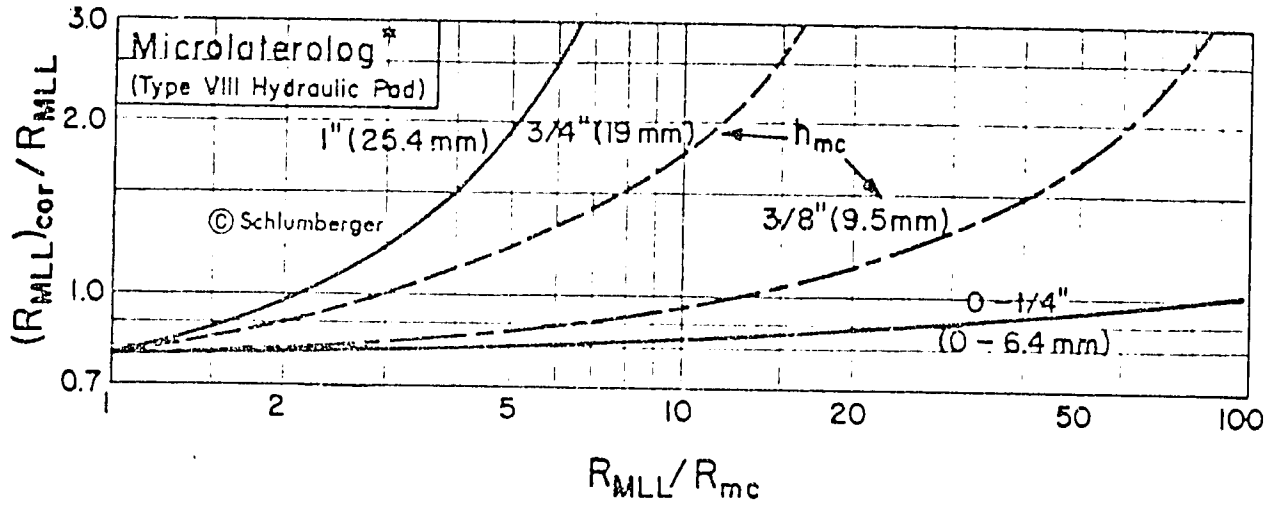


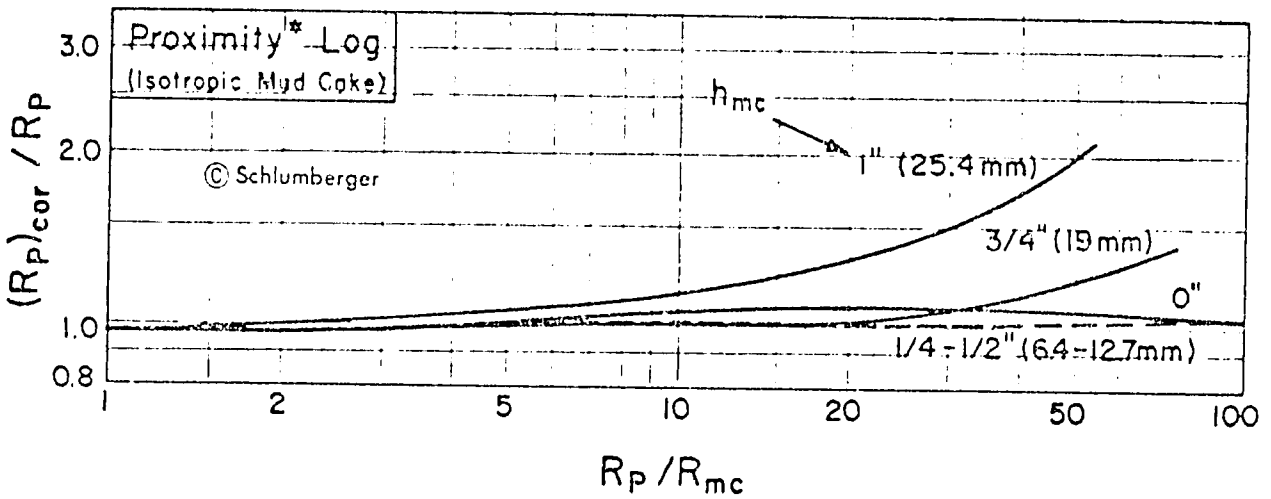
MICROLOG

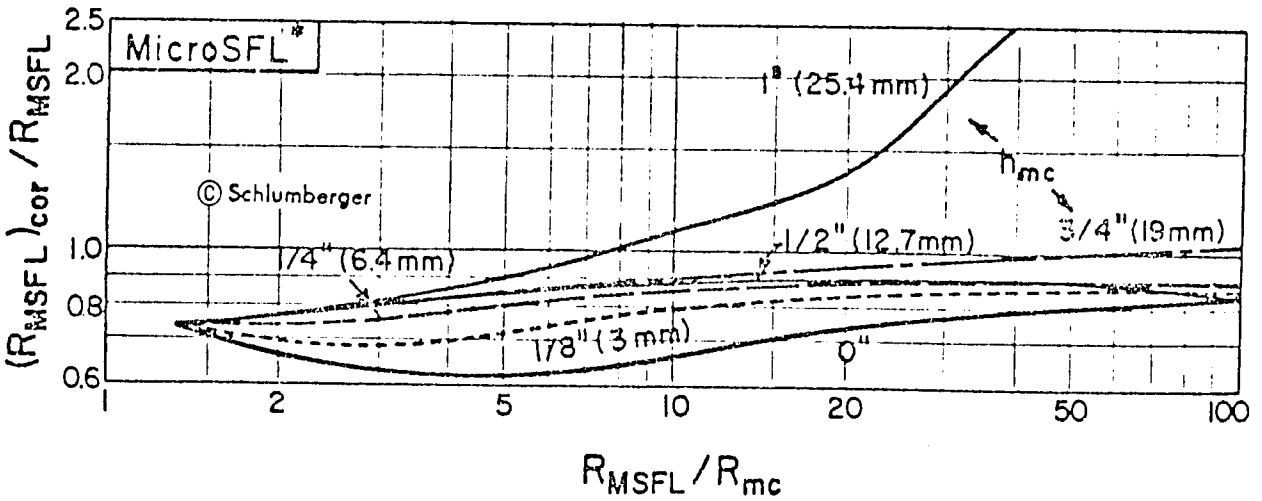
Courtesy of Schlumberger Well Surveying Corp.

MICROLATEROLOG*, PROXIMITY* LOG, AND MICROSFL*

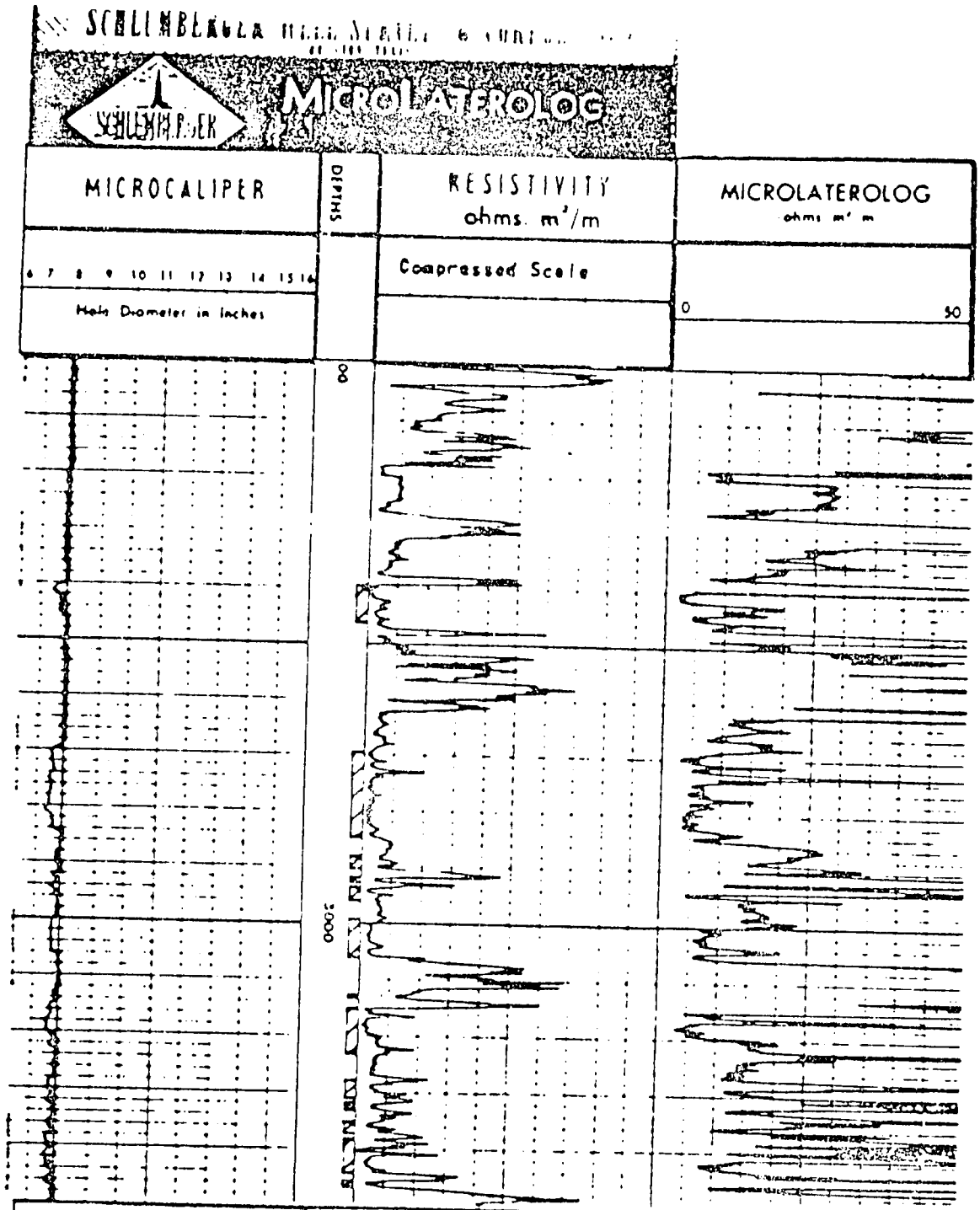
MUD-CAKE CORRECTION
FOR HOLE DIAMETER OF 8 in. OR 203mm







*Mark of Schlumberger



WELL FORMATION.

FORMATION
COUNTY

COMPLETION DATA

HOLE SIZE 7 7/8
Rm at FT 1.2
Rmf at FT .085
Rmc at FT
MUD LOSS
Time
Rw at FT

DRILL STEM TESTS
DEPTH RECOVERY

CORE ANALYSIS
DEPTH POROSITY

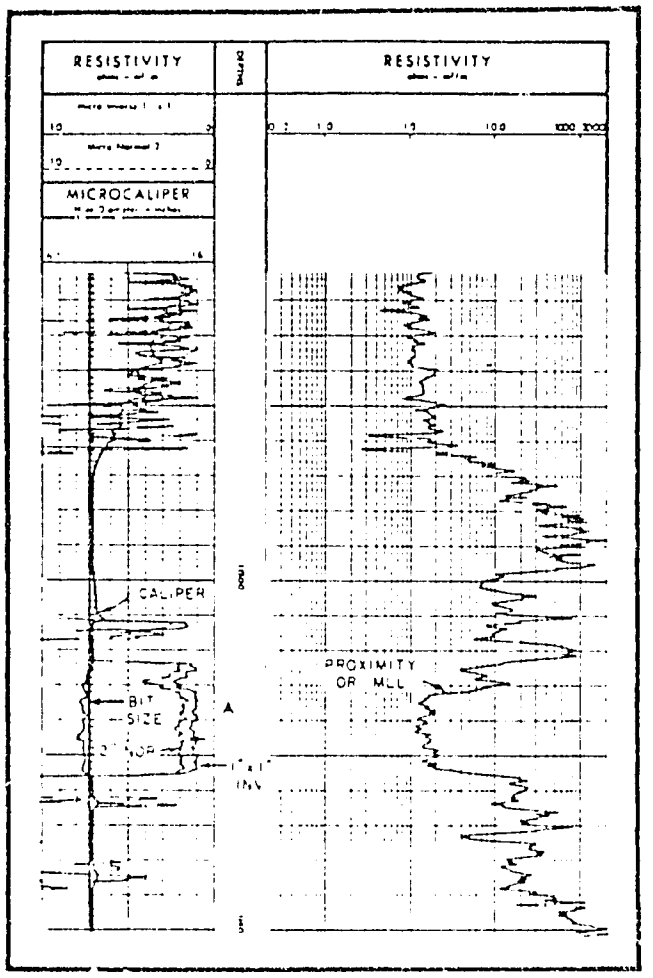
PERFORATIONS
DEPTH RECOVERY

FROM LOG
ZONE 2970-85

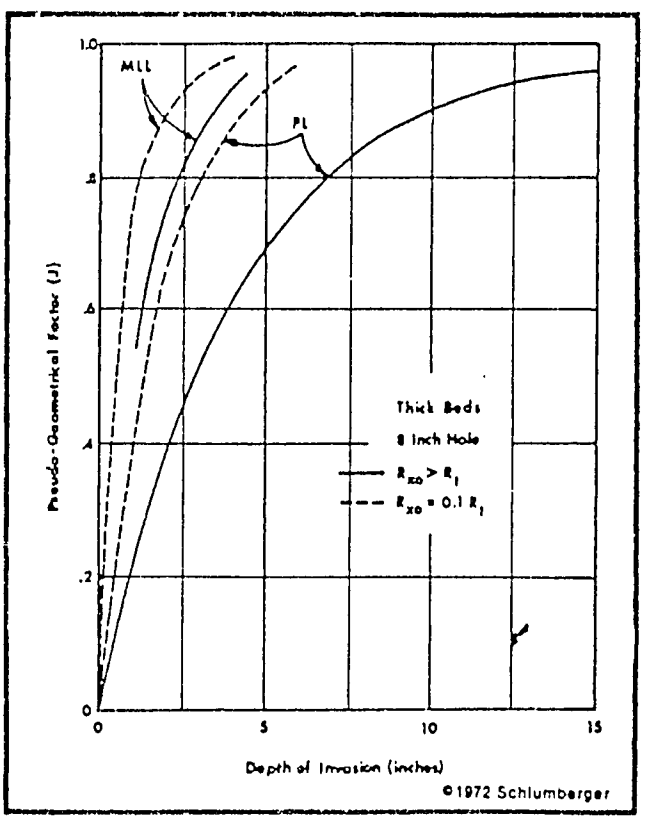
POROSITY DETERMINATION

RxO= Ohms
TMC= 1/4"

Fa= 60
ROS= 20%
F= 30
M= 2
Ø= 16.5%



— *Presentation of Proximity Log-Microlog.*

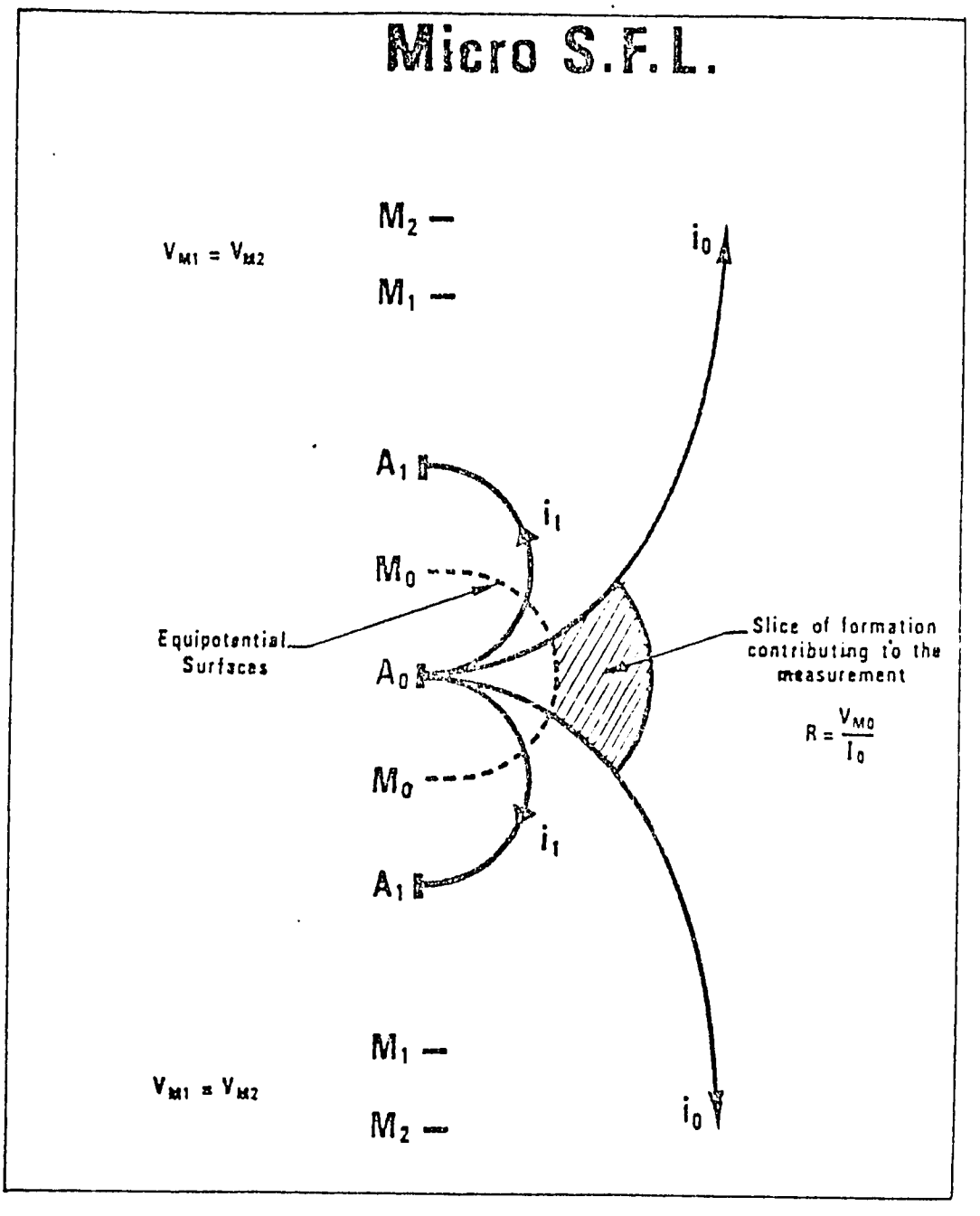


— *Pseudo-Geometrical Factors, MLL and PL.*

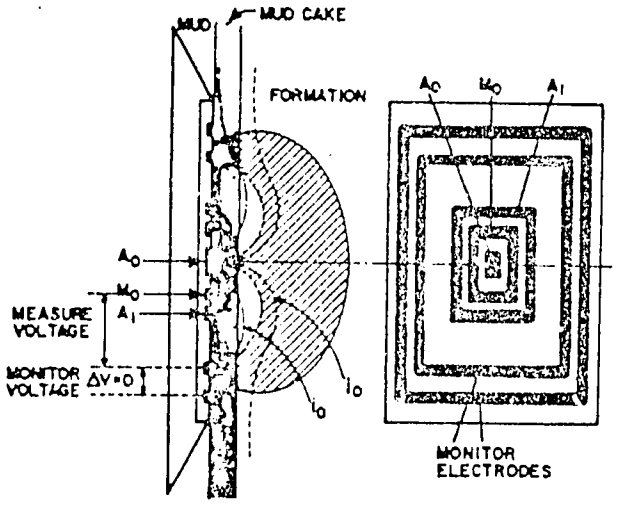
Courtesy of Schlumberger Well Surveying Corp.

. MICRO S F L

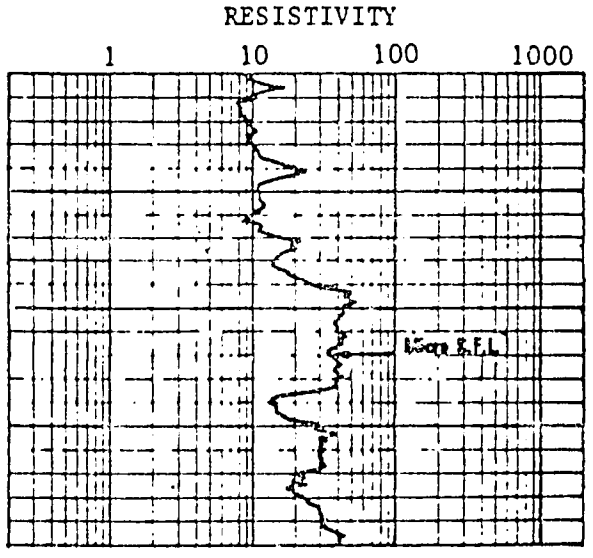
- USES A HARD TYPE PAD WITH RECTANGULAR ELECTRODES
- ADVANTAGES OVER M L, M L L, & P L
  .. COMBINABILITY WITH OTHER LOGGING TOOLS (FDC & DLL) THUS, ELIMINATING NEED FOR SEPARATE LOGGING RUN
  .. MEASURES GOOD R_{XO} IN THICK MUD CAKES & DOES NOT REQUIRE MUCH INVASION
- A CALIPER CURVE IS PROVIDED
- SPHERICAL FOCUSING IS SHAPING OF EQUIPOTENTIAL SURFACES TO APPROXIMATELY SPHERICAL FORM
  .. FOCUSING IS ACCOMPLISHED BY AUXILIARY ELECTRODES
  .. INSTEAD OF BEING FORCED INTO A NARROW BEAM, CURRENT IS MERELY PREVENTED FROM FOLLOWING THE BOREHOLE MUD OR MUDCAKE PATHS
  .. CAREFUL SELECTION OF ELECTRODE SPACINGS ACHIEVES AN OPTIMUM COMPROMISE BETWEEN TOO MUCH & TOO LITTLE DEPTH OF INVESTIGATION
- HOLE RUGOSITY IS PRESENT WHEN THE CURVE BECOMES VERY NOISY WITH LARGE AMPLITUDE
- LIMITATIONS
  .. $H_{MC} \leq 3/4''$
  .. DEPTH OF INVASION $> 4''$

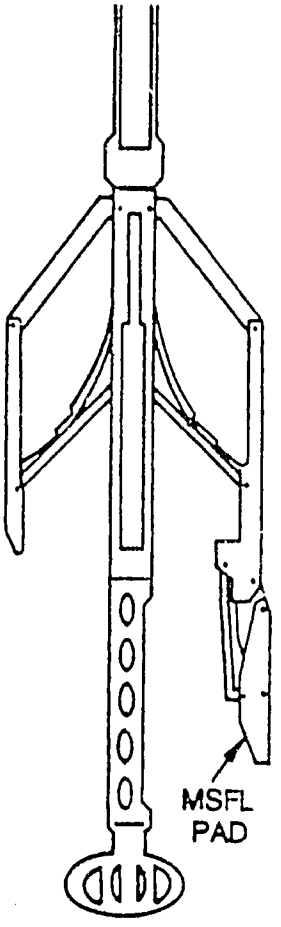

Micro S.F.L.
M_2
$V_{M1} = V_{M2}$
M_1
i_0
A_1
i_1
M_0
Equipotential Surfaces
A_0
Slice of formation contributing to the measurement
$R = \frac{V_{M0}}{I_0}$
M_0
i_1
A_1
M_1
$V_{M1} = V_{M2}$
M_2
i_0

The Micro-Spherically Focused Log (courtesy Schlumberger)



Electrode arrangement of MICROSFL (right) and current distribution (left). (Schematic)





MICRORESISTIVITY LOGS (CONT'D)

- DETERMINATION OF F & ϕ
  - IN AQUIFERS (CLEAN)

$$F = \frac{R_{XO}}{R_{MF}} = \frac{A}{\phi^M}$$

  - LOGS GIVE R_{XO} AND KNOWING R_{MF}, F CAN BE COMPUTED. A & M MUST BE KNOWN OR ASSUMED TO OBTAIN POROSITY
  - IN HYDROCARBON ZONES (CLEAN)

$$S_{XO} = \left(\frac{F\ R_{MF}}{R_{XO}}\right)^{1/2}$$

SINCE $S_{XO} = 1 - S_{OR}$

$$F = \frac{R_{XO}}{(1-S_{OR})^2\ R_{MF}}$$

THE PROCEDURE HERE IS THE SAME AS FOR AQUIFERS, EXCEPT IN ADDITION, S_{OR} NEEDS TO BE KNOWN

ELASTIC WAVE LOG--SONIC LOG--ACOUSTIC LOG

- WHAT IS IT?
  - A RECORDING VS DEPTH OF TIME ΔT, FOR A COMPRESSIONAL WAVE TO TRAVERSE ONE FOOT OF FORMATION
  - INTERVAL TRANSIT TIME, ΔT, IS THE RECIPROCAL OF THE COMPRESSIONAL SOUND WAVE VELOCITY IN μSEC.

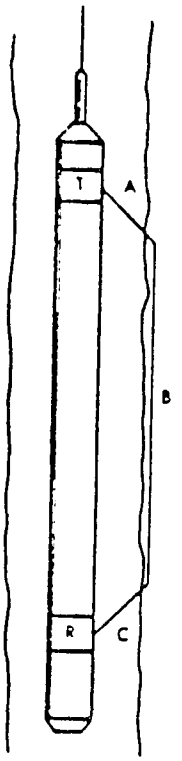
$$\Delta T = \frac{10^6}{V_{MA}} \mu \text{SEC/FT}$$

$$\Delta T = F(\text{LITHOLOGY}, \phi, \text{FLUID CONTENT})$$

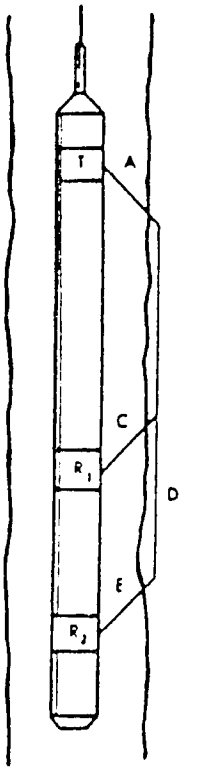
- ORIGINALLY DEVELOPED TO HELP INTERPRET SEISMIC DATA BY MEASURING THE VELOCITY OF SOUND THROUGH VARIOUS TYPES OF ROCKS
- SELF-DRIVEN MAGNETOSTRICTIVE OSCILLATOR IS THE MEANS OF CONVERTING ELECTRICAL ENERGY INTO VIBRATIONAL ENERGY
  - DEVICE OSCILLATES BY CONTRACTION AND EXPANSION WHEN IT IS USED AS THE TRANSMITTOR OF ELASTIC WAVE PULSES
  - WAVE TRAINS ARE OF SHORT DURATION AND OF CONSTANT AMPLITUDE AND FREQUENCY (ABOUT 30,000 CPS)

. ACOUSTIC LOGGING TOOLS

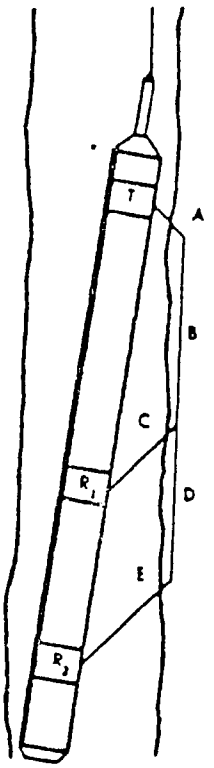
- SINGLE RECEIVER
  - .. EARLIEST SONIC LOGGING TOOL
  - .. INCLUDE ONE TRANSMITTER & ONE RECEIVER SPACED 6' APART
  - .. ΔT INCLUDED THE TRAVEL TIME IN THE MUD WHICH WAS DIFFICULT TO CORRECT FOR SINCE NO CALIPER WAS INCLUDED--A CONSTANT MUD TRAVEL TIME WAS SUBTRACTED
- CONVENTIONAL SONIC TOOL
  - .. CONSISTS OF TRANSMITTER AND THREE RECEIVERS--ONLY TWO OF WHICH ARE USED AT ANY ONE TIME
  - .. DISTANCE FROM TRANSMITTER TO FIRST RECEIVER IS ABOUT 3'
  - .. DISTANCE BETWEEN THE TWO RECEIVERS USED IS 1' OR 3'--SWITCH PERMITS SELECTION OF EITHER SPACING
  - .. 3' SPACING IS NORMALLY USED--USEFUL FOR BOTH ϕ AND SEISMIC VELOCITY DETERMINATION
  - .. FIRST ARRIVAL SOUND STARTS TIMING DEVICE IN THE FIRST RECEIVER & TRAVELS ON TO THE SECOND RECEIVER WHERE IT STOPS THE TIMING DEVICE
  - .. PATH DIFFERENCE FOR THE TWO RECEIVERS IS EQUAL TO THEIR SPACING IF THEY ARE EQUIDISTANT TO BOREHOLE WALL--NOT TRUE WHEN TOOL MOVES PAST A CHANGE IN BOREHOLE SIZE OR SONDE IS NOT PARALLEL TO WALL--THIS PROBLEM LED TO DEVELOPMENT OF B H C



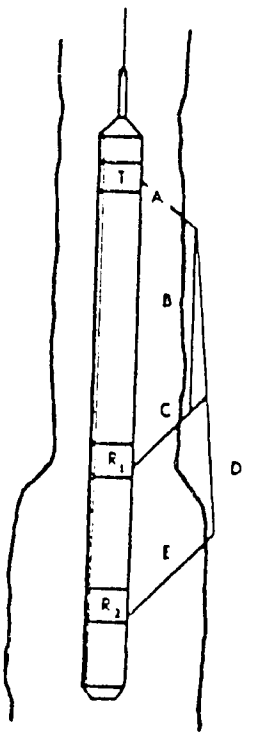
Single receiver system.



Dual receiver system.



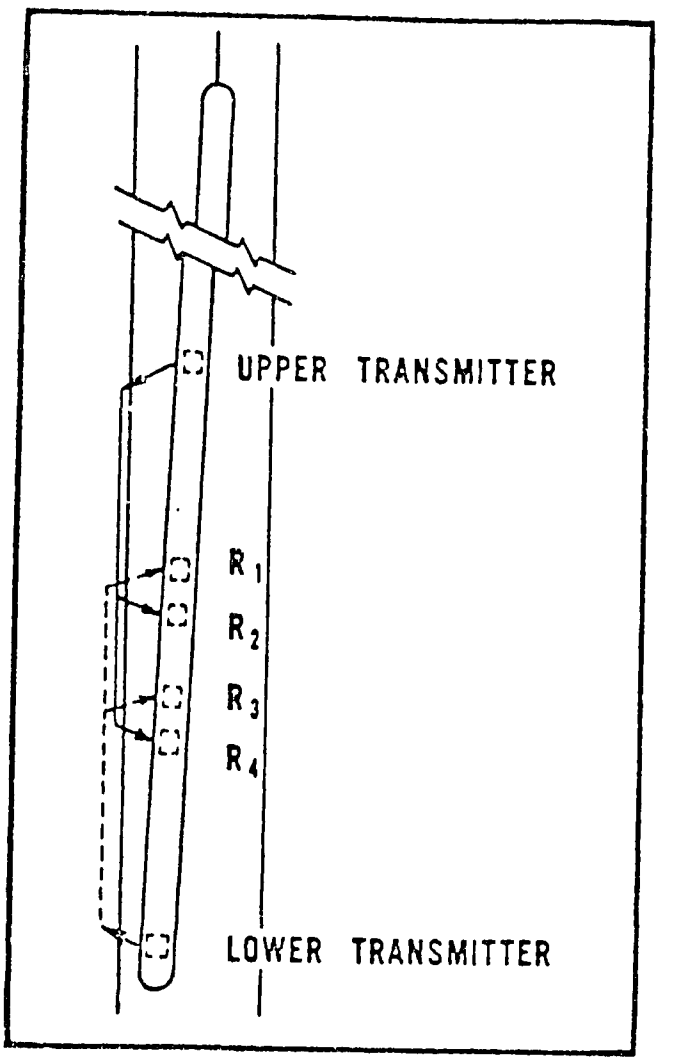
Effect of tool tilt.



Effect of cave boundary.

ELASTIC WAVE LOG (CONT'D)

. BOREHOLE COMPENSATED SONIC TOOL (B H C SONIC)
- MODIFICATION OF CONVENTIONAL SONIC TOOL
- CONSISTS OF TWO CONVENTIONAL ACOUSTIC TOOLS--ONE INVERTED WITH RESPECT TO THE OTHER
- SUPPRESSES UNDESIRABLE FLUCTUATIONS OF TRANSIT TIME CURVE, WHICH ARE CAUSED BY CHANGES IN BOREHOLE SIZE
- USUALLY ELIMINATES ERRORS CAUSED BY SONDE TILT
- AVERAGES ΔT FOR 2' OF ROCK INSTEAD OF 1' OR 3'
- BASIC OPERATION IS SIMILAR TO CONVENTIONAL TOOL
- MEASURES ΔT OF ROCK TWICE--ONCE USING UPPER TRANSMITTER AND ONCE USING LOWER TRANSMITTER
- THE TWO VALUES OF ΔT ARE AVERAGED, DIVIDED BY 2' & RECORDED IN μSEC/FT.



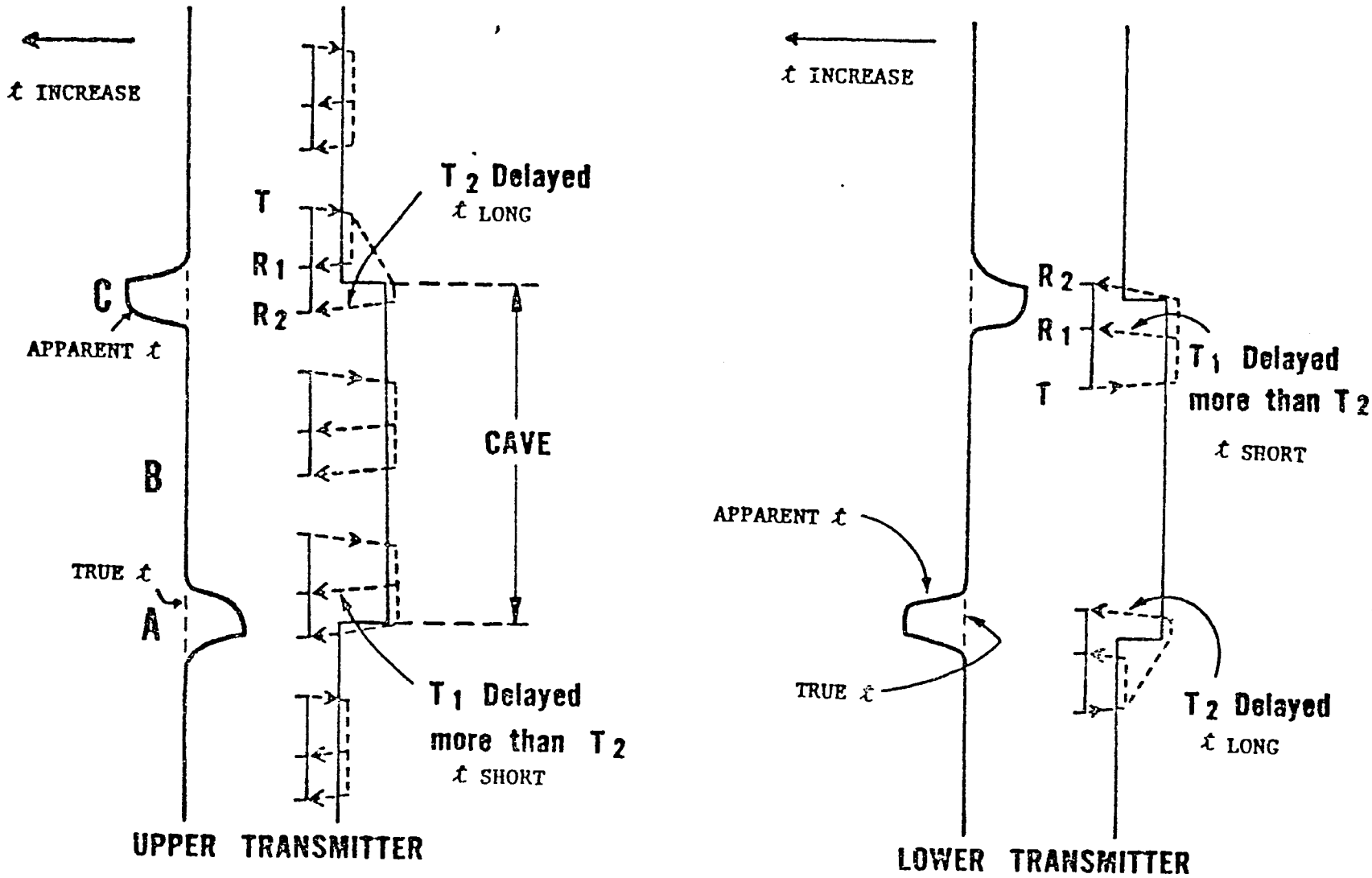
Schematic of BHC Sonde, showing ray paths for the two transmitter-receiver sets. Averaging the two Δt measurements cancels errors due to sonde tilt and hole-size changes.

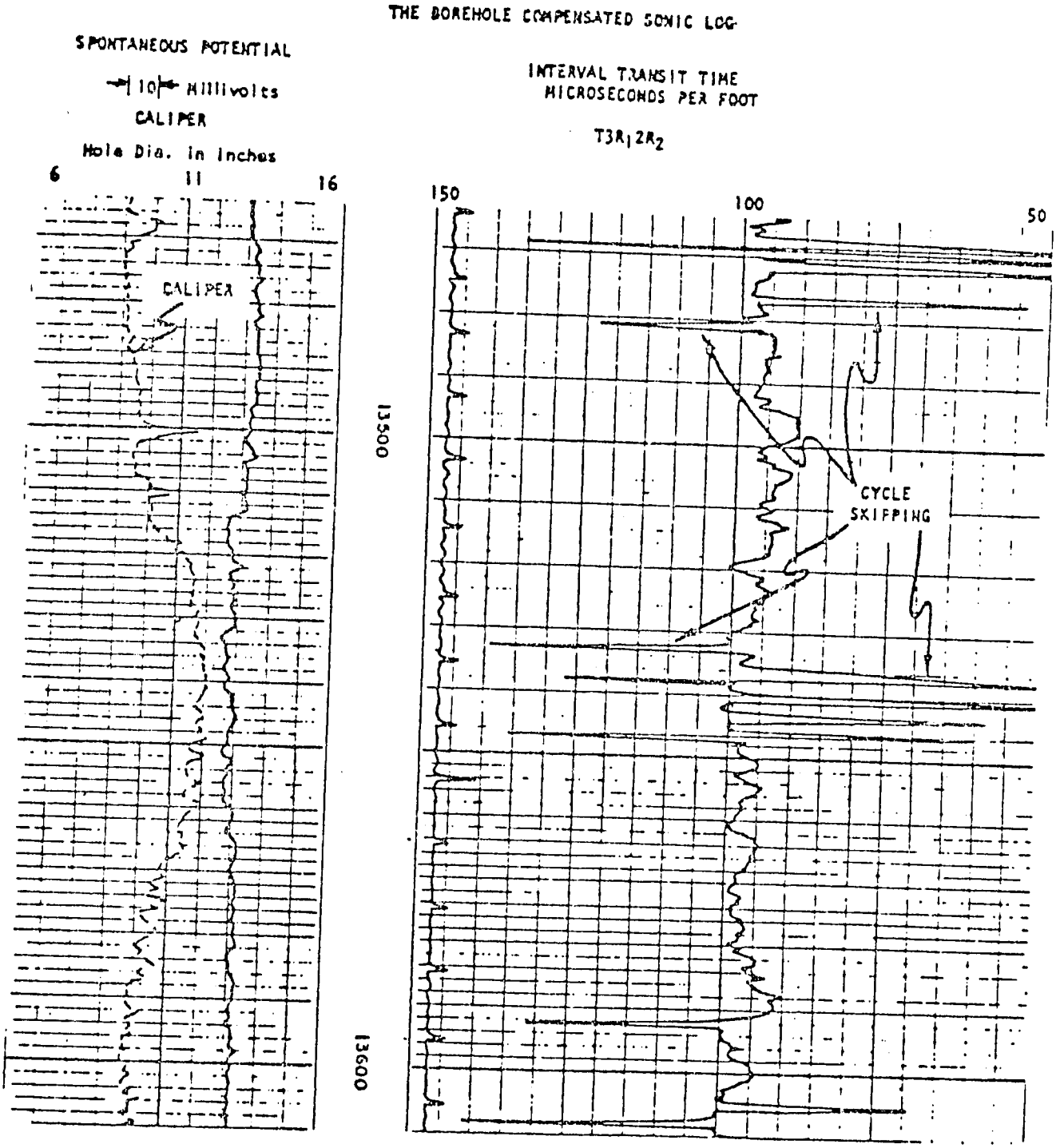
From Schlumberger Log Interpretation Principles (1972)

ELASTIC WAVE LOG (CONT'D)

- CYCLE SKIPPING
  - THEORETICAL CONCEPTS
    - .. A SOUND WAVE WILL TRIP TIMING MECHANISM IN RECEIVERS ONLY IF ENERGY OF WAVE IS ABOVE A MINIMUM
    - .. THIS PREVENTS BACKGROUND NOISE FROM TRIPPING THE TIMERS PREMATURELY
    - .. IF THE AMPLITUDE OF A SOUND WAVE STARTS THE TIMING DEVICE OF THE FIRST RECEIVER, & IS THEN ATTENUATED OR DAMPENED, IT WILL NOT CLOSE THE TIMER AT THE SECOND RECEIVER--IT WILL STAY OPEN UNTIL A WAVE WITH SUFFICIENT ENERGY CLOSES IT
    - .. PERIOD BETWEEN EACH PEAK OF A TRANSMITTED WAVE IS 33 MICRO SEC/FT
    - .. FOR CONVENTIONAL TOOL CYCLE, SKIPPING CAUSES HIGHER VALUES OF ΔT
    - .. FOR B H C TOOL CYCLE, SKIPPING CAN EITHER CAUSE ΔT TO BE SMALL OR LARGE

Bore hole enlargement effects on acoustic logs (courtesy Schlumberger)





An example of multiple cycle skipping on the BHC Sonic log. Note that the skips on the compensated sonic log "kick" in both directions.

CYCLE SKIPPING (CONT'D)

. WHAT CAUSES CYCLE SKIPPING

- GAS OCCUPYING PORE SPACES--LACK OF CYCLE SKIPPING DOES NOT MEAN GAS IS NOT PRESENT (MUD FILTRATE INVASION)
- HORIZONTAL FLUID-FILLED FRACTURES--REFLECT A PORTION OF THE ENERGY AT FLUID-ROCK INTERFACES
- DEEP CAVING OPPOSITE ONE OR BOTH RECEIVERS--ATTENUATION OF ENERGY OVER LONG MUD PATH--OCCURS WHEN $D_h > 13''$
- LACK OF SUFFICIENT ACOUSTIC COUPLING BETWEEN MUD COLUMN AND ROCKS--CAN OCCUR AT SHALLOW DEPTHS ($<$ 1500')--RESULTS IN LARGE ATTENUATION
- LACK OF SUFFICIENT ACOUSTIC COUPLING BETWEEN ROCK GRAINS (LACK OF RIGIDITY OF ROCK--UNCONSOLIDATED SANDS)
- GAS IN MUD COLUMN--GREATLY REDUCES THE WAVE ENERGY BETWEEN ROCK & SONDE
- BOREHOLE NOISE--WAVE MOTION GENERATED IN MUD BY SONDE--BUMPING OF SONDE AGAINST BOREHOLE WALL

. LOG PRESENTATION

- SONIC VELOCITIES IN COMMON ROCKS RANGE FROM 6,000 TO 23,000 FT/SEC
- TO AVOID SMALL DECIMAL FRACTIONS, THE RECIPROCAL OF VELOCITY, ΔT, IS RECORDED IN MICRO SEC/FT---44 μSEC/FT FOR ZERO-POROSITY DOLOMITE TO 190 μSEC/FT FOR WATER
- ΔT IS RECORDED ON A LINEAR SCALE IN TRACKS 2 & 3
- A 3-ARM CALIPER CURVE AND A GAMMA RAY CURVE ARE RECORDED IN TRACK 1
- AN SP CURVE, BUT BECAUSE OF METAL SONDE, IS USEFUL ONLY FOR CORRELATION
- INTEGRATED TRAVEL TIME IS GIVEN BY A SERIES OF PIPS AT LEFT EDGE OF TRACK 2--USEFUL FOR SEISMIC PURPOSES
- ΔT SCALES USED INCLUDE

40-90-140	NORMAL SCALE
50-100-150	GULF COAST UNCONSOLIDATED SHALES
40-70-100	WEST TEXAS CARBONATES

TABLE I

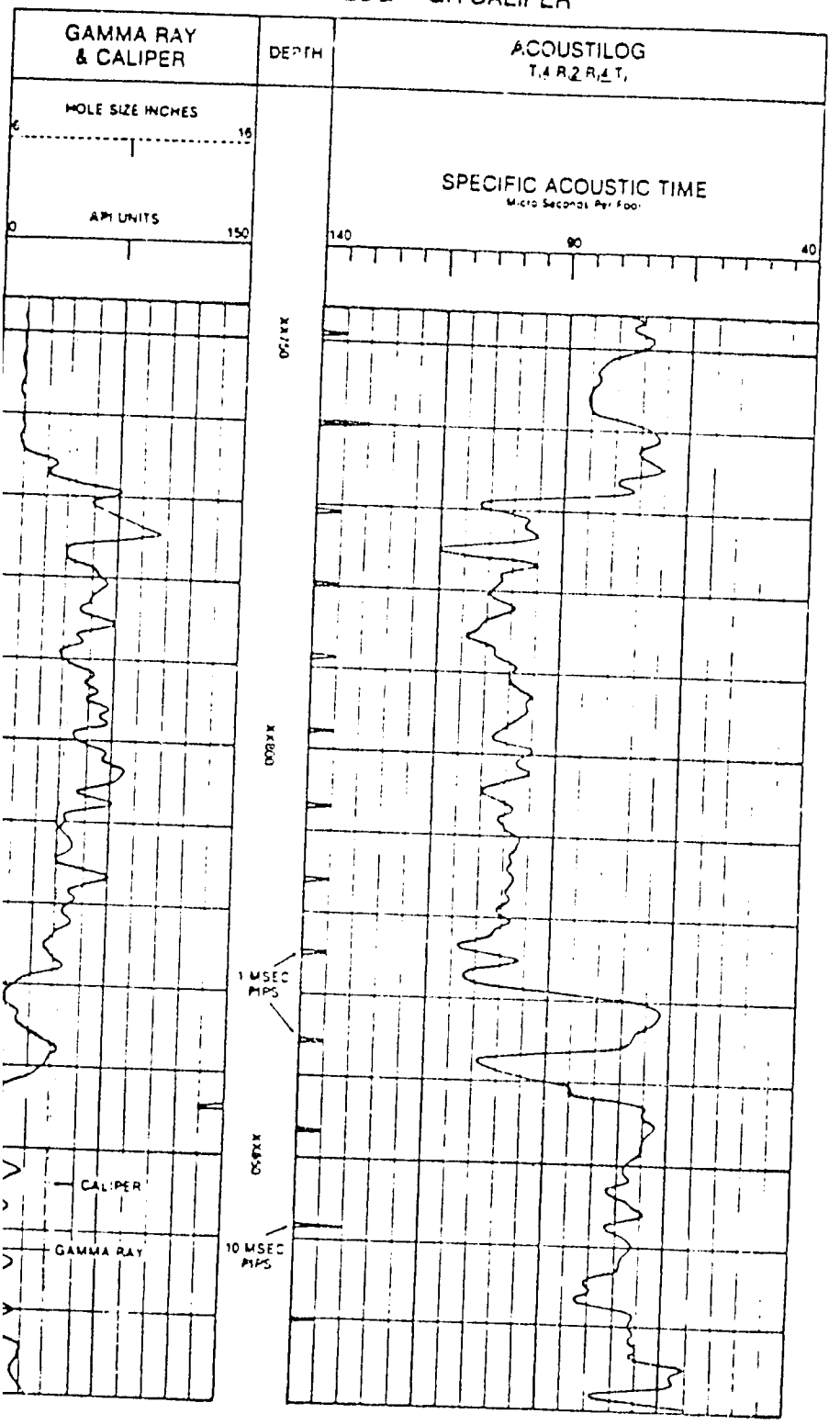
Fluid	v_f ft./sec.	Δt_f μ sec/ft.
Water with 20% NaCl	5,300	189
Water with 15% NaCl	5,000	200
Water with 10% NaCl	4,800	208
Water (pure)	4,600	218
Oil	4,200	238
Methane	1,600	626
Air	1,100	910

TABLE II

Formation	v_{ma} ft./sec.	Δt_{ma} μ sec/ft.
Sandstone:		
Unconsolidated	17,000 or less	58.8 or more
Semi-consolidated	18,000	55.6
Consolidated	19,000	52.6
Limestone	21,000	47.6
Dolomite	23,000	43.5
Shale	6,000 to 16,000	167. to 62.5
Calcite	22,000	45.5
Anhydrite	20,000	50.0
Granite	20,000	50.0
Gypsum	19,000	52.6
Quartz	18,000	55.6
Salt	15,000	66.7

From Dresser Atlas Log Review I (1974)

BHC ACOUSTILOG® -GR-CALIPER



From Dresser Atlas 1981 Booklet on Acoustic Logs

ELASTIC WAVE LOG (CONT'D)

- INVESTIGATION CHARACTERISTICS
  - DEPTH OF PENETRATION--A FEW INCHES--6" TO 12"
  - VERTICAL RESOLUTION IS APPROXIMATELY EQUAL TO THE DISTANCE BETWEE RECEIVERS

