Schlumberger

Log Interpretation Charts

1997

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An asterisk (*) is used throughout this document to denote a mark of Schlumberger.

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1997

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†New or modified chart

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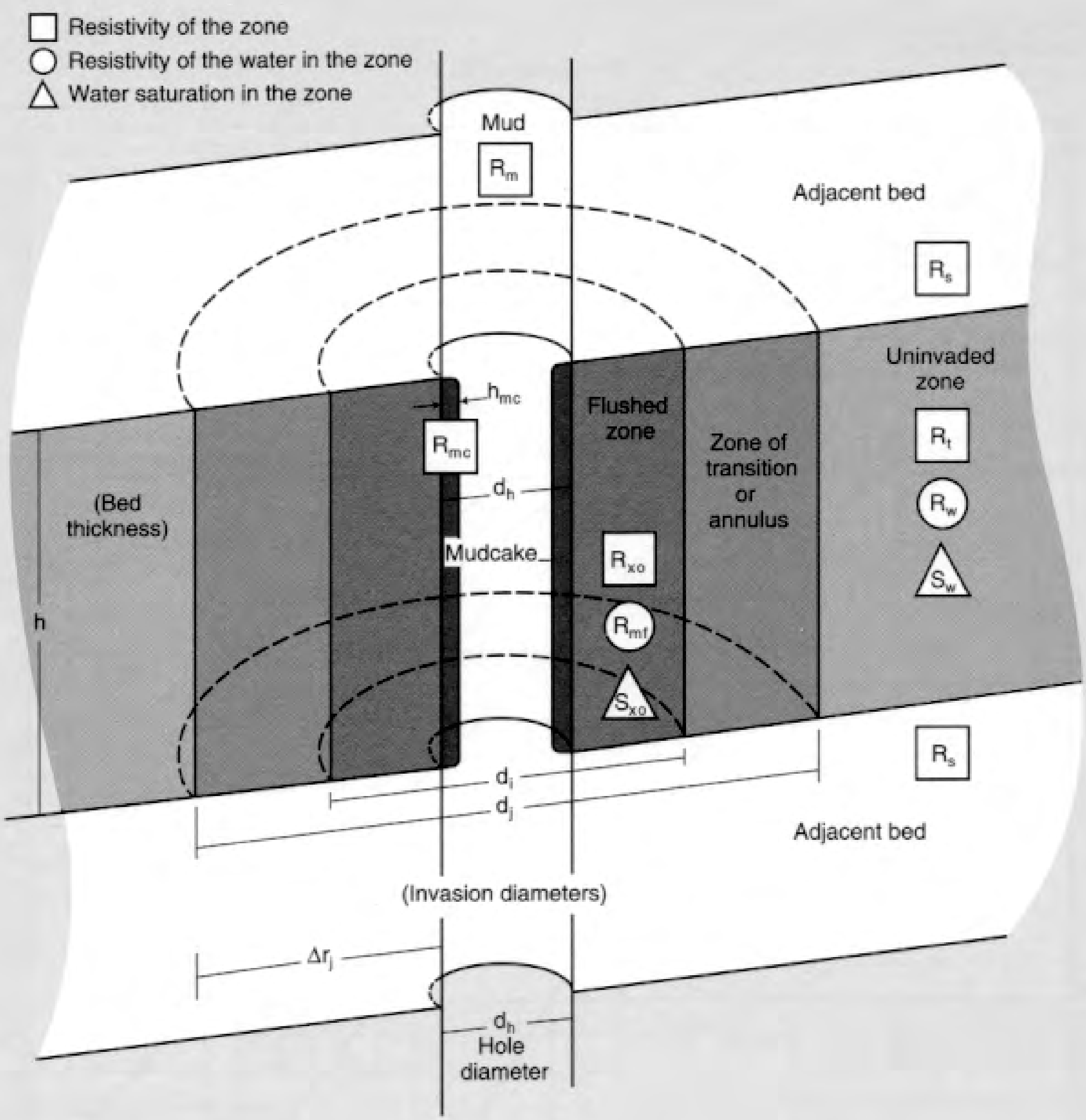
7. Through-Pipe Evaluation

Foreword

This edition of the Schlumberger Log Interpretation Charts book contains the charts, nomograms and tables necessary for quantitative interpretation of data from various Schlumberger logging tools. Several new charts are included for new services, and some of the previous charts have been replotted as a result of additional lab measurements and advanced computer modeling.

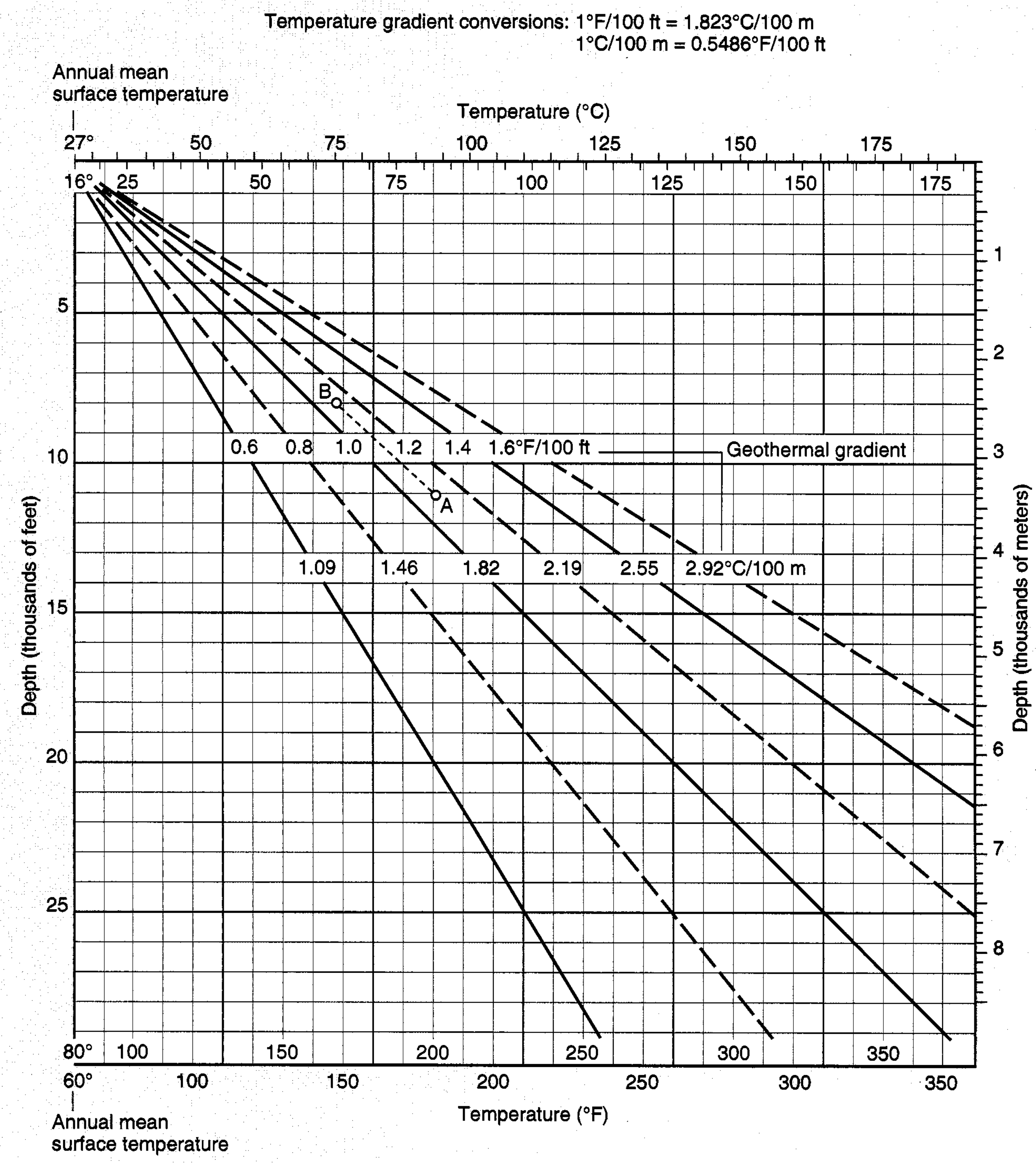
A brief description on how to use each chart or series of charts is included. Details are available from a companion volume, *Log Interpretation Principles/Applications—1989,* which describes the principles of measurements used by our openhole logging tools, the basic principles for interpreting those measurements, and the various applications for the services. *Cased Hole Log Principles/Applications—1989* provides similar information for cased hole services.

Symbols Used in Log Interpretation



Estimation of Formation Temperature

Linear gradient assumed



Example: Bottomhole temperature (BHT) at 11,000 ft = 200°F (Point A)

Temperature at 8000 ft = 167°F (Point B)

Estimation of R_{mf} and R_{mc}

Direct measurements of filtrate and mudcake samples are preferred. When not available, filtrate resistivity, R_{mf}, and mudcake resistivity, R_{mc}, may be estimated from one of the following methods.

Method 1

Lowe and Dunlap (Reference 36)

For freshwater muds with mud resistivity, R_m, in the range from 0.1 to 2.0 ohm-m at 75°F [24°C], and *measured* values of R_m and mud density, ρ_m, in pounds per gallon:

$$\log\left(\frac{R_{mf}}{R_m}\right) = 0.396 - 0.0475\,\rho_m$$

Method 2

Overton and Lipson (Reference 1)

For drilling muds with mud resistivity, R_m, in the range from 0.1 to 10.0 ohm-m at 75°F [24°C], where K_m is given as a function of mud weight in the table below:

$$R_{mf} = K_m (R_m)^{1.07}$$

$$R_{mc} = 0.69 (R_{mf}) \left(\frac{R_m}{R_{mf}}\right)^{2.65}$$

Example: $R_m = 3.5$ ohm-m at 75°F [24°C]

Mud weight = 12 lbm/gal [1440 kg/m^3]

Therefore, $K_m = 0.584$

$R_{mf} = (0.584)(3.5)^{1.07} = 2.23$ ohm-m at 75°F

$R_{mc} = 0.69(2.23)(3.5/2.23)^{2.65} = 5.07$ ohm-m at 75°F

The calculated value of R_{mf} is more reliable than that of R_{mc}.

Mud Weight		K_m
lbm/gal	kg/m^3	
10	1200	0.847
11	1320	0.708
12	1440	0.584
13	1560	0.488
14	1680	0.412
16	1920	0.380
18	2160	0.350

Method 3

A statistical approximation, for predominantly NaCl muds, is $R_{mc} = 1.5\ R_m$, and $R_{mf} = 0.75\ R_m$.

Resistivities of Solutions

Actual resistivity measurements are always preferred, but if necessary, the chart on the opposite page may be used to estimate the resistivity of a water sample at a given temperature when the salinity (NaCl concentration) is known, or to estimate the salinity when resistivity and temperature are known. It may also be used to convert resistivity from one temperature to another temperature.

Example: Resistivity of a water sample is 0.3 ohm-m at 25°C; what is the resistivity at 85°C?

Enter the chart with 25°C and 0.3 ohm-m. Their intersection indicates a salinity of approximately 20,000 ppm. Moving along this constant salinity line yields a water sample resistivity of 0.13 ohm-m at 85°C.

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 Chart Gen-9 to estimate the resistivity of the sample.

The chart is entered in 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 obtain equivalent NaCl concentration. Concentrations are expressed in ppm or mg/kg, both by weight. These units are numerically equal.

For more information see Reference 2.

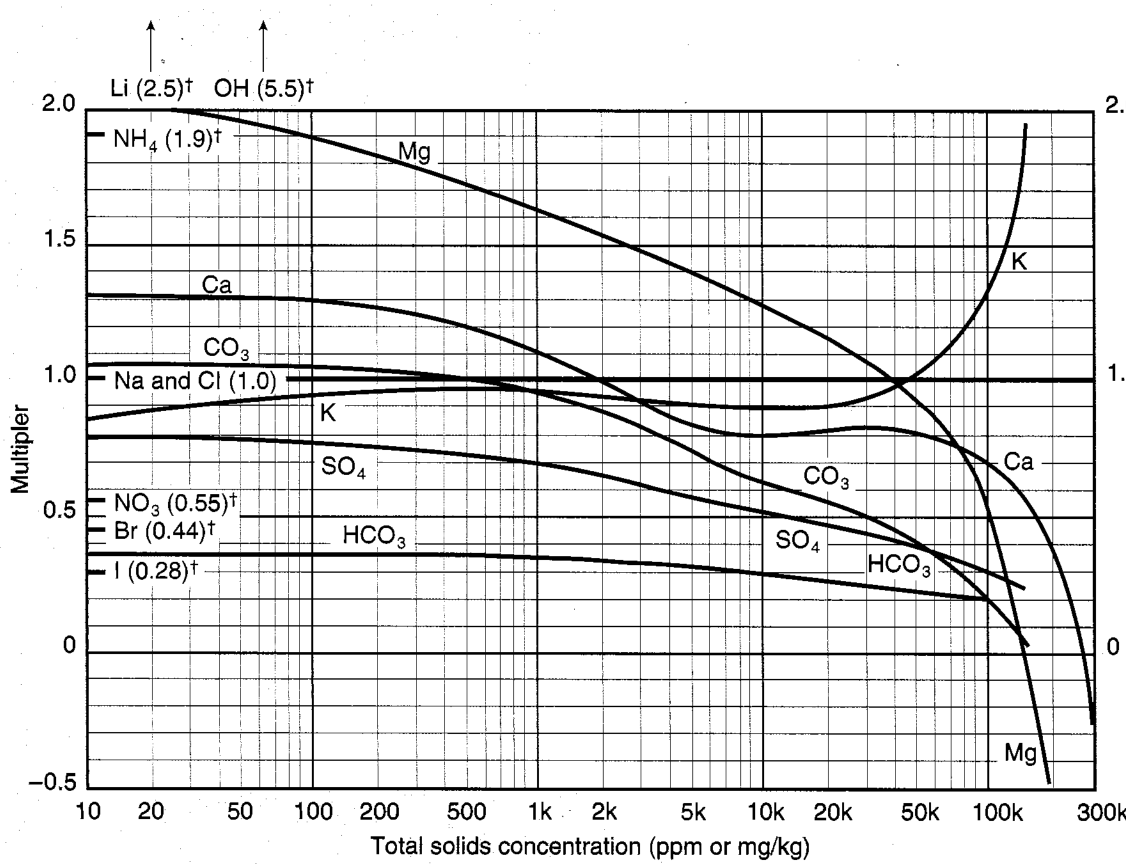
Example: A formation-water sample analysis shows 460 ppm Ca, 1400 ppm SO_4 and 19,000 ppm Na plus Cl.

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 concentration by the corresponding multipliers, the equivalent NaCl concentration is found as approximately

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

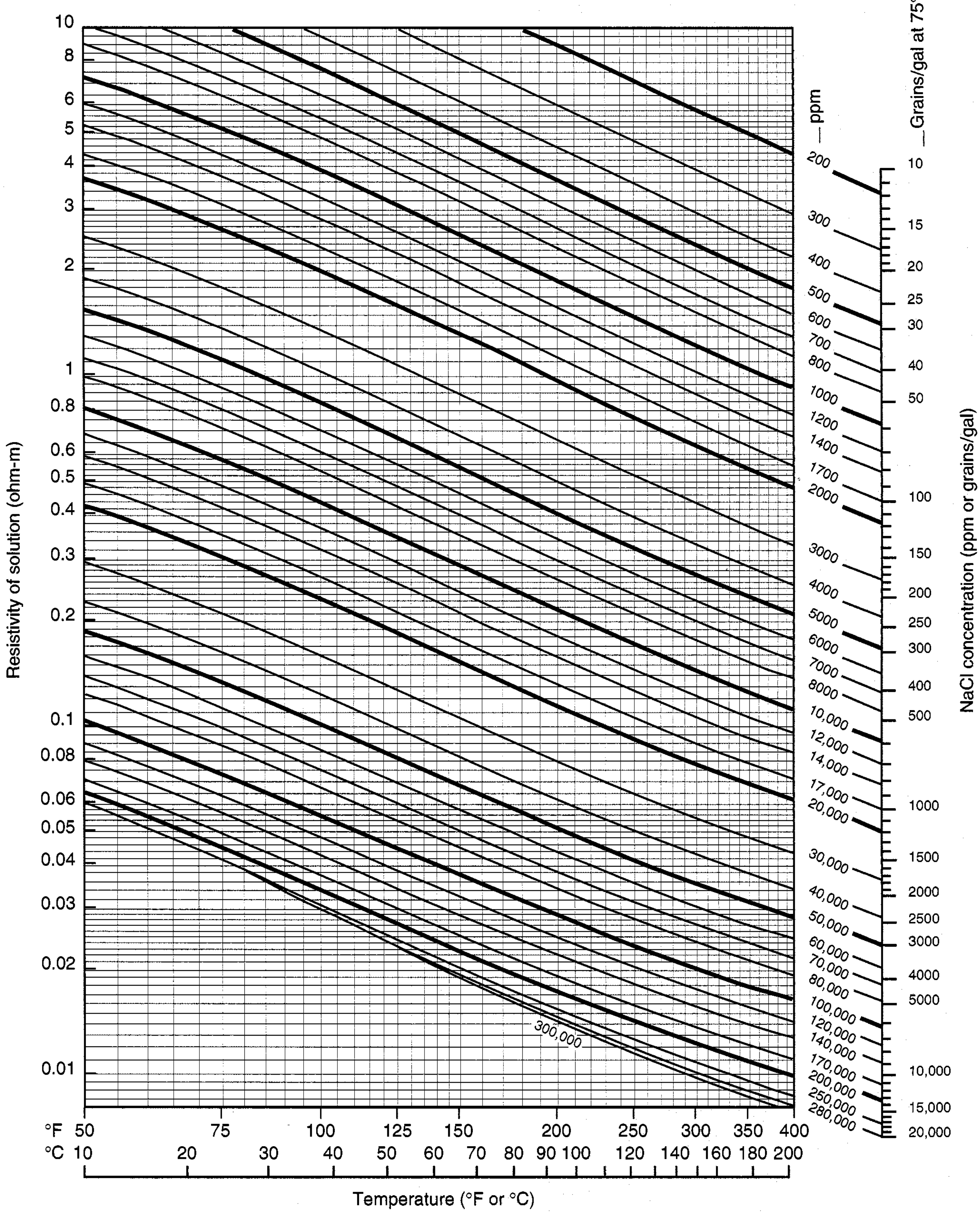
Entering the NaCl resistivity-salinity nomograph (Gen-9) with 20,000 ppm and 75°F (24°C), the resistivity is found to be 0.3 at 75°F.



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

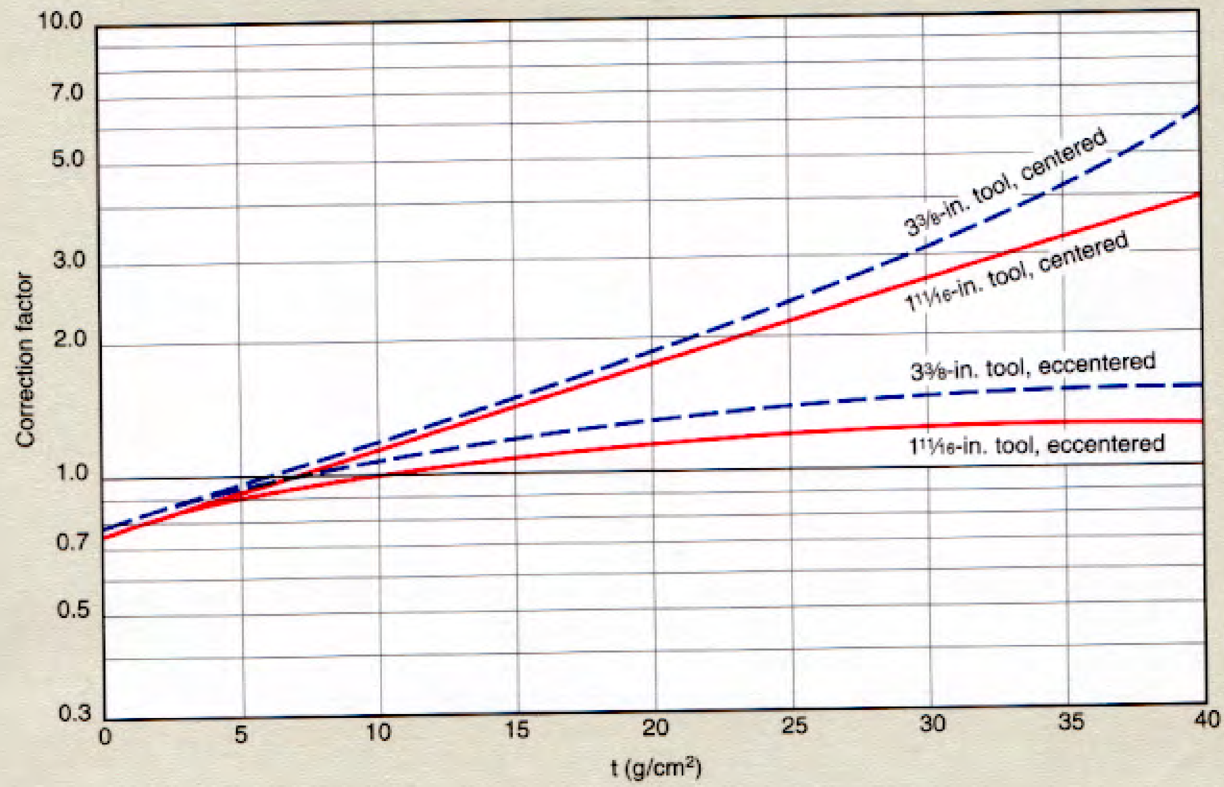
Resistivity of NaCl Solutions

Conversion **approximated** by $R_2 = R_1\,[(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1\,[(T_1 + 21.5)/(T_2 + 21.5)]$°C



Gamma Ray Corrections for Hole Size and Mud Weight

For 3⅜-in. and 1¹¹⁄₁₆-in. SGT wireline gamma ray tools



Log interpretation Charts GR-1 and GR-2, replacing Chart Por-7, are based on laboratory work and Monte Carlo calculations to provide improved corrections for 3⅜- and 1¹¹⁄₁₆-in. SGT gamma ray tools. The corrections normalize the response of both tools to eccentered positions in an 8-in. borehole with 10-lbm mud. Chart GR-2 provides a correction for barite mud in small boreholes.

Although these charts are more difficult to use than the ones they replaced, the results are more exact since they are normalized to current tools, no interpolation is required, and the ranges are extended.

The input parameter, t, in g/cm², is calculated as follows:

$$t = \frac{W_{mud}}{8.345}\left(\frac{2.54\,(d_{hole})}{2} - \frac{2.54\,(d_{sonde})}{2}\right).$$

The correction for standoff is

$$CF' = CF'_m + (CF_o - CF'_m)\left(\frac{S - S_m}{S_m}\right)^2.$$

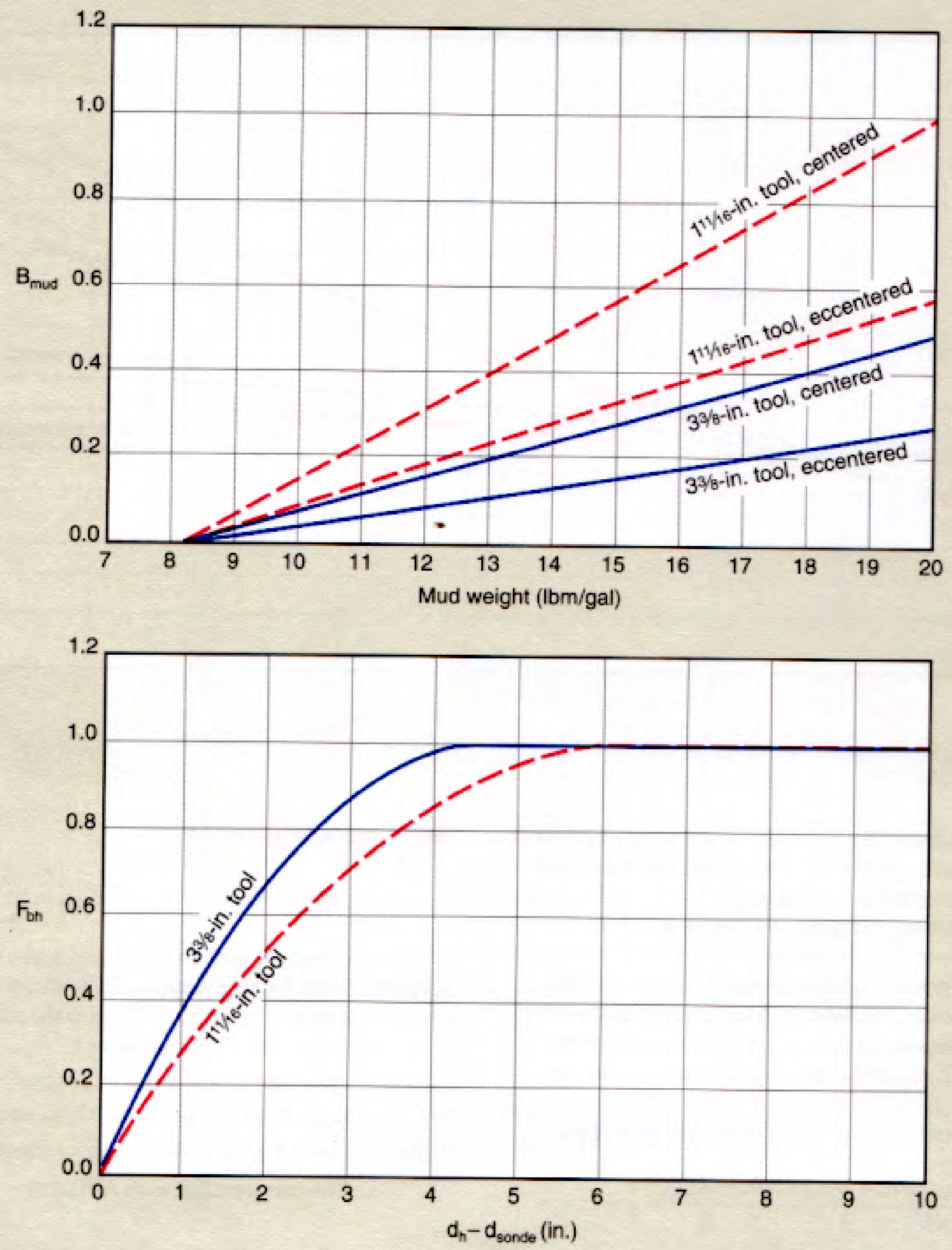
CF'_m is the correction factor for centered tools, while CF'_o is the correction factor for eccentered tools. Both are corrected for barite if it is present in the borehole. S is the actual standoff, and S_m is the standoff with the tool centered.

Example: GR reads 36 API units, d_h is 12 in., and mud weight is 12 lbm/gal. The tool is 3⅜ in. and centered.

Therefore, t = 15.8 g/cm², resulting in a correction factor of 1.6.

The corrected GR = 58 API units.

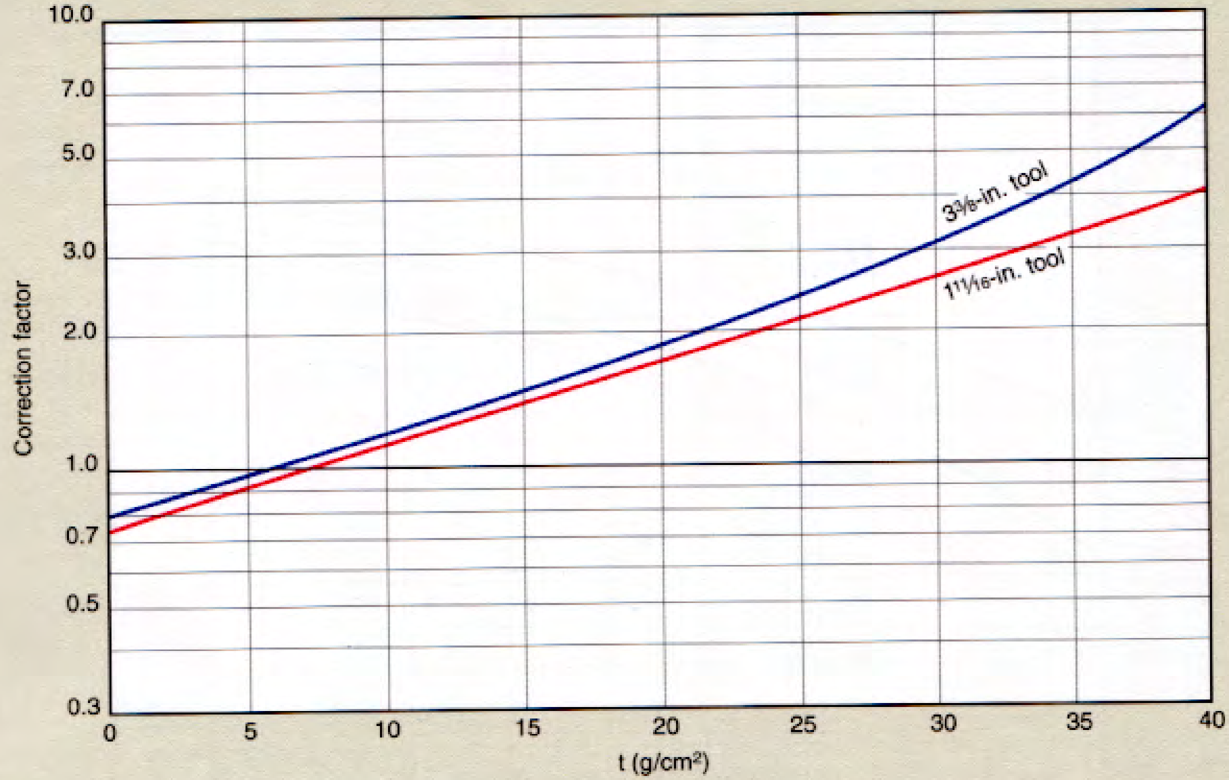
Gamma Ray Corrections for Barite Mud in Small Boreholes



These charts correct for the barite mud effect in hole sizes smaller and larger than the 8-in. standard. In these cases, the correction factor from Chart GR-1 is multiplied by the borehole correction factor $1 + B_{mud} \times F_{bh}$.

Example: With the same conditions shown in the example on Chart GR-1 except for a 6-in. hole, $t = 4.8$ g/cm^2, resulting in a correction factor of 0.95. Using Chart GR-2, $B_{mud} = 0.15$ and $F_{bh} = 0.81$ for a borehole correction of 1.12 and a revised correction factor of 1.06. The corrected GR = 38 API units.

Gamma Ray Correction for Cased Holes



Log interpretation Chart GR-3 is based on laboratory work and Monte Carlo calculations to provide gamma ray corrections in cased holes. This chart is based on the openhole model in Chart GR-1. In this case, t, in g/cm^2, is calculated as the sum of density-thickness products for the casing, cement sheath and borehole fluid. The density of J-55 casing is 7.96 g/cm^3, and the density of cement is typically 2.0 g/cm^3.

$$t = \frac{2.54}{2}\left(\frac{W_m}{8.345}(ID_{csg} - d_{sonde}) + \rho_{csg}(OD_{csg} - ID_{csg}) + \rho_{cement}(d_h - OD_{csg})\right)$$

The chart correction factor provides a corrected gamma ray to the standard reference condition of an eccentered 3⅜-in. tool in an 8-in. borehole with 10-lbm mud.

Example: GR reads 19 API units; d_h is 12 in.; casing is 9⅝ in., 43.50 lbm/ft; GR tool is 3⅜ in.; W_m = 8.345 lbm/gal; and t = 21.7 g/cm^2 for a correction factor of 2.1. The corrected GR = 40 API units.

LWD Gamma Ray Correction for Hole Size and Mud Weight

For gamma ray with CDR* Compensated Dual Resistivity tools

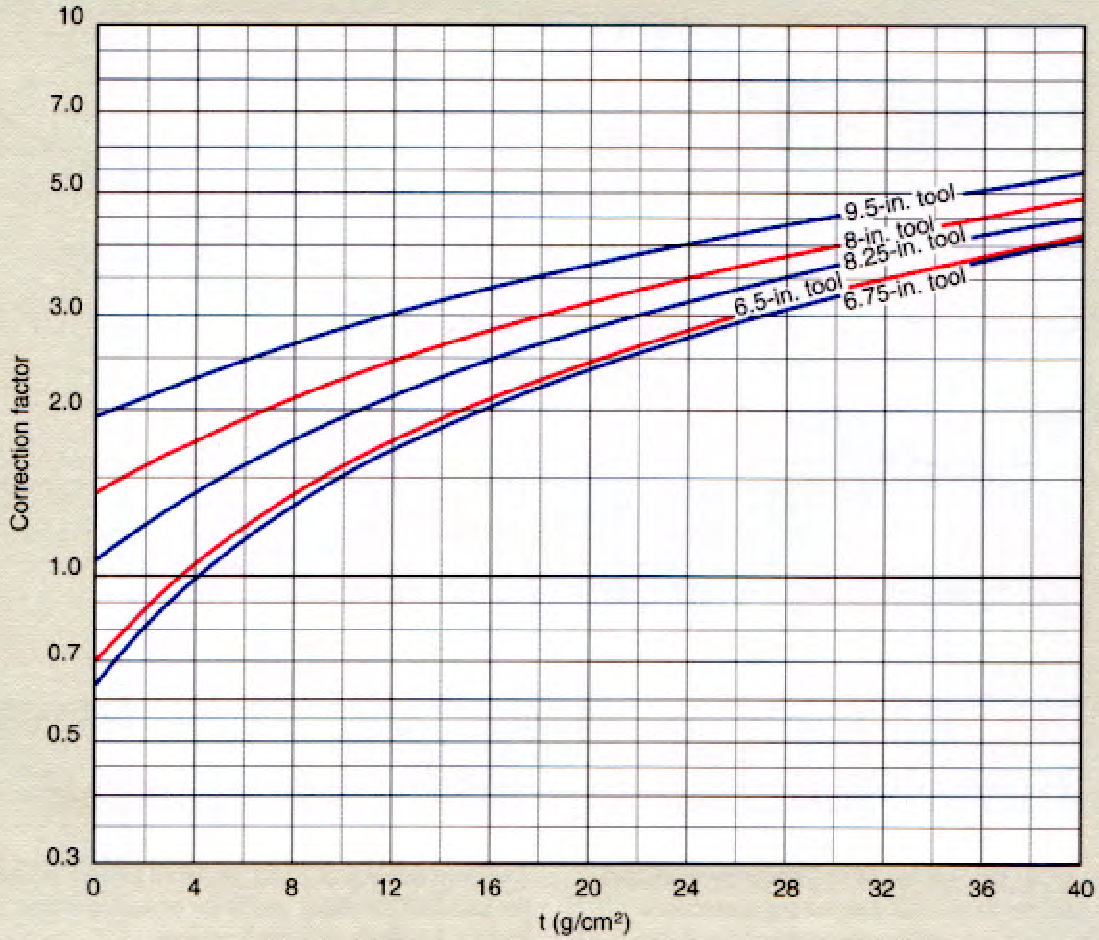


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Chart GR-4 can be used to normalize gamma ray readings of the 9.5-, 8.25-, 8-, 6.75- and 6.5-in. CDR tools to the 6.5-in. tool in 10-lbm/gal mud.

The corrections illustrated by this chart are routinely applied to LWD data before delivery; therefore, be careful not to duplicate the correction. The input parameter, t, in g/cm^2, is calculated from

$$t = \frac{W_m}{8.345}\left(d_{hole} - 3.5 - ST\right)$$

where ST varies with tool size as follows:

Tool size (in.)	ST
6.5	2.125
6.75	2.031
8.0	3.156
8.25	2.656
9.5	3.937

R_{weq} Determination from E_{SSP}

Clean formations

This chart and nomograph calculate the equivalent formation water resistivity, R_{weq}, from the static spontaneous potential, E_{SSP}, measurement in clean formations.

Enter the nomograph with E_{SSP} in mV, turning through the reservoir temperature in °F or °C to define the R_{mfeq}/R_{weq} ratio. From this value, pass through the R_{mfeq} value to define R_{weq}.

For predominantly NaCl muds, determine R_{mfeq} as follows:

a. If R_{mf} at 75°F (24°C) is greater than 0.1 ohm-m, correct R_{mf} to formation temperature using Chart Gen-9, and use $R_{mfeq} = 0.85\ R_{mf}$.

b. If R_{mf} at 75°F (24°C) is less than 0.1 ohm-m, use Chart SP-2 to derive a value of R_{mfeq} at formation temperature.

Example: SSP = 100 mV at 250°F

R_{mf} = 0.70 ohm-m at 100°F or 0.33 ohm-m at 250°F

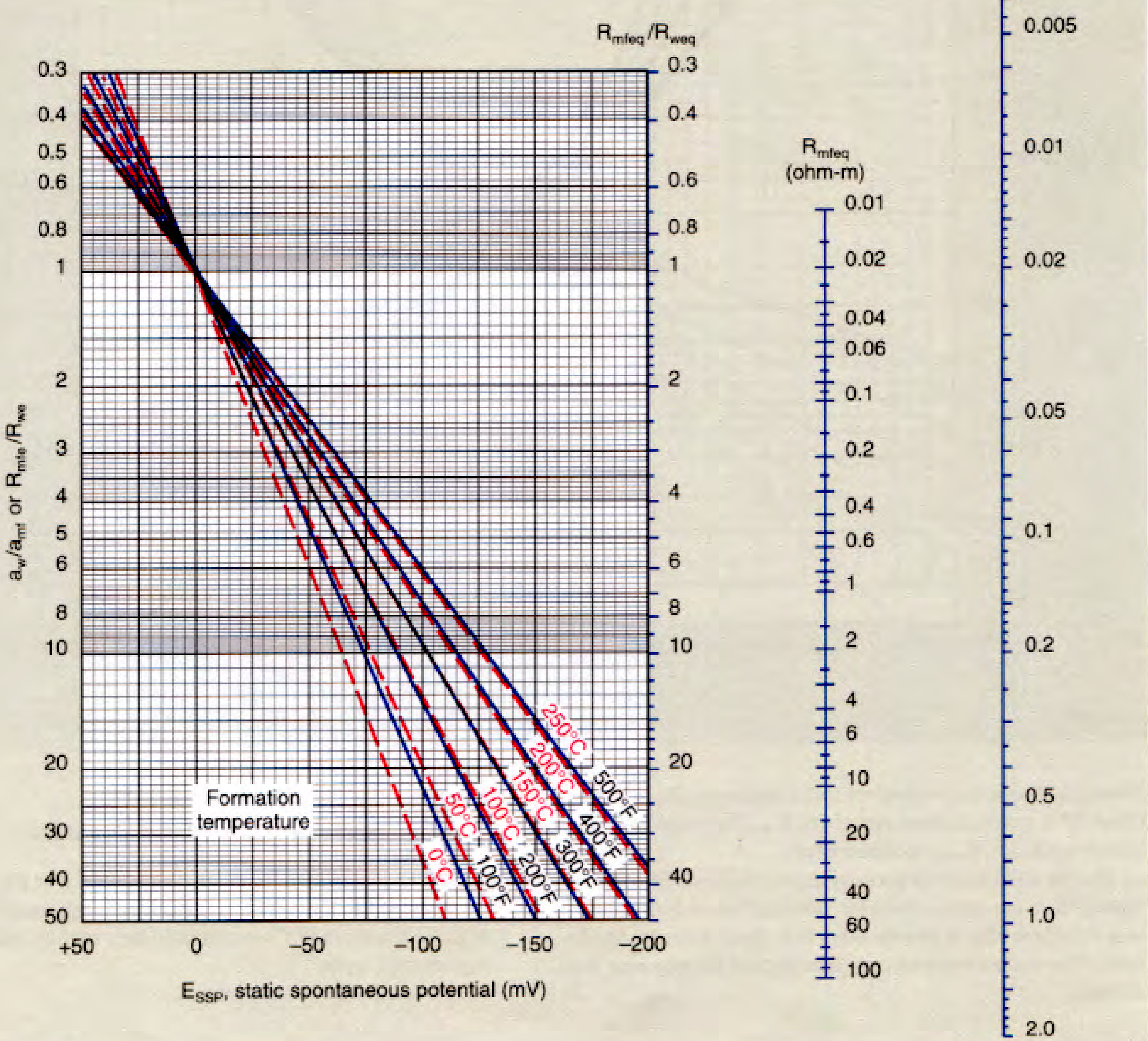
Therefore, $R_{mfeq} = 0.85 \times 0.33 = 0.28$ ohm-m at 250°F

R_{weq} = 0.025 ohm-m at 250°F

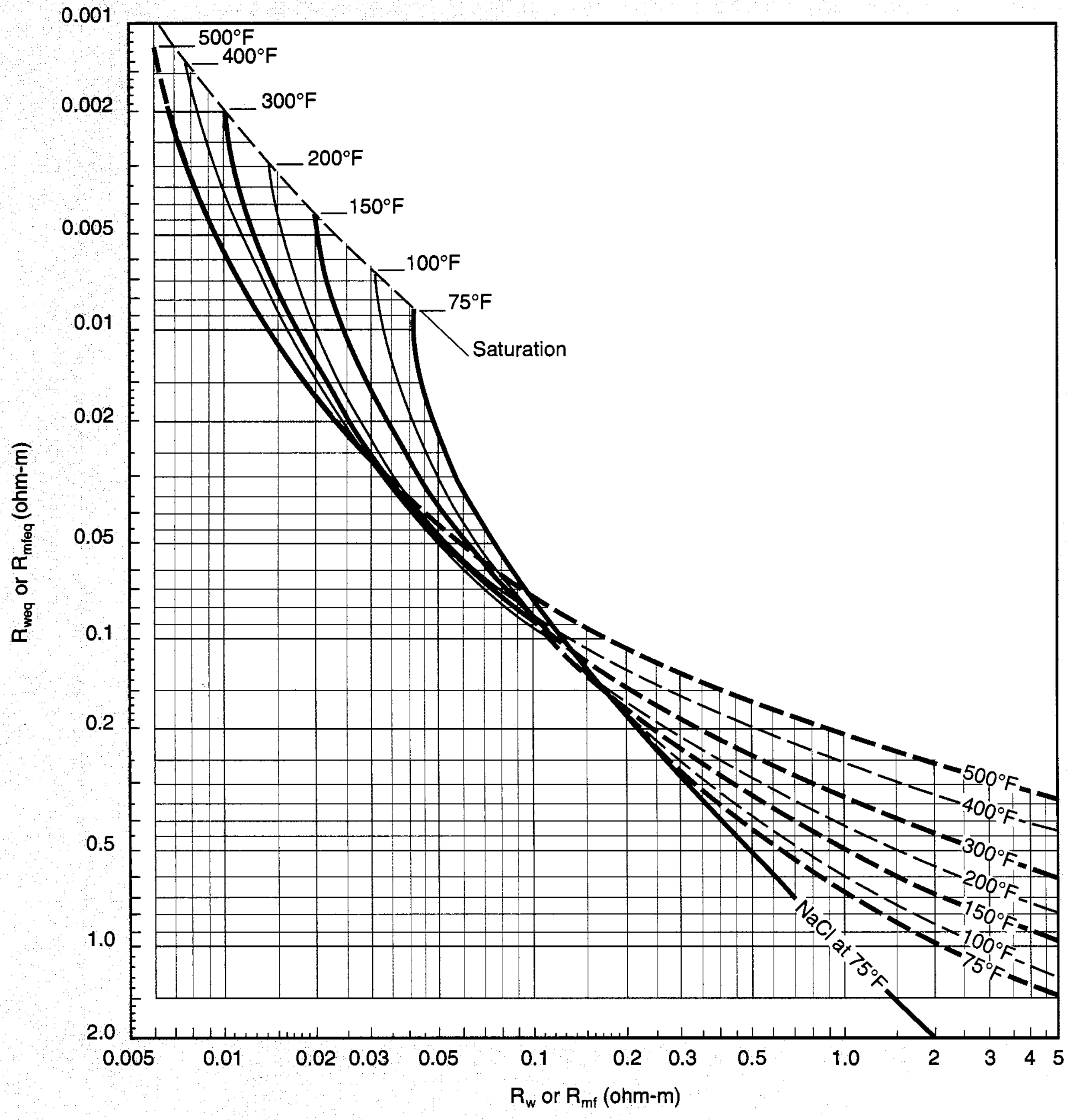
$E_{SSP} = -K_c \log(R_{mfeq}/R_{weq})$

$K_C = 61 + 0.133\ T_{°F}$

$K_C = 65 + 0.24\ T_{°C}$



R_w versus R_{weq} and Formation Temperature



These charts convert equivalent water resistivity, R_{weq}, from Chart SP-1 to actual water resistivity, R_w. They may also be used to convert R_{mf} to R_{mfeq} in saline muds.

Use the solid lines 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} = 0.025 ohm-m at 120°C
From chart, R_w = 0.031 ohm-m at 120°C

Special procedures for muds containing Ca or Mg in solution are discussed in Reference 3. Lime-base muds usually have a negligible amount of Ca in solution; they may be treated as regular mud types.