- EVALUATION OF POROSITY
  - FOR CLEAN CONSOLIDATED FORMATIONS WITH UNIFORMLY DISTRIBUTED PORE M.R.J. WYLIE'S MODEL HAS BEEN VERIFIED BY EXTENSIVE FIELD APPLICATIONS

$$\Delta T_L = \phi \Delta T_F + (1-\phi)\Delta T_{MA}$$

OR

$$\phi = \frac{\Delta T_L - \Delta T_{MA}}{\Delta T_F - \Delta T_{MA}}$$

∴ ΔT_L IS READING OF SONIC LOG IN μSEC/FT

∴ ΔT_{MA} IS TRANSIT TIME OF MATRIX MATERIAL--DEPENDS ON MINERAL COMPOSITION

∴ ΔT_F IS TRANSIT TIME IN PORE FLUID (ASSUMED TO BE MUD FILTRATE) 189 μSEC/FT--DEPENDS ON TEMPERATURE, SALINITY AND PRESSURE OF FLUID--ΔT_F VARIES FROM 180 TO 200 μSEC/FT

- EVALUATION OF POROSITY (CONT'D)
  - IN UNCONSOLIDATED AND ABNORMALLY PRESSURED SANDS ΔT_L's ARE TOO HIGH & GIVE POROSITIES WHICH ARE GREATER THAN THE TRUE POROSITY
  - AN ADJUSTMENT IS NECESSARY TO ADJUST THE SONIC POROSITY OF UNCONSOLIDATED SANDS

$$\phi = \frac{\Delta T_L - \Delta T_{MA}}{\Delta T_F - \Delta T_{MA}} \times \frac{1}{C_P} = \frac{\phi_S}{C_P}$$

WHERE C_P = COMPACTION CORRECTION FACTOR

$= \frac{\phi_S}{\phi}$ ϕ_S IS SONIC POROSITY

ϕ IS TRUE POROSITY

- DETECTION OF UNCONSOLIDATED SAND CONDITIONS
  - ΔT_{SH} VARIES FROM ABOUT 625 TO 167 μSEC/FT

    FOR $\Delta T_{SH} \leqslant 100$ SEDIMENTS ARE COMPACTED

    FOR $\Delta T_{SH} > 100$ SEDIMENTS ARE UNCONSOLIDATED
  - PRESSURE GRADIENT $> .5$ PSI/FT

- DETERMINATION OF COMPACTION CORRECTION FACTOR
  - USING ΔT_{SH} WHEN $\Delta T_{SH} > 100$

$$C_P = \frac{\Delta T_{SH} \; C}{100}$$

    .. C = SHALE COMPACTION COEFFICIENT--RANGES FROM 0.8 TO 1.2--SELECTION DEPENDS ON EXPERIENCE AND THE GEOGRAPHICAL AREA
  - USING RESISTIVITY LOGS
    .. DETERMINE R_O IN A CLEAN WATER-BEARING SAND
    .. SELECT APPROPRIATE MODEL TO OBTAIN POROSITY

$$\frac{R_O}{R_W} = F = \frac{A}{\phi^M}$$

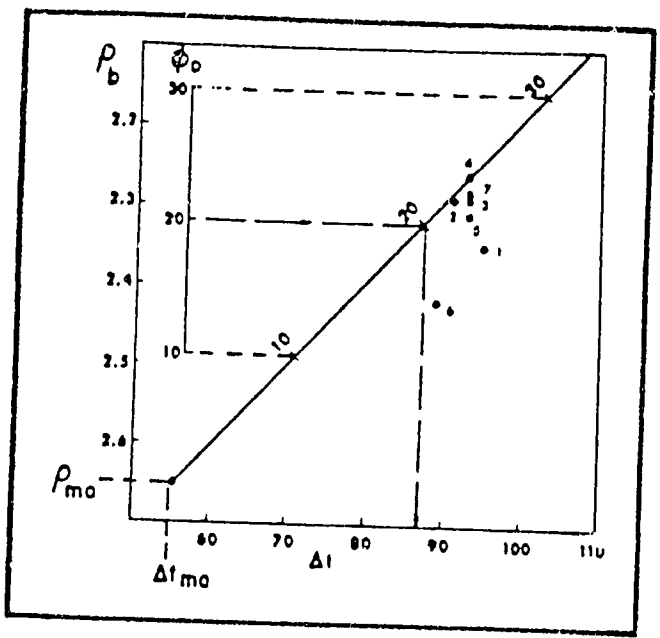
$$C_P = \frac{\phi_S}{\phi_{R_o}}$$

ELASTIC WAVE LOG (CONT'D)

- DETERMINATION OF C_P (CONT'D)
  - USING DENSITY LOG
    - .. DETERMINE ϕ_D AND $C_P = \frac{\phi_S}{\phi_D}$
    - .. DENSITY--SONIC CROSS-PLOT
      - --WHEN DENSITY AND SONIC LOGS ARE AVAILABLE READ THEM AT COMMON DEPTHS, ρ_B AND Δ_T
      - --PLOT ρ_B VS Δ_T USING LINEAR SCALES
      - --IF THE INTERVAL CONTAINS CLEAN SANDS WITH S_W = 100%, A LINE DRAWN FROM THE MATRIX POINT THROUGH THE POINTS LYING TOWARD THE UPPER LEFT WILL BE THE CLEAN SAND LINE. ANY Δ_T WILL GIVE A ϕ_D AND

$$C_P = \frac{\phi_S}{\phi_D}$$

      - --POINTS FALLING BELOW THOSE AT THE UPPER LEFT REPRESENT SHALINESS OR PORES CONTAINING OIL OR GAS



— *Density-Sonic crossplot as used for compaction-factor determination.*

From Schlumberger Log Interpretation Principles (1972)

- DETERMINATION OF C_P (CONT'D)
  - USING NEUTRON LOG
    - .. PREVIOUS METHODS REQUIRE PRESENCE OF A CLEAN SAND FULL OF WATER --IF SANDS ARE SHALY THEY CANNOT BE USED
    - .. IF A NEUTRON LOG IS AVAILABLE, ϕ_N MAY BE COMPARED WITH ϕ_S TO ESTIMATE C_P--IN PRESENCE OF SHALE BOTH ϕ_S & ϕ_N WILL BE HIGH

$$C_P = \frac{\phi_S}{\phi_N}$$

    - .. EXPERIENCE SHOWS THAT DISCREPANCIES BETWEEN ϕ_N & ϕ_S IN SHALY WATER-FILLED SANDS ARE DUE TO LACK OF COMPACTION

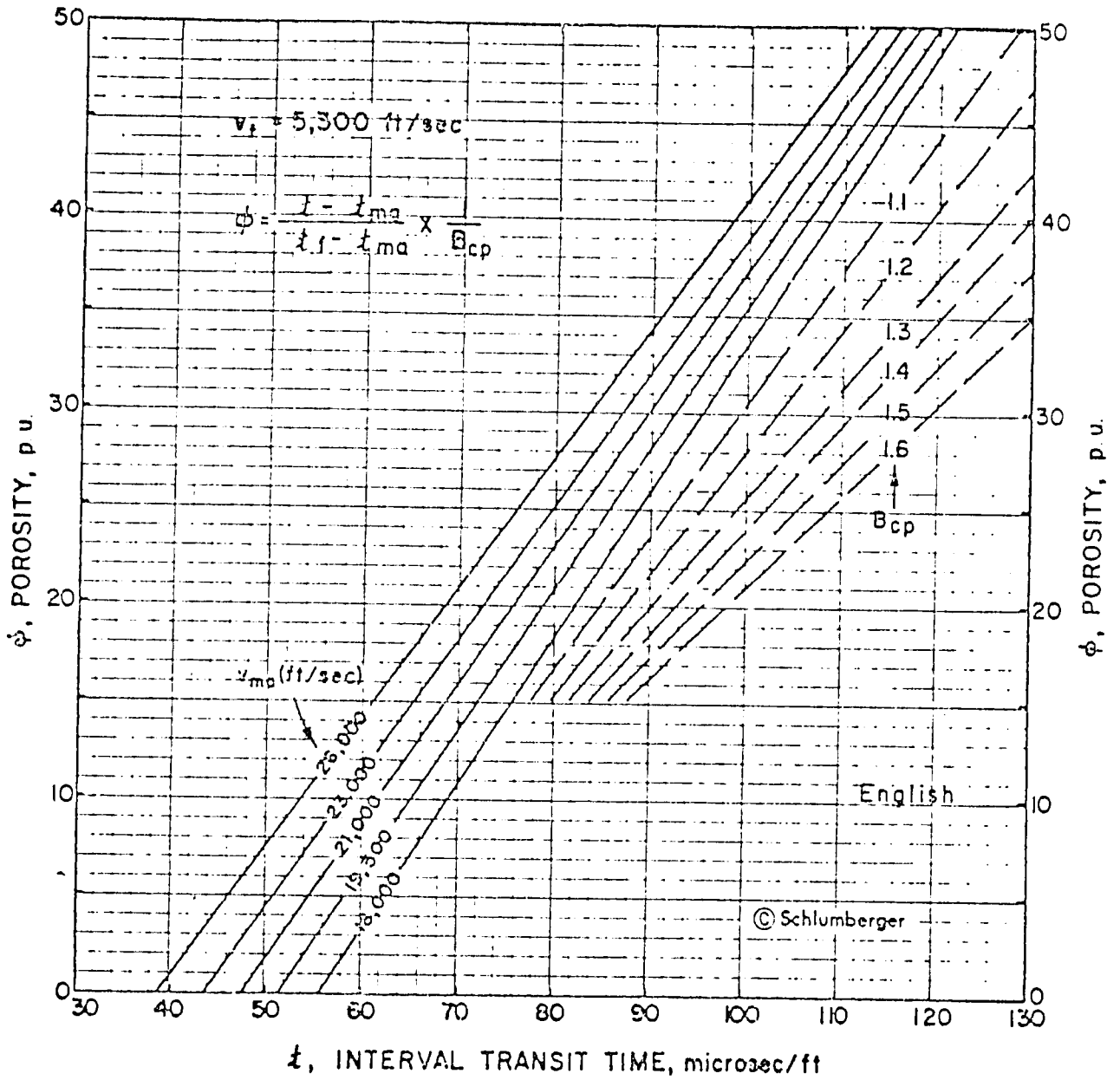
ELASTIC WAVE LOG (CONT'D)

- DETERMINATION OF POROSITY IN CARBONATES
  - IN CARBONATES HAVING INTERGRANULAR POROSITY, THE TIME AVERAGE FORMULA APPLIES
  - AT TIMES PORE STRUCTURE AND PORE SIZE DISTRIBUTION ARE NOT SIMIL TO INTERGRANULAR, BUT CONSIST OF VUGS AND/OR FRACTURES WITH MUCH LARGER DIMENSIONS
  - IN ROCKS CONTAINING SECONDARY POROSITY, THE VELOCITY OF SOUND DEPENDS MOSTLY ON THE PRIMARY POROSITY AND ϕ_s WILL TEND TO BE LOW BY AN AMOUNT APPROACHING SECONDARY POROSITY
  - IN MANY CASES A MODIFIED TIME AVERAGE FORMULA CAN BE USED

    $$\Delta T = A\phi + B(1-\phi)$$

    .. A & B NEED TO BE DETERMINED EMPIRICALLY FOR A GIVEN FORMATION, INTERVAL OR FIELD

POROSITY EVALUATION FROM SONIC



	v_{ma} (ft/sec)	t_{ma} (microsec/ft)
Sandstones	18,000-19,500	55.5-51.3
Limestones	21,000-23,000	47.6-43.5
Dolomites	23,000-26,000	43.5-38.5

ELASTIVE WAVE LOG (CONT'D)

- ΔT VS RESISTIVITY CROSSPLOT

  ARCHIE'S WATER SATURATION EQUATION CAN BE WRITTEN AS

$$S_W^N = \frac{A\,R_W}{\phi^M R_T}$$

USING $N = M = 2$ AND $A = 1$

$$\phi S_W = \left(\frac{R_W}{R_T}\right)^{1/2}$$

THIS SHOWS THAT FOR R_W CONSTANT, ϕS_W IS PROPORTIONAL TO $1/\sqrt{R_T}$ OR

$$\phi = \frac{\sqrt{R_W}}{S_W}\,\frac{1}{\sqrt{R_T}}$$

ϕS_W IS QUANTITY OF WATER PER UNIT VOLUME OF FORMATION

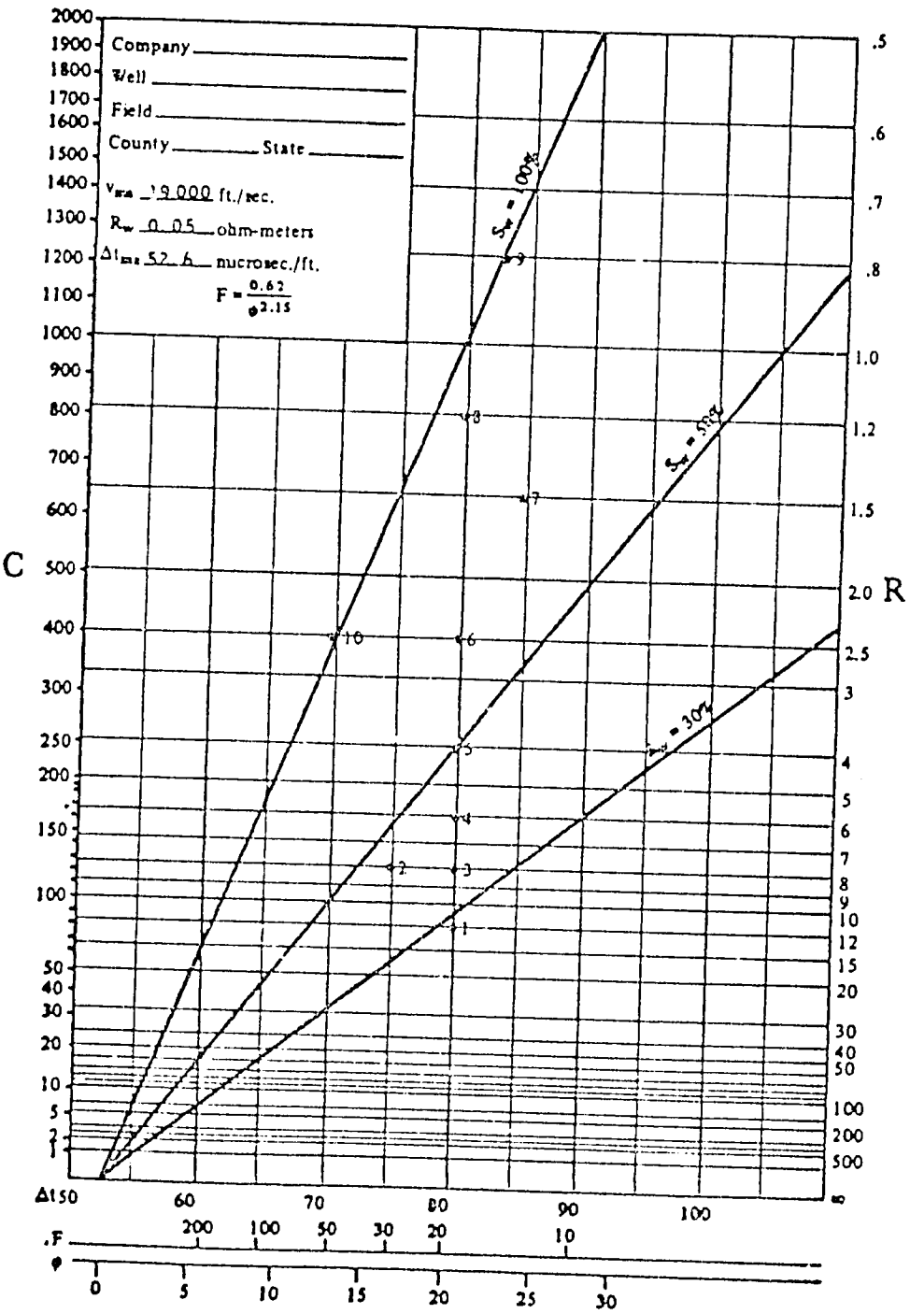
THUS PLOTTING R_T ON AN INVERSE SQUARE ROOT SCALE VS ϕ SHOULD GIVE STRAIGHT LINES FOR CONSTANT VALUES OF WATER SATURATION.

THE CROSSPLOT PROVIDES ESTIMATES OF ΔT_{MA} AND R_W.

WHEN AN INTERVAL CONTAINS ZONES WHERE S_W = 100%, THESE POINTS WILL PLOT TO THE UPPER LEFT HAND PORTION OF CROSSPLOT.

Δt VS. RESISTIVITY

Dresser Atlas



ELASTIC WAVE LOG (CONT'D)

- INTERPRETATION - SHALINES CORRECTION
  - COMPACTED OR UNCONSOLIDATED BEDS CONTAINING SHALE OR CLAY EXHIBIT LONGER ΔT_L THAN CLEAN BED OF SAME ϕ
  - INCREASE IN TRAVEL TIME RESULTS FROM DIFFERENCE IN ΔT_{SH} AND ΔT_{MA}
  - WHEN NOT ACCOUNTED FOR PRESENCE OF SHALES MAKES $\phi_S > \phi$
  - ΔT_{SH} VARIES WITH AREA & DEPENDS ON
    - .. TYPE OF SHALE
    - .. DEGREE OF COMPACTION
    - .. AMOUNT OF SHALE PRESENT
  - NECESSARY TO DETERMINE V_{SH} FROM OTHER LOG MEASUREMENTS
    - .. VARIOUS SHALE INDICATORS ARE USED WITH EACH PROVIDING AN UPPER LIMIT ESTIMATE
    - .. USE OF MINIMUM SHALINESS OBTAINED FROM A NUMBER OF INDICATORS IS USED
  - SHALE CONTENT IS FOUND AS LAMINAL DISPERSED PARTICLES OR AS MATRIX STRUCTURE

ELASTIC WAVE LOG (CONT'D)

. SHALINESS CORRECTION

- FOR LAMINATED SHALE STREAKS, IT MAY BE ASSUMED THAT THESE HAVE THE SAME CHARACTERISTICS AS ADJACENT THICK SHALE BEDS

.. FOR COMPACTED BEDS

$$\Delta T_L = \phi \Delta T_F + V_{SH} \Delta T_{SH} + (1-\phi-V_{SH}) \Delta T_{MA}$$

SOLVING FOR ϕ

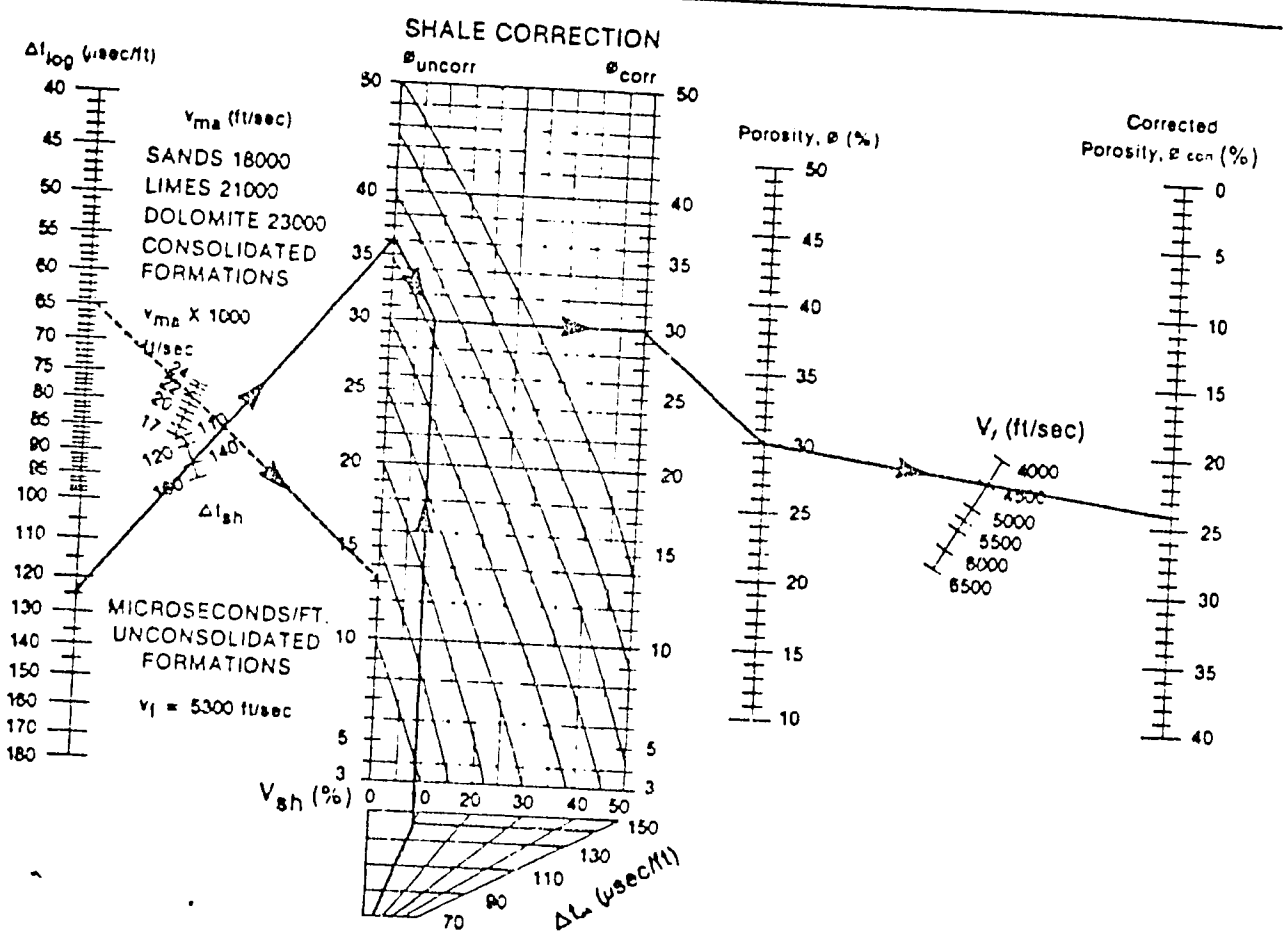
$$\phi = \frac{\Delta T_L - \Delta T_{MA}}{\Delta T_F - \Delta T_{MA}} - V_{SH} \frac{\Delta T_{SH} - \Delta T_{MA}}{\Delta T_F - \Delta T_{MA}}$$

OR

$$\phi = \phi_S - V_{SH} \phi_{SH}$$

.. FOR UNCOMPACTED BEDS

$$= \frac{\phi_S}{C_P} - V_{SH} \phi_{SH}$$



Acoustilog® porosity-shaliness and fluid corrections.

From Dresser Atlas 1981 Booklet on Acoustic Logs

ELASTIC WAVE LOG (CONT'D)

. SHALINESS CORRECTION

- FOR DISSEMINATED OR DISPERSED SHALE PARTICLES IN INTERSTICES
  .. ACOUSTIC RESPONSE IS ABOUT THE SAME AS IF TOTAL PORE SPACE WERE FILLED WITH WATER
  .. THIS WILL BE TRUE FOR DISPERSED SHALE OR CLAY VOLUME NOT EXCEEDING 50% OF PORE VOLUME. HERE

$$Q = \frac{\text{VOL. OF CLAY}}{\text{P.V.}}$$

  .. FOR $Q > 50\%$ ACOUSTIC VELOCITY IN PORES TENDS TO BE HIGHER THAN THAT FOR WATER
  .. ACTUALLY WHEN $Q > 50\%$, A BED LOOSES COMMERCIAL INTEREST BECAUSE OF LOW PERMEABILITY

$$\Delta T_L = \Delta T_F(\phi + V_{SH}) + \Delta T_{MA}(1 - \phi - V_{SH})$$

OR

$$\phi = \frac{\Delta T_L - \Delta T_{MA}}{\Delta T_F - \Delta T_{MA}} - V_{SH}$$

AND

$$\phi = \phi_S - V_{SH}$$

SHALINESS CORRECTION (CONT'D)

. FOR DISSEMINATED OR DISPERSED SHALE AND UNCOMPACTED BEDS

$$\therefore \phi = \frac{\phi_S}{C_P} - V_{SH}$$

THUS

$$Q = \frac{\frac{\phi_S}{C_P} - \phi}{\frac{\phi_S}{C}}$$

.. Q FACTOR IS INDICATIVE OF PRODUCIBILITY OF SHALY RESERVOIR ROCKS

.. PSEUDO Q FACTORS CAN BE GOTTEN FROM DENSITY AND ACOUSTIC LOG POROSITIES

$$Q = \frac{\phi_S - \phi_D}{\phi_S} = \frac{V_{SH}(\phi_{S_{SH}} - \phi_{D_{SH}})}{\phi_S}$$

HERE $\phi_D \approx \phi$ WHEN $\rho_{SH} \approx \rho_{MA}$ AND

$$\phi = \phi_D - V_{SH}\phi_{D_{SH}}$$

ALSO

$$\phi_S - \phi_D = V_{SH}(\phi_{S_{SH}} - \phi_{D_{SH}})$$

SHALINESS CORRECTION (CONT'D)

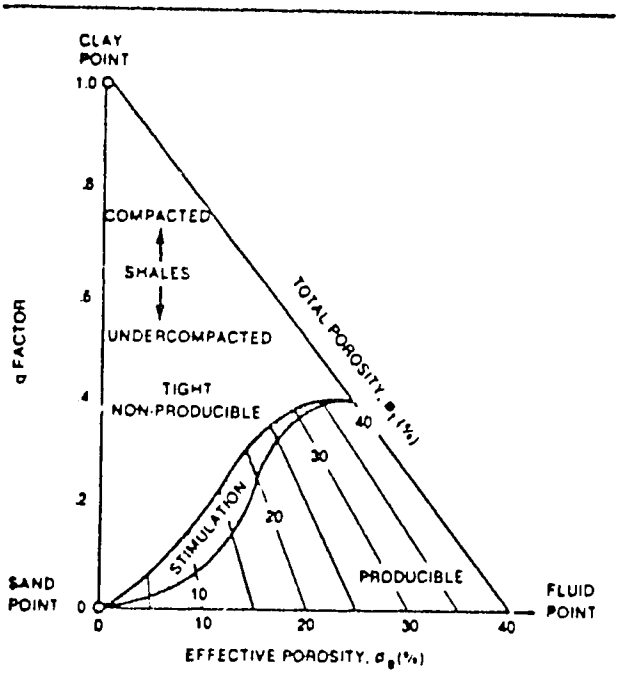
. FOR DISSEMINATED OR DISPERSED SHALE

.. THE FOLLOWING PLOT IS BASED ON FIELD DATA FROM THE GULF COAST AREA, NEW MEXICO, COLORADO AND WYOMING

.. IT CAN BE USED FOR PREDICTING THE PRODUCIBILITY OF SHALY SANDS

.. TENTATIVE PERMEABILITY CUT-OFFS SUCH AS $Q \geqslant 0.4$ AND $Q \geqslant 2$ HAVE BEEN USED

.. THE FIGURE WAS TAKEN FROM DRESSER-ATLAS 1981 BOOKLET ON ACOUSTIC LOGS



Reservoir producibility in shaly sands.

From Dresser Atlas 1981 Booklet on Acoustic Logs

ELASTIC WAVE LOG (CONT'D)

. EFFECT OF HYDROCARBONS

.. RESIDUAL HYDROCARBONS IN THE FLUSHED ZONE CAUSE $\Delta T_F > 189$

.. IN HIGHLY POROUS BEDS INVASION DEPTH IS A MINIMUM AND ΔT_L IS INFLUENCED BY ORIGINAL FORMATION FLUIDS

.. THUS IN HYDROCARBON BEARING BEDS $\phi_S > \phi$

.. CORRECTIONS FOR HYDROCARBONS ARE APPROXIMATE AT PRESENT--BASED ON LIMITED EMPIRICAL DATA COMPARING ΔT_{LOG} IN CLEAN WATER BEARING BEDS TO ΔT_{LOG} IN THE SAME BEDS BUT CONTAINING OIL AND GAS

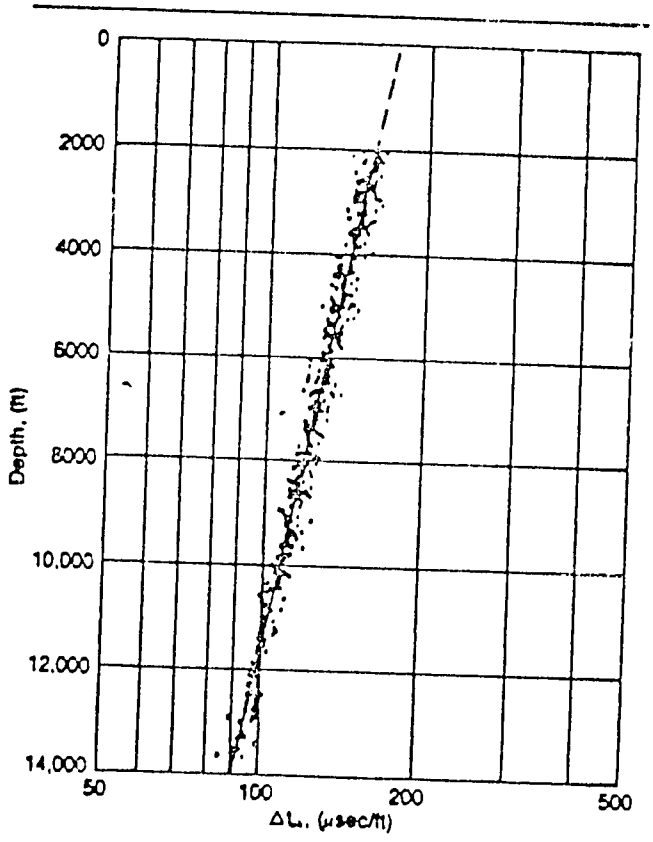
.. FOR AN OIL BEARING SECTION $\phi = \phi_S \times .9$

.. FOR A GAS BEARING SECTION $\phi = \phi_S \times .7$

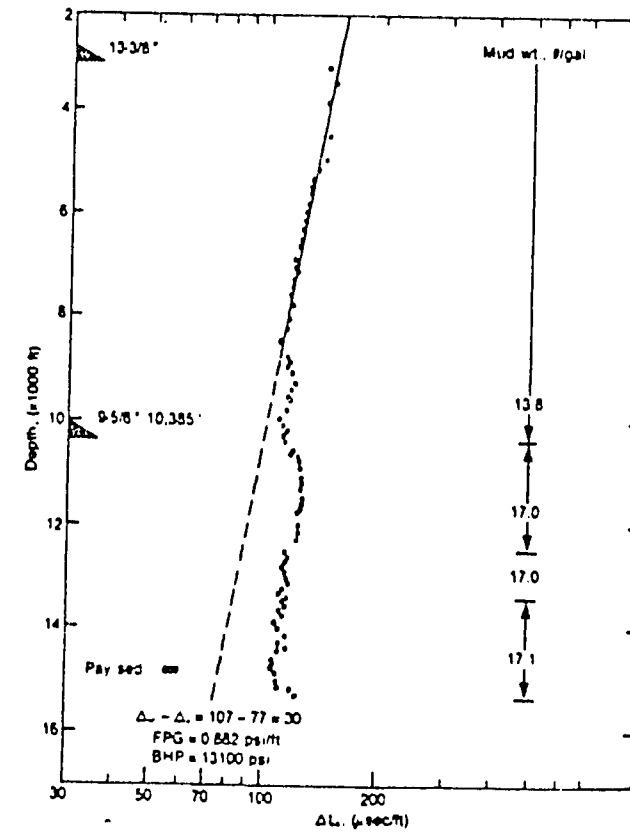
.. DIFFERENT FACTORS MAY BE REQUIRED FOR A PARTICULAR AREA

ELASTIC WAVE LOG (CONT'D)

- ABNORMAL FORMATION PRESSURE DETERMINATION
  - SUBSURFACE PRESSURE GRADIENTS
    0.43 PSI/FT TO 0.5 PSI/FT--NORMAL, >0.50 PSI/FT--ABNORMAL
  - FORMATIONS HAVING ABNORMALLY HIGH PRESSURES ARE OFTEN OVERLAIN BY OVERPRESSURED SHALES WITH EXCESS PORE WATER
  - NORMALLY SHALE POROSITY DECREASES WITH DEPTH AND ΔT_{SH} DECREASES WITH DEPTH EXCEPT WHEN OVERPRESSURED SHALES ARE ENCOUNTERED



Shale Acoustic travel time versus depth of burial for Miocene and Oligocene shales, Upper Texas and Southern Louisiana Gulf Coast area.



Shale transit travel-time plot and application of equivalent depth method for quantitative pressure evaluation. Casing points and mud weight requirements are also given.

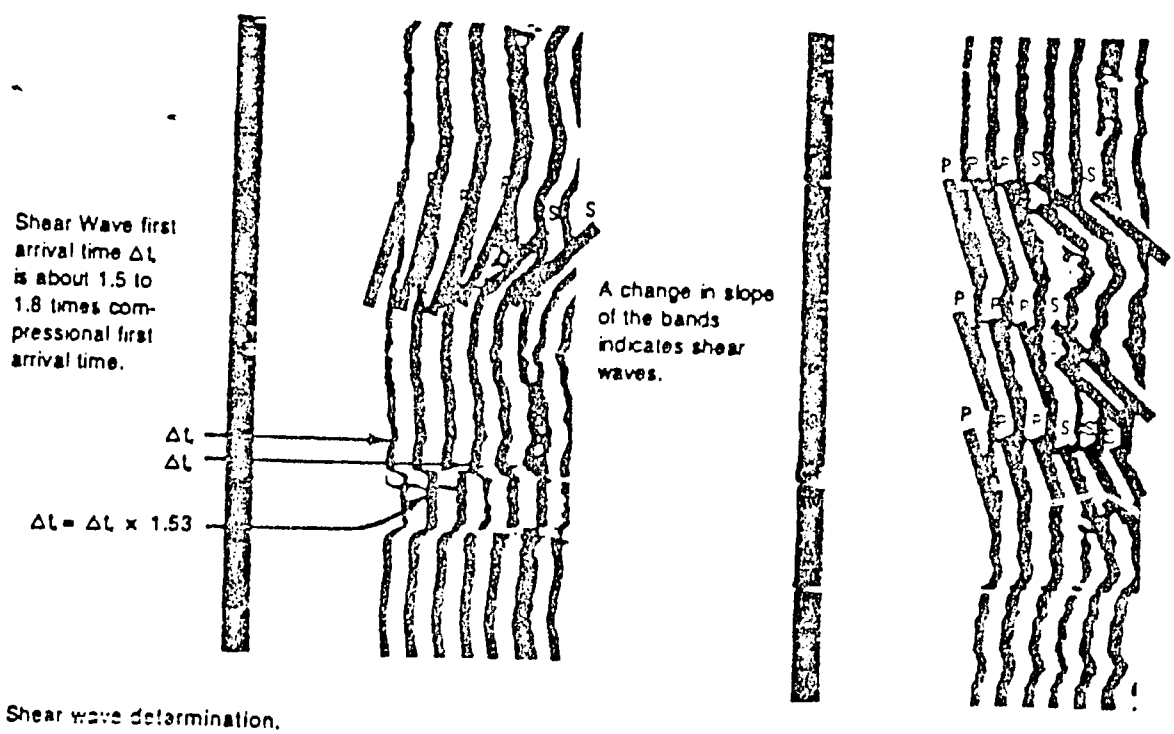
From Dresser Atlas 1981 Booklet on Acoustic Logs

ELASTIC WAVE LOG (CONT'D)

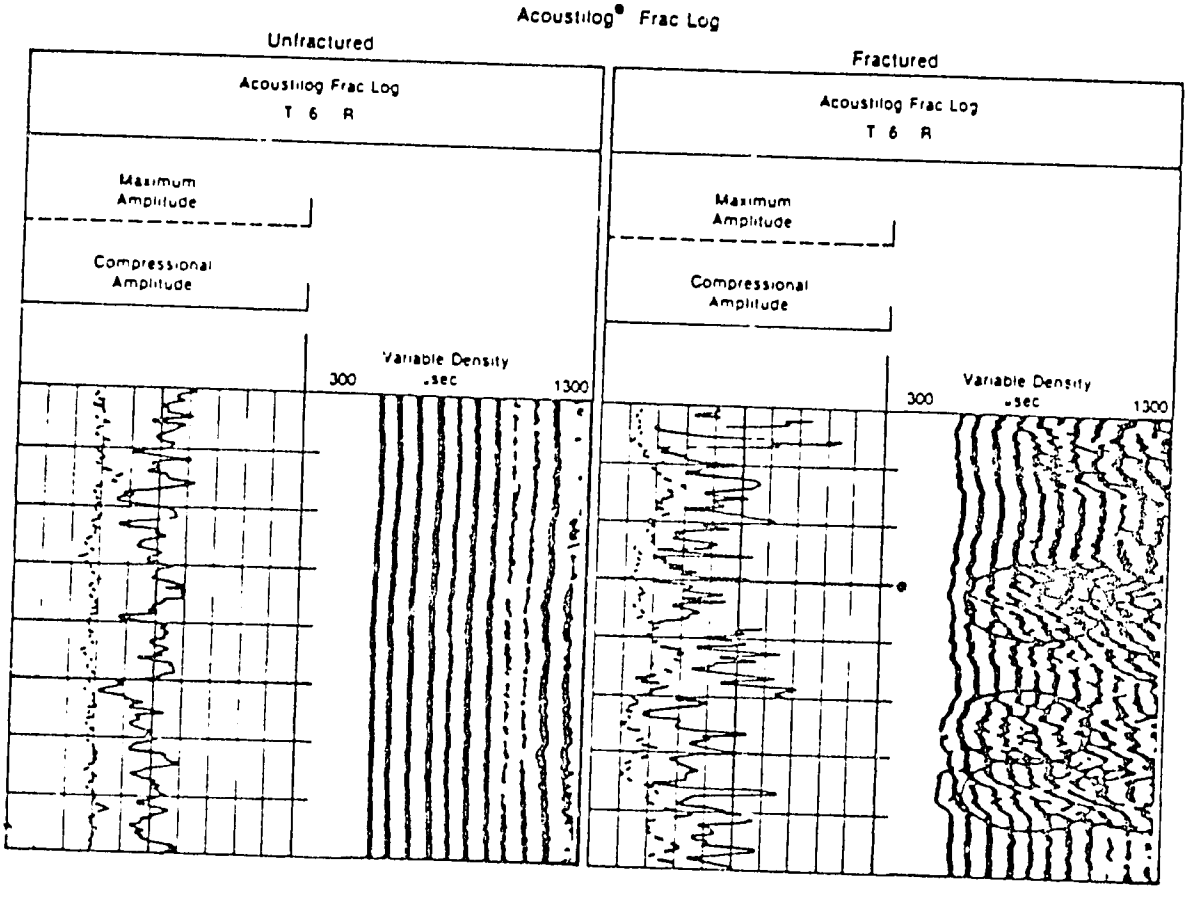
FRACTURE DETECTION

- ACOUSTIC AMPLITUDE LOGS CAN INDICATE PRESENCE OF FRACTURES
  - AMPLITUDE OF COMPRESSIONAL WAVES IS ATTENUATED BY VERTICAL AND HIGH ANGLE FRACTURES
  - AMPLITUDE OF SHEAR WAVES IS ATTENUATED BY HORIZONTAL AND LOW ANGLE FRACTURES
- INTERPRETATION FOR FRACTURE DETECTION IS QUALITATIVE & EMPIRICAL--BASED ON COMPARISON OF LOGS WITH CORE AND DRILLING DATA
- BEDDING PLANES, THIN SHALE STREAKS, HEALED FRACTURES GIVE SAME RESPONSE AS OPEN FRACTURES

From Dresser Atlas 1981 Booklet on Acoustic Logs



Shear wave determination.



Fracture detection from the Variable Density Log.

From Dresser Atlas 1981 Booklet on Acoustic Logs

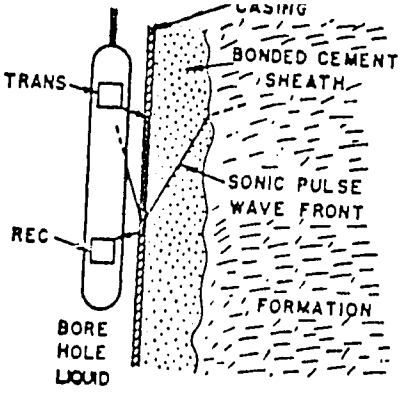
ELASTIC WAVE LOG (CONT'D)

- USES
  - DETERMINE ϕ
  - ASSIST IN GEOPHYSICAL INTERPRETATIONS
    - .. MEASURE VELOCITY
    - .. PROVIDE DATA FOR SYNTHETIC SEISMOGRAMS
  - INDICATE PRESENCE OF SECONDARY ϕ
  - IN COMBINATION WITH OTHER LOGS
    - .. COMPUTE S_W
    - .. DEFINE LITHOLOGY
    - .. RECOGNIZE PRESENCE OF GAS
- LIMITATIONS
  - CANNOT PROVIDE RELIABLE ESTIMATE OF FRACTURE & VUG POROSITY
  - GIVE SATISFACTORY RESULTS UNDER CONDITIONS OF HIGH ATTENUATION
  - PROVIDE ϕ WHEN ΔT_{MA} & ΔT_F ARE UNKNOWN
  - INTERPRETATION BECOMES DIFFICULT IN SHALY FORMATIONS

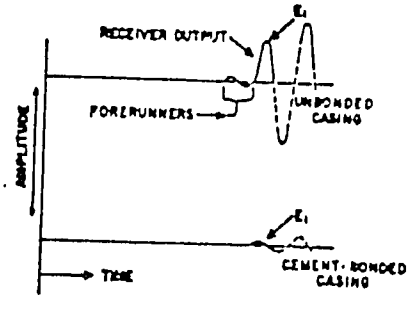
ELASTIC WAVE LOG (CONT'D)

CEMENT BOND LOGGING

- USED TO ASSESS QUALITY OF CEMENT-TO-CASING BOND
- MAY BE RECORDED WITH STANDARD SONIC TOOL ON MULTI-CONDUCTOR CABLE OR WITH A CEMENT BOND TOOL ON MONO CABLE
- RECORDS AMPLITUDE IN MV OF FIRST 1/2 CYCLE OF THE SIGNAL AT A RECEIVER 3' FROM TRANSMITTER
  - .. MAXIMUM IN UNSUPPORTED CASING
  - .. MINIMUM IN WELL CEMENTED CASING
  - .. IS A FUNCTION OF CASING SIZE AND THICKNESS, CEMENT STRENGTH AND THICKNESS, DEGREE OF CEMENT BONDING AND TOOL CENTERING



–SCHEMATIC DIAGRAM OF THE CEMENT BOND LOGGING TOOL.



–COMPARISON OF TYPICAL RECEIVER SIGNAL IN UNBONDED CASING AND IN CEMENT-BONDED CASING.

From J. Petr. Tech., Feb. 1961

ELASTIC WAVE LOG (CONT'D)

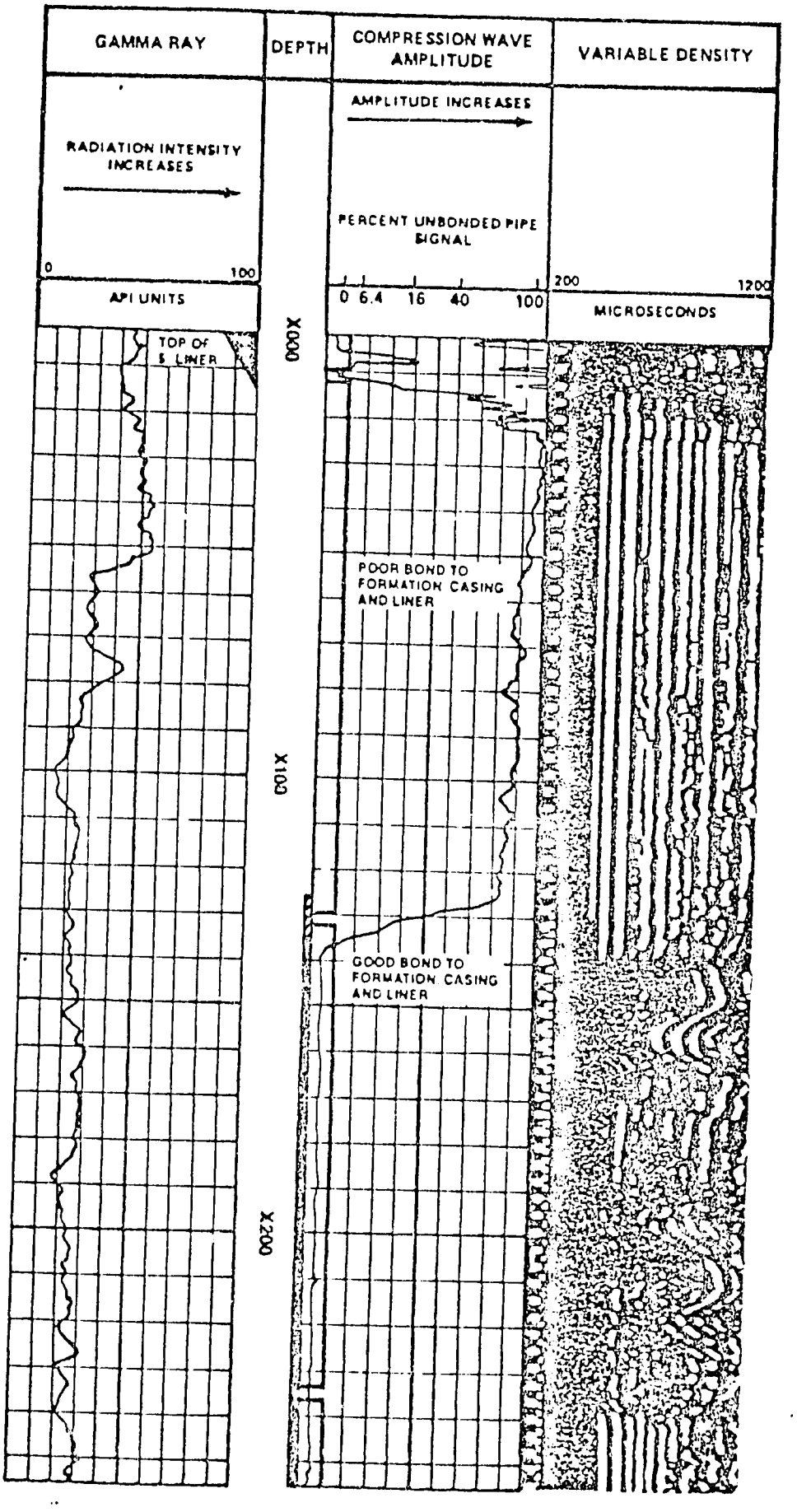
VARIABLE DENSITY LOG (VDL)

- VDL WAVE TRAIN IS RECORDED AT A RECEIVER 5' FROM TRANSMITTER
- SAME TOOL CAN HAVE ANOTHER RECEIVER 3' FROM TRANSMITTER FOR CBL
- EQUIPMENT INCLUDES AN OSCILLOSCOPE
- OSCILLOSCOPE TRACES ARE PHOTOGRAPHED PRODUCING A VARIABLE DENSITY DISPLAY
- ON OSCILLOSCOPE DARK AREAS CORRESPOND TO POSITIVE AND LIGHT AREAS TO NEGATIVE EXCURSIONS OF WAVE FORM
- IN CEMENTED CASING THERE ARE FOUR POSSIBLE SOUND PATHS FROM TRANSMITTER TO RECEIVER
  - .. ALONG CASING (FASTEST)
  - .. ALONG CEMENT
  - .. THROUGH FORMATIONS
  - .. THROUGH MUD
- IN FREE, UNCEMENTED CASING MOST OF SOUND ENERGY TRAVELS VIA PIPE--LITTLE IS TRANSFERRED TO CEMENT & FORMATIONS

VARIABLE DENSITY LOG (CONT'D)

- STRONG CASING ARRIVALS ARE SHOWN BY STRAIGHT, STRONGLY CONTRASTING DARK & LIGHT BANDS AT LOW ARRIVAL-TIME RANGE
- WHEN CEMENT IS BONDED TO THE PIPE, ENERGY IS TRANSFERRED TO CEMENT A CASING ARRIVALS ARE WEAKENED
- SOUND TRAVELING ALONG CEMENT IS ATTENUATED
- IF CEMENT IS WELL BONDED TO FORMATION, ENERGY IS TRANSFERRED TO ROCKS AND STRONG FORMATION SIGNALS DEVELOP
- GOOD CEMENT BONDING IS INDICATED BY WEAK CASING SIGNALS ARRIVING, FIRST FOLLOWED BY STRONGER P WAVE SIGNALS FROM ROCKS
- CASING ARRIVALS CAN BE DIFFERENTIATED FROM FORMATION ARRIVALS BECAUSE THE FORMER HAVE A CONSTANT ΔT WHILE THE LATTER ARE LIKELY TO VARY
- IF FORMATION ARRIVALS ARE NOT CLEARLY SHOWN, POSSIBLE POOR BOND WITH ROCKS OR HIGH FORMATION ATTENUATION ARE INDICATED
- PRESENCE OF GAS IN MUD ATTENUATES THE WHOLE WAVE TRAIN

From Dresser Atlas 1981 Booklet on Acoustic Logs

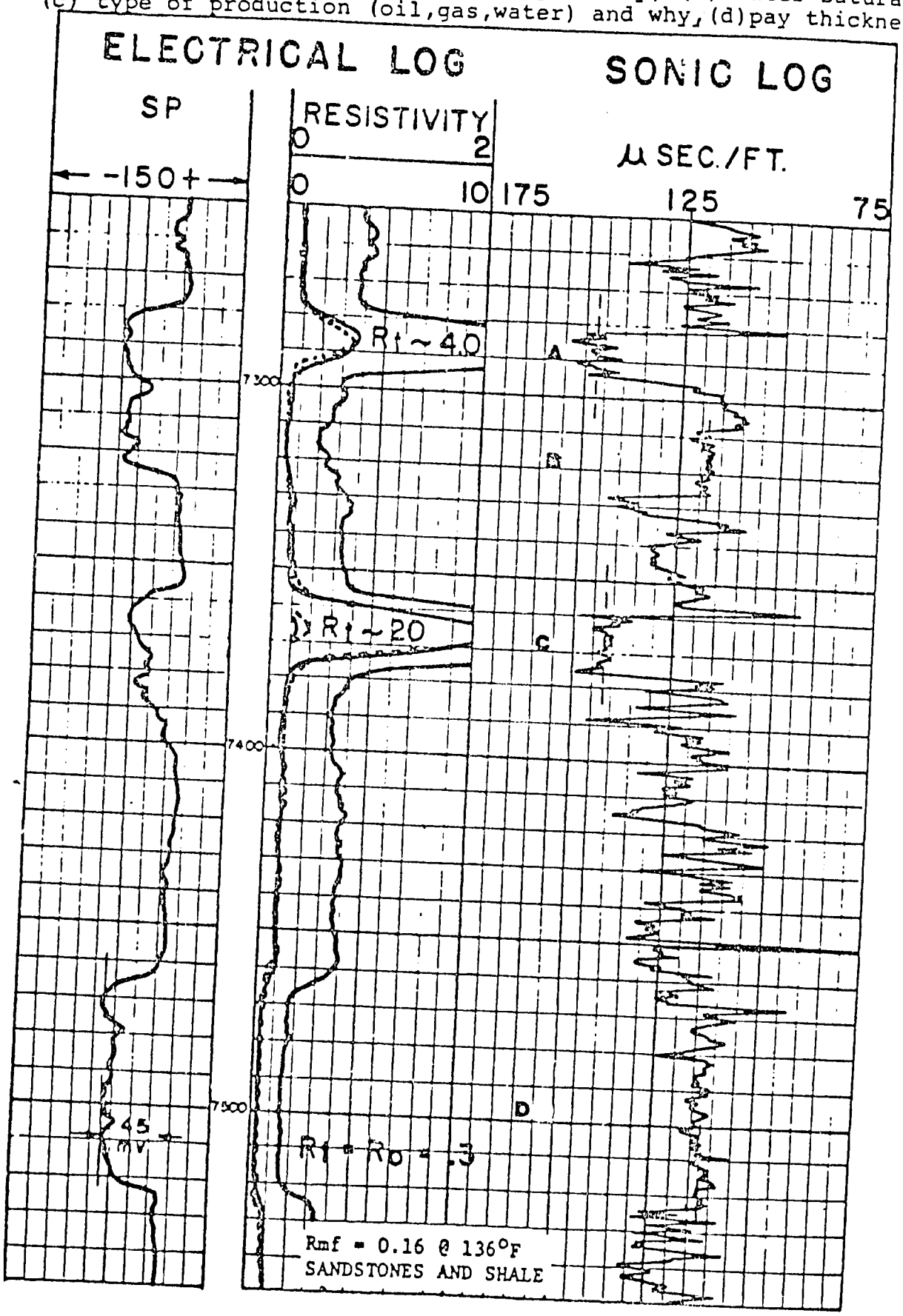


Acoustic Cement Bond/Variable Density Log.

Sonic Log Problem

Given: Electrical and Sonic Logs through sandstone and shale beds. Assume the R_t values shown are correct. It is estimated that zones A & B contain 20% shale and zones C&D contain 30% shale.

Required: Determine for each marked zone (a) porosity, (b) water saturation, (c) type of production (oil,gas,water) and why, (d) pay thickness if cut-off porosity is 15



THE FORMATION DENSITY LOG (DENSILOG)

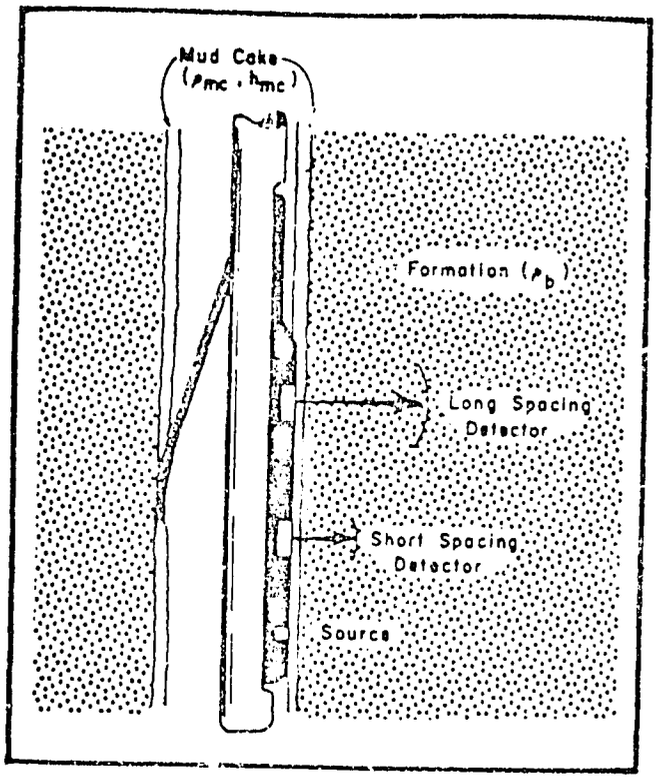
DENSITY LOG IS AN OPENHOLE TOOL DESIGNED TO MEASURE THE BULK DENSITY OF ROCKS

DENSITY LOG USES

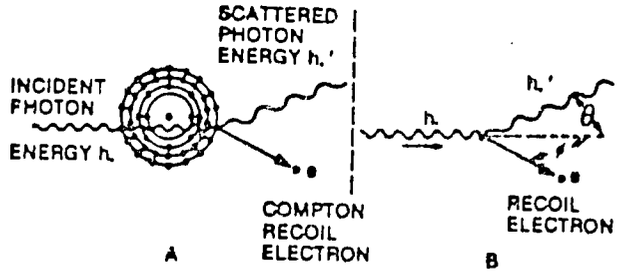
- DETERMINATION OF POROSITY
- IDENTIFICATION OF MINERALS IN EVAPORITE DEPOSITS
- DETECTION OF GAS
- EVALUATION OF SHALY SANDS AND COMPLEX LITHOLOGIES
- DETERMINATION OF OIL SHALE YIELD

PRINCIPLE

- A RADIOACTIVE (COBALT-60 OR CESIUM 137) SOURCE ON A SHIELDED SIDEWALL SKID EMITS MEDIUM ENERGY (.6 TO 1.3 MEV) GAMMA RAYS
- GAMMA RAYS COLLIDE WITH ROCK ELECTRONS--ON EACH COLLISION A GAMMA RAY LOOSES SOME OF ITS ENERGY & CONTINUES ON--THIS PHENOMENA IS CALLED COMPTON SCATTERING
- SCATTERED GAMMA RAYS REACHING THE DETECTOR, AT A FIXED DISTANCE FROM THE SOURCE, ARE COUNTED AS AN INDICATION OF FORMATION DENSITY



— *Schematic drawing of the dual spacing Formation Density Logging Device (FDC). (Courtesy AIME)*



(A) Schematic of the Compton process (B) Geometrical relations in the Compton process

PRINCIPLE CONT'D

- NUMBER OF COMPTON-SCATTERING COLLISIONS IS RELATED DIRECTLY TO NUMBER OF ELECTRONS IN THE FORMATION
- RESPONSE OF DENSITY TOOL DEPENDS ON THE ELECTRON DENSITY (NUMBER OF ELECTRONS PER CC) OF THE FORMATION
- ELECTRON DENSITY IS RELATED TO TRUE BULK DENSITY, ρ_B, IN GMS/CC
- BULK DENSITY, ρ_B DEPENDS ON ρ_{MA}, ϕ, AND ρ_{MF}
- FEWER GAMMA RAYS ARE DETECTED AS THE DENSITY OF A FORMATION INCREASES
- TOOL INVESTIGATES ABOUT 6" INTO THE ROCK FROM THE BOREHOLE

TWO DETECTOR FORMATION DENSITY COMPENSATED LOG (FDC)

- REPRESENTS A MAJOR IMPROVEMENT OVER INITIAL SINGLE SPACED FORMATION LOG (FDL) IN BOTH ACCURACY AND CONVENIENCE OF OBTAINING CORRECTED VALUES FROM RAW DATA
- MUD COLUMN INFLUENCE IS MINIMIZED
- EMPLOYS TWO DETECTORS SPACED AT DIFFERENT INTERVALS FROM THE SOURCE
- SOURCE AND DETECTORS ARE MOUNTED ON A SKID AND SHIELDED
- SHIELDS ARE APPLIED AGAINST BOREHOLE WALL BY STRONG ECCENTERING ARM
- SKID HAS A PLOW-SHAPED LEADING EDGE DESIGNED TO REMOVE AT LEAST 1/2 OF MUD CAKE

$$H_{MC} = D_H - D_{CALIPER}$$

DENSITY LOG (CONT'D)

FDC CONT'D

- SHORT SPACED DETECTOR IS PARTICULARLY SENSITIVE TO DENSITY OF MATERIAL ADJACENT TO PAD
- MUD CAKE & MINOR BOREHOLE WALL IRREGULARITIES AFFECT RESPONSE OF EACH DETECTOR TO A DIFFERENT DEGREE
- SIGNALS FROM BOTH DETECTORS ARE COMBINED IN ANALOG COMPUTER TO PROVIDE AUTOMATIC MUD CAKE & HOLE SIZE CORRECTIONS
- BOTH ρ_B AND AMOUNT OF COMPENSATION, $\Delta\rho$ ARE RECORDED ON THE LOG
- HAS A VERTICAL RESOLUTION OF ABOUT 2'
- MAXIMUM RECOMMENDED LOGGING SPEED IS 1800 FT/HR
- MINIMUM REQUIRED BOREHOLE DIAMETER IS 5"
- HAS A MAXIMUM PRESSURE RATING OF 20,000 PSI
- HAS A TEMPERATURE RATING OF 350°F

DENSITY LOG (CONT'D)

LOG PRESENTATION

- FDC IS RECORDED IN TRACKS 2 & 3 USING A LINEAR DENSITY SCALE IN GMS/CC
- $\Delta\rho$ CURVE IS RECORDED IN TRACK 3
- CALIPER & GAMMA RAY ARE RECORDED IN TRACK 1

SONDES

FDC - GR - CALIPER

FDC - MSFL - GR - CALIPER

FDC - CNL - GR - CALIPER

DENSITY LOG (CONT'D)

FACTORS AFFECTING LOG RESPONSE

. BOREHOLE SIZE

.. CORRECTIONS ARE NEGLIGIBLE FOR HOLES SMALLER THAN 10" DIAMETER

.. FOR LARGER HOLES SMALL CORRECTIONS ARE REQUIRED AS SHOWN BY CHART POR-5B

. MUD CAKE

.. ATTENUATING EFFECT OF MUD CAKE DEPENDS ON ρ_{MC}, T_{MC} AND MUD COMPOSITION

.. ANY MUD CAKE OR MUD REMAINING BETWEEN THE TOOL & THE FORMATION IS SEEN AS PART OF FORMATION AND REQUIRES CORRECTION

.. ROUGHNESS OF BOREHOLE WALL CAN MAKE CONTACT IMPERFECT BETWEEN TOOL AND FORMATION--SOME MUD IS ADDED TO MEASUREMENTS

.. FDC USES TWO DETECTORS--A LONG SPACING COUNT RATE VS A SHORT-SPACING COUNT RATE IS RECORDED

.. FDC USES THE TWO COUNT RATES WITH THE "SPINE & RIB" CORRECTION CHART TO DETERMINE CORRECTED ρ_B WITHOUT MEASUREMENT OF ρ_{MC} & T_{MC}

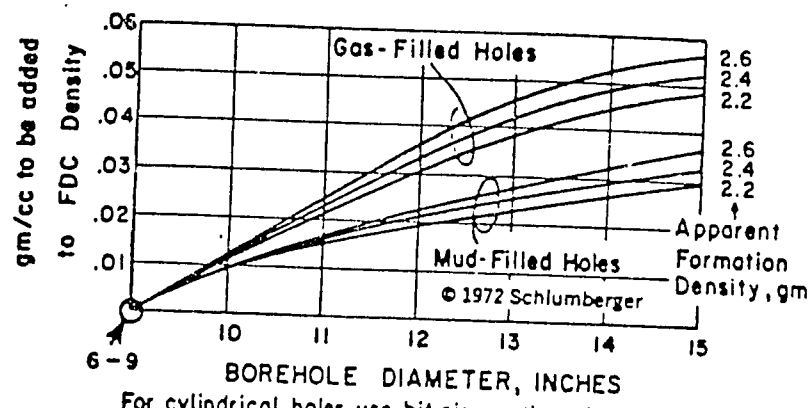
.. THIS CORRECTION IS MADE AUTOMATICALLY

.. "SPINE & RIB" PLOT FOR EMPTY HOLES IS DIFFERENT THAN THAT FOR HOLES WITH MUD

Schlumberger

FDC BOREHOLE CORRECTIONS

(For small mud-cake thicknesses)



For cylindrical holes use bit size rather than caliper.

Par-5b

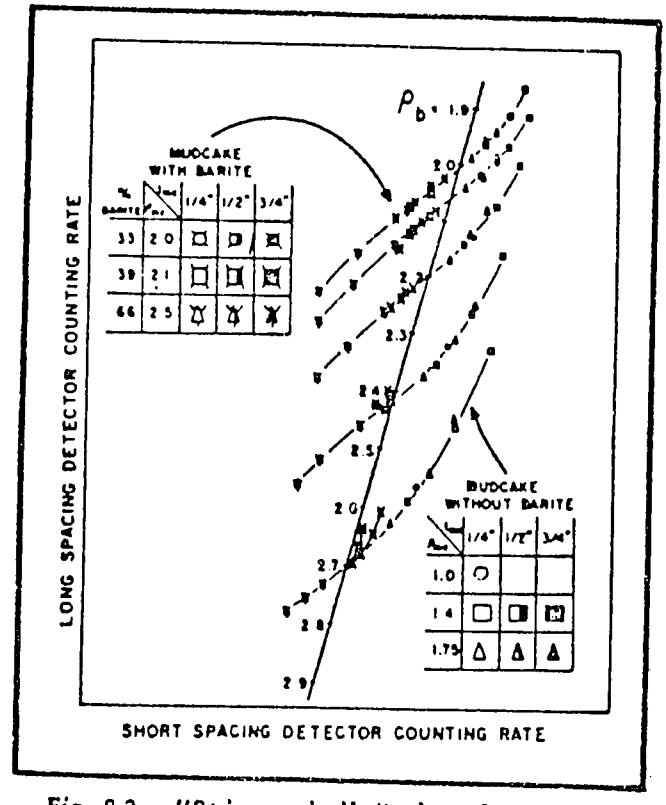


Fig. 8-2 — "Spine-and-ribs" plot, showing response of FDC counting rates to mud cake (Courtesy AIME)

TIME CONSTANT AND LOGGING SPEED

- DENSITY LOG MEASURES PHENOMENA THAT IS RADIOACTIVE & DISPLAYS STATISTICAL VARIATIONS
- ENOUGH MEASUREMENTS MUST BE TAKEN AT EACH POINT TO PROVIDE A REPRESENTATIVE AVERAGE VALUE
- DATA ARE SMOOTHED BEFORE RECORDING BY PASSING SIGNALS THROUGH CIRCUIT HAVING A TIME CONSTANT OF 2, 3, OR 4 SECONDS
- TWO SECONDS ARE USED WHEN ρ_{MA} IS LOW (HIGH POROSITIES) AND FOUR SECONDS ARE USED WHEN ρ_{MA} IS HIGH (LOW POROSITIES)
- LOGGING SPEED IS CHOSEN SO THAT TOOL WILL NOT TRAVEL MORE THAN ONE FOOT PER TIME CONSTANT
- MAXIMUM RECOMMENDED LOGGING SPEED IS 1800 FT/HR

DENSITY LOG (CONT'D)

CALIBRATION

- PRIMARY CALIBRATION STANDARDS ARE LABORATORY FRESH WATER-FILLED LIMESTONE BLOCKS OF HIGH PURITY AND ACCURATELY KNOWN DENSITIES
- SECONDARY STANDARDS ARE LARGE ALUMINUM & SULFUR BLOCKS INTO WHICH SONDE IS INJECTED--OF DESIGNED GEOMETRY & COMPOSITION--CHARACTERISTICS RELATED TO LIMESTONE BLOCKS
- TWO DIFFERENT THICKNESSES OF ARTIFICIAL MUD CAKES ARE USED TO CHECK AUTOMATIC MUD CAKE CORRECTION
- SECONDARY STANDARDS ARE KEPT AT THE LOCATION SHOPS
- AT WELL SITE, A RADIOACTIVE TEST JIG IS USED TO PRODUCE A SIGNAL OF KNOWN INTENSITY TO CHECK DETECTION SYSTEM

ELECTRON DENSITY & BULK DENSITY

- DENSITY LOG RESPONDS TO THE ELECTRON DENSITY OF ROCKS BUT RECORDS BULK DENSITY
- THE QUESTION IS THEN WHAT IS THE RELATION BETWEEN ρ_e AND ρ_B?
  - .. LET AN ELECTRON DENSITY INDEX, ρ_e, BE DEFINED WHICH IS PROPORTIONAL TO ELECTRON DENSITY. THUS FOR A SINGLE ELEMENT

$$\rho_e = \rho_B \left(\frac{2Z}{A} \right)$$

Z = ATOMIC NUMBER (NUMBER OF ELECTRONS PER ATM

A = ATOMIC WEIGHT (ρ_B/A IS PROPORTIONAL TO NUMBER OF ATOMS PER CC OF SUBSTANCE)

.. FOR A SUBSTANCE

$$\rho_e = \rho_B \left[\frac{2 \sum Z's}{\text{MOL. WT.}} \right]$$

∴ FOR MOST ROCKS THE BRACKETED QUANTITIES IN THE ABOVE EQUATIONS ARE ABOUT UNITY. THUS

$$\rho_e \approx \rho_B$$

DENSITY LOG (CONT'D)

ELECTRON DENSITY & BULK DENSITY CONT'D

- APPARENT BULK DENSITY, ρ_L, IS RELATED TO ELECTRON DENSITY BY

$$\rho_L = 1.0704\,\rho_e - 0.1883$$

- FOR LIQUID FILLED SANDSTORES, LIMESTONES & DOLOMITES $\rho_L \approx \rho_B$
- FOR A FEW SUBSTANCES--SYLVITE, ROCK SALT, GYPSUM, ANHYDRITE, COAL & GAS - BEARING FORMATIONS

$\rho = \rho$ + CORRECTION

Element	A	Z	$2\frac{Z}{A}$
H	1.008	1	1.9841
C	12.011	6	.9991
O	16.000	8	1.0000
Na	22.99	11	.9569
Mg	24.32	12	.9868
Al	26.98	13	.9637
Si	28.09	14	.9968
S	32.07	16	.9978
Cl	35.46	17	.9588
K	39.10	19	.9719
Ca	40.08	20	.9980

Z/A RATIOS OF COMMON EARTH ELEMENTS

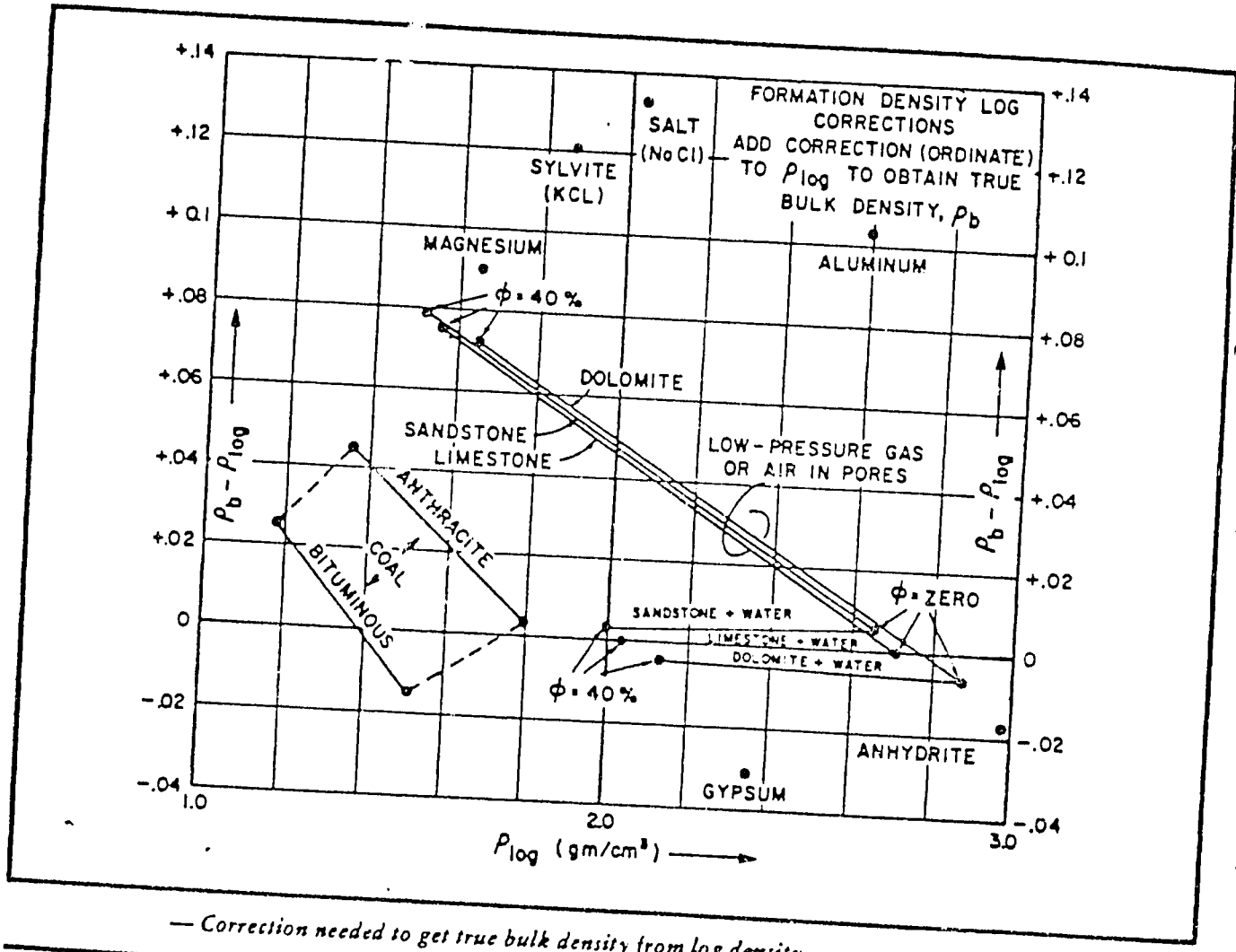
ELEMENT	SYMBOL	A	Z/A
Hydrogen	H	1.008	0.992
Oxygen	O	16.0	0.500
Nitrogen	N	14.007	0.500
Carbon	C	12.011	0.499
Calcium	Ca	40.08	0.499
Sulfur	S	32.06	0.499
Silicon	Si	28.086	0.498
Magnesium	Mg	24.312	0.495
Potassium	K	39.102	0.487
Aluminum	Al	26.98	0.482
Sodium	Na	23.00	0.479
Chlorine	Cl	35.45	0.479
Iron	Fe	55.85	0.466
Barium	Ba	137.34	0.407

From Schlumberger's Log Interpretation Principles, (1972)

VARIATIONS IN DENSITY DUE TO CALIBRATION AND ELECTRON DENSITY EFFECTS

MATERIAL	FORMULA	ACTUAL DENSITY g/cm³	$\frac{\Sigma Z}{M}$	DENSITY SEEN BY DENSILOG® g/cm³
Quartz	SiO_2	2.65	0.499	2.65
Calcite	$CaCo_3$	2.71	0.500	2.71
Dolomite	$CaCo_3 \cdot MgCo_3$	2.87	0.499	2.875
Anhydrite	$CaSO_4$	2.96	0.499	2.98
Gypsum	$CaSO_4 \cdot 2H_2O$	2.32	0.511	2.35
Halite	NaCl	2.165	0.479	2.03
Sylvite	KCl	1.98	0.483	1.86
Anthracitic Coal		1.40 - 1.80	0.515	1.36 - 1.80
Bituminous Coal		1.20 - 1.50	0.530	1.17 - 1.51
Lignite		0.70 - 1.50	0.545	0.63 - 1.56
Water	H_2O	1.00	0.555	1.00
Saltwater	(100,000 PPM)	1.07	0.548	1.067
Saltwater	(200,000 PPM)	1.146	0.540	1.135
Oil	$C_n(CH_2)$	0.80	0.570	0.80
Gas	C_nH_{2n+2}	0.20	0.619	0.08

From Dresser Atlas 1980 Booklet on Compensated Densilog



— *Correction needed to get true bulk density from log density*

DENSITY LOG (CONT'D)

POROSITY DETERMINATION

. FOR CLEAN FORMATIONS

$$\rho_B = \phi\rho_F + (1-\phi)\rho_{MA} \approx \rho_L$$

. FOR COMMON MATRIX MINERALS THE DIFFERENCE BETWEEN ρ_L AND ρ_B IS SO TRIVIAL THAT IT CAN BE DISREGARDED AND

$$\phi = \frac{\rho_{MA} - \rho_L}{\rho_{MA} - \rho_F}$$

. TO OBTAIN ϕ, ρ_{MA} & ρ_F MUST BE KNOWN

. ROCK MATRIX DENSITY, ρ_{MA}

.. DENSITY IS DEFINED AS MASS PER UNIT VOLUME--OFTEN EXPRESSED AS SPECIFIC GRAVITY

$$\text{SP.GR.} = \frac{\text{WT. OF UNIT VOL. OF MATERIAL}}{\text{WT. OF UNIT VOL. OF WATER}}$$

.. MATRIX DENSITY IS DEPENDENT ON MINERAL COMPOSITION, TEMPERATURE & PRESSURE

.. THE DENSITY OF SEDIMENTARY ROCKS RANGES FROM ABOUT 2.0 GM/CC TO 3.0 GM/CC

.. SEVERAL SHALE MINERALS HAVE DENSITIES CLOSE TO THAT OF QUARTZ--THUS PRESENCE OF SHALE HAS LITTLE EFFECT IN SHALY SAND STONES EXCEPT WHEN PREDOMINANT SHALE MINERAL IS MONTMORILLONITE

.. MONTMORILLONITE IS THE PRINCIPAL CONSTITUENT OF BENTONITE--COMMON IN CALIFORNIA

The grain densities of the more common minerals

Anhydrite	2.95	Magnesite	3.00-3.12
Dolomite	2.85	Kaolinite	2.63
Calcite	2.71	Illite	2.76
Feldspar	2.55-2.80	Montmorillonite	2.00
Gypsum	2.32	Halite	2.17
Quartz	2.65	Sulphur	2.05-2.09
Anthracite	1.30-1.70	Sylvite	1.85
Bituminous Coal	1.14-1.40	Carnallite	1.56
Lignite	1.15-1.30	Langbeimite	2.81

Fluid Densities used with common liquids and gases

Fluid and Gas	(gm/cc)
Air (STP)	0.00129
Natural Gas (STP)	0.00078
Natural Gas 3000 psi 180°	0.146
Oil 50° API	0.780
Oil 30° API	0.876
Oil 10° API	1.000
Water (STP)	
Fresh	1.000
Sea	1.026
Highly saline	1.180

From Dresser Atlas 1980 Booklet Compensated Densilog

DENSITIES OF CLAY MINERALS

	(g/cm³)	
Chlorite	2.60 - 2.95	Low water absorptive properties
Halloysite	2.55 - 2.56	Completely evacuated
	2.76 - 3.00	Muscovite
	2.70 - 3.10	Biotite
	2.642 - 2.688	No absorbed water
Kaolinite	2.609	Theoretical density
	2.60 - 2.68	Extensive literature
	2.63	Most frequently quoted
Palygorskite	2.29 - 2.36	Limited data
Sepiolite	2.08	Limited data
Smectite	2.20 - 2.70	Nontronite essentially
	2.24 - 2.30	Saponite dehydrated
	2.348	
	2.20 - 2.70	Montmorillonite
	2.53	Low-iron smectite
	2.74	3.6% iron content
Vermiculite	No precise data; oven-dried similar to biotite-mica	

DENSITY LOG (CONT'D)

POROSITY DETERMINATION CONT'D

. PORE FLUID DENSITY, $_F$

.. ρ_F DEPENDS ON CHEMICAL COMPOSITION, TEMPERATURE, AND PRESSURE

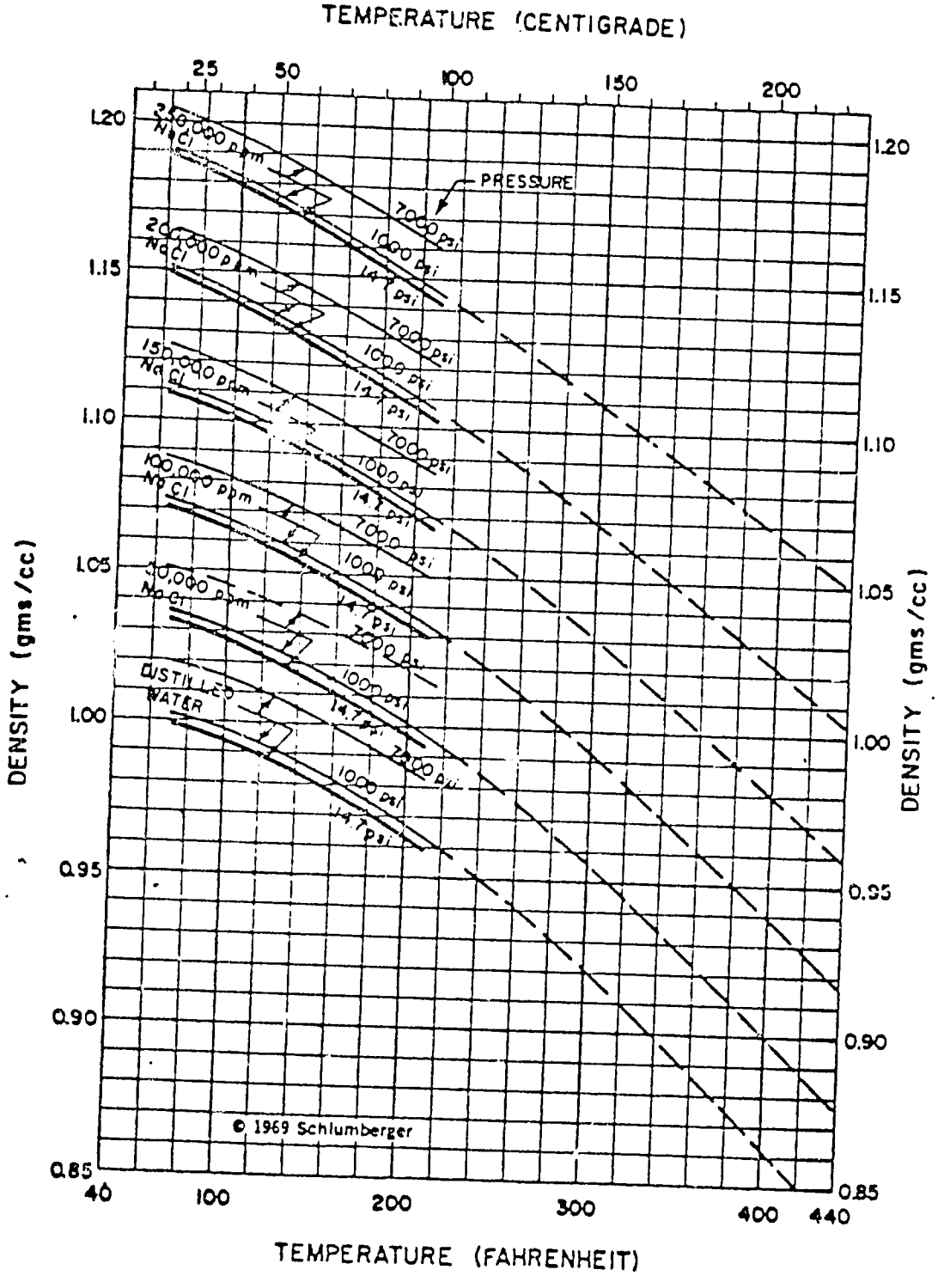
.. CHART IS AVAILABLE TO DETERMINE ρ_F WHEN SALINITY, TEMPERATURE AND PRESSURE ARE KNOWN

.. AS A RULE FRESH WATER ($<$25,000 PPM NACL) HAS $\rho_F \approx 1.0$ AND SALT WATER ($\approx$ 150,000 PPM NACL) HAS $\rho_F \approx 1.1$ GM/CC

.. MEASUREMENTS (ρ_L) ARE IN R_{XO} AREA WHERE PREDOMINANT FLUID IS MUD FILTRATE

- IN AQUIFERS $\rho_F \approx 1.0$
- IN HYDROCARBON RESERVOIRS WITH BLACK OILS, ρ_F 1.0
- IN HYDROCARBON RESERVOIRS WITH LIGHT OILS OR GASES $\rho_F < 1.0$-- USE OF ρ_F = 1.0 LEADS TO ϕ BEING TOO HIGH

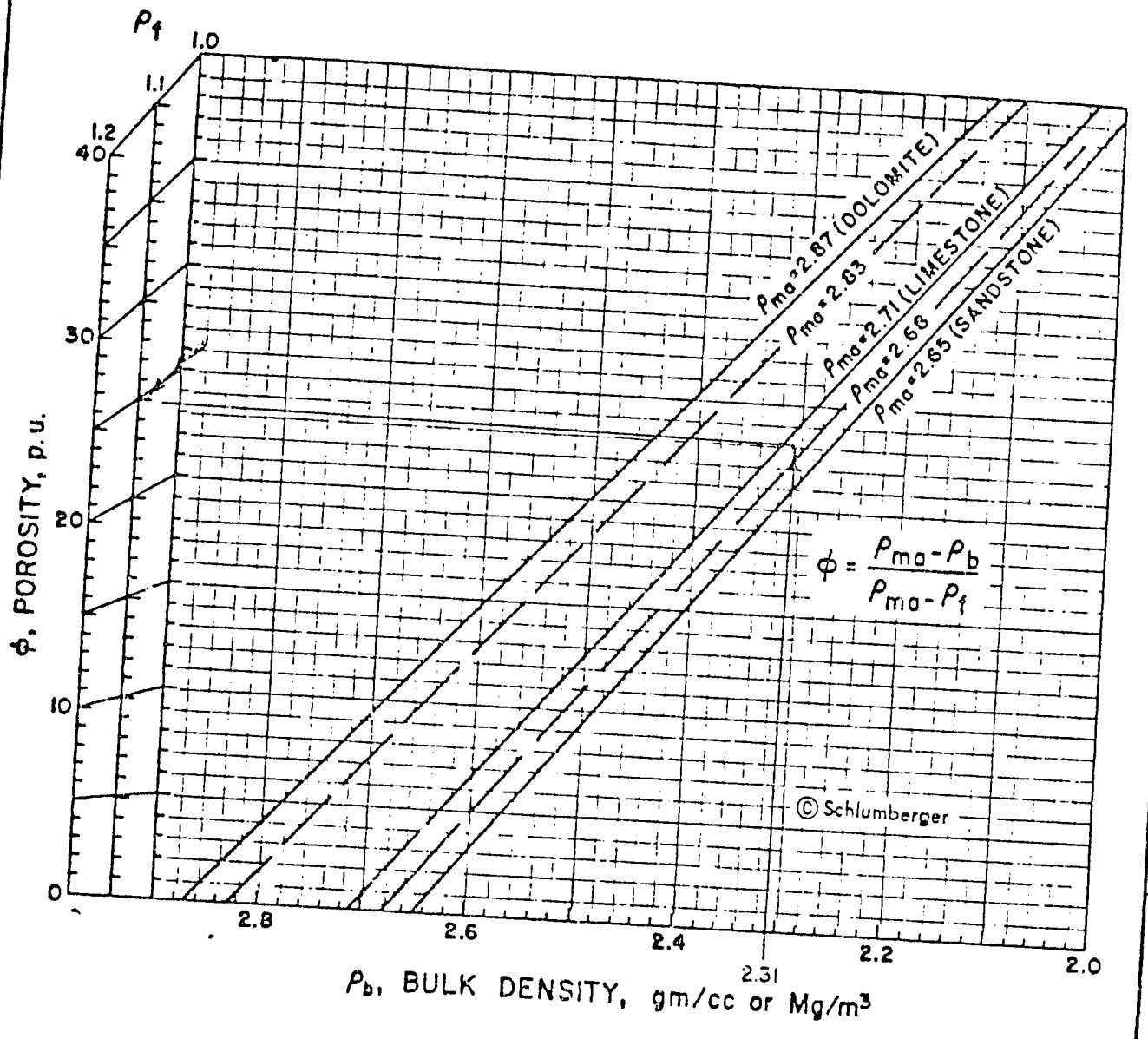
DENSITIES OF WATER AND NaCl SOLUTIONS



Groups of curves plotted versus pressure are shown for Distilled Water, and for NaCl solutions of five different salinities. Use the 1000 psi lines to estimate the density at the given salinity and temperature. Then estimate the pressure correction on the basis of the separation between the 1000 psi and 7000 psi lines.

Curves for temperatures above 212° are derived from data given by Ellis and Golding, American Journal of Science, Vol. 261, pp. 47-60 (Jan 1963).

FORMATION DENSITY LOG
DETERMINATION OF POROSITY



EXAMPLE: $\rho_b = 2.31$ Mg/m³ in limestone lithology

$\rho_{ma} = 2.71$ (limestone)

$\rho_f = 1.1$ (salt mud)

SOLUTION: $\phi_D = 25$ p.u.

DENSITY LOG (CONT'D)

EFFECT OF SHALE

- POROSITY DETERMINATION MAY BE AFFECTED BY PRESENCE OF SHALE
- ρ_{SH} VARIES WITH AREA, CLAY, MINERALS PRESENT AND DEGREE OF COMPACTION
- MINERAL COMPOSITION OF SHALE VARIES OVER A WIDE RANGE
- SHALE DENSITIES ARE USUALLY BETWEEN 2.20 GM/CC AND 2.85 GM/CC
- WHEN $\rho_{SH} \approx 2.65$ GM/CC DENSITY LOG GIVES CORRECT POROSITY FOR SHALY BED
- DEPENDING ON ρ_{SH} $\phi_D \gtreqless \phi$
- AT SHALLOW DEPTH ρ_{SH} TEND TO BE LOWER AND EFFECT IS GREATER
- SHALE DISSEMINATED IN PORES TENDS TO HAVE LOWER DENSITY THAN ADJACENT LAMINAR SHALE STREAKS

DENSITY LOG (CONT'D)

EFFECT OF SHALE CONT'D

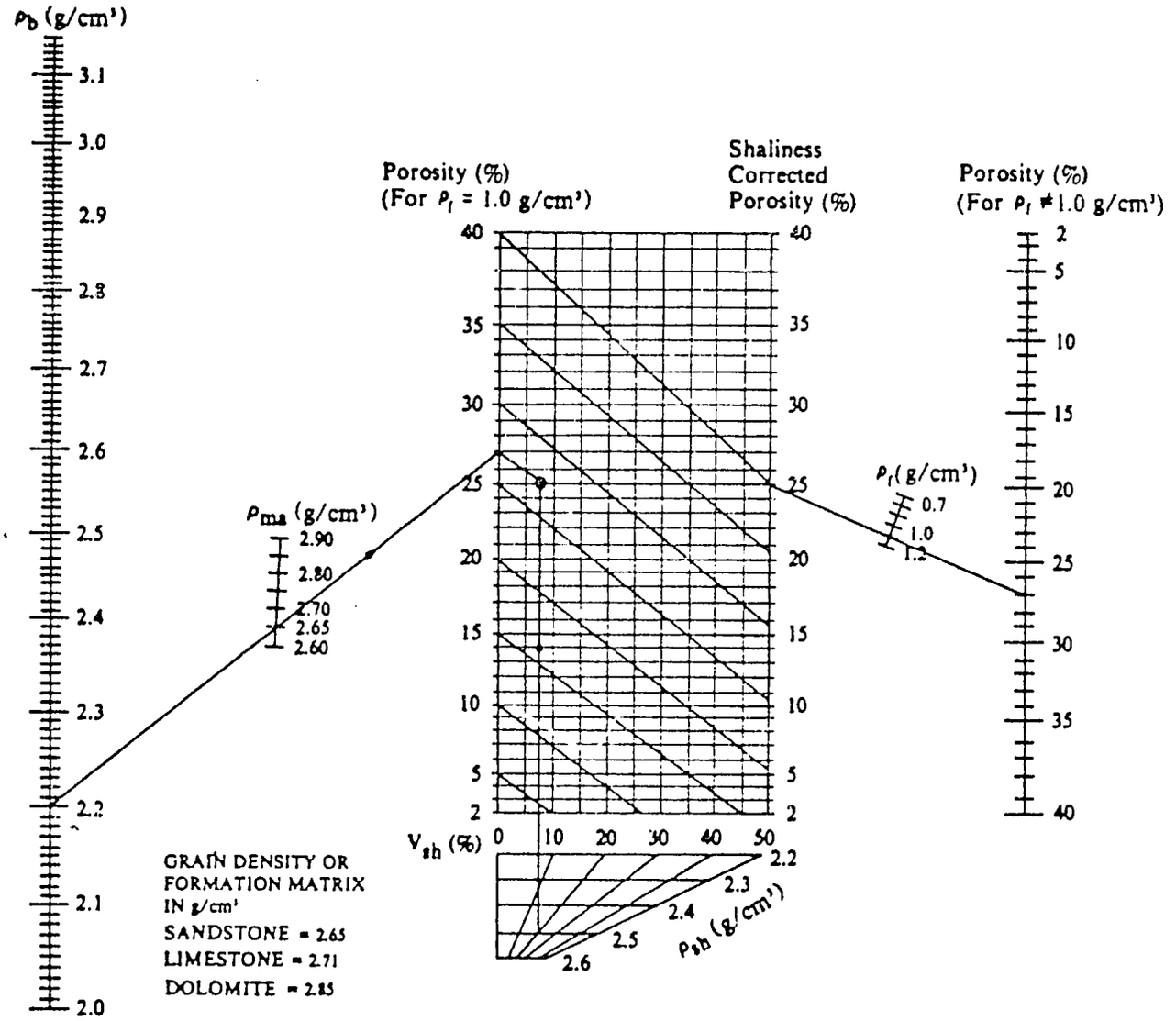
- FOR A SHALY (S_W = 100%) BED THE BULK DENSITY IS GIVEN BY

$$\rho_b = \phi\rho_F + V_{SH}\rho_{SH} + (1-\phi-V_{SH})\rho_{MA} \quad \text{or}$$

$$\phi = \frac{\rho_{MA}-\rho_B}{\rho_{MA}-\rho_F} - V_{SH}\frac{\rho_{MA}-\rho_{SH}}{\rho_{MA}-\rho_F}$$

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

$$\phi = \phi_D - V_{SH}\phi_{DSH}$$



Densilog porosity - shaliness and fluid density correction

From Dresser Atlas 1980 Booklet on Compensated Densilog

DENSITY LOG (CONT'D)

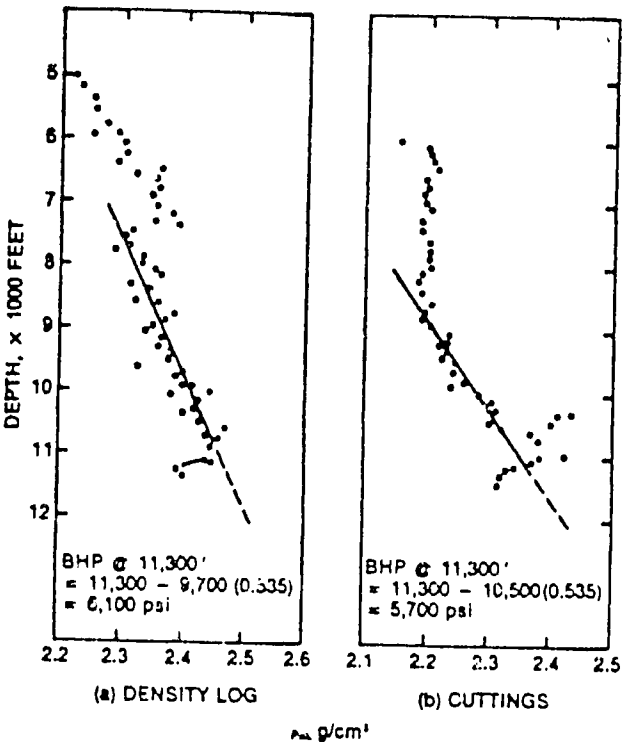
SHALE BULK DENSITY, ρ_{SH}

- BULK DENSITY OF SHALE NORMALLY INCREASES WITH DEPTH DUE TO COMPACTION
- PLOT OF ρ_{SH} WITH DEPTH GIVES A COMPACTION TREND LINE
- NORMAL COMPACTION TREND REVERSES WITHIN OVERPRESSURED ZONES
- IN OVERPRESSURED ZONES SHALES ARE UNDERCOMPACTED DUE TO EXCESS WATER--THUS BULK DENSITIES ARE LOWER THAN NORMAL
- A DECREASE IN SHALE BULK DENSITY WITH DEPTH REFLECTS PRESENCE OF OVER-PRESSURED ENVIRONMENT

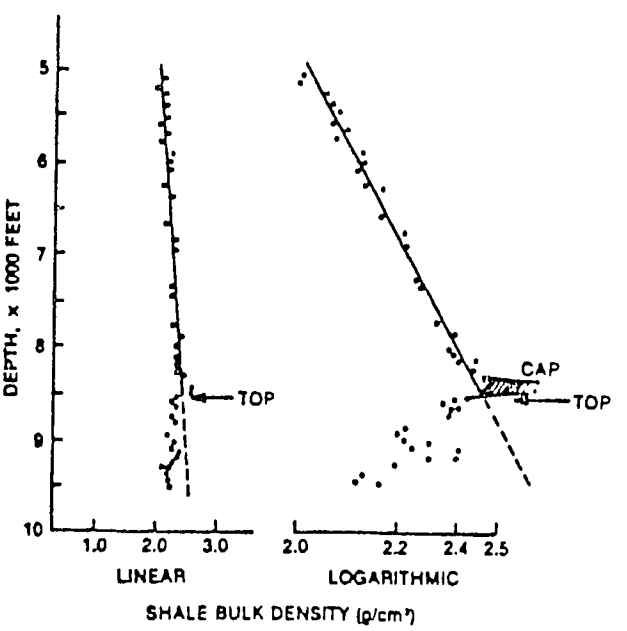
GULF COAST SHALE DENSITIES

DEPTH (Feet)	BULK DENSITY (g/cm^3)
0	1.80
2000	2.20
4000	2.34
6000	2.44
8000	2.52
10000	2.57
12000	2.60
16000	2.63

From Dresser Atlas 1980 Booklet on Compensated Densilog



Shale bulk densities measured by density log and from cuttings plotted vs. depth in an offshore Louisiana well.



Log derived shale bulk density plots on linear and logarithmic scales for detection of overpressure zones.