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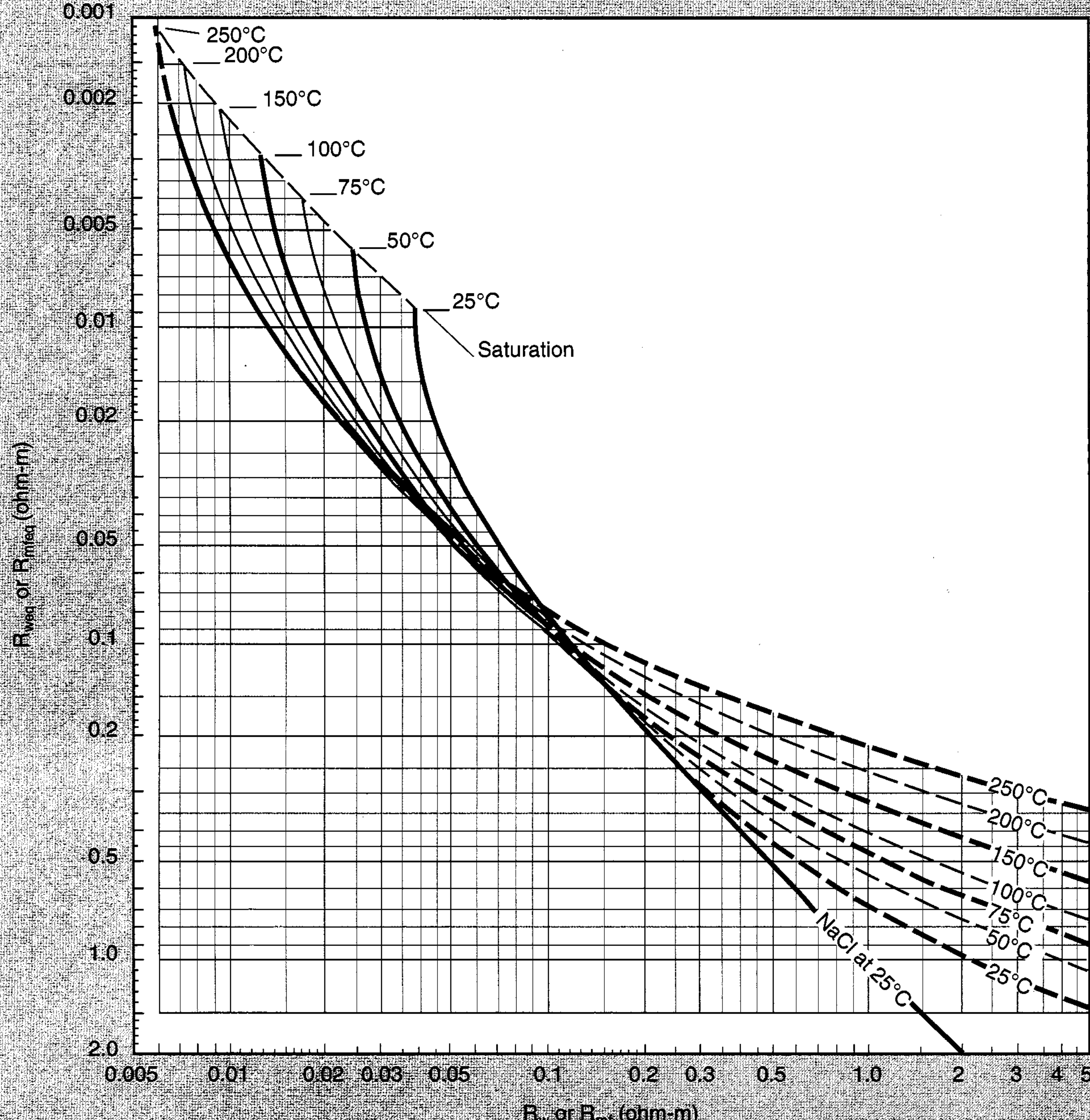
R_w versus R_{weq} and Formation Temperature

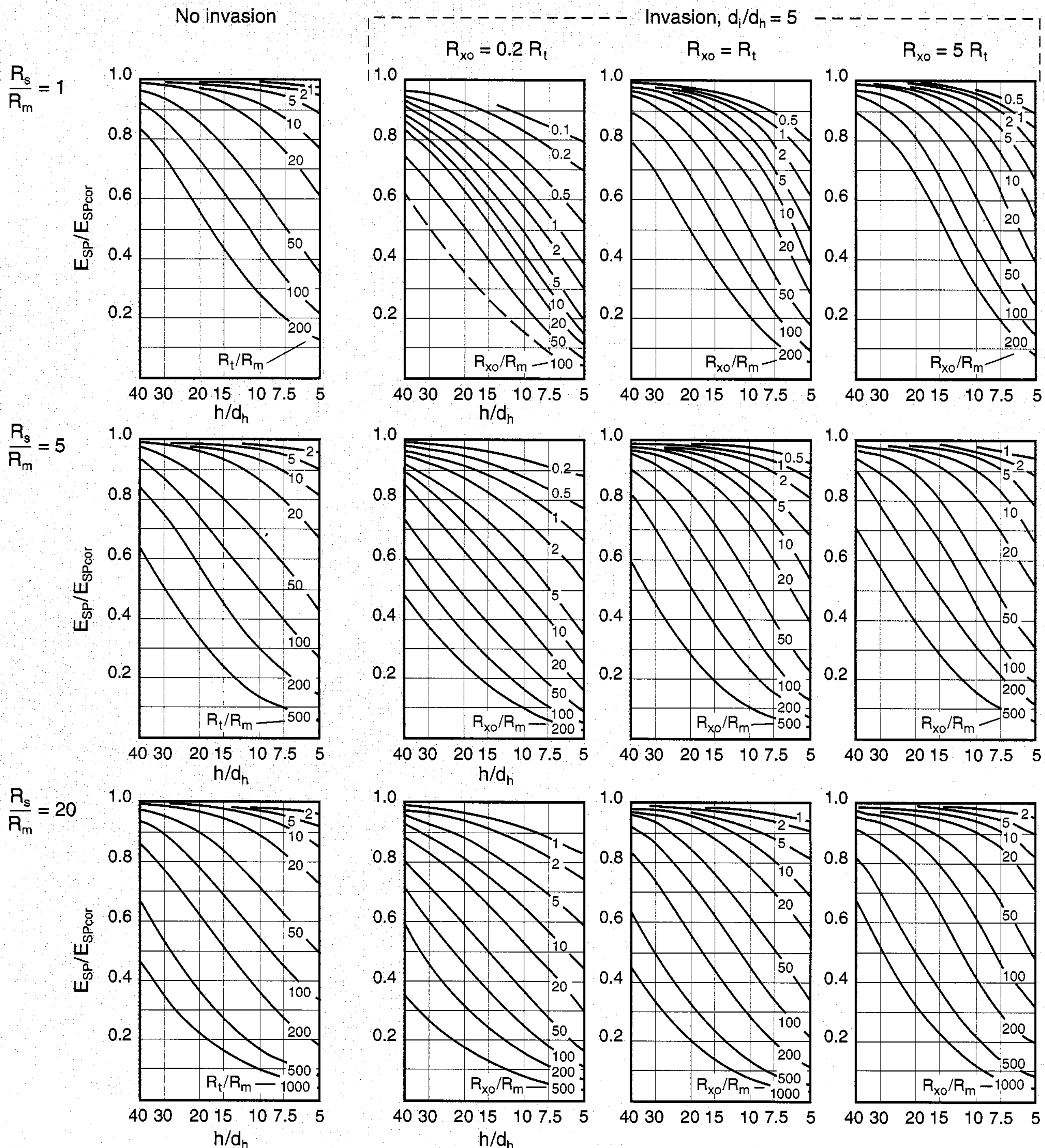
SP-2m (Metric)



SP Correction Charts

For representative cases

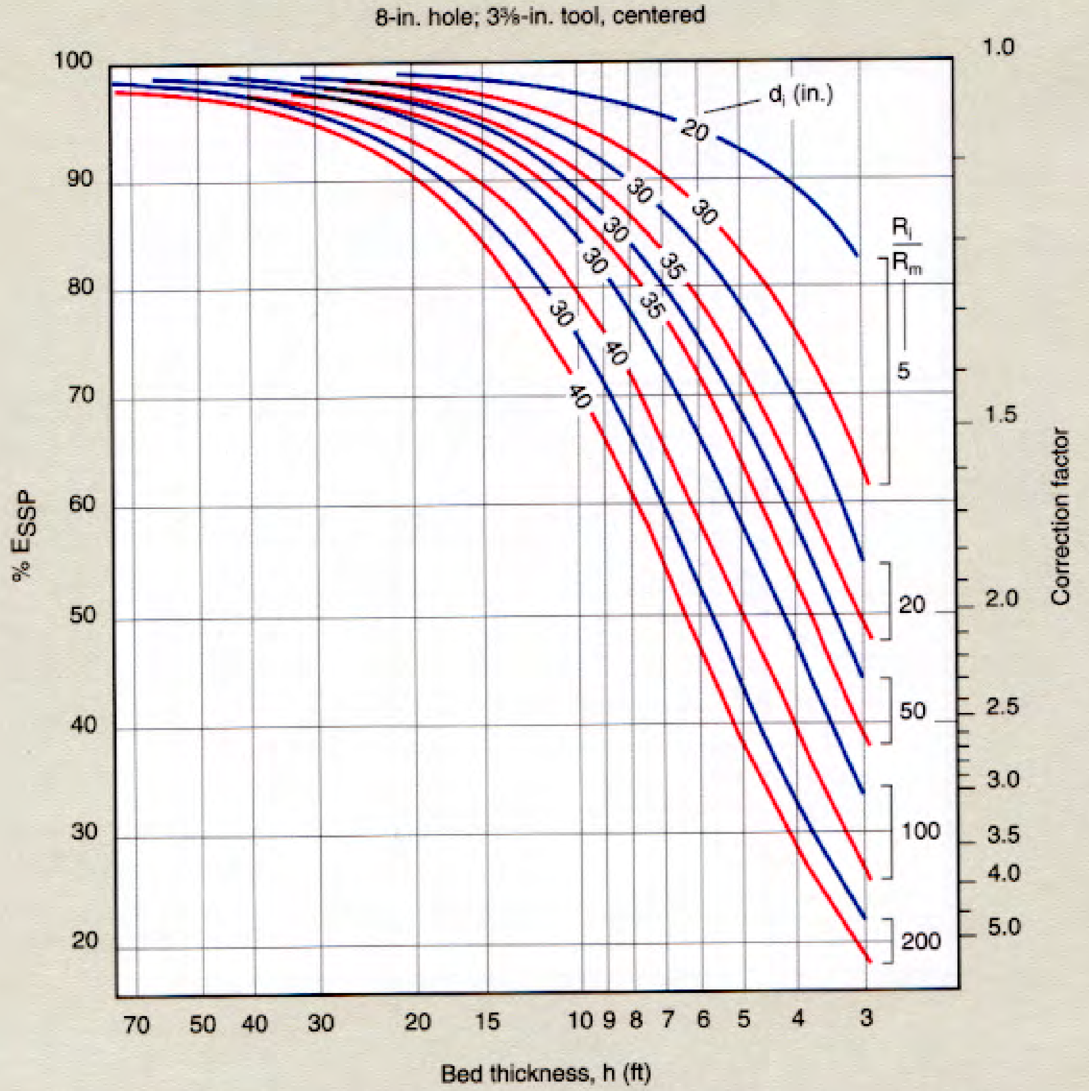
SP



1. Select row of charts for most appropriate value of R_s/R_m.
2. Select chart for No Invasion or for Invasion of d_i/d_h = 5, whichever is 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 References 4 and 33.

SP Correction Chart (Empirical)



This chart provides an empirical correction to the SP for the effects of invasion and bed thickness obtained by averaging a series of thin-bed corrections in Reference 37. This chart considers only h, bed thickness, as variable, and R_i/R_m and d_i as parameters of fixed value. Hole diameter is set at 8 in.

Enter the chart with bed thickness, h; go to the appropriate invasion diameter, d_i, and invaded zone resistivity/mud resistivity ratio, R_i/R_m. The recorded SP measurement is then corrected by the resulting correction factor.

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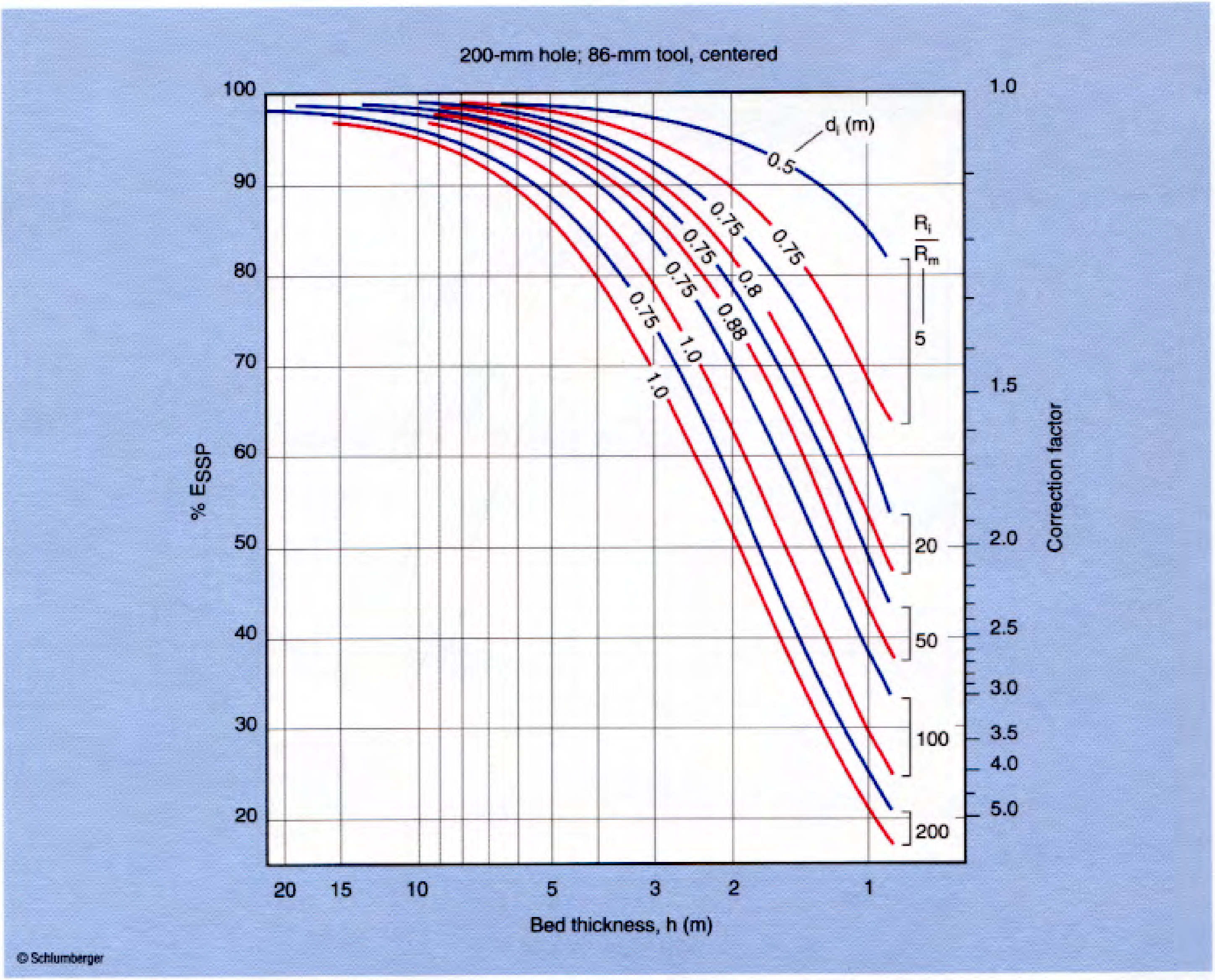
SP Correction Chart (Empirical)

SP-4m (Metric)



Example: SP = –80 mV in a 3-m bed

R_m = 0.5 ohm-m, and R_i (invaded zone resistivity) = 10 ohm-m (both at formation temperature)

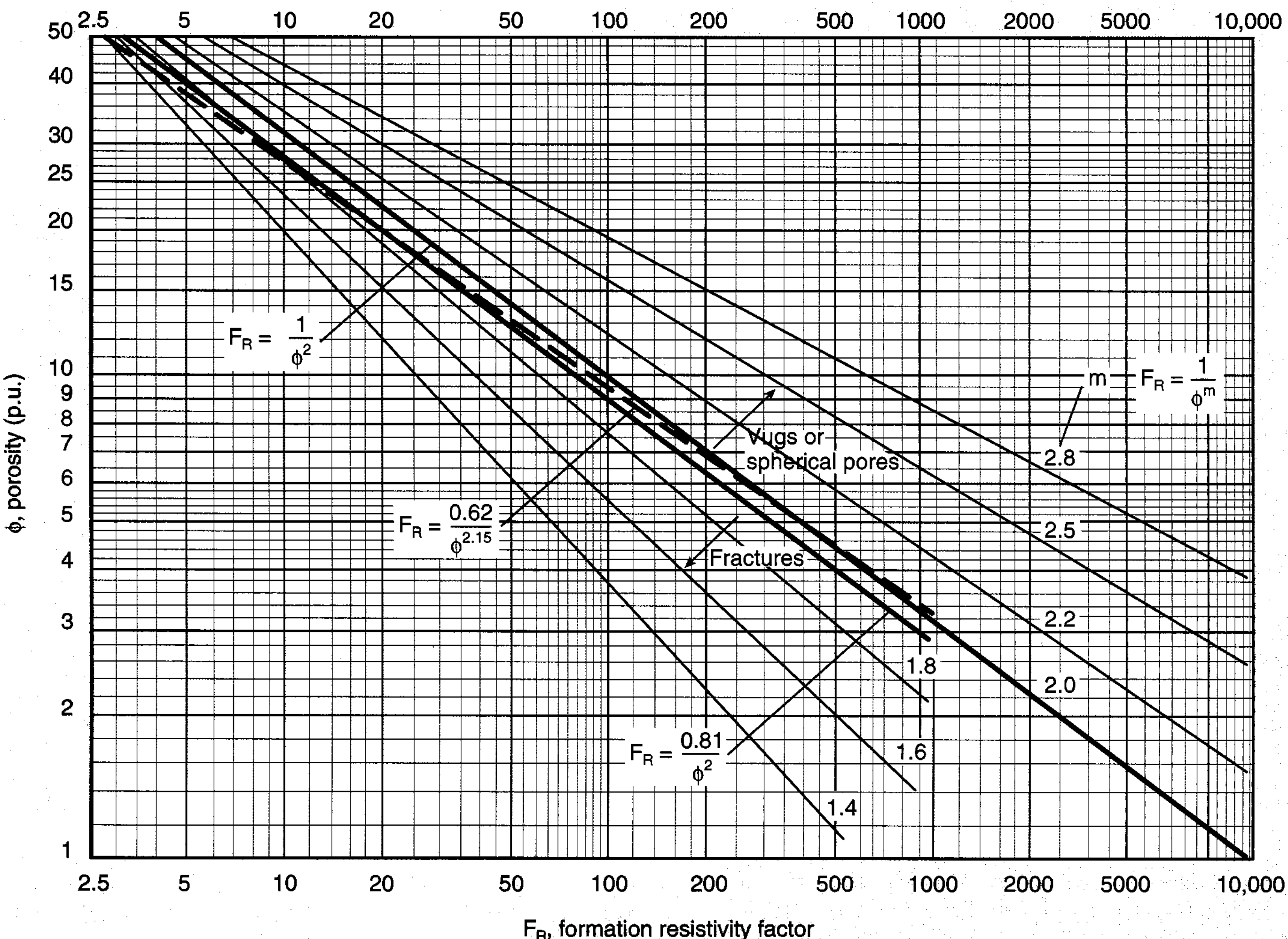
Invasion diameter = 0.80 m

Therefore, R_i/R_m = 10/0.5 = 20

SP correction factor = 1.1

Corrected SP, E_{SSP} = –80 (1.1) = –88 mV

Formation Resistivity Factor Versus Porosity



This chart gives a variety of formation resistivity factor-to-porosity conversions. The proper choice is best determined by laboratory measurement or experience in the area. In the absence of this knowledge, recommended relationships are the following:

For soft formations (Humble formula):

$$F_R = \frac{0.62}{\phi^{2.15}}, \text{ or } F_R = \frac{0.81}{\phi^2}$$

For hard formations:

$$F_R = \frac{1}{\phi^m}$$

with appropriate cementation factor, m.

Example: $\phi = 6\%$ in a carbonate in which a cementation factor, m, of 2 is appropriate

Therefore, from chart,

$F_R = 280$

Isolated and Fracture Porosity

Por

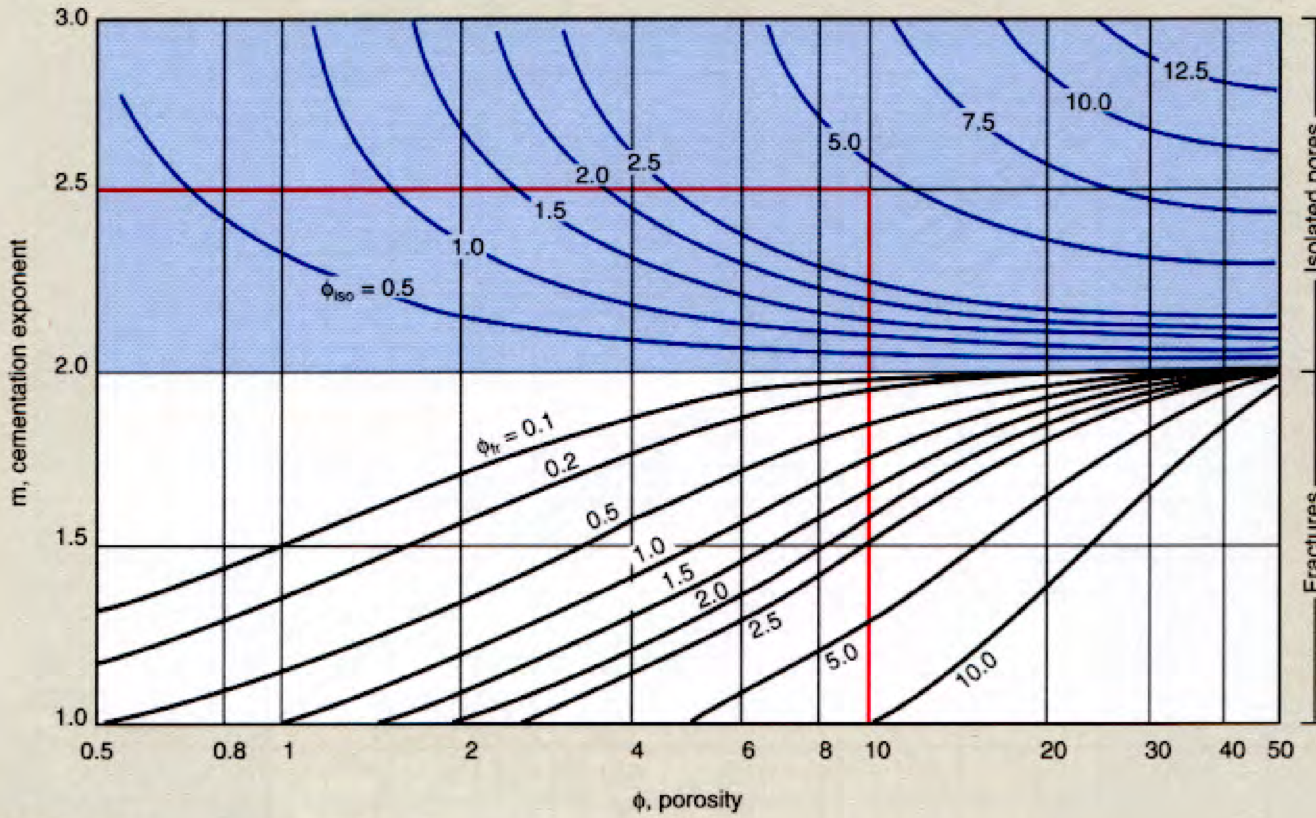


Chart Por-1a is based on a simplified model that assumes there is no contribution to formation conductivity from vugs and moldic porosity, and that the cementation exponent, m, of fractures is 1.0.

When the pores of a porous formation have an aspect ratio close to 1 (e.g., vugs or moldic porosity), the cementation exponent, m, of the formation will usually be greater than 2, while fractured formations generally have a cementation exponent less than 2.

If a value of m is available (from the interpretation of a log suite including a microresistivity measurement, such as a MicroSFL* log, and a dielectric measurement, such as an EPT* log, for example), Chart Por-1a can be used to estimate how much of the measured porosity is isolated porosity. In fractured formations, the apparent m obtained from a microresistivity measurement assumes total flushing and provides an upper limit for the amount of fracture porosity in the rock.

Entering the chart with the porosity, ϕ, and cementation exponent, m, gives an estimate of either ϕ_{iso}, the amount of isolated porosity, or ϕ_{fr}, the porosity resulting from fractures.

Example: ϕ = 10 p.u.
m = 2.5

Therefore, ϕ_{iso} = 4.5 p.u.

and intergranular porosity = 10 – 4.5 = 5.5 p.u.

See Reference 39 for more information about the use of this chart, and Reference 40 for a discussion of spherical pores.

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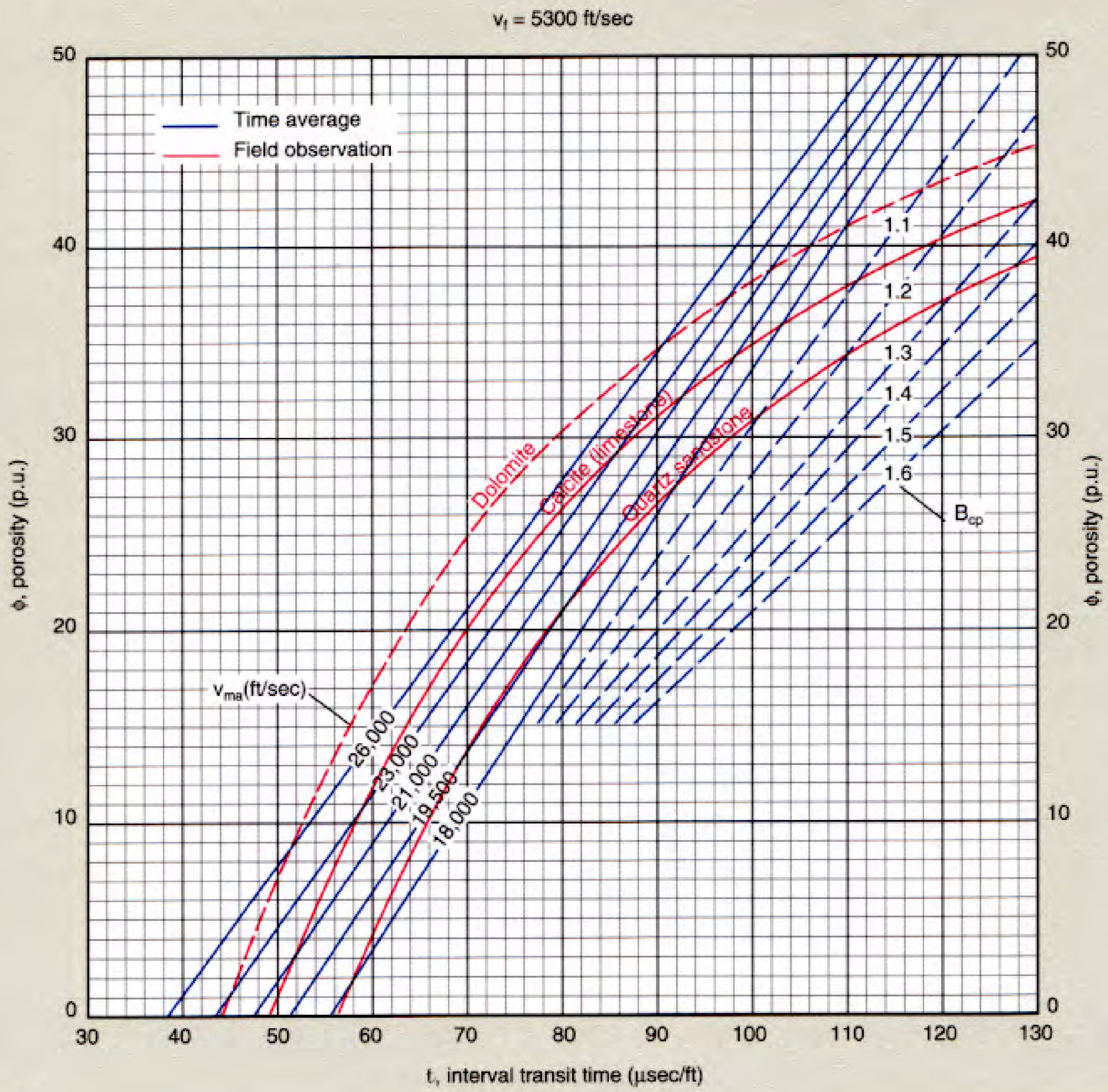
Porosity Evaluation from Sonic



These two charts (Por-3) convert sonic log interval transit time, t, into porosity, φ. Two sets of curves are shown. The blue set employs a weighted-average transform. The red set is based on empirical observation (see Reference 20). For both, the saturating fluid is assumed to be water with a velocity of 5300 ft/sec (1615 m/sec).

To use, enter the chart with the interval transit time from the sonic log. Go to the appropriate matrix velocity or lithology curve and read the porosity on the ordinate.

For rock mixtures such as limy sandstones or cherty dolomites, intermediate matrix lines may be required. When using the weighted-average transform in unconsolidated sand, a lack-of-compaction correction, B_{cp}, must be made. To accomplish this, enter the chart with the interval transit time; go to the appropriate compaction correction line, and read the porosity on the ordinate. If the compaction correction is unknown, it can be determined by working backward from a nearby clean water sand whose porosity is known.

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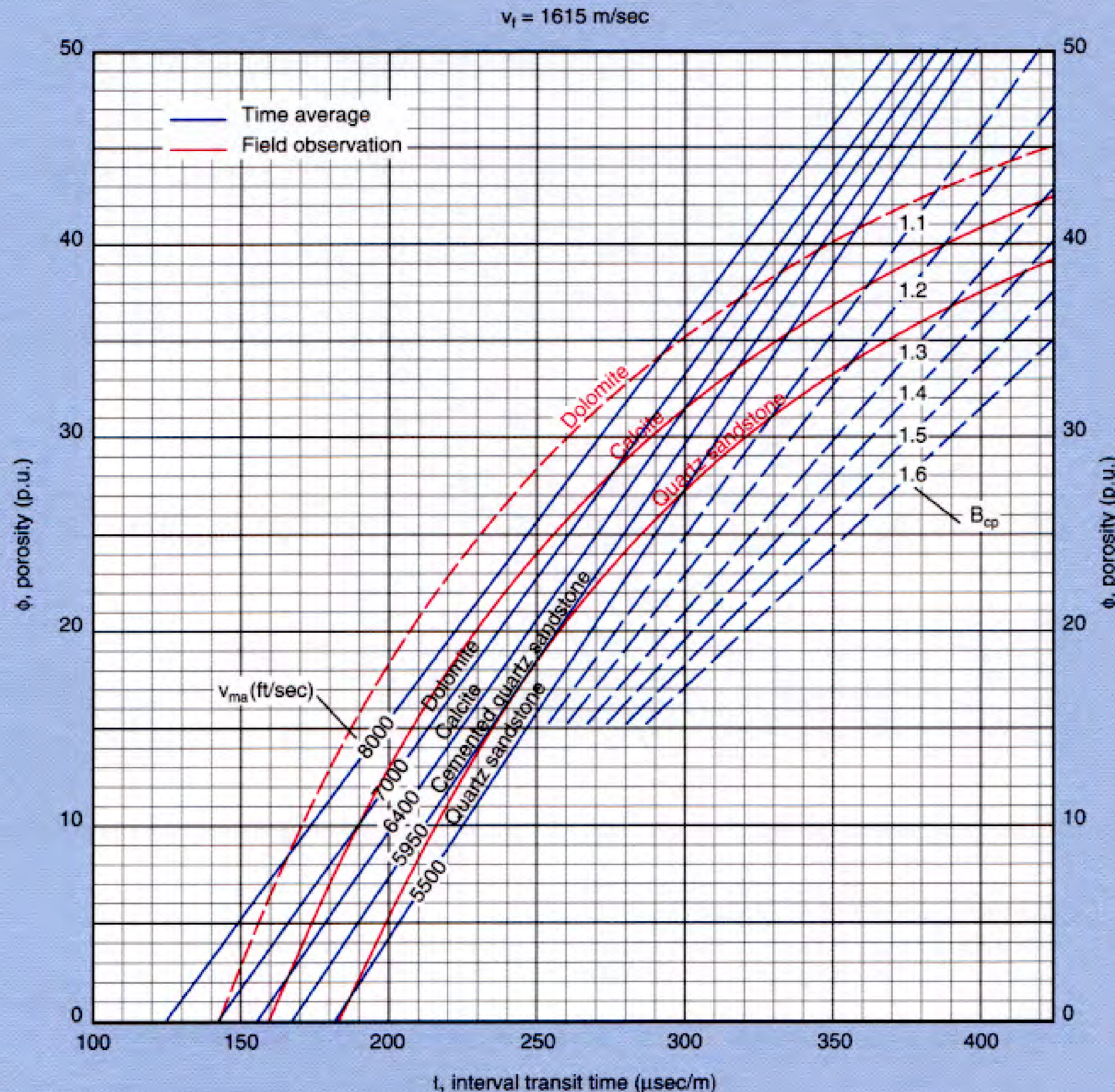
Porosity Evaluation from Sonic



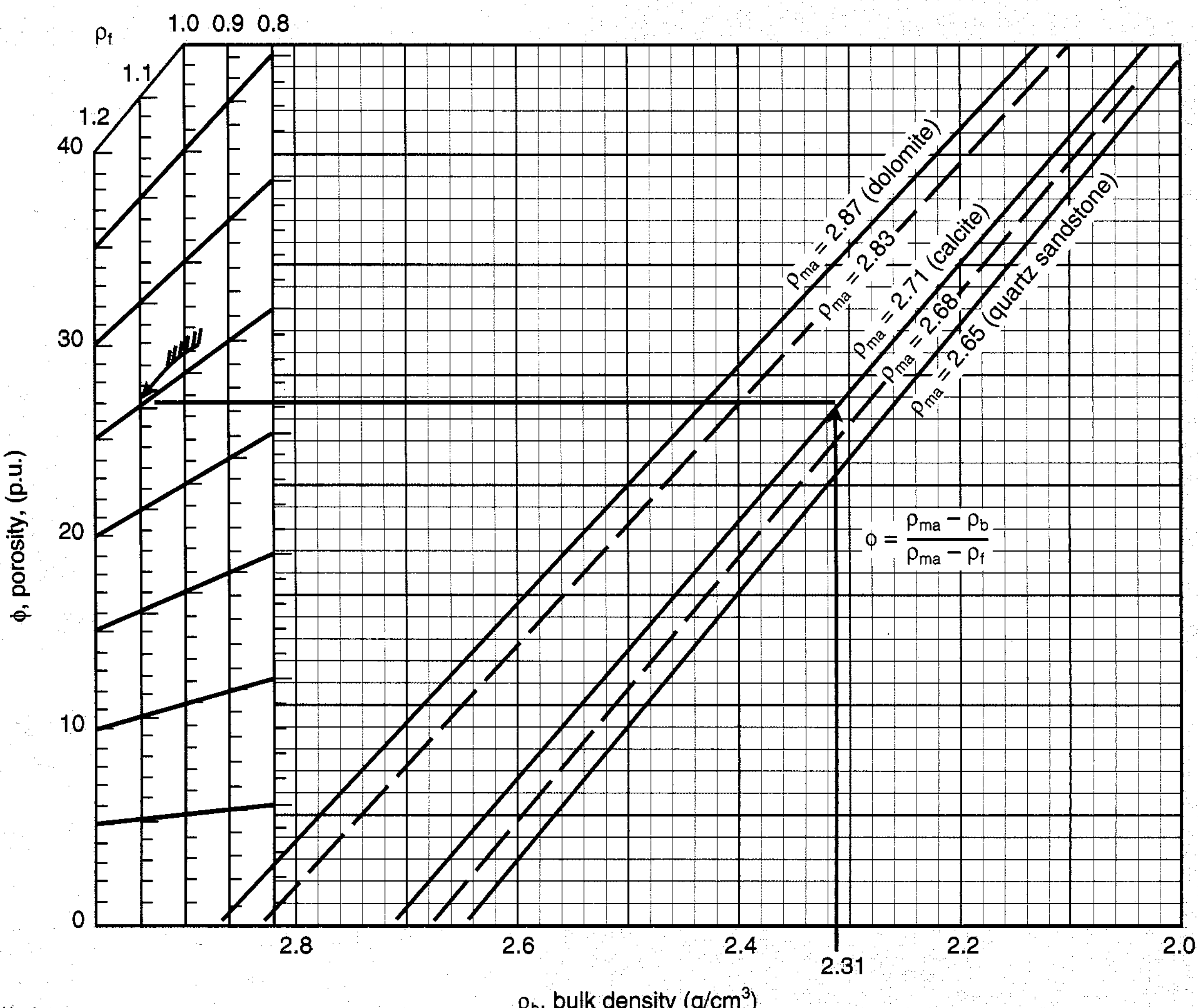
Example: t = 76 µsec/ft [249 µsec/m]
v_{ma} = 19,500 ft/sec [5950 m/sec]—sandstone

Therefore, φ = 18%
(by either weighted average or empirical transform)

For more information see References 18, 19 and 20.

Lithology	v_{ma} (ft/sec)	t_{ma} (µsec/ft)	v_{ma} (m/sec)	t_{ma} (µsec/m)
Sandstones	18,000–19,500	55.5–51.3	5486–5944	182–168
Limestones	21,000–23,000	47.6–43.5	6400–7010	156–143
Dolomites	23,000–26,000	43.5–38.5	7010–7925	143–126

Formation Density Log Determination of Porosity



Bulk density, ρ_b, as recorded with the FDC* Compensated Formation Density or Litho-Density* logs, is converted to porosity with this chart. To use, enter bulk density, corrected for borehole size, in abscissa; go to the appropriate reservoir rock type and read porosity on the appropriate fluid density, ρ_f, scale in ordinate. (ρ_f is the density of the fluid saturating the rock immediately surrounding the borehole—usually mud filtrate.)

Example: ρ_b = 2.31 g/cm^3 in limestone lithology
ρ_{ma} = 2.71 (calcite)
ρ_f = 1.1 (salt mud)

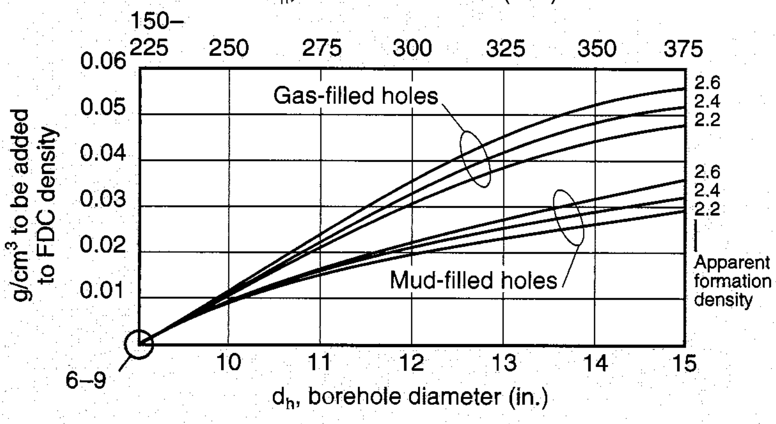
Therefore, ϕ_D = 25 p.u.

Environmental Corrections to Formation Density Log, Litho-Density* Log and Sidewall Neutron Porosity Log

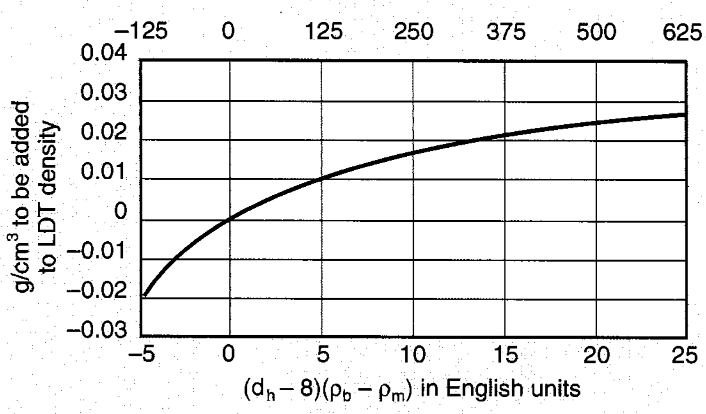
Under some circumstances, the FDC* Compensated Formation Density log and Litho-Density log must be corrected for borehole size, and the SNP sidewall neutron log must be corrected for mudcake thickness. These charts provide those corrections.

For the FDC log, enter the chart with borehole diameter, d_h. Go to the apparent formation density, ρ_b (FDC log density reading), and read, in ordinate, the correction to be added to the FDC log density reading.

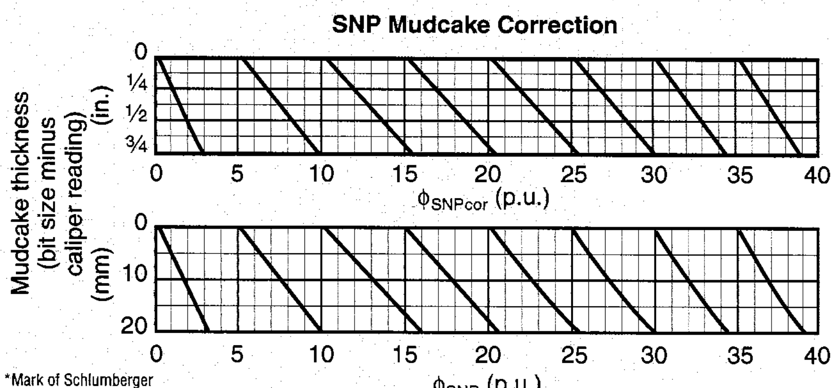
FDC Borehole Correction



Litho-Density Borehole Correction



SNP Mudcake Correction



Example: $d_h = 12$ in.
$\rho_b = 2.20$ g/cm^3 (mud-filled borehole)
Therefore, correction = 0.02 g/cm^3
$\rho_{bcor} = 2.20 + 0.02 = 2.22$ g/cm^3

For the LDT log, enter the chart abscissa with the product of the borehole diameter, d_h, less 8 in. [200 mm] and the LDT density reading, ρ_b, less mud density, ρ_m. Read, in ordinate, the correction to be added to the Litho-Density bulk density reading.

Example: $d_h = 325$ mm
$\rho_b = 2.45$ g/cm^3
$\rho_m = 1.05$ g/cm^3
giving $(d_h - 200)(\rho_b - \rho_m) =$
$(325 - 200)(2.45 - 1.05) = 175$
Therefore, correction = 0.014 g/cm^3
$\rho_{bcor} = 2.45 + 0.014 = 2.464$ g/cm^3

Note: If the borehole diameter from the FDC or LDT caliper is less than bit size, use the bit size in the above charts.

For the SNP log, enter the bottom of the chart with the SNP apparent porosity, ϕ_{SNP}; go vertically to the bit size minus caliper reading value; then, follow the diagonal curves to the top edge of the chart to obtain the corrected SNP apparent porosity.

Example: $\phi_{SNP} = 13$ p.u.
Caliper = 7⅝ in.
Bit size = 7⅞ in.
giving Bit size – caliper = 7⅞ – 7⅝ = ¼ in.
Therefore, $\phi_{SNPcor} = 11.3$ p.u.

Note: The full borehole diameter reduction shown on the SNP caliper is used as mudcake thickness, since the SNP backup shoe usually cuts through the mudcake.

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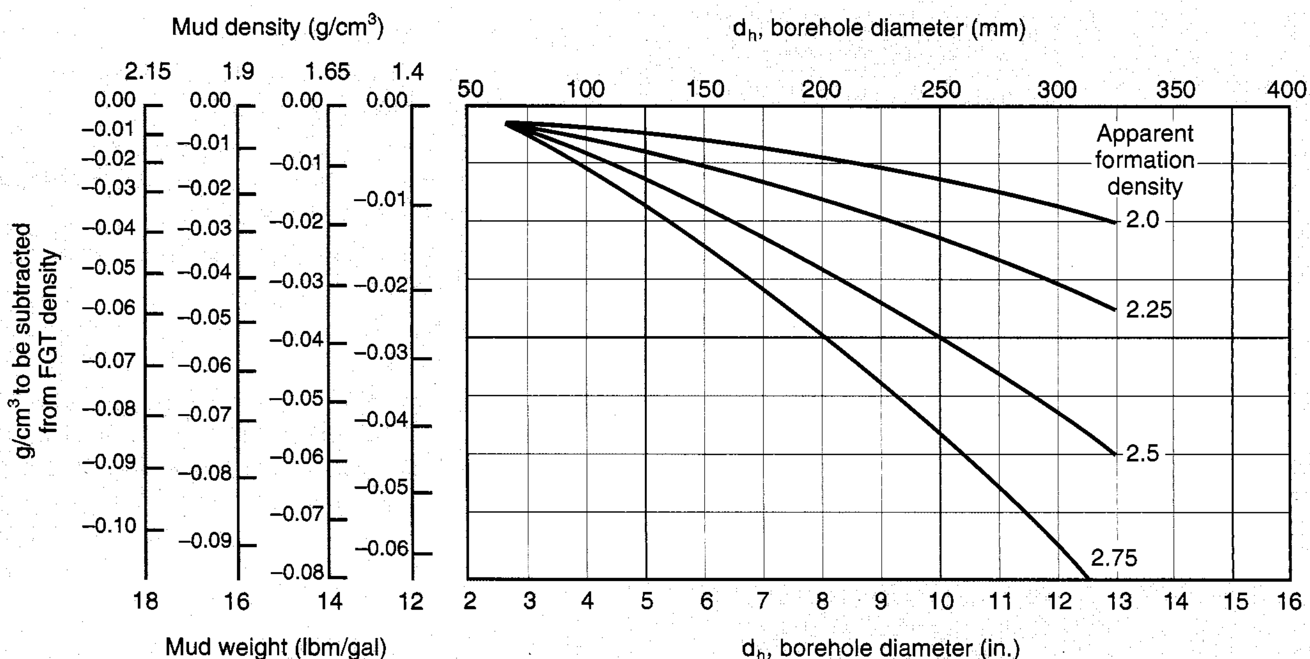
Environmental Corrections to FGT Density Log

FGT borehole correction



Borehole corrections of the slimhole 2¾-in. FGT formation density log can be made automatically by the logging unit. To determine if corrections have been made, refer to the log. "ALLO" (for allowed) following the constant "MWCO" indicates the FGT log was recorded with borehole correction. "DISA" (for disallowed) indicates that no borehole corrections were made.

In case the FGT log was recorded without automatic borehole correction, this chart provides the correction. Enter the chart abscissa with borehole diameter. Go to the apparent formation density and read in ordinate, as a function of mud weight, the correction to be subtracted from the FGT log bulk density reading.

Example: $\rho_b = 2.53$ g/cm³

$d_h = 260$ mm

Mud density = 1.65 g/cm³

Therefore, correction = –0.040 g/cm³

$\rho_{bcor} = 2.53 - 0.040 = 2.49$ g/cm³

Dual-Spacing CNL* Compensated Neutron Log Charts

This section contains interpretation charts to cover the latest developments in CNL Compensated Neutron Log porosity transforms, environmental corrections, and porosity and lithology determination.

CSU software (versions CP-30 and later) and MAXIS* software compute three thermal porosities: NPHI, TNPH and NPOR.

NPHI is our "classic NPHI," computed from instantaneous near and far count rates, using "Mod-8" ratio-to-porosity transform with a caliper correction.

TNPH is computed from deadtime-corrected, depth- and resolution-matched count rates, using an improved ratio-to-porosity transform and performing a complete set of environmental corrections in real time. These corrections may be turned on or off by the field engineer at the wellsite. For more information see Reference 32.

NPOR is computed from the near-detector count rate and TNPH to give an enhanced resolution porosity. The accuracy of NPOR is equivalent to the accuracy of TNPH if the environmental effects on the near detector change less rapidly than the formation porosity. For more information on enhanced resolution processing, see Reference 35.

Cased hole CNL logs are recorded on NPHI, computed from instantaneous near and far count rates, with a cased hole ratio-to-porosity transform. Chart Por-14a should be used for environmental corrections.

Using the neutron correction charts

For logs labeled NPHI:

1. Enter Chart Por-14e with NPHI and caliper reading to convert to uncorrected neutron porosity.
2. Enter Charts Por-14c and -14d to obtain corrections for each environmental effect. Corrections are summed with the uncorrected porosity to give a corrected value.
3. Enter corrected porosity in Chart Por-13b for conversion to sandstone or dolomite.
4. Use Crossplots CP-1e, -1f, -2c and -2cm for porosity and lithology determination.

For logs labeled TNPH or NPOR, the CSU/MAXIS software has applied environmental corrections as indicated on the log heading. Refer to Charts Por-14c and -14d to gain an appreciation for the relative importance of each correction prior to using crossplot charts. If the CSU/MAXIS software has applied all corrections, TNPH or NPOR can be used directly with the crossplot charts. In this case, follow these steps:

1. Enter TNPH or NPOR in Chart Por-13b for conversion to sandstone or dolomite.
2. Use Crossplots CP-1e, -1f, -2c and -2cm to determine porosity and lithology.

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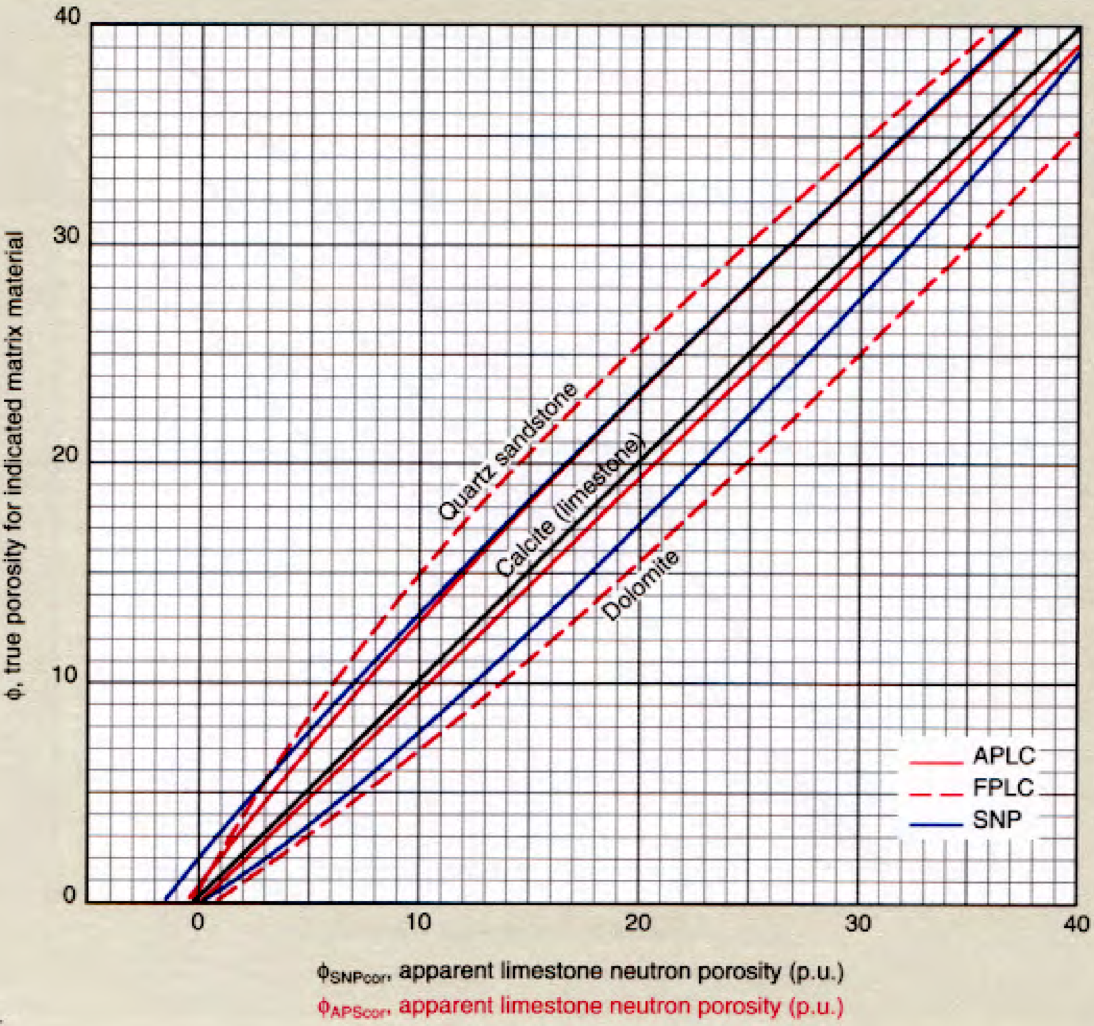
Epithermal Neutron Porosity Equivalence Curves

Sidewall Neutron Porosity (SNP) log;
Accelerator Porosity Sonde (APS) Near-to-Array (APLC) and Near-to-Far (FPLC) logs



When the APS or SNP log is recorded in limestone porosity units, this chart is used to find porosity in sandstones or dolomites. First, correct the SNP log for mudcake thickness (Chart Por-15a).