From Dresser Atlas 1980 Booklet on Compensated Densilog

DENSITY LOG (CONT'D)

EFFECT OF RESIDUAL HYDROCARBONS

- THE BULK DENSITY FOR A SHALY BED CONTAINING RESIDUAL HYDROCARBON (R_{XO} ZONE) IS

$$\rho_B = \phi(S_{XO}\rho_{MF} + S_{HR}\rho_H) + V_{SH}\rho_{SH} + (1-\phi-V_{SH})\rho_{MA}$$

- NORMALLY IT IS ASSUMED THAT $S_{HR} = 0$ AND THAT PORES ARE FULL OF MUD FILTRATE
- THE EFFECT WILL BE SMALL FOR BLACK OILS WHERE $\rho_H \approx 0.8$ AND S_{HR} 20%
- FOR LIGHT OILS AND GASES THE EFFECT IS SIGNIFICANT BECAUSE $\rho_H \approx .5$ TO 0.2
- THE ABOVE EQUATION CAN BE REARRANGED TO GIVE

$$\phi_D = \phi + V_{SH}\phi_{DSH} + \phi(1-S_{XO})(\phi_{DH} - 1)$$

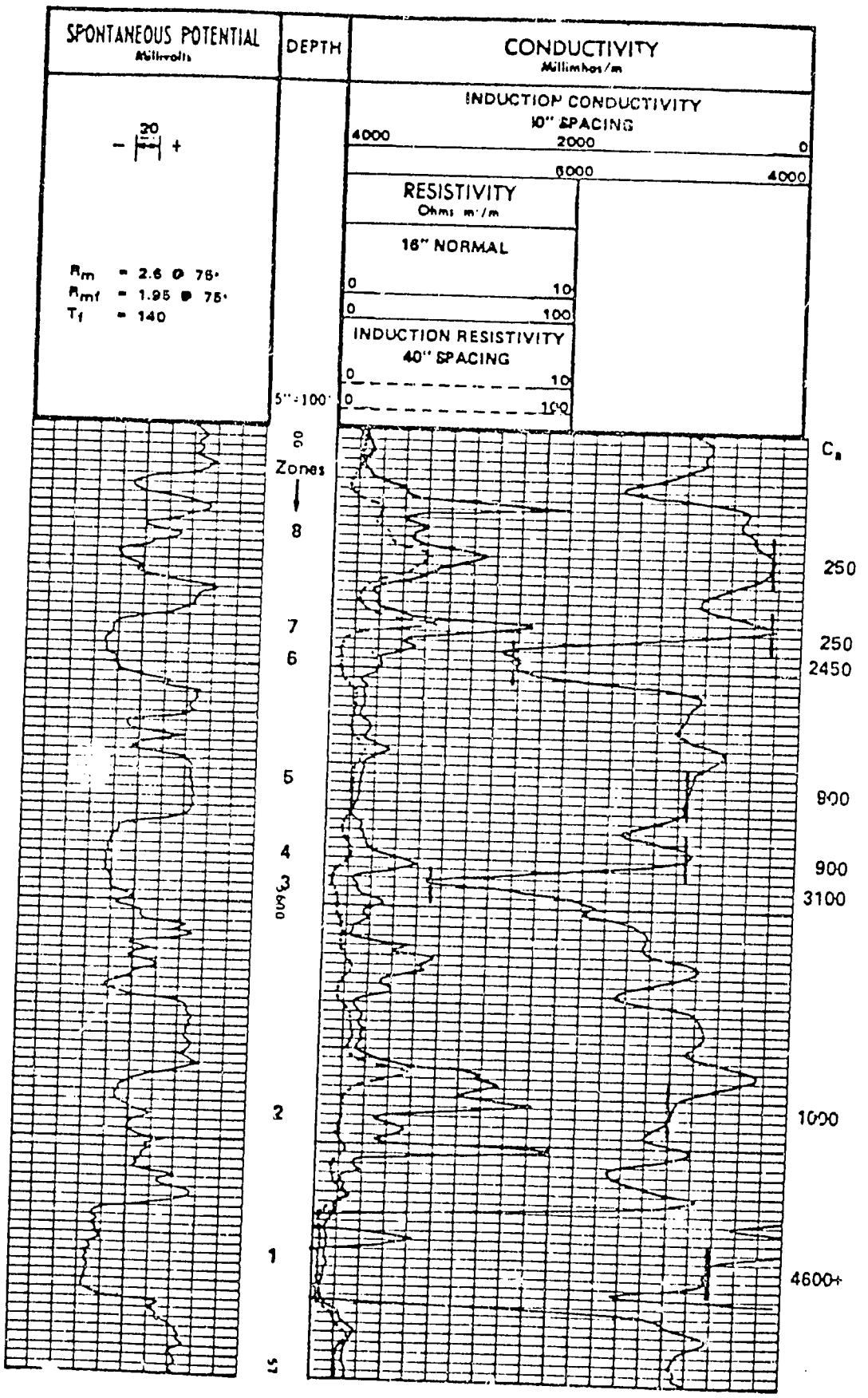
HERE $(1-S_{XO})(\phi_{DH}-1)$ IS THE RESIDUAL HYDROCARBON EFFECT. WHEN S_{XO}=100% THE EQUATION REDUCES TO THE SHALY BED MODEL WHEN S_W = 100%

IT SHOULD BE NOTED THAT

$$\phi_D = \frac{\rho_{MA} - \rho_L}{\rho_{MA} - \rho_F} \qquad \rho_F \approx 1.0$$

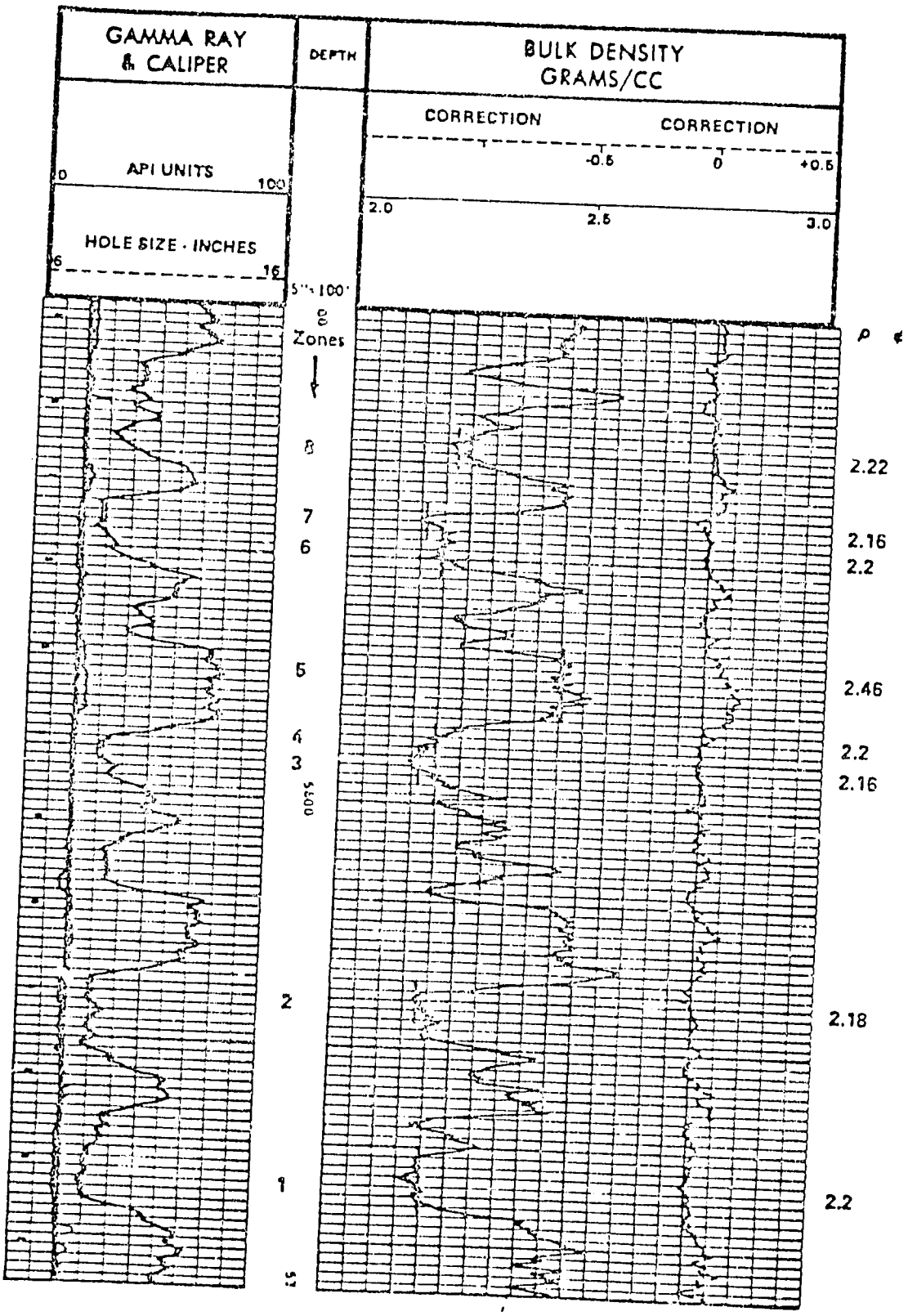
$$\phi_{D_{SH}} = \frac{\rho_{MA} - \rho_{SH}}{\rho_{MA} - \rho_F}$$

$$\phi_{D_H} = \frac{\rho_{MA} - \rho_H}{\rho_{MA} - \rho_F}$$



Example 181a

From Dresser Atlas Log Interpretation Fundamentals (1975)



L. Cretaceous Sand. in Mississippi
Assume all sands are clean.

Example 181b

From Dresser Atlas Log Interpretation Fundamentals (1975)

NEUTRON LOG

WHAT IS IT?

A WELL LOGGING METHOD IN WHICH FORMATIONS ARE BOMBARDED WITH NEUTRONS & MEASUREMENTS ARE MADE OF RESULTING EFFECTS WHICH DEPEND PRIMARILY ON THE H_2 CONTENT OF THE ROCKS

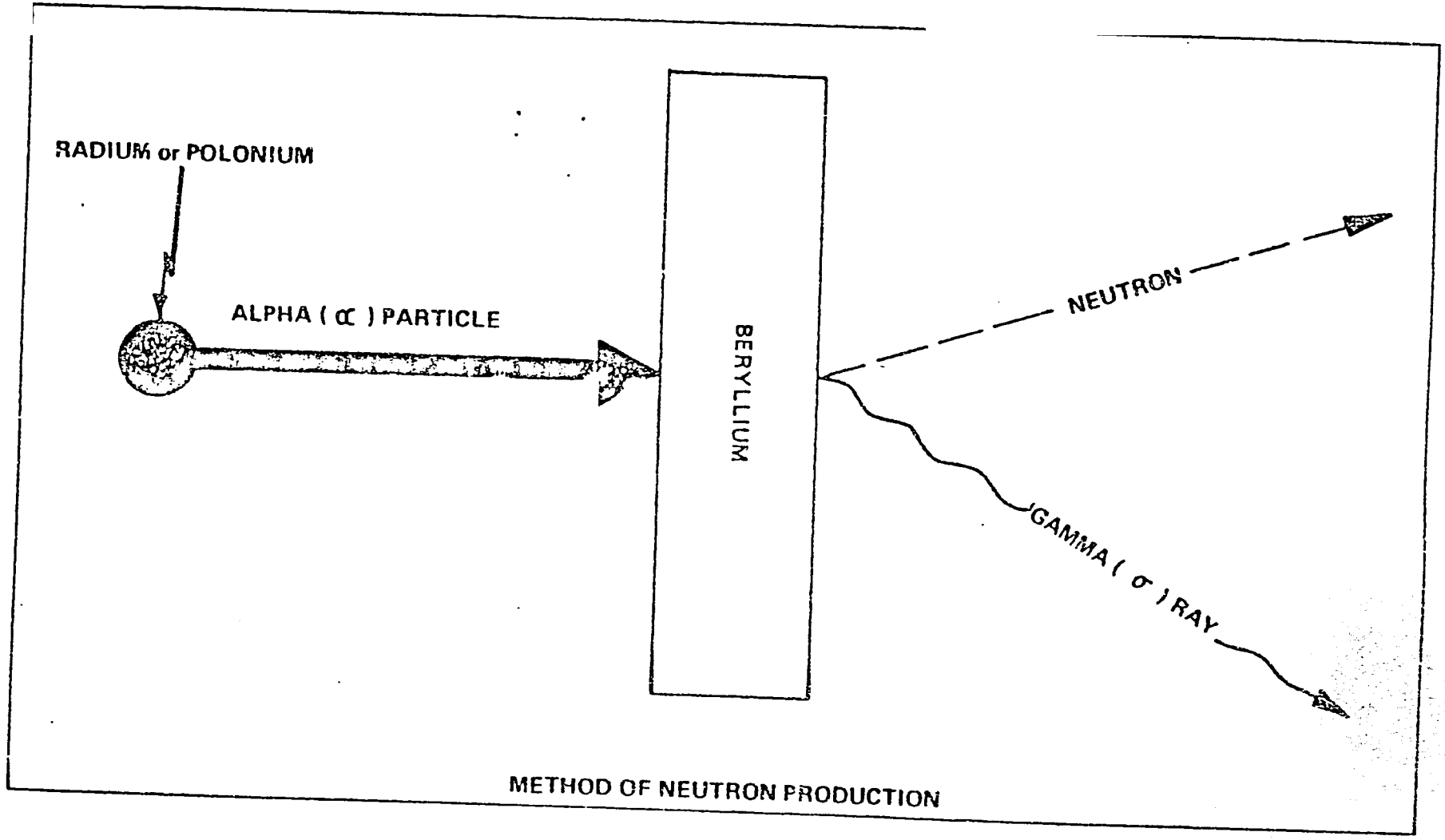
WHAT ARE ITS USES?

- DELINEATION OF POROUS FORMATIONS
- DETERMINATION OF POROSITY
- IDENTIFICATION OF GAS ZONES
- IDENTIFICATION OF LITHOLOGY
- EVALUATION OF SHALE CONTENT

NEUTRON LOG (CONT'D)

INDUCED NUCLEAR RADIATION

- THE SOURCE OF NEUTRONS IS A MIXTURE OF A RADIOACTIVE ELEMENT & BERYLLIUM OR POLONIUM
- WHEN BERYLLIUM ATOMS ARE STRUCK BY ALPHA PARTICLES FROM THE RADIOACTIVE ELEMENT, THEY DISINTEGRATE & EMIT NEUTRONS AT HIGH VELOCITIES
- FAST NEUTRONS HAVE VELOCITIES OF SEVERAL THOUSAND MILES PER SECOND
- NEUTRONS ARE ELECTRICALLY NEUTRAL PARTICLES THAT HAVE THE MASS OF A H_2 ATOM, THEY PASS THROUGH THE FOLLOWING ENERGY LEVELS:
  - FAST--$>$100 KeV
  - INTERMEDIATE--100 EV TO 100 KeV
  - SLOW-- $<$ 100 eV
    - EPITHERMAL--0.1eV TO 100 eV
    - THERMAL--0.025 eV



METHOD OF NEUTRON PRODUCTION

INDUCED NUCLEAR RADIATION CONT'D

- IN AN ELASTIC COLLISION A NEUTRON'S ENERGY IS REDUCED BY THAT AMOUNT TRANSFERRED TO THE STRUCK NUCLEUS
- ENERGY LOSS IS A FUNCTION OF COLLISION ANGLE AND RELATIVE MASS OF STRUCK NUCLEUS
- A HEAD-ON COLLISION BETWEEN A NEUTRON & A NUCLEUS OF THE SAME MASS RESULTS IN A TOTAL LOSS OF NEUTRON ENERGY
- OTHER COLLISIONS OCCURRING AT AN ANGLE OR INVOLVING A HEAVIER NUCLEUS RESULT IN A PARTIAL ENERGY LOSS
- H_2 ATOMS ARE ABUNDANT & HAVE A MASS ABOUT EQUAL TO THAT OF NEUTRON-ARE PRINCIPAL ENERGY REDUCERS OF FAST NEUTRONS TO THERMAL STATE
- WHERE H_2 IS ABUNDANT, NEUTRONS ARE SLOWED CLOSE TO SOURCE--WHERE H_2 IS SCARCE NEUTRONS MOVE FURTHER FROM SOURCE BEFORE A BEING SLOWED

NEUTRON ENERGY LOSS
(2.0 MEV TO THERMAL ENERGY STATE

ELEMENT	AVG. NUMBER OF COLLISIONS	MAX. ENERGY LOSS/COLLISION	ATOMIC WT.	ATOMIC NUMBER
CALCIUM	371	8%	40.1	20
CHLORINE	316	10%	35.5	17
SILICON	261	12%	28.1	14
OXYGEN	150	21%	16.0	8
CARBON	115	28%	12.0	6
HYDROGEN	18	100%	1.0	1

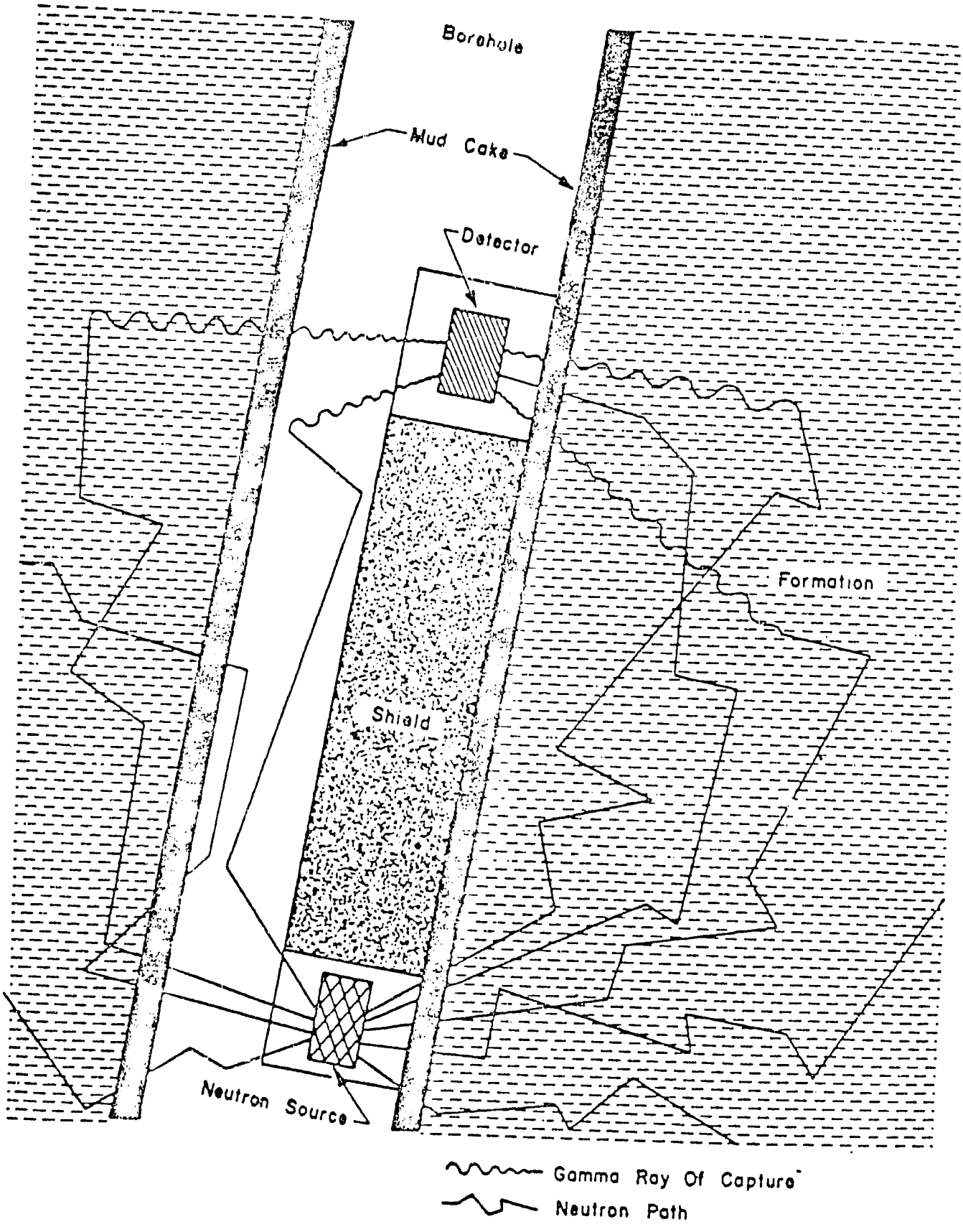
HYDROGEN - AVG. LOSS DUE TO ANGULAR COLLISION IS 63%.

NEUTRON LOG (CONT'D)

PRINCIPLE

- HIGH ENERGY (FAST) NEUTRONS ARE CONTINUOUSLY EMITTED FROM A RADIOACTIVE SOURCE--THEY COLLIDE WITH NUCLEI OF ROCKS IN ELASTIC "BILLARD-BALL" COLLISIONS--WITH EACH COLLISION NEUTRON LOOSES SOME ENERGY
- GREATEST ENERGY LOSS OCCURS WHEN A NEUTRON COLLIDES WITH A NUCLEUS OF EQUAL MASS--H_2
- SLOWING DOWN OF NEUTRONS DEPENDS LARGELY ON AMOUNT OF H_2 PRESENT IN H_2O, H C, SHALE, COAL, ETC.
- WITHIN A FEW MICROSECONDS NEUTRONS HAVE SLOWED DOWN BY SUCCESSIVE COLLISIONS TO THERMAL VELOCITIES--THEY THEN DIFFUSE RANDOMLY WITHOUT LOOSING ANY MORE ENERGY UNTIL CAPTURE BY NUCLEI OF $C\ell$, H_2, SILICON, ETC.
- CAPTURING NUCLEI BECOME EXCITED & EMIT HIGH-ENERGY GAMMA RAYS OF CAPTURE--LOGGING TOOLS MEASURE GAMMA RAYS OF CAPTURE OR SLOW NEUTRONS
- ABILITY TO DETECT GAMMA RAYS OF CAPTURE OR SLOW NEUTRONS DEPENDS ON DISTANCE OF DETECTOR FROM SOURCE & BIAS LEVELS OF EQUIPMENT

PRINCIPLE OF OPERATION OF NEUTRON LOG



NEUTRON LOG (CONT'D)

NEUTRON LOGGING TOOLS

SINGLE SPACED NEUTRON TOOL (GNT)

.. COMPRISED OF NEUTRON SOURCE AND NEUTRON OR GAMMA RAY DETECTOR SEPARATED BY MATERIAL THAT PREVENTS RADIATION FROM SOURCE REACHING DETECTOR THROUGH TOOL

.. SOURCE TO DETECTOR DISTANCE VARIES IN TOOLS FROM 13" TO 24"--MOST COMMON SPACING LIES BETWEEN 18" AND 30"

.. TOOL IS SENSITIVE TO GAMMA RAYS FROM THREE SOURCES
- GAMMA RAYS OF CAPTURE
- NATURAL GAMMA RAYS
- GAMMA RAYS FROM NEUTRON SOURCE

.. NATURAL GAMMA RAYS ARE SHIELDED FROM DETECTOR BY BIAS DISCRIMINATION

.. IS A NON-DIRECTIONAL DEVICE USING A DETECTOR SENSITIVE TO HIGH-ENERGY GAMMA RAYS OF CAPTURE OR THERMAL NEUTRONS

.. IT CAN BE RUN IN CASED OR UNCASED HOLES

NEUTRON LOG (CONT'D)

SIDEWALL NEUTRON POROSITY TOOL (SNP)

- A DIRECTIONALLY-SENSITIVE EPITHERMAL NEUTRON DETECTION SYSTEM IS INCORPORATED IN A SIDEWALL SOURCE-DETECTOR SKID TO MINIMIZE BOREHOLE EFFECTS
- DESIGNED FOR OPERATION IN UNCASED WELLS
- EFFECTS OF VARIATIONS IN BOREHOLE SIZE AND SHAPE, MUD TYPE, TEMPERATURE AND SALINITY ARE LARGELY ELIMINATED
- A SURFACE CONTROL PANEL COMPUTATIONALLY ACCOUNTS FOR SMALL RESIDUAL BOREHOLE EFFECTS TO PROVIDE A BOREHOLE CORRECTED LOG
- LOG PRESENTS A DIRECT RECORDING OF NEUTRON-DERIVED POROSITY ON A LINEAR SCALE

NEUTRON LOG (CONT'D)

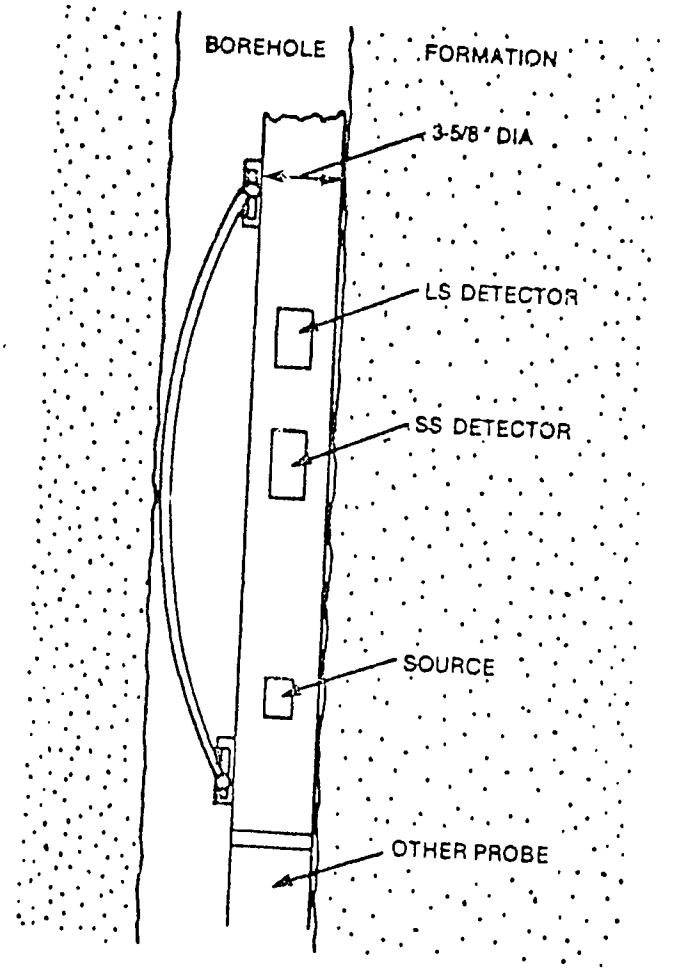
DUAL-SPACING NEUTRON LOG (CNL)

- DESIGNED FOR USE IN CASED & UNCASED HOLES
- USES TWO DETECTORS THAT ARE SENSITIVE TO THERMAL NEUTRONS
- RATIO OF COUNTING RATES FROM THE TWO DETECTORS IS CONVERTED BY A SURFACE PANEL TO POROSITY INDEX
- THE TWO THERMAL NEUTRON DETECTORS ARE MOUNTED AT DIFFERENT SPACINGS ABOVE SOURCE ALONG AXIS OF 3 3/8" DIAMETER SONDE
- SENSITIVE VOLUME OF FAR DETECTOR IS MUCH LARGER THAN THAT OF THE NEAR DETECTOR, THUS ASSURING GOOD COUNTING RATES AT THE LONGER SPACING
- NEUTRON SOURCE WITH YIELD OF 4×10^7 NEUTRONS/SEC IS USED--THIS IS 4 TIMES THAT OF CONVENTIONAL SOURCES USED IN NEUTRON LOGS

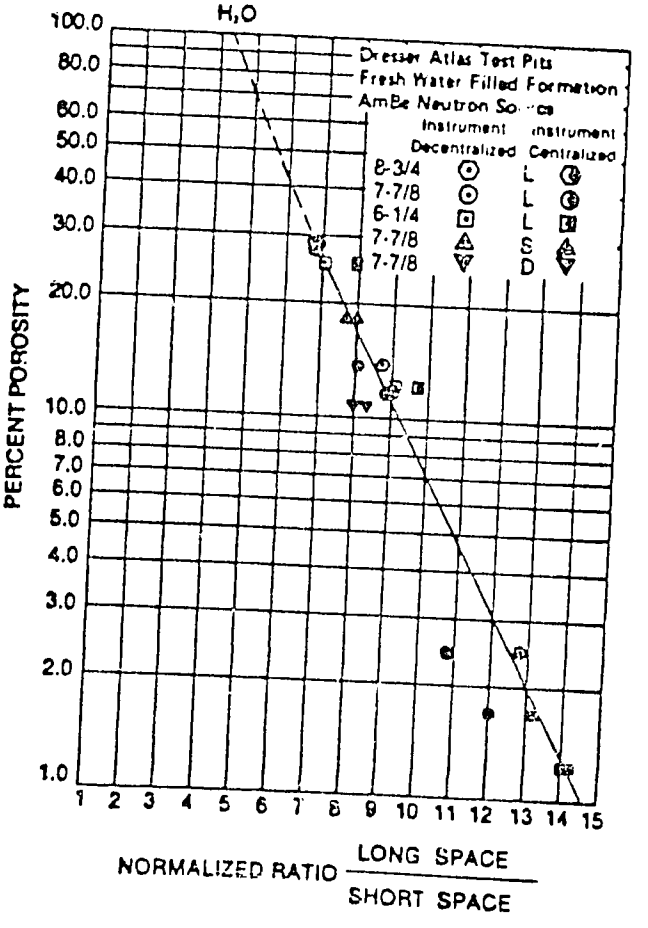
NEUTRON LOG (CONT'D)

CNL CONT'D

- COMBINATION OF SENSITIVE DETECTORS & HIGH STRENGTH SOURCE PERMITS A LOGGING SPEED OF 1800 FT/HR
- TEMPERATURE & PRESSURE RATINGS ARE 400°F & 20000PSI
- TO MINIMIZE BOREHOLE EFFECTS SONDE IS RUN ECCENTERED IN HOLE
- FOR D_H = 6" TO 16" A LARGE BOW-SPRING IS USED TO ASSURE TOOL LIES AGAINST BOREHOLE WALL
- FOR $D_H < 6"$ & IN CASED HOLES TOOL IS ASSUMED TO FOLLOW LOW SIDE OF HOLE
- MAY BE RUN WITH OTHER LOGGING TOOLS SUCH AS FDC, TDT, ISF AND SONIC, THUS PROVIDING COMBINATIONS FOR OVERLAY-TYPE PRESENTATIONS AND QUICK-LOOK INTERPRETATION AT WELL SITE



CN instrument configuration



From Dresser Atlas 1980 Booklet on Neutron Logs

NEUTRON LOG (CONT'D)

DETECTORS

- GAMMA RAY DETECTORS
  - IONIZATION CHAMBER
  - GEIGER-MULLER COUNTER
  - SCINTILLATION COUNTER
- THERMAL NEUTRON DETECTORS
  - SAME TYPES AS FOR GAMMA RAYS BUT USUALLY INCORPORATE BORON WHICH REACTS WITH EPITHERMAL NEUTRONS TO PRODUCE ALPHA PARTICLES WHICH INITIATE IONIZATION PULSES
- EPITHERMAL NEUTRON DETECTORS
  - IONIZATION CHAMBER CONTAINING H_2--H_2 NUCLEUS IS ENERGIZED BY IMPACT OF A NEUTRON--IONIZATION IS INITIATED RESULTING IN AN ELECTRICAL PULSE
  - SCINTILLATION COUNTER USING A LITHIUM IODIDE CRYSTAL--INCIDENT NEUTRONS REACT WITH LITHIUM NUCLEI TO CAUSE LIGHT-FLASHES THAT ARE COUNTED BY A PHOTO-MULTIPLIER TUBE

NEUTRON LOG (CONT'D)

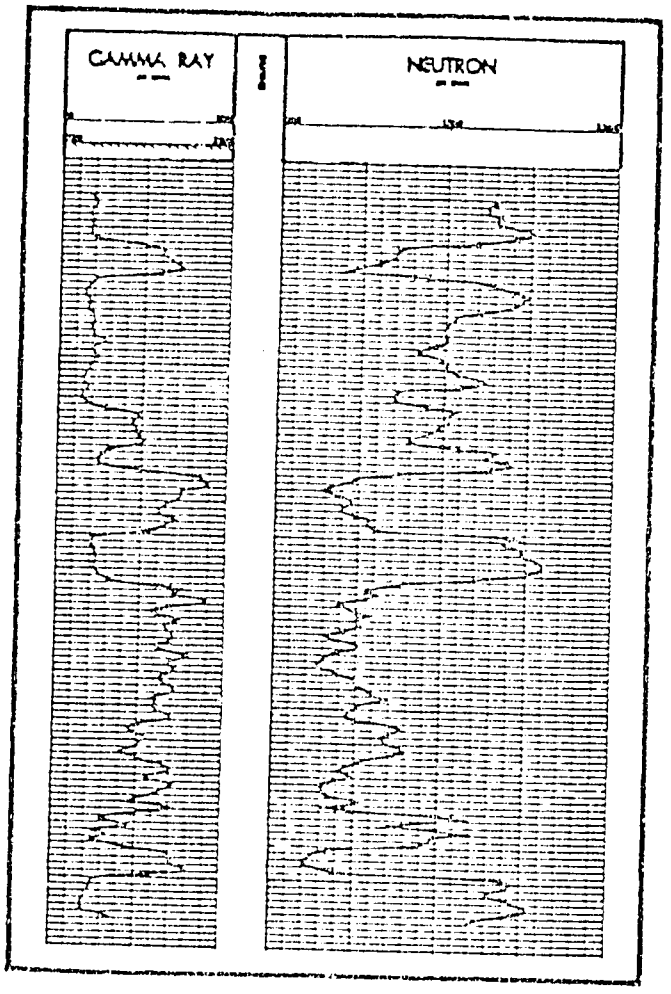
TIME CONSTANT & LOGGING SPEED

- TO PRODUCE NEUTRON LOGS FOR QUANTITATIVE INTERPRETATION TIME CONSTANT (T_C SECS.) AND LOGGING SPEED (L FT/MIN) MUST BE PROPERLY CHOSEN
- TIME CONSTANT IS DEFINED AS TIME NECESSARY FOR RECORDER TO DEFLECT TO 63% OF ULTIMATE VALUE--2 T_C GIVE 86% & 3 T_C GIVE 95% OF ULTIMATE RESPONSE
- COUNTING RATE AT DETECTOR FLUCTUATES BECAUSE OF STATISTICAL NATURE OF RADIOACTIVITY PHENOMENA
- TO OBTAIN ENOUGH COUNTS FOR A REPRESENTATIVE AVERAGE READING, THE COUNT RATE IS AVERAGED IN A TIME-CONSTANT CIRCUIT
- APPEARANCE & STATISTICAL ACCURACY OF THE LOG ARE FUNCTIONS OF TIME-CONSTANT SETTING & LOGGING SPEED
- A TIME CONSTANT OF 2 SEC. & A SPEED OF 1800 FT/HR PROVIDE GOOD LOGS IN MOST CASES
- FOR LARGE HOLES OR BEDS SHOWING LITTLE RADIOACTIVITY CONTRAST MORE SENSITIVITY IS NEEDED REQUIRING LONGER TIME CONSTANT AND SLOWER LOGGING SPEED

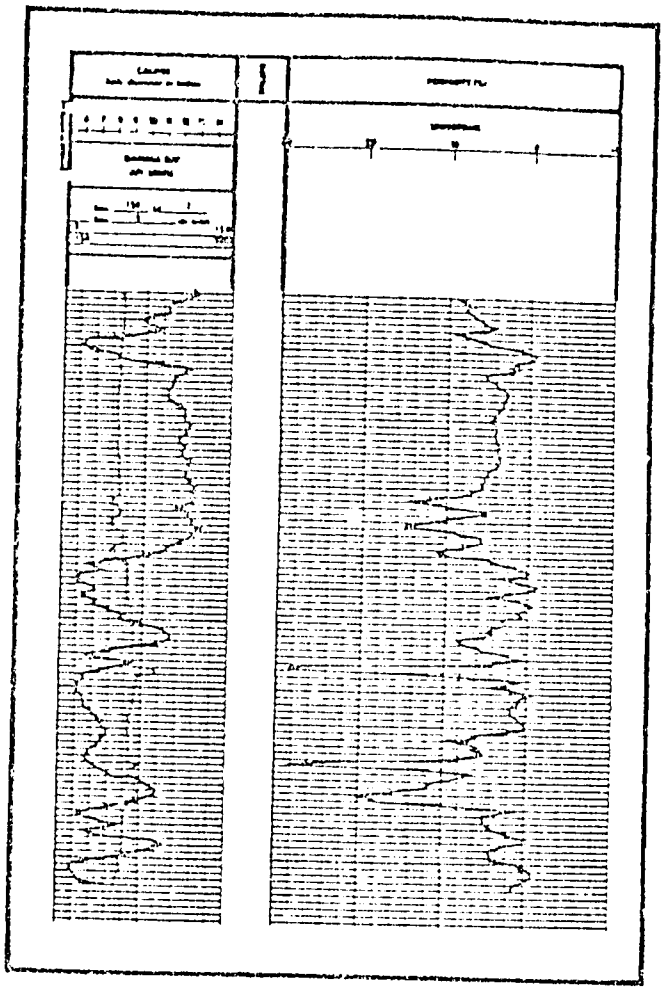
NEUTRON LOG (CONT'D)

LOG PRESENTATION

- GNT TOOLS - SCALED LINERALY IN API UNITS ACROSS TRACKS 2 & 3 WITH THE GAMMA RAY LOG IN TRACK 1
- SNP TOOL - TOOL RESPONSE IS CONVERTED TO ϕ VALUES BASED NORMALLY ON A LIMESTONE MATRIX--SURFACE PANEL AUTOMATICALLY PROVIDES CORRECTIONS IN LIQUID FILLED HOLES FOR MUD WEIGHT, SALINITY, TEMPERATURE & HOLE SIZE VARIATIONS
  - IN GAS-FILLED HOLES ONLY THE HOLE SIZE CORRECTION IS REQUIRED & IS DONE MANUALLY
  - GAMMA RAY LOG AND CALIPER ARE FOUND IN TRACK 1 WITH THE SNP IN TRACKS 2 & 3
- CNL - RECORDED IN LINEAR ϕ UNITS USUALLY FOR A LIMESTONE MATRIX IN TRACKS 2 & 3. THE GAMMA RAY LOG AND CALIPER ARE PLACED IN TRACK 1

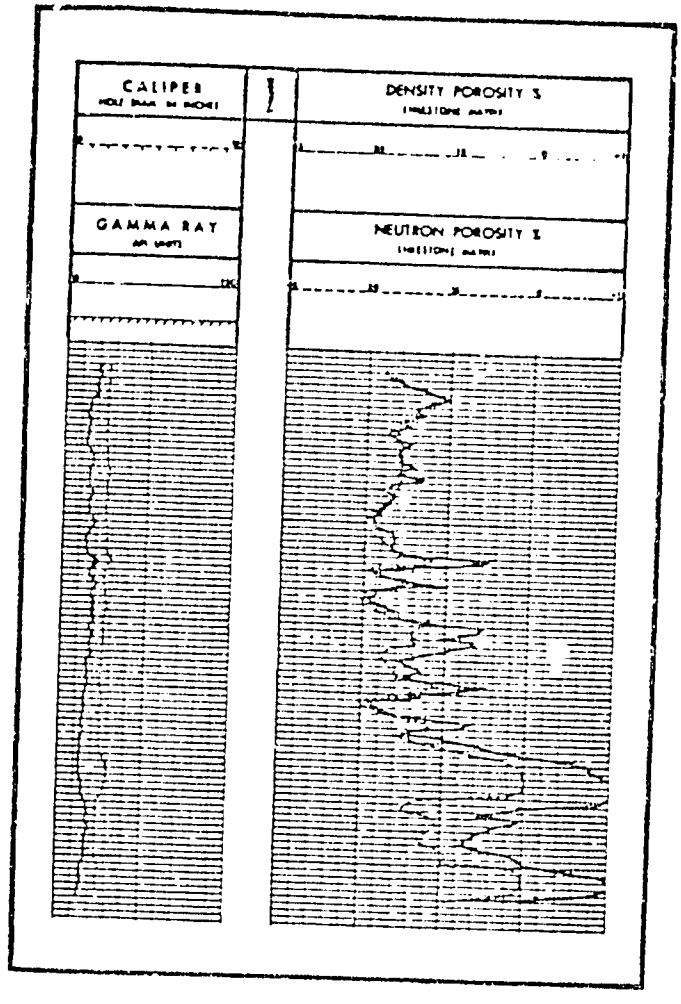


— *Presentation of GNT Neutron Log.*



— *Presentation of SNP Log.*

From Schlumberger Log Interpretation Principles (1972)



— *Presentation of CNL-FDC Log.*

From Schlumberger Log Interpretation Principles (1972)

NEUTRON LOG (CONT'D)

CALIBRATION

. GNT TOOLS

.. PRIMARY STANDARD IS THE API NEUTRON PIT @ UNIVERSITY OF HOUSTON

.. RESPONSE OF A LOGGING TOOL IN 19% POROSITY WATER-FILLED LIMESTONE IS DEFINED AS 1000 API UNITS

.. CALIBRATING DEVICES ACCURATELY RELATED TO THE API PIT ARE USED FOR FIELD CALIBRATION

.. API TEST PIT PROVIDES THREE LIMESTONE POROSITY POINTS (26%, 19%, 1.9%), USING A FRESH WATER FILLED 7 7/8" BOREHOLE

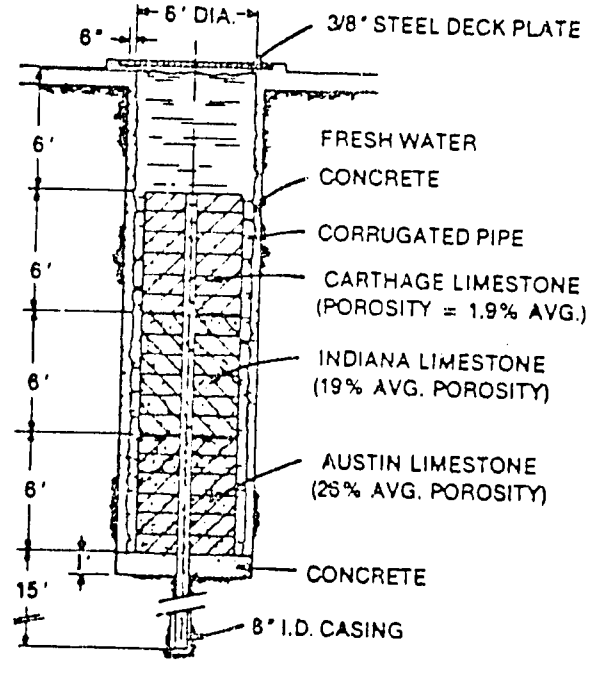
.. NO MUD CAKE OR STAND-OFF ARE PRESENT DURING THE CALIBRATION THAT IS DONE AT 75°F.

.. API UNIT DOES NOT FULLY DEFINE THE RESPONSES OF DIFFERENT LOGGING SYSTEMS OVER THEIR ENTIRE RANGE OF OPERATING CONDITIONS--THUS DIFFERENT LOGGING SYSTEMS WILL NOT EXHIBIT IDENTICAL CURVE AMPLITUDES

NEUTRON LOG (CONT'D)

CALIBRATION CONT'D

- SNP TOOLS - CALIBRATED BASED ON MANY READINGS IN FORMATIONS OF HIGH PURITY AND KNOWN POROSITIES
- CNL TOOLS - FOR LIMESTONES AND SANDSTONES CALIBRATION IS BASED ON A LARGE NUMBER OF LABORATORY MEASUREMENTS. FOR DOLOMITES, TOOL RESPONSE IS BASED ON FIELD DATA.



Neutron Log calibration pit

From Dresser Atlas 1980 Booklet on Neutron Logs

INVESTIGATION CHARACTERISTICS

- NEUTRON TOOLS HAVE VERTICAL INVESTIGATION ABOUT EQUAL TO SOURCE-DETECTOR SPACING--15.5" OR 19.5" FOR GNT AND 16" FOR SNP
- RADIAL INVESTIGATION - IS A FUNCTION OF ϕ, LITHOLOGY, SOURCE ENERGY, STRONG-THERMAL-NEUTRON-ABSORBER DENSITY, HYDROGEN DENSITY AND SOURCE-DETECTOR SPACING
- AVERAGE RADII OF INVESTIGATION IN AN 8" BOREHOLE (EXCLUDING CNL) ARE:

% POROSITY	RADIUS OF INVESTIGATION
0 TO 5%	24"
5% TO 10%	12"
10% TO 20%	6"
20% & GREATER	VERY SHALLOW

- DEPTH OF INVESTIGATION OF GNT & SNP IS LESS THAN FOR CNL - FOR POROUS BEDS CNL READS 8 TO 10" FROM BOREHOLE WALL

NEUTRON LOG (CONT'D)

HYDROGEN INDEX (HI)

- THE SLOWING DOWN OF FAST NEUTRONS BY H_2 NUCLEI IS THE PREDOMINANT PHENOMENON
- RESPONSE DEPENDS ON HI OF FORMATION
- HI IS PROPORTIONAL TO QUANTITY OF H_2 PER UNIT VOLUME OF FORMATION NEAR BOREHOLE
- HI OF FRESH WATER AT SURFACE CONDITIONS IS TAKEN AS 1.0
- IN CLEAN WATER BEARING BEDS THE NEUTRON READING IS DIRECTLY RELATED TO ϕ
- FOR MOST OILS HI WILL BE PRACTICALLY THE SAME AS IN WATER
- GAS AND LIGHT OILS HAVE SUBSTANTIALLY LOWER VALUES OF HI WHICH ALSO VARY WITH TEMPERATURE AND PRESSURE--CAUSE NEUTRON LOG TO READ LOW

$$HI_{LIGHT\ OIL} < HI_{H_2O}$$

$$HI_{GAS} << HI_{H_2O}$$

NEUTRON LOG (CONT'D)

HYDROGEN INDEX CONT'D

. FOR A HYDROCARBON BEARING FORMATION

$$\phi_N = \phi\left[(1-S_{HR})HI_{MF} + S_{HR}\, HI_H\right]$$

. $HI_{\substack{FRESH \\ H_2O}}$ = 1.0 BY DEFINITION WHILE $HI_{\substack{SALT \\ WATER}}$ IS SLIGHTLY LESS THAN 1.0

. ANOTHER WAY TO DEFINE HI IS

$$HI_{SUBSTANCE} = \frac{\text{HYDROGEN DENSITY OF SUBSTANCE}}{\text{HYDROGEN DENSITY OF FRESH WATER}}$$

$$= \frac{H_2 \text{ DENSITY OF SUBSTANCE}}{2/2+16}$$

. THUS HI_H CAN BE DETERMINED IF COMPOSITION AND HYDROCARBON DENSITY (ρ_H) ARE KNOWN--SUPPOSE THERE ARE X ATOMS OF H_2 FOR EACH CARBON ATOM

$$HI_H = (9)\left(\frac{X}{12 + X}\right)\rho_H = \left(\frac{9X}{12 + X}\right)\rho_H$$

NEUTRON LOG (CONT'D)

HYDROGEN INDEX CONT'D

. FOR CH_4

$$HI_{CH_4} = \frac{(9)(4)}{12 + 4}\rho_H = 2.25\rho_H$$

. FOR OIL OF COMPOSITION N CH_2

$$HI_H = \frac{(9)(2)}{12 + 2}\rho_H = 1.28\rho_H$$

. IF HYDROCARBON COMPOSITION IS UNKNOWN BUT ρ_H CAN BE ESTIMATED, THEN AN APPROXIMATE VALUE OF HI_H CAN BE GOTTEN FROM

$$HI_H = 9\rho_H\left[(0.15 + .2\ (0.9 - \rho_H)^2\right]$$

- THIS CAN FURTHER BE SIMPLIFIED TO

$$HI_H = \rho_H + 0.3 \qquad 0.25 \leq \rho_H \leq 0.9$$

AND

$$HI_H = 2.2\rho_H \qquad \rho_H < 0.25$$

NEUTRON LOGS (CONT'D)

HYDROGEN INDEX CONT'D

- HYDROGEN INDEX OF MUD FILTRATE CAN BE EXPRESSED AS

$$HI_{MF} = \rho_{MF} \, (1 - PPM_{NACL} 10^{-6})$$

- USING THIS RELATION AND THOSE FOR HI_H, THE NEUTRON RESPONSE IN HYDROCARBON BEARING BEDS BECOMES

$$\phi_N = \phi \left[(1 - S_{HR}) + S_{HR} \, (\rho_H + 0.3) / \rho_{MF} (1 - PPM_{NACL} \, 10^{-6}) \right]$$

WHERE $0.25 \leqslant \rho_H \leqslant 0.9$

AND

$$\phi_N = \phi \left[(1 - S_{HR}) + S_{HR} (2.2 \rho_H) / \rho_{MF} \, (1 - PPM_{NACL} 10^{-6}) \right]$$

WHERE $\rho_H < 0.25$

NEUTRON LOG (CONT'D)

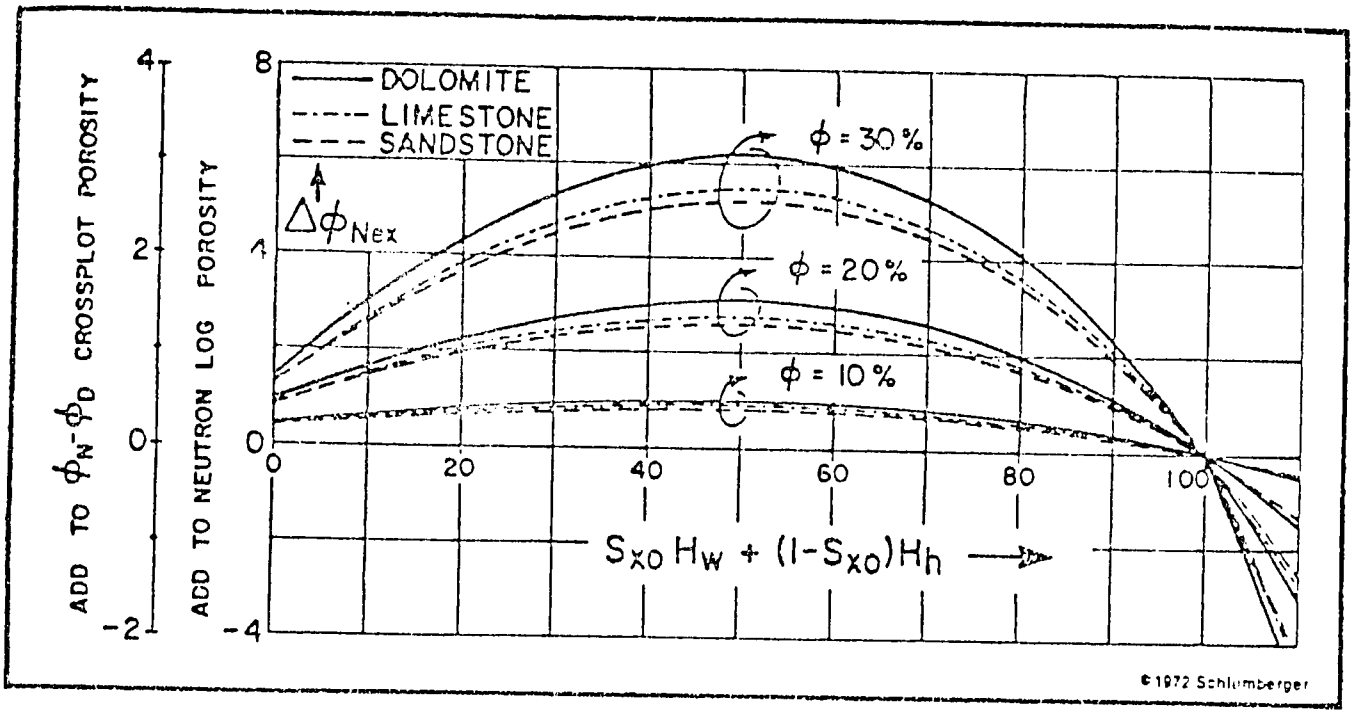
EXCAVATION EFFECT

- MATHEMATICAL STUDIES SHOW THAT THE EFFECT OF GAS NEAR THE BOREHOLE IS GREATER THAN WOULD BE EXPECTED BY TAKING INTO ACCOUNT ONLY ITS SMALLER H_2 DENSITY
- PREVIOUS WORK HAD BEEN DONE ASSUMING GAS-FILLED PORTION OF ϕ WAS REPLACED BY ROCK MATRIX
- NEW STUDIES SHOW THAT WHEN THIS ROCK MATRIX IS "EXCAVATED" AND REPLACED WITH GAS, THE FORMATION HAS A SMALLER NEUTRON-SLOWING-DOWN CHARACTERISTIC--NAMED EXCAVATION EFFECT
- TO IGNORE THE EXCAVATION EFFECT RESULTS IN HIGH FLUSHED ZONE GAS SATURATIONS AND LOW VALUES OF POROSITY
- ASSUMING THE SONDE WAS CALIBRATED IN FRESH-WATER-BEARING FORMATIONS

$$S_{WH} = S_{XO} H_W + (1-S_{XO})H_H$$

WHERE $H_W = HI_{WATER}$

$H_H = HI_{HYDROCARBON}$



— *Correction for Excavation Effect as a function of S_{xo}, for three values of porosity and for $H_v = 0$. Effect of limestone, sandstone, and dolomite included within the shaded bands.*