This chart can also be used to find apparent limestone porosity (needed for entering the various CP crossplot charts) if the APS or SNP recording is in sandstone or dolomite porosity units.

Example: Sandstone bed

ϕ_{SNP} = 13 p.u. (apparent limestone porosity)

Bit size = 7⅞ in.

SNP caliper = 7⅝ in.

giving h_{mc} = ¼ in.

ϕ_{SNP} = 11.3 p.u. (corrected for mudcake)

and ϕ_{SNP} (sandstone) = 14.5 p.u.

Thermal Neutron Porosity Equivalence Curves

CNL* Compensated Neutron Log; TNPH and NPHI porosity logs

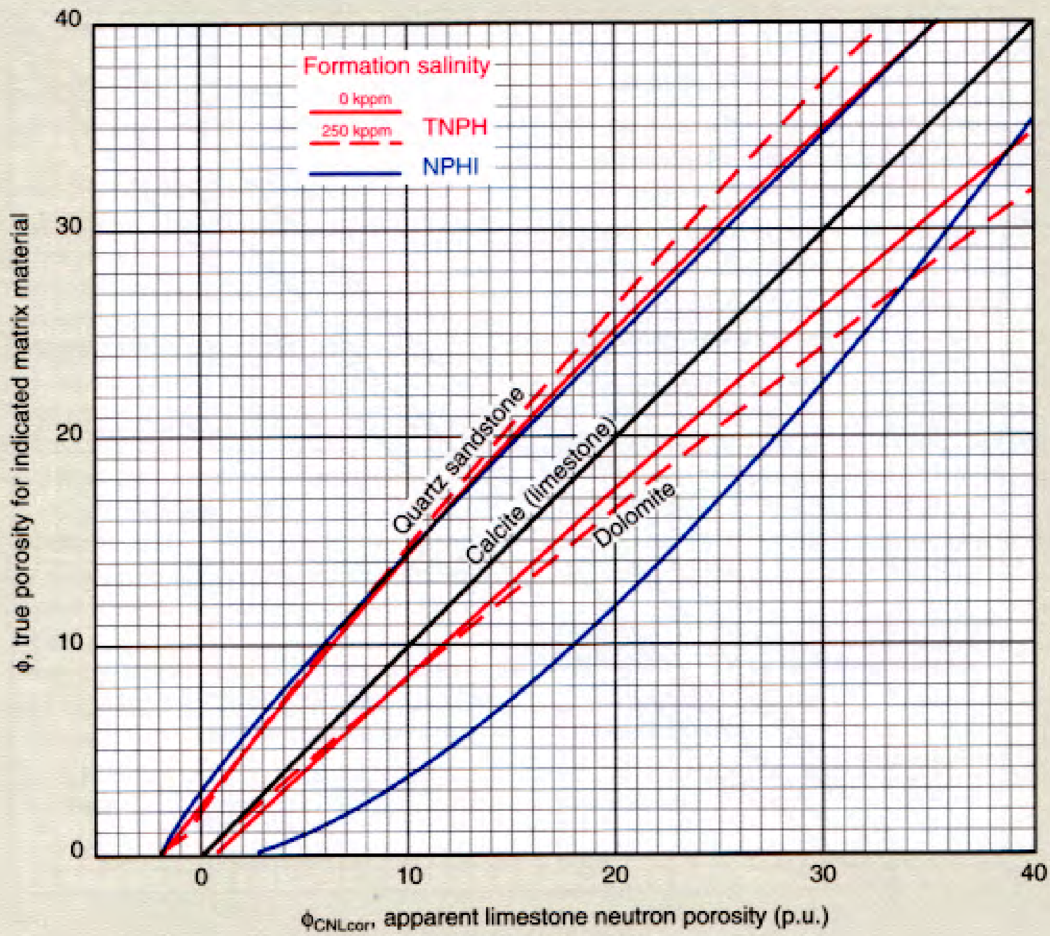


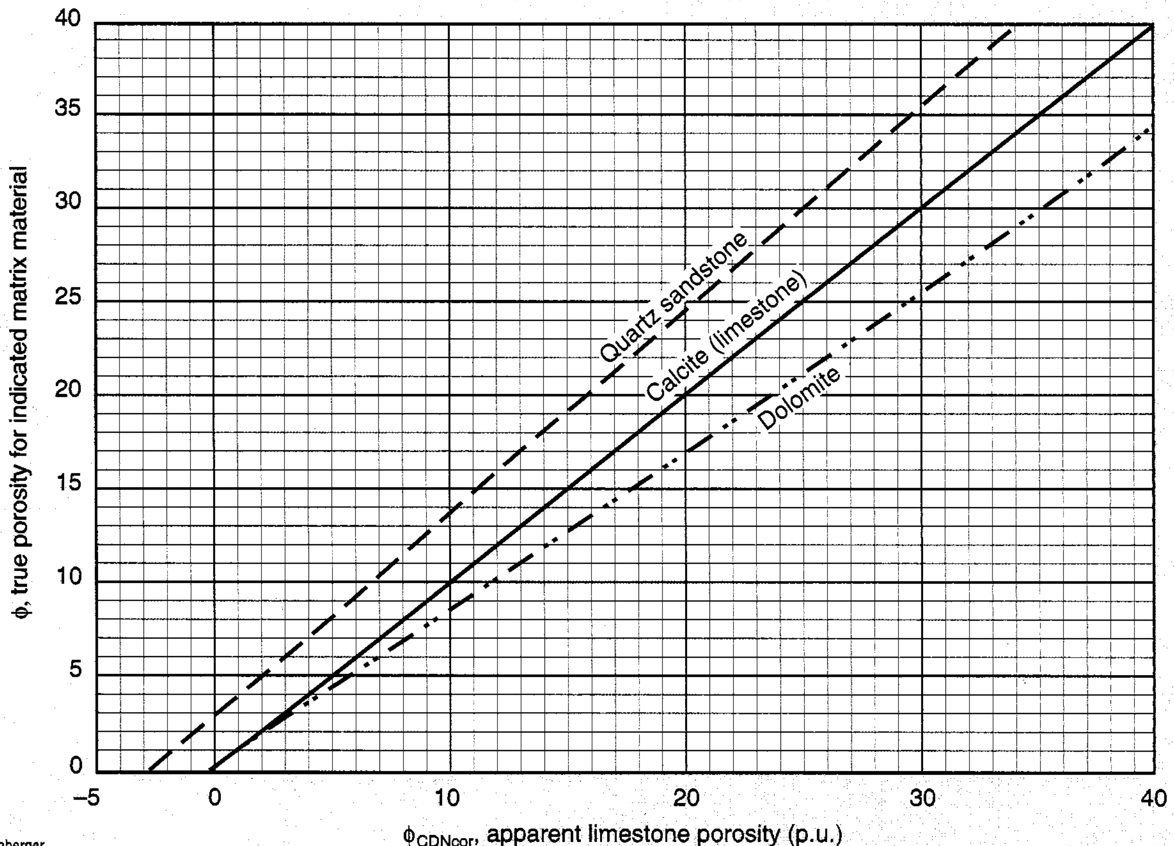
Chart Por-13b can be used in the same way as Chart Por-13a, on the previous page, to convert CNL porosity logs (TNPH or NPHI) from one lithology to another. If a log is recorded in limestone porosity units in a pure quartz sandstone formation, the true porosity can be derived.

Example: Quartz sandstone formation
TNPH = 18 p.u. (apparent limestone porosity)
Formation salinity = 250 kppm

giving True porosity in sandstone = 24 p.u.

LWD Neutron Porosity Equivalence Curves

6.5-in. CDN* Compensated Density Neutron tool



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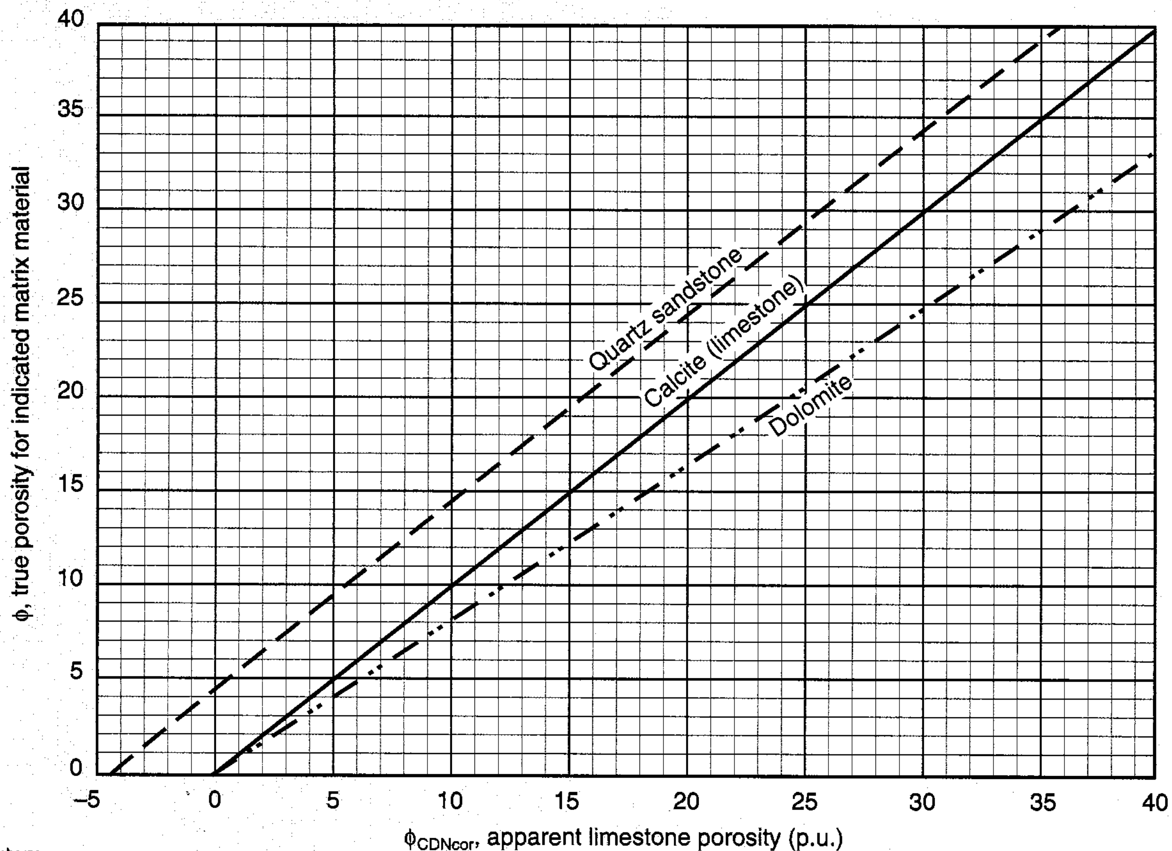
LWD Neutron Porosity Equivalence Curves

8-in. CDN* Compensated Density Neutron tool



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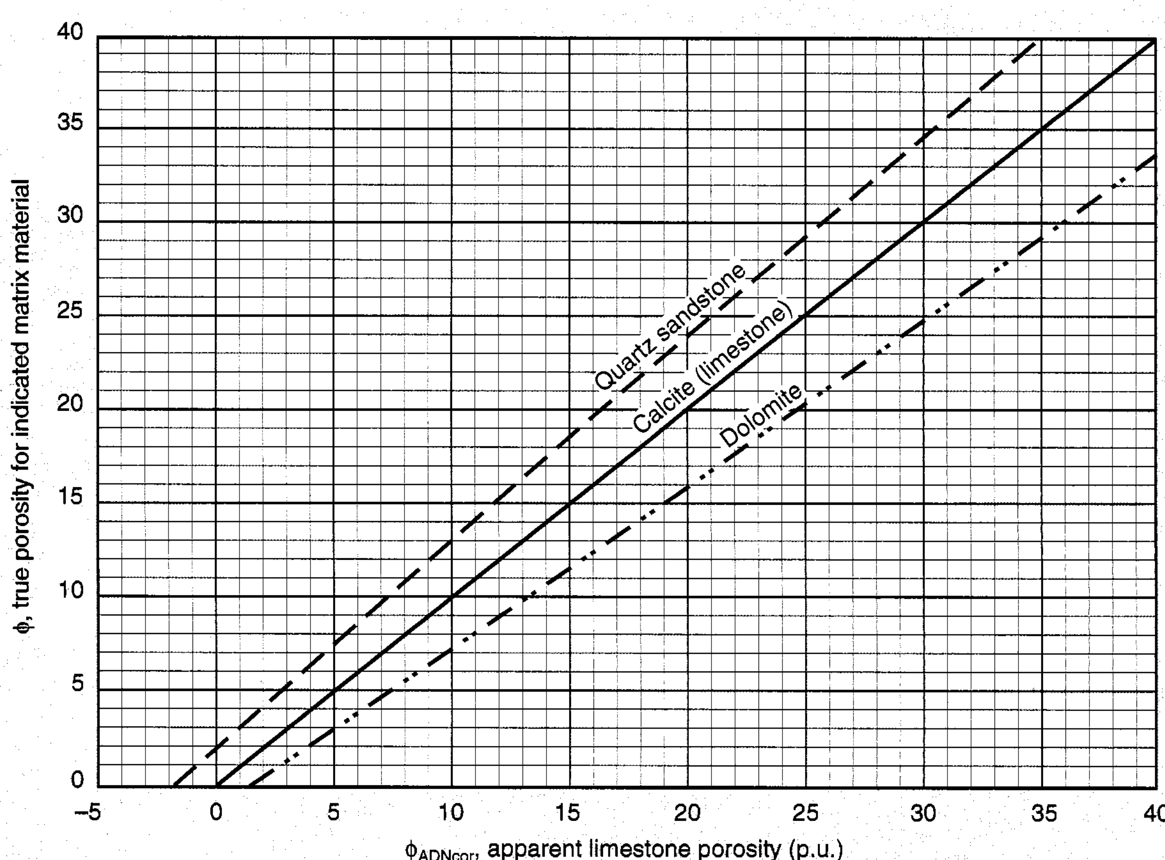
LWD Neutron Porosity Equivalence Curves

6.75-in. ADN* Azimuthal Density Neutron tool



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Dual-Spacing CNL* Compensated Neutron Log Environmental Corrections for Cased Hole

The nomographs of Charts Por-14 provide environmental corrections for the CNL Compensated Neutron Log when run in cased hole or openhole. Before using the nomographs, CNL log values must be corrected for matrix effect (Chart Por-13b).

Cased hole (Chart Por-14a)

For cased hole logs, enter the appropriate Chart Por-14a with the matrix-corrected CNL reading; draw a vertical line through the chart blocks. Find the corrections, relative to the reference lines (dashed lines indicated with asterisks), for each block. Then, go to Chart Por-14c, and starting with the borehole salinity block, continue through the remaining blocks. Algebraically sum all the corrections to obtain the correction to the CNL reading.

Example: ϕ_{CNL} = 27 p.u. (matrix corrected)
Borehole size = 10 in.
Casing thickness = 0.255 in.
Cement thickness = 1.4 in.
giving $\Sigma\Delta\phi = -1.0 + 0.3 + 0.5 + \ldots$

This provides casing, cement and borehole corrections for the cased hole CNL log. Continue to Chart Por-14c for salinity, borehole fluid, pressure and temperature corrections.

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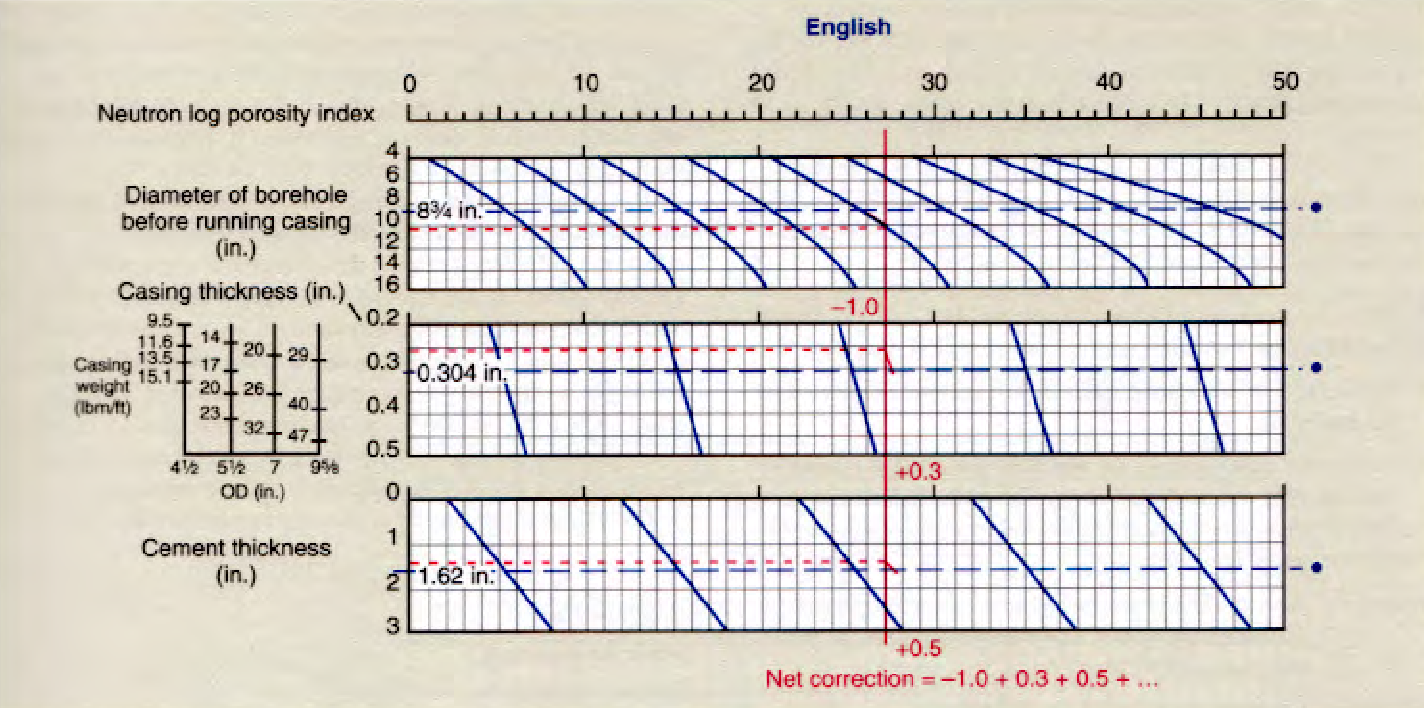
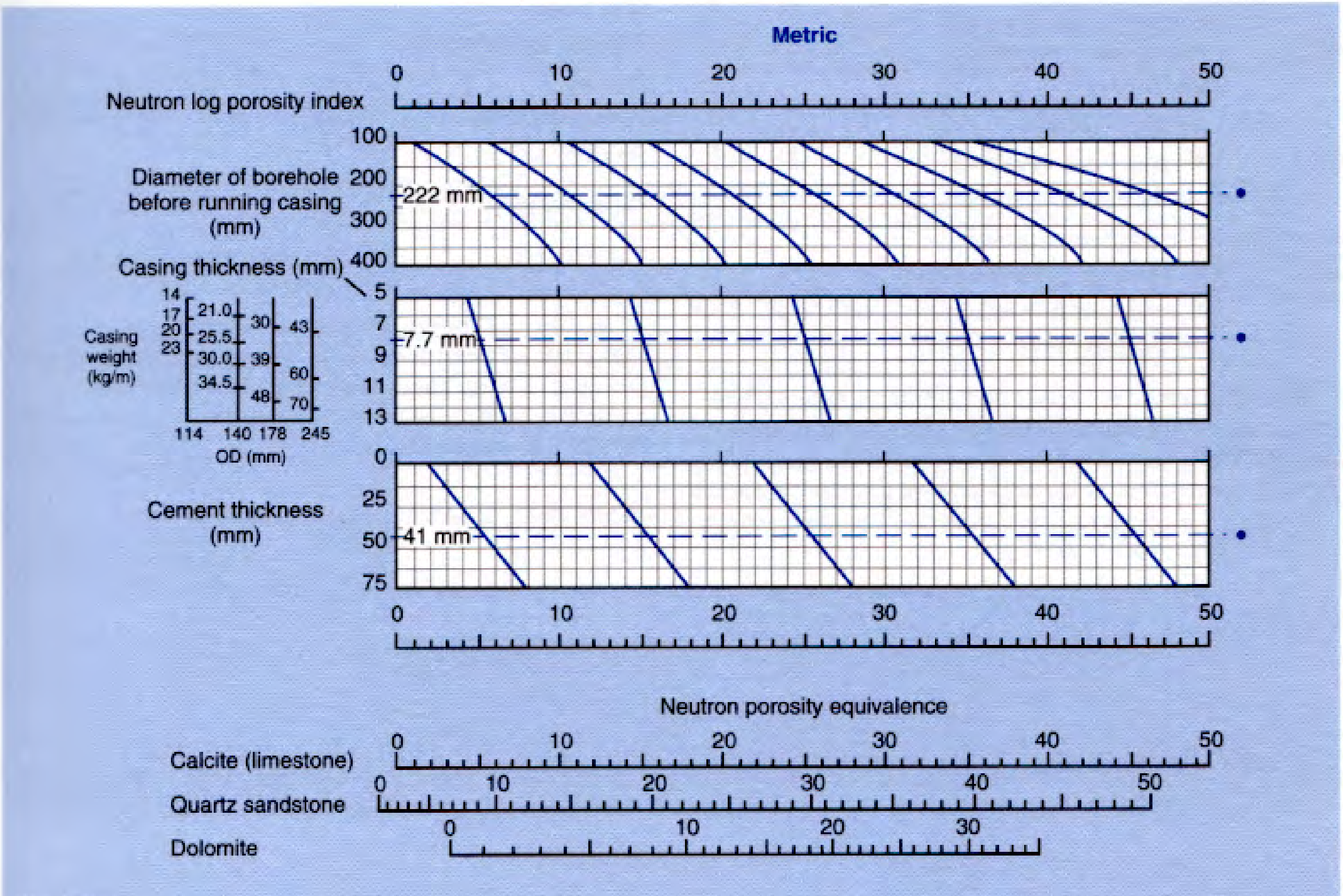
Dual-Spacing CNL* Compensated Neutron Log Correction Nomograph for Cased Hole





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• Reference lines indicated by bullets

Dual-Spacing CNL* Compensated Neutron Log Correction Nomograph for Openhole

The CNL tool is normally run with only a caliper correction applied. Refer to the CNL log heading to determine whether the log was run with or without automatic caliper correction. To use Charts Por-14c and -14d, this borehole correction must be removed.

The way the "automatic" borehole correction is "backed out" depends on whether the NPHI or TNPH and NPOR curves are used. With NPHI, the correction is backed out with Chart Por-14e. For TNPH or NPOR, follow these steps:

1. Enter the top block of Chart Por-14c or -14d, labeled "actual borehole size," with the matrix-corrected CNL porosity.
2. Go to the 8-in. standard condition borehole size indicated by the bullet (•).
3. Follow the trend lines to the borehole size used to correct the log—usually the caliper reading. This value is the uncorrected TNPH value, which should be used to determine the rest of the environmental corrections.

Example: Assume TNPH on the log was 32 p.u. (apparent limestone units) in a 12-in. borehole. This gives an uncorrected TNPH of 34 p.u.

The rest of the example assumes the following:

Uncorrected neutron porosity = 34 p.u. (apparent limestone units)
12-in. borehole
¼-in. thick mudcake
100-kppm borehole salinity
11-lbm/gal mud weight (natural mud)
150°F borehole temperature
5-kpsi pressure (water-base mud)
100-kppm formation salinity
½-in. standoff

Enter Charts Por-14c, -14cm, -14d and -14dm at the top with the uncorrected log reading in apparent limestone units, and project a line downward through all the correction nomographs. For each correction, enter the environmental parameter at the left of the nomograph and project a line to the right. Then, follow the trend lines from the intersection of the uncorrected porosity reading and the environmental parameter to the intersection of the trend line and the standard condition (for example, for the borehole size correction, the trend line would be followed downward from 12 in. and 34 p.u. to intersect the 8-in. line at 32 p.u.).

The porosity reading where the trend line intersects the standard conditions is the corrected porosity considering only that effect; the difference between the corrected and uncorrected porosity values, or $\Delta\phi$, represents the magnitude of the correction for each environmental effect. Since several environmental effects are usually made, a net correction to the uncorrected log reading is computed by summing the individual $\Delta\phi$'s for all effects. Once the net correction has been determined, it is added to the uncorrected log value to obtain the environmentally corrected neutron porosity in apparent limestone units.

For the conditions listed above, the corrections are

	$\Delta\phi$
Borehole size	–2¾ p.u.
Mudcake thickness	≈0
Borehole salinity	+1
Mud weight	+1½
Borehole temperature	+4
Pressure	–1
Formation salinity	–3
Standoff	–2
Net correction	–2¼
Corrected porosity	34 p.u. – 2¼ p.u. = 31¾ p.u. (apparent limestone units)

The "oil mud" curves in the pressure correction panel are appropriate for liquid components whose compressibility is four times that of water. The correction for other cases can be obtained by multiplying the WBM correction by the ratio of the OBM/WBM compressibilities.

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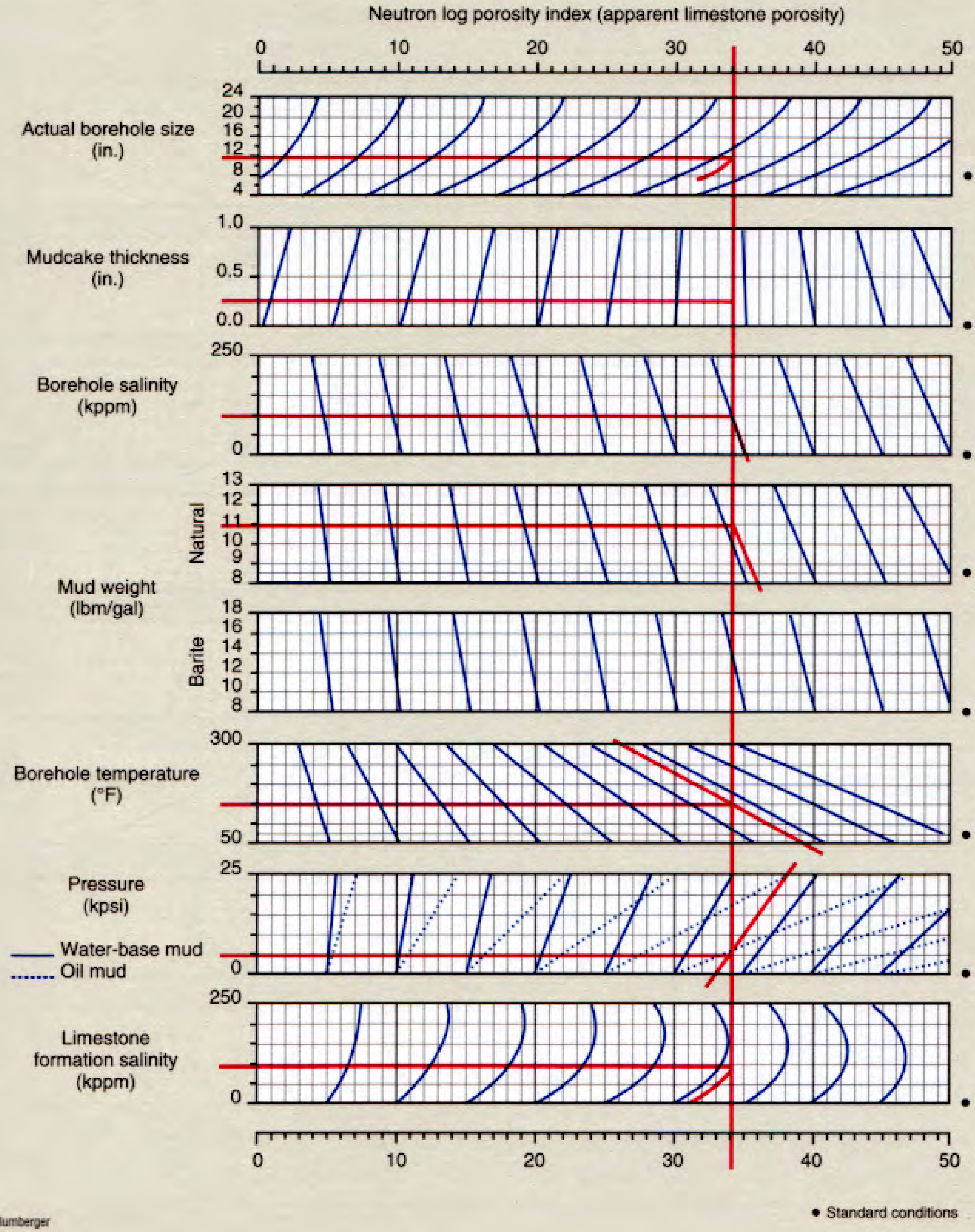
Dual-Spacing CNL* Compensated Neutron Log Correction Nomograph for Openhole

For CNL curves without environmental corrections

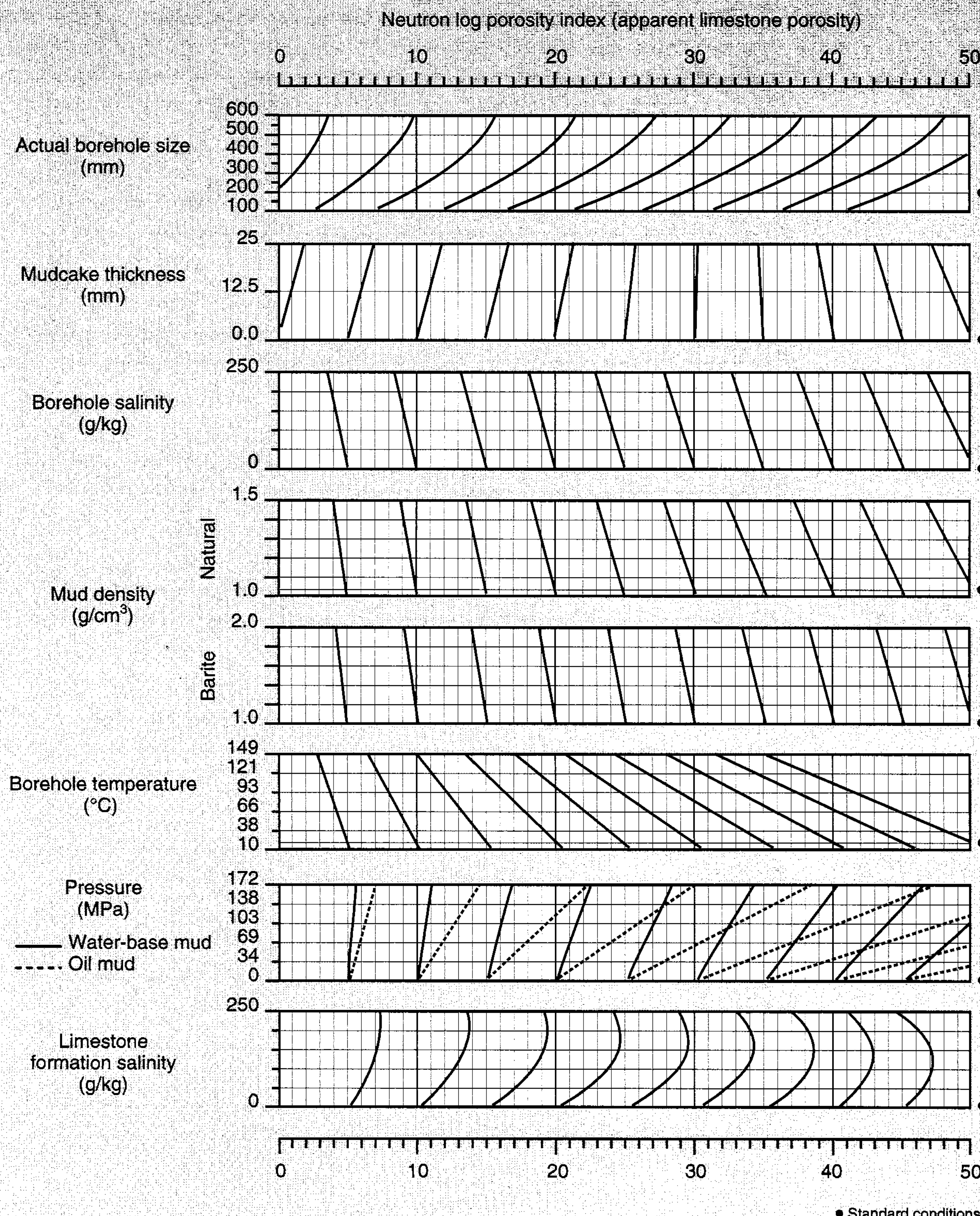


Por

Dual-Spacing CNL* Compensated Neutron Log Correction Nomograph for Openhole

For CNL curves without environmental corrections

Por-14cm (Metric)



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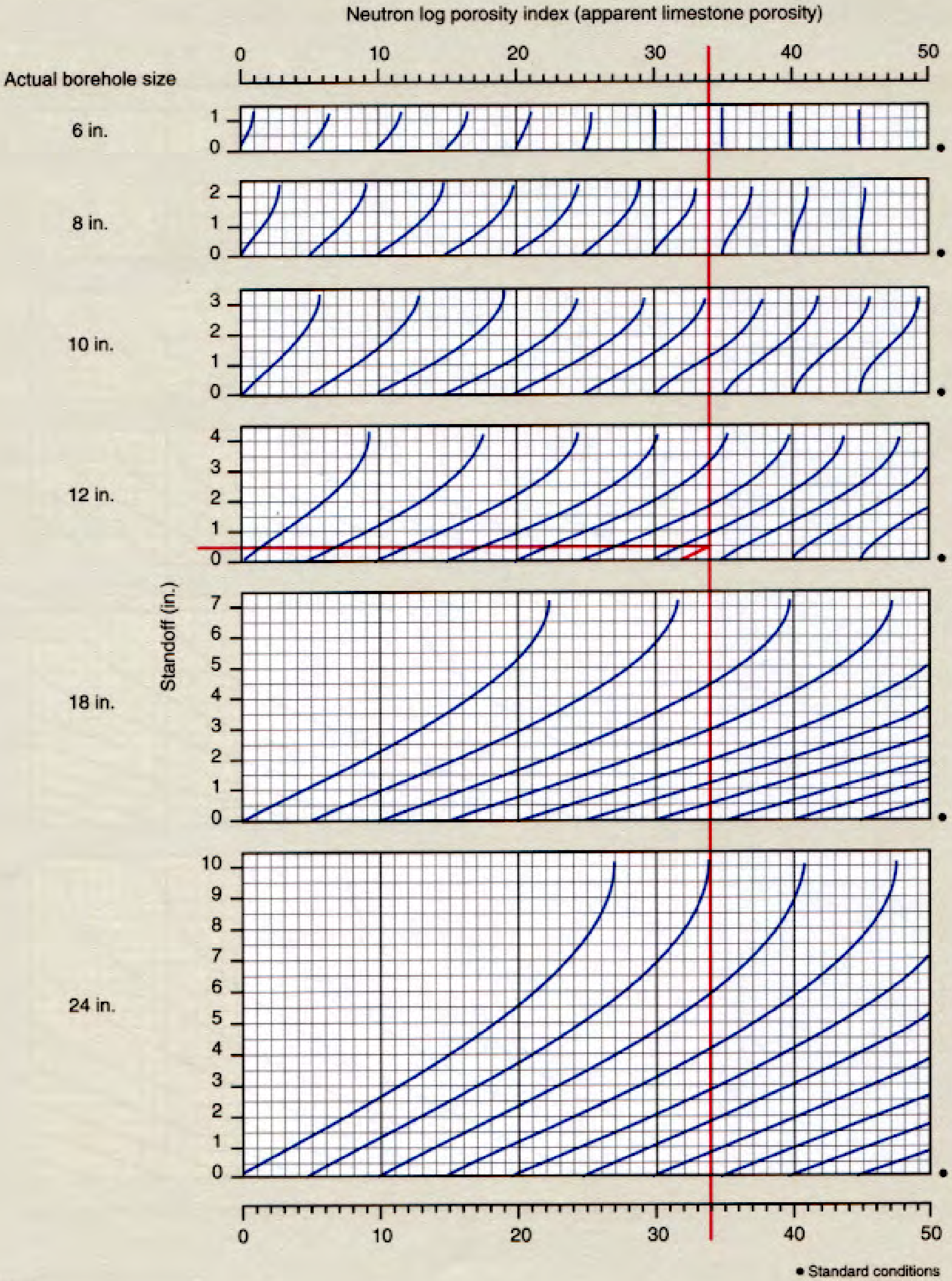
Dual-Spacing CNL* Compensated Neutron Log Standoff Correction Nomograph for Openhole

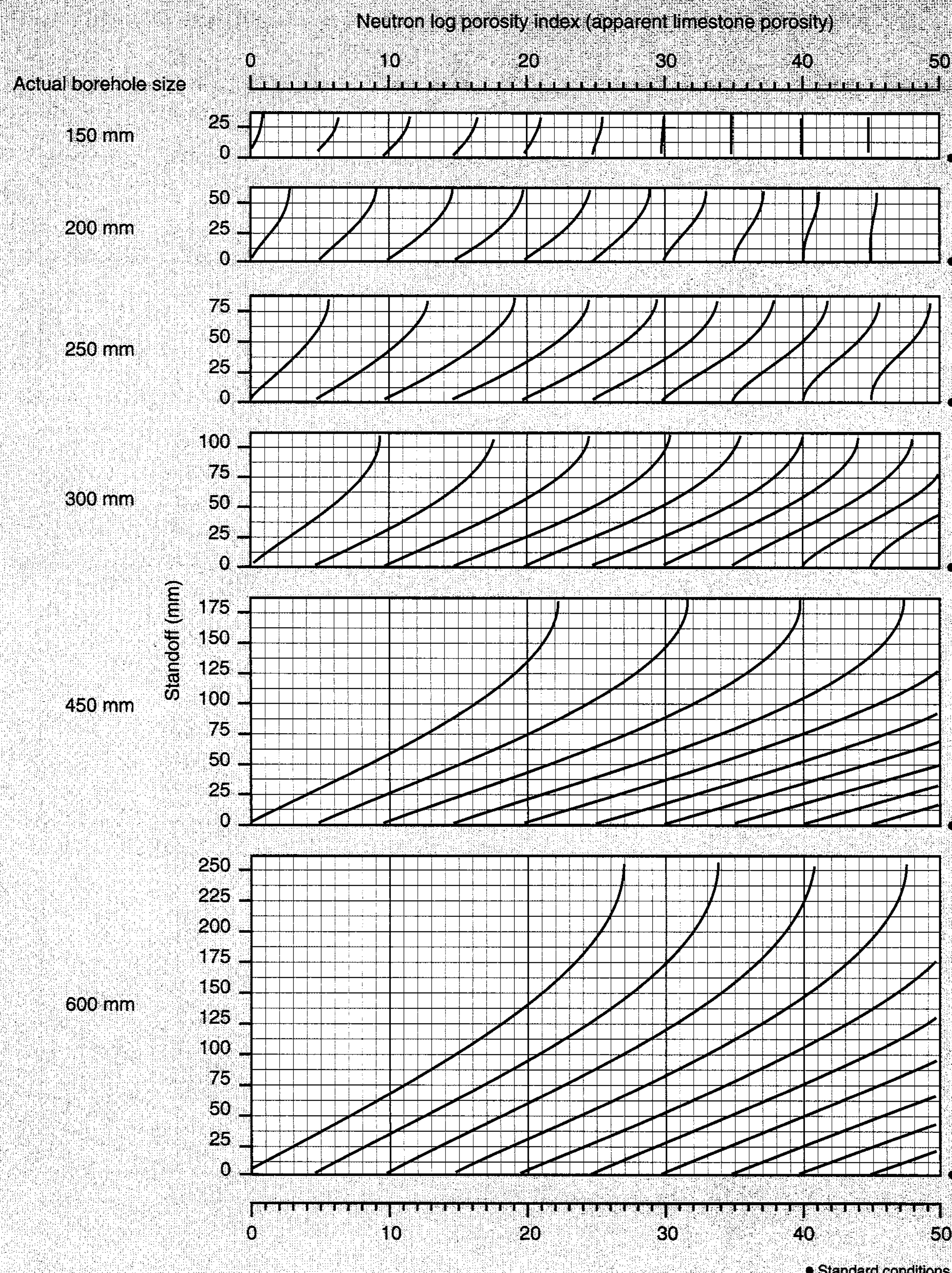
For CNL curves without environmental corrections

Por-14d
(English)



Dual-Spacing CNL* Compensated Neutron Log Standoff Correction Nomograph for Openhole

For CNL curves without environmental corrections



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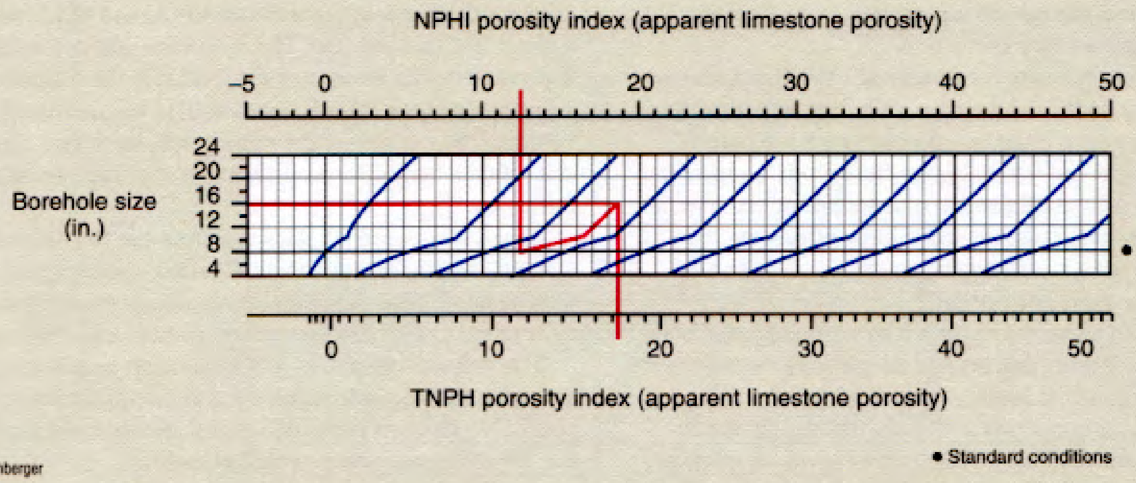
Dual-Spacing CNL* Compensated Neutron Log NPHI-TNPH Conversion Nomograph for Openhole



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Example: NPHI = 12.5 p.u.
Caliper = 16 in.

Enter the chart from the top at 12.5 p.u.; drop down to 7⅞-in. hole size, labeled with a bullet (•) for standard conditions. Follow the trend lines upward to 16 in. From that point drop straight down to the TNPH scale and read the uncorrected TNPH = 17.25 p.u.

If NPHI is recorded in units other than limestone units, it must be converted using Chart Por-13 before it can be used in this chart. The NPHI scale is for use with logs recorded after January 1976.

Accelerator Porosity Sonde (APS) Corrections

Openhole APLU and FPLU logs

Epithermal neutron detection with borehole-shielded detectors considerably reduces the environmental effects on the APS response and simplifies their correction.

The near-to-array porosity measurement (APLU in apparent limestone porosity units) and the near-to-far porosity measurement (FPLU in apparent limestone porosity units) require different mud weight and borehole size corrections, so there are individual sets of correction nomographs for each measurement. Formation temperature, pressure and salinity effects are, however, the same on each measurement, so there is only one set of nomographs for these corrections.

Chart Por-23a includes corrections for mud weight and borehole size for near-to-array and near-to-far porosity measurements in both English and metric units.

The borehole size correction is slightly mudweight dependent, even with natural muds, so there are two sets of splines—solid lines for light muds (8.345 lbm/gal) and dashed lines for heavy muds (16 lbm/gal). Intermediate mud weights can be interpolated.

The nomograph for formation temperature, pressure and formation salinity correction of both APLU and FPLU curves appears in Chart Por-23b. The formation salinity correction is dependent on the amount of salt (NaCl) in the formation. This is a function of both the salinity of fluid in the formation and its volume. The last part of the nomograph, therefore, applies to the correction a multiplier proportional to the true porosity of the formation.

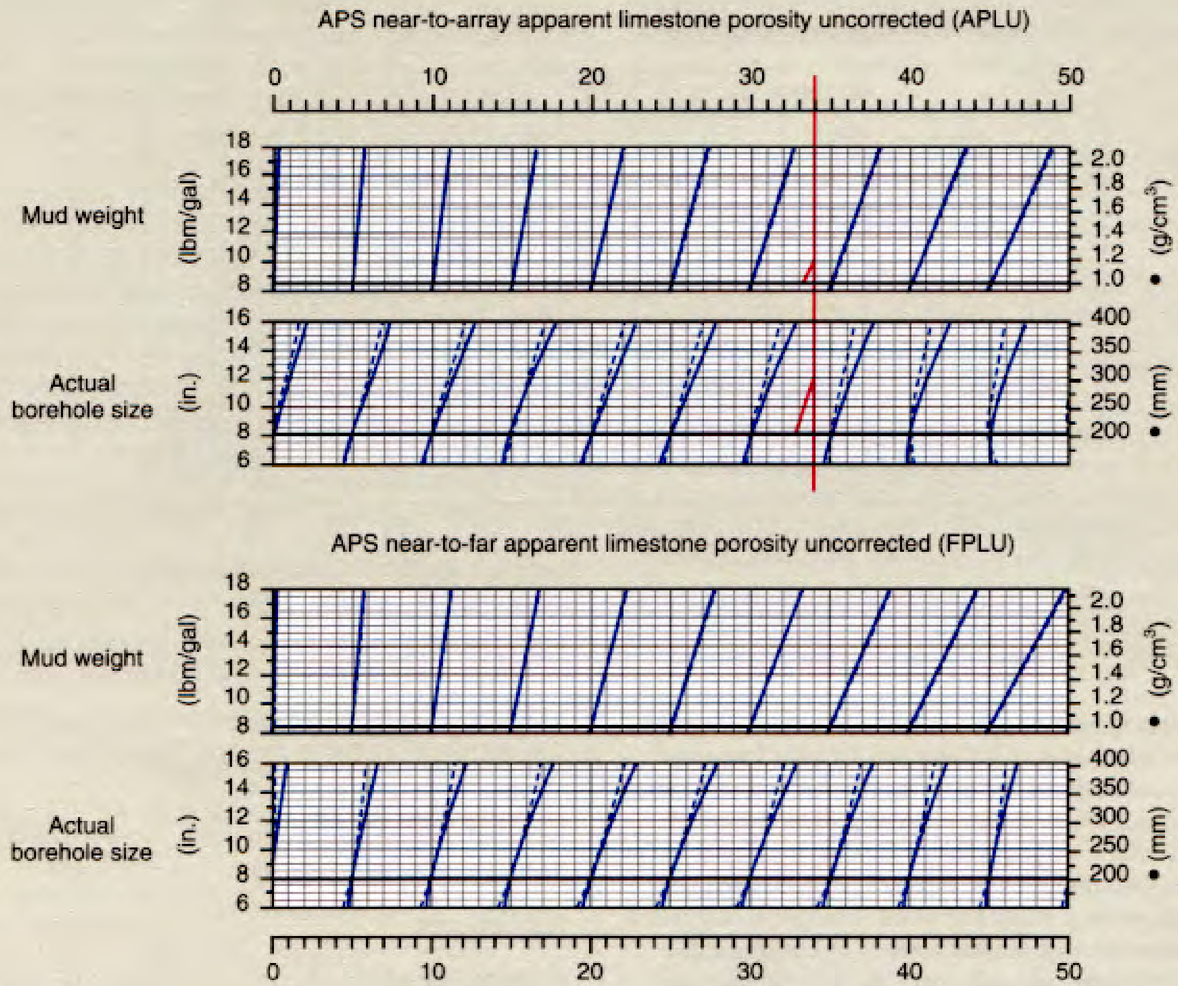
Standoff between the APS detectors and the formation is computed from measurements acquired while logging. This real-time standoff measurement allows realistic standoff corrections to be made to the porosity measurements for the first time.

The standoff correction is automatically applied during acquisition but is difficult to represent accurately on two-dimensional charts. No standoff correction charts are currently available, so the automatic correction should be used.

Continued on next page

Openhole APS Corrections for Mud Weight and Borehole Size

For APLU and FPLU curves without environmental correction



Charts Por-23a and -23b are used to apply environmental corrections to APLU and FPLU measurements.

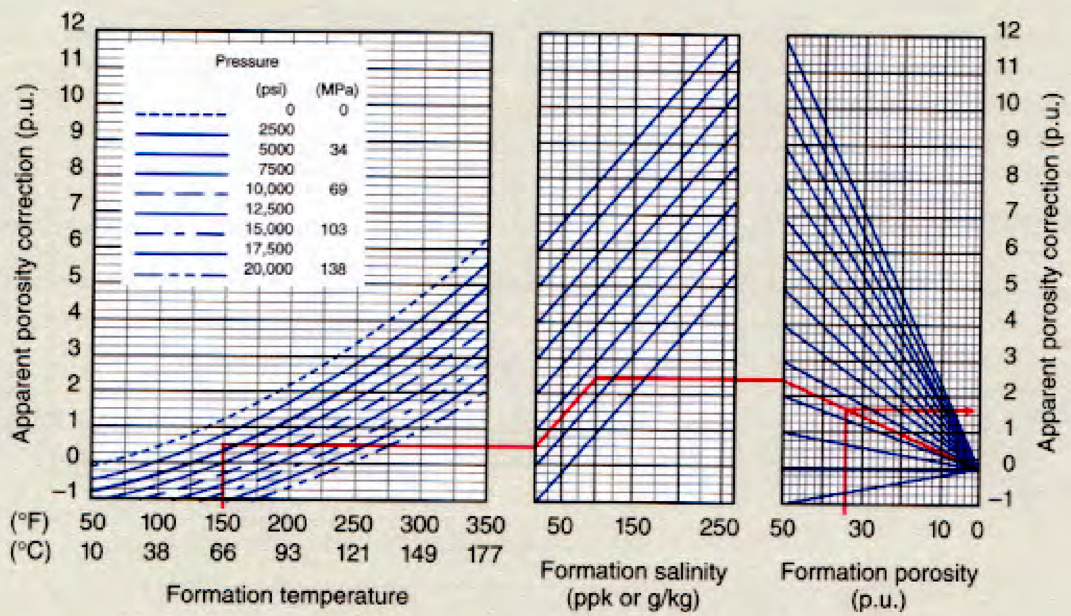
Enter at the top of each nomograph on Chart Por-23a with the relevant uncorrected log reading in apparent limestone units and project a line down through the nomographs. For each correction to be applied, enter the environmental parameter at the left of the nomograph if using English units or at the right if using metric units. Draw a horizontal line to meet the uncorrected log reading, then follow the direction of the trend lines downward to meet the standard condition (for example, 8 in. for the borehole size correction). At this point, you will have moved to the left (minus) or the right (plus) by a distance readable on the porosity scale. Make a note of this correction, $\Delta\phi$, to be applied to the uncorrected log reading for that environmental effect.

Since several small corrections are usually made for different environmental effects, including mud weight and borehole size using Chart Por-23a, and formation temperature, pressure and formation salinity using Chart Por 23b, the small corrections, $\Delta\phi$, for each relevant environmental effect are added together.

Continued on next page

Openhole APS Corrections for Temperature, Pressure and Formation Salinity

For APLU and FPLU curves without environmental corrections



For pressure, temperature and salinity corrections, enter the bottom of the left-hand part of Chart Por-23b with formation temperature, and project a line up to the relevant pressure curve. Draw a horizontal line to the left-hand edge of the formation salinity part of the nomograph, then follow the trend lines to the correct formation salinity. Draw another horizontal line to the left-hand edge of the porosity part of the nomograph, and follow the trend lines to the approximate porosity. A horizontal line from here to the right-hand scale gives the apparent porosity correction, $\Delta\phi$, to be applied for temperature, pressure and salinity effects. If the correction, $\Delta\phi$, given by Chart Por-23b is large and the first estimate of porosity is incorrect, it may be necessary to reiterate this correction with an improved porosity estimate.

Example: Assume an uncorrected APLU = 34 p.u. (apparent limestone porosity)

Borehole size = 12 in.

Mud weight = 11 lbm/gal

Borehole temperature = 150°F

Pressure = 5 kpsi

Formation salinity = 100 kppm

Then, using Chart Por-23a,

	$\Delta\phi$
Mud weight correction (none)	–0.7
Borehole size (interpolate mud weight)	–1
and using Chart Por-23b,	
Temperature/pressure/salinity	+1†
Net correction	–0.7
Corrected porosity	34 p.u. – 0.7 p.u. = 33.3 p.u. (apparent limestone units)

The overall correction is small. If this is a limestone formation, the first estimate of porosity used in Chart Por-23b is good and no reiteration is required.

† The apparent porosity correction is a true hydrogen index correction. Recent detailed saltwater measurements indicate that the red correction is slightly smaller than this. It is therefore recommended the apparent correction be multiplied 0.70 for APLU values and by 0.78 for FPLU curves.

Dual-Spacing CNL* Compensated Neutron Log Formation Σ Correction Nomograph for Openhole

When measured formation Σ data are available, Chart Por-16 may be used for correcting thermal neutron porosity from the CNL log for the effect of total formation capture cross section. At the bottom of the chart, an additional nomograph is provided to correct the resulting porosity for salt displacement in cases where elevation of formation Σ is due to salinity. This chart can be used instead of the salinity correction on Chart Por-14c or Por-14cm. Do not use both charts.

In each of the lithology panels, the nominal situation for freshwater pore fluid is drawn to correspond to the values of Σ_{ma} of the formations used to calibrate the porosity response. For reference, the sloping dashed line indicates the value of Σ for the formations filled with salt-saturated water.

To use Chart Por-16, enter the apparent porosity and measured Σ into the appropriate lithology box. Follow the equiporosity trend lines down to the nominal Σ line, and read the corrected porosity there. If at least some of the Σ reading is caused by salt water, a correction for salt displacement is made as follows:

1. Enter the top of the formation salinity box at 0 ppm with the corrected porosity from the previous step.
2. Follow the equiporosity trend lines down to the known water salinity value, and read the final corrected porosity there.

If other environmental corrections are required, the amount of correction for formation Σ and formation salinity should be calculated by taking the difference between the final corrected and apparent porosity values. This difference can then be summed with corrections for other environmental effects to determine the total correction for all effects.

Example:

Given:	Apparent neutron porosity	37.9 p.u. (sandstone)
	Formation Σ from log	32.7 c.u.
	Formation water salinity	160.0 kppm
Results:	Porosity corrected for Σ	32.9 p.u. (sandstone)
	Final corrected porosity	35.0 p.u. (sandstone)

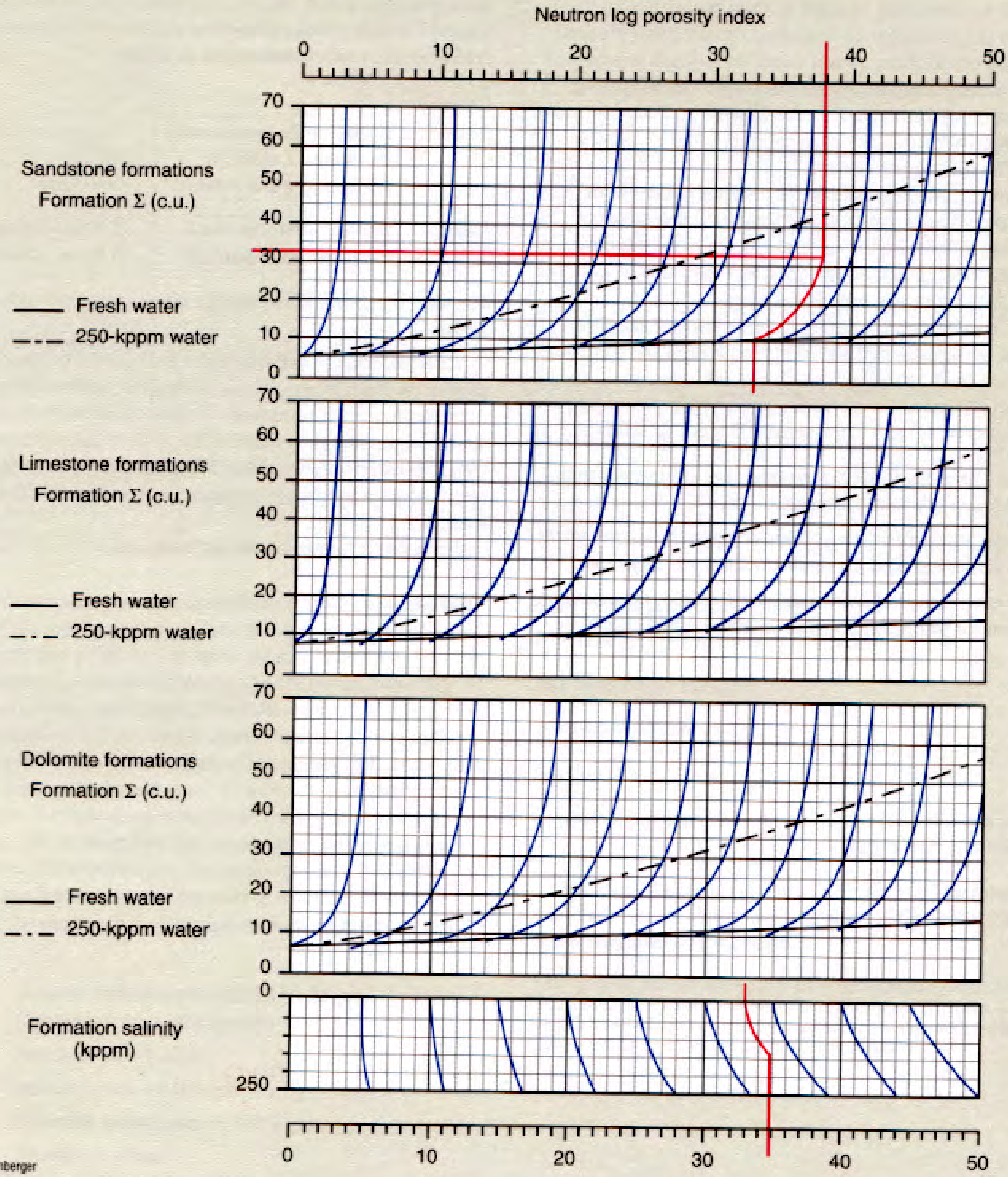
The total formation Σ and salinity effect in this example is 2.9 p.u.

As an alternate approach, with Chart Por-17 it is possible to correct the neutron porosity for the matrix capture cross section in freshwater-filled formations if matrix Σ is known from auxiliary measurements. Chart Por-18 provides corrections for CNL thermal neutron porosity for Σ of the formation fluid and, optionally, for hydrogen displacement in saltwater-filled formations.

For more information see Reference 38.

*Mark of Schlumberger

Dual-Spacing CNL* Compensated Neutron Log Formation Σ Correction Nomograph for Openhole



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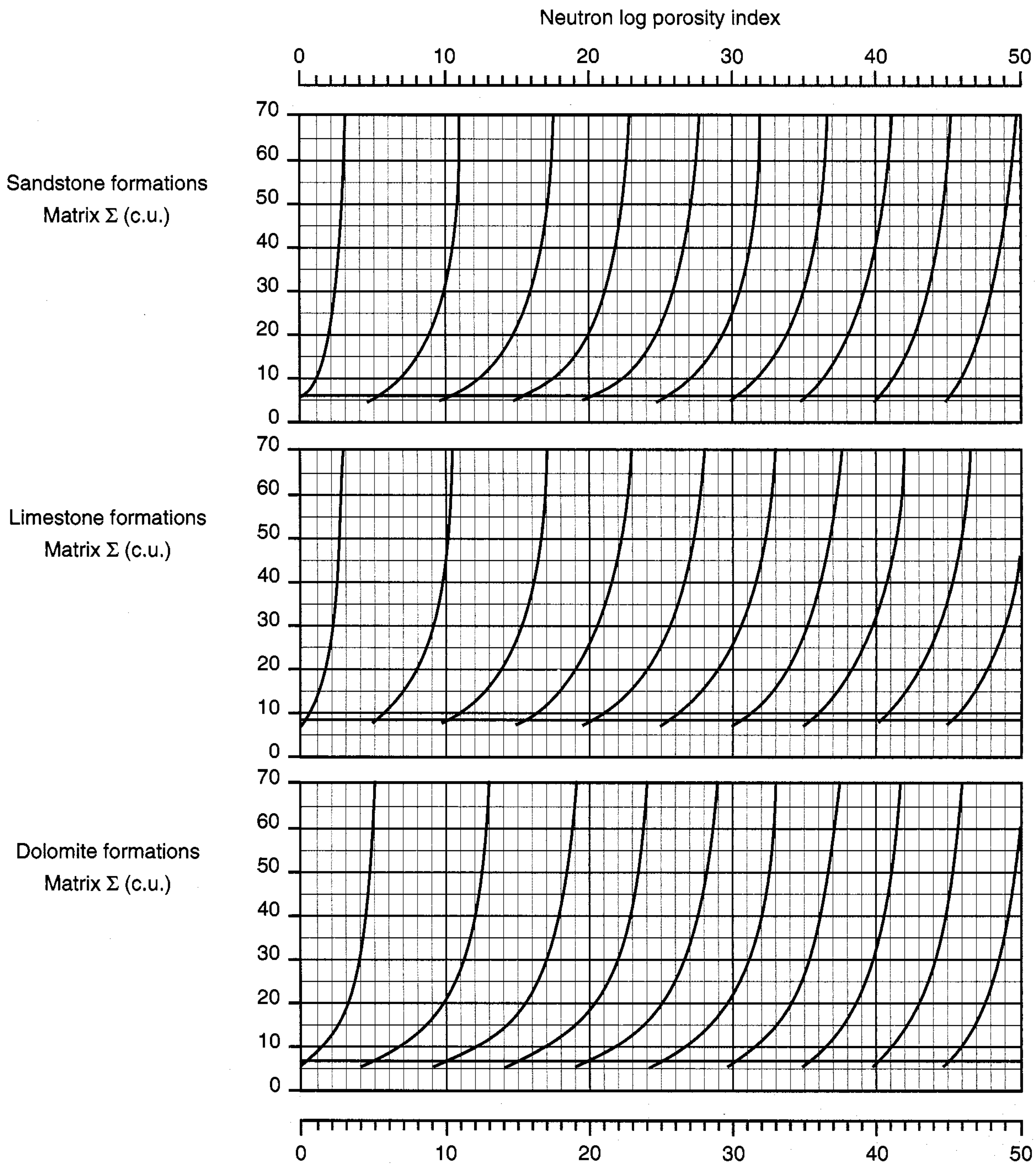
Dual-Spacing CNL* Compensated Neutron Log Matrix Σ Correction Nomograph for Openhole



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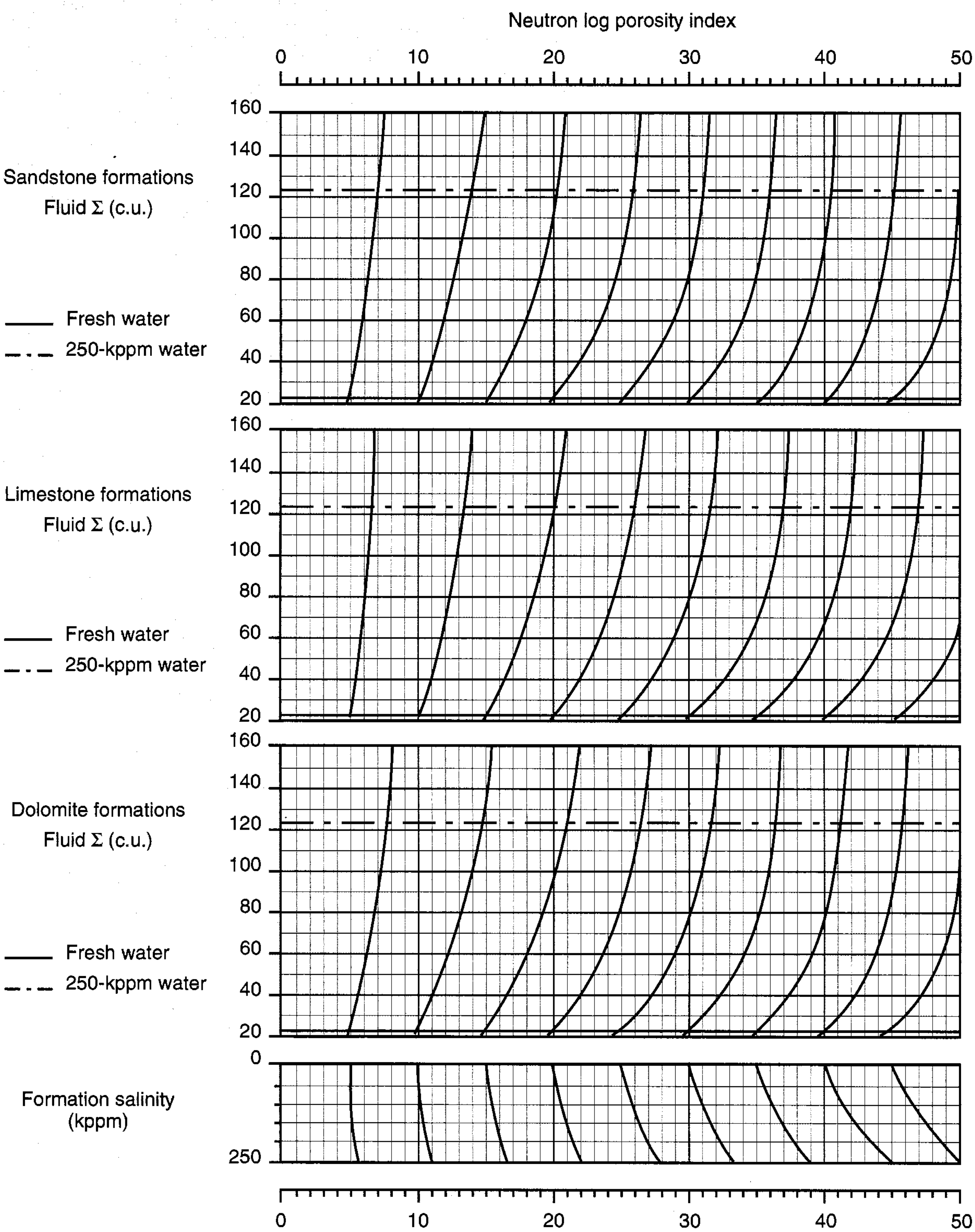
Dual-Spacing CNL* Compensated Neutron Log Fluid Σ Correction Nomograph for Openhole



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CDN* Compensated Density Neutron Log Correction Nomographs

This section contains log interpretation charts for the logging-while-drilling CDN neutron porosity measurement. Correction Nomographs Por-19 through Por-21 provide an environmentally corrected neutron porosity referenced to the appropriate lithology matrix. The neutron-density crossplot, Chart CP-22, provides insight into the formation lithology and permits the determination of porosity. The following example illustrates the procedure for using the charts.

Assume the following:

Uncorrected neutron log porosity	40 p.u. (apparent limestone units)
Tool size	6.5 in.
Borehole size	10 in.
Mud weight	14 lbm/gal (barite mud)
Mud salinity	100 kppm
Mud temperature	150°F
Mud pressure	5 kpsi
Formation salinity	100 kppm

First, determine the temperature and pressure-corrected hydrogen index of the mud (H_m). Enter the left of the bottom chart of Nomograph Por-19 at the 14-lbm/gal mud weight. Project a line to the right until it intersects the line for barite mud (point A). From this point, draw a line straight up until it intersects the bottom of the middle chart (point B). Follow the trend lines up to the mud temperature of 150°F (point C), then go straight up to the bottom of the top chart (point D). Follow the trend lines up to the line for 5-kpsi mud pressure (point E) and then straight up to the top of the chart to read the value of 0.78—the corrected hydrogen index of the mud.

Second, determine the environmental corrections with the appropriate Por-20 or -24 chart. Since the hydrogen index of the mud, mud salinity and formation salinity effects is strongly dependent on the hole size, correction nomographs are provided for 8-, 10-, 12-, 14- and 16-in. borehole sizes and for 6.5- and 8-in. tools.

Because the borehole size in the example is 10 in. and the tool size is 6.5 in., Chart Por-20b is selected for the corrections. Enter the top of the chart with the uncorrected CDN neutron porosity of 40 p.u. and drop a straight line down to the 10-in. borehole size (point B). Follow the sloping trend lines down to the standard conditions of an 8-in. borehole (point C), and then drop straight down to the borehole temperature value of 150°F (point D). Again follow the trend lines to the temperature at standard conditions, 75°F (point E). From this point drop vertically to the H_m value of 0.78, as determined from Chart Por-19. From here (point F), follow the trend lines to the standard conditions of H_m = 1.0 (point G). Then, drop straight down to the borehole salinity value of 100 kppm (point H). Follow the trend lines to the standard conditions of 0 kppm (point I). Drop straight down to the 100-kppm value for formation salinity (point J), and follow the trend lines down to 0 kppm, the standard condition value (point K). There, read the environmentally corrected apparent limestone porosity of 34 p.u. for this example.

Chart Por-24d shows another example for the larger 8-in. tool in a 14-in. borehole.

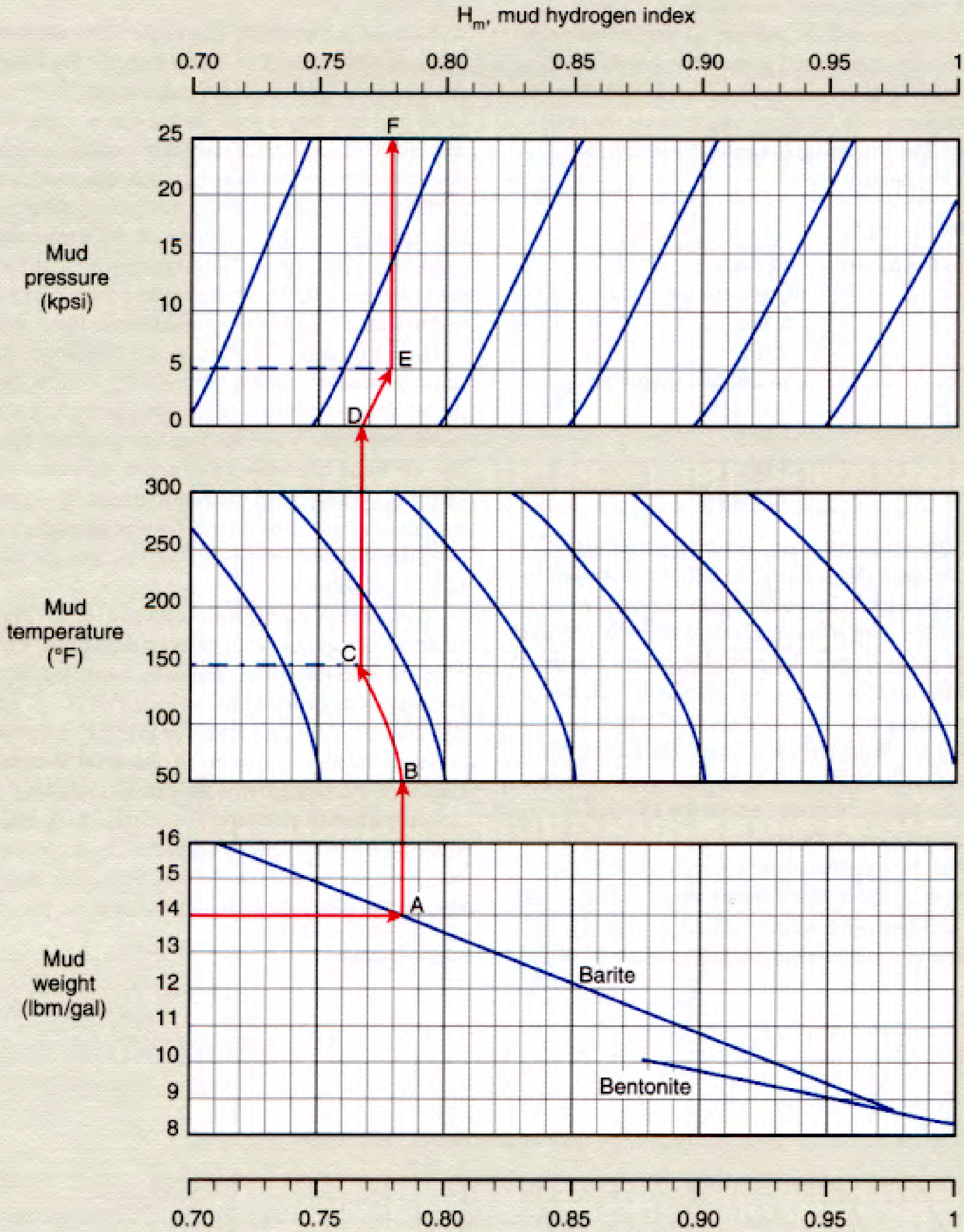
The porosity equivalence curves in Chart Por-21 are used to find the porosity of sandstones or dolomites. Enter the chart in abscissa with the environmentally corrected apparent limestone porosity as determined from Chart Por-20, go up to the appropriate matrix line, and read true porosity on the ordinate.

If the lithology is unknown, the neutron-density crossplot, Chart CP-22, can provide insight into lithology and permit the determination of porosity. To use this chart, enter the abscissa with the environmentally corrected apparent limestone porosity and the ordinate with the bulk density. The point of intersection defines the lithology (mineralogy) and the porosity.

*Mark of Schlumberger

CDN* Compensated Density Neutron Log and ADN* Azimuthal Density Neutron Log Correction Nomograph

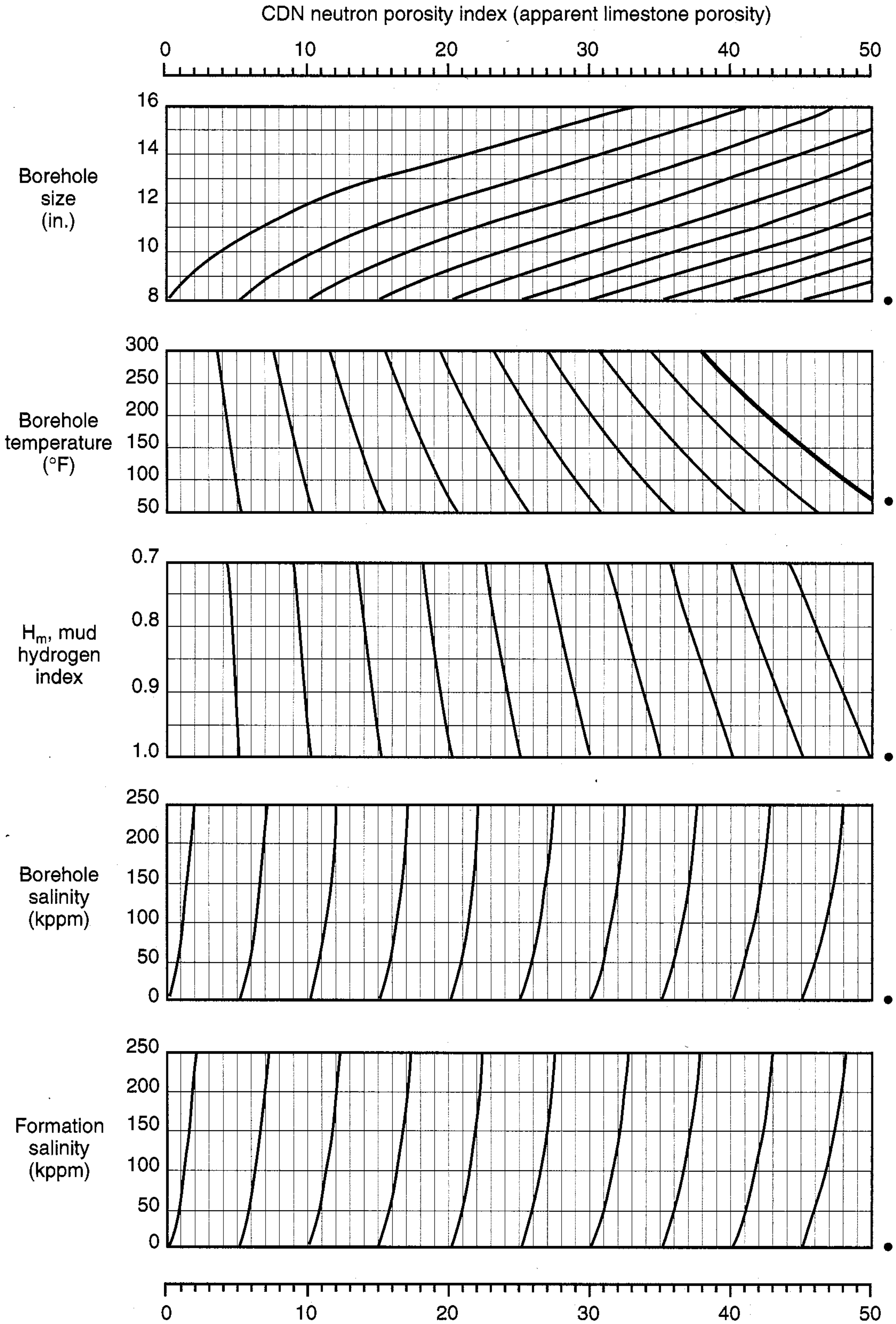
Mud hydrogen index determination



*Mark of Schlumberger

CDN* Compensated Density Neutron Log Correction Nomograph for 6.5-in. Tool

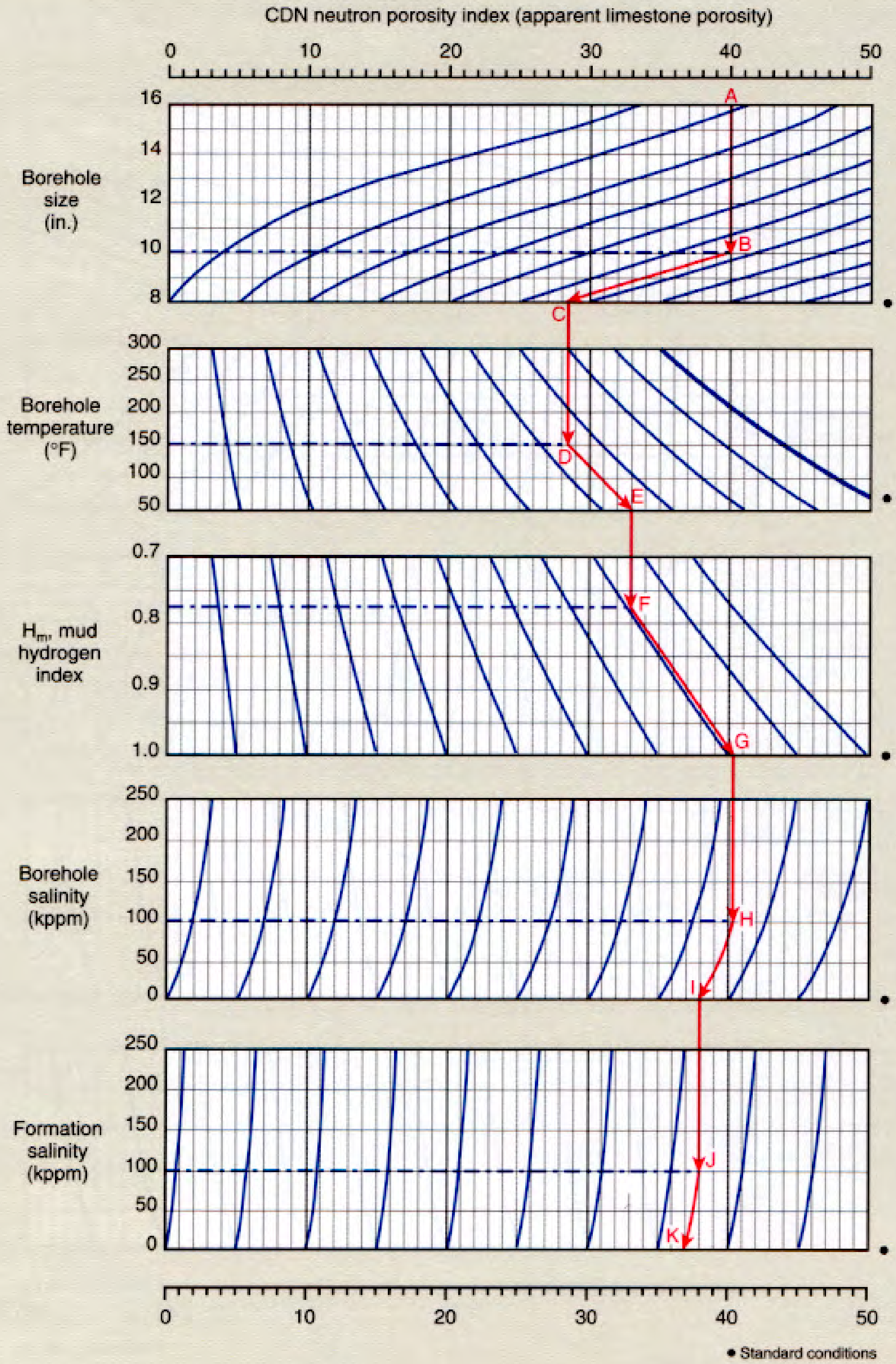
8-in. borehole



*Mark of Schlumberger

CDN* Compensated Density Neutron Log Correction Nomograph for 6.5-in. Tool

10-in. borehole



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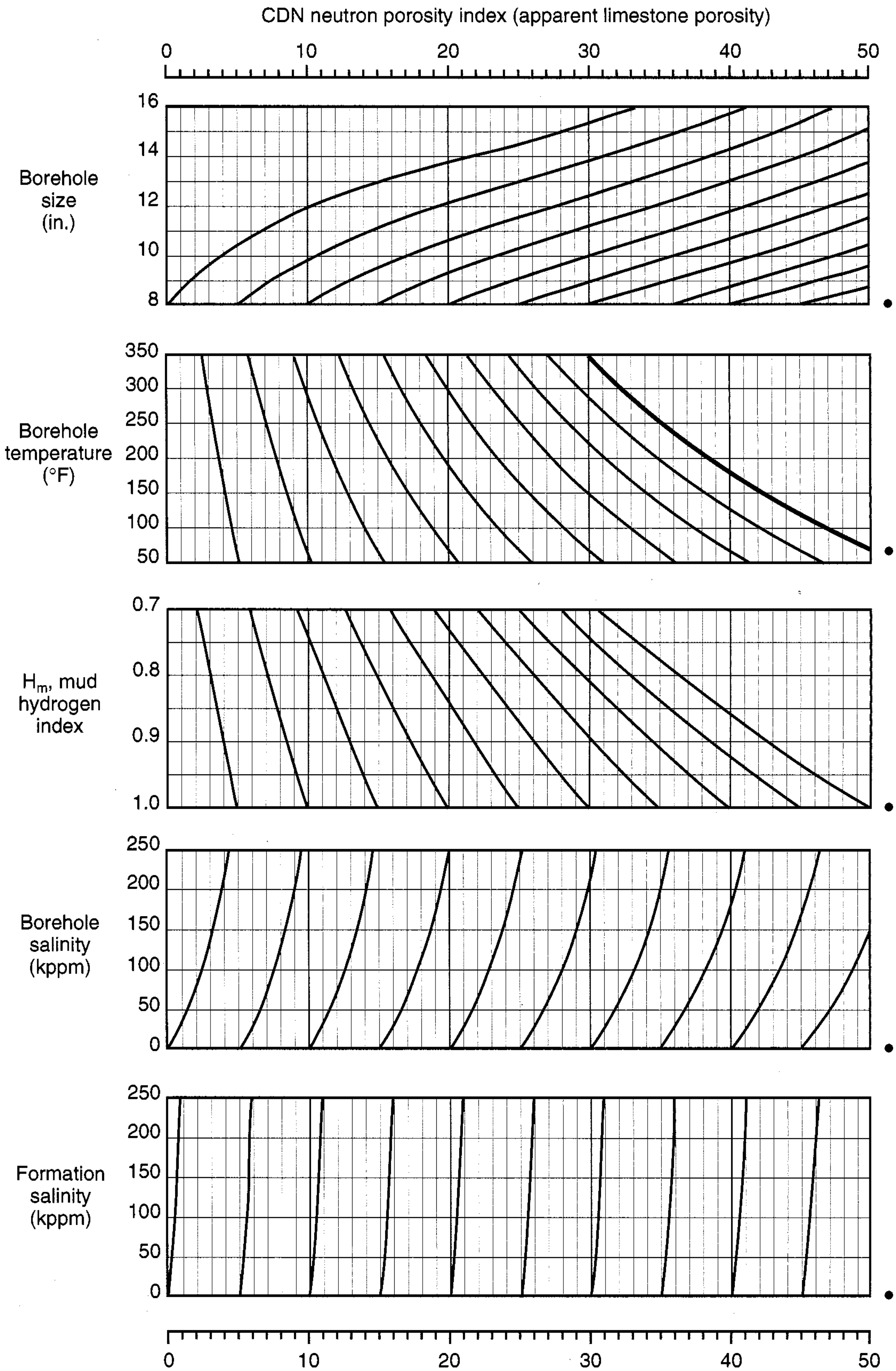
CDN* Compensated Density Neutron Log Correction Nomograph for 6.5-in. Tool

12-in. borehole



Por

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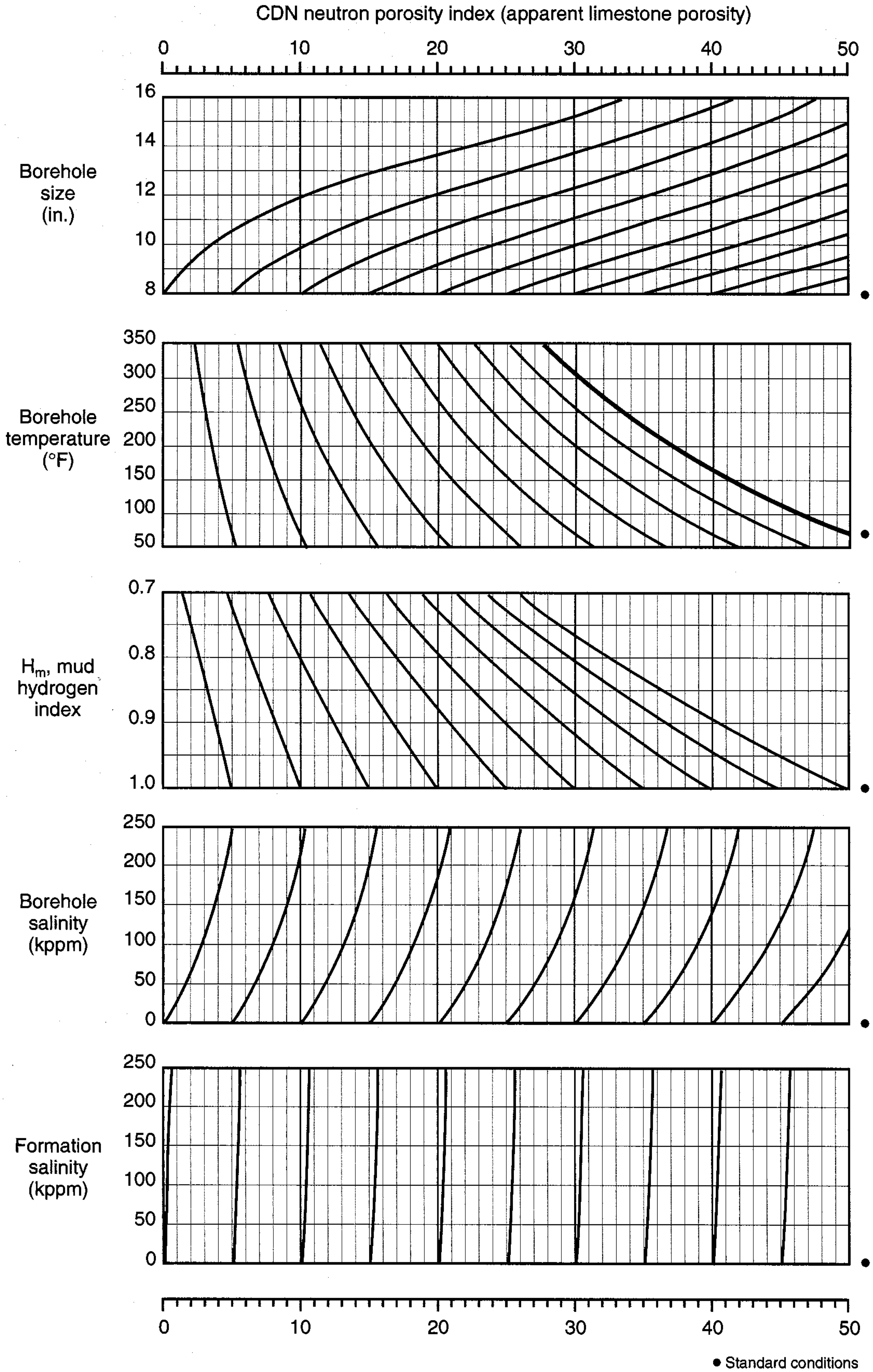
CDN* Compensated Density Neutron Log Correction Nomograph for 6.5-in. Tool

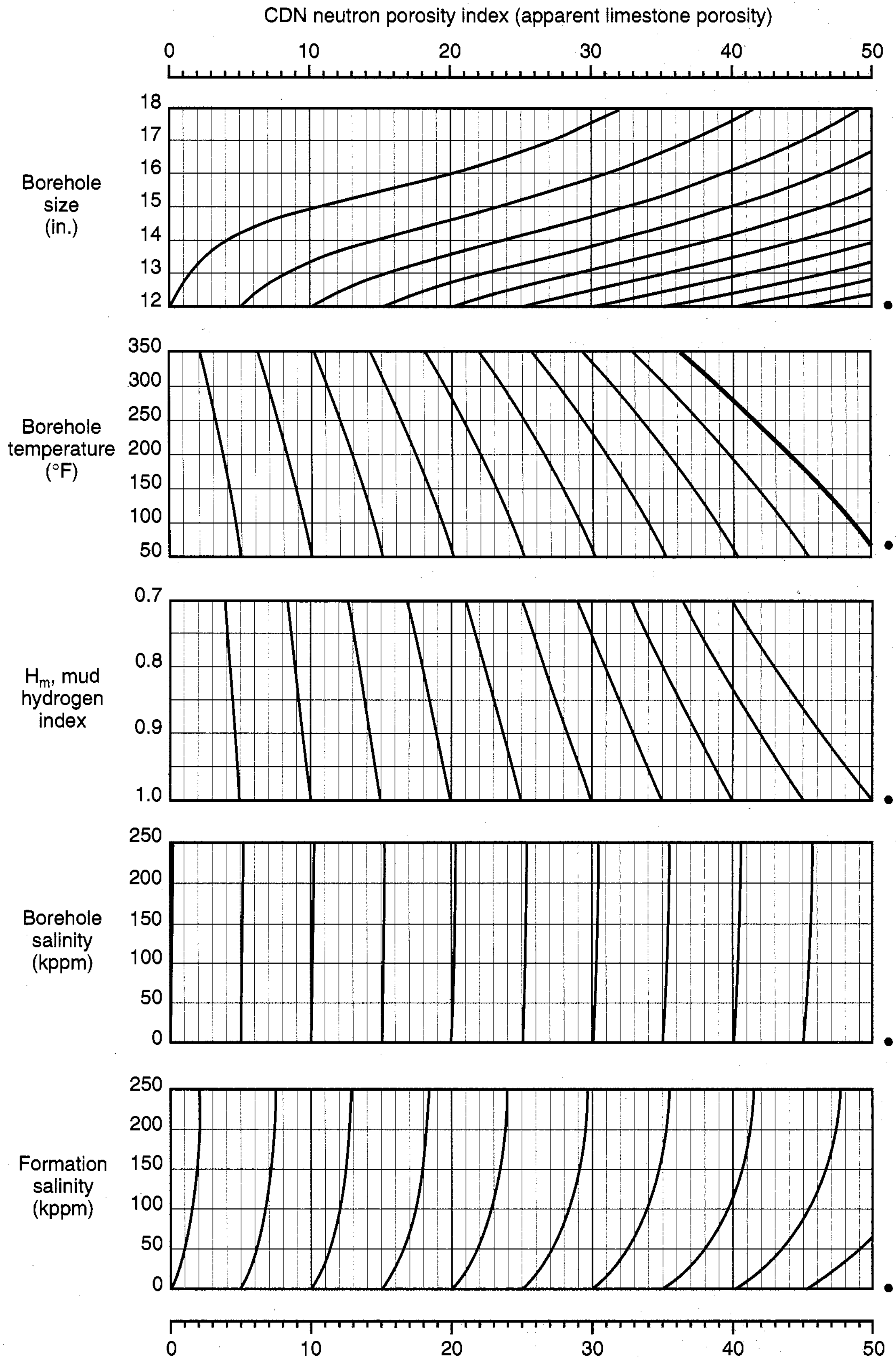
14-in. borehole



*Mark of Schlumberger

CDN* Compensated Density Neutron Log Correction Nomograph for 8-in. Tool

12-in. borehole



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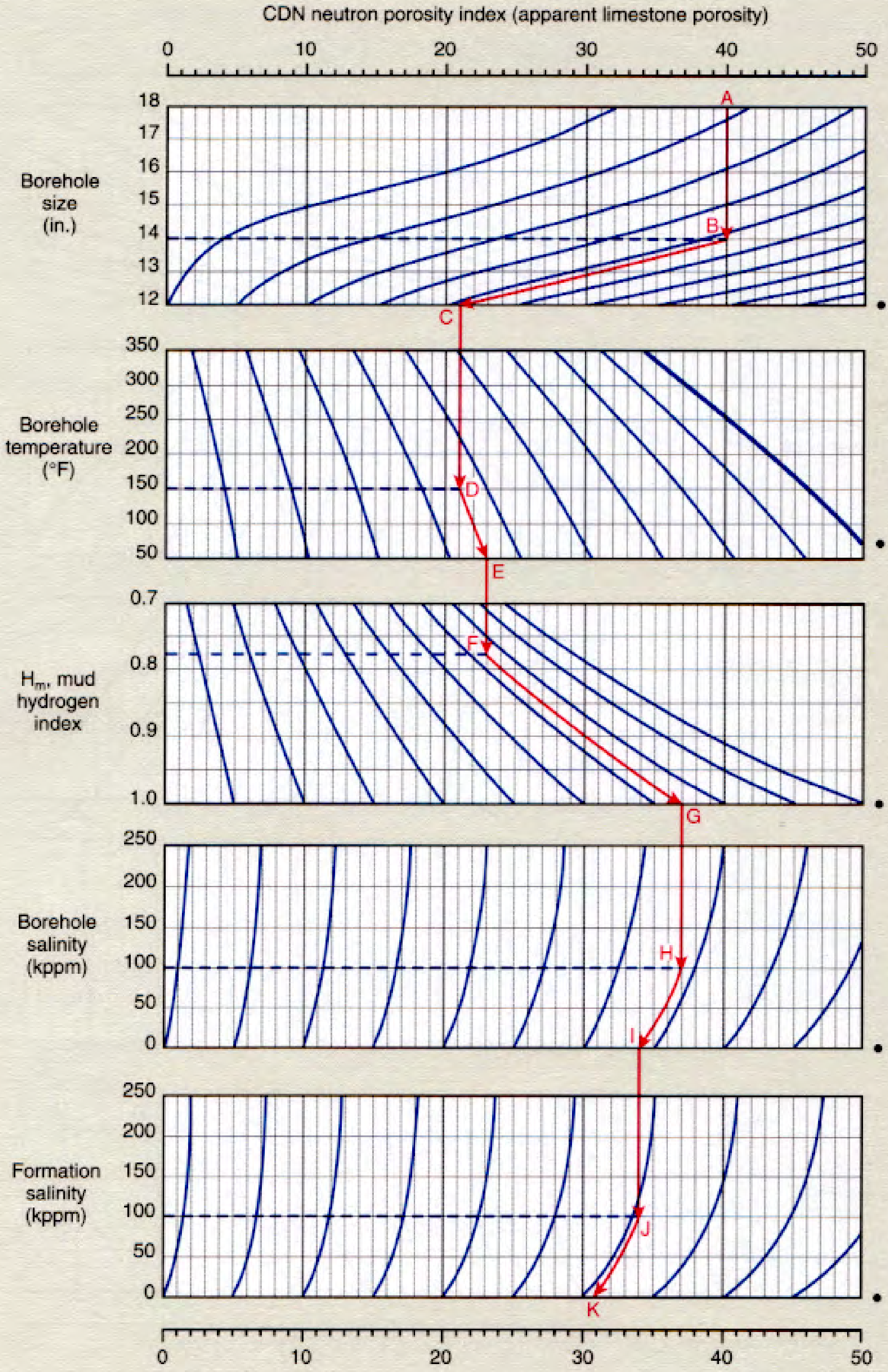
CDN* Compensated Density Neutron Log Correction Nomograph for 8-in. Tool

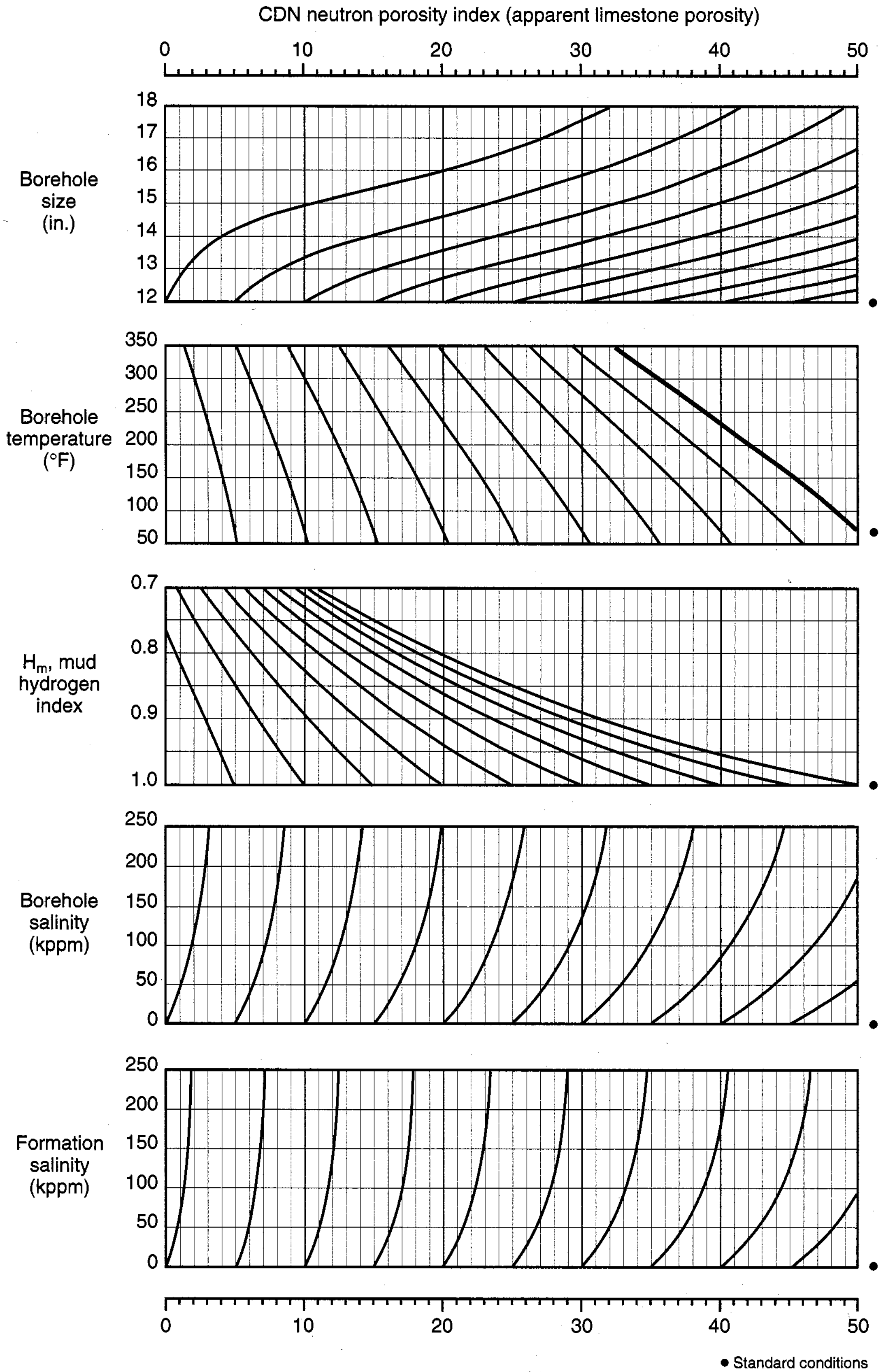
14-in. borehole



*Mark of Schlumberger

CDN* Compensated Density Neutron Log Correction Nomograph for 8-in. Tool

16-in. borehole



*Mark of Schlumberger

ADN* Azimuthal Density Neutron Log Correction Nomographs

This section contains log interpretation charts for the logging-while-drilling ADN azimuthal neutron porosity measurement. It is assumed that the tool is stabilized in the borehole. Correction Nomographs Por-19, Por-26a and Por-26b provide an environmentally corrected neutron porosity referenced to the appropriate lithology matrix. The neutron-density crossplot, Chart CP-24, provides insight into the formation lithology and permits the determination of porosity. The following example illustrates the procedure for using the charts.