From Schlumberger Log Interpretation Principles (1972)

NEUTRON LOG (CONT'D)

EXCAVATION EFFECT CONT'D

. CORRECTION VALUES CAN BE ESTIMATED WITH

$$\Delta\phi_{N_{EX}} = K\left[2\phi^2 S_{WH} + 0.04\phi\right](1-S_{WH})$$

WHERE $\Delta\phi_{N_{EX}}$, ϕ & S_{W_H} ARE IN FRACTIONAL UNITS

AND K = 1.0 FOR SANDSTONES

= 1.046 FOR LIMESTONES

= 1.173 FOR DOLOMITES

THE SECOND TERM IN THE EQUATION ABOVE IS SMALL & CAN OFTEN BE DISREGARDED

. IN SHALY BEDS THERE IS H_2 IN THE CLAY AND AN APPROXIMATE CORRECTION CAN BE MADE FOR IT BY REPLACING S_{WH} AND ϕ IN THE ABOVE EQUATION WITH

$$\phi' = \phi + V_{SH}\phi_{N_{SH}}$$

AND

$$S'_{WH} = (\phi S_{WH} + V_{SH}\phi_{N_{SH}})/$$

HERE THE APPROXIMATION IS THAT $\phi_{N_{SH}}$ INDICATES H_2 CONTENT OF SHALE

NEUTRON LOG (CONT'D)

FACTORS AFFECTING TOOL RESPONSE

- BOREHOLE--SIZE, FLUID CONTENT, CASING, CEM
- FORMATION--LITHOLOGY, POROSITY, FLUID CONT
- SOURCE--DETECTOR SPACING
- STATISTICAL VARIATIONS
- LOGGING SPEED AND TIME CONSTANT
- EXCAVATION EFFECT

NEUTRON LOG (CONT'D)

LITHOLOGY & POROSITY

- ELEMENT WHICH MOST EFFECTS NEUTRON LOG IS H_2
- ROCK FORMING MINERALS CONTAINING H_2
  - CLAY MINERALS--SHALE, SHALY SANDS & CARBONATE, ARKOSE
  - GYPSUM--EVAPORITE SEQUENCES
  - IRON HYDRATES--FERRUGINOUS SANDSTONES & LIMESTONES, SEDIMENTARY ORE DEPOSITS
  - GLAUCONITE--GLAUCONITIC SANDSTONES
  - ORGANIC MATERIALS--COALS, BITUMINOUS SANDS AND LIMESTONES
- OTHER ELEMENTS HAVING SIGNIFICANT EFFECTS IN NEUTRON LOGGING ARE CHLORINE, IRON, BORON AND ALUMINUM
- LOG INDICATES RELATIVE AMOUNT OF H_2 & MOST OF H_2 IS CONTAINED IN THE VOID SPACES--THUS IT MEASURES TOTAL POROSITY

NEUTRON LOG (CONT'D)

POROSITY FROM GNT

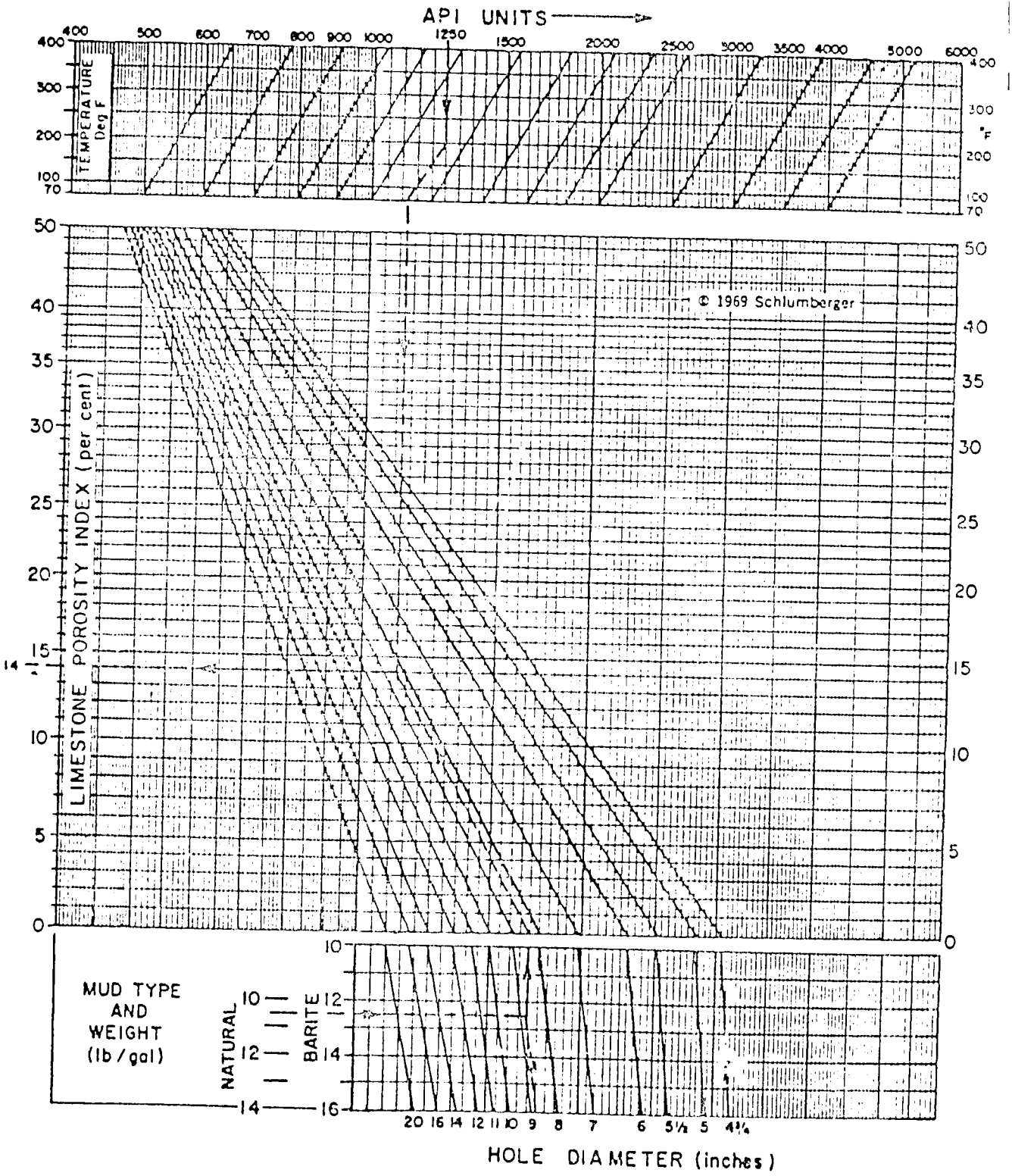
- NEUTRON LOG RESPONSE IS AN EXPONENTIAL FUNCTION OF POROSITY
- TO DETERMINE ϕ THE EFFECTS OF BOREHOLE CONDITIONS AND FORMATION LITHOLOGY MUST BE ELIMINATED
- SERVICE COMPANIES HAVE PREPARED NEUTRON DEPARTURE CURVES FOR SPECIFIC TOOLS AND SETS OF CONDITIONS

NEUTRON DEPARTURE CURVES

GNT F, G, or H

Pu-Be or Am-Be Source, 15½" Spacing

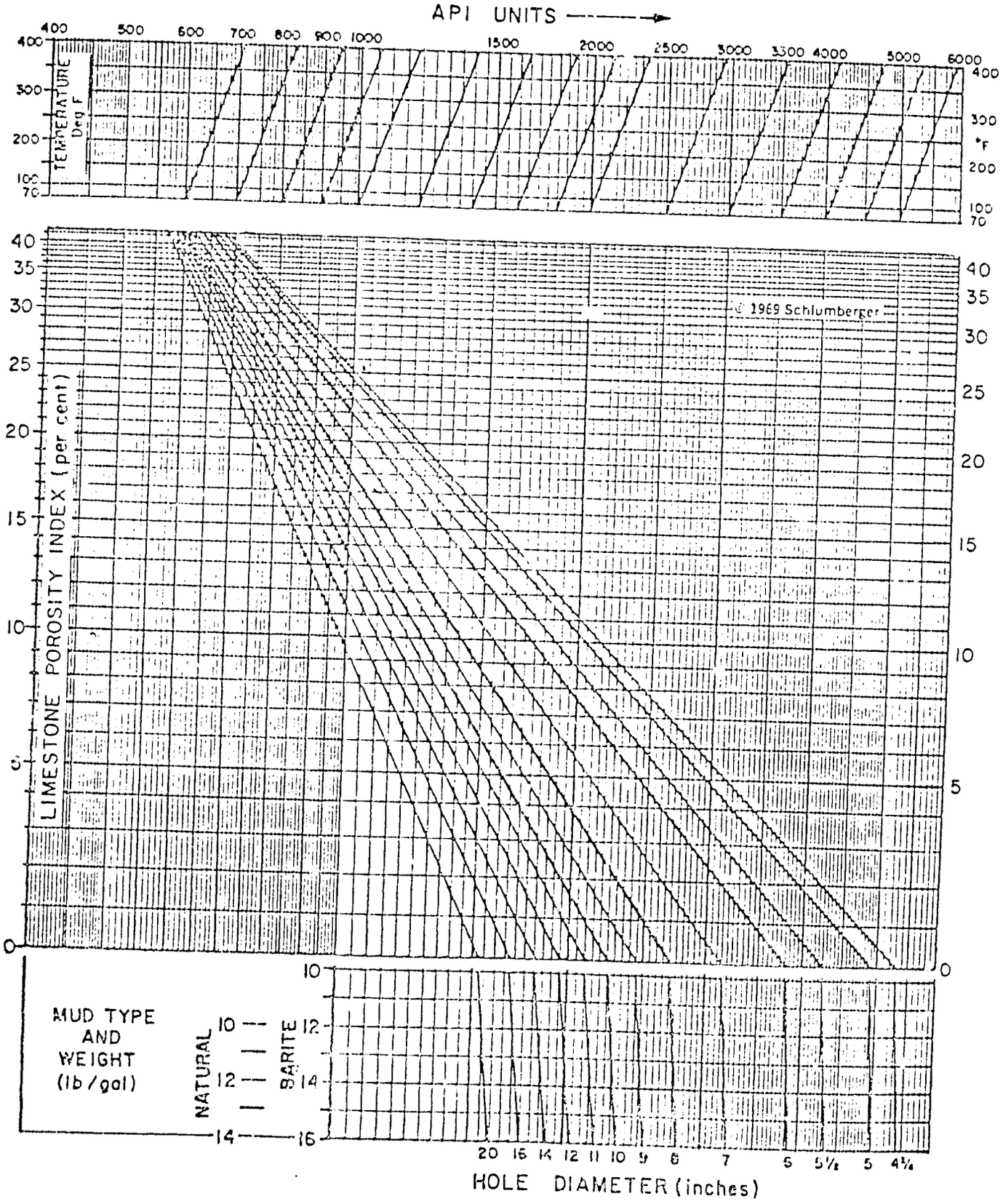
FRESH MUD, UNCASED HOLES, LIMESTONE



NEUTRON DEPARTURE CURVES
GNT F, G, or H

Pu-Be or Am-Be Source, 15½" Spacing

SALTY MUD, UNCASED HOLES, LIMESTONE



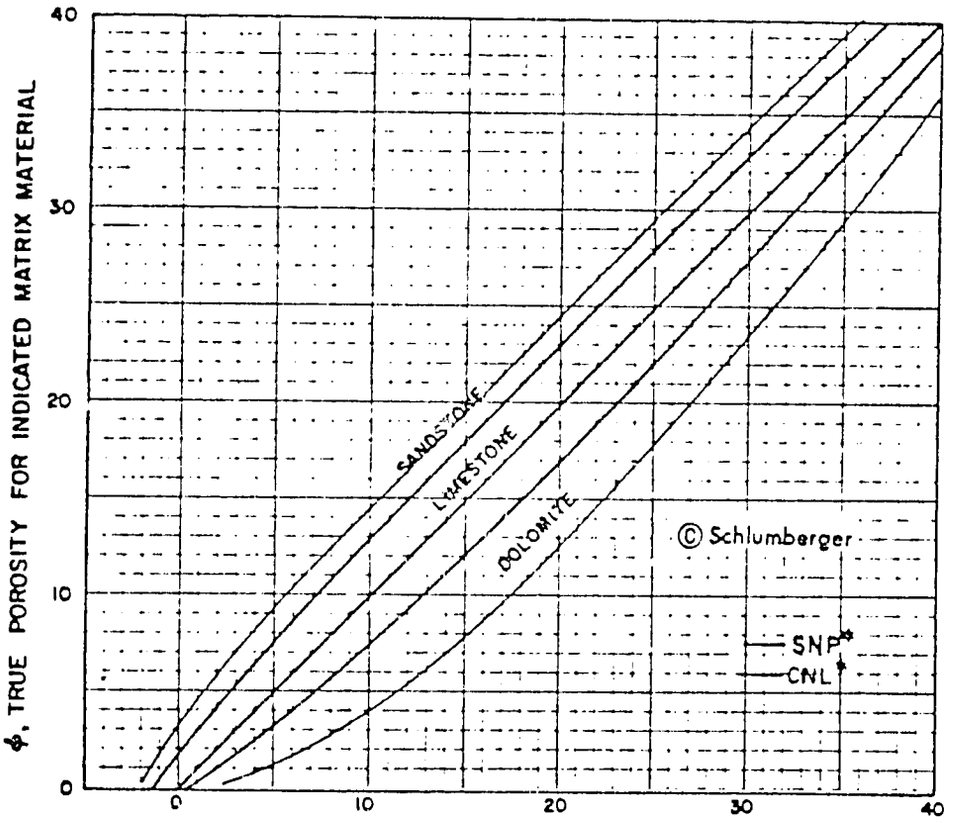
NEUTRON POROSITY EQUIVALENCE CURVES

SIDEWALL NEUTRON POROSITY LOG (SNP*)
COMPENSATED NEUTRON LOG (CNL*)

When the SNP is recorded in limestone porosity units, the large chart is used to find true porosities in sandstones or dolomites. First, correct the SNP for mud-cake thickness using the small charts. The upper chart is in English units, the lower in S I units. For mud-cake thickness value use the full hole-diameter reduction shown on SNP caliper (since the backup shoe usually cuts through the mud cake). Then the corrected porosity value is entered on the abscissa of the chart and carried to the appropriate matrix line. Read ordinate for true porosity. The chart can also be used to find limestone porosity (needed for entering Charts CP-1 and CP-2) if recording is in sandstone or dolomite porosity units. Always correct mud cake before entering equivalence chart.

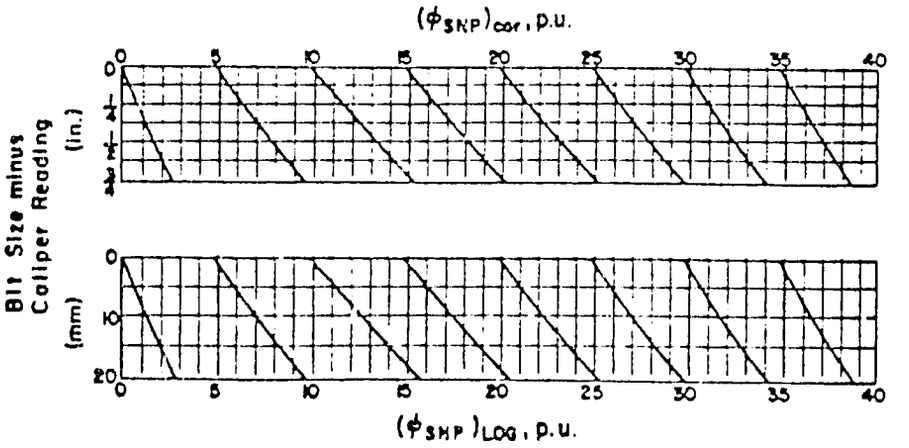
EXAMPLE (English Units):
SANDSTONE BED: The SNP reads 13 p.u. (limestone). Bit size 7⅞ in. Caliper reads 7⅝ in., so h_{mc} = ¼ in. Corrected limestone porosity is 11 p.u. Sandstone porosity is 14 p.u.

No mud-cake correction is needed for CNL conversions. Simply enter the chart in abscissa with CNL limestone porosity, go to appropriate matrix line, and read true porosity on the ordinate.



$(\phi_{SNP})_{cor}$ NEUTRON POROSITY INDEX (LIMESTONE), p.u.

$(\phi_{CNL})_{cor}$ NEUTRON POROSITY INDEX (LIMESTONE), p.u.



*Mark of Schlumberger

NEUTRON LOG (CONT'D)

POROSITY FROM GNT CONT'D

- LOGARITHMIC METHOD--BASED ON ASSUMPTION THAT LOG ϕ VS NEUTRON RESPONSE RESULTS IN A LINEAR GRAPH

  $\text{LOG } \phi = C - K N_A$

  C & K ARE CONSTANTS RELATED TO TOOL DESIGN & BOREHOLE PARAMETERS

  N_A IS NEUTRON LOG RESPONSE (RDG.)

  --THIS METHOD IS OFTEN REFERRED TO AS THE TWO POINT CALIBRATION--THAT IS, TWO POROSITY VALUES ARE NEEDED TO DRAW THE PLOT

  SHALE--$\phi \simeq 40\%$

  DENSE ZONE-LIMESTONE--1%-2% (BASED ON LOCAL KNOWLEDGE)

  SANDSTONES--USE VALUE BASED ON LOCAL KNOWLEDGE

  --METHOD CAN BE USED TO PLOT NEUTRON RESPONSE VS POROSITY VALUES OBTAINED FROM CORE OR DENSITY LOGS

NEUTRON LOG (CONT'D)

POROSITY FROM SNP

- LOG PRESENTS A DIRECT RECORDING OF NEUTRON-DERIVED POROSITY (NURMALLY LIMESTONE BASIS) ON A LINEAR SCALE
- EFFECTS OF VARIATIONS IN BOREHOLE SIZE AND SHAPE, MUD TYPE, TEMPERATURE AND SALINITY ARE LARGELY REDUCED
- SMALL RESIDUAL BOREHOLE EFFECTS ARE COMPUTATIONALLY ACCOUNTED FOR IN SURFACE CONTROL PANEL
- LOG READINGS MUST BE CORRECTED FOR
  - LITHOLOGY IF NOT LIMESTONE
  - MUD CAKE USING A MUD CAKE THICKNESS OF

    H_{MC} = BIT SIZE - CALIPER RDG.

NEUTRON LOG (CONT'D)

POROSITY FROM CNL

- DESIGNED TO MINIMIZE THE EFFECTS OF HOLE SIZE, MUD CAKE, ETC.
- WHEN RUN IN COMBINATION WITH THE FDC, THE CALIPER SIGNAL IS USED TO PROVIDE AN AUTOMATIC HOLE SIZE CORRECTION
- STANDARD CONDITIONS OF CALIBRATION ARE

  7 7/8" D_H

  FRESH WATER IN BOREHOLE & FORMATION

  NO MUD CAKE

  NO STAND OFF

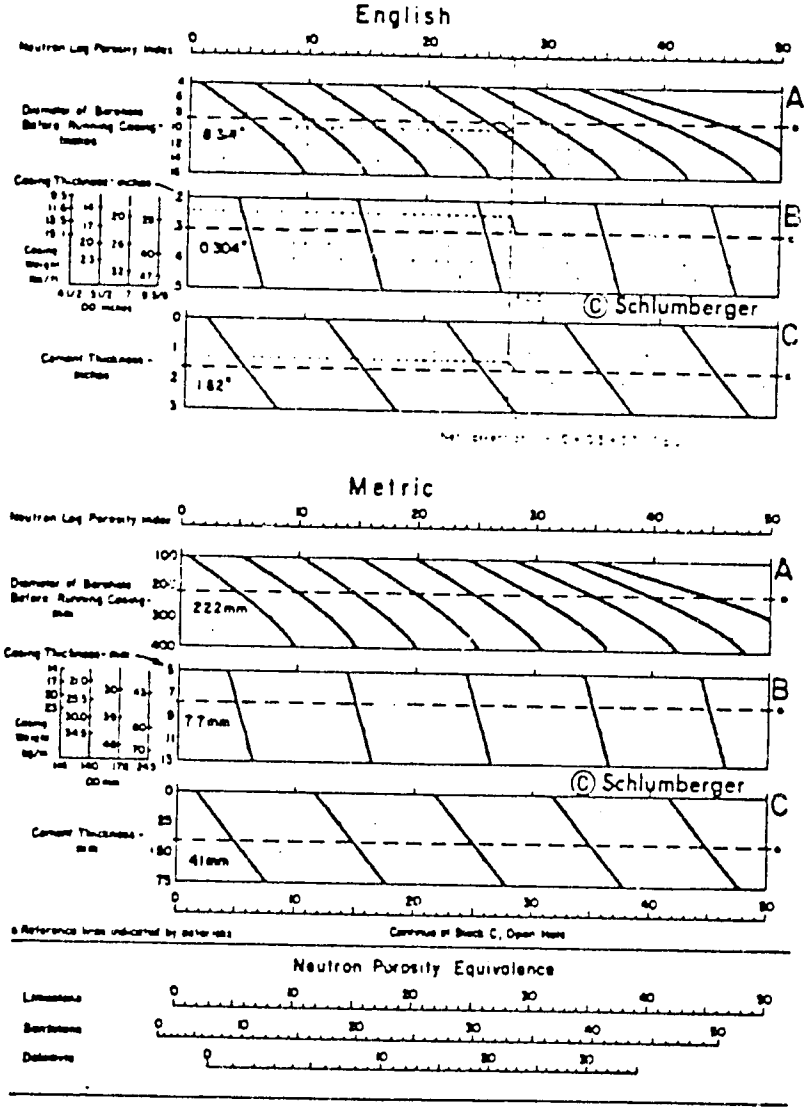
  75°F TEMPERATURE

  ATMOSPHERIC PRESSURE

  TOOL ECCENTERED IN BOREHOLE
- DEPARTURES FROM THE STANDARD CALIBRATION CONDITIONS RESULT IN A COMBINED CORRECTION TO THE LOG WHICH IS QUITE SMALL

DUAL SPACING NEUTRON LOG (CNL*) CORRECTION NOMOGRAPH FOR CASED HOLE

CNL ENVIRONMENTAL CORRECTIONS (Cased and Open Hole)



Before using these nomographs, log values must be corrected for any matrix effect (**Por 13**).

For cased-hole logs, enter **Por 14a** with the corrected CNL reading and draw a vertical line through the chart blocks. Find the corrections, as shown by the red line. Then go to Block C, **Por 14b**, and continue. Apply the algebraic sum of all corrections to the corrected log reading.

For open-hole logs, enter **Por 14b** with the corrected CNL reading. If the log was run with automatic caliper correction:

- "Back out" the caliper correction to find the "chart-base" porosity. Go down to Reference (*), Block A, and follow trend lines to "Borehole Size Minus Panel Setting". This value (27 p.u. in example) is the chart-base porosity. Draw a vertical line through all chart blocks at this value.
- If "Borehole Size Minus Panel Setting" is negative, as in the example, normally assume that this is caused by mud cake. Do not make both borehole-size (Block A) and mud-cake (Block B) corrections. Beginning at Block B, find corrections for each block and add the algebraic total to the chart-base porosity. This is the environmentally-corrected CNL porosity.
- If "Borehole Size Minus Panel Setting" is positive, normally assume that the hole is washed out and mud-cake thickness, if any, is indeterminate. Beginning with Block A, but skipping Block B, find corrections and proceed as above.

If the log was not run with automatic caliper corection:

- Draw a vertical line through all blocks at the corrected CNL reading.
- If "Borehole Size Minus Panel Setting" is positive, begin at Block A and find corrected CNL porosity as above. Do not use both Blocks A and B.
- If "Borehole Size Minus Panel Setting" is negative, begin at Block B and find corrected CNL porosity as above.

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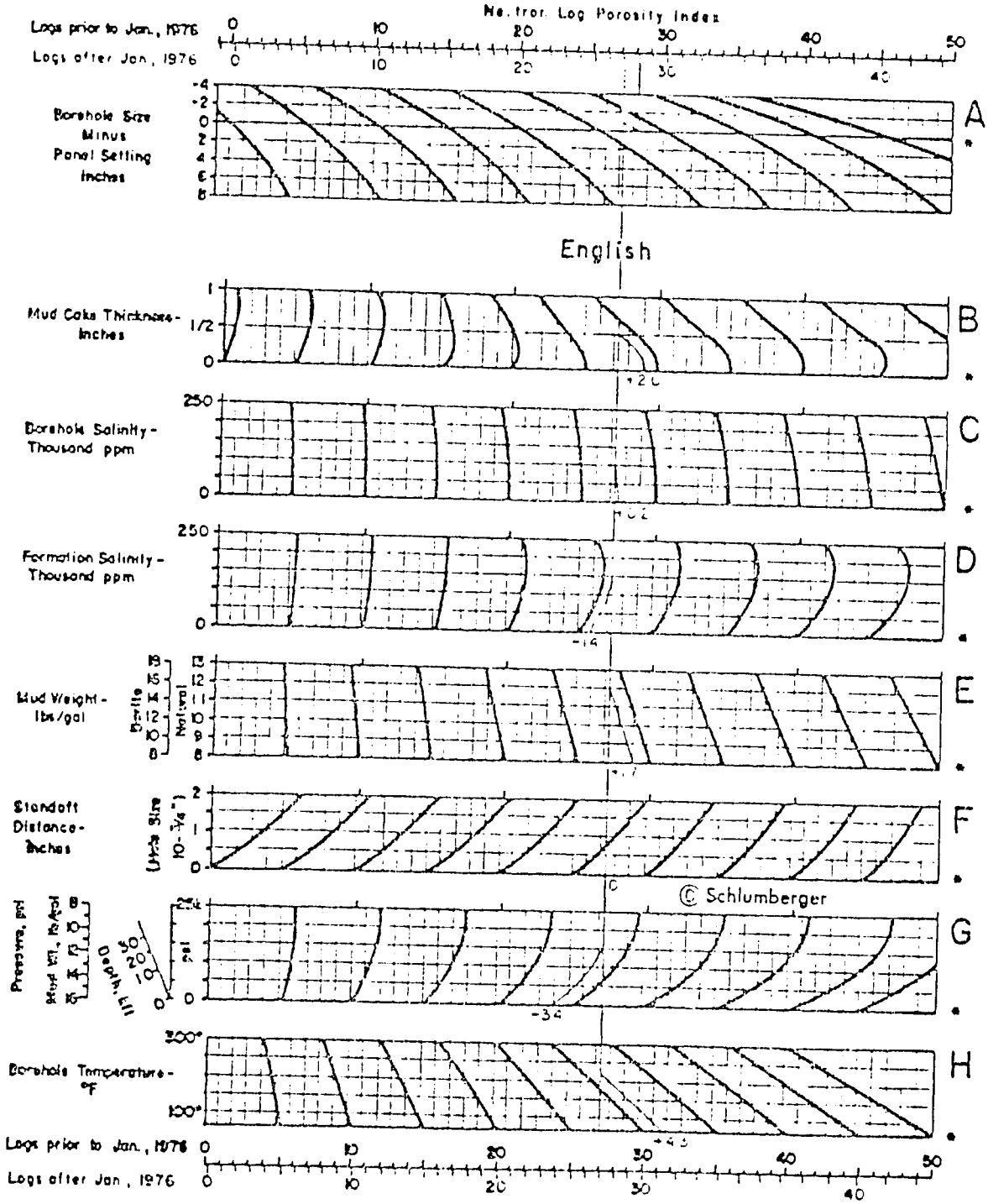
DUAL SPACING NEUTRON LOG (CNL*) CORRECTION NOMOGRAPH FOR OPEN HOLE[5]



EXAMPLE 1. Auto. Caliper (in red)

GIVEN:

CNL Rdg (corr. for bh)	.... 28 p.u.
Mud Wt.	.... 12 lb/gal
h_{mc}	.... ½ in.
T_{bh}	.... 225°F
Salinity (bh)	.... 100 kppm
Salinity (fm)	.... 150 kppm
Standoff	 0
Depth	.... 21,000 ft

SOLUTION:

Enter at 28 p.u.
Go to Index, Block A
Follow trend lines to − ½ in.
Draw chart-base line at this point (27 p.u.)
Find corrections as shown:
$\Sigma\Delta\phi$ = + 2.0 + 0.2 − 1.4 + 1.7 − 3.4 + 4.3 = 3.4
ϕ_{cor} = 27 + 3.4 = 30.4 p.u.

EXAMPLE 2. Separate Caliper

GIVEN:

CNL Rdg. (corr. for bh)	.... 30 p.u.
"BH − Cal."	.... + 4 in.
Mud Wt.	.... 9.3 lb/gal
T_{bh}	.... 175°F
Salinity (bh)	.... 50 kppm
Salinity (fm)	.... 150 kppm
Standoff	 0
Depth	.... 12,500 ft

SOLUTION:

Enter at 30 p.u.
Draw chart-base porosity line through all blocks.
Find corrections as shown (skip Block B)
$\Sigma\Delta\phi$ = − 4.0 + 0 − 1.5 + 0.7 + 0 − 2.5 + 3.3 = − 4.0
ϕ_{cor} = 30 − 4.0 = 26 p.u.

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Por-14a Correct log values for lithology and draw a vertical line through the chart.

A. Tool calibrated for 8 3/4" d_h--actual d_h = 9½". Correction is negative because more H_2O is present than calibrated for.

B. Tool calibrated for 0.304" casing thickness--actual thickness is .240"--correction is positive since it has been calibrated for more interference from steel.

C. Tool calibrated for 1.62" of cement thickness--actual thickness is 1.30"--correction is positive since it has been calibrated for more interference from cement.

Por-14b For case-hole logs make the above corrections and then go to Block C and continue. For openhole logs enter Por 14b with lithology corrected reading. If applicable back out Automatic Caliper correction and draw vertical line through the chart. If

Caliper Rdg.--d_h is negative skip A--mud cake

Caliper Rdg.--d_h is positive skip B--wash out

A. For Caliper Rdg.--d_h negative--mud cake--correction is positive (back-out is negative)--instrument is calibrated for no mud-cake and H_2O has higher H concentration than mud-cake. With Automatic Caliper--when a mud cake is encountered the caliper senses a reduction in hole diameter and applies a correction appropriate for a hole reduced by twice h_{mc}. This results in mud-cake effect being aggravated at low ϕ and reduced at high ϕ.

For Caliper Rdg.--d_h positive--washout--correction is negative because instrument is seeing more borehole than it was calibrated for--more H_2 atoms are seen in mud as ϕ.

Bar graph A is used to subtract out mud cake correction and to correct for wash-outs. If the latter is done, Bar graph B is skipped and vice-versa.

B. This bar graph is used when mud cake exists and is skipped when wash-out exists. Presence of mud-cake reduces counting rate, increasing ϕ. However both detectors are affected and the use of the ratio of their readings results in a positive correction for high ϕ and negative correction for low ϕ.

C. Borehole salinity--tool is calibrated in fresh water. Salt water has a lowe H_2 concentration than fresh water, thus the correction is positive.

D. Formation Salinity--Here the correction is negative. The lower H_2 concentration of the formation water is offset by thermal-ion absorption by the chlorine.

E. Mud-weight--this is a positive correction--tool is calibrated in water--the presence of solids to make up the mud reduces the H_2 concentration.

F. Stand-off--this is a negative correction--the tool was calibrated for zero stand-off--Presence of stand-off places mud between tool and formations, thus decreasing the count rate and increasing apparent ϕ.

G. Pressure--this is a negative correction--tool was calibrated at atmospheric pressure--as pressure increases, H_2 concentration in mud, water, etc., is increased.

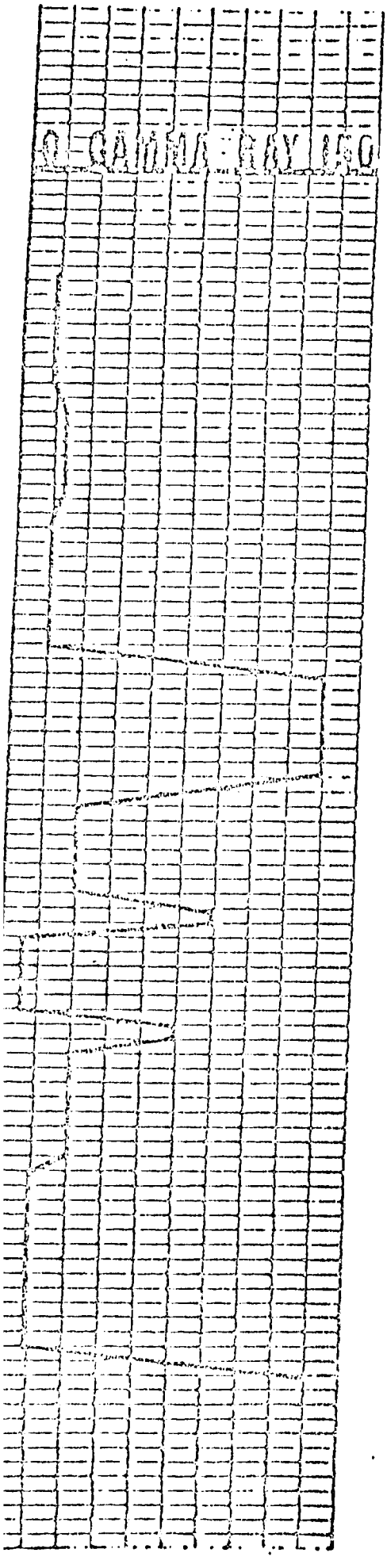
H. Borehole temperature--this is a positive correction--tool was calibrated at 75°F--higher temperature causes expansion and a decrease in H_2 concentration.

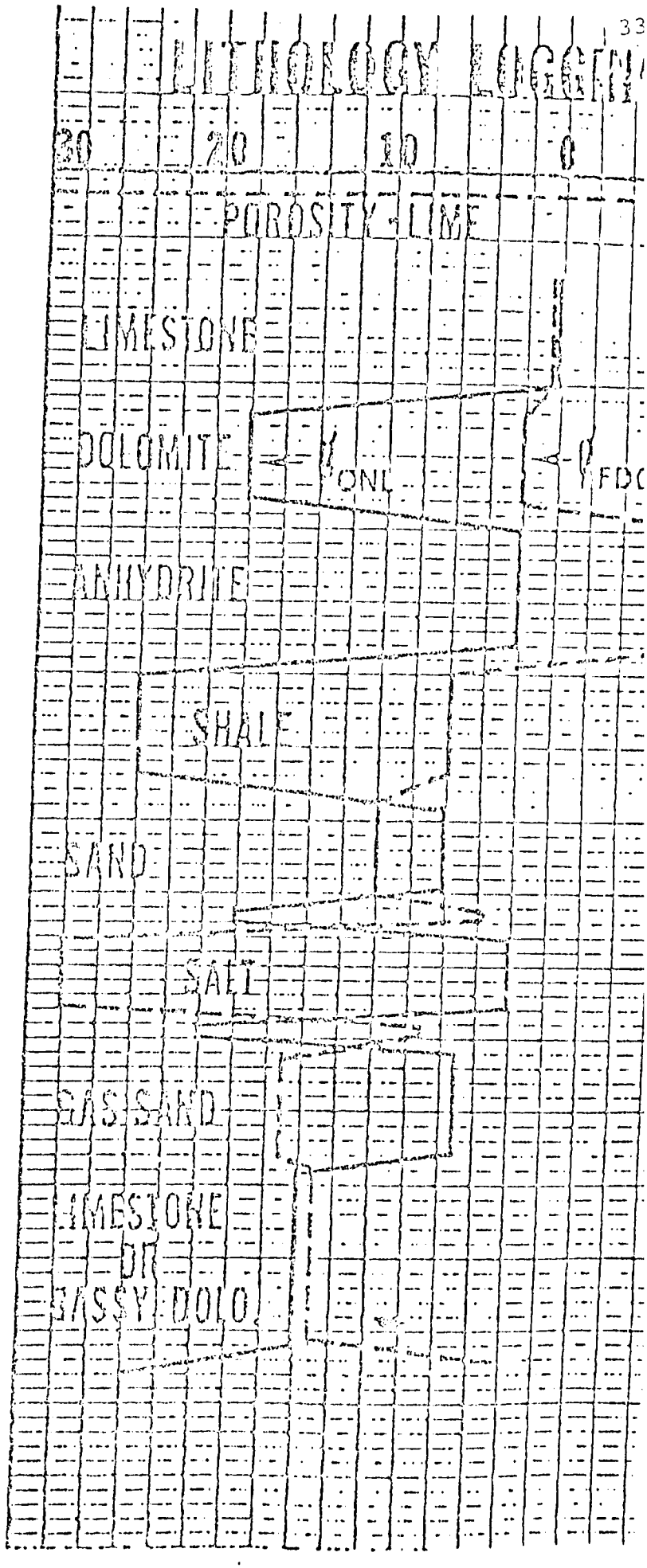
Reference: Alger, R.P.. Locke, S., Nagel, W.A., and Sherman, H.: "The Dual Spacing Neutron Log-CNL", SPE of AIME, New Orleans, Oct. 1971, Paper SPE 3565.

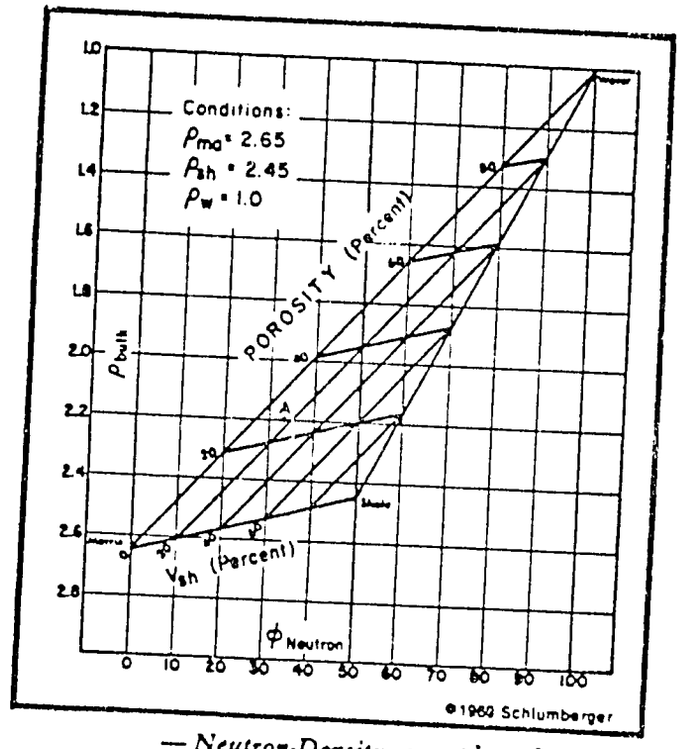
NEUTRON LOG (CONT'D)

LIMITATIONS

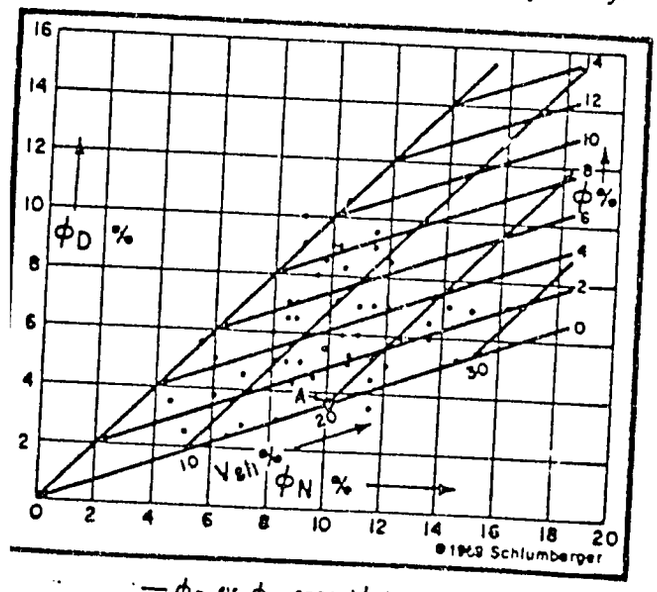
- RESPONSE GREATLY AFFECTED BY BOREHOLE CONDITIONS--CHECK D_H VARIATIONS WITH CALIPER LOG
- VALUES FROM CASED HOLES ARE SEMI-QUANTITATIVE DUE TO VARIATIONS IN ECCENTRICITY OF CASING, HOLE SIZE BEHIND CASING, CEMENT THICKNESS, ETC.
- PRESENCE OF GAS MAY MAKE TOOL RESPONSE AMBIGUOUS
- UNRECOGNIZED CHANGES IN MINERAL COMPOSITION MAY RESULT IN ERRONEOUS INTERPRETATION
- SNP SEES LESS THAN 1/4 OF AREA AROUND THE BOREHOLE AND THUS MAY NOT BE ADEQUATE IN BEDS WITH SCATTERED VUGS & FRACTURES
- CNL RESPONDS SOMEWHAT ANOMALOUSLY IN DOLOMITE FORMATIONS DUE POSSIBLY TO PRESENCE OF BORON AND GADOLIMIUM AND TO TYPE OF NEUTRON SOURCE USED


0 GAMMA RAY 150

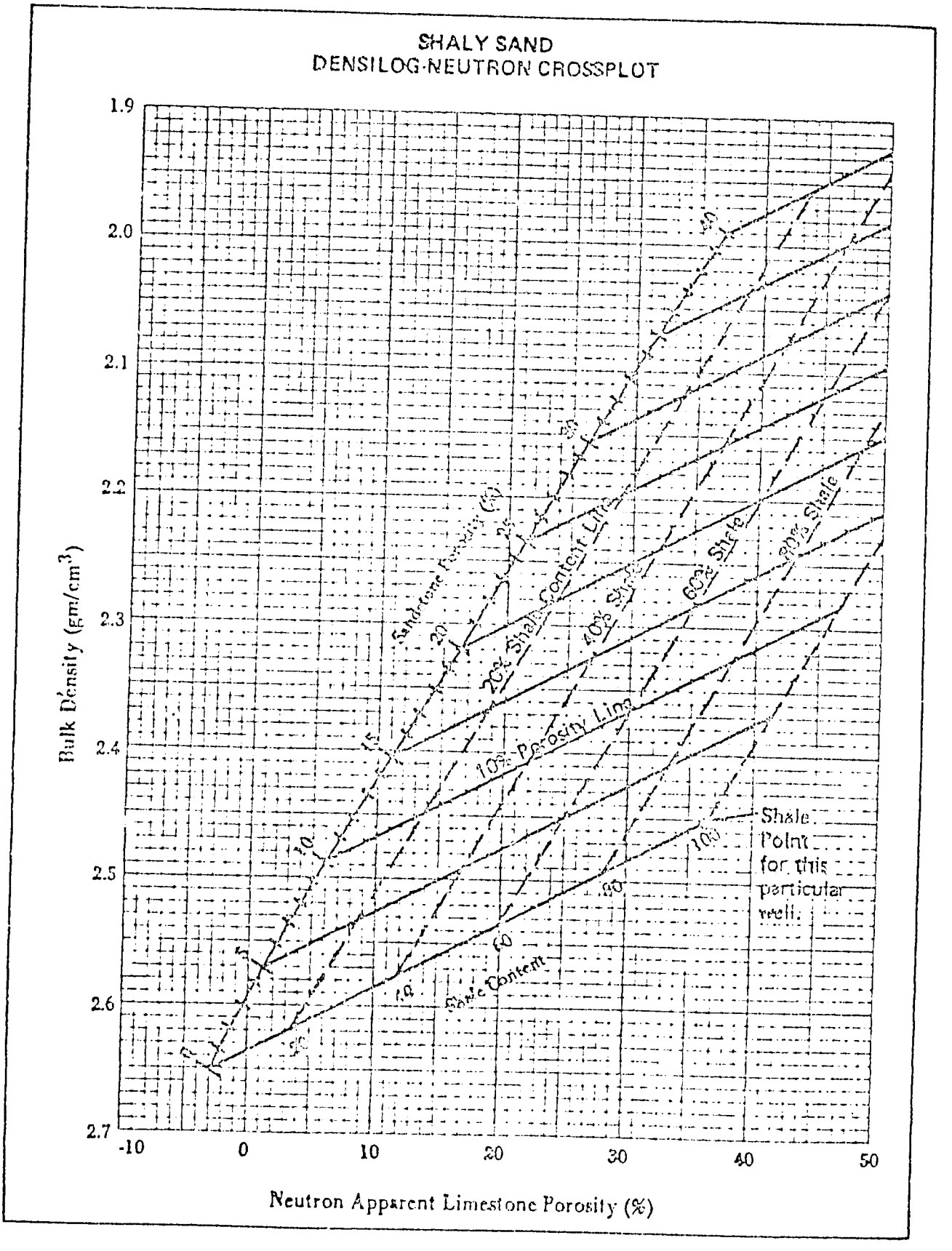

LITHOLOGY LOGGING
30
20
10
0
POROSITY LIME
LIMESTONE
DOLOMITE
ONL
FDC
ANHYDRITE
SHALE
SAND
SALT
GAS SAND
LIMESTONE
OR
GASSY DOLO



— *Neutron-Density crossplot showing matrix, water, and shale points, scaled for determination of V_{sh} and porosity.*

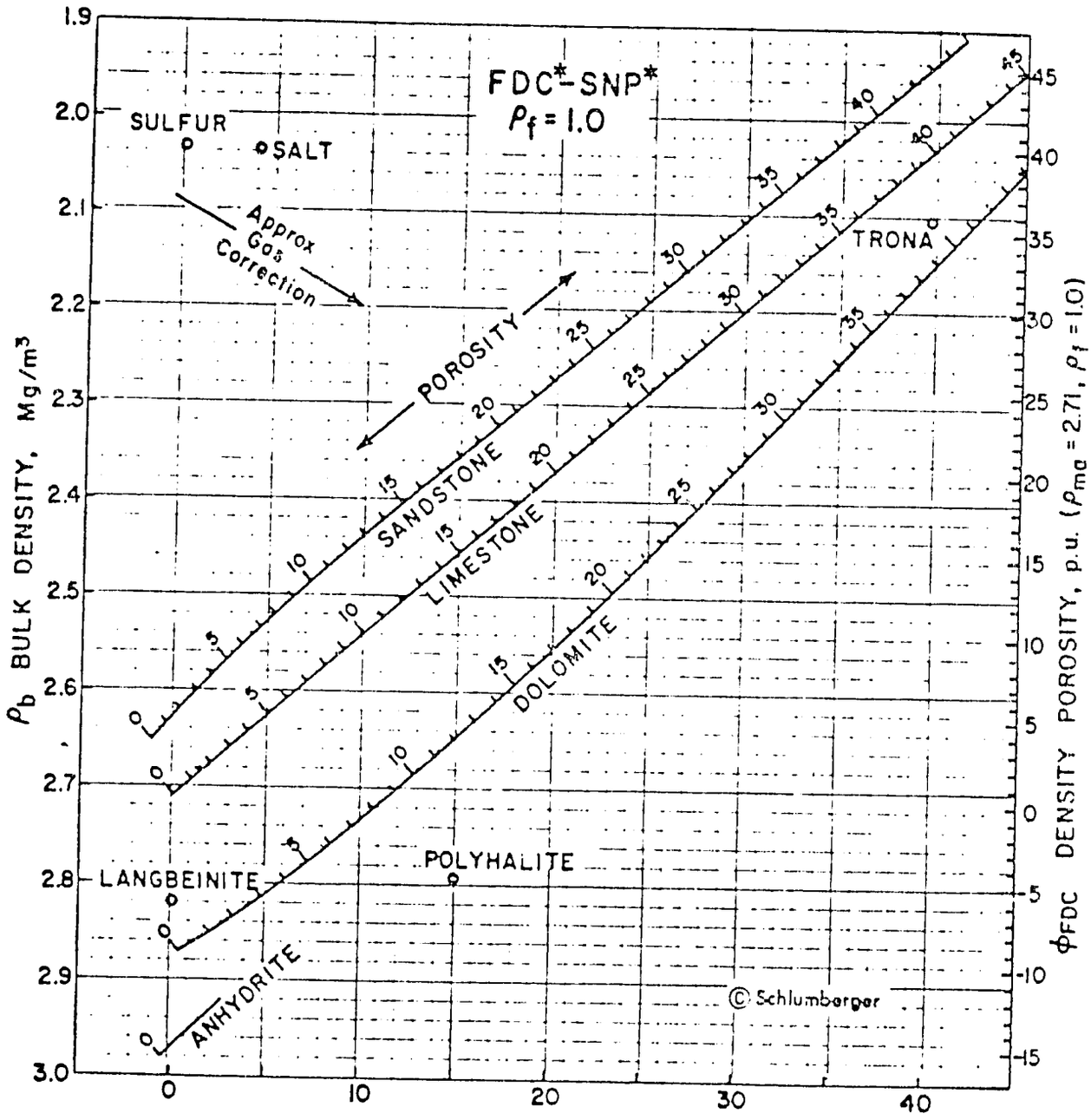


— *ϕ_D vs ϕ_N crossplot over a section of shaly limestone.*


SHALY SAND
DENSILOG-NEUTRON CROSSPLOT
Bulk Density (gm/cm³)
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
-10
0
10
20
30
40
50
Neutron Apparent Limestone Porosity (%)
Sandstone Porosity (%)
20% Shale Content Line
40% Shale
60% Shale
80% Shale
10% Porosity Line
Shale Content
Shale Point for this particular well.