Assume the following:

Uncorrected neutron log porosity	40 p.u. (apparent limestone units)
Borehole size	10 in.
Mud weight	14 lbm/gal (barite mud)
Mud salinity	100 kppm
Mud temperature	150°F
Mud pressure	5 kpsi
Formation salinity	100 kppm

First, determine the temperature and pressure-corrected hydrogen index of the mud (H_m). Enter the left of the bottom chart of Nomograph Por-19 at the 14-lbm/gal mud weight. Project a line to the right until it intersects the line for barite mud (point A). From this point, draw a line straight up until it intersects the bottom of the middle chart (point B). Follow the trend lines up to the mud temperature of 150°F (point C), then go straight up to the bottom of the top chart (point D). Follow the trend lines up to the line for 5-kpsi mud pressure (point E) and then straight up to the top of the chart to read the value of 0.78—the corrected hydrogen index of the mud.

Second, determine the environmental corrections with the appropriate Por-26 chart. Since the hydrogen index of the mud, mud salinity and formation salinity effects is strongly dependent on the hole size, correction nomographs are provided for 8- and 10-in. borehole sizes.

Since the borehole size in the example is 10 in. and the tool size is 6.5 in., Chart Por-26b is selected for the corrections. Enter the top of the chart with the uncorrected CDN neutron porosity of 40 p.u. and drop a line straight down to the 10-in. borehole size (point B). Follow the sloping trend lines down to the standard conditions (8-in. borehole), and then drop straight down to the H_m value of 0.78, as determined from Chart Por-19. From here (point D), follow the trend lines to the standard conditions of $H_m = 1.0$ (point E). Then, drop straight down to the mud salinity value of 100 kppm (point F). Follow the trend lines to the standard conditions of 0 kppm. Drop straight down to the 100-kppm value for formation salinity (point H) and follow the trend lines down to 0 kppm—the standard condition value (point I). There, read the environmentally corrected apparent limestone porosity of 31 p.u. for this example.

The porosity equivalence curves in Chart Por-27 are used to find the porosity of sandstones or dolomites. Enter the chart in abscissa with the environmentally corrected apparent limestone porosity as determined from Chart Por-26b, go up to the appropriate matrix line, and read true porosity on the ordinate.

If the lithology is unknown, the neutron-density crossplot, Chart CP-24, can provide insight into lithology and permit the determination of porosity. To use this chart, enter the abscissa with the environmentally corrected apparent limestone porosity and the ordinate with the bulk density. The point of intersection defines the lithology (mineralogy) and the porosity.

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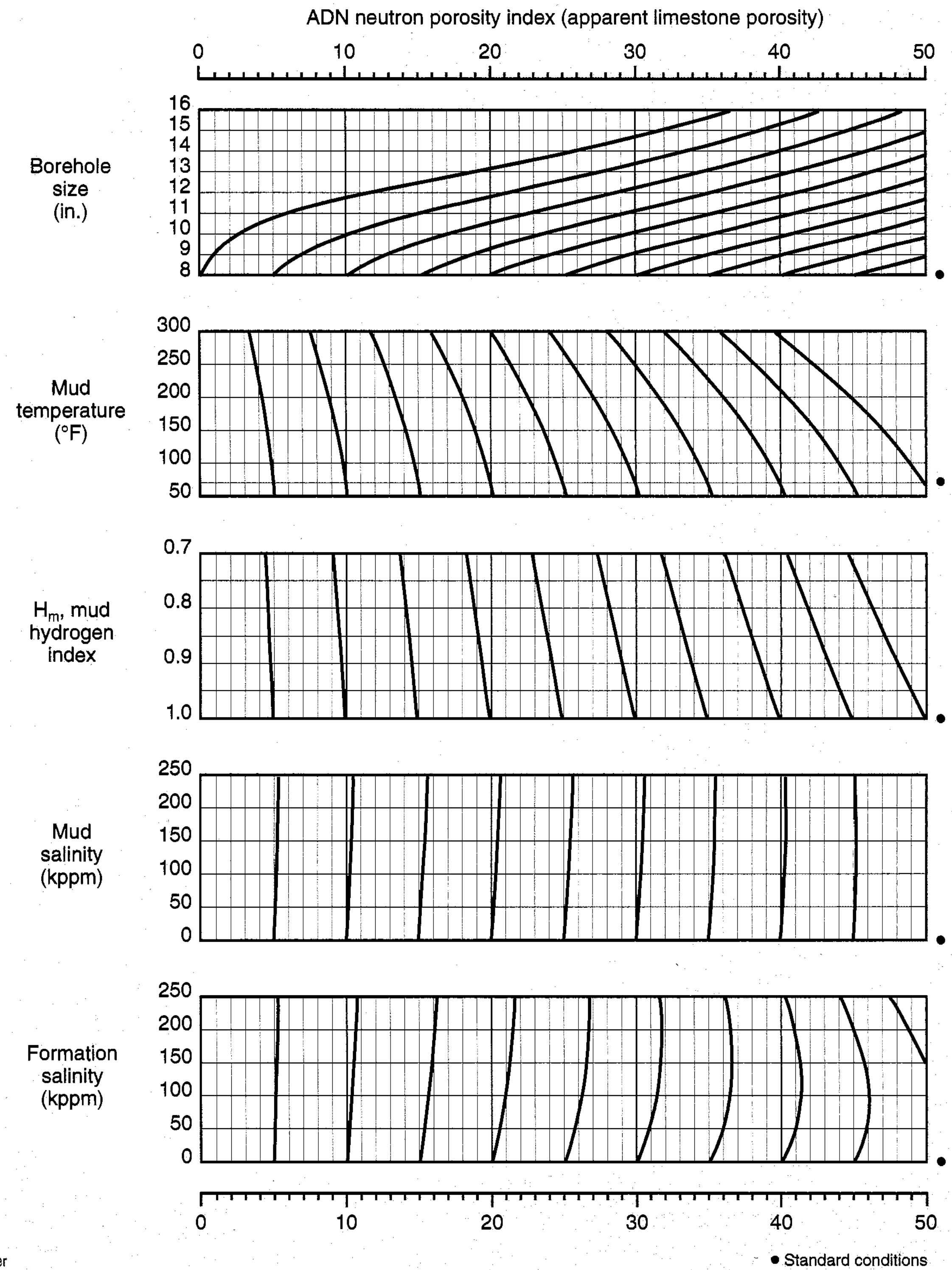
ADN* Azimuthal Density Neutron Log Correction Nomograph for 6.75-in. Tool

8-in. borehole



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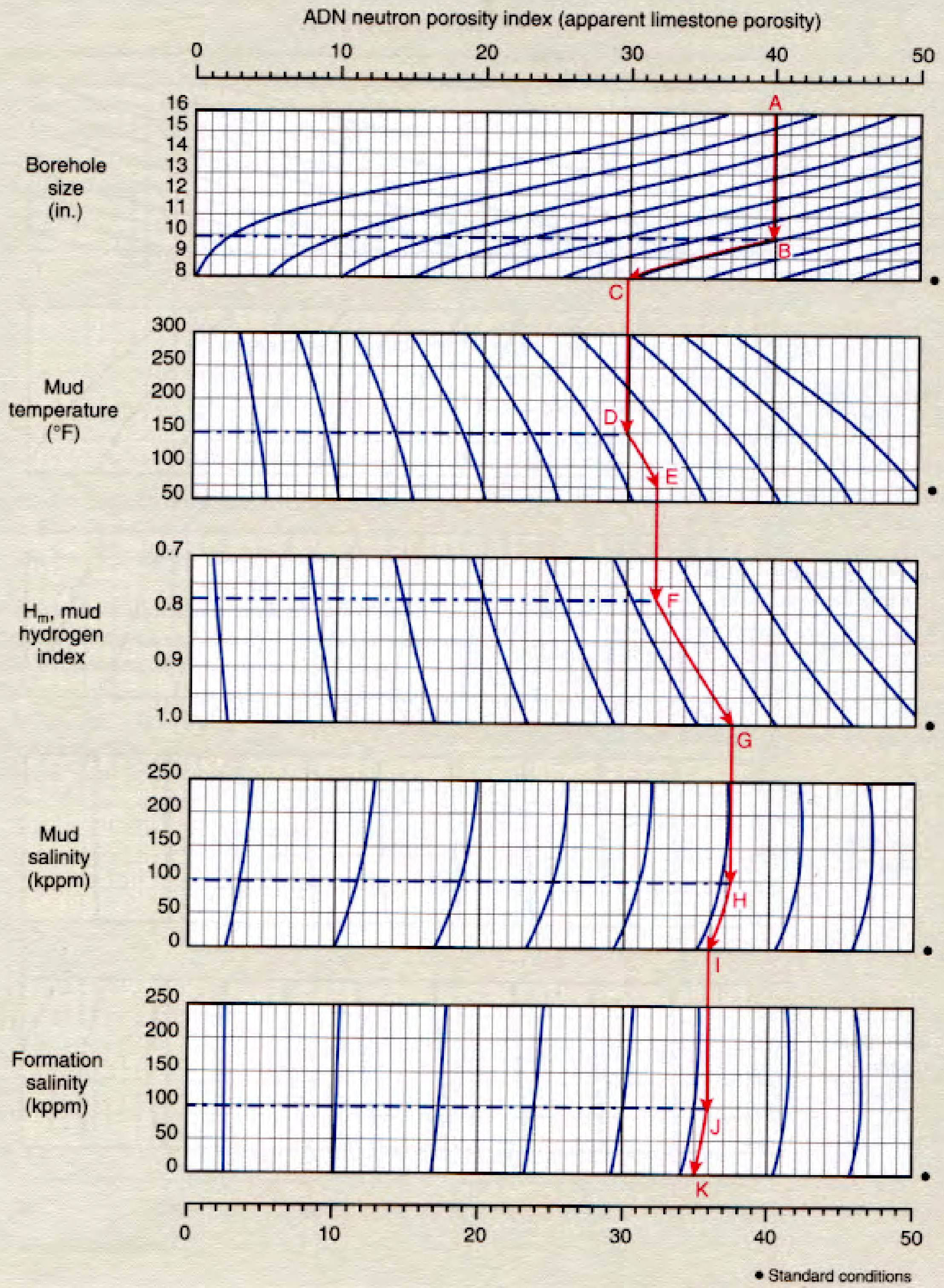
ADN* Azimuthal Density Neutron Log Correction Nomograph for 6.75-in. Tool

10-in. borehole



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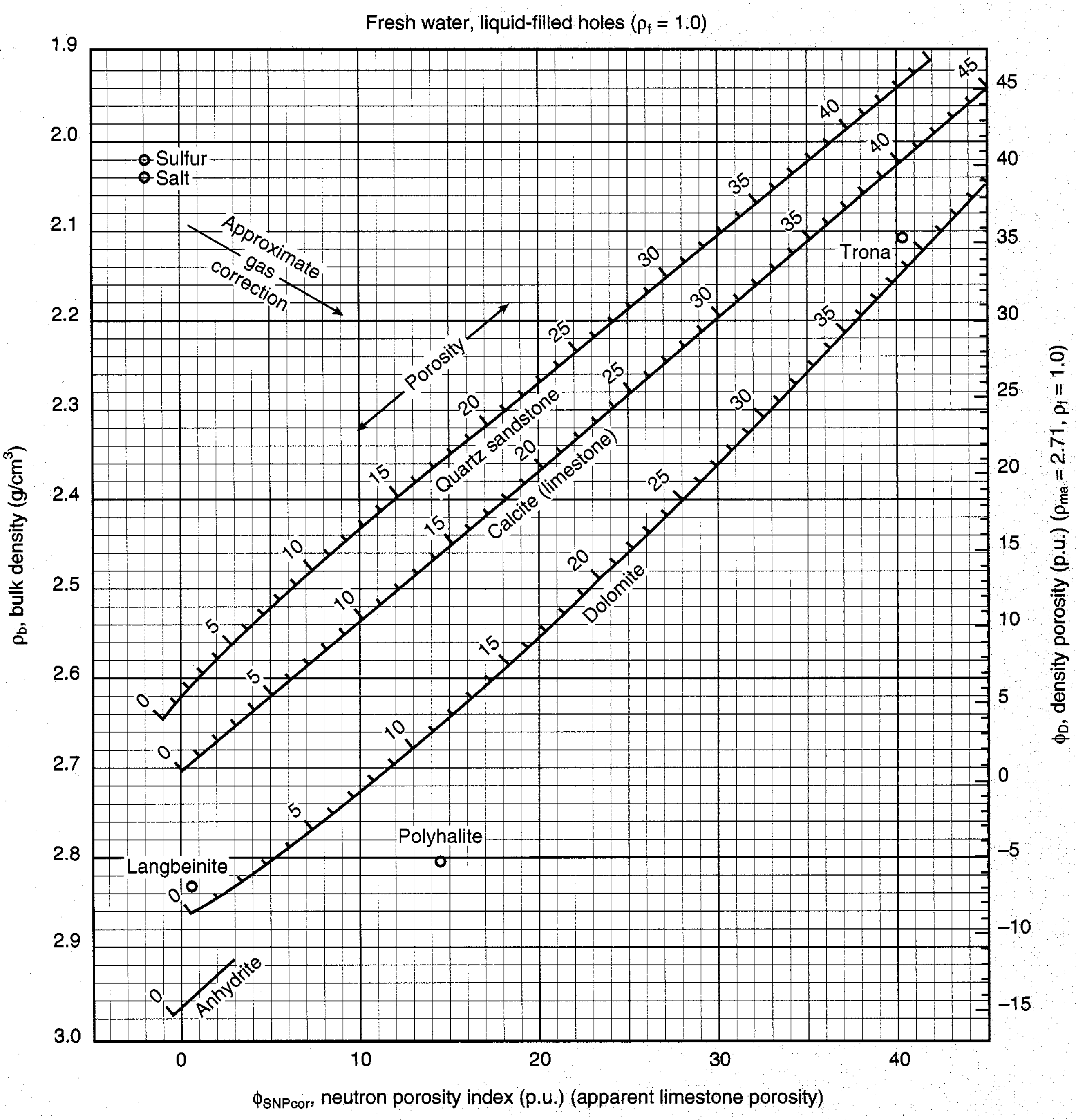
Porosity and Lithology Determination from Formation Density Log and SNP Sidewall Neutron Porosity Log

CP-1a

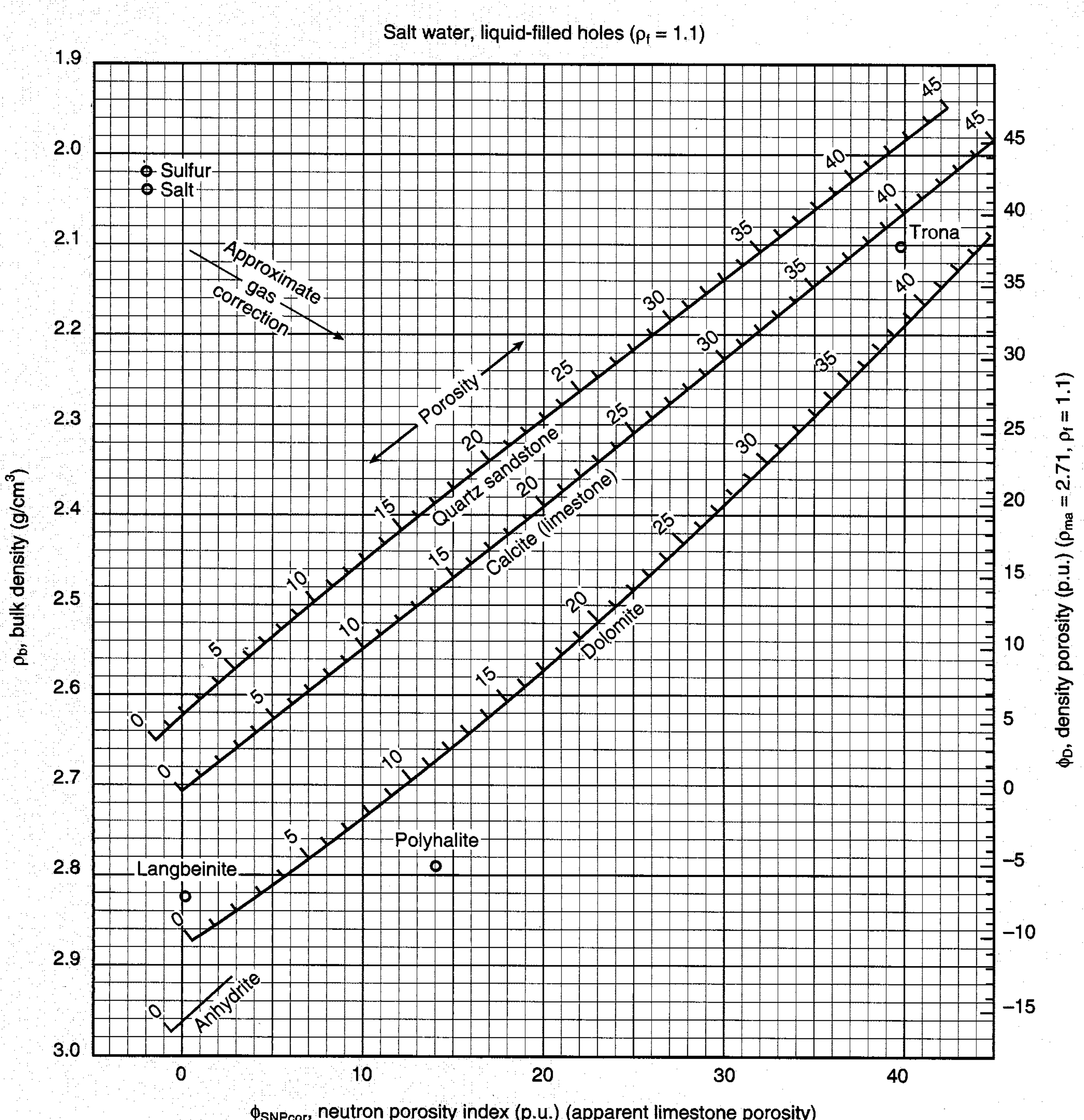


The neutron-density-sonic crossplot charts (Charts CP-1, CP-2 and CP-7) provide insight into lithology and permit the determination of porosity. Chart selection depends on the anticipated mineralogy. Neutron-density can be used to differentiate between the common reservoir rocks [quartz sandstone, calcite (limestone) and dolomite] and shale and some evaporites.

Sonic-neutron can be used to differentiate between the common reservoir rocks when clay content is negligible. Sonic-density can be used to differentiate between a single known reservoir rock and shale and to identify evaporate minerals.

Continued on next page

Porosity and Lithology Determination from Formation Density Log and SNP Sidewall Neutron Porosity Log



To use any of these charts, enter the abscissa and ordinate with the required neutron, density or sonic value. The point of intersection defines the lithology (mineralogy) and the porosity, ϕ.

Note that all neutron input is in apparent limestone porosity, that charts for fresh water (ρ_f = 1.0 g/cm³) and saline water (ρ_f = 1.1 g/cm³) invasion exist, and that the sonic charts contain curves assuming weighted average response (blue) and empirical observation response (red).

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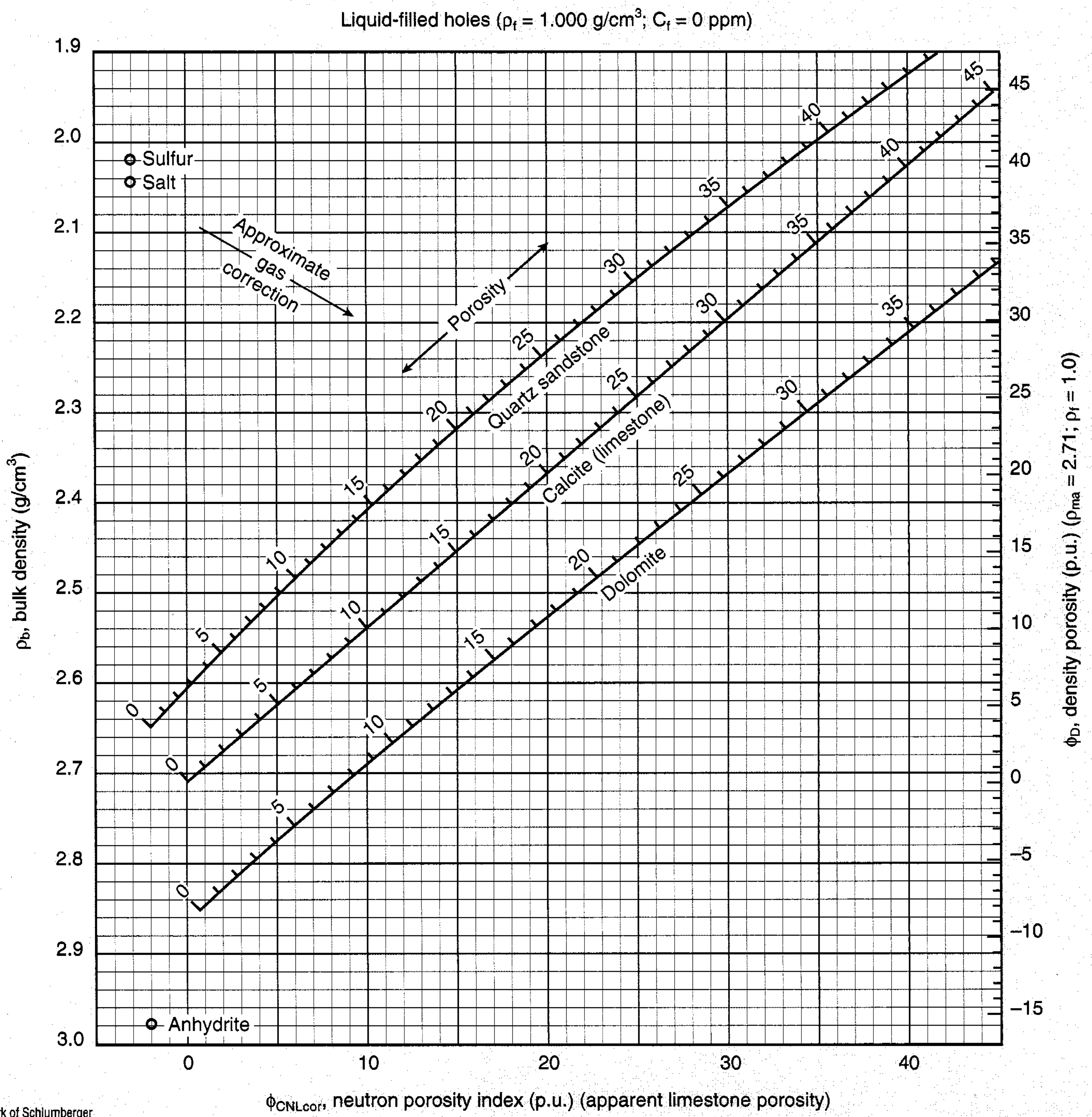
Porosity and Lithology Determination from Litho-Density* Log and CNL* Compensated Neutron Log

CP-1e

For CNL curves after 1986 labeled TNPH



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CP

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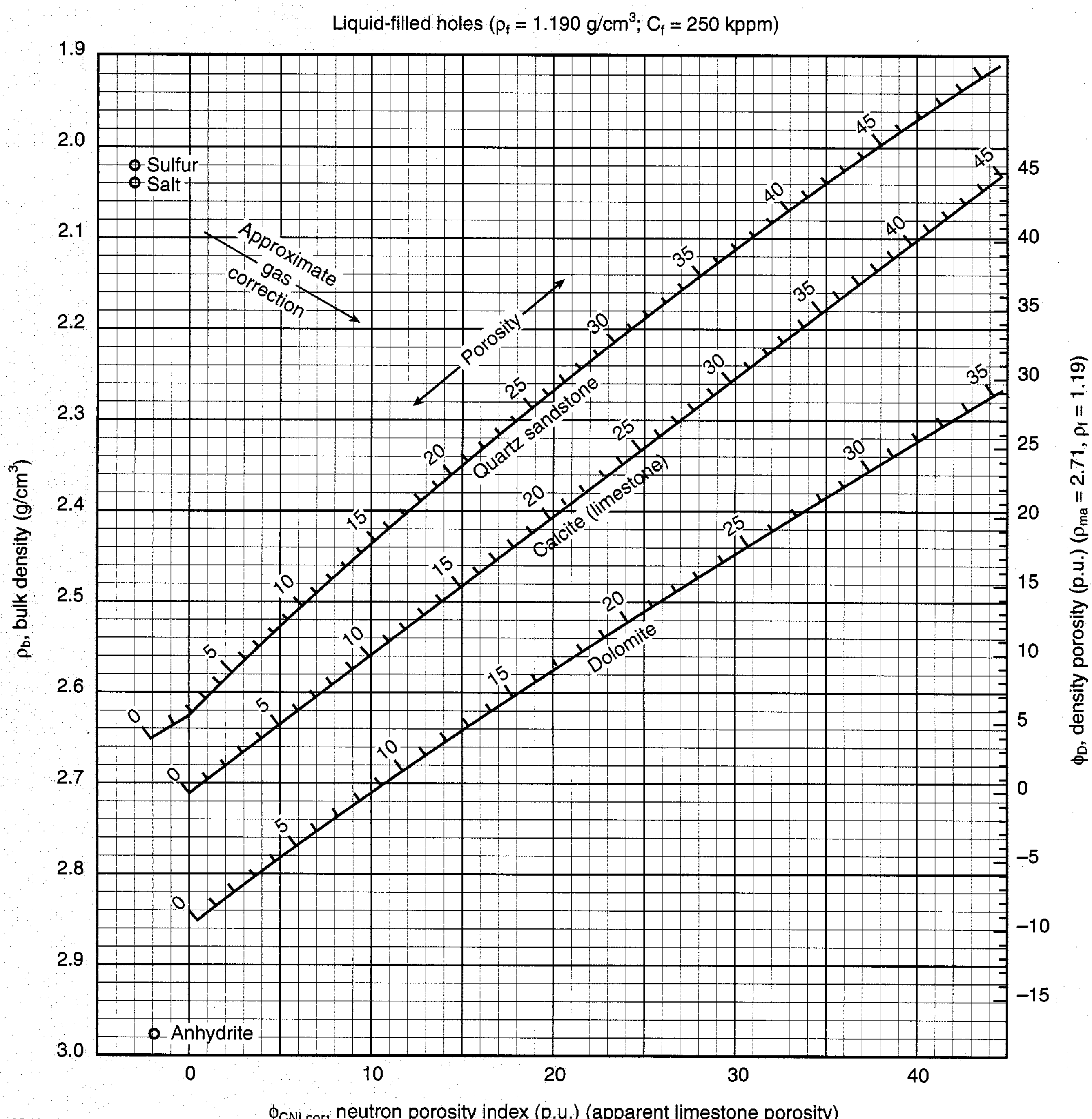
CP-1f

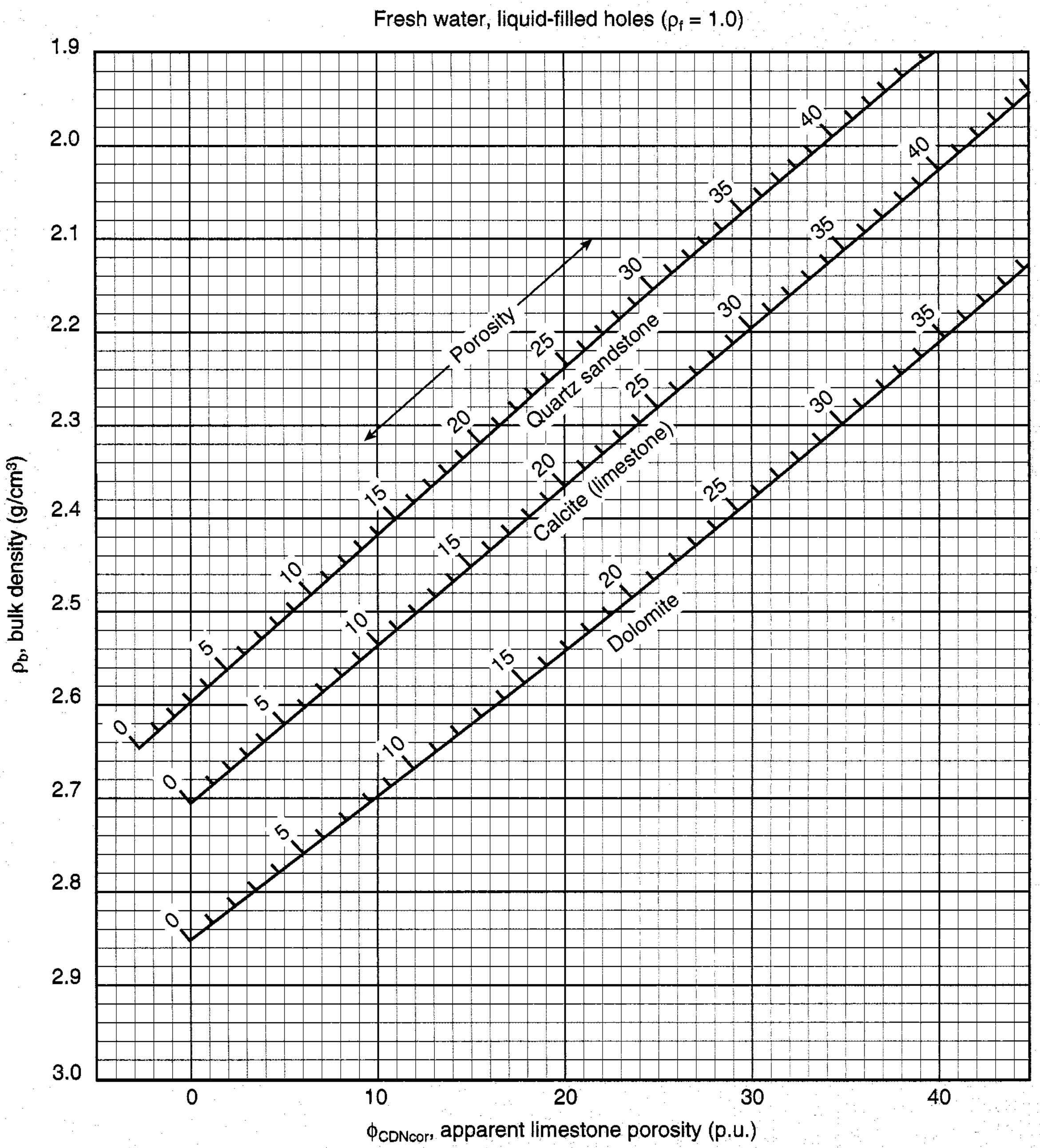
Porosity and Lithology Determination from Litho-Density* Log and CNL* Compensated Neutron Log

For CNL curves after 1986 labeled TNPH



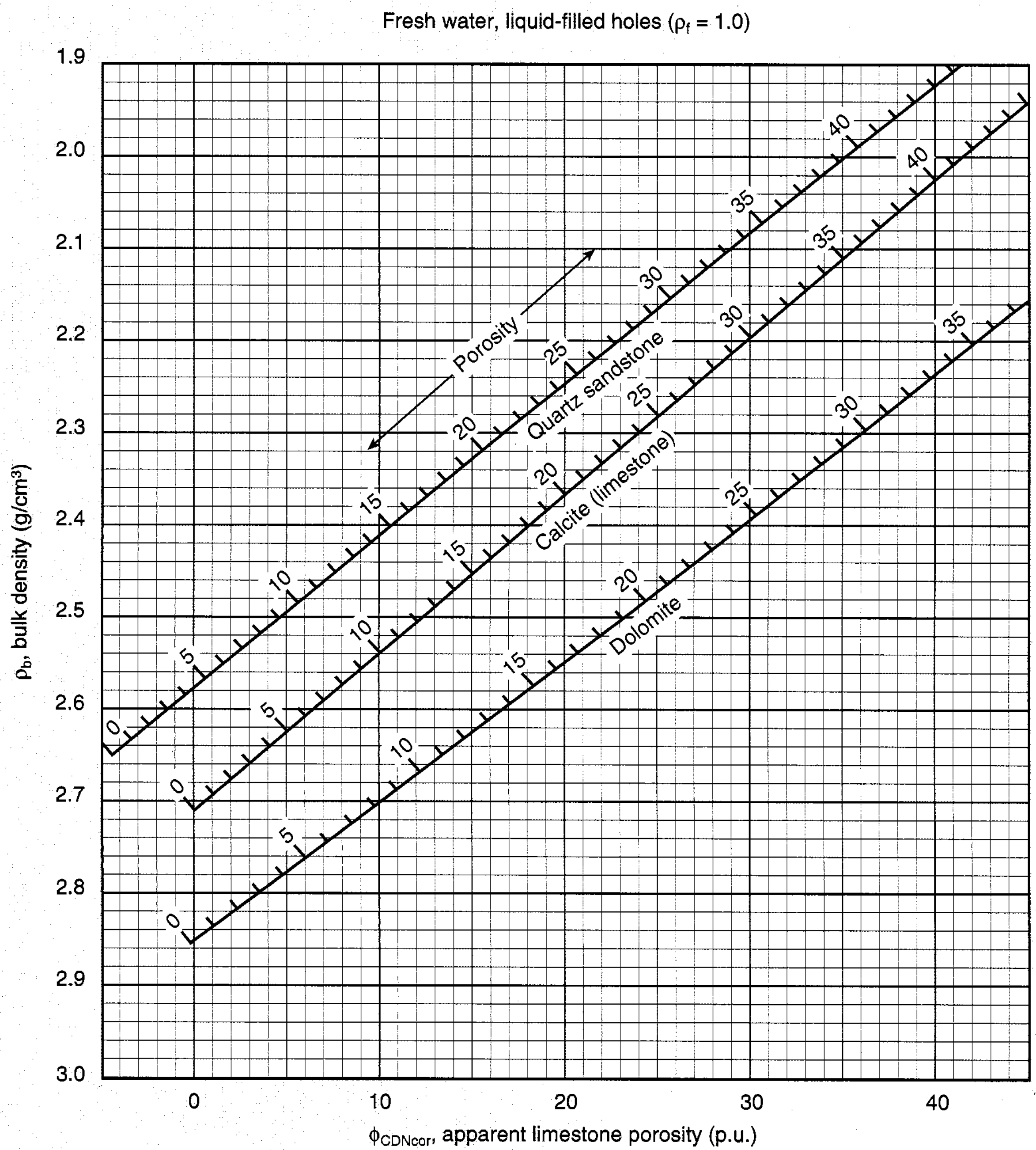
*Mark of Schlumberger

Porosity and Lithology Determination from Formation Density Log and CDN* Compensated Density Neutron Log for 6.5-in. Tool



*Mark of Schlumberger

Porosity and Lithology Determination from Formation Density Log and CDN* Compensated Density Neutron Log for 8-in. Tool



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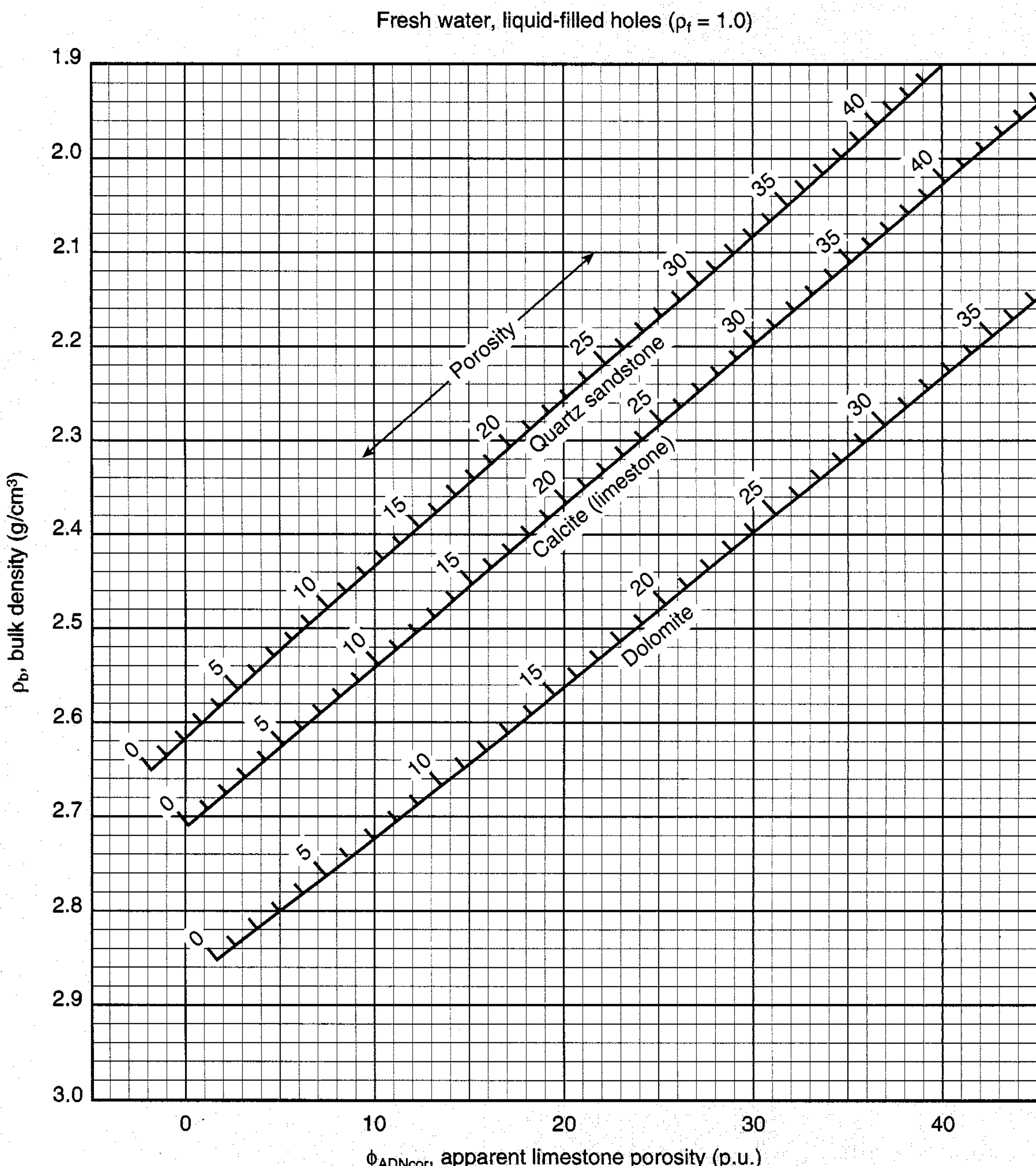
Porosity and Lithology Determination from Formation Density Log and ADN* Azimuthal Density Neutron Log for 6.75-in. Tool

CP-24



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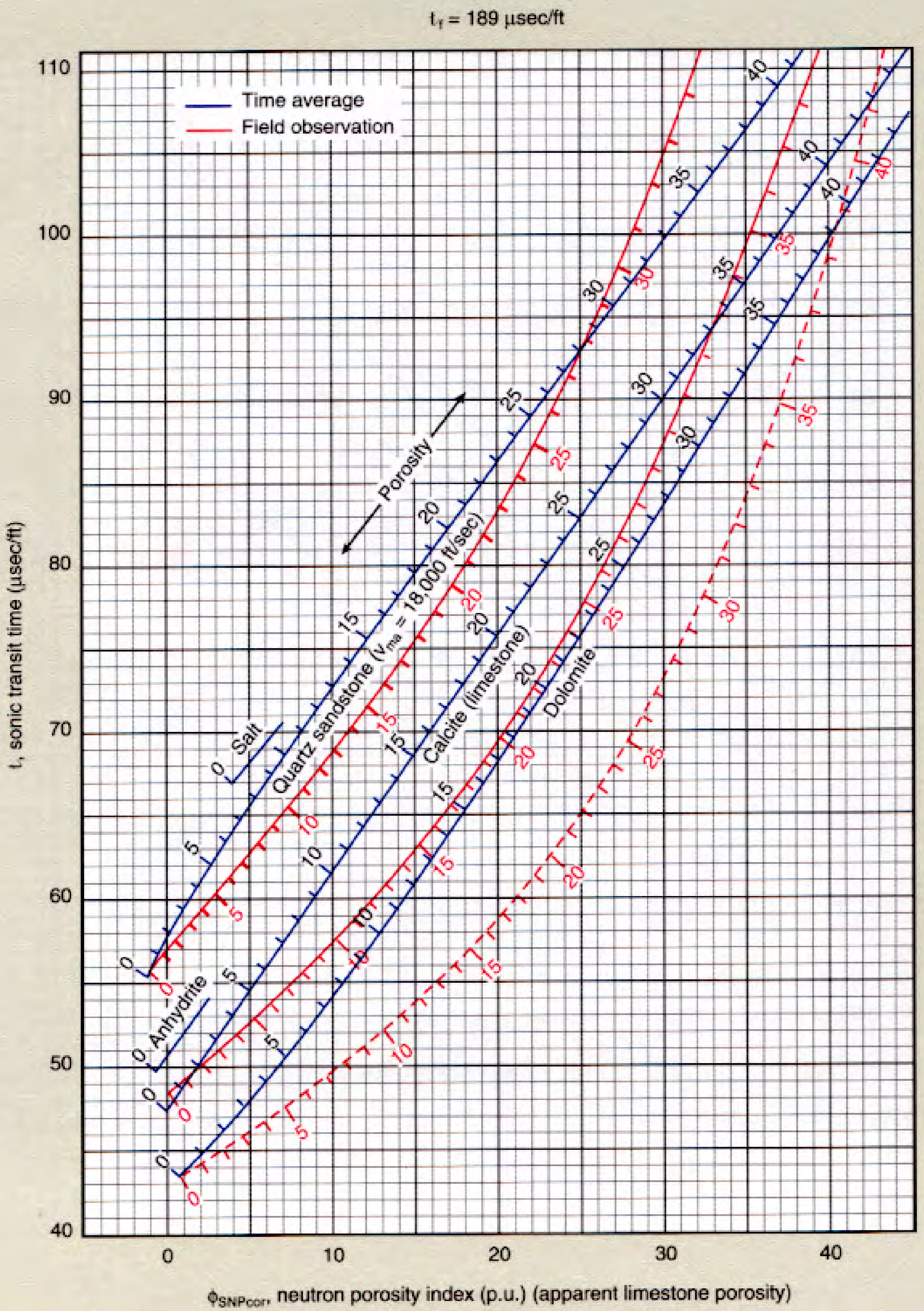
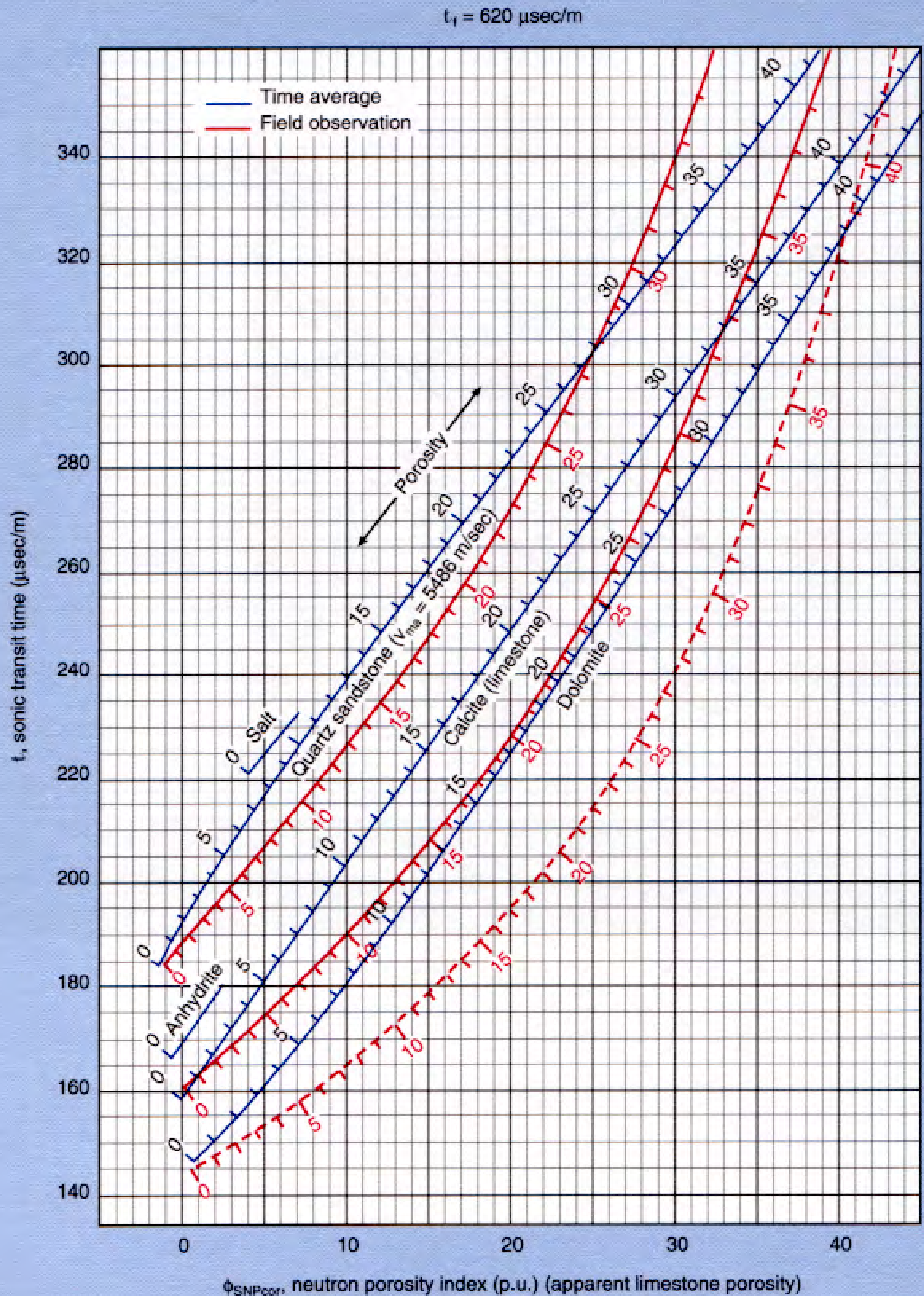
Porosity and Lithology Determination from Sonic Log and SNP Sidewall Neutron Porosity Log