POROSITY AND LITHOLOGY DETERMINATION FROM FORMATION DENSITY LOG AND SIDEWALL NEUTRON POROSITY LOG (SNP*)

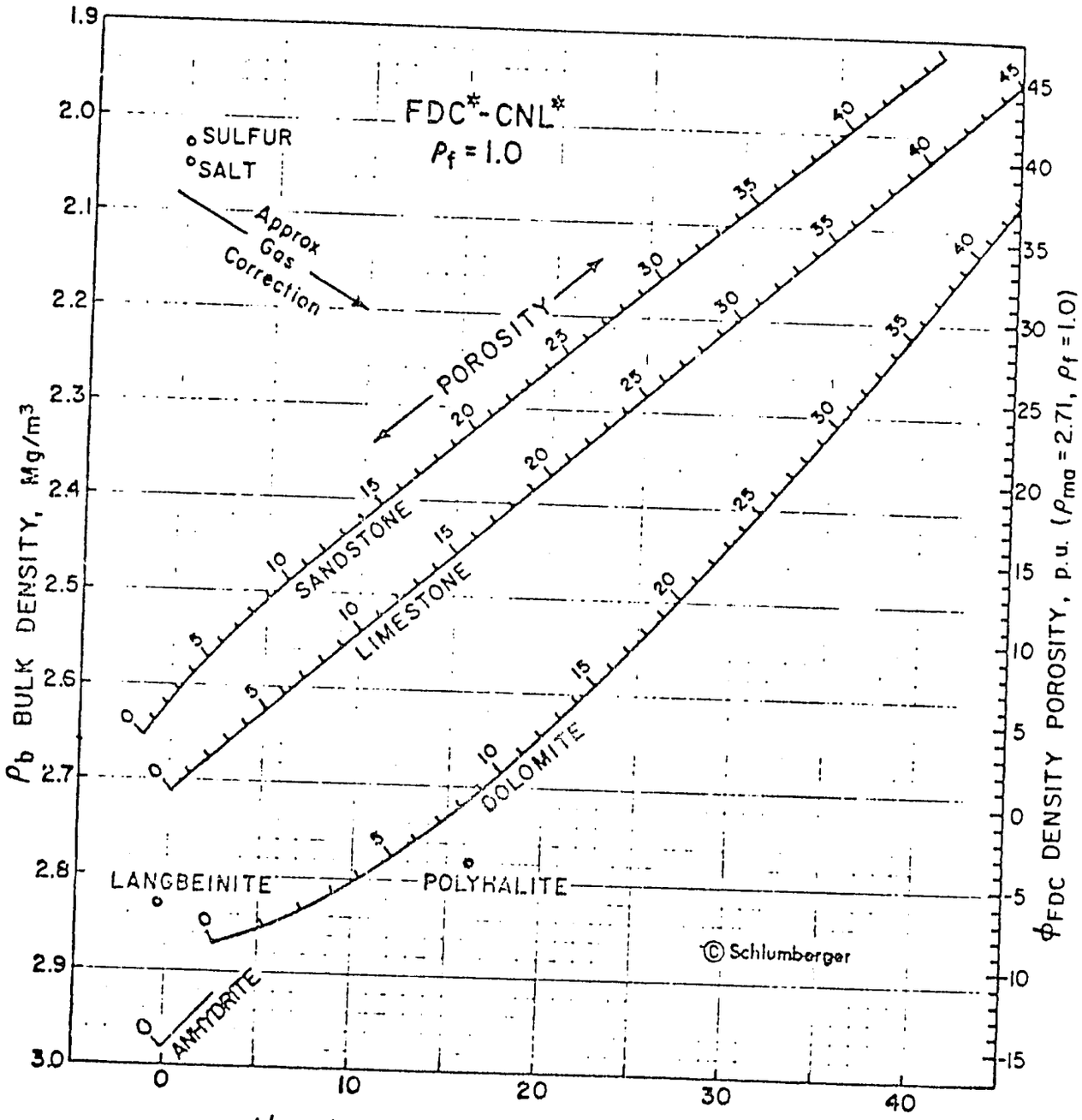
MAY ALSO BE USED WITH GNT F, G, or H NEUTRON LOGS
FRESH WATER, LIQUID-FILLED HOLES



*Mark of Schlumberger

POROSITY AND LITHOLOGY DETERMINATION FROM FORMATION DENSITY LOG AND COMPENSATED NEUTRON LOG (CNL*)

FRESH WATER, LIQUID-FILLED HOLES



*Mark of Schlumberger

PROBLEM #1

This is a Gulf Coast example from South Louisiana. Please note the log scales carefully.

1-1. The lithology of the formation from 11,588-11,618' is:

(a) Dolomite (b) Limestone (c) Sandstone
(d) Shale (e) Coal (f) Anhydrite (g) Salt
(h) Granite Wash

1-2. The above zone (11,588-618') should produce:

(a) Gas (b) Oil (c) Water (d) Nothing

1-3. The zone at 11,639' is:

(a) Dolomite (b) Limestone (c) Sandstone
(d) Shale (e) Coal (f) Anhydrite (g) Salt
(h) Granite Wash

PROBLEM #2

The Berry #1, in Roger Mills Co., Oklahoma, was drilled and logged in fresh mud. The zone of interest was logged from 14,976-15,002'.

2-1. The lithology of this interval is:

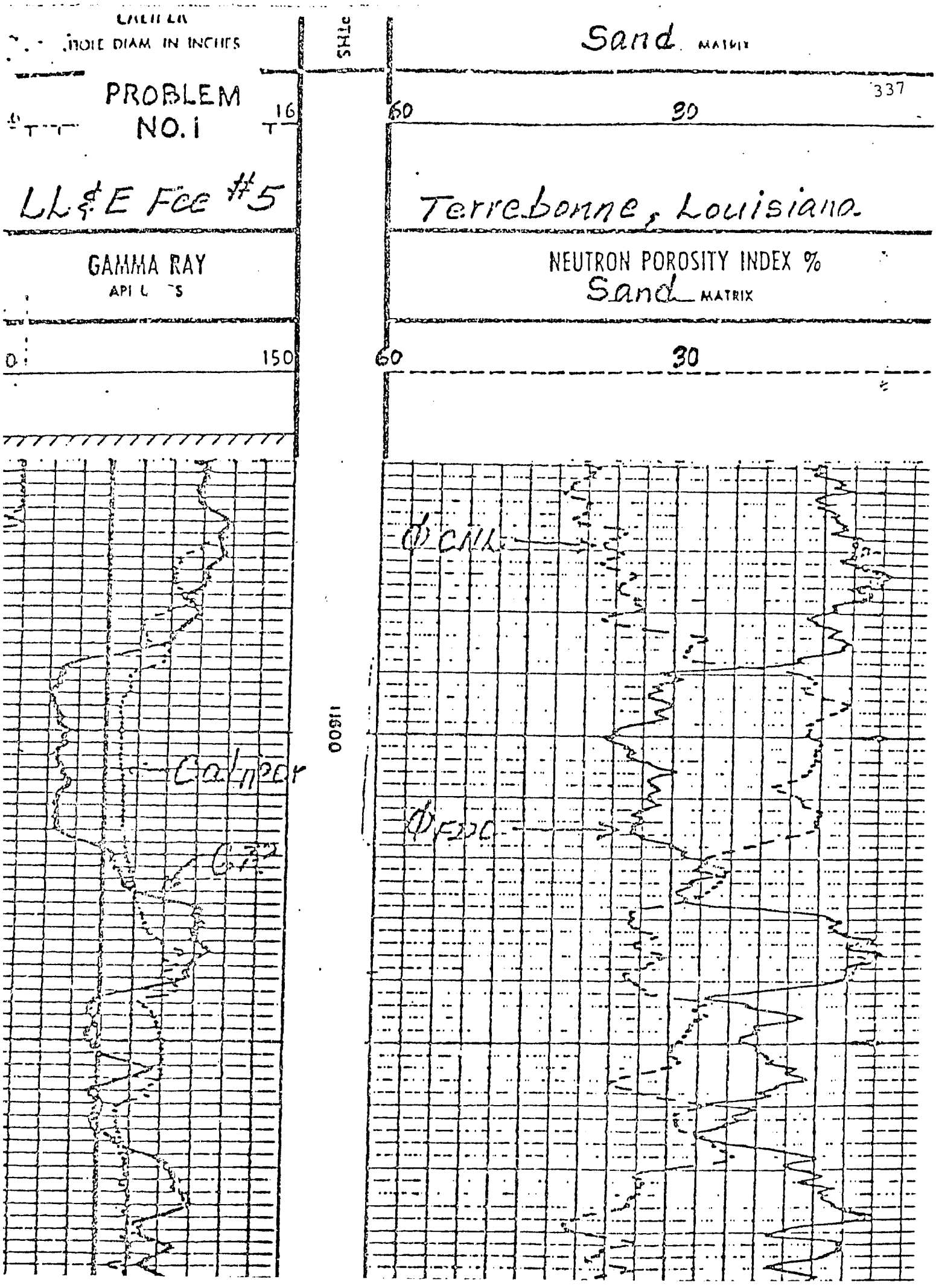
(a) Dolomite (b) Limestone (c) Sandstone
(d) Shale (e) Coal (f) Anhydrite (g) Salt
(h) Granite Wash

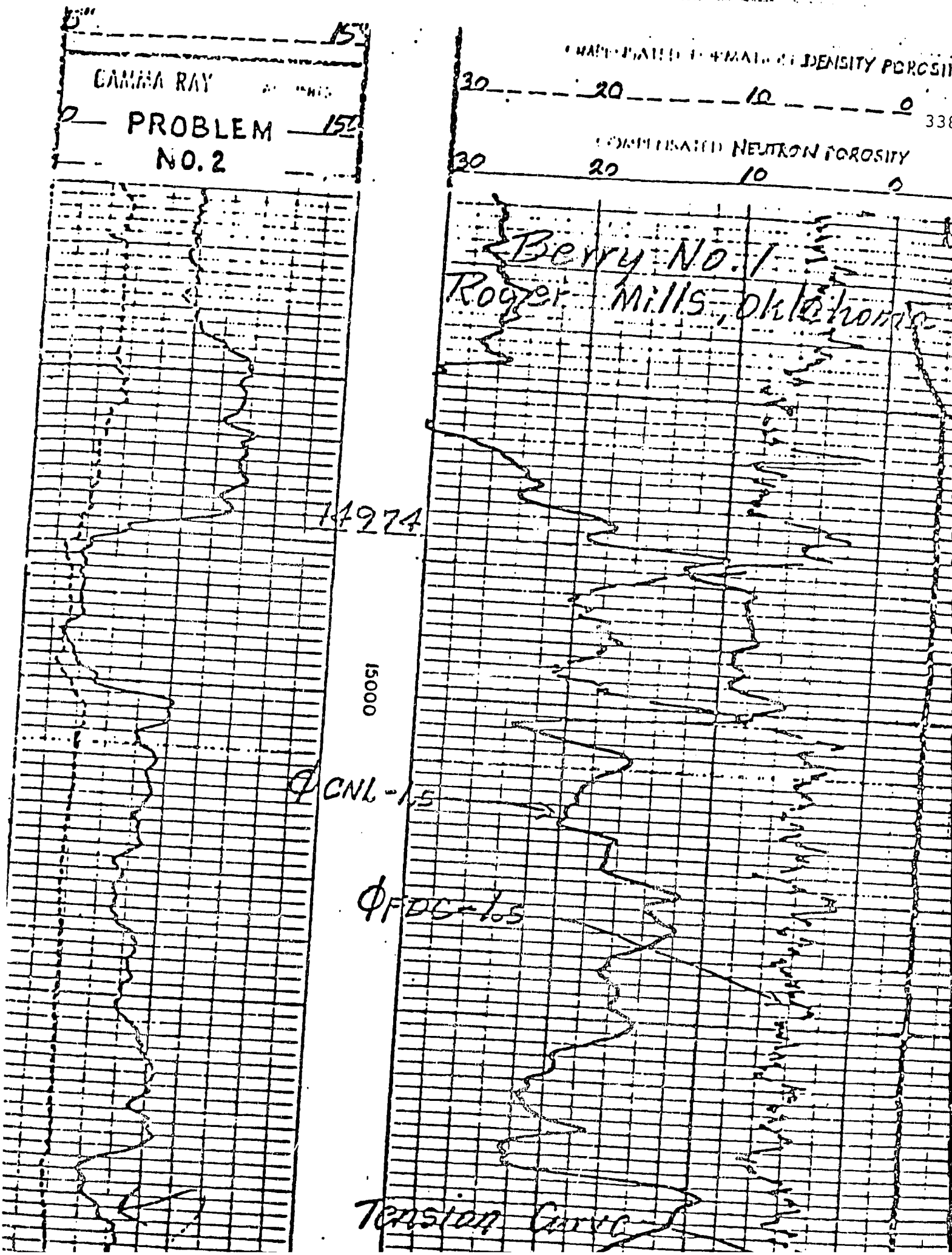
2-2. The Neutron-Density crossplot indicates that the formation should produce:

(a) Gas (b) Oil (c) Water (d) Nothing

2-3. The net productive footage in this zone is:
(Use a porosity cut-off of 8% for sandstone and 5% for carbonate. Remember, the log is scaled in Apparent Limestone porosity units).

(a) 20' (b) 22' (c) 24' (d) 26'


CALIPER
HOLE DIAM IN INCHES
PROBLEM
NO.1
16
LL&E Fee #5
GAMMA RAY
API UNITS
0
150
Caliper
Sand MATRIX
60
30
337
Terrebonne, Louisiana
NEUTRON POROSITY INDEX %
Sand MATRIX
60
30
11600


GAMMA RAY
PROBLEM
NO. 2
DENSITY POROSITY
30
20
10
0
NEUTRON POROSITY
30
20
10
0
Berry No. 1
Roger Mills, Oklahoma
14974
15000
φCNL-1.5
φFDC-1.5
Tension Curve

APPENDIX

Circle Correct Answer

1. If the mud filtrate (R_{mf}) is 2.0 at 70° and the formation water salinity is 30,000 ppm NaCl, the porosity in a carbonate is 15% and the zone is water filled, the formation temperature is 180° F., the true resistivity of the formation is:
   (a) 1.6 (b) 360 (c) 35 (d) 4.1 — a b c d

   The resistivity of the flushed zone filled with mud filtrate is:
   (a) 1.6 (b) 30 (c) 35 (d) 90 — a b c d

   If the resistivity of the flushed zone (R_{xo}) is 100 ohm-m, what is the water saturation in the flushed zone (S_{xo})?
   (a) 39% (b) 50% (c) 70% (d) 60% — a b c d

   If the true resistivity (R_t) of the formation is 14 ohm-m, what is the water saturation?
   (a) 55% (b) 35% (c) 41% (d) 60% — a b c d

   If the true conductivity is 100 millimho/m, the water saturation is:
   (a) 40 (b) 63 (c) 55 (d) 35 — a b c d

2. Which resistivity in the table in the text is wrong?
   (a) g (b) h (c) c (d) d — a b c d

   The value for resistivity should be:
   (a) 2 (b) 10 (c) 14 (d) 7 — a b c d

Check the following table of numbers and find which one is wrong.

	Reservoir Type	Porosity %	Water Saturation %	Fluid Resistivity	Resistivity
(a)	Sand	25	100	R_w = .09	1.1
(b)	Sand	25	100	R_{mf} = .4	5.0
(c)	Sand	25	50	R_w = .09	4.4
(d)	Sand	25	20	R_w = .09	28.0
(e)	Carbonate	20	100	R_w = .2	5.0
(f)	Carbonate	10	100	R_w = .2	20.0
(g)	Carbonate	5	100	R_w = .2	80.0
(h)	Carbonate	10	100	R_{mf} = .02	500.0

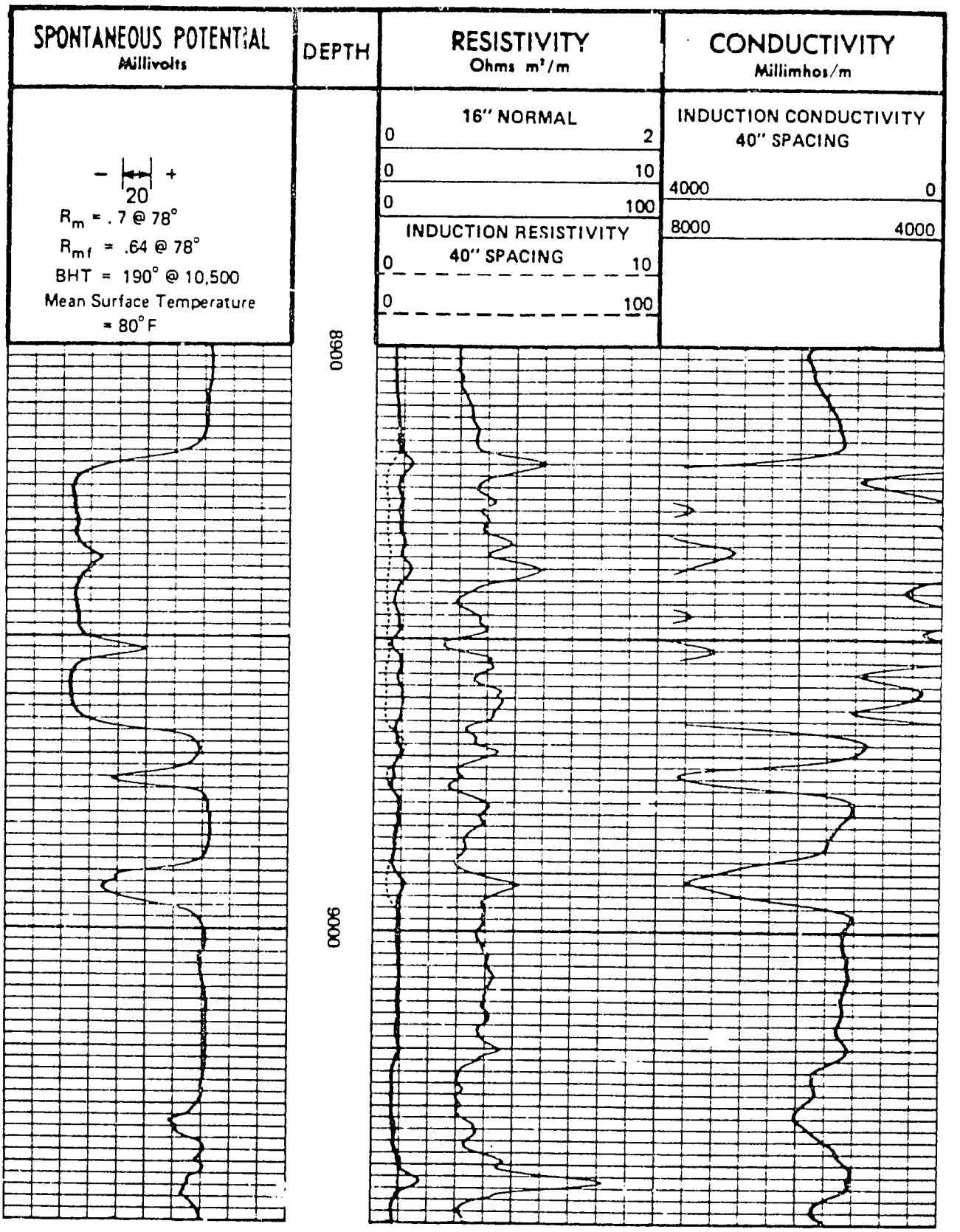
LOG INTERPRETATION

QUESTIONS LESSON 3

Dresser Atlas

	Circle Correct Answer
1. The water resistivity for the Problem log (Example 104) is about (a) .017 (b) .027 (c) .29 (d) .19	a b c d
2. Shale in a reservoir (a) reduces SP amplitude (b) rounds the shoulders (c) has no effect (d) reverses	a b c d
3. If sand #1 has a 100 mv SP and sand #2 has a 90 mv SP, sand #1 has (a) a higher permeability (b) a lower permeability (c) the same permeability (d) not enough information	a b c d
4. Permeable bed #1 has a resistivity of 100 ohm-m (Rm = 1.0) while permeable bed #2 has a resistivity of 20 ohm-m (Rm = 1.0). If both are shale free, 15 feet thick and have the same very salty formation water: (a) SP #1 will be greater than SP #2 (b) SP #1 will be less than SP #2 (c) both SP's will be the same (d) not enough information	a b c d
5. On log Example 104, mark all shaly zones on log and return log.	

PROBLEM

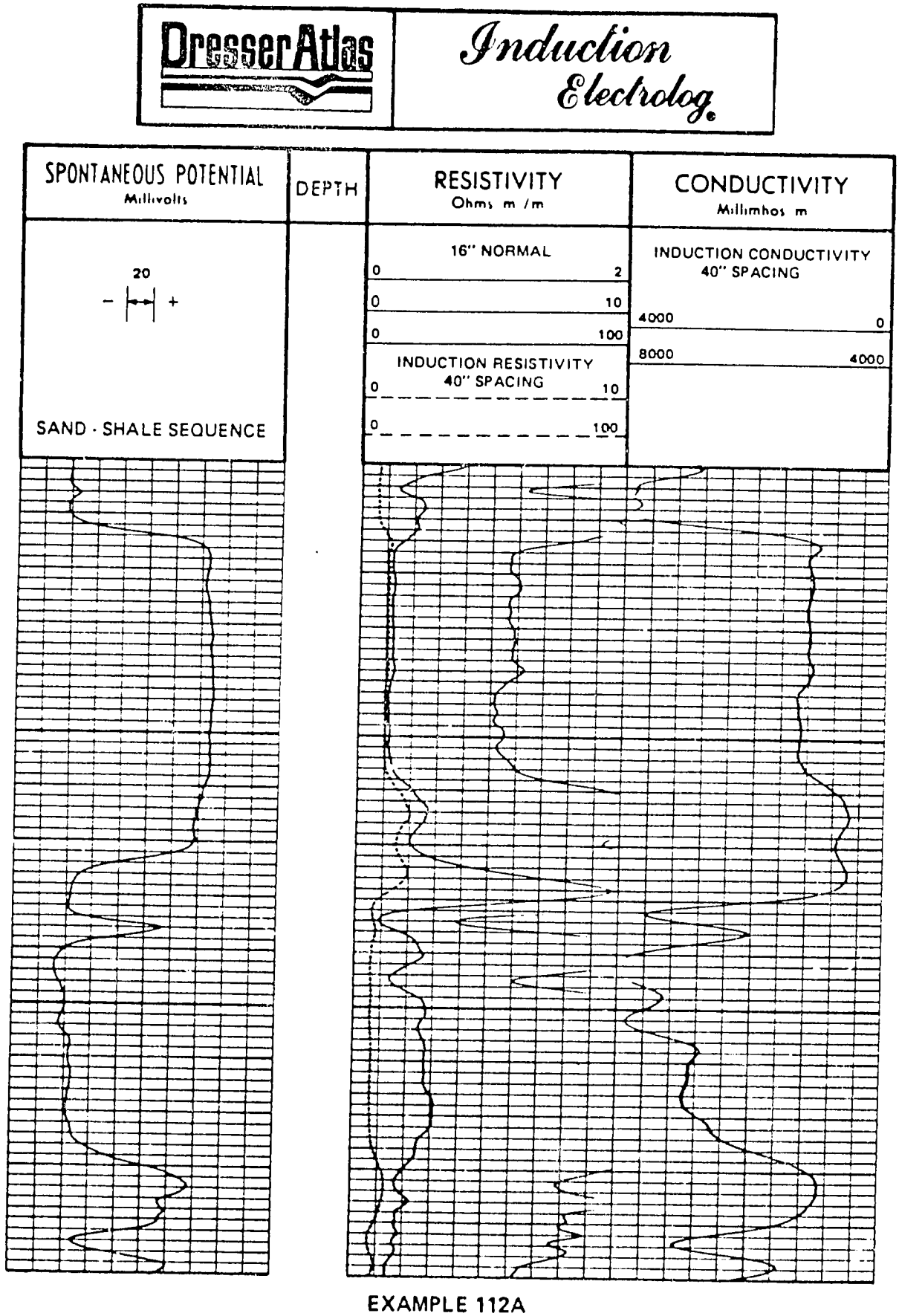


Example 104

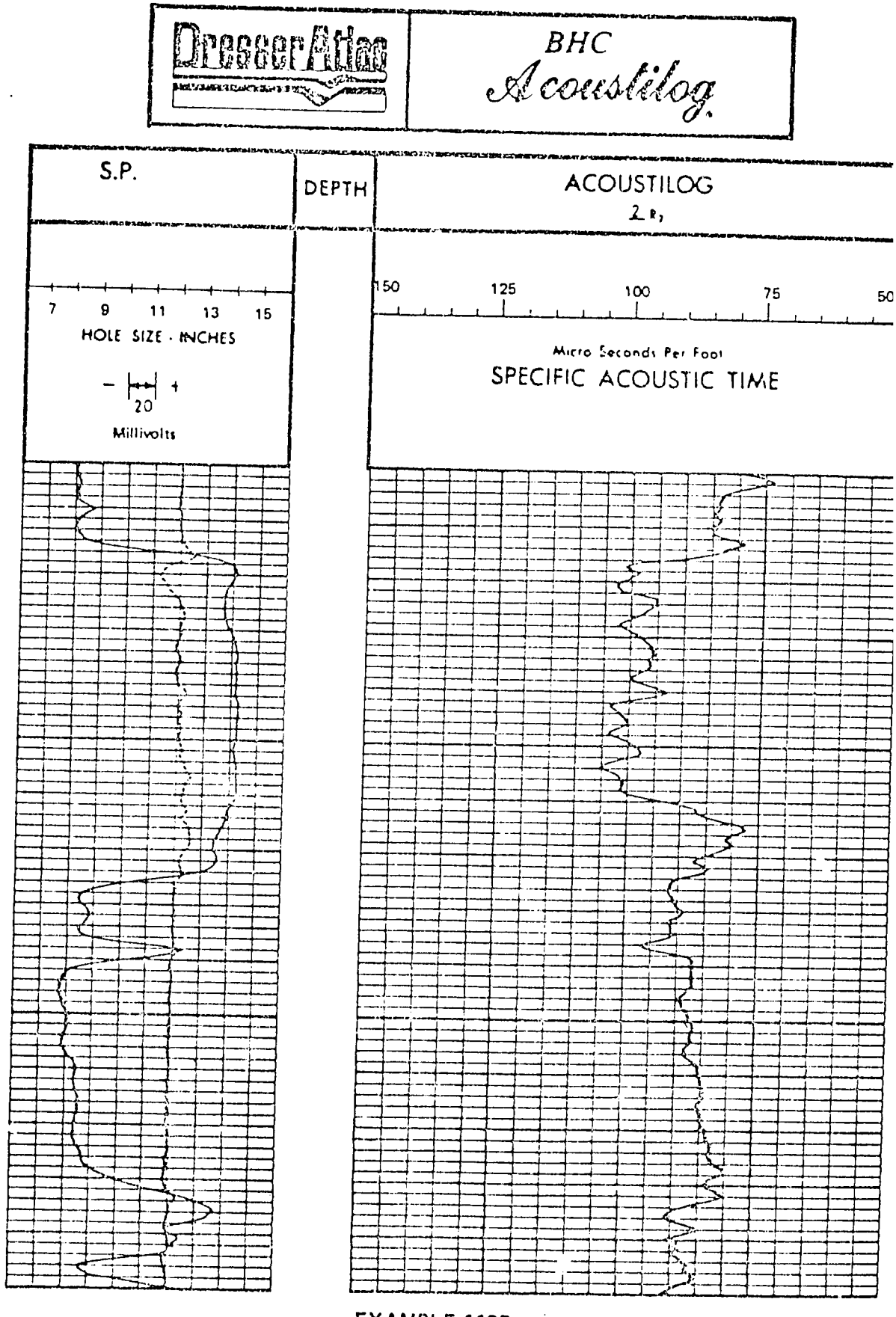
LOG INTERPRETATION

QUESTIONS LESSON 4

	Circle Correct Answer
Acoustic Log	
1. The Wyllie "time average formula" (4-1) is really applicable in: (a) shales (b) uniform intergranular porosity (c) secondary porosity (d) fractures	a b c d
2. In hydrocarbon bearing unconsolidated sands the calculated porosities are generally: (a) too high (b) too low (c) right	a b c d
3. On the Acoustilog in a zone of constant compacted lithology (rock type) curve movements to the left are: (a) meaningless (b) lower porosity (c) higher porosity (d) something else	a b c d
4. On example 112A and 112B: (a) mark the permeable zones on the log (b) calculate ϕ, R_{wa} and S_w on log, using algorithm 2. Be sure to indicate R_w used.	
5. Could you follow the algorithm and write-up? (a) yes (b) no (c) much difficulty (d) didn't try	a b c d



EXAMPLE 112A



EXAMPLE 112B

LOG INTERPRETATION

QUESTIONS LESSON 5

Dresser Atlas DRESSER

Fill in Blanks (Use Chart 9)

1.

R_e	R_w	ρ Log	Formation	Porosity %	S_w %
200	.083	2.54	Limestone	10	____
200	.1	2.54	Dolomite	16.5	____
10	.18	2.54	Sand	6.5	____
1	____	2.16	Sand	29	100
1	____	2.37	Limestone	20	100
14	.11	2.56	Limestone	9	____
10	.015	2.7	Dolomite	7.5	____

Circle Correct Answer

2. Most interpretation nomographs use a ρ_f (fluid density) of 1 gm/cc. This is good where invasion is deep and residual hydrocarbons are minimal.

A. In a gas reservoir with little or no invasion the apparent porosity calculated using $\rho_f = 1$ is:

(a) too low (b) too high (c) true porosity (d) not enough information

a b c d

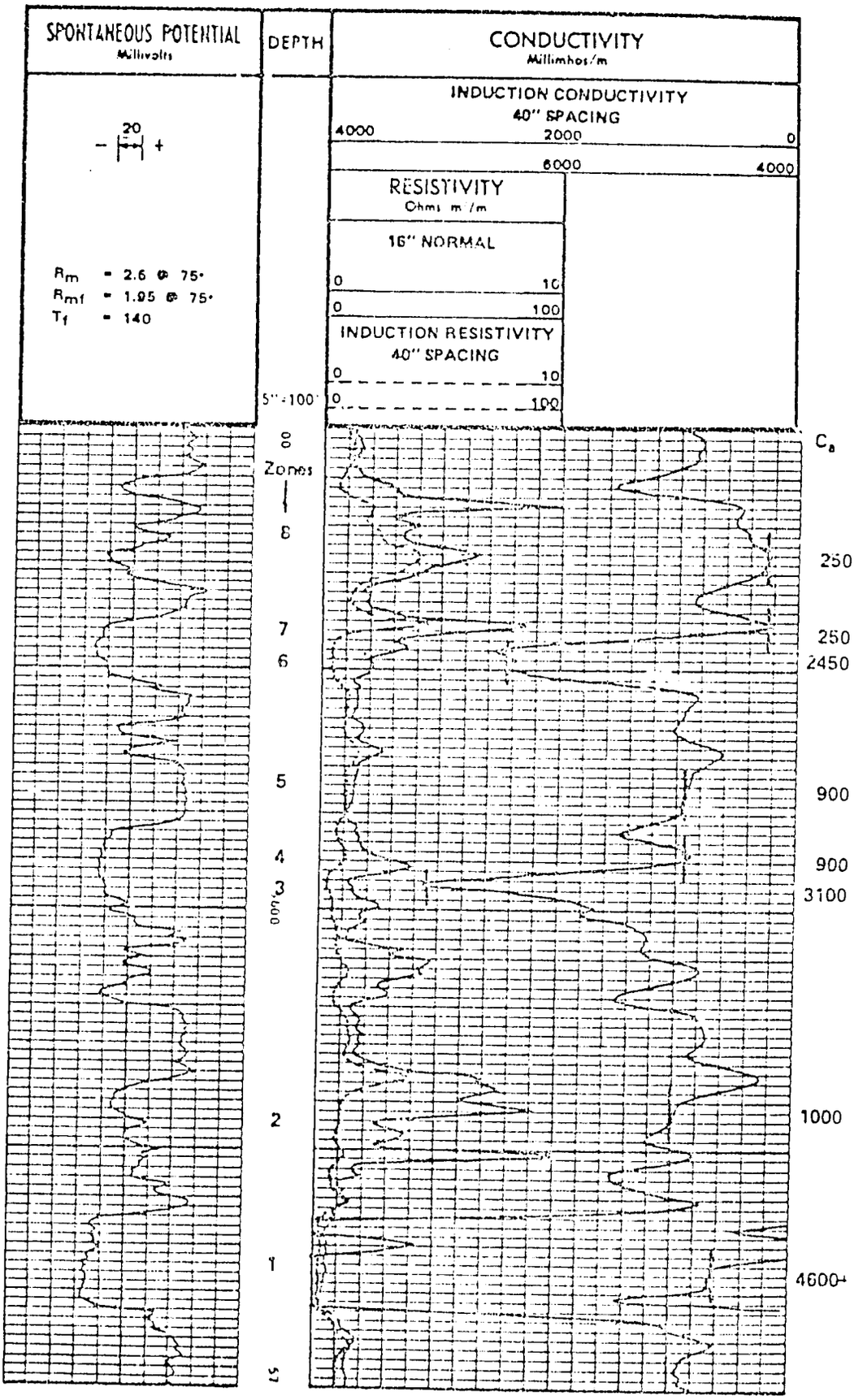
B. If there is no invasion in a water zone filled with very salty water, the apparent porosity using $\rho_f = 1$ is:

(a) too low (b) too high (c) true porosity (d) not enough information

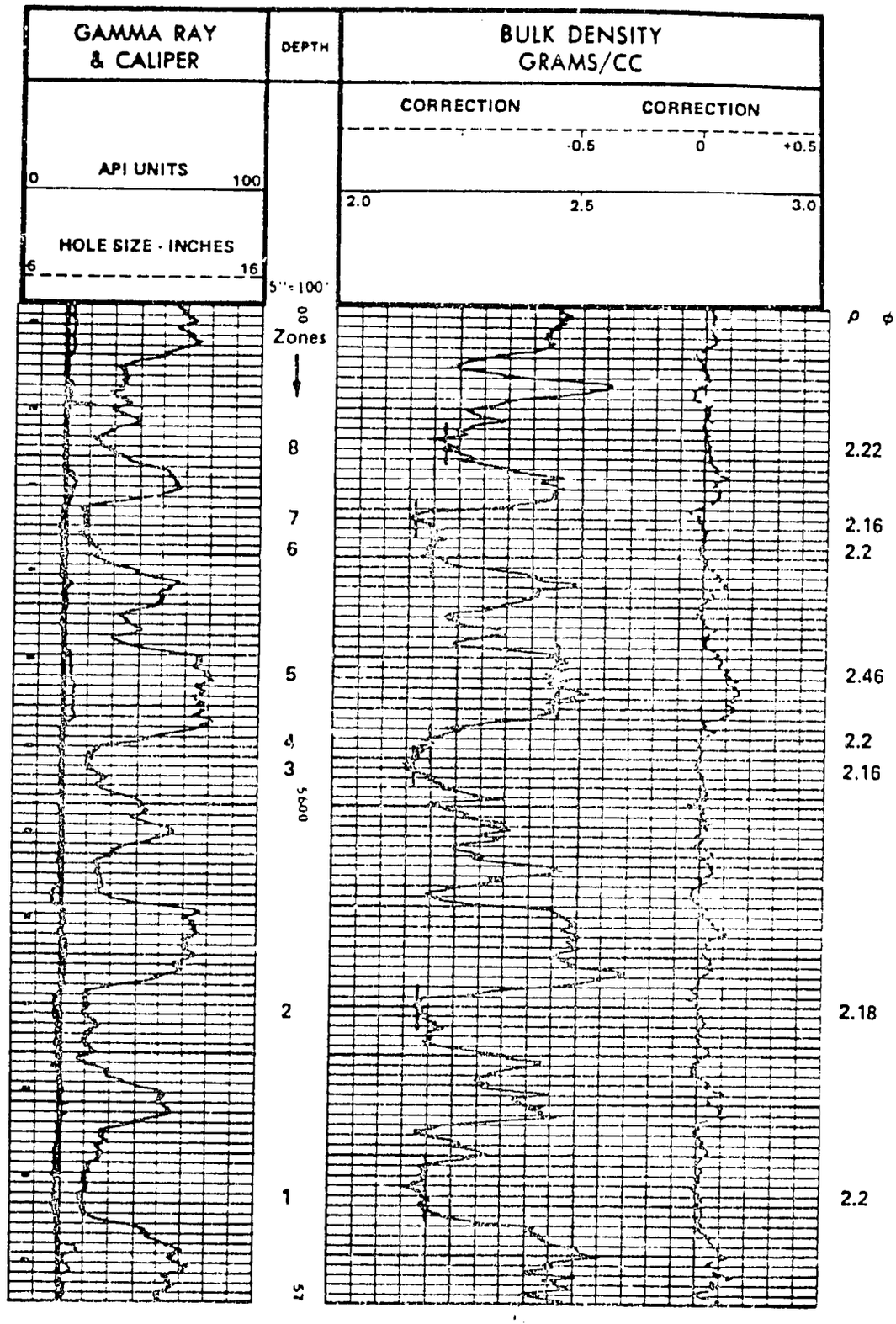
a b c d

3. Finish calculation of R_{we} on figures 181a and 181b.

a. Write answers on logs
b. Calculate R_{we}
c. Find R_w
d. Calculate S_w for each zone
e. Which zones are productive?



Example 181a



L. Cretaceous Sand. in Mississippi

Assume all sands are clean.

Example 181b

LOG INTERPRETATION

QUESTIONS
LESSON 6

Dresser Atlas

Circle Correct Answer

1. The gamma ray log may be considered:
   (a) permeability log
   (b) density log
   (c) shale log
   (d) caliper log

   a b c d

2. The neutron logs see dry gas as
   (a) high porosity
   (b) liquid
   (c) low porosity
   (d) no influence

   a b c d

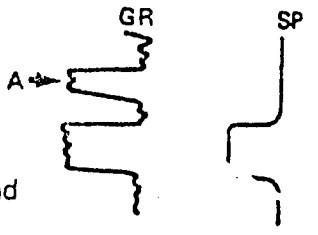
3. A sidewall neutron log indicates the apparent limestone porosity as 13%. The real porosity is:
   (a) 13% (b) 16.5% (c) 10% (d) unknown

   a b c d

4. A compensated neutron log indicated porosity is 20%. The zone is a sand. The real porosity is:
   (a) 16.8 (b) 23.5 (c) 14.2 (d) 24.1

   a b c d

5. Zone A could be



   (a) permeable sand
   (b) shale
   (c) nonpermeable limestone
   (d) potash

   a b c d

LOG INTERPRETATION

QUESTIONS
LESSON 7

Dresser Atlas DRESSER

1. Given a Compensated Neutron and density log fill in the porosity and lithology.

Comp. Neutron (ϕ_{ls} apparent)	Density	Porosity	Lithology
18%	2.40	_____	_____
12	2.39	_____	_____
10	2.30	_____	_____
0	2.03	_____	_____
26	2.50	_____	_____

2.

Sidewall Neutron	Density	Acoustic	Porosity	Lithology	Comment
5%	2.62	50	_____	_____	_____
4	2.90	55	_____	_____	_____
15.5	2.62	60	_____	_____	_____
39	2.35	52.5	_____	_____	_____
0	2.03	67	_____	_____	_____
-1	2.81	52	_____	_____	_____

3. In a clean sand the best two porosity logs to see gas are:

   a. Density/acoustic b. Density/neutron
   c. Acoustic/neutron

   a b c

4. In a very shaly sand the best two porosity logs to see gas are:

   a. Density/acoustic b. Density/neutron
   c. Acoustic/neutron

   a b c

5. In a gas bearing sandstone the sidewall neutron has an apparent limestone porosity of 12% and the density is 2.23. Estimate the porosity.

   a. 18.5% b. 19.7
   c. 20.2 d. 20.8

   a b c d

LOG INTERPRETATION

QUESTIONS
LESSON 8

1. Example: 8-2a and 8-2b.
   Fill in the blanks

Zone	Depth.	ϕ Acoustic	Cond. Millimho/m	ϕ_w CDP	S_w
A	7066-70	16	65	9.5	59%
B	7072-78	____	____	____	____
C	7082-89	____	____	____	____
D	7089-95	____	____	____	____
E	7095-99	____	____	____	____

2. As the formation grain size (and thus pore space) become smaller the irriducible water saturation increases
   a) false b) true
   c) did not read Lesson 1, so I don't know. — a b c

3. Is the computed porosity on the Acoustilog
   a) right b) wrong
   c) don't know how to check — a b c

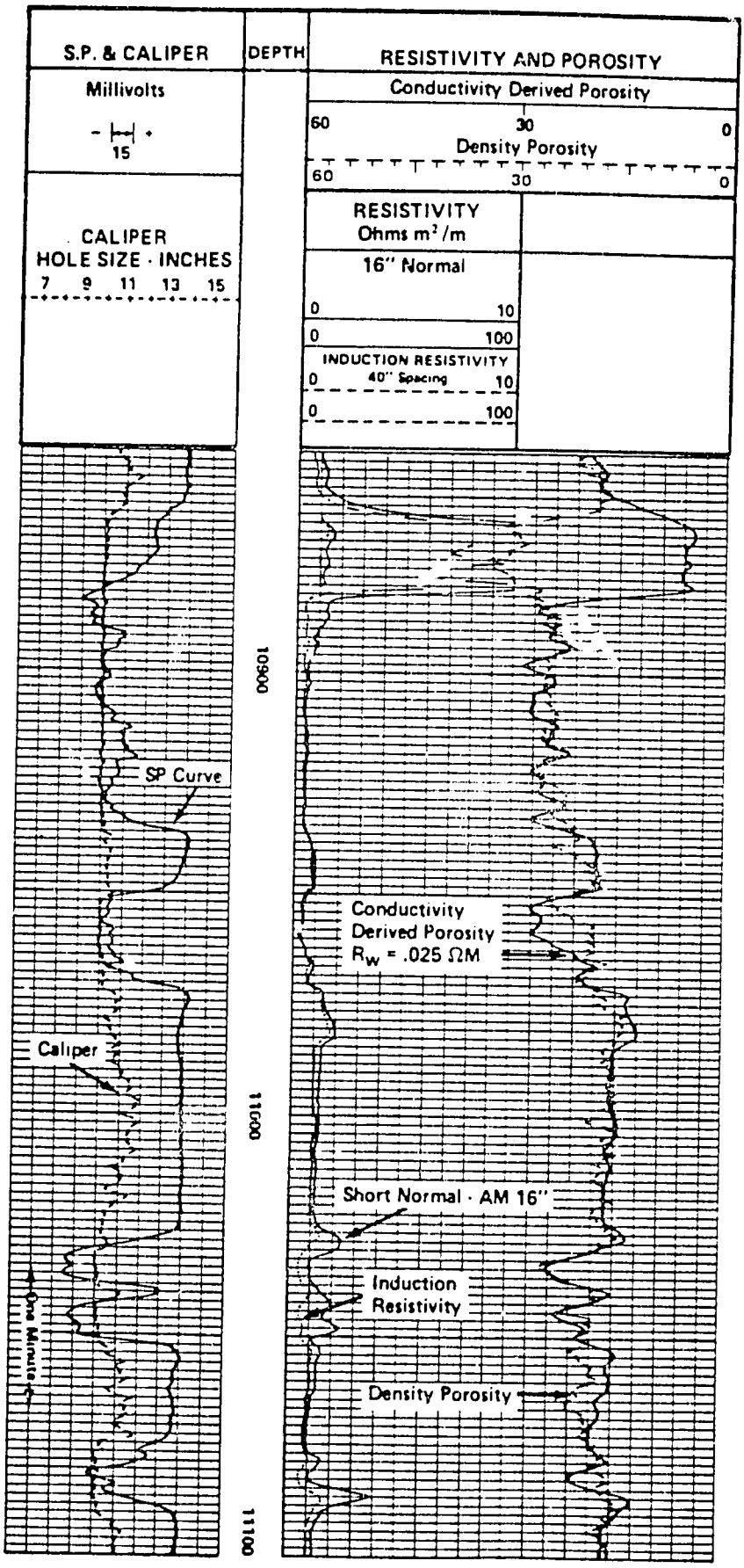
   If b) the log is off by _____ % porosity

4. If the velocity of the matrix is really 18,000 ft/sec show how it affects S_w and ϕ

	ϕ	S_w
A	____	____
B	____	____
C	____	____
D	____	____
E	____	____

5. Log example 8-3 is a combination Induction Electrolog/Densilog with a CDP run simultaneously in track 3.
   Calculate

10864 - 82	S_w = _____
10900 - 10	S_w = _____
10956 - 60	S_w = _____
11031 - 37	S_w = _____
11070 - 73	S_w = _____


S.P. & CALIPER
DEPTH
RESISTIVITY AND POROSITY
Millivolts
- 15 +
Conductivity Derived Porosity
60
30
0
Density Porosity
60
30
0
CALIPER
HOLE SIZE · INCHES
7 9 11 13 15
RESISTIVITY
Ohms m² /m
16" Normal
0 10
0 100
INDUCTION RESISTIVITY
0 40" Spacing 10
0 100
10900
11000
11100
SP Curve
Caliper
One Minute
Conductivity
Derived Porosity
R_w = .025 ΩM
Short Normal · AM 16"
Induction
Resistivity
Density Porosity

Example 8-3

LOG INTERPRETATION

QUESTIONS
LESSON 9

For the attached Example 30, crossplot the 13 zones designated on the logs and be sure to return the attached crossplot paper used.

1. What is the R_w from the crossplot?
   (Show work on chart)

2. What is R_w from the SP?
   (Show work on chart)

3. What is the matrix travel time?
   (Show work on chart)

4. On the log example mark the oil water contact.

5. The zone from 9922 – 25 was not picked. Was this because:
   a. The zone was too thin for the induction log to measure a good value.
   b. The zone was too thin for the Acoustilog to measure a good value.