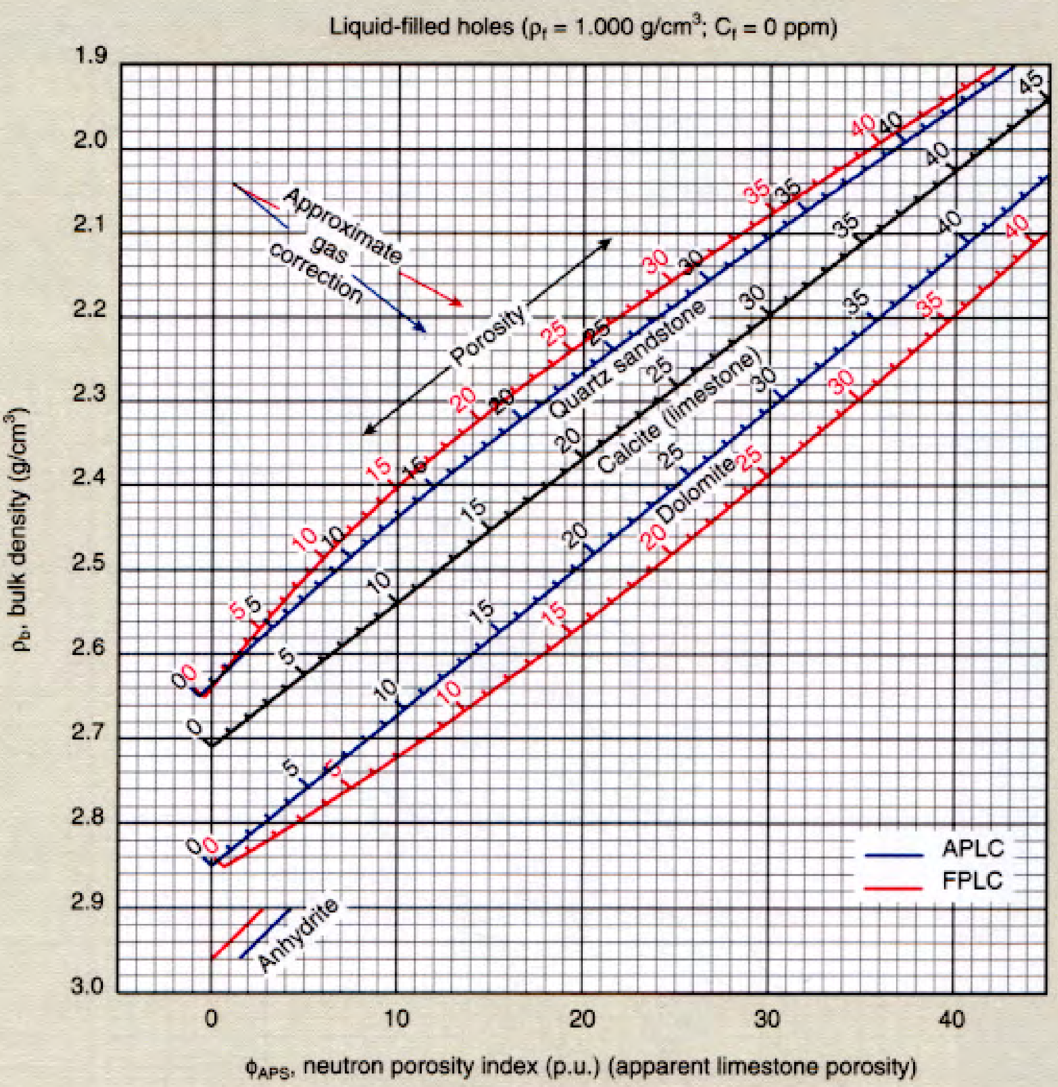


Porosity and Lithology Determination from Sonic Log and SNP Sidewall Neutron Porosity Log

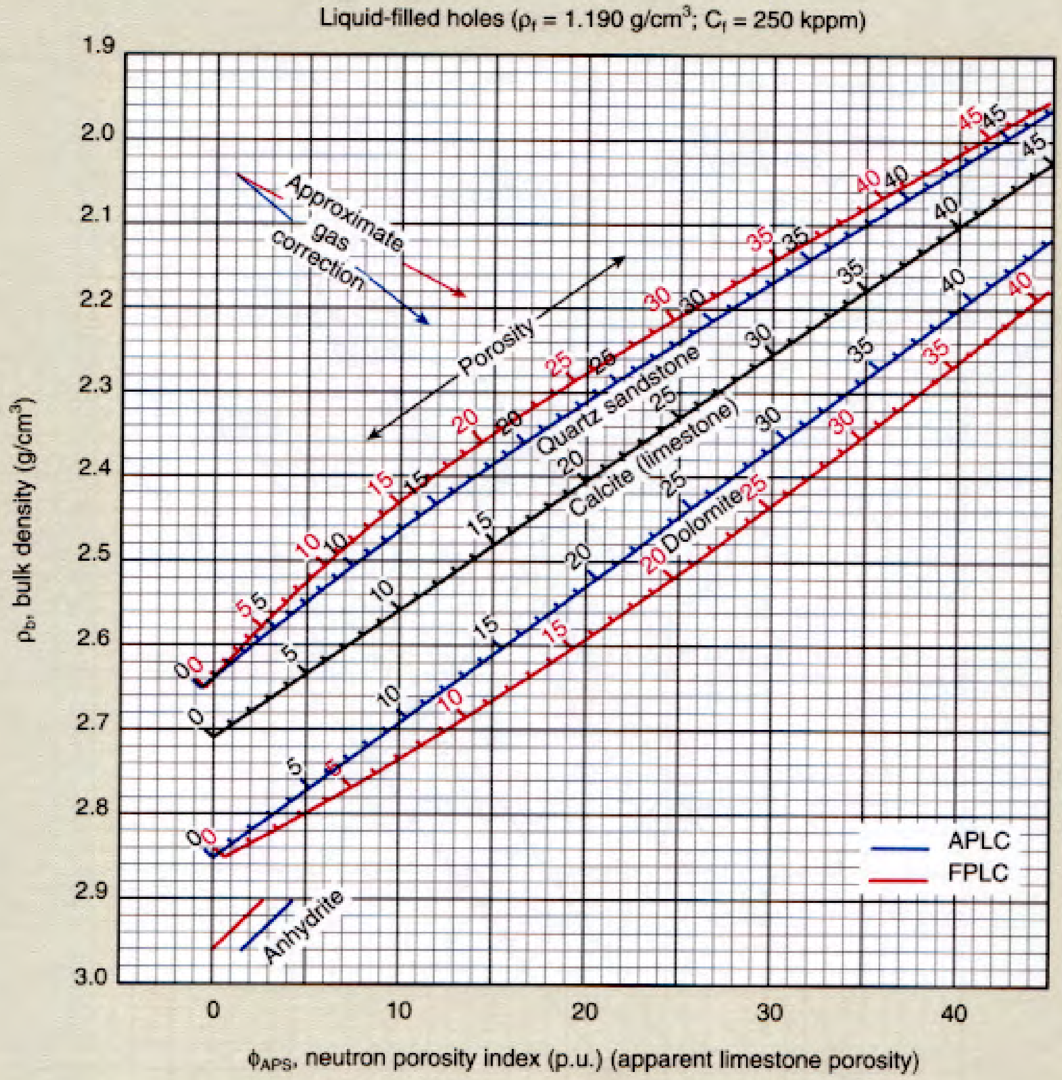
CP-2am (Metric)



Porosity and Lithology Determination from Litho-Density* Log and Array Porosity Sonde (APS)



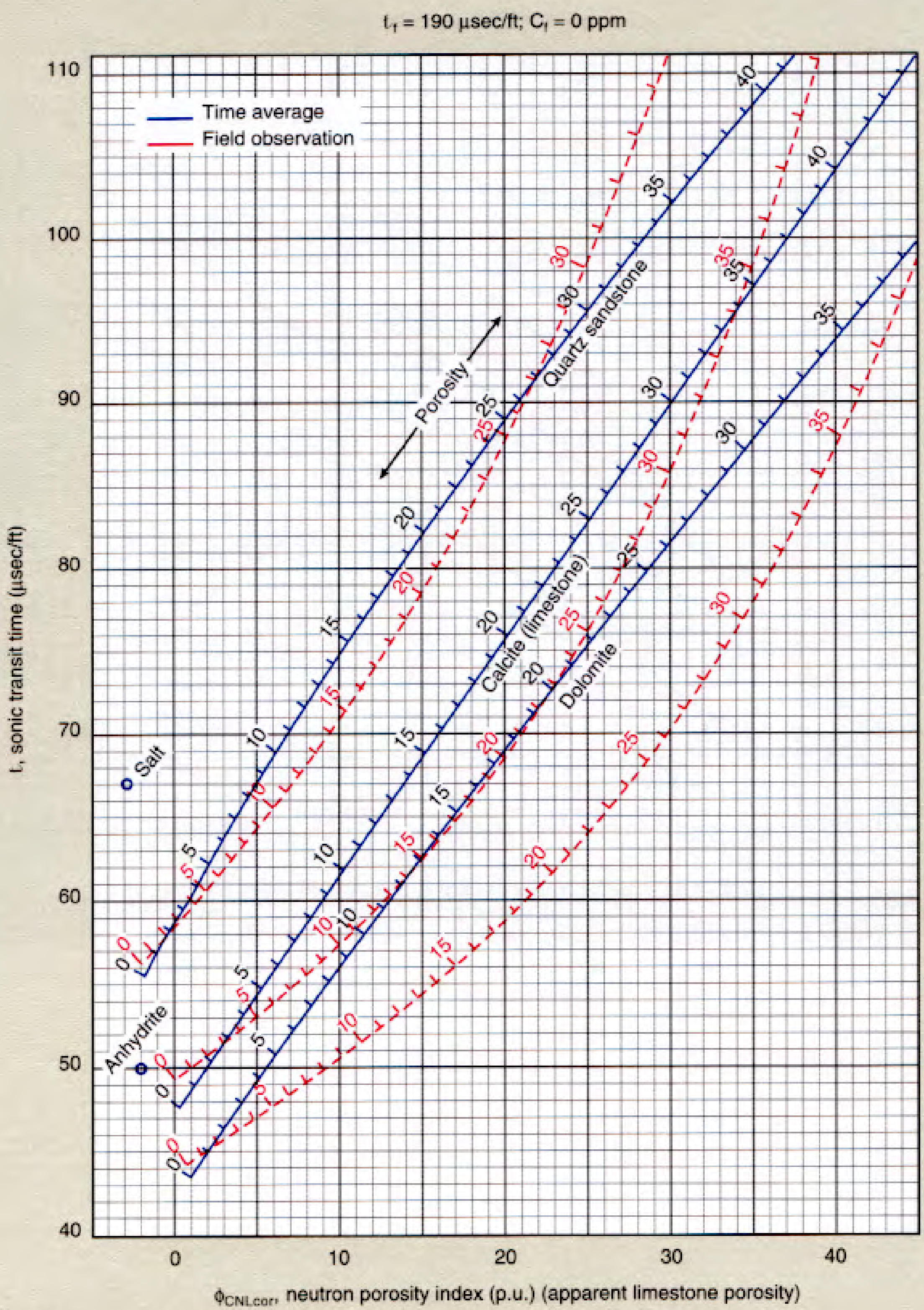
Porosity and Lithology Determination from Litho-Density* Log and Array Porosity Sonde (APS)



*Mark of Schlumberger

Porosity and Lithology Determination from Sonic Log and CNL* Compensated Neutron Log

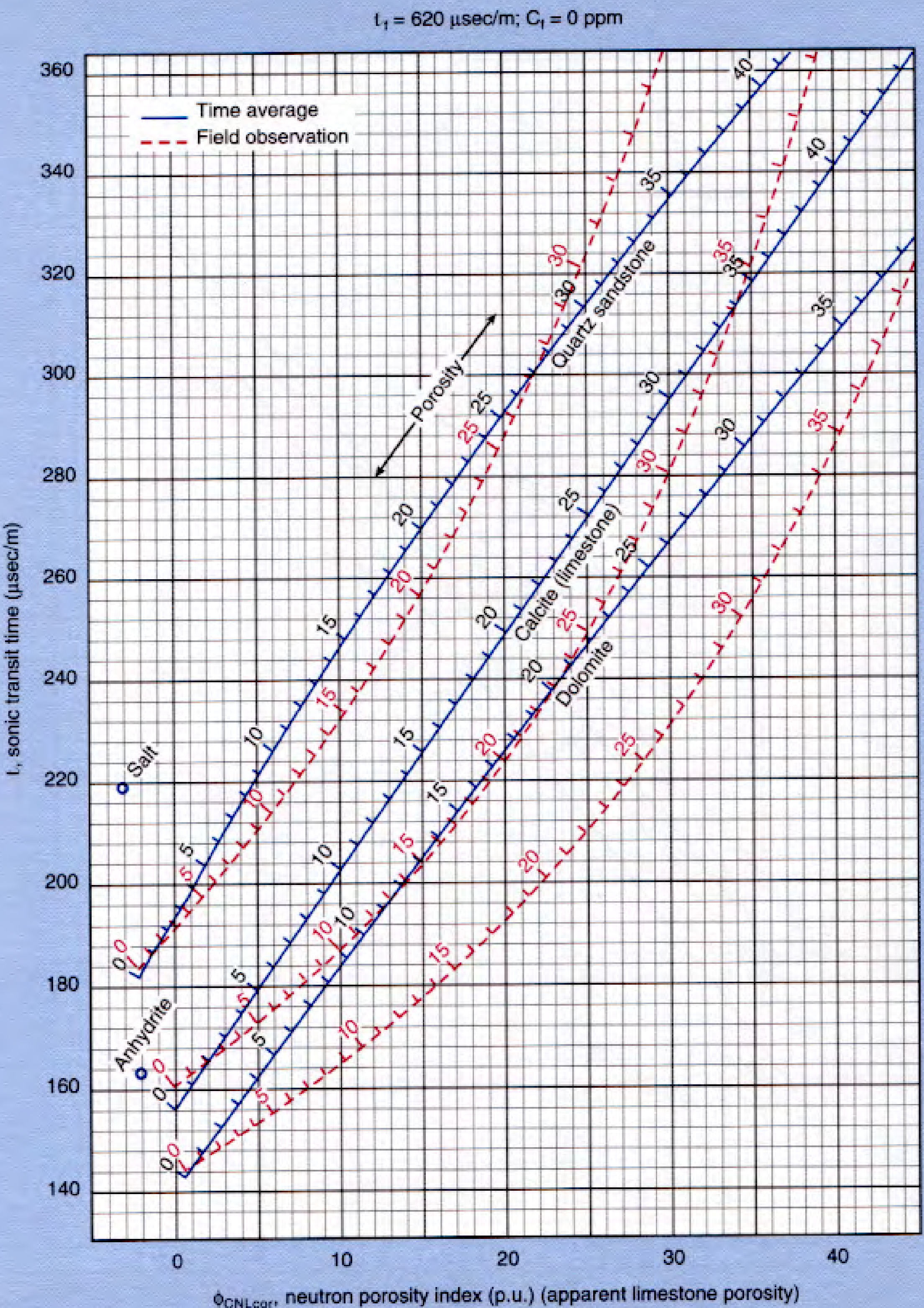
For CNL logs after 1986 labeled TNPH



Porosity and Lithology Determination from Sonic Log and CNL* Compensated Neutron Log

For CNL logs after 1986 labeled TNPH

CP-2cm (Metric)



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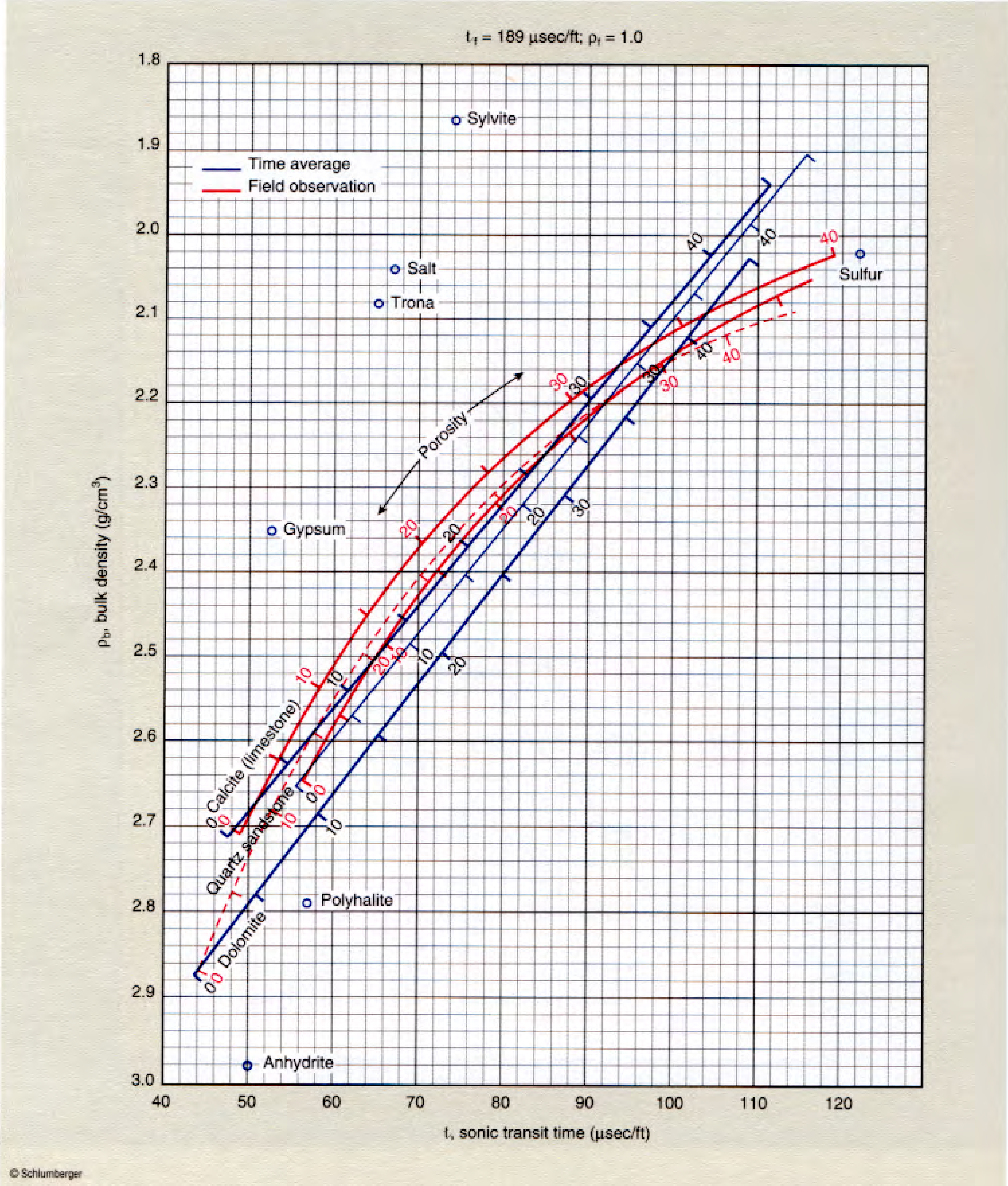
Lithology Identification from Formation Density Log and Sonic Log

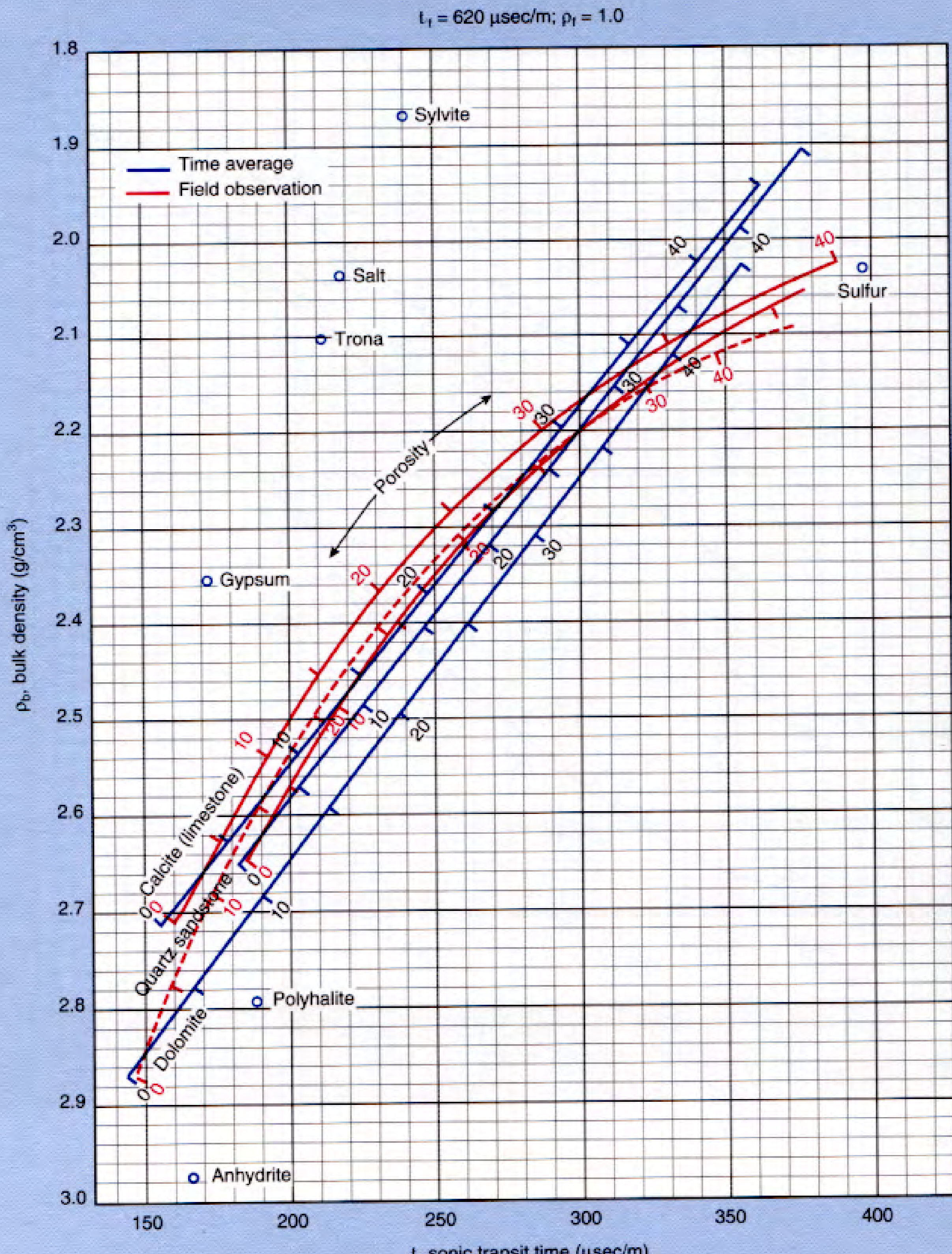
CP-7
(English)

CP



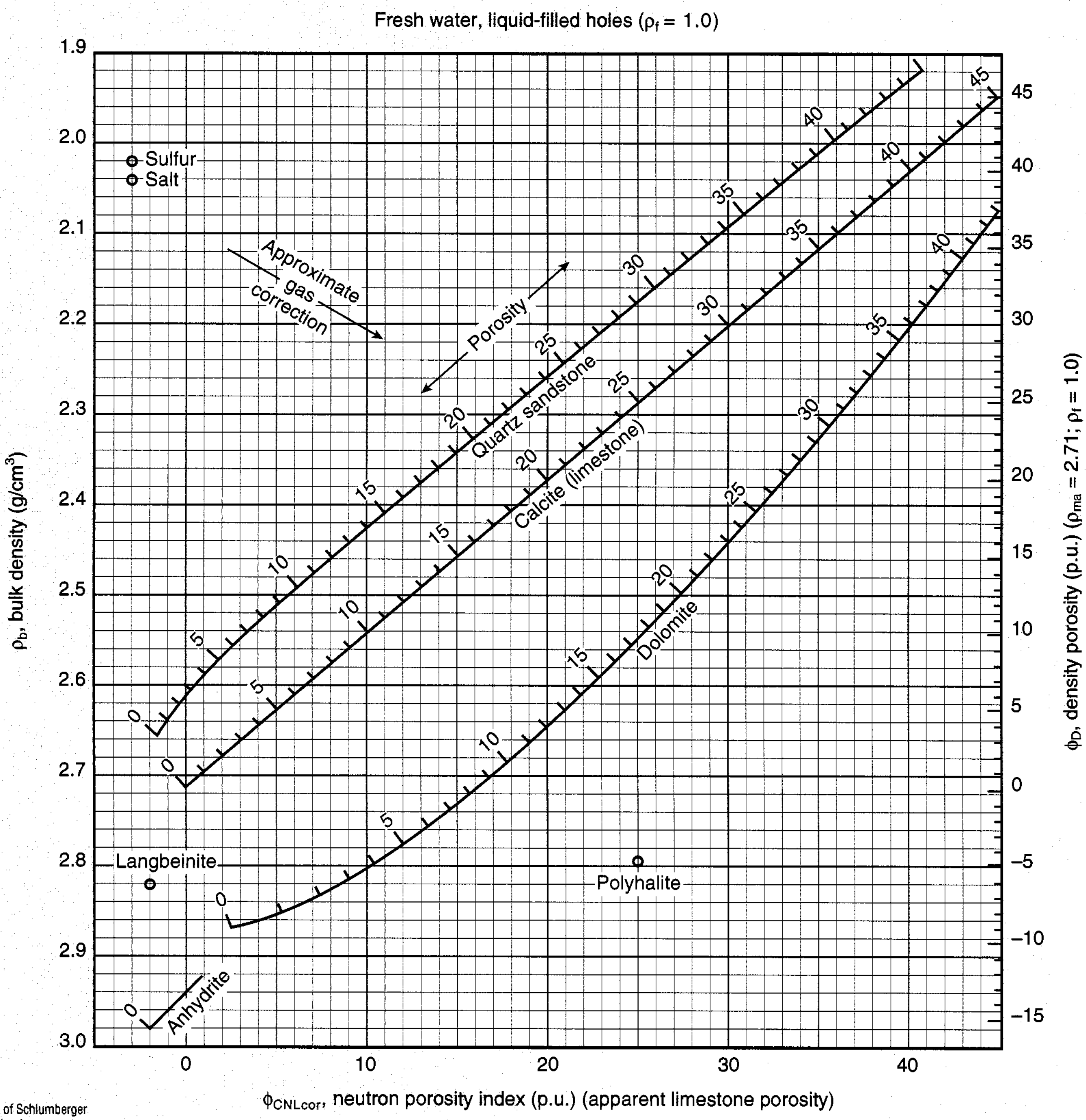
Lithology Identification from Formation Density Log and Sonic Log

CP-7m (Metric)



Porosity and Lithology Determination from Formation Density Log and CNL* Compensated Neutron Log

For CNL logs before 1986, or labeled NPHI



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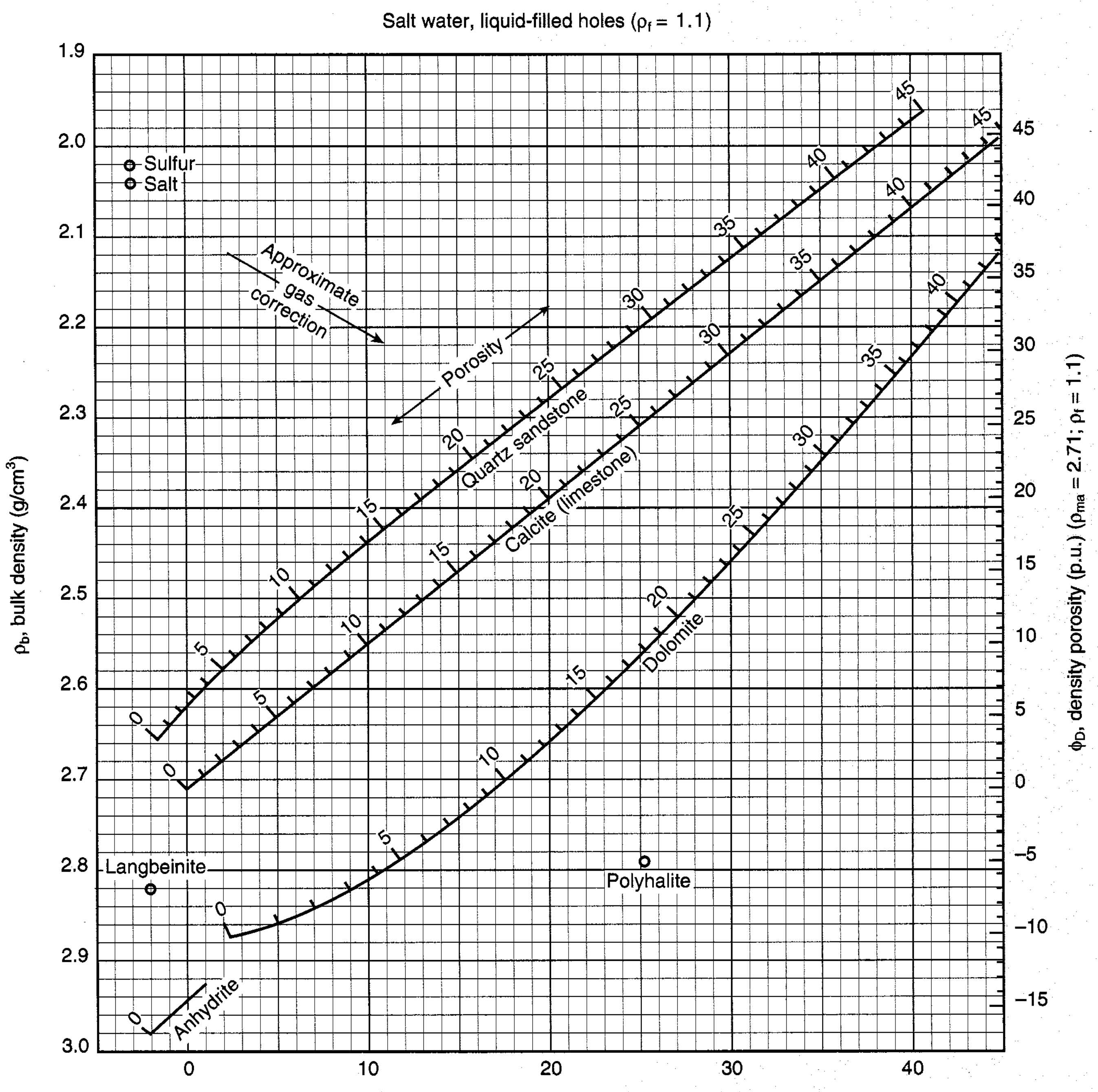
Porosity and Lithology Determination from Formation Density Log and CNL* Compensated Neutron Log

For CNL logs before 1986, or labeled NPHI

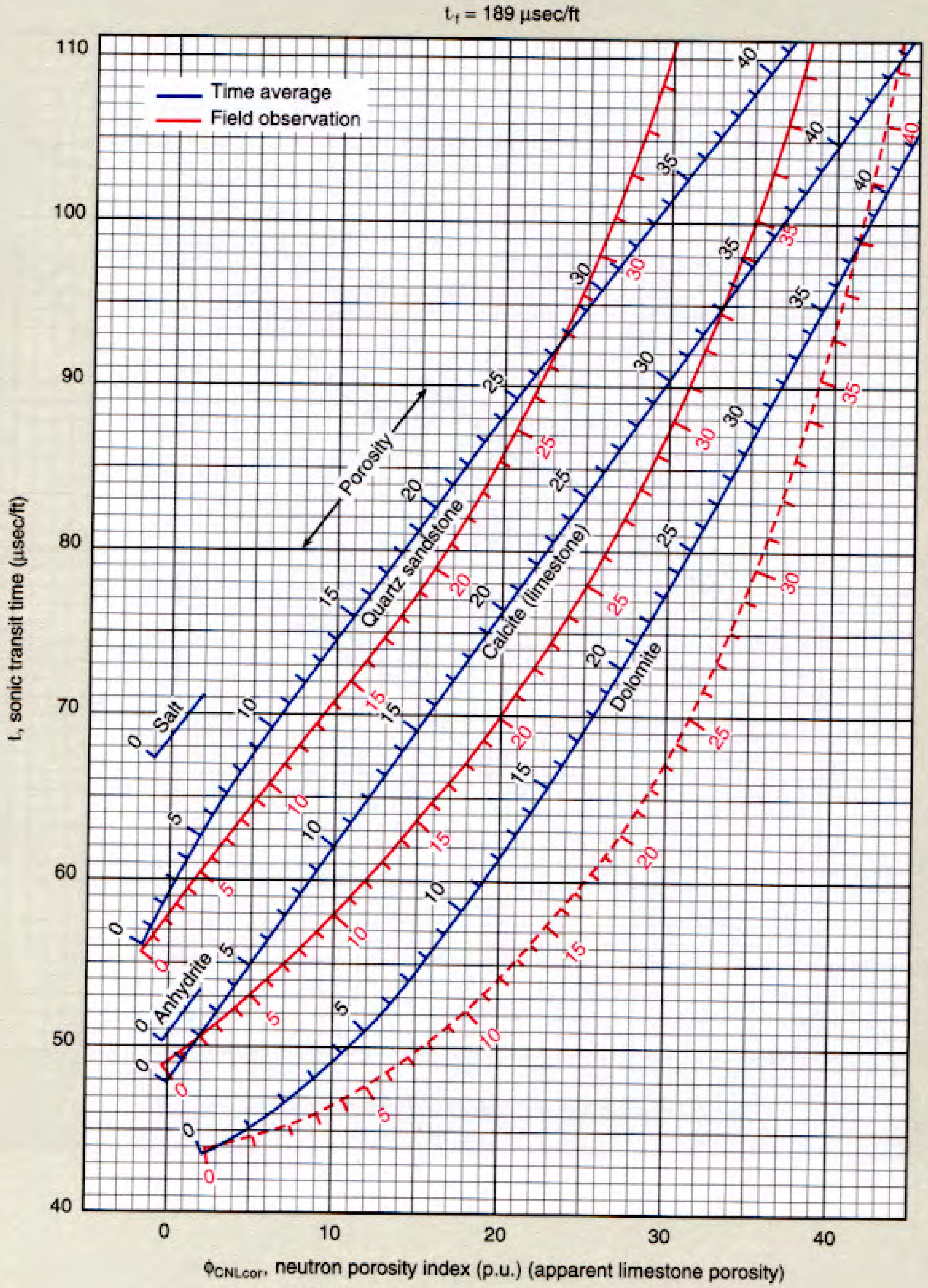
CP-1d



*Mark of Schlumberger

Porosity and Lithology Determination from Sonic Log and CNL* Compensated Neutron Log

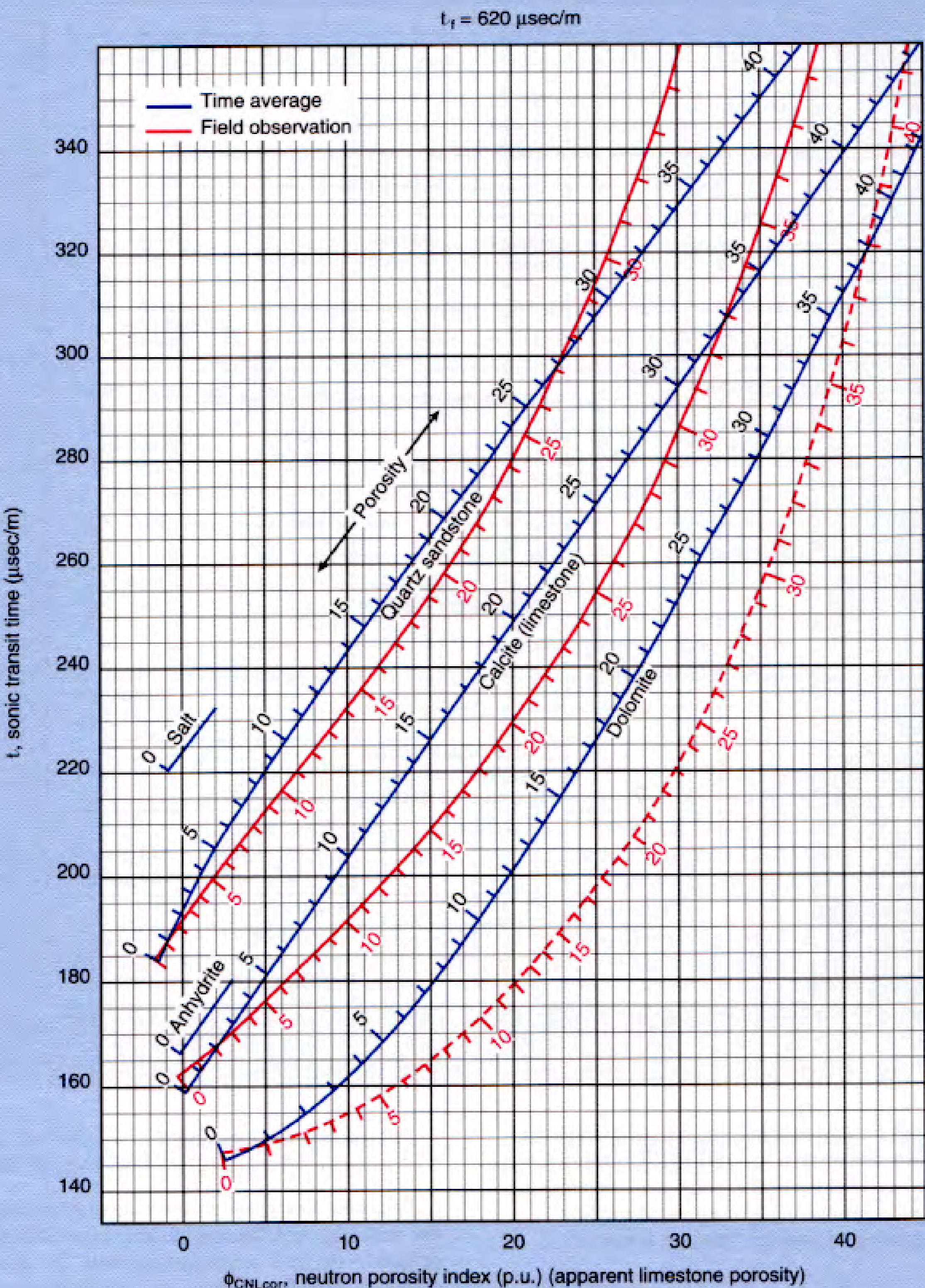
For CNL logs before 1986, or labeled NPHI



Porosity and Lithology Determination from Sonic Log and CNL* Compensated Neutron Log

For CNL logs before 1986, or labeled NPHI

CP-2bm (Metric)



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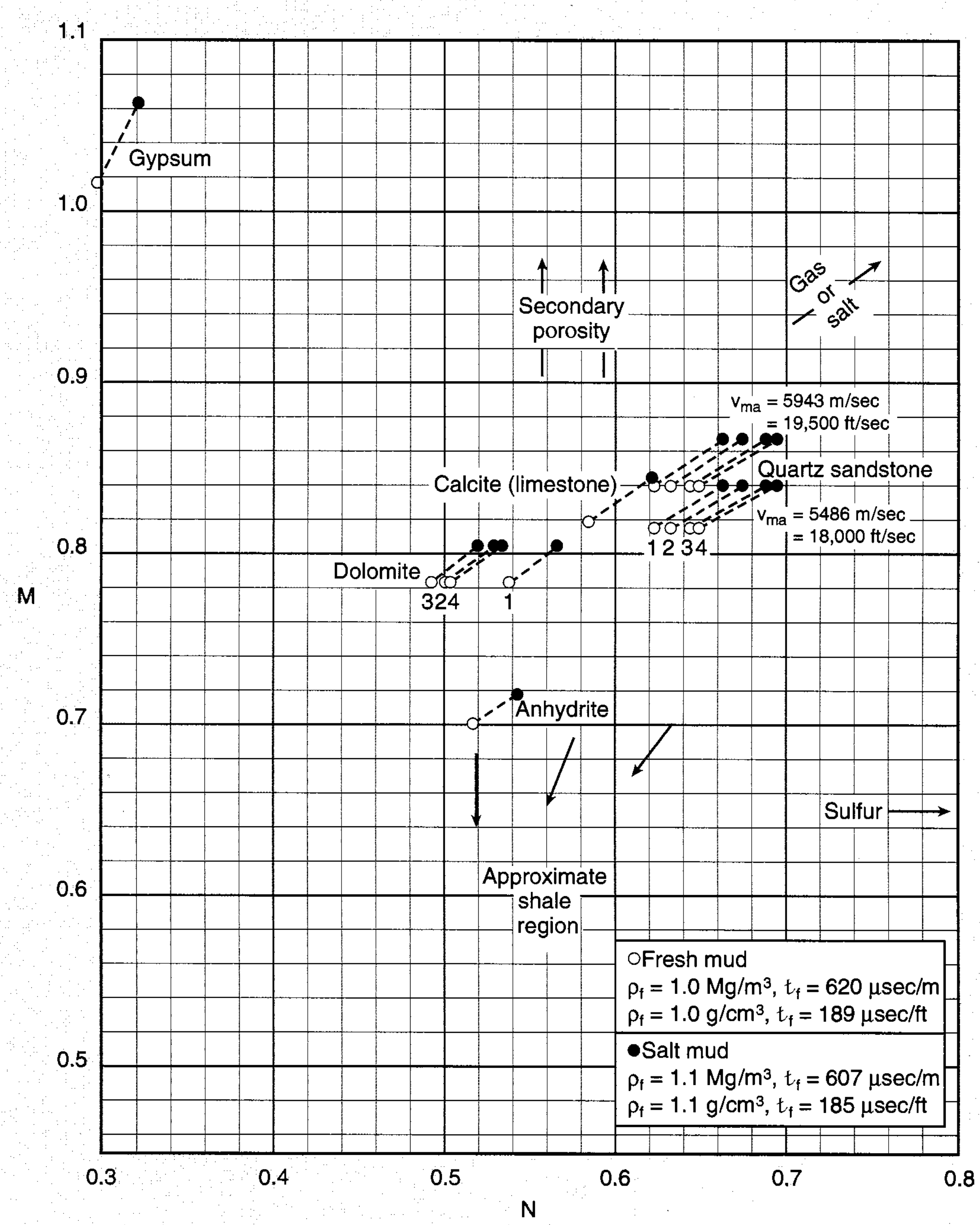
M-N Plot for Mineral Identification

For CNL* curves that have been environmentally corrected



This crossplot may be used to help identify mineral mixtures from sonic, density and neutron logs. (The CNL neutron log is used in the above chart; the time average sonic response is assumed.) Except in gas-bearing formations, M and N are practically independent of porosity. They are defined as:

$$M = \frac{t_f - t}{\rho_b - \rho_f} \times 0.01 \text{ (English)}$$

$$M = \frac{t_f - t}{\rho_b - \rho_f} \times 0.003 \text{ (metric)}$$

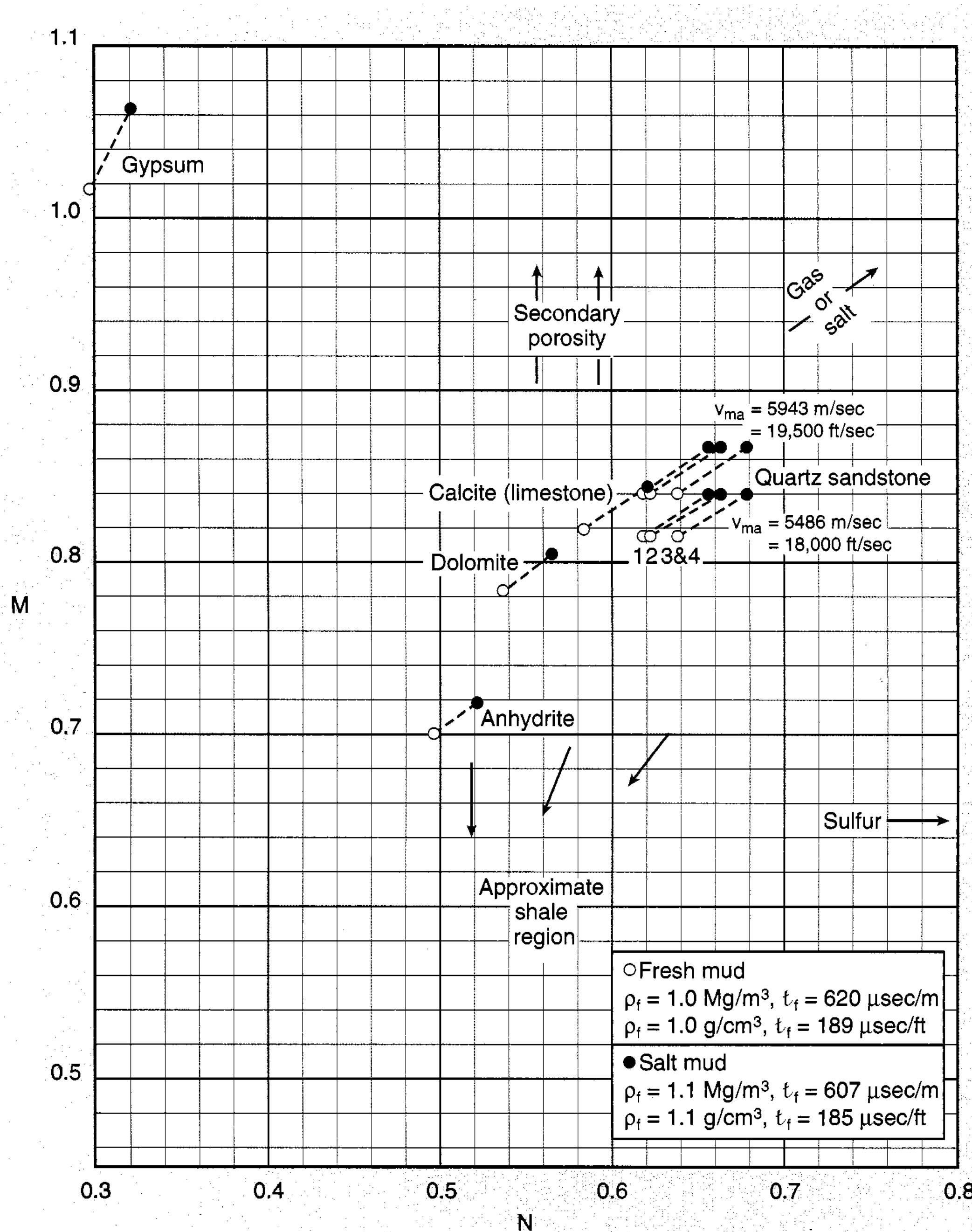
$$N = \frac{(\phi_N)_f - \phi_N}{\rho_b - \rho_f} \text{ (English or metric)}$$

Points for binary mixtures plot along a line connecting the two mineral points. Ternary mixtures plot within the triangle defined by the three constituent minerals. The effect of gas, shaliness, secondary porosity, etc., is to shift data points in the directions shown by the arrows.

The dolomite and sandstone lines on Chart CP-8 are divided by porosity range as follows: 1) $\phi = 0$ (tight formation); 2) $\phi = 0$ to 12 p.u.; 3) $\phi = 12$ to 27 p.u.; and 4) $\phi = 27$ to 40 p.u.

M-N Plot for Mineral Identification

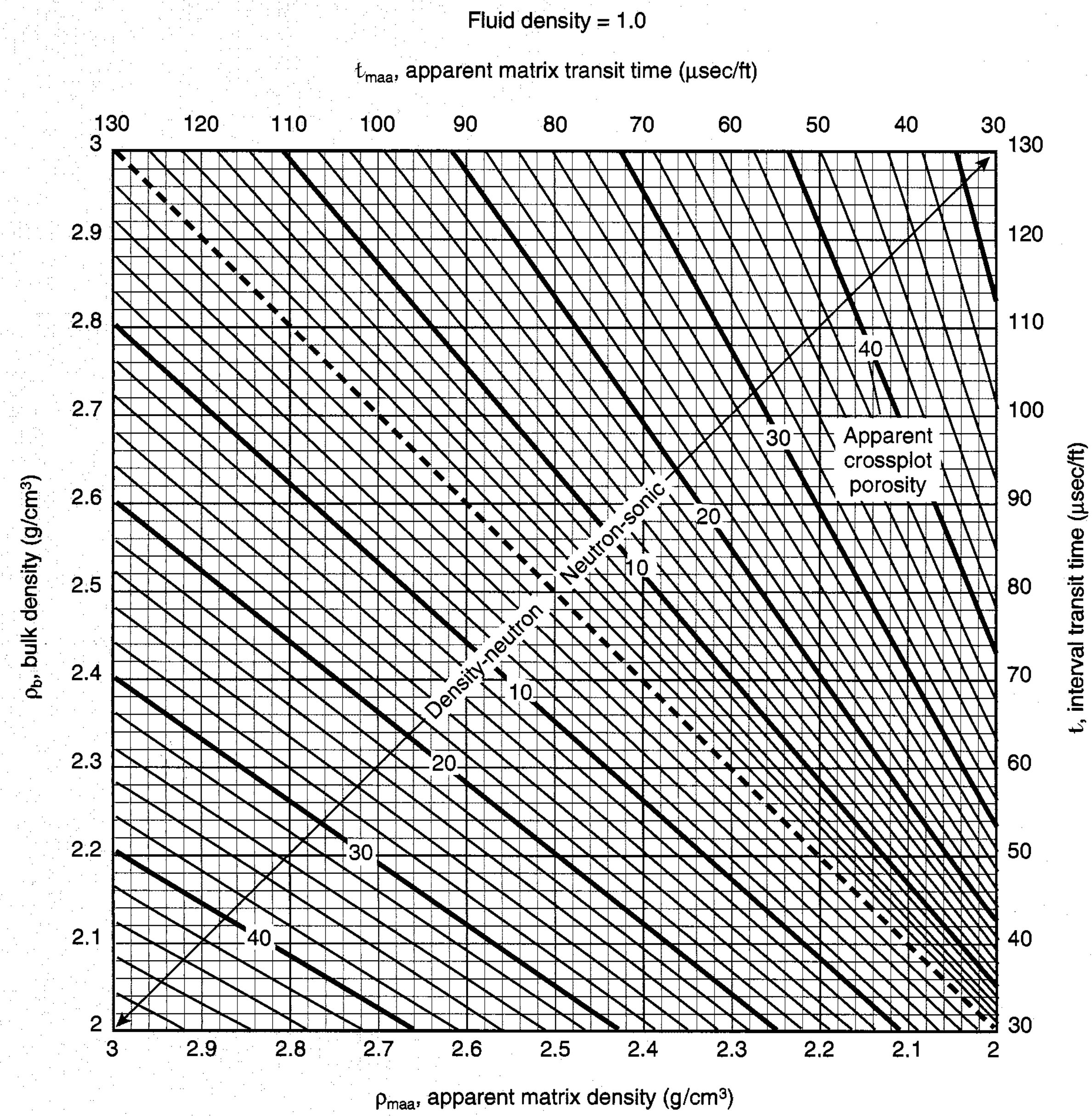
For APS curves that have been environmentally corrected



On Chart CP-8a, the APS apparent limestone porosity (APLC) replaces the CNL* apparent limestone porosity (NPHI) used on Chart CP-8.

Since there is negligible dolomite spread, a single dolomite point is plotted for each mud.

Determination of Apparent Matrix Parameters from Bulk Density or Interval Transit Time and Apparent Total Porosity



The MID plot permits the identification of rock mineralogy or lithology through a comparison of neutron, density and sonic measurements.

To use the MID plot, three steps are required. First, an apparent crossplot porosity must be determined using the appropriate neutron-density and empirical (red curves) neutron-sonic crossplot (Charts CP-1 through CP-7). For any data plotting above the sandstone curve on these charts, the apparent crossplot porosity is defined by a vertical projection to the sandstone curve.

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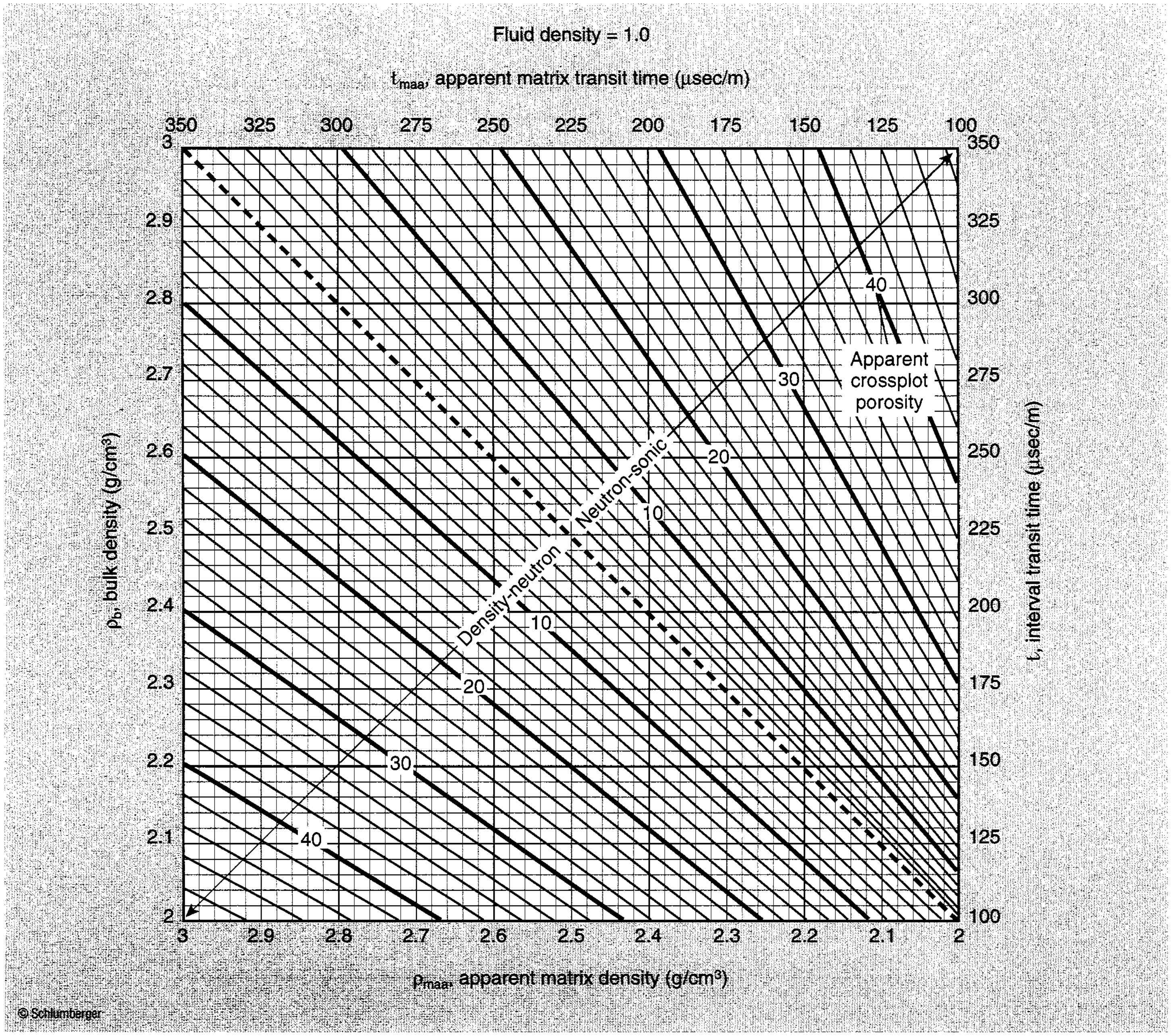
Determination of Apparent Matrix Parameters from Bulk Density or Interval Transit Time and Apparent Total Porosity

CP-14m (Metric)



Next, enter the appropriate CP-14 chart with the interval transit time. Go to the apparent crossplot porosity previously found on the appropriate neutron-sonic crossplot chart. This defines an apparent matrix interval transit time, t_{maa}. Similarly, enter the same chart with the bulk density, ρ_b. Go to the apparent crossplot porosity previously found on the appropriate density-neutron crossplot chart. This defines an apparent matrix grain density, ρ_{maa}.

Finally, the crossplot of the apparent matrix interval transit time and apparent grain density on the MID plot (Chart CP-15) identifies the rock mineralogy by its proximity to the labeled points on the plot.

The presence of secondary porosity in the form of vugs or fractures produces displacements parallel to the t_{maa} axis. The presence of gas displaces points as shown on the MID plot. Identification of shaliness is best done by plotting some shale points to establish the shale trend lines.

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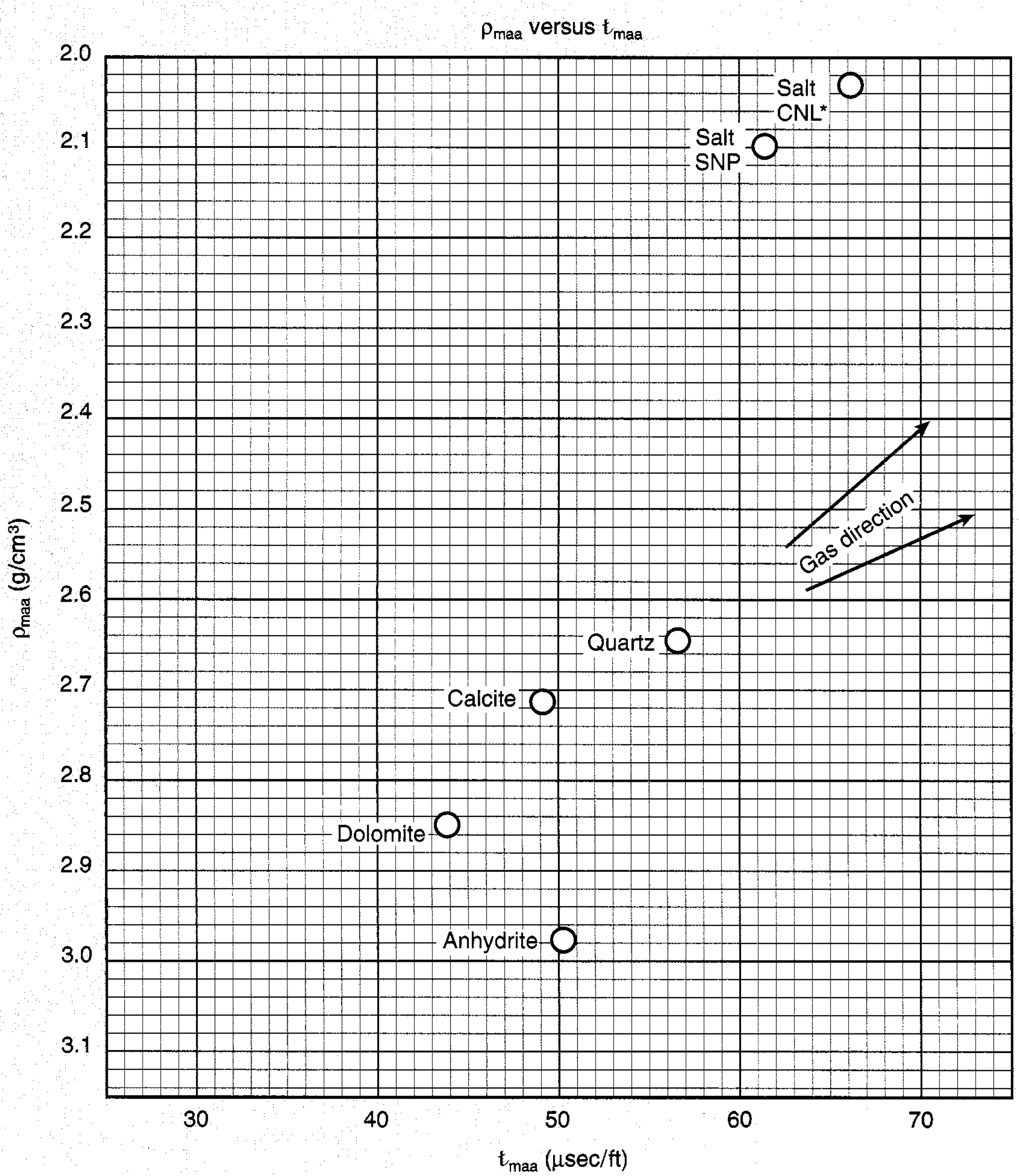
Matrix Identification (MID) Plot



Examples:

	Level 1	*Level 2*			
	$t = 67$ μsec/ft	$t = 63$ μsec/ft	giving	$\phi_{aND} = -1$	$\phi_{aND} = 21$
	$\rho_b = 2.04$ g/cm^3	$\rho_b = 2.46$ g/cm^3		$\phi_{aNS} = -1$	$\phi_{aNS} = 21$
	$\phi_{CNL} = -3$	$\phi_{CNL} = 24$ p.u.	and	$t_{maa} = 66$ μsec/ft	$t_{maa} = 43.5$ μsec/ft
	$\rho_f = 1.0$ g/cm^3			$\rho_{maa} = 2.03$ g/cm^3	$\rho_{maa} = 2.85$ g/cm^3

From the MID plot, Level 1 is identified as salt and Level 2 as dolomite.

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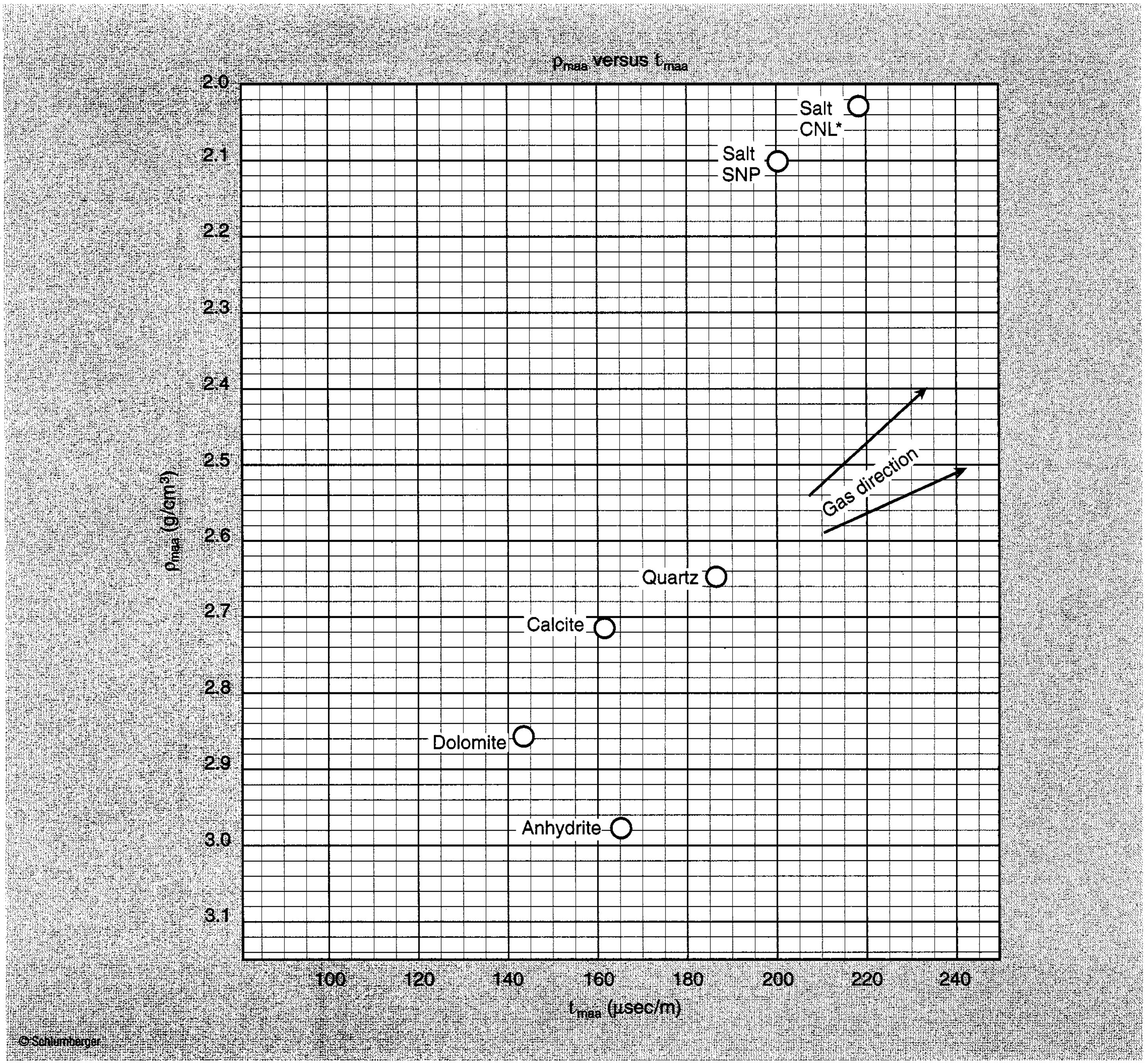
Matrix Identification (MID) Plot

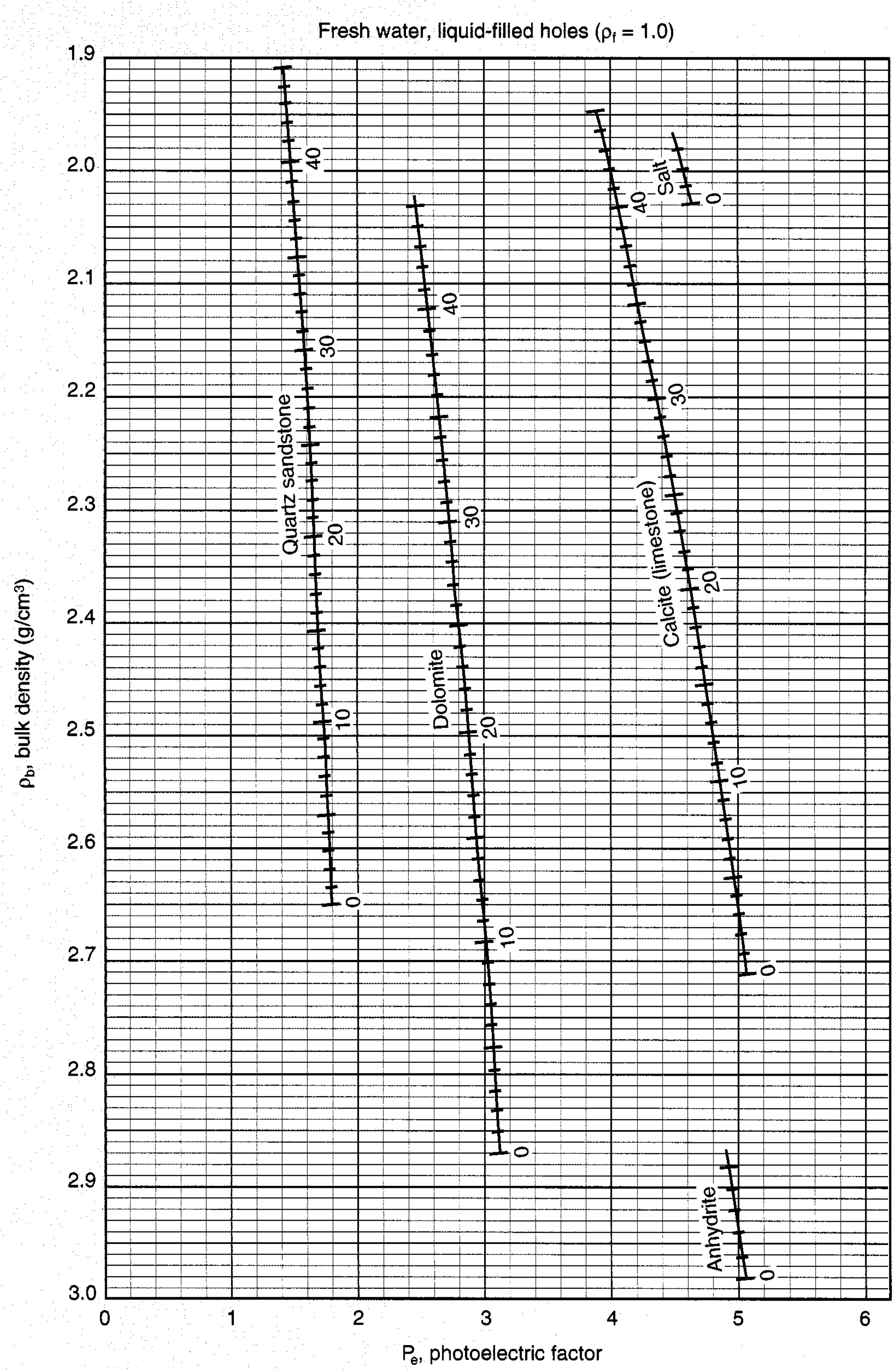


For fluid density, ρ_f (other than 1.0 g/cm³), correct (multiply) the apparent total porosity by the multiplier in the table before entry into the density portion of the chart.

For more information see Reference 8.

ρ_f	Multiplier
1.0	1.00
1.05	0.98
1.1	0.95
1.15	0.93

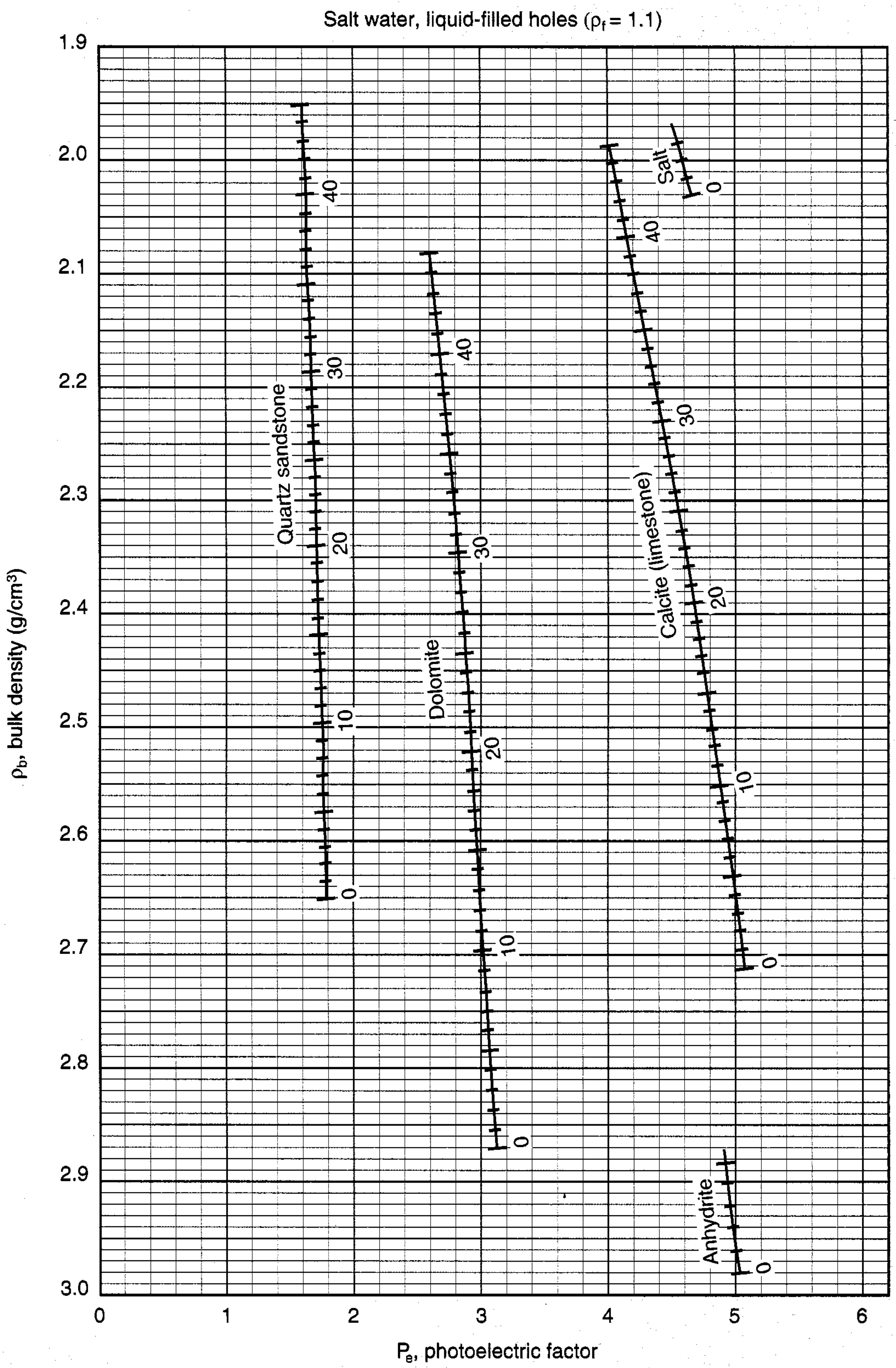
Porosity and Lithology Determination from Litho-Density* Log



*Mark of Schlumberger

For more information see Reference 27.

Porosity and Lithology Determination from Litho-Density* Log



*Mark of Schlumberger

For more information see Reference 27.

Mineral Identification from Litho-Density* Log and NGS* Natural Gamma Ray Spectrometry Log

Chart CP-18 provides clay mineralogy information using NGS Natural Gamma Ray Spectrometry and Litho-Density measurements. Because the porosity and the composition of many clay minerals may vary, the minerals plot on these crossplots not as unique points but as general areas.

After environmental correction, the appropriate parameters are plotted to provide qualitative information about the mineralogy.

Example: $Th_{NGScor} = 10.6$ ppm

$U_{NGScor} = 4.5$ ppm

$K_{NGScor} = 3.9\%$

$P_e = 3.2$

giving $Th/K = 10.6/3.9 = 2.7$

Plotting these parameters on Chart CP-18 suggests that the clay mineral is illite.

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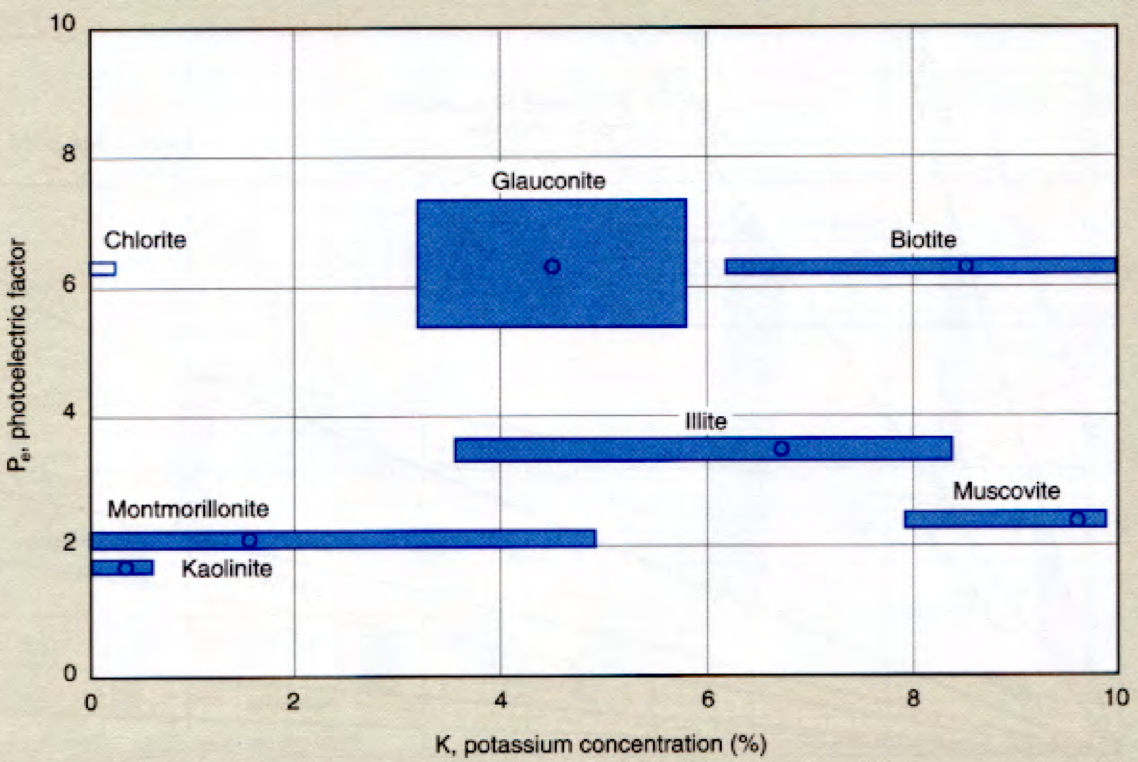
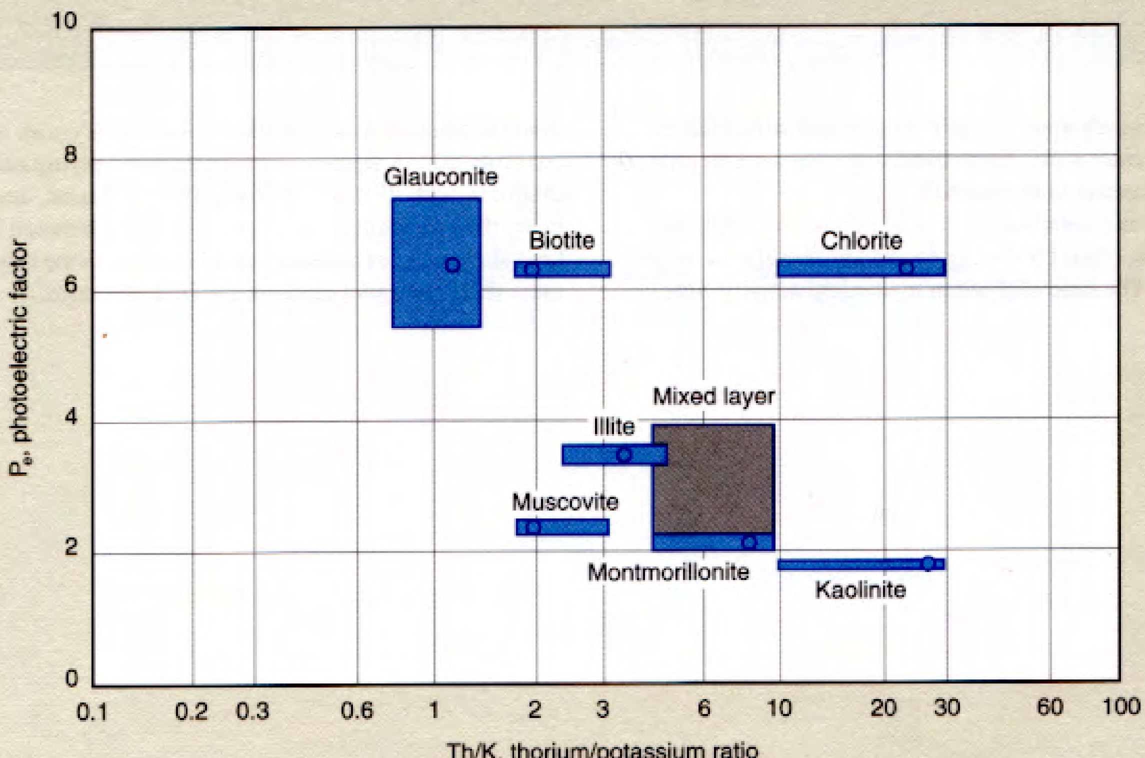
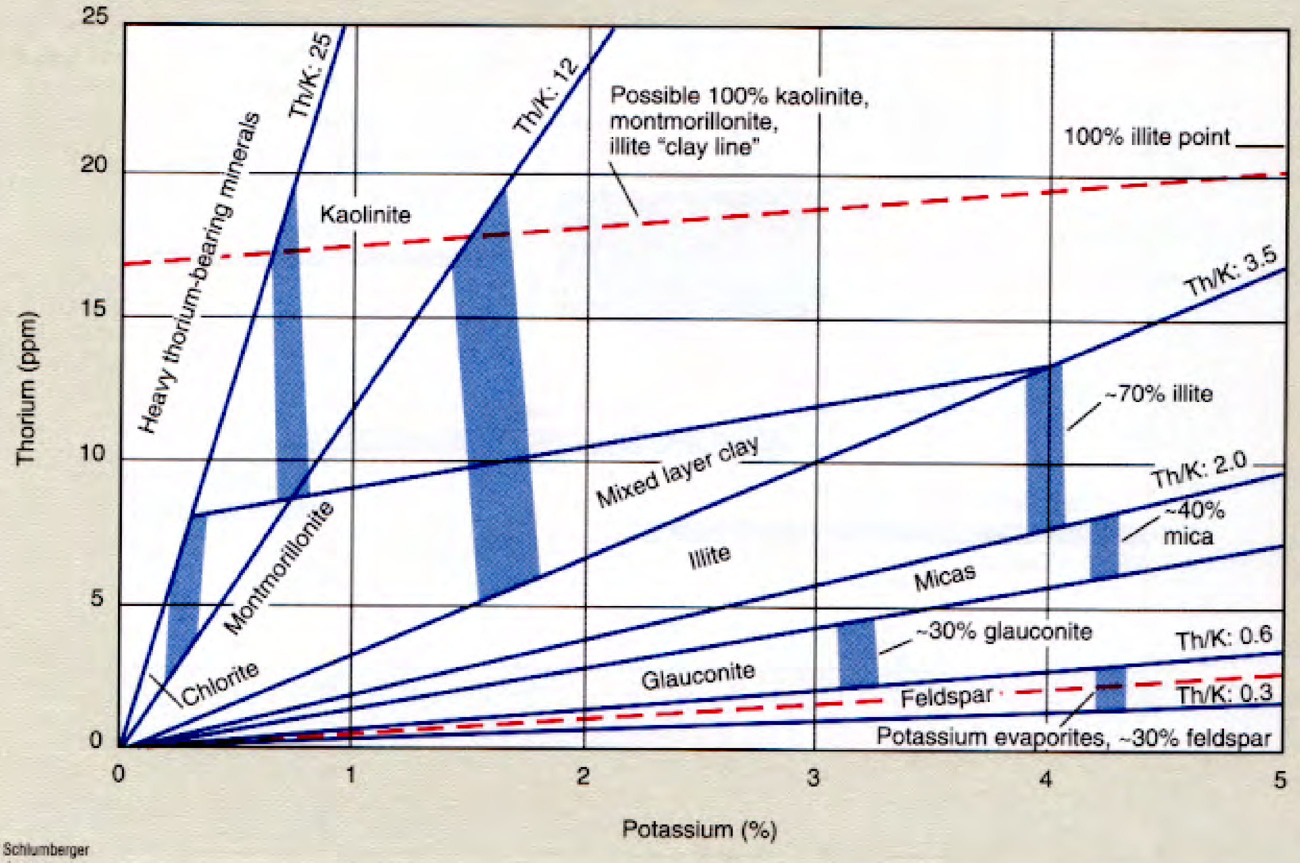
Mineral Identification from Litho-Density* Log and NGS* Natural Gamma Ray Spectrometry Log





*Mark of Schlumberger

Mineral Identification from NGS* Natural Gamma Ray Spectrometry Log

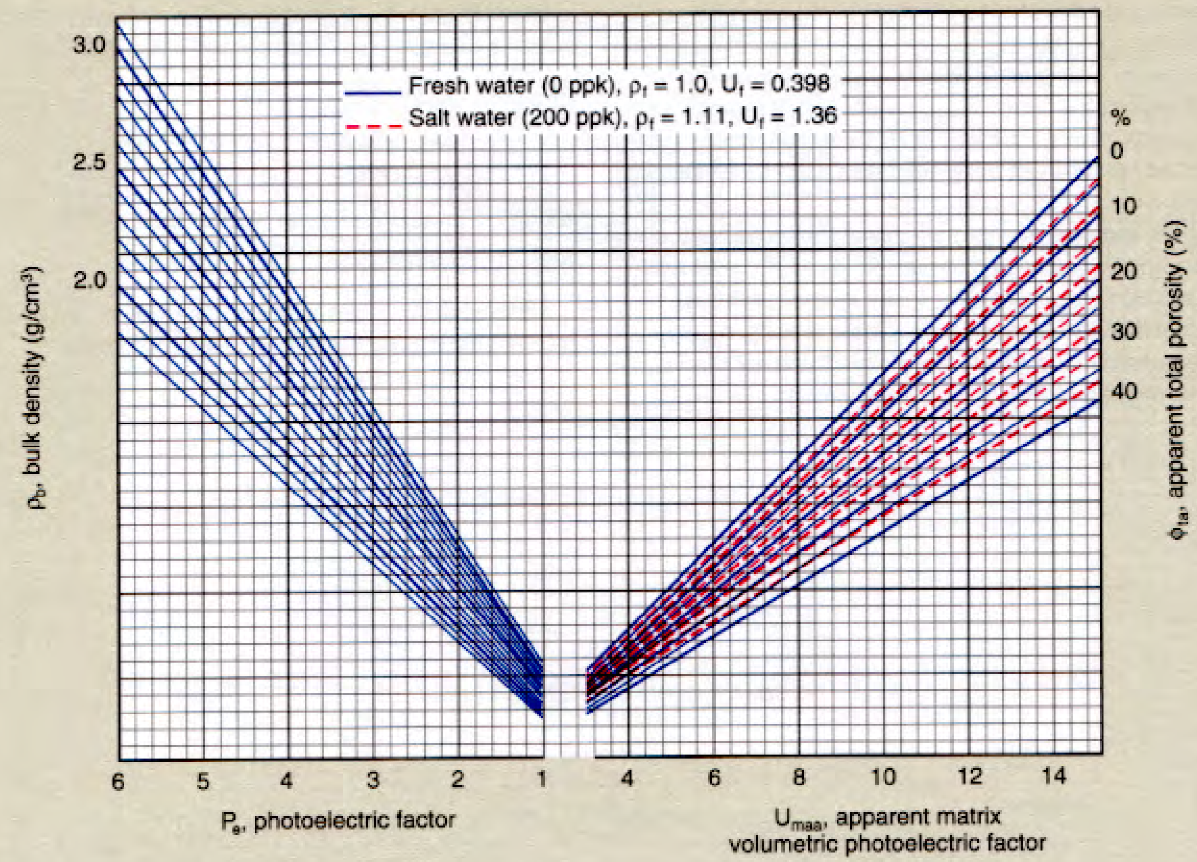


*Mark of Schlumberger

Radioactive minerals often occur in relatively small concentrations in sedimentary rocks. Even shales typically contain only 30 to 70% radioactive clay minerals.

Unless there is a complex mixture of radioactive minerals in the formation, Chart CP-19 can be used to identify the more common ones. The ratio of thorium to uranium activity—the thorium/potassium ratio, Th/K—does not vary with mineral concentration. A sandstone reservoir with varying amounts of shaliness, with illite as the principal clay mineral, usually plots in the illite segment of the chart, with Th/K between 2.0 and 2.5. Less shaly parts of the reservoir plot closer to the origin, and more shaly parts plot closer to the 70% illite area.

Determination of Apparent Matrix Volumetric Photoelectric Factor



Lithology Identification Plot

Plot CP-21 identifies rock mineralogy through a comparison of apparent matrix grain density and apparent volumetric photoelectric factor.

To use, apparent matrix grain density, ρ_{maa}, and apparent volumetric photoelectric factor, U_{maa}, are entered in ordinate and abscissa, respectively, on Plot CP-21. Rock mineralogy is identified by the proximity of the plotted data point to the labeled points on the plot.

To determine apparent matrix grain density, an apparent total porosity must first be determined (using, for example, a neutron-density crossplot). Then, Chart CP-14 may be used with bulk density, ρ_b, to define the apparent matrix grain density, ρ_{maa}.

To find the apparent matrix volumetric photoelectric factor, U_{maa}, enter Nomograph CP-20 with the photoelectric factor, P_e; go vertically to the bulk density, ρ_b; then, go horizontally across to the total porosity, ϕ_t; and finally, go vertically downward to define the matrix volumetric photoelectric factor, U_{maa}.

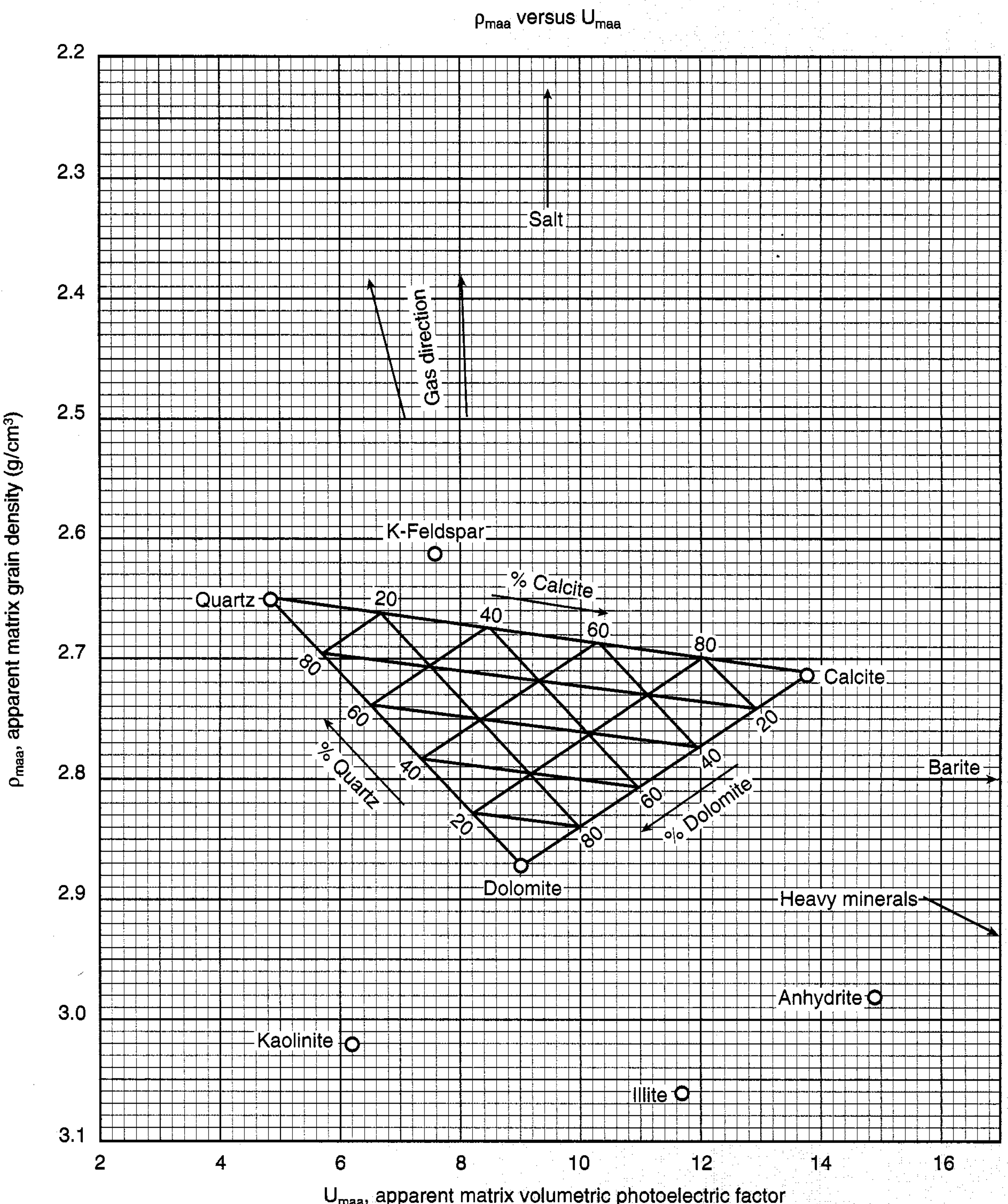
Example: $P_e = 3.65$
$\rho_b = 2.52$ g/cm^3 ($\rho_f = 1.0$ g/cm^3)
$\phi_{ta} = 16\%$
giving $\rho_{maa} = 2.81$ g/cm^3 (from Chart CP-14)
and $U_{maa} = 10.9$

Plotting these values indicates the level to be a mixture of approximately 60% dolomite and 40% limestone.

For more information see Reference 27.

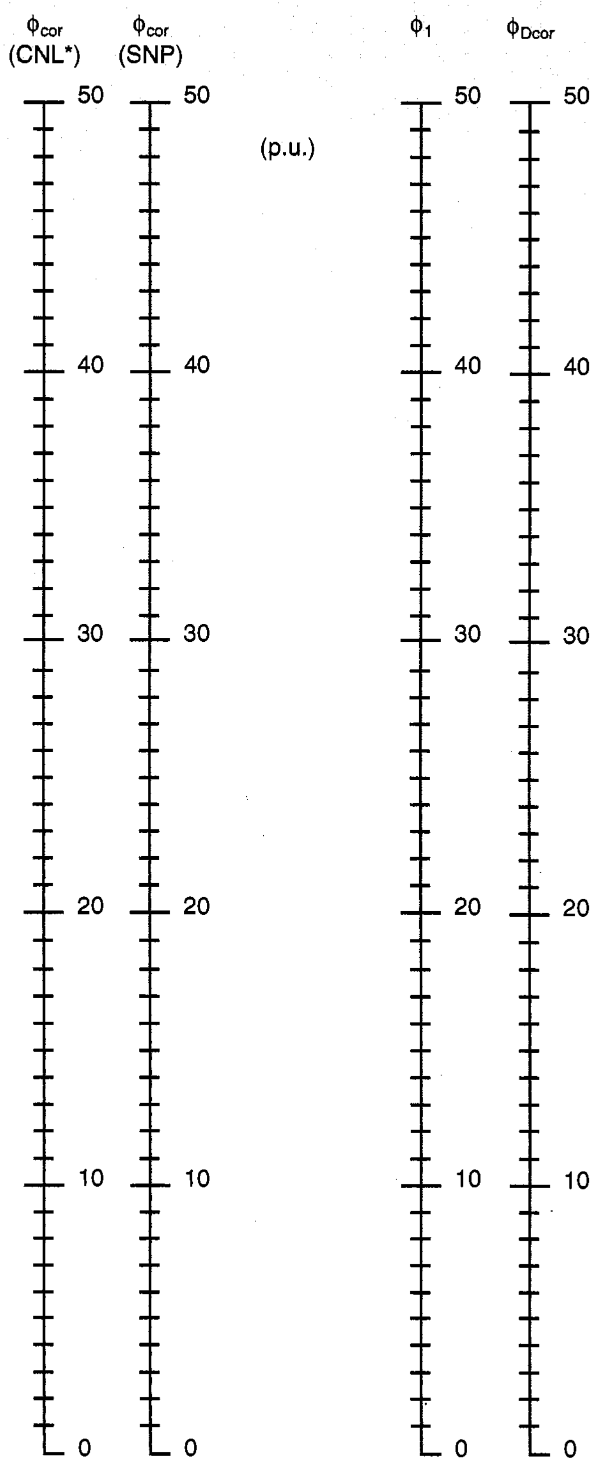
CP

Lithology Identification Plot



Porosity Estimation in Hydrocarbon-Bearing Formations

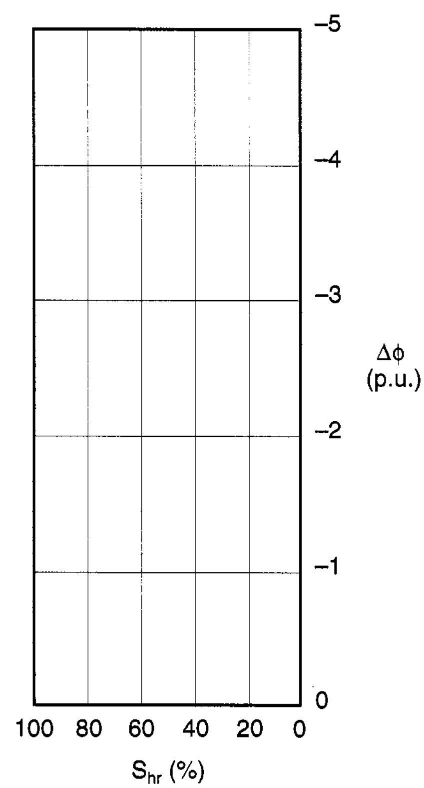
From neutron, density and R_{xo} logs



This nomograph estimates porosity in hydrocarbon-bearing formations using neutron, density and R_{xo} logs. The neutron and density logs must be corrected for environmental effects and lithology prior to entry into the nomograph. The chart includes an approximate correction for excavation effect, but if $\rho_h < 0.25$ (gases), the chart may not be accurate in some extreme cases: very high values of porosity (> 35 p.u.) coupled with medium to high values of S_{hr}, and for $S_{hr} \approx 100\%$ for medium to high values of porosity.

To use, connect the apparent neutron porosity point on the appropriate neutron stem with the apparent density porosity on the density stem with a straight line. From the intersection of this line with the porosity, ϕ_1, stem, draw a line to the origin of the S_{hr} versus $\Delta\phi$ chart. Entering this chart with the hydrocarbon saturation, S_{hr}, ($S_{hr} = 1 - S_{xo}$) defines a porosity correction factor $\Delta\phi$. This correction factor algebraically added to porosity, ϕ_1, gives the true porosity.

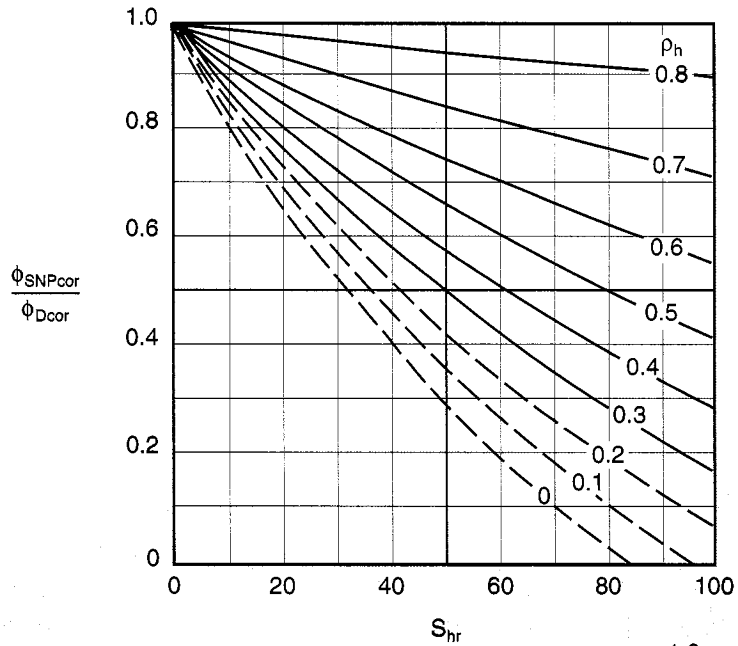
Example: $\phi_{CNLcor} = 12$ p.u. giving $\phi_1 = 32.2$ p.u.
$\phi_{Dcor} = 38$ p.u. and $\Delta\phi = -1.6$ p.u.
$S_{hr} = 50\%$ Therefore, $\phi = 32.2 - 1.6 = 30.6$ p.u.

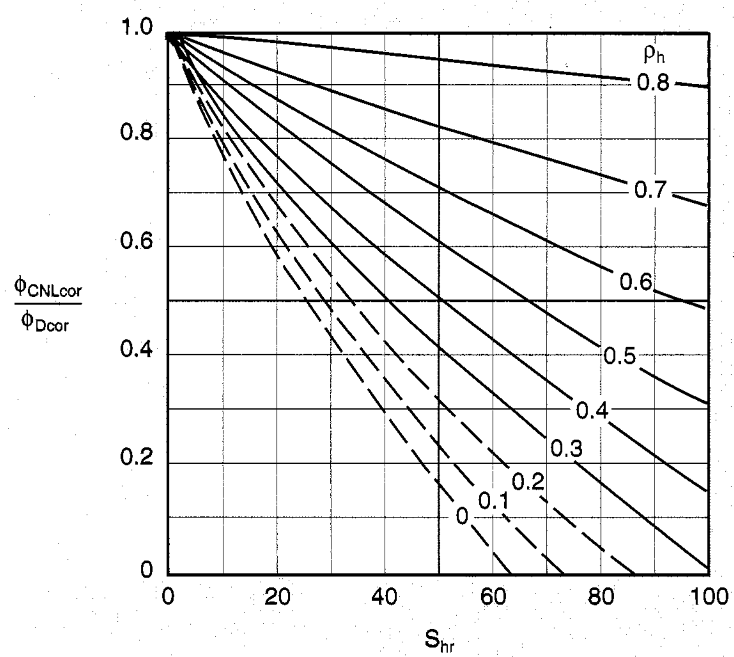


*Mark of Schlumberger

Estimation of Hydrocarbon Density

From neutron and density logs





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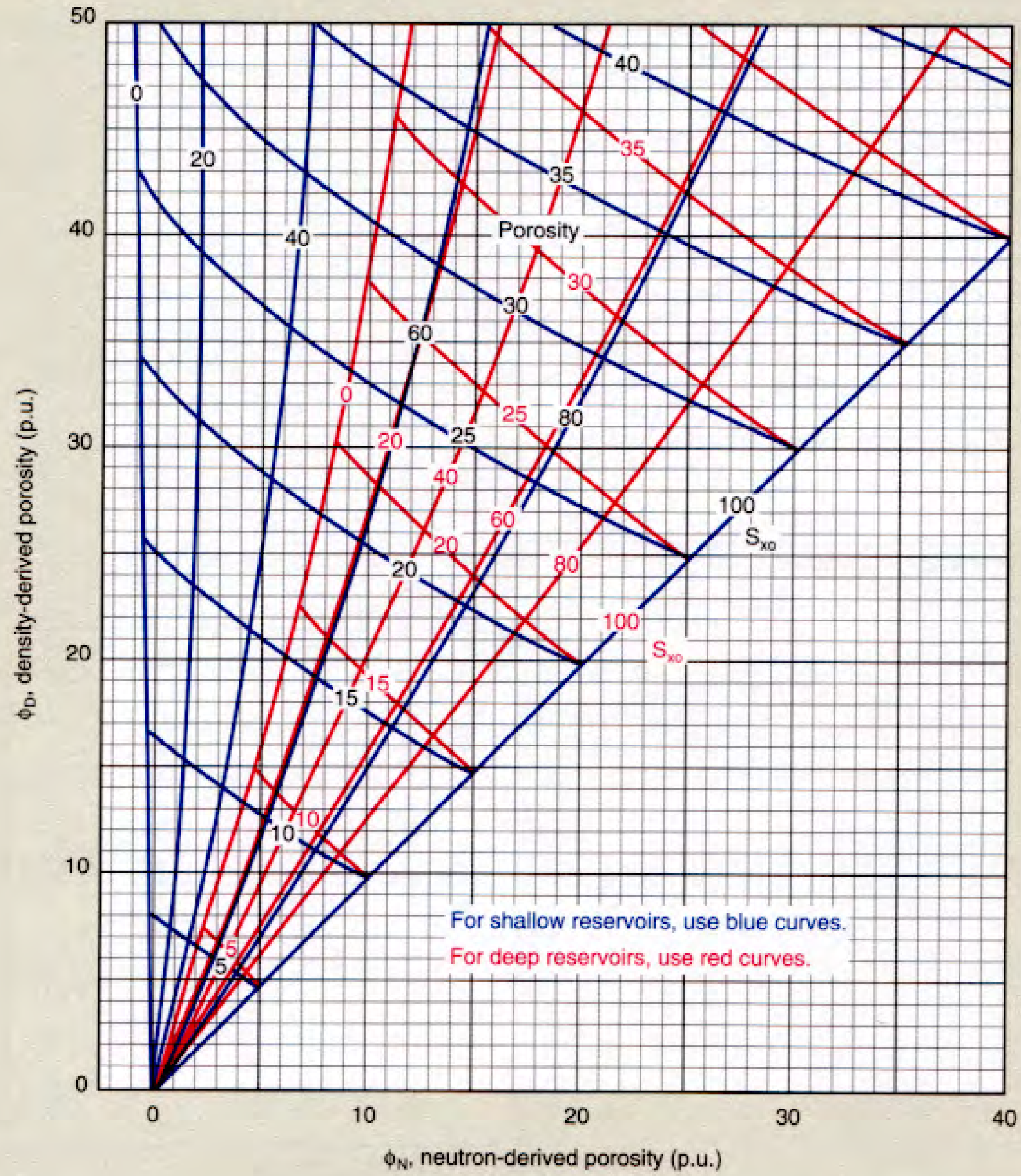
These charts estimate the density of the saturating hydrocarbon from a comparison of neutron and density measurements, and the hydrocarbon saturation in the portion of the rock investigated by the neutron and density logs (invaded or flushed zone). The neutron log (either CNL* or SNP log) and the density log must be corrected for environmental effect and lithology before entry into the charts.

To use, enter the appropriate chart with the ratio of neutron porosity to density porosity, and the hydrocarbon saturation. The intersection defines the hydrocarbon density in g/cm^3.

Example: ϕ_{CNLcor} = 15 p.u.
ϕ_{Dcor} = 25 p.u.
and S_{hr} = 30%
Therefore, ρ_h = 0.28 g/cm^3

Charts CP-9 and CP-10 have not been updated for CNL logs run after 1986 or labeled TNPH; approximations may therefore be greater with more recent logs. For approximate results with APLC porosity (from IPL* logs), use Charts CP-9 and CP-10 for SNP logs.

Gas-Bearing Formations—
Porosity from Density and Neutron Logs



Based on reservoir depth and conditions, enter the appropriate chart with matrix-corrected porosity values. Average water saturation in the flushed zone, S_{xo}, and porosity are derived. This chart assumes fresh water and gas of composition $C_{1.1}H_{4.2}$, and it includes correction of the neutron log for "excavation effect."

For more information see Reference 6.

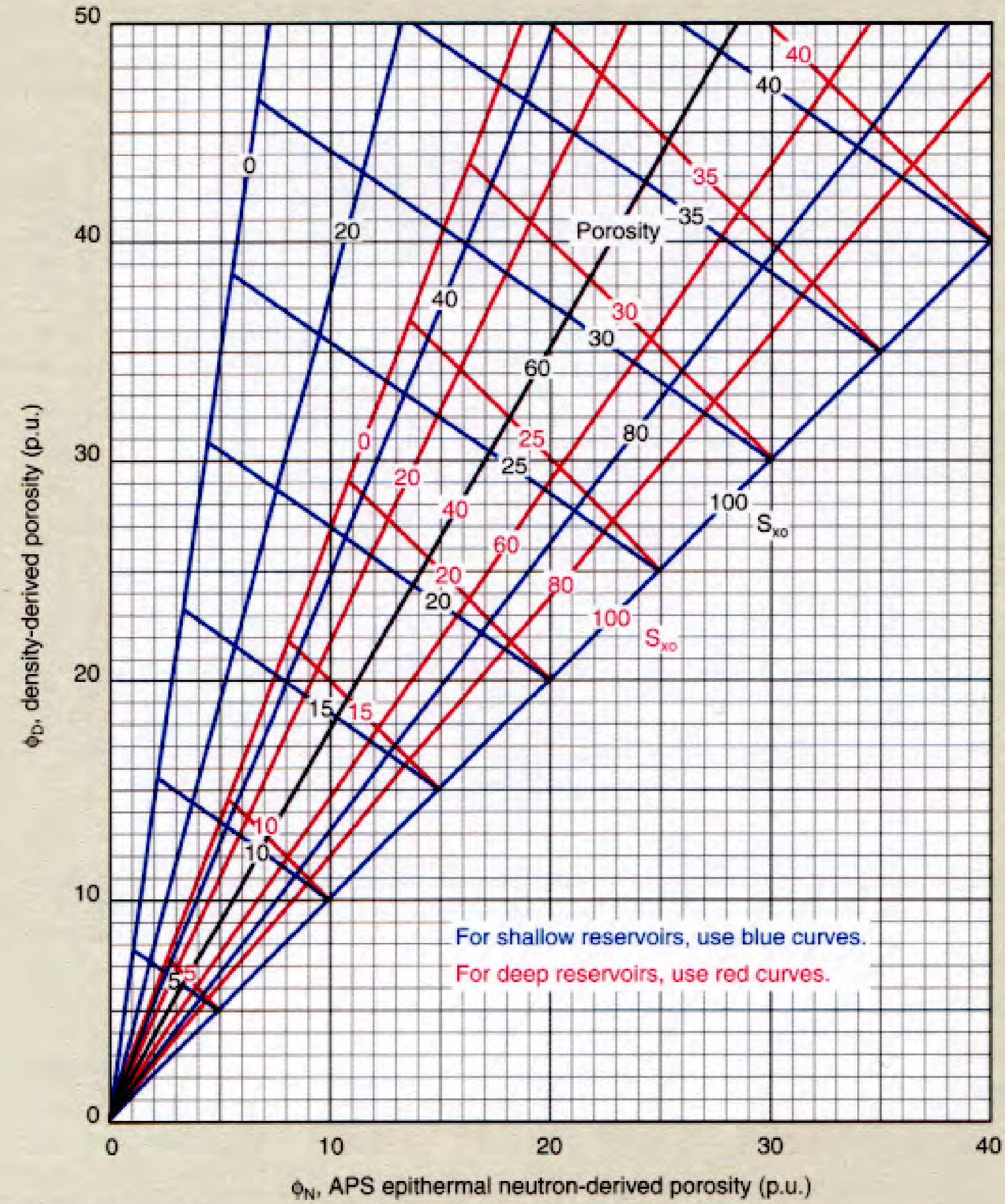
The conditions represented by the curves are listed in the table below.

Example: ϕ_D reads 25%, and ϕ_N reads 10% in a low-pressure, shallow (4000-ft) reservoir.

Therefore, ϕ = 20%, and S_{xo} = 62%.

Depth	Pressure	Temperature	P_w	I_{Hw}	P_g	I_{Hg}
Shallow reservoirs (blue)	~2000 psi [~14,000 kPa]	~120°F [~50°C]	1.00	1.00	0	0
Deep reservoirs (red)	~7000 psi [~48,000 kPa]	~240°F [~120°C]	1.00	1.00	0.25	0.54

Gas-Bearing Formations— Porosity from Density and APS Epithermal Neutron Logs



Based on reservoir depth and conditions, enter the chart with sandstone-corrected porosity values. Average water saturation in the flushed zone, S_{xo}, and porosity are derived. This chart assumes fresh water and gas of composition CH_4.

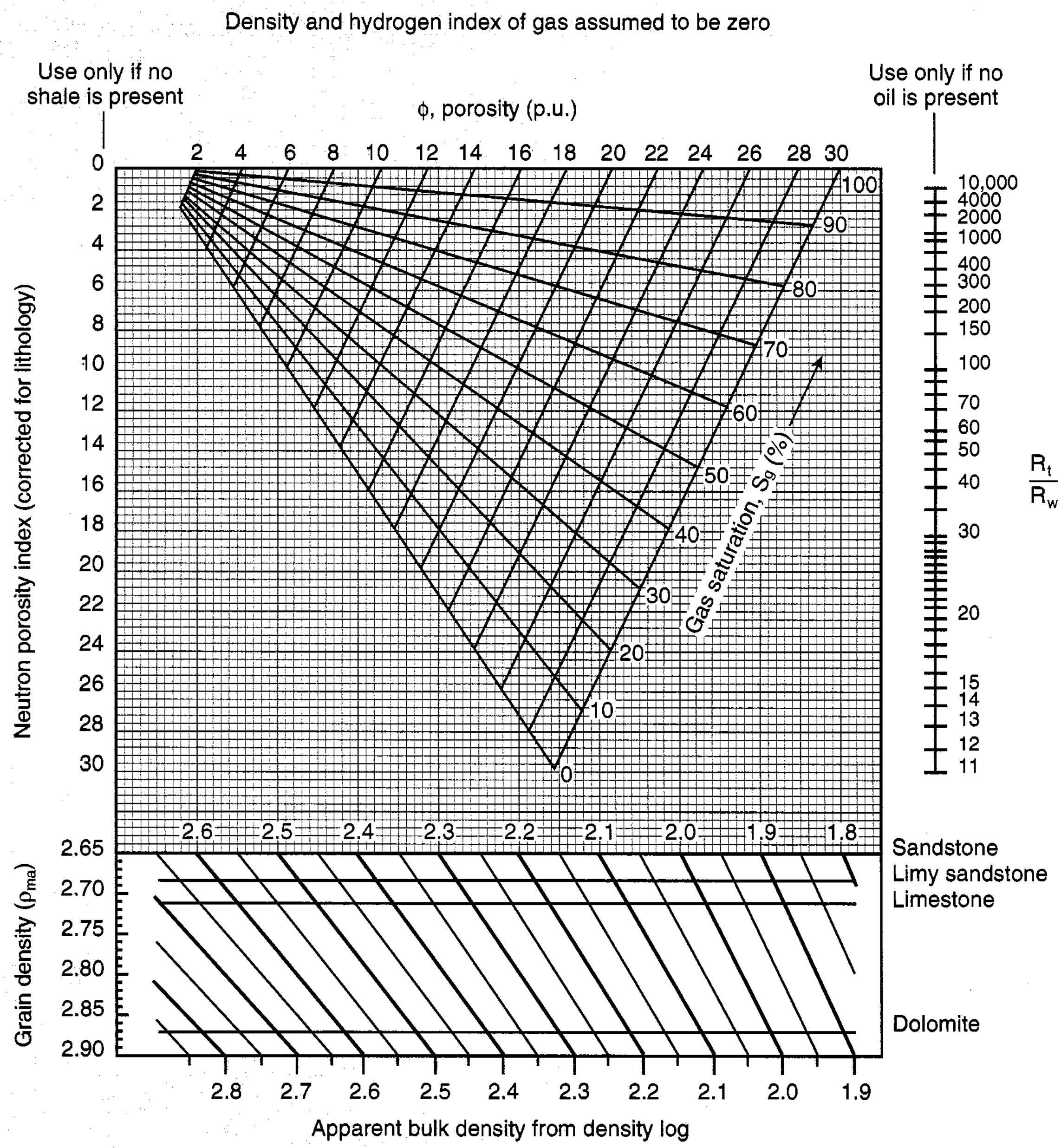
The conditions represented by the curves are listed in the table below.

Example: ϕ_D reads 24%, and ϕ_N reads 14% in a low-pressure, shallow (4000-ft) reservoir.

Therefore, ϕ = 20%, and S_{xo} = 62%.

Depth	Pressure	Temperature	ρ_w	I_{Hw}	ρ_g	I_{Hg}
Shallow reservoirs (blue)	~2000 psi [~14,000 kPa]	~120°F [~50°C]	1.00	1.00	0.10	0.23
Deep reservoirs (red)	~7000 psi [~48,000 kPa]	~240°F [~120°C]	1.00	1.00	0.25	0.54

Porosity and Gas Saturation in Empty Holes



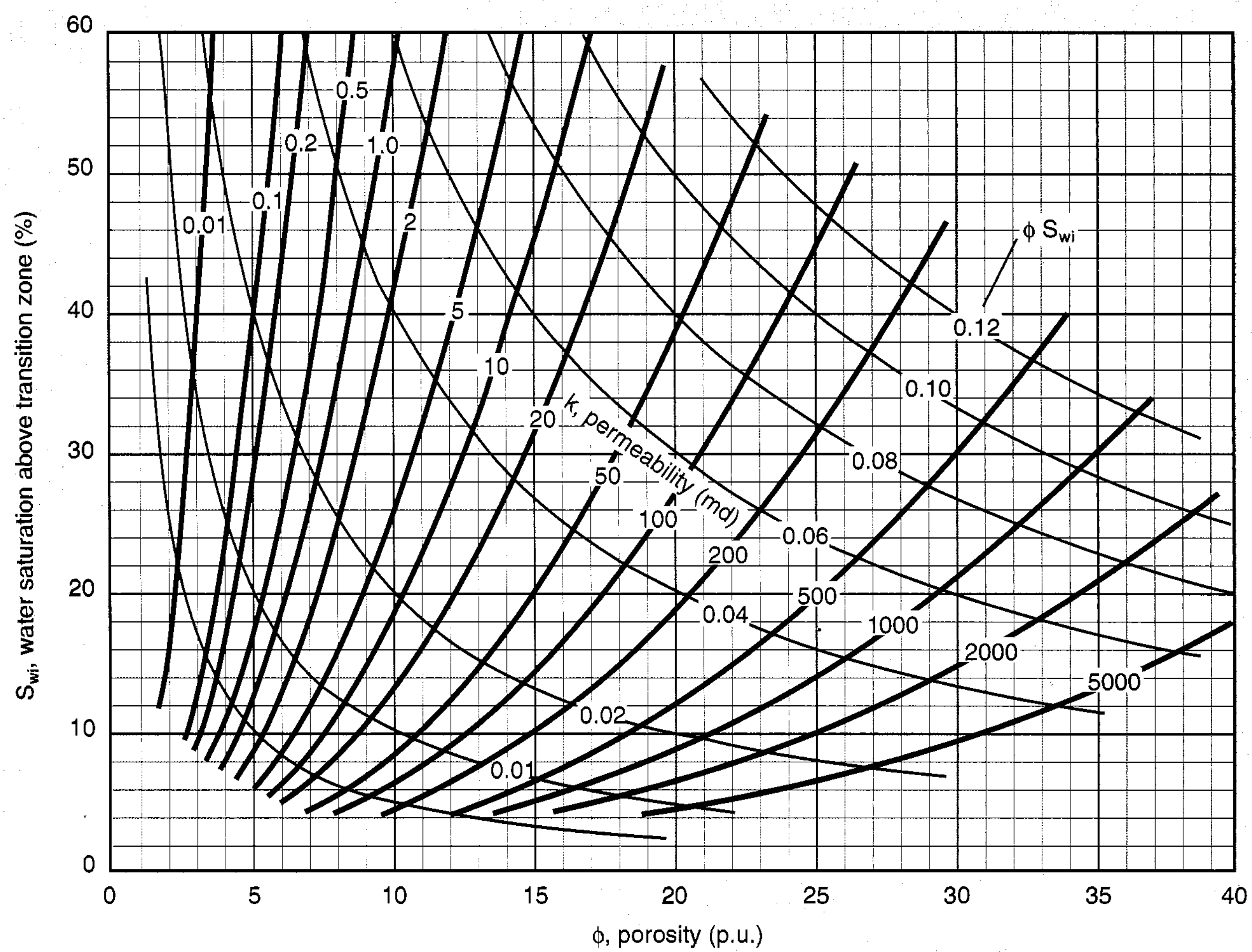
Porosity, φ, and gas saturation, S_g, can be determined from this chart using either the combination of density-neutron measurements or density-resistivity measurements. To use, enter the chart vertically from the intersection of the apparent bulk density and appropriate grain density values. The intersection of this line with either the neutron porosity (corrected for lithology) or the R_t/R_w ratio (true resistivity/connate water resistivity) defines actual porosity and gas saturation.

With all three measurements (density, neutron and resistivity), oil saturation can be determined as well. To do so, enter the chart with apparent bulk density and neutron porosity (as described above) to define porosity and gas saturation. Moving along the defined porosity to its intersection with the R_t/R_w ratio gives the total hydrocarbon saturation. For more information see Reference 14.

Example: In a limy sandstone (ρ_{ma} = 2.68)
ρ_b = 2.44 g/cm^3
ϕ_N = 9 p.u.
R_t = 74
R_w = 0.1

Therefore, R_t/R_w = 740
and φ = 12 p.u.
S_g = 25%
S_h = 70% (total hydrocarbon saturation)
S_o = 70 – 25 = 45%
S_w = 100 – 70 = 30%

Permeability from Porosity and Water Saturation



Charts K-3 and K-4 provide an estimate of permeability for sands, shaly sands or other hydrocarbon-saturated intergranular rocks at irreducible water saturation, S_{wi}. Both charts are based on empirical observations and are similar in form to a general expression proposed by Wyllie and Rose (1950): $k^{1/2} = (c\phi/S_{wi}) + C'$.

Chart K-3 presents the results of one study; the relationship observed was $k^{1/2} = 100\ \phi^{2.25}/S_{wi}$. Chart K-4 presents the results of another study; the relationship observed was $k^{1/2} = 70\ \phi_e^2[(1 - S_{wi})/S_{wi}]$. Both charts are valid only for zones at irreducible water saturation.

To use, porosity, ϕ, and irreducible water saturation, S_{wi}, are entered. Their intersection defines the intrinsic (absolute) rock

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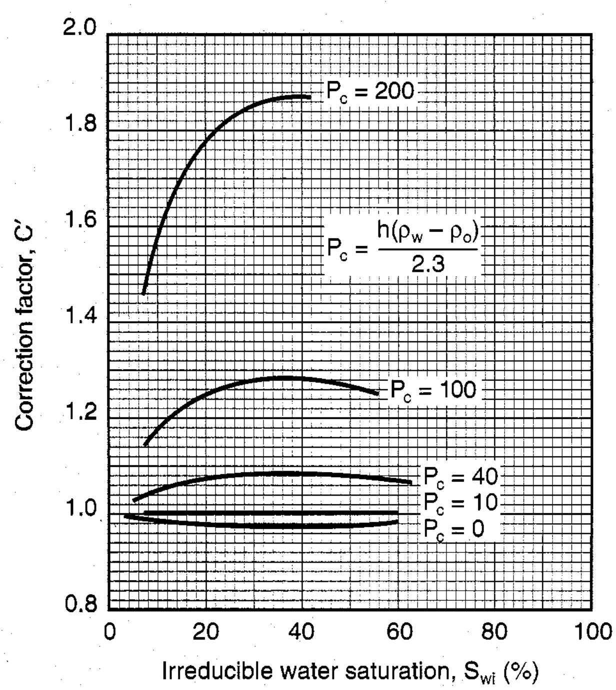
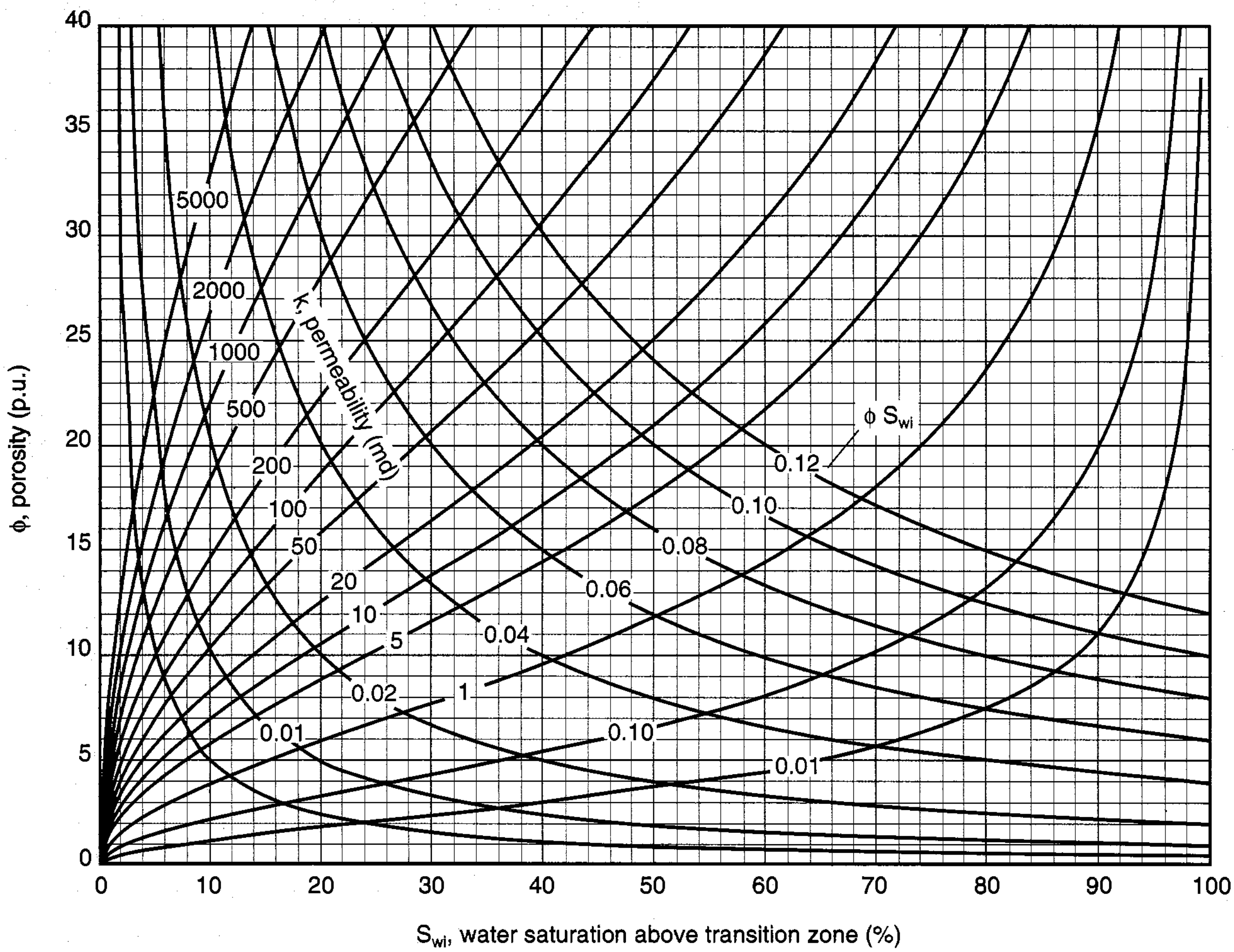


Permeability from Porosity and Water Saturation



permeability. A medium-gravity oil is assumed. If the saturating hydrocarbon is other than a medium-gravity oil, a correction factor based upon fluid densities, ρ_w and ρ_h, and elevation above the free water level, h, should be applied to the irreducible water saturation prior to entry into Chart K-3 or K-4. The inset figure provides this correction factor.

Example: $\phi = 23\%$

$S_{wi} = 30\%$

Gas saturation ($\rho_h = 0.3$ g/cm^3, $\rho_w = 1.1$ g/cm^3)

h (elevation above water) ≈ 120 ft

Therefore, $P_c = \dfrac{h(\rho_w - \rho_h)}{2.3} = \dfrac{120\,(1.1 - 0.3)}{2.3} = 42$

C′ correction factor = 1.08

Corrected S'_{wi} for chart entry = 1.08 (30) = 32.4%

giving k ≈ 130 md (Chart K-3)

or k ≈ 65 md (Chart K-4)

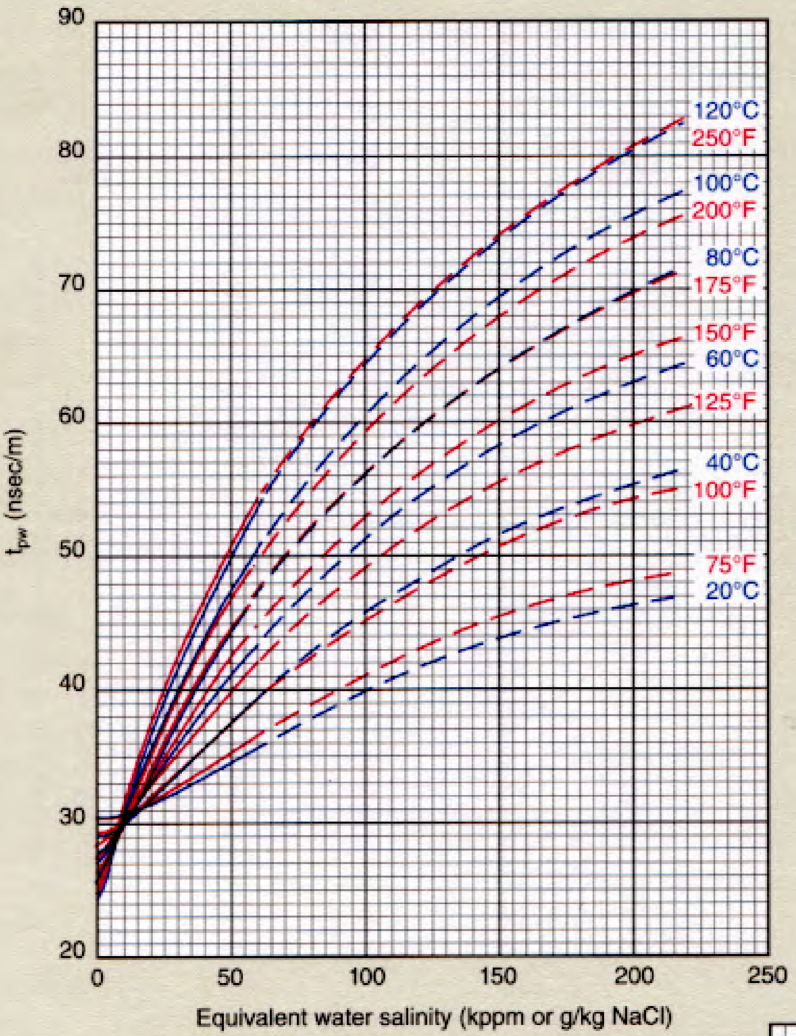
These charts can also be used to recognize zones at irreducible water saturation. Over intervals at irreducible water saturation, the product of porosity and water saturation is generally a constant; thus, data points from levels at irreducible water saturation should plot in a fairly coherent pattern on or parallel to one of the $\phi \cdot S_w$ lines.

For more information see References 16, 17, 21 and 22.

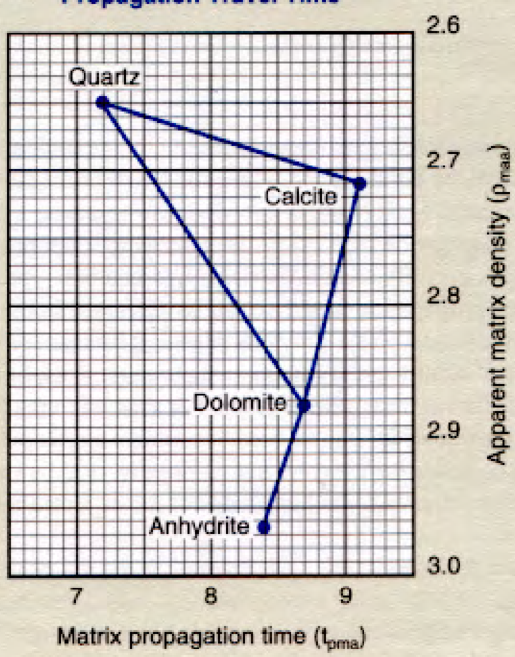
Schlumberger

EPT* Propagation Time for NaCl Solutions

EPTcor-1



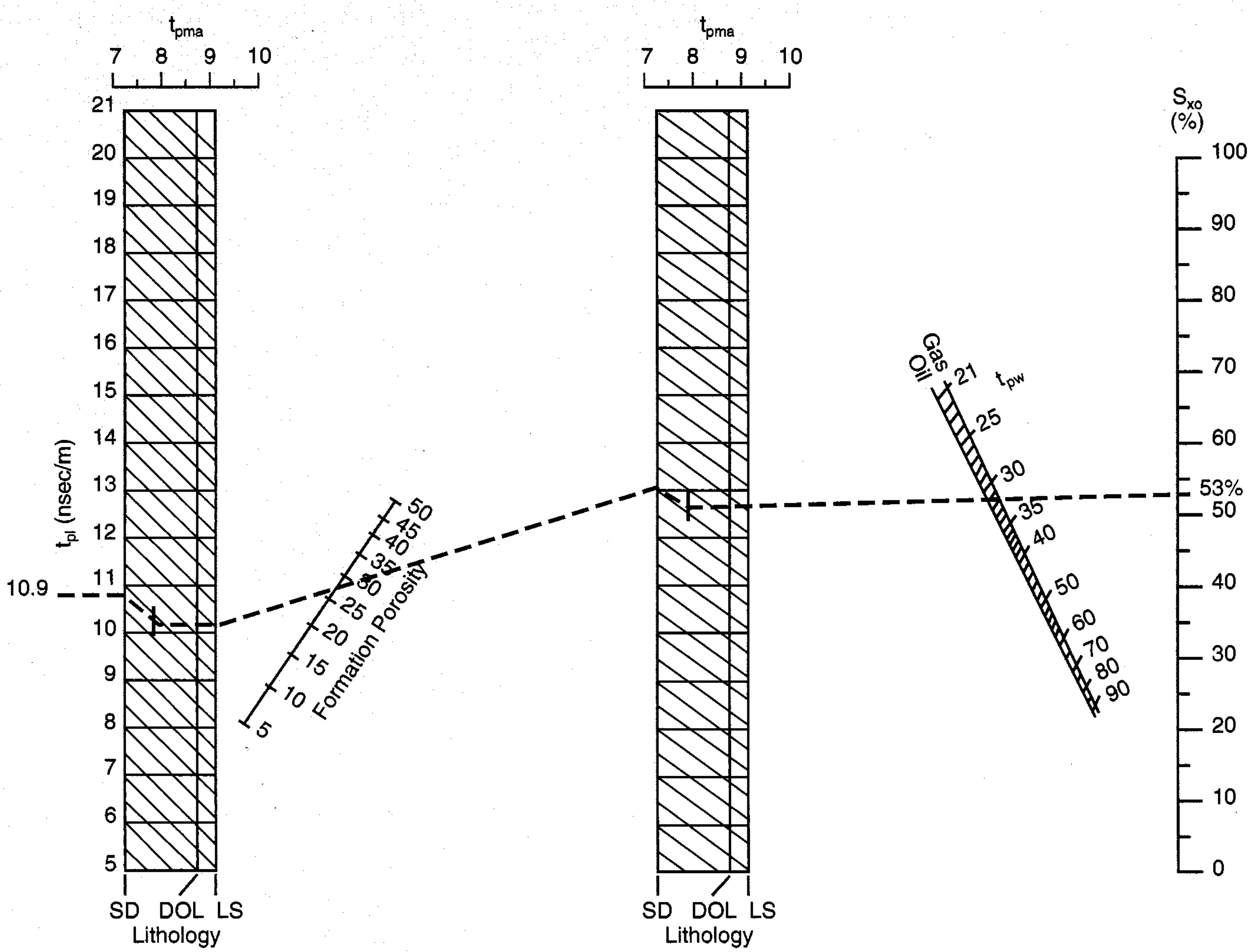
EPT Matrix Propagation Travel Time



EPT

*Mark of Schlumberger

Flushed Zone Saturation from EPT* Propagation Time



*Mark of Schlumberger

This nomograph defines water saturation in the rock immediately adjacent to the borehole, S_{xo}, using the EPT* propagation time measurement, t_{pl}. It requires knowledge of reservoir lithology or matrix propagation time (t_{pma}), the saturating water propagation time (t_{pw}), porosity and the expected hydrocarbon type.

Water propagation time, t_{pw}, can be estimated from the appropriate chart on the previous page as a function of equivalent water salinity and formation temperature. Rock lithology must be known from other sources. For rock mixtures the chart on the previous page can be used to estimate matrix propagation time, t_{pma}, when the apparent matrix density, ρ_{maa}, is known. The estimation requires some knowledge of the expected mineral mixture.

To use the nomograph, t_{pl} is entered on the left grid; follow the diagonal lines to the appropriate t_{pma} value, then horizontal to the right edge of the grid. From this point, a straight line is extended through the porosity to the center grid; again follow the diagonal lines to the appropriate t_{pma} value, then horizontal to the right edge of the grid. From this point, extend a straight line through the intersection of t_{pw} and hydrocarbon type point to the S_{xo} axis.

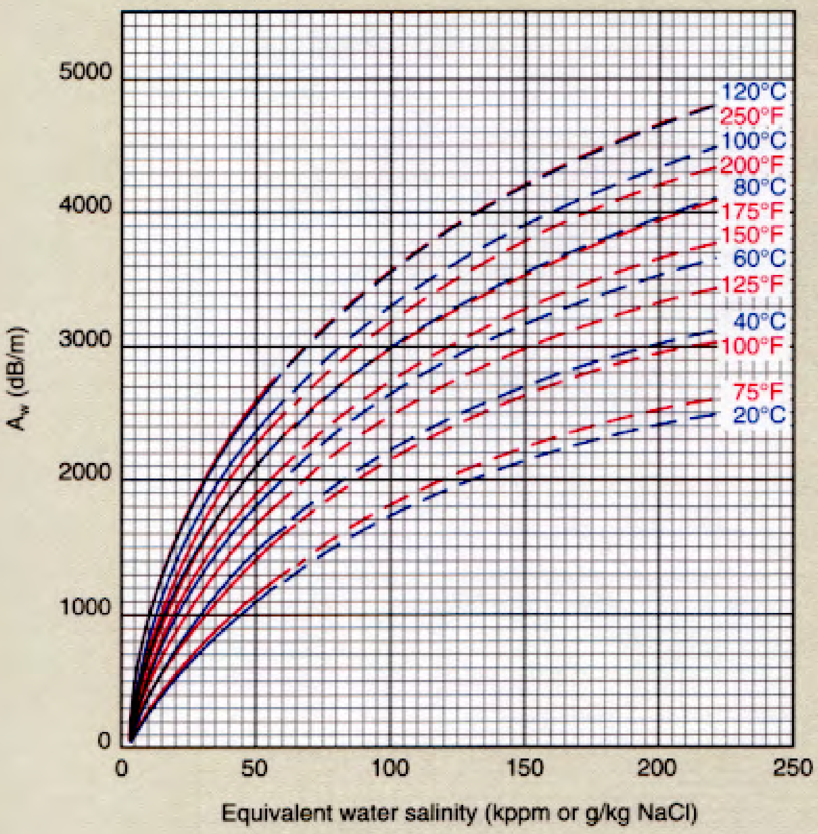
For more information see Reference 25.

Example: t_{pl} = 10.9 nsec/m
ϕ = 28%
Limy sandstone with ρ_{maa} = 2.67 g/cm^3
Water salinity ≈ 20 kppm
BHT = 150°F
Gas saturation expected

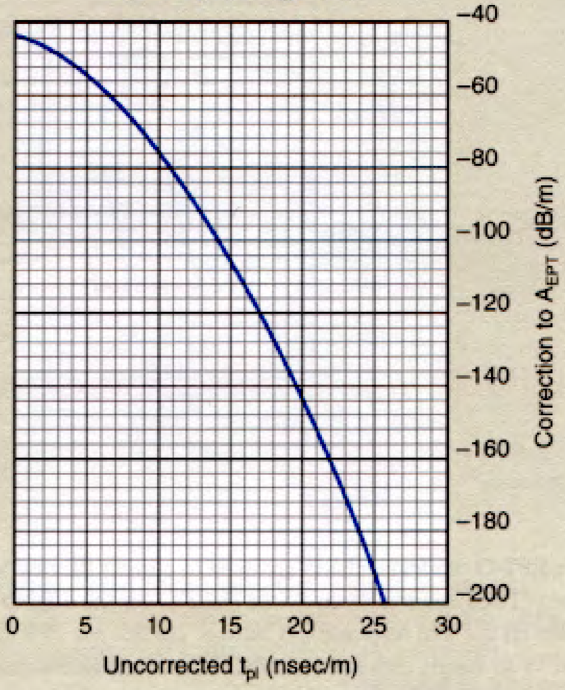
giving t_{pma} = 7.8 nsec/m (sand-lime mixture)
t_{pw} = 32 nsec/m

and S_{xo} = 53%

EPT* Attenuation for NaCl Solutions



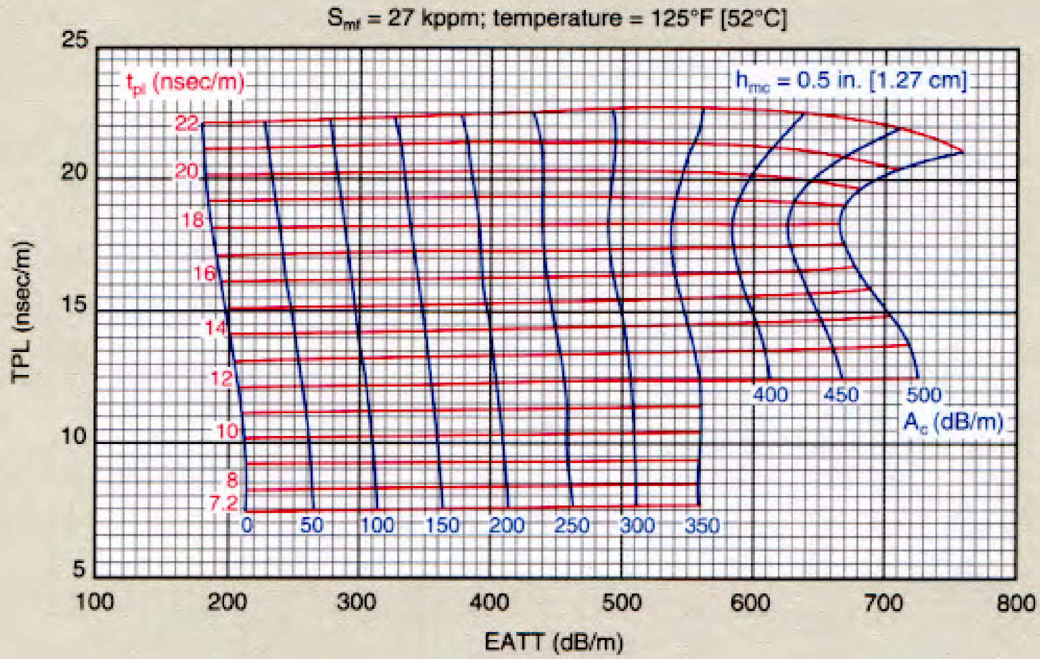
EPT-D Spreading Loss

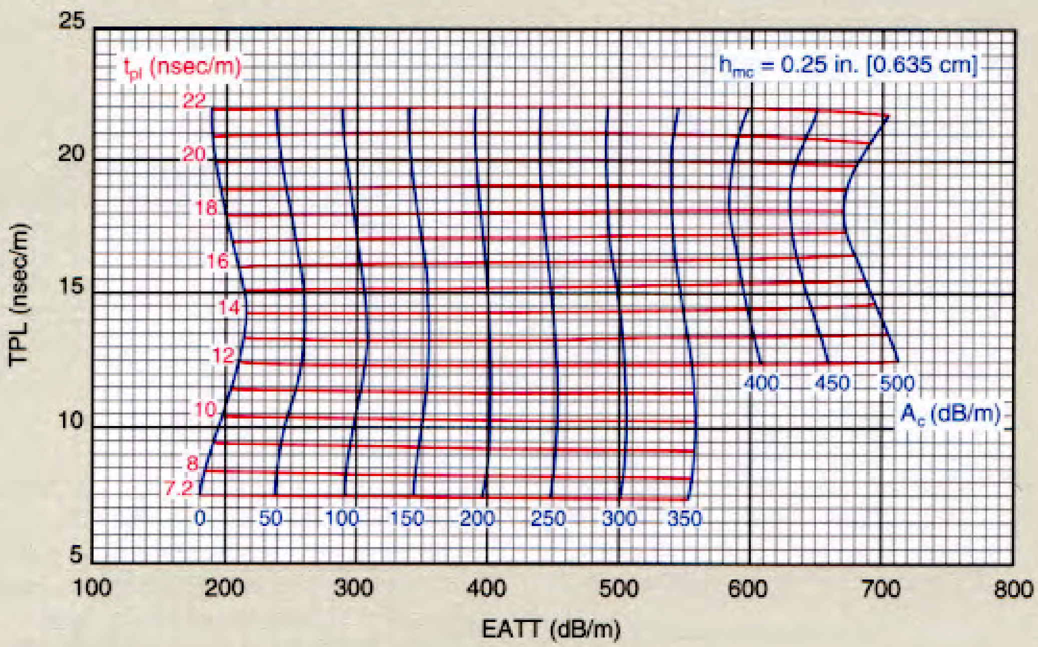


*Mark of Schlumberger

EPT-G Mudcake Correction Charts for Water-Base Mud

EMD-L (endfire array)





The EPT-G mudcake charts are used to correct the raw