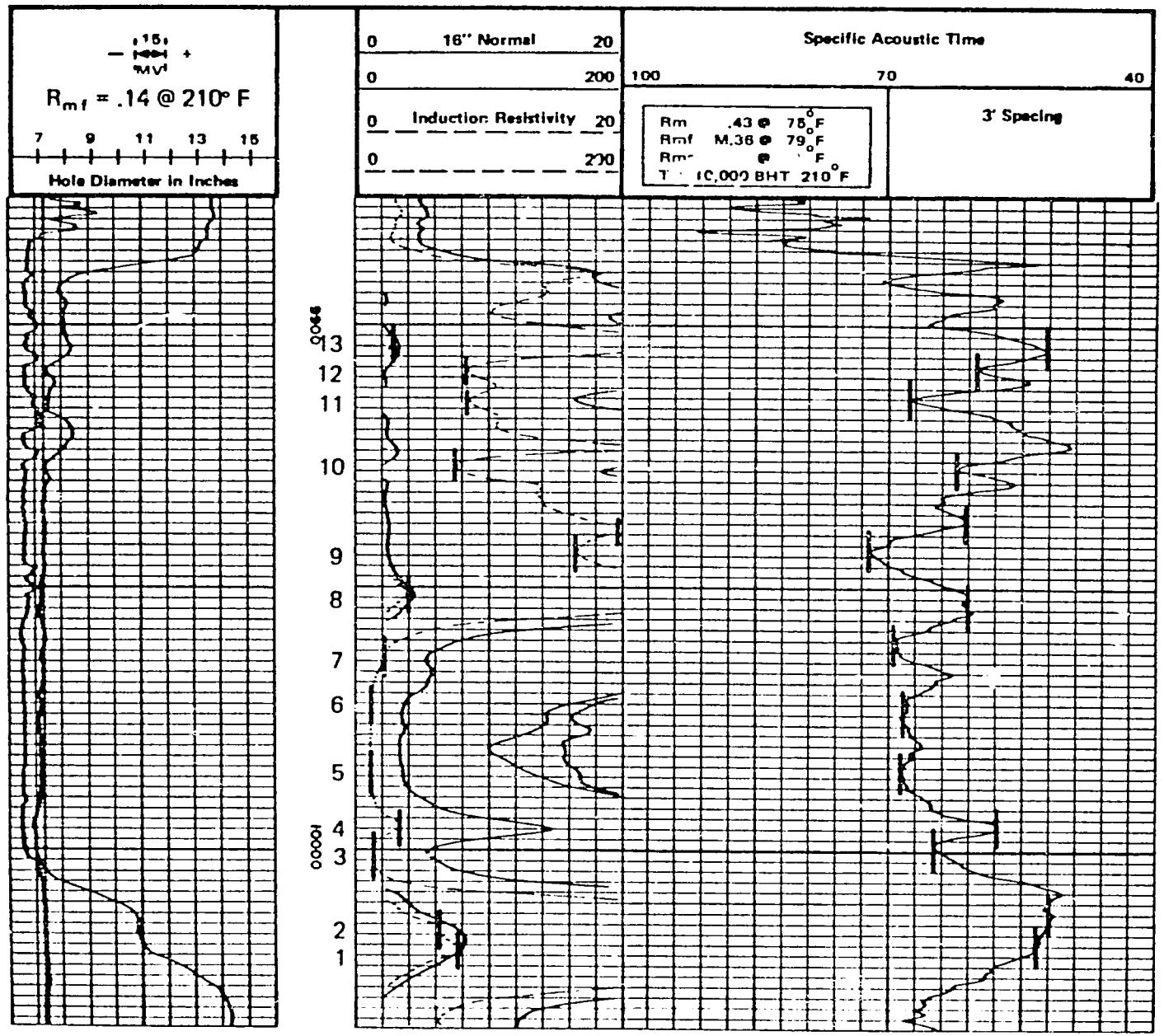
6. On page 9-11 what is the water resistivity of the unlabelled line (Example 2)
   a) .2 b) .07
   c) .05 d) .02

Circle Correct Answer

a b

a b c d

Limestone



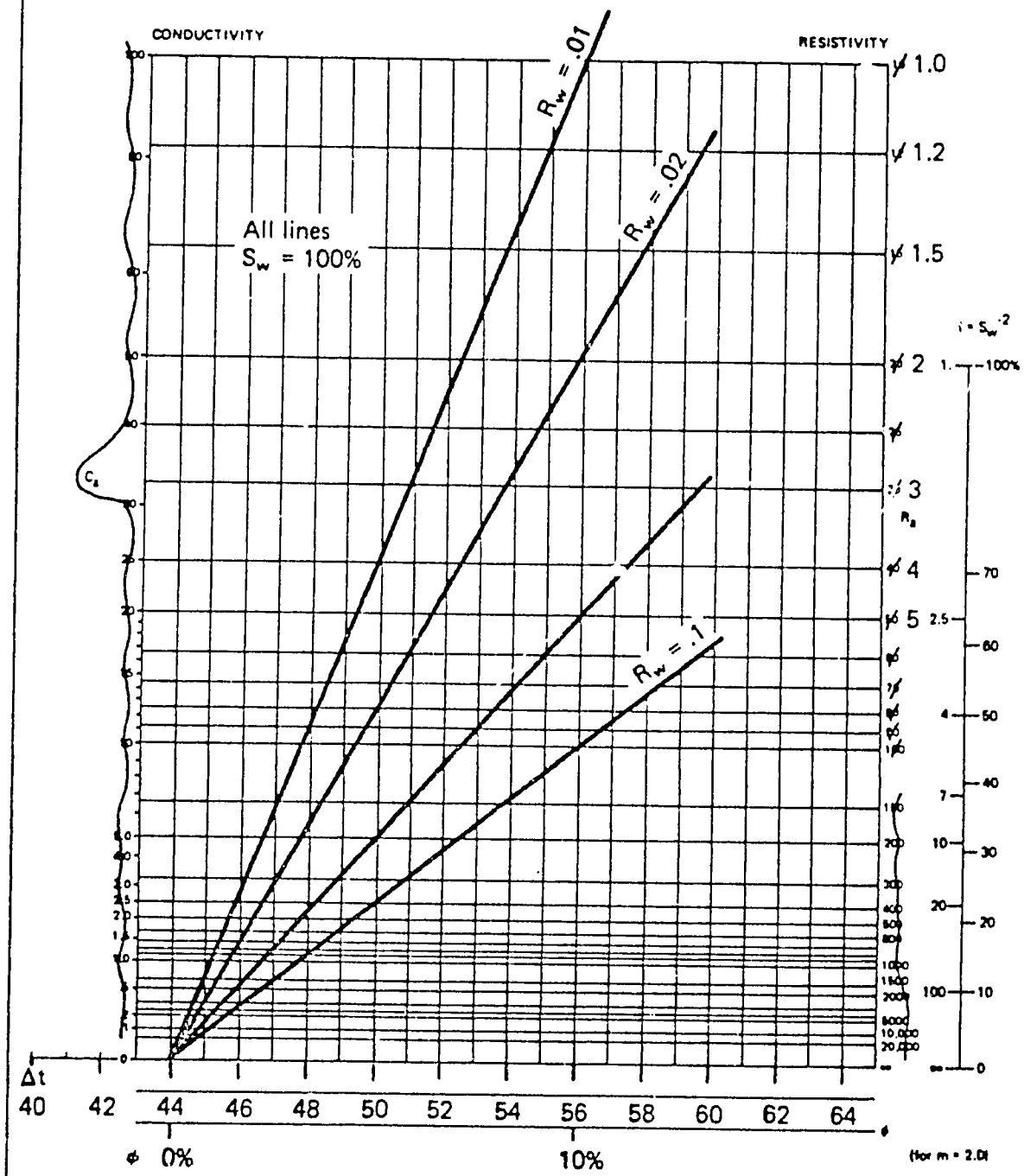
Example 30

Example 2

RESISTIVITY/POROSITY CROSSPLOT (RPCP)

Change in R_o line
Slope as R_w changes

Divided
Scale by 10



Dresser Atlas DRESSER

RESISTIVITY/POROSITY CROSSPLOT (RPCP)

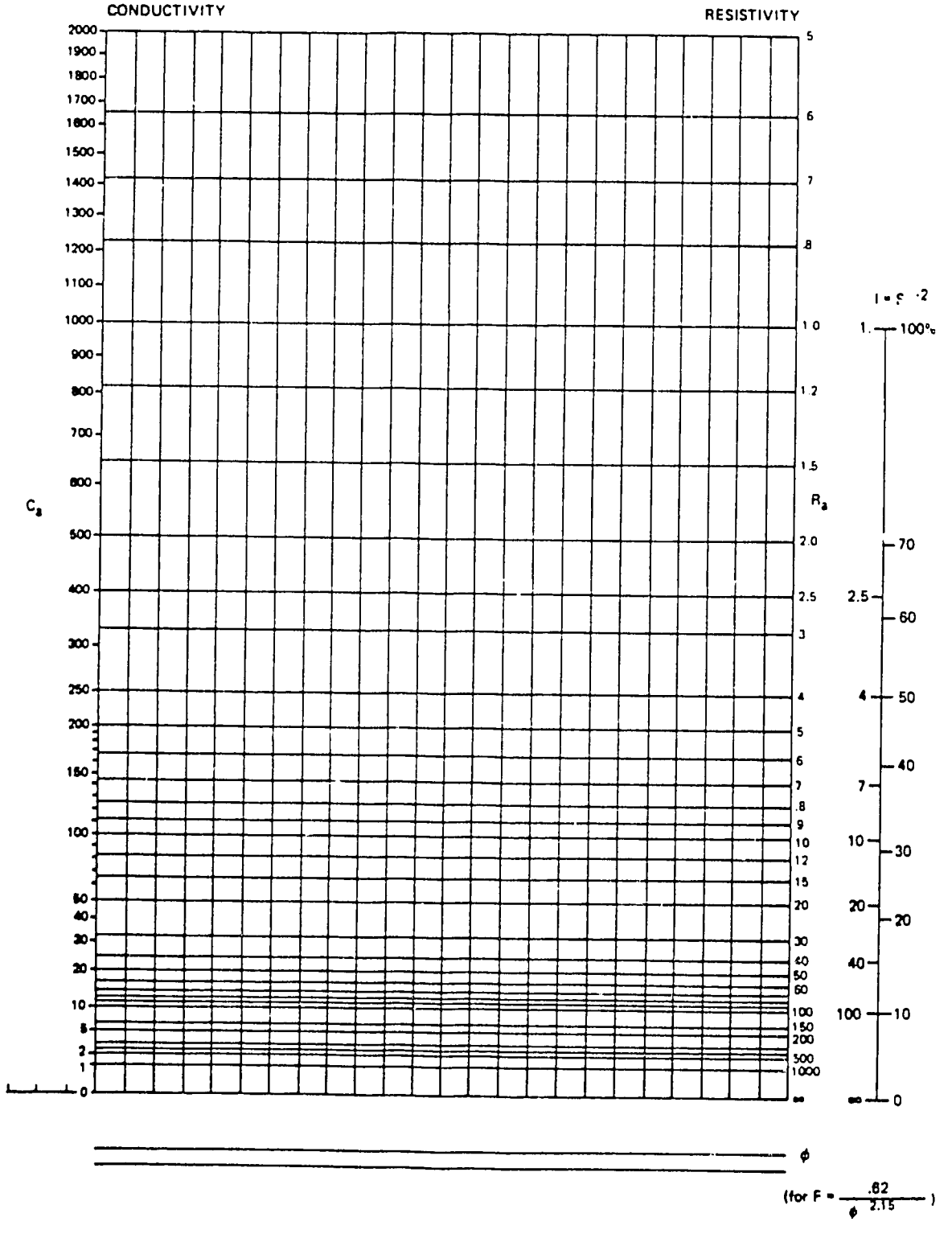


CHART 10

Dresser Atlas

RESISTIVITY/POROSITY CROSSPLOT (RPCP)

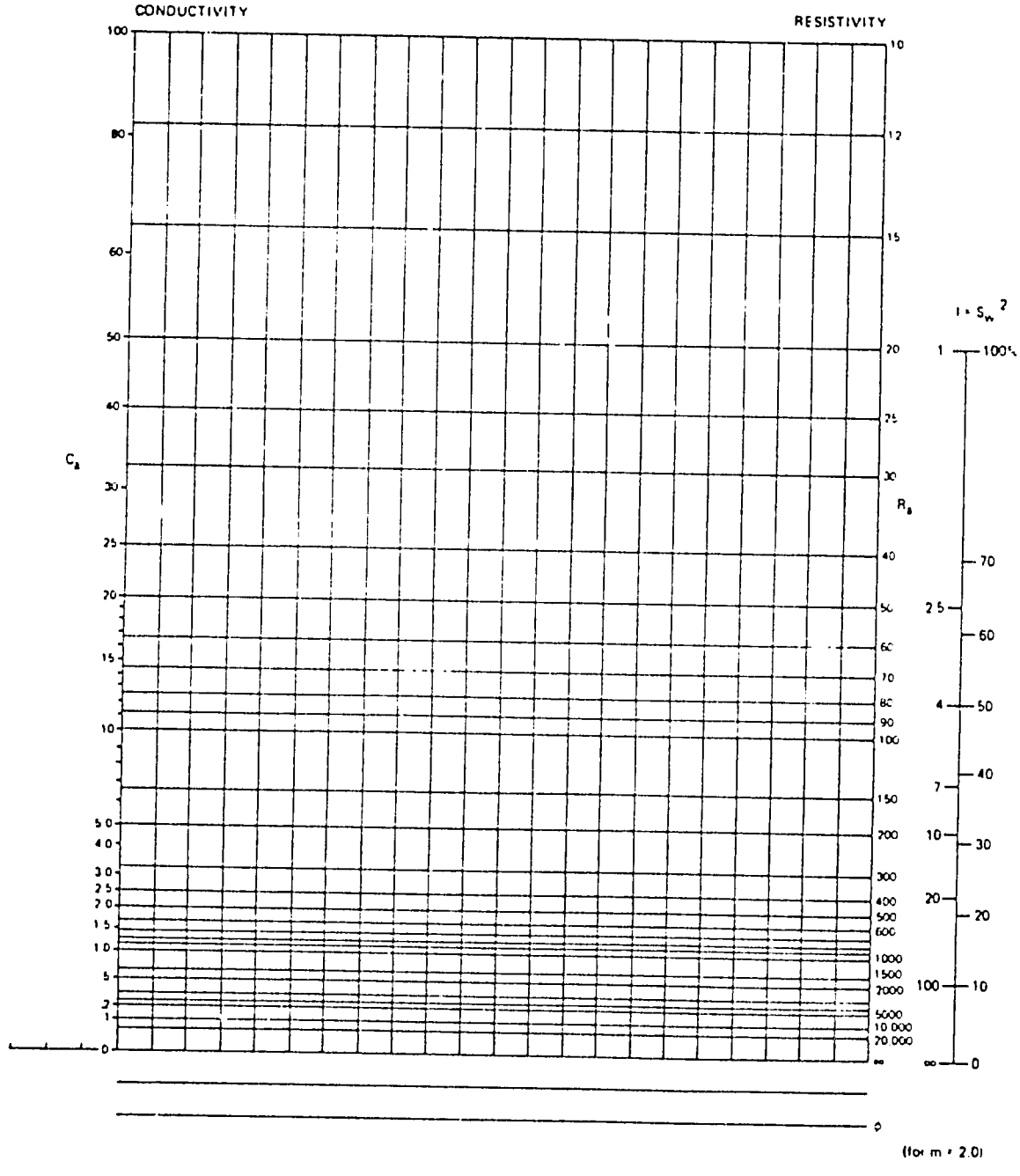


CHART 11

LOG INTERPRETATION

QUESTIONS
LESSON 10

Circle Correct Answer

1. On Example 197 zone B the R_t is
   (a) 18 (b) 4
   (c) .22 (d) .2

   a b c d

   The R_{xo} is
   (a) .13 (b) 4
   (c) .22 (d) .2

   a b c d

2. On Example 197d the Proximity log appears to be reading
   (a) Higher than R_{xo}
   (b) Lower than R_{xo}
   (c) R_{xo}
   (d) R_t

   a b c d

3. In Example 197 where the borehole diameter is 8 inches and the diameter of invasion is 52 inches the apparent step profile invasion is beyond the sand face by
   (a) 46 inches
   (b) 22 inches
   (c) 26 inches
   (d) 33 inches

   a b c d

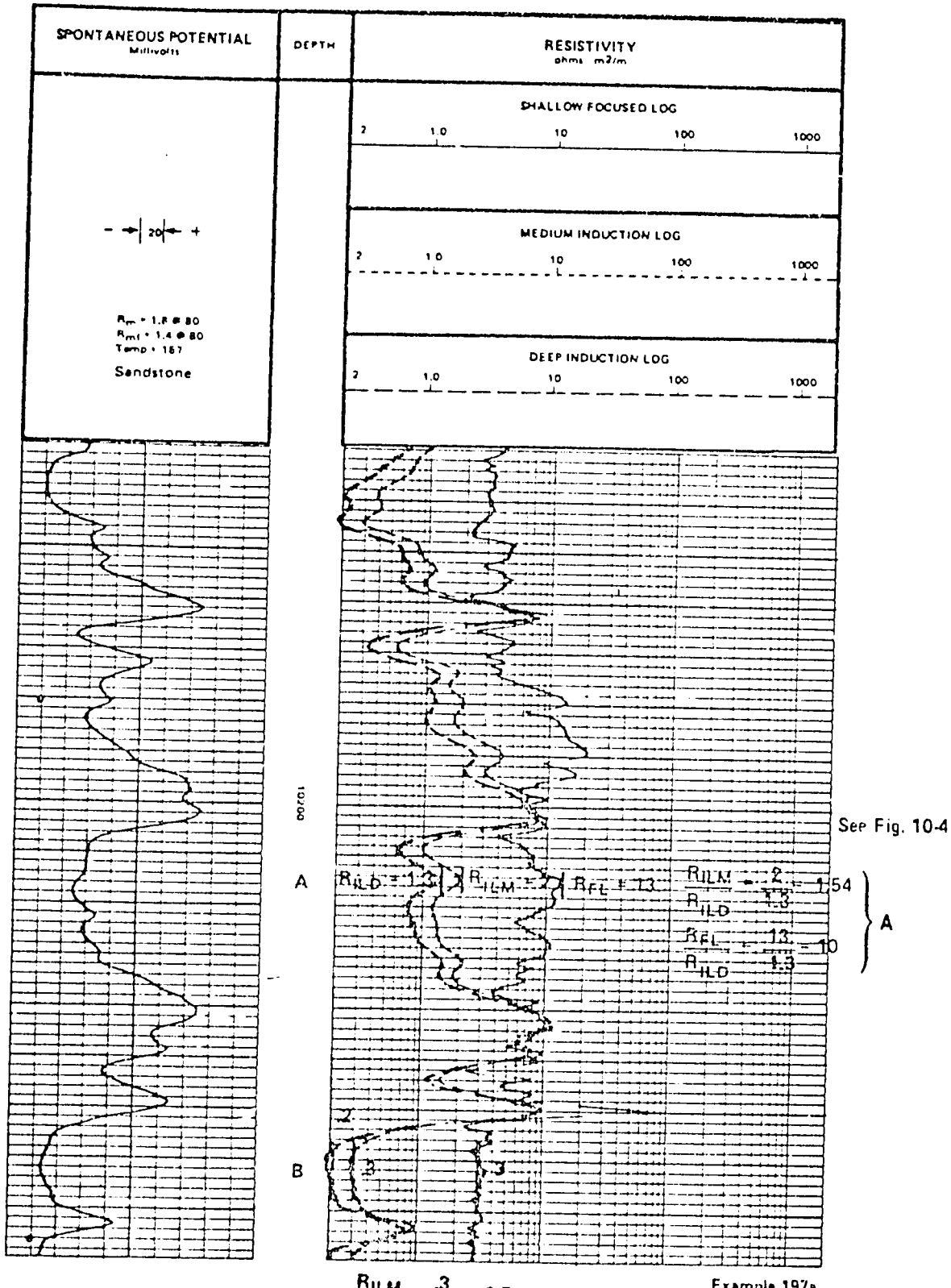
4. On Example 189a the oil water contact is at
   (a) 8790
   (b) 8700
   (c) 8636
   (d) 8590

   a b c d

5. R_{xo} or the value read from the Micro-Laterolog or Proximity log does not do one of the following.
   (a) R_{xo} increases going from a water bearing zone to a oil bearing zone of constant porosity.
   (b) R_{xo} increases as porosity decreases
   (c) R_{xo} decreases as R_{mf} decreases
   (d) R_{xo} increases as R_{mf} decreases

   a b c d

DUAL INDUCTION FOCUSED LOG

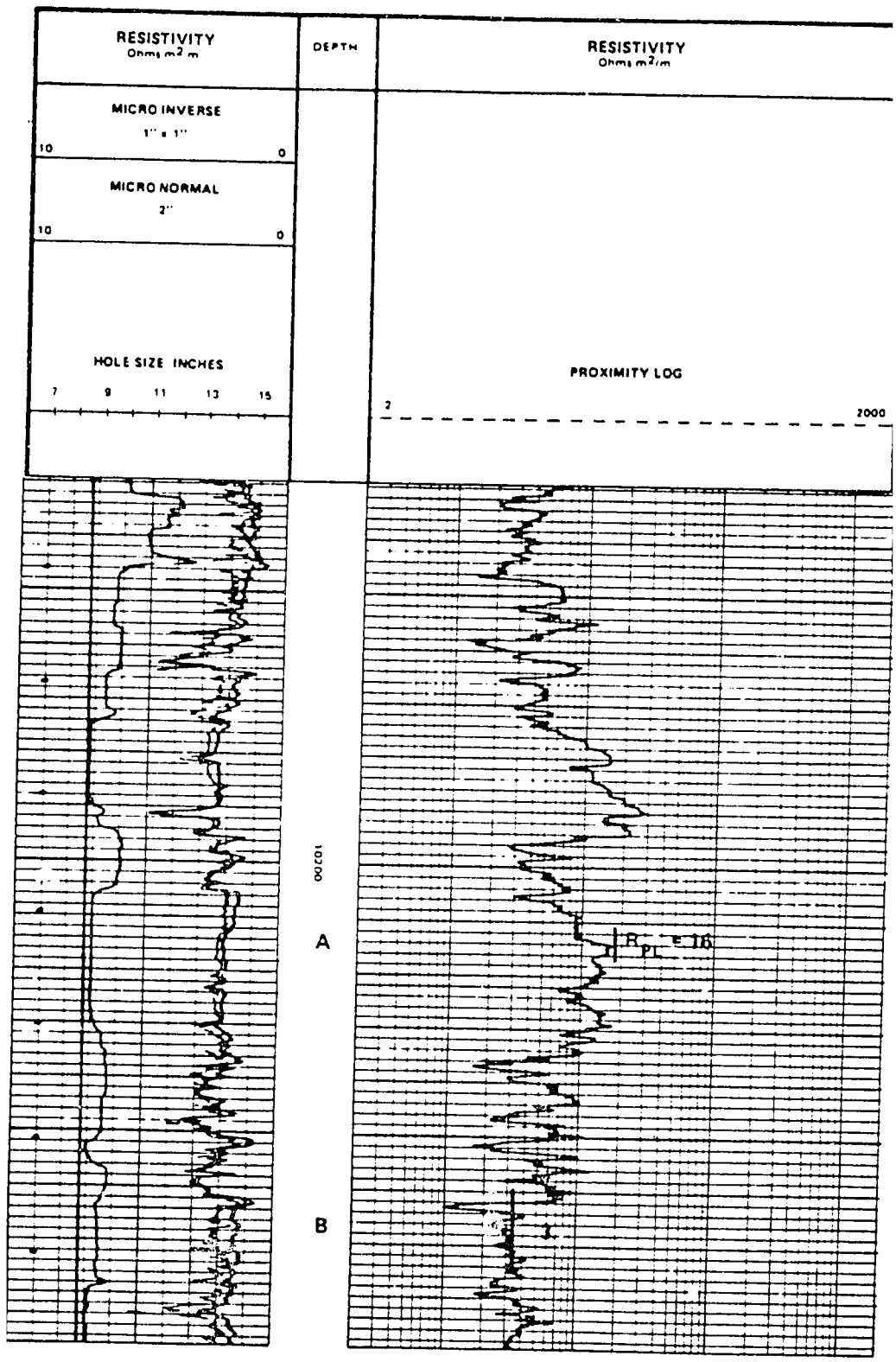


$$\frac{R_{ILM}}{R_{ILD}} = \frac{.3}{.2} = 1.5$$

$$\frac{R_{FL}}{R_{ILD}} = \frac{3}{.2} = 15$$

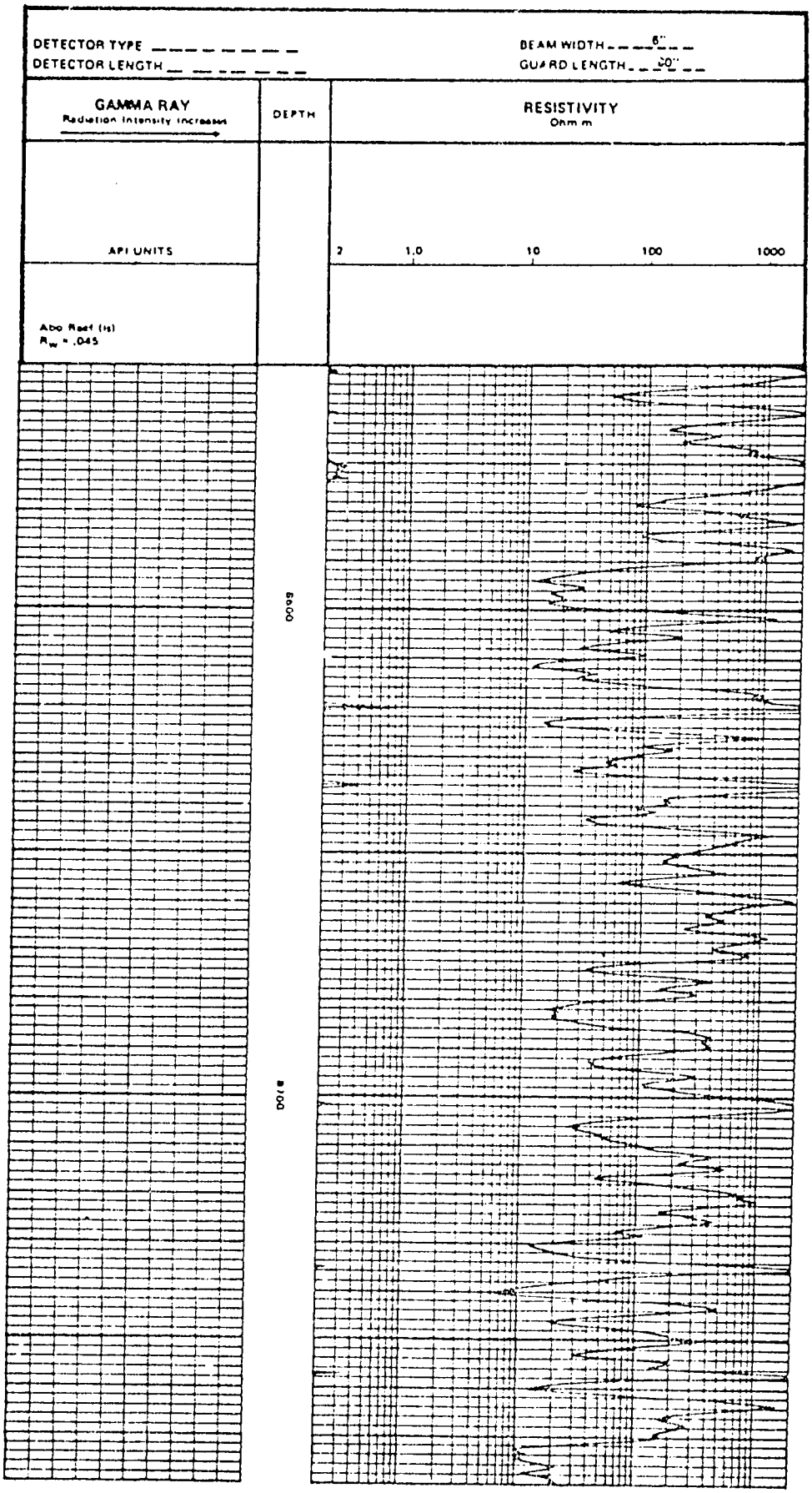
Example 197a

PROXIMITY LOG



Example 197d

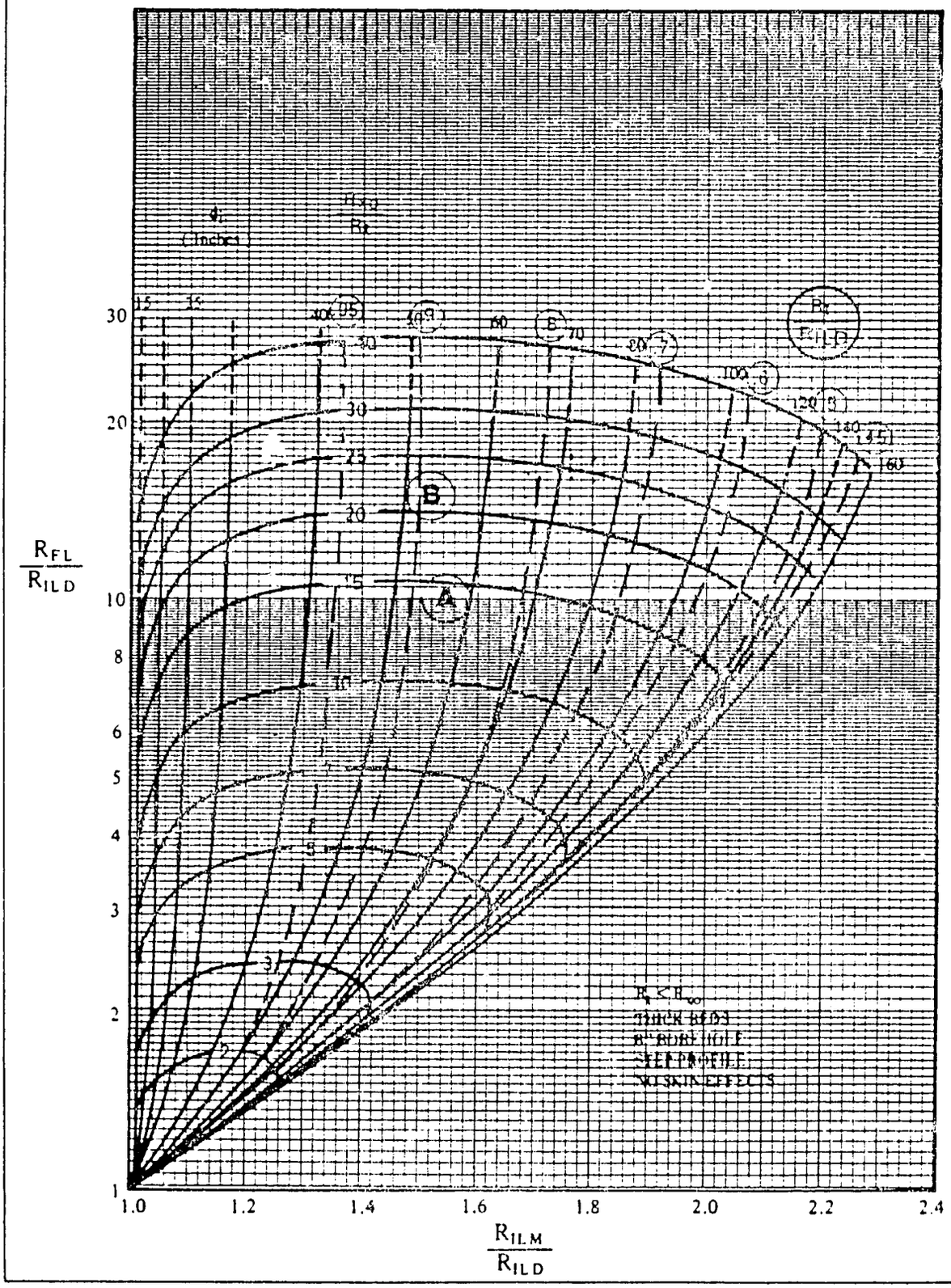
LATEROLOG



Example 189a

Dresser Atlas

R_t FROM DUAL INDUCTION FOCUSED LOG



d_i = 57"

$\frac{R_{xo}}{R_t} = 15$

$\frac{R_t}{R_{ILD}} = .88$

$R_{ILD} = 1.3$

$R_t = .88 \times 1.3 = 1.14$

$\frac{R_{xo}}{R_t} = 15$

$R_{xo} = 15 \times 1.14 = 17$

LOG INTERPRETATION

DresserAtlas

QUESTIONS LESSON 11

Circle Correct Answer

1. The porosity from the density log Example 106 - ,ne B is:
   a) 17% b) 13%
   c) 24% d) 20%

   a b c d

2. On example 106 the water saturation for zone A using density log porosity data is:
   a) 30% b) 46%
   c) 19% d) 10%

   a b c d

3. The water saturation on example 106a zone B, using density log data is:
   a) 19% b) 10%
   c) 46% d) 60%

   a b c d

4. The porosity from the sidewall neutron in zone B is:
   a) 21% b) 22.5%
   c) 15% d) 5%

   a b c d

5. Did you review Lesson 7 on page 6 on the use of cross plots for shaly formations?
   a) yes
   b) no
   c) other

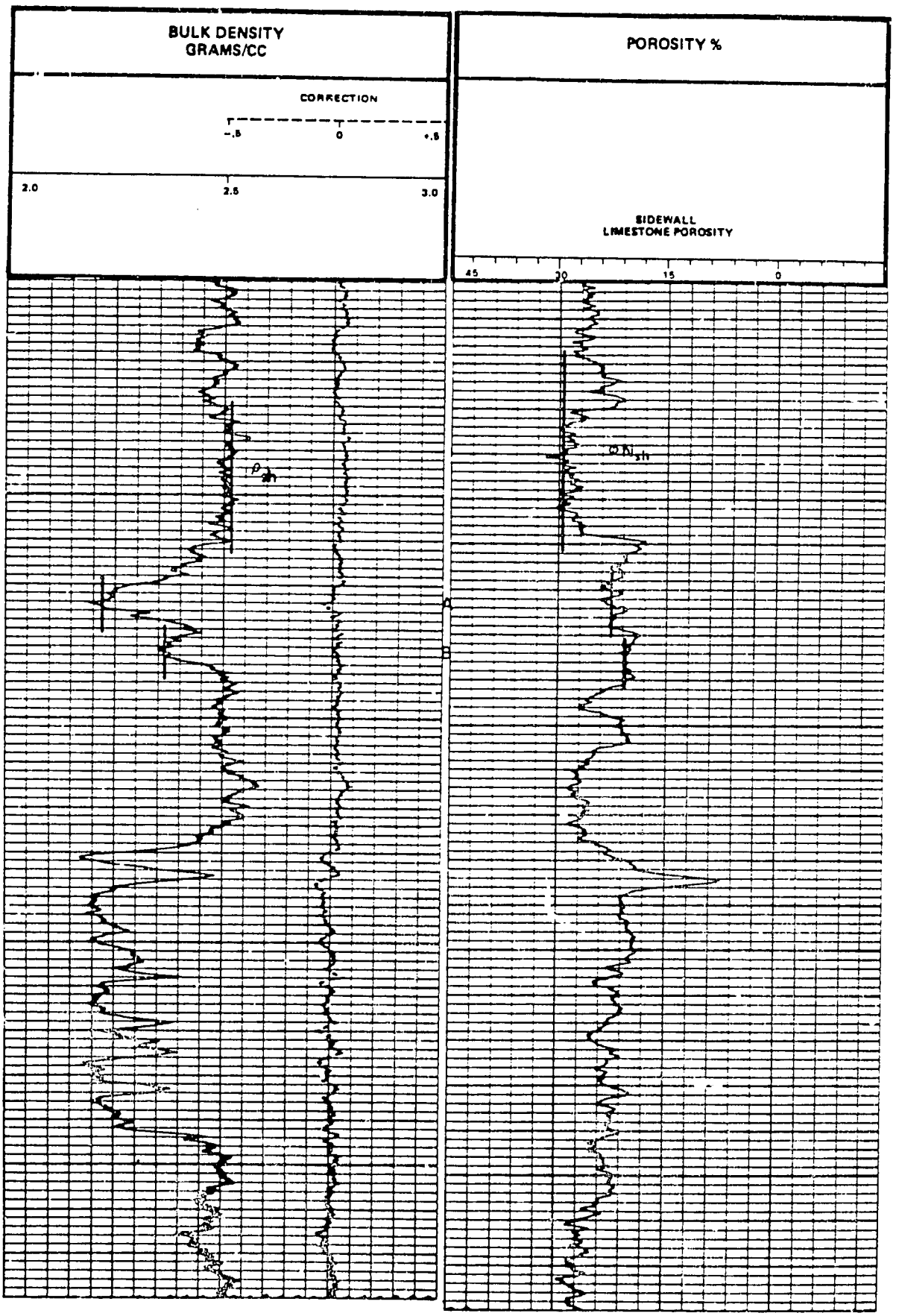
   a b c

6. On example 106 the calculated density porosities are:
   a) too high
   b) too low
   c) right
   d) don't know

   due to the fact the well was drilled with oil base mud and the density of oil is normally less than water.

   a b c d

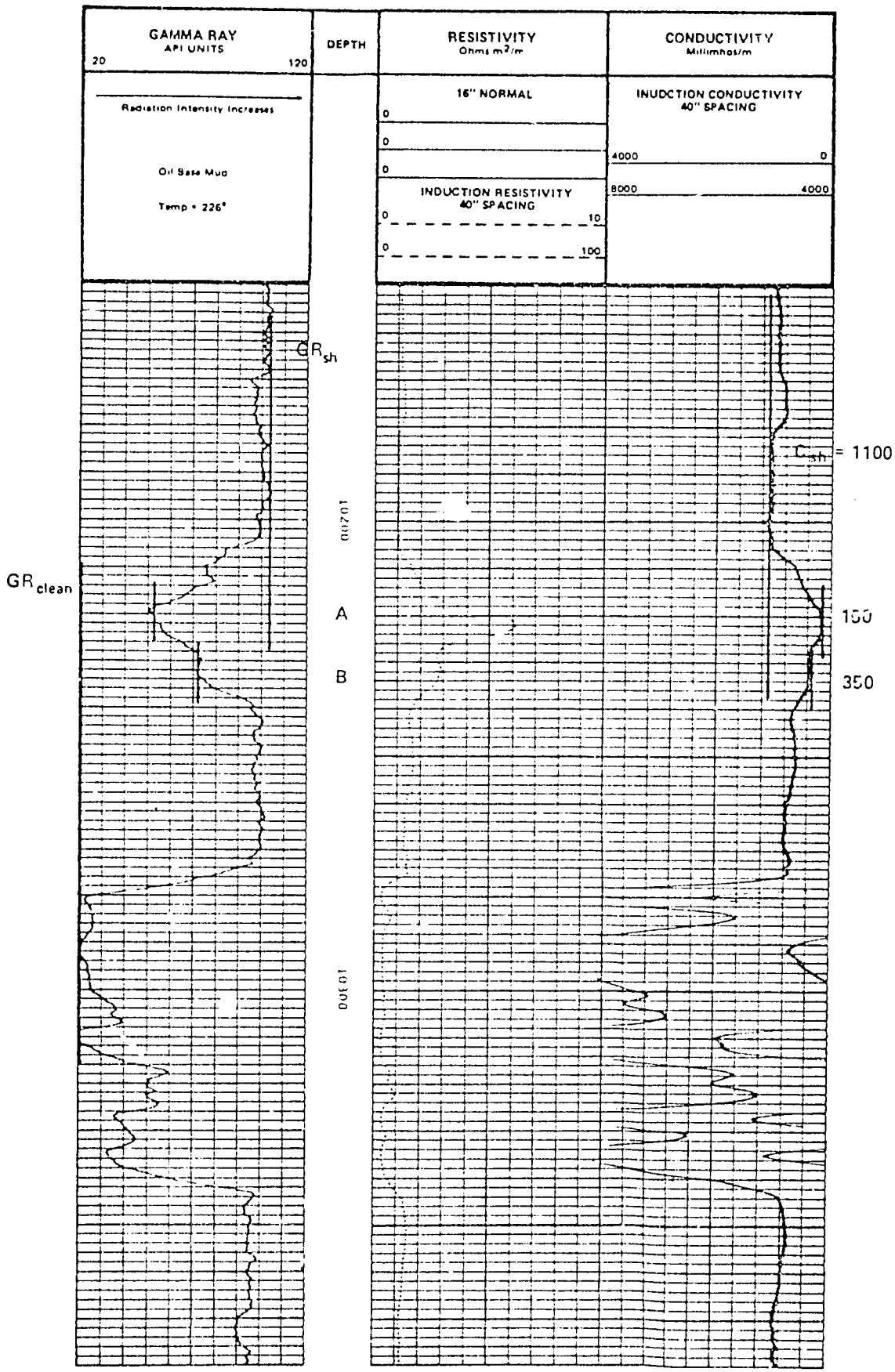
SANDSTONE



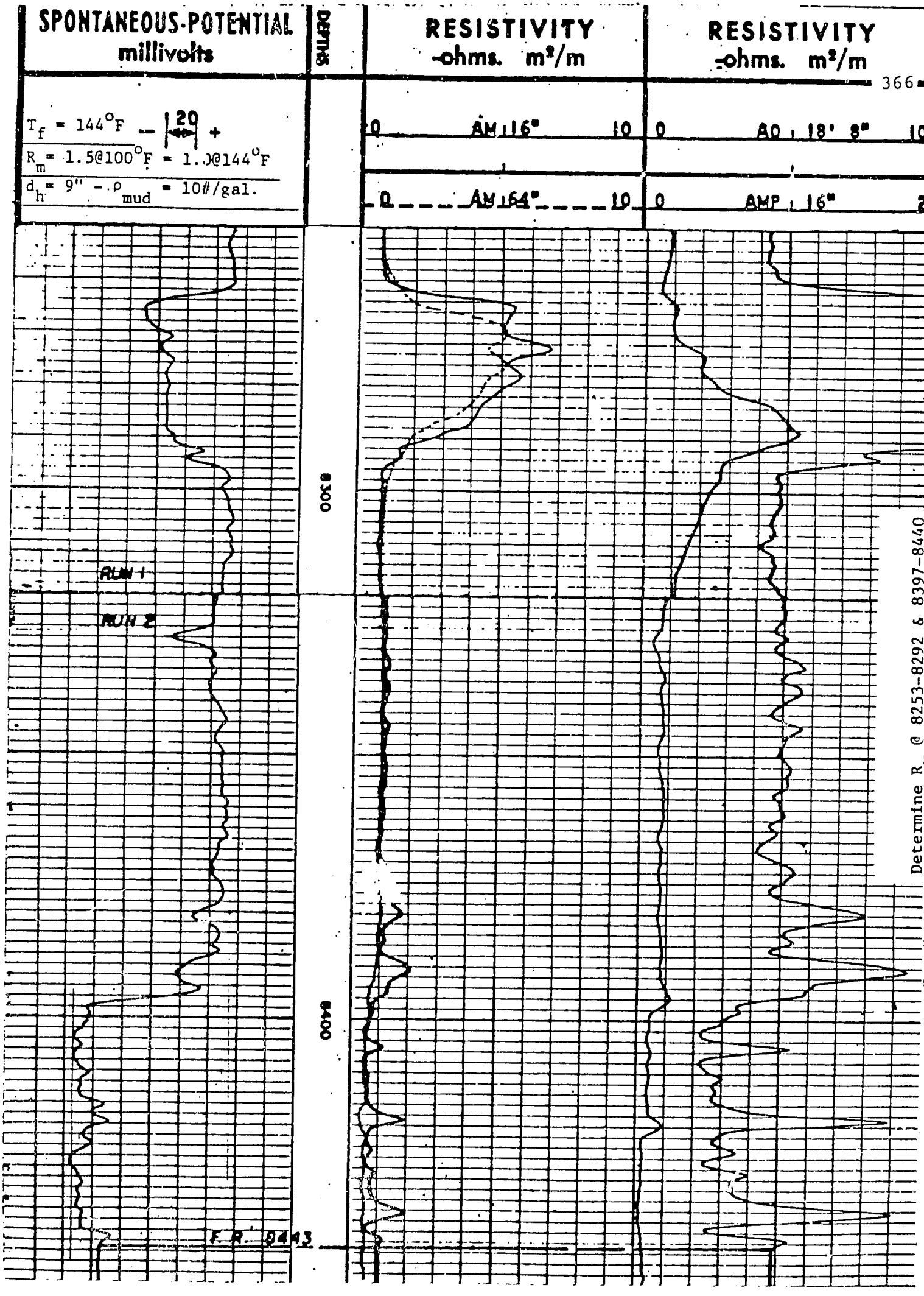
EXAMPLE 106

TERTIARY FORMATION

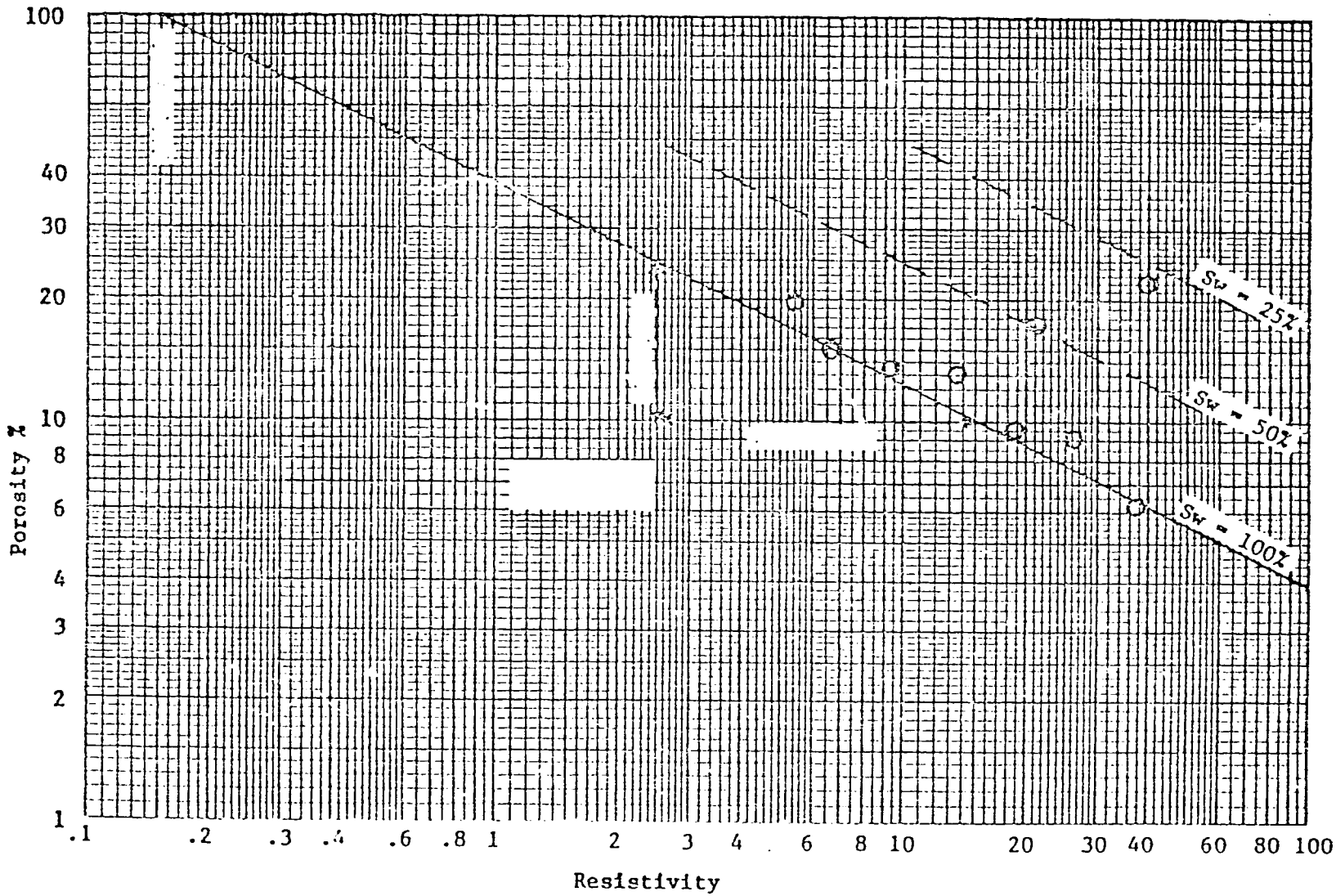
$R_w = .02 @ T_f$



EXAMPLE 106a


SPONTANEOUS-POTENTIAL
millivolts
DEPTHS
RESISTIVITY
-ohms. m²/m
RESISTIVITY
-ohms. m²/m
T_f = 144°F
20
R_m = 1.5@100°F = 1.0@144°F
d_h = 9" - ρ_{mud} = 10#/gal.
0
AM 16"
10
0
AO 18' 8"
10
0
AM 64"
10
0
AMP 16"
2
8300
8400
RUN 1
RUN 2
F. R. 8443
Determine R_w @ 8253-8292 & 8397-8440

A log-log resistivity-porosity crossplot



dh = 8"
RHS = 20%
mud wt 12 lbs/gal
Rmf = .05
Rw = 0.055

Schlumberger

DUAL LATEROLOG
(SIMULTANEOUS)

7

368

GAMMA RAY 0 100 | DEPTHS | RESISTIVITY 2 1 10 100 100

Calc: Sw from 2LL-Rxo chart, use 7SMP and m = 2 for Rxo. Calc Sw(Archie)

Grayburg

San Andres

1500

LLD

LLS

Schlumberger

SIDEWALL NEUTRON POROSITY LOG

GAMMA RAY

0 20

16

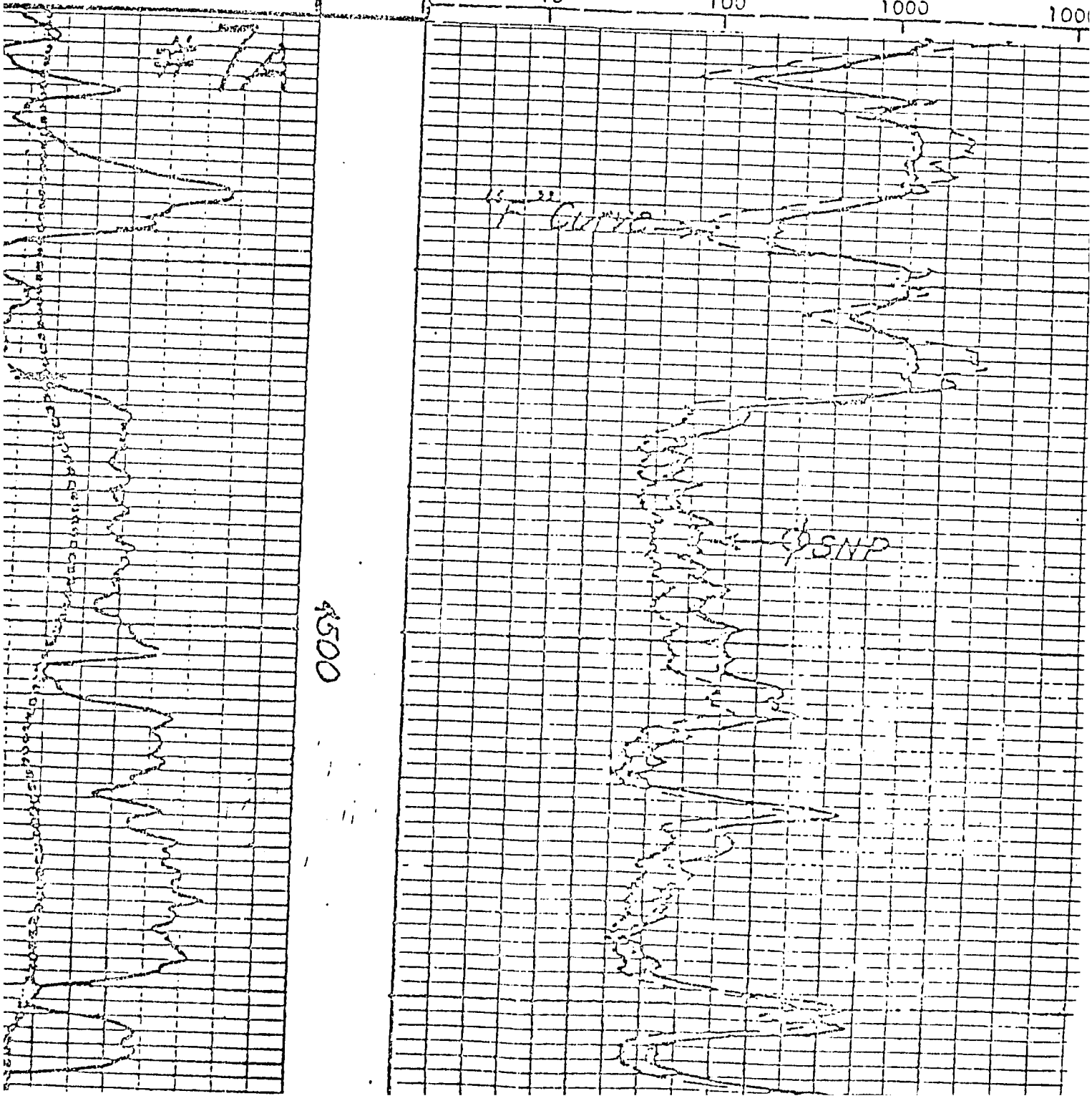
POROSITY INDEX (%)

LIMESTONE

30 20 10 0

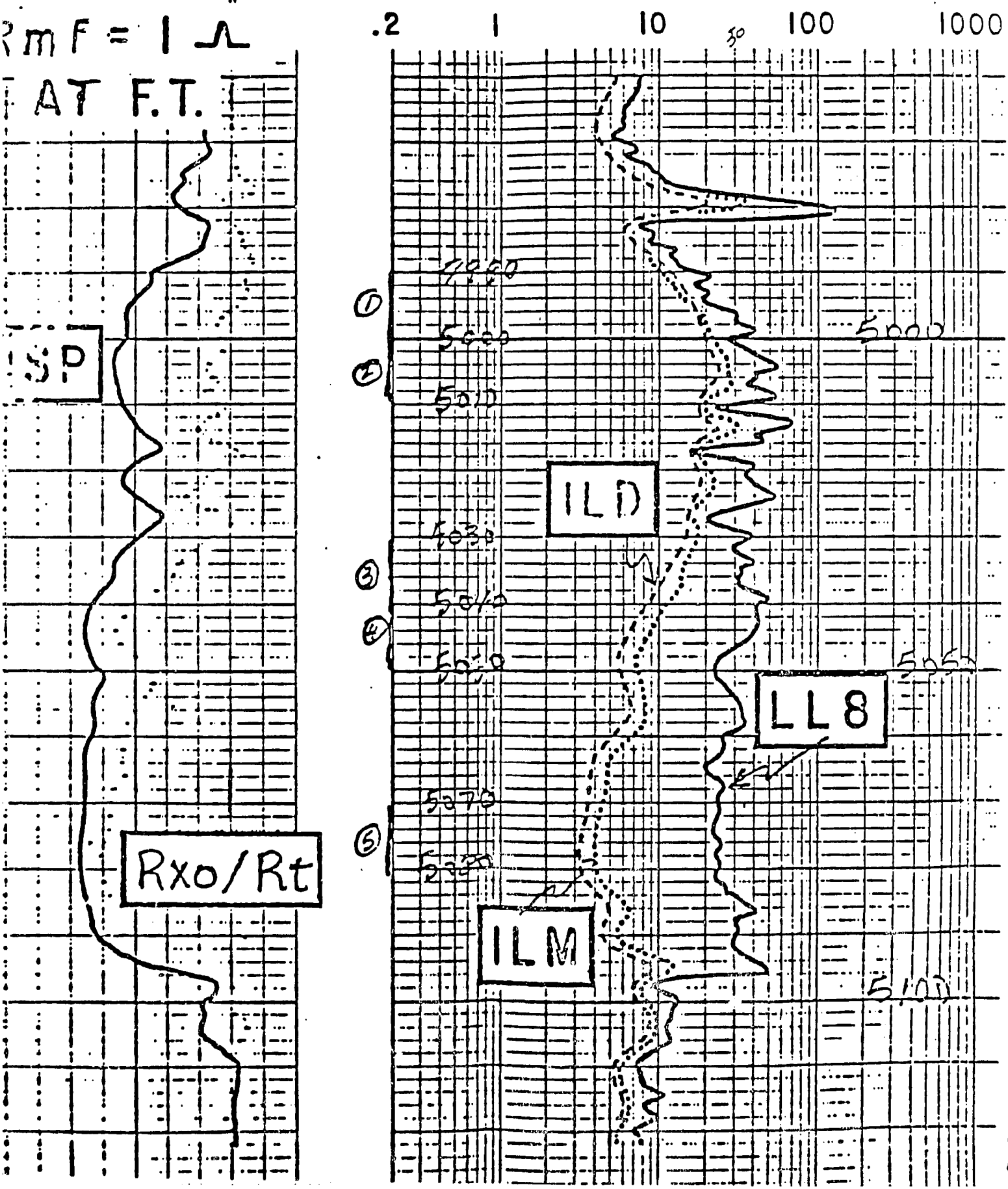
"F" CURVE

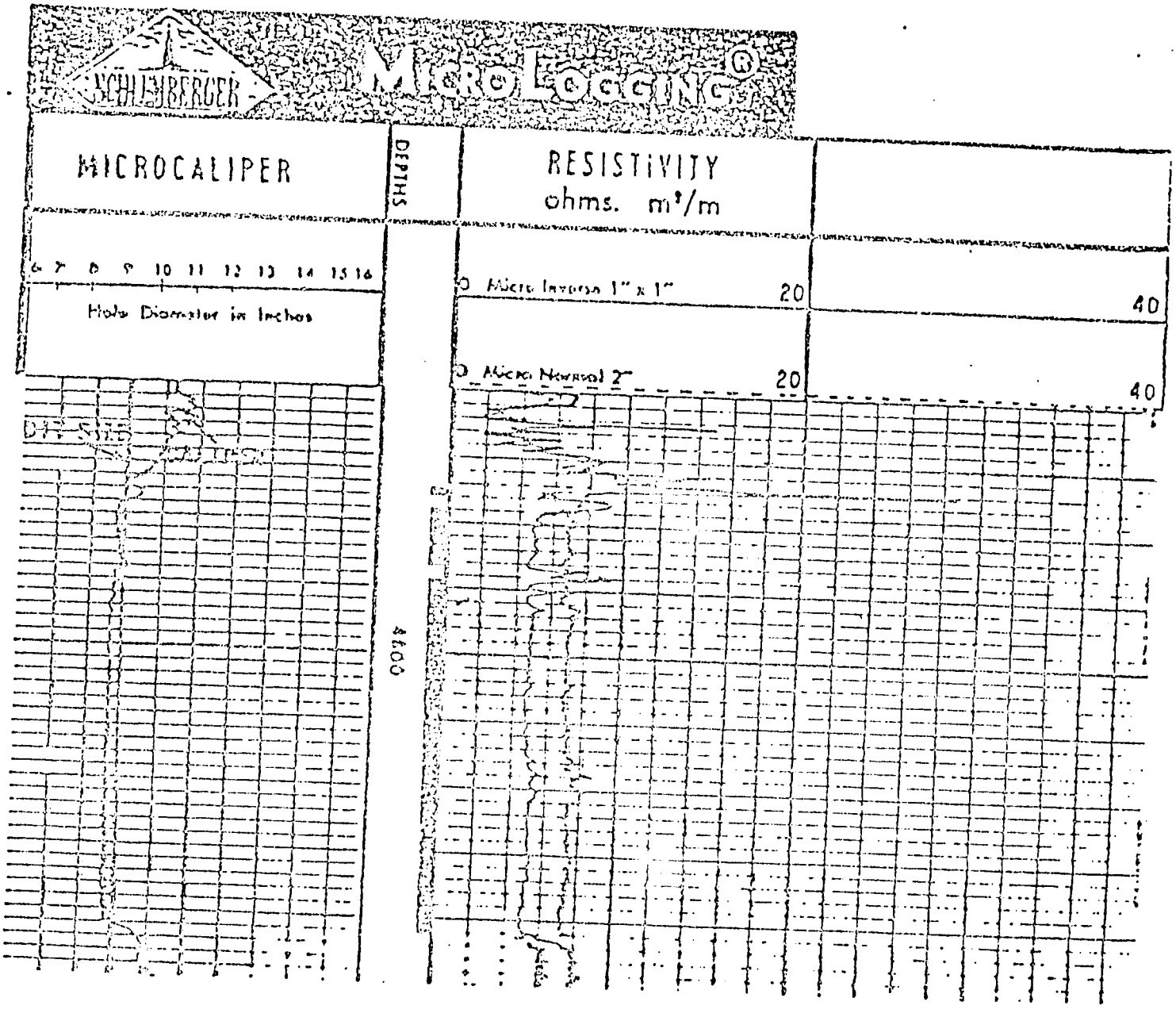
2 10 100 1000 1000



Induction Log Problem

Given:
Dual Induction LLS plus SP Logs and d_h = 8 3/4", stand off = 1.5" T_f = 150°F R_m = 1.2@ 150°F.
The logs show a bed of 100 + ft. thick with possible hydrocarbons on top and an aquifer in the lower portion.
Required: Determine S_w for interval 2 (5000 to 5010 ft).





R_m = 0.8 @ F.T.

R_{mc} = 0.9 @ F.T.

R_{mf} = 0.70 @ F.T.

ZONE = 4578-4640

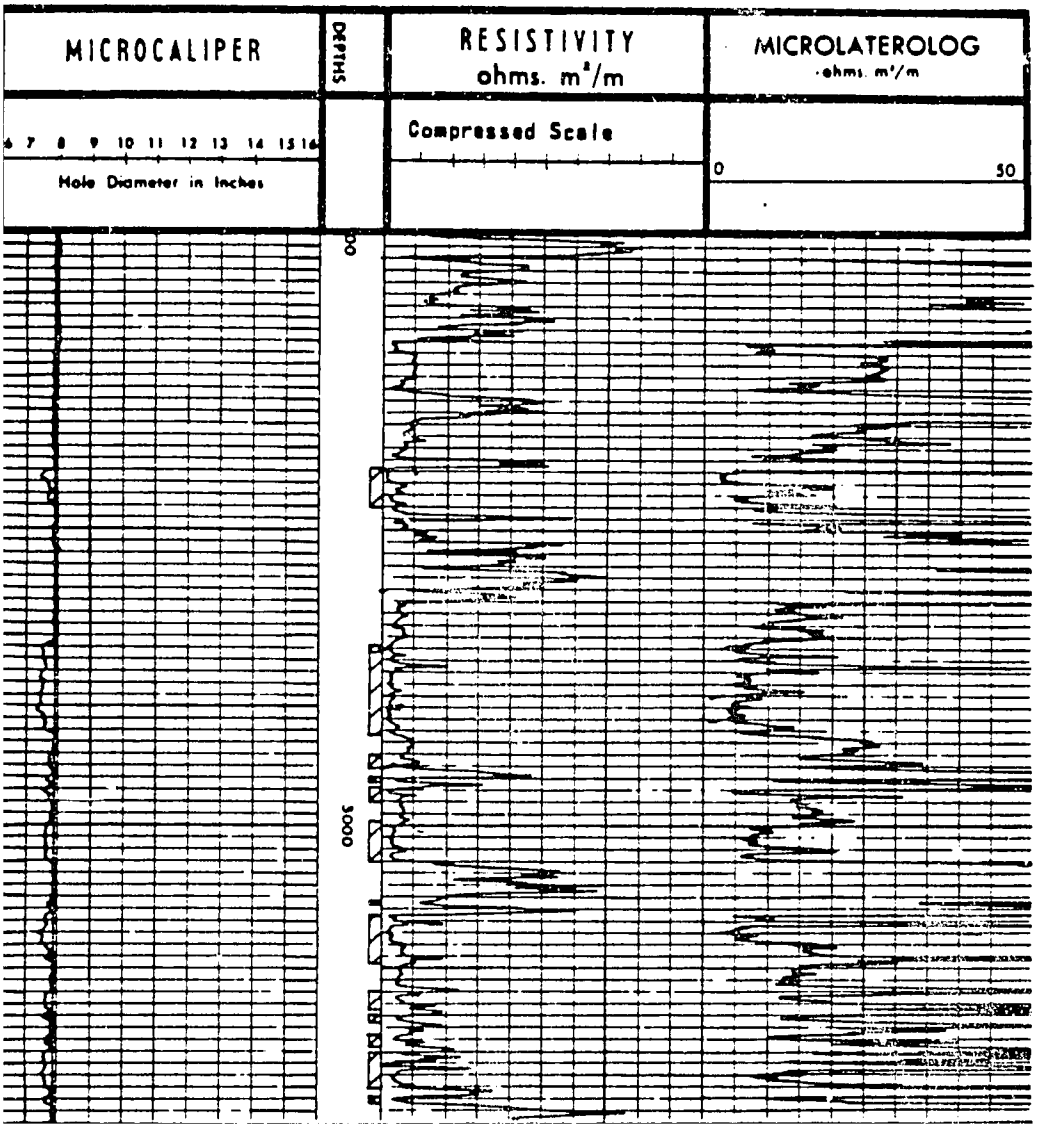
HOLE SIZE = 9"

RHS = 208

Determine the porosity of the formation

Given: Micro laterlog

Required: Determine ϕ over the interval 2979-2984 if



P.E. 4053
Induction and Density Log Problems

Given: Problem Logs 1, 2, 3, 4, and 5.

Required:

1. Problem logs 1 and 2 have several zones picked to assist in learning interpretat All potential hydrocarbon zones have not been picked. Each permeable bed isolat by shale beds should be considered a separate reservoir.

   a) Indicate all the permeable zones.

   b) Determine S_w for each of the permeable zones.

   c) Determine R_w by the R_{wa} technique.

   d) If $R_{w_{sp}}$ = .08, why is this different from R_w obtained by the R_{wa} technique?

2. In problem log 3, the induction and density logs were run simultaneously. The density log has been scaled in sandstone porosity. The conductivity derived porosity was obtained by calculating the apparent porosity, assuming the zones were water saturated.

   a) Pick out the gas bearing zone.

   b) What is the porosity of this zone?

   c) What is the water saturation of this zone?

   d) Why do the conductivity derived and density porosities separate above 10,900 ft?

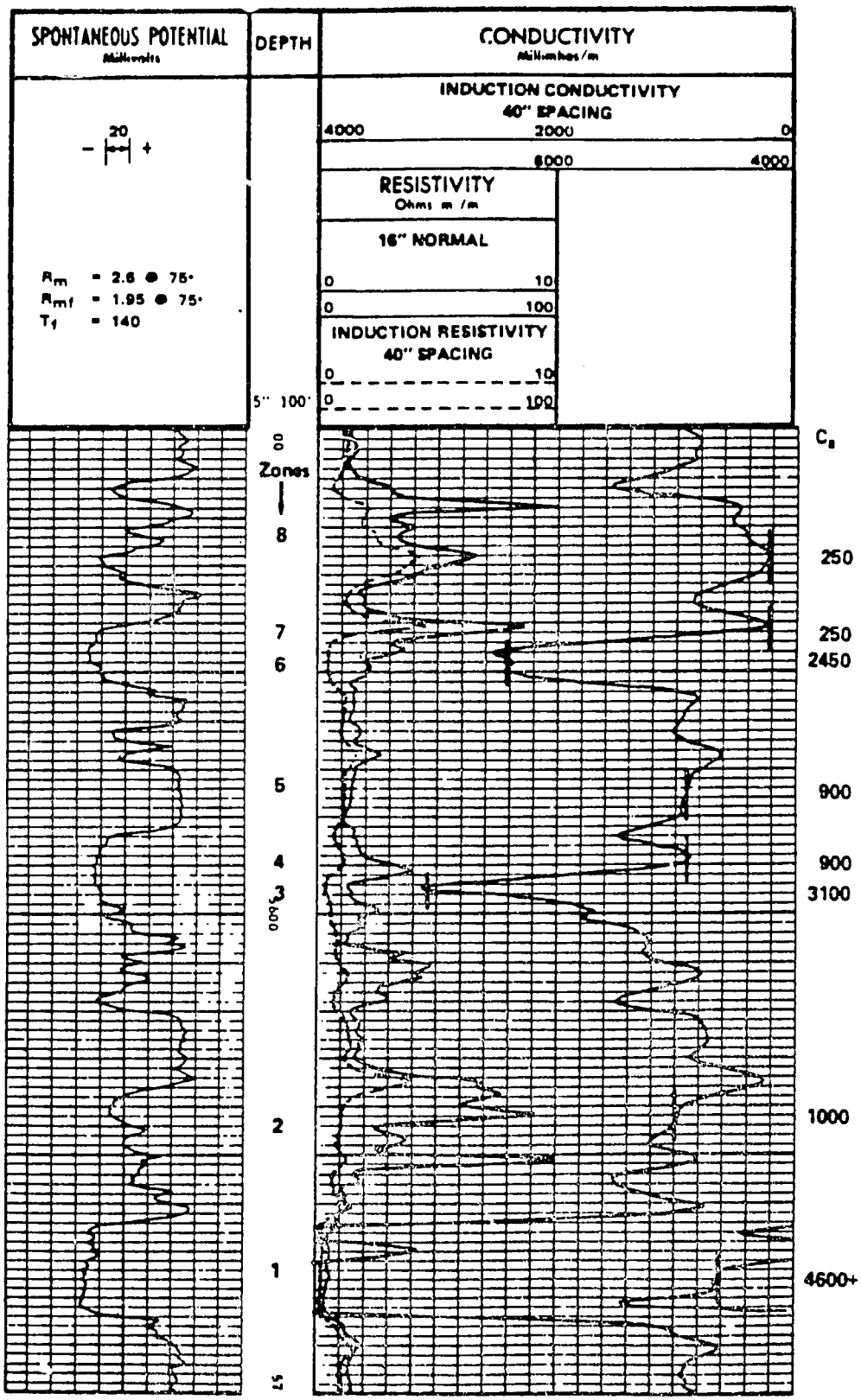
3. Problem logs 4 and 5 represent a tertiary sequence in the Louisiana Gulf Coast.

   a) Interpret zone 1, 2, 3, 4, and 5.

   b) Which zones are hydrocarbon bearing?

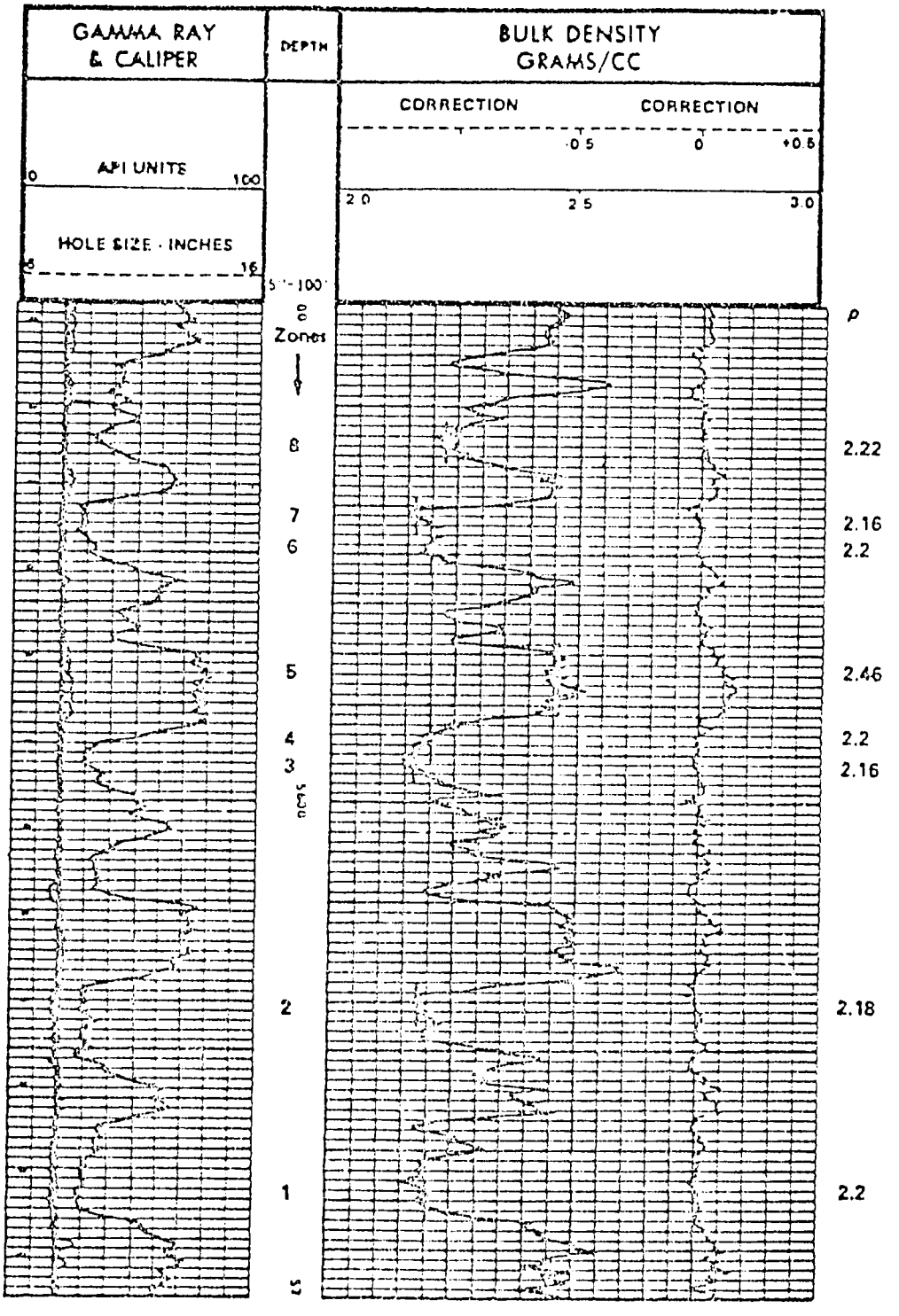
   c) If a limestone (shell bed) exists in the interval, which one would you pick to be this zone? Why?

Problem Log 1



Courtesy of Dresser Atlas

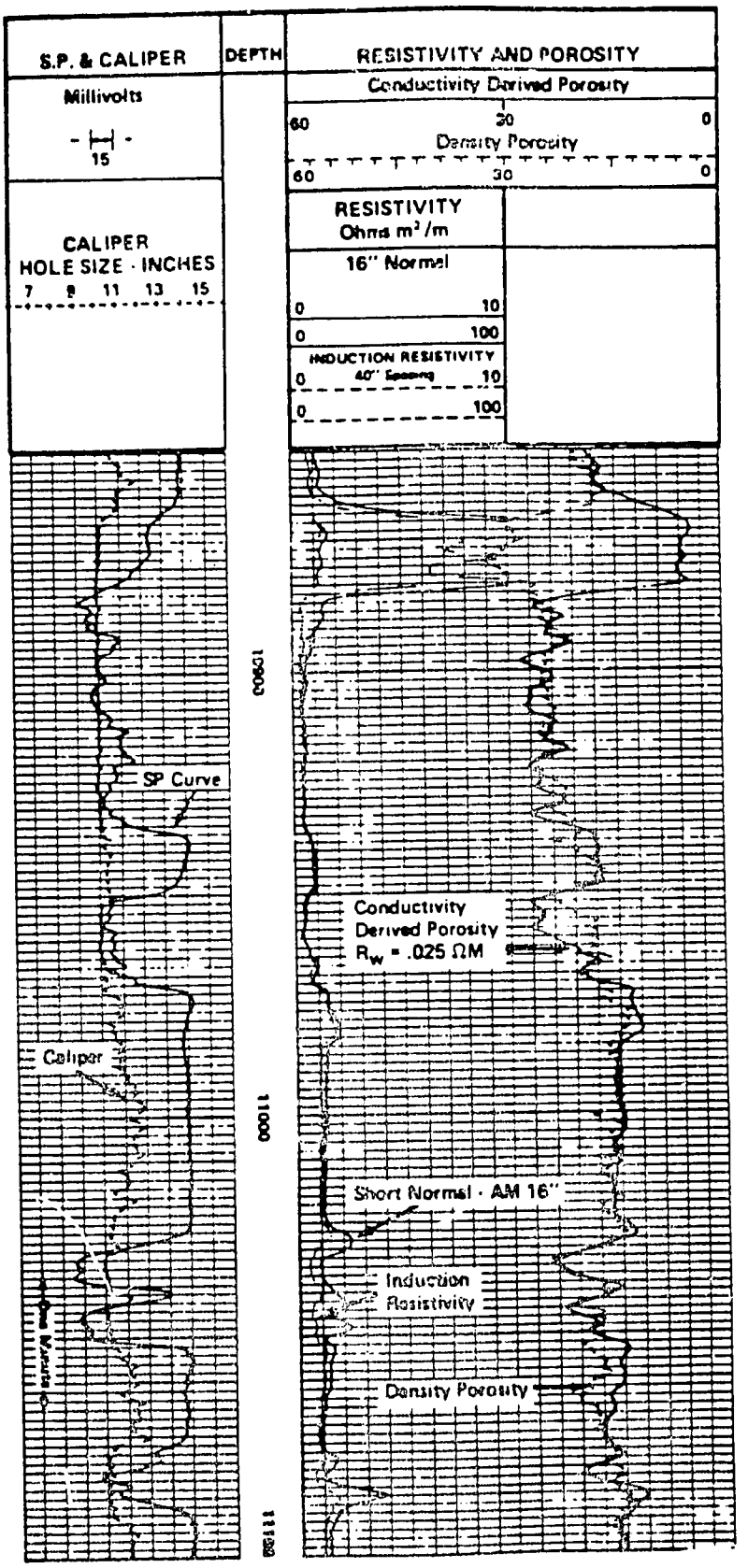
Problem Log 2



L. Cretaceous Sand, In Mississippi
Assume all sands are clean.

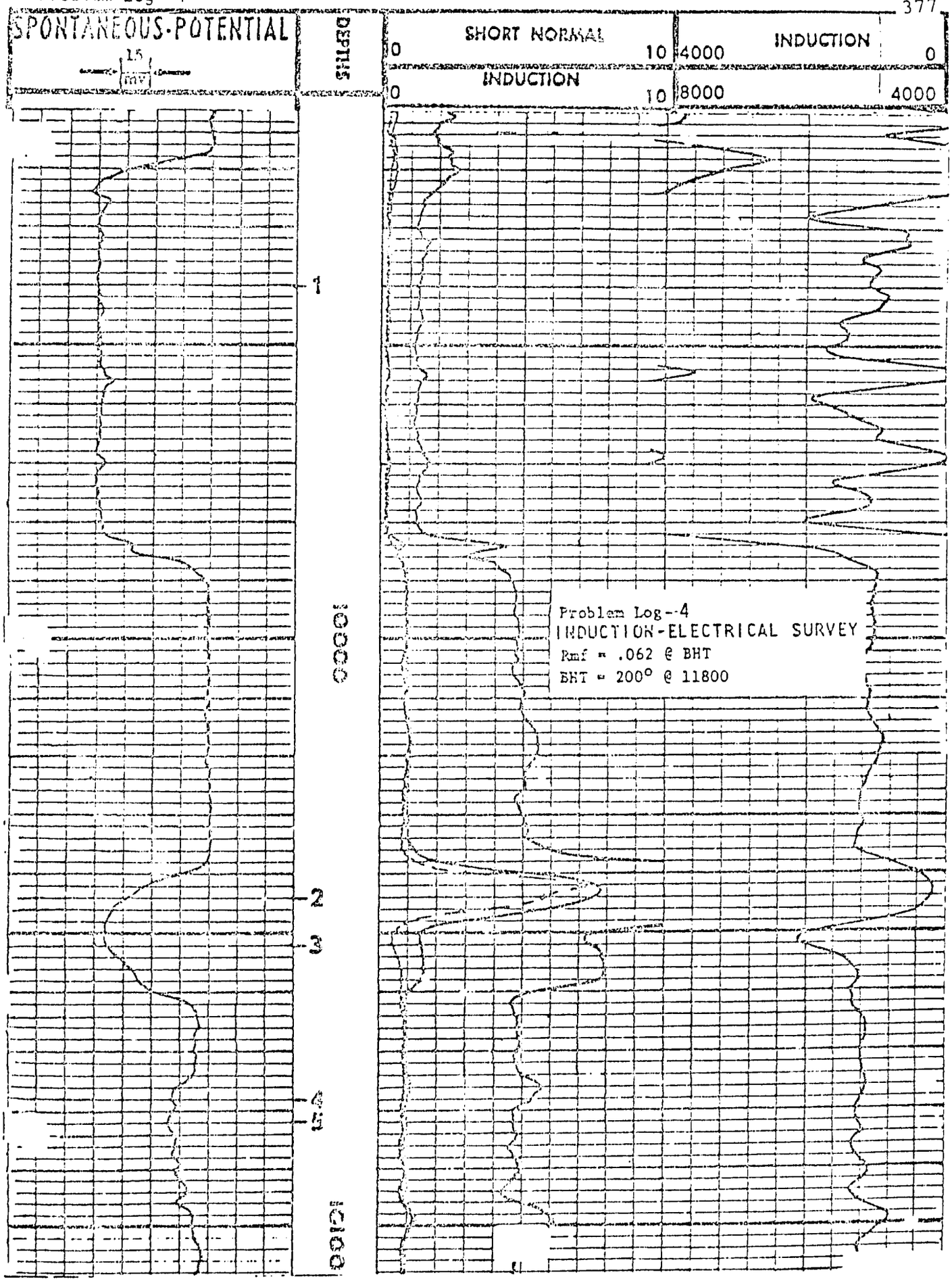
Courtesy of Dresser Atlas

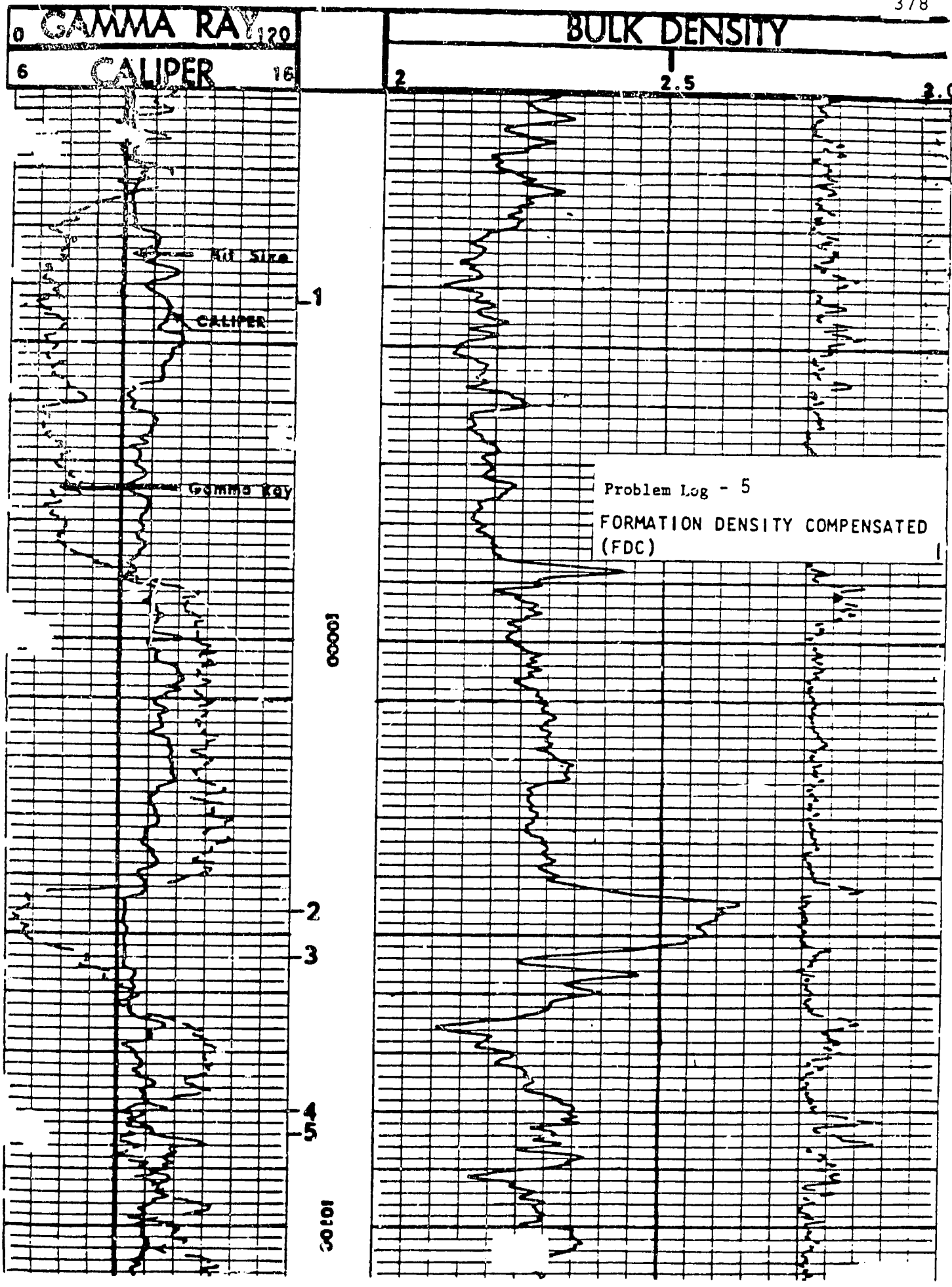
Problem Log 3



Courtesy of Dresser Atlas

Problem Log 4




0 GAMMA RAY 120
6 CALIPER 16
Bit Size
CALIPER
Gamma Ray
1
2
3
4
5
BULK DENSITY
2
2.5
Problem Log - 5
FORMATION DENSITY COMPENSATED
(FDC)

Name _____

PROBLEM

The Norwich #E-6 in Roscommon Co., Michigan was drilled and logged in salt mud.

3-1. The lithology at 4164' is:

(a) Dolomite (b) Limestone (c) Sandstone
(d) Shale (e) Coal (f) Anhydrite (g) Salt
(h) Granite Wash

3-2. The lithology at 4210' is which of the above:

(a) (b) (c) (d) (e) (f)
(g) (h)

PROBLEM

The FDC-CNL on this well was logged in salt mud. Determine the following data.

The lithology of the formation from 6942-7072' is:
(a) Dolomite (b) Limestone (c) Sandstone (d) Shale
(e) Coal (f) Anhydrite (g) Salt (h) Granite Wash

The formation should produce:
(a) Gas (b) Oil (c) Water (d) Nothing

Note: You may determine your answers from the one point at 6975'.

PROBLEM

This Wexford Co., Michigan well was drilled with salt mud.
The lithology of the zone at 4914' is:

(a) Dolomite (b) Limestone (c) Sandstone (d) Shale
(e) Coal (f) Anhydrite (g) Salt (h) Granite Wash

GAMMA RAY API UNITS

PROBLEM NO. 3

COMPENSATED FORMATION DENSITY POROSITY

Norwich No. E-6

Roscommon Co, Michigan

380

COMPENSATED NEUTRON POROSITY

45 30 15 0

FIELD PRINT SECTION

CALIPER DIAM. IN INCHES

6 16

GAMMA RAY API UNITS

0 150

150 300

DEPTH

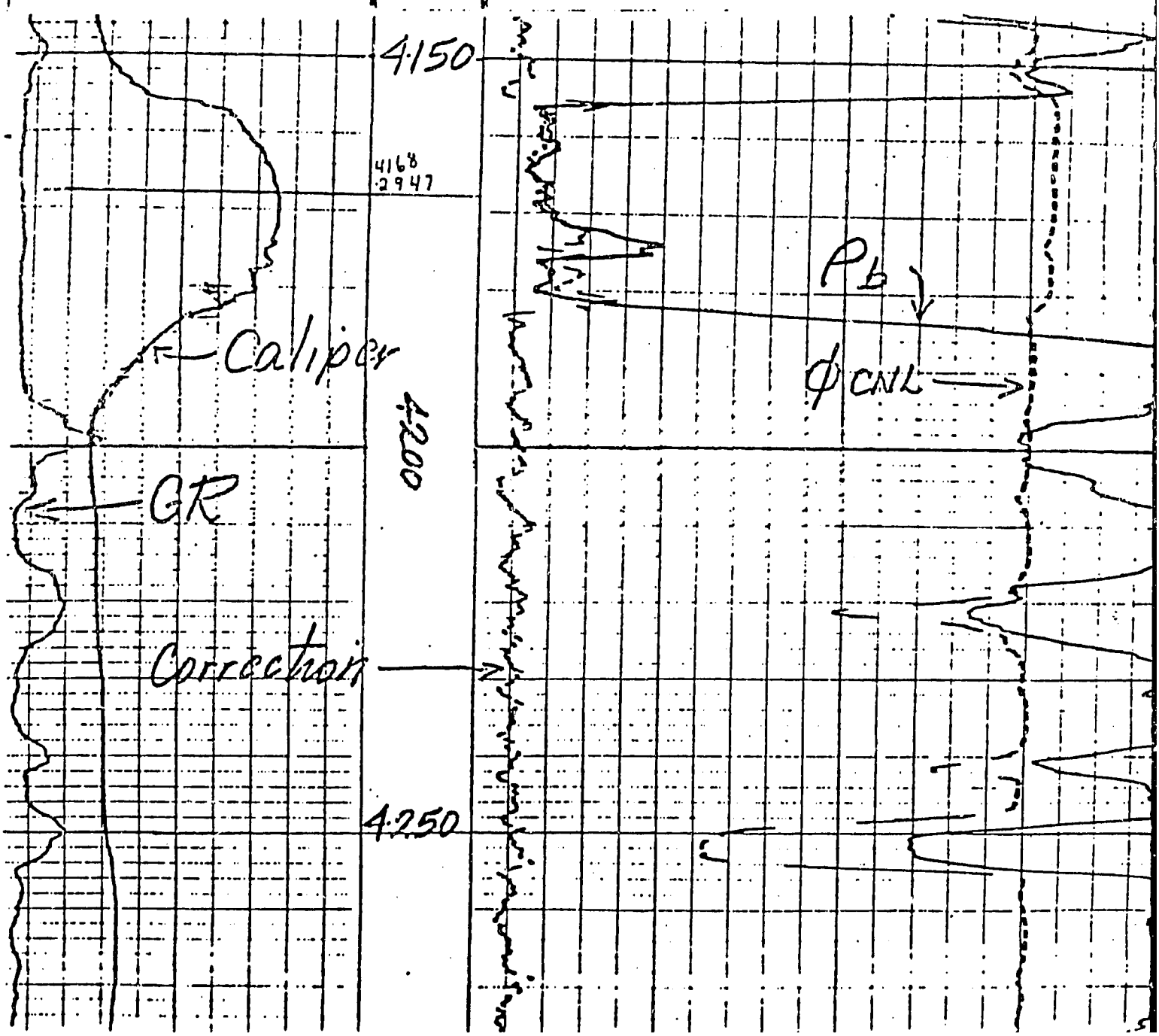
CORRECTION GRAMS CC

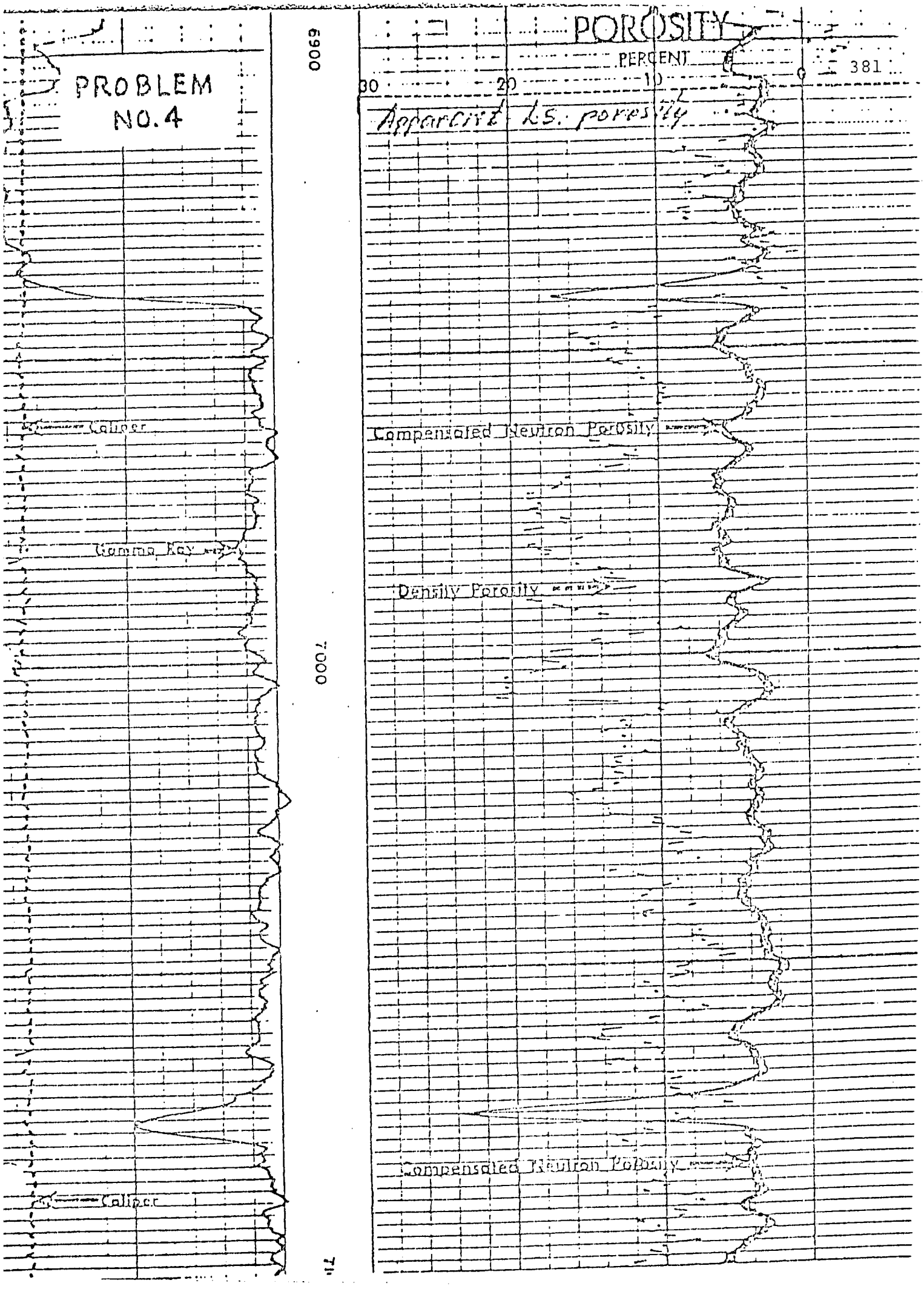
Use this scale when correction curve is presented in Track 2 OR Use this scale when correction curve is presented in Track 3

0 -.25 -.25 0

BULK DENSITY GRAMS CC

2.0 2.25 2.50 2.75




PROBLEM
NO.4
6900
7000
Caliper
Gamma Ray
Caliper
POROSITY
PERCENT
30
20
10
0
381
Apparent Ls. porosity
Compensated Neutron Porosity
Density Porosity
Compensated Neutron Porosity

PROBLEM NO. 5

COMPENSATED FORMATION DENSITY POROSITY

Wexford Co, Michigan

382

COMPENSATED NEUTRON POROSITY

45 30 15 0

FIELD PRINT SECTION

CALIPER DIAM. IN INCHES

6 16

GAMMA RAY API UNITS

0 100

DEPTH

CORRECTION

Use this scale when correction curve is presented in Track 2

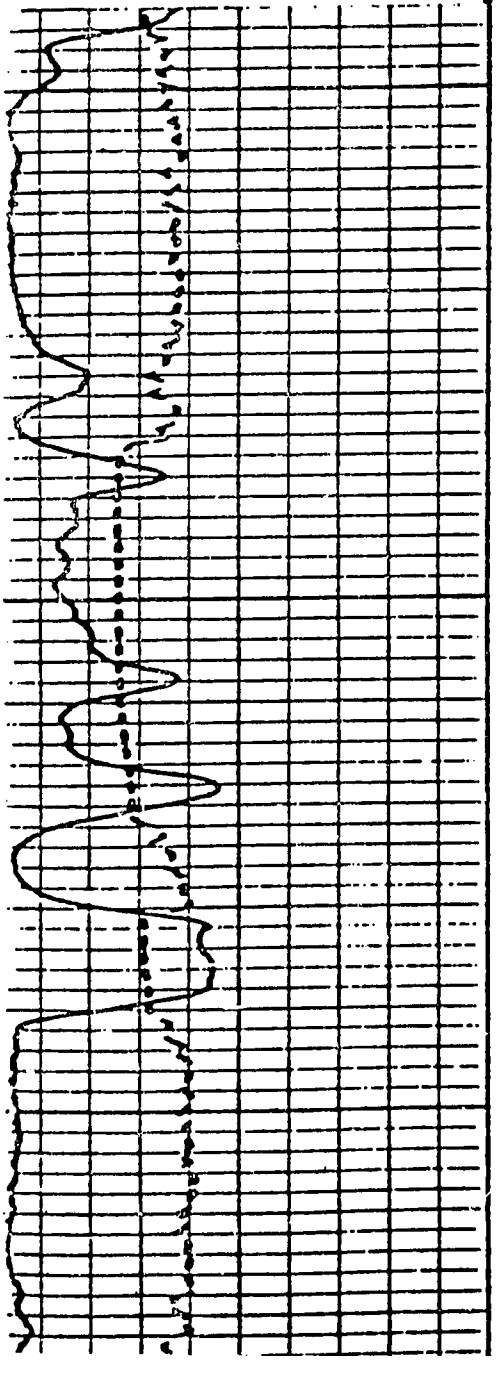
0 +.25

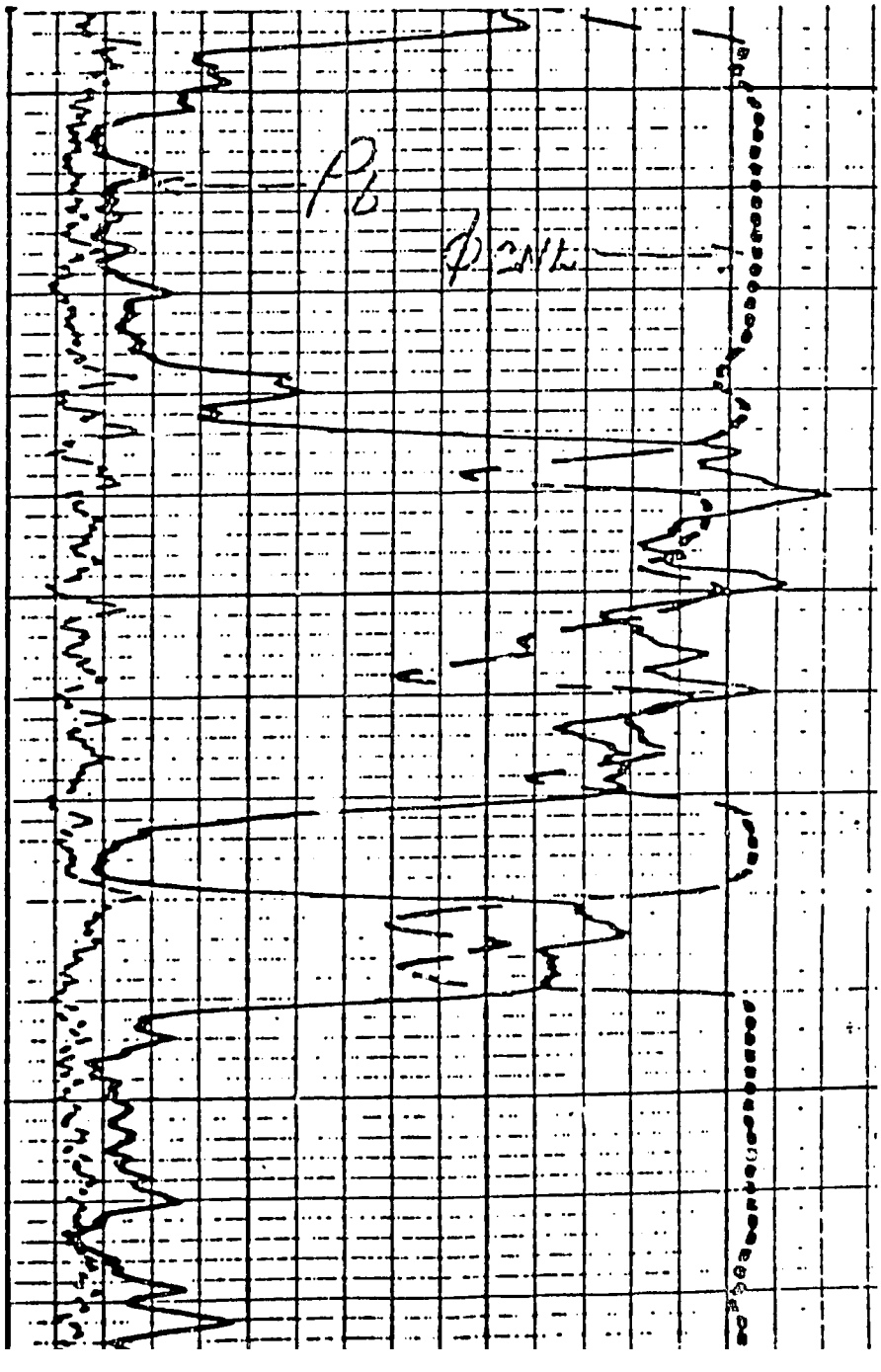
BULK DENSITY GRAMS CC

2.0 2.5

4800

4900





Resumé

Dr. E. T. Guerrero

Dr. E. T. Guerrero has been a Trustee Professor of Petroleum Engineering at the University of Tulsa since 1956. Educated at Texas A & M, he earned B.S. degrees in both Mechanical and Petroleum Engineering there, followed by a M.S. and Ph.D. in Petroleum Engineering. After three years in industry, principally with Seeligson, he joined the faculty at the University of Tulsa. Besides teaching, Dr. Guerrero has held administrative positions at the university as the Head of the Petroleum Engineering Department, Director of Information Services, and Dean of the College of Engineering and Physical Sciences.

Throughout his career, Dr. Guerrero has published extensively on the applications of reservoir engineering and well logging; he has to his credit over 102 articles in "The Oil and Gas Journal." In addition, he has been a consultant nationally and internationally to the petroleum industry. With such organizations as Continental Oil and Sunray Mid-Continent Oil Company, Dr. Guerrero has conducted annual courses for eight years.

With membership in scientific and professional societies, as well as in honoraries such as Tau Beta Pi, Society Sigma Xi, Phi Gamma Kappa, and Pi Epsilon Tau, Dr. Guerrero has been listed in Who's Who in American Education, American Men and Women of Science, Who's Who in America and Leaders in American Science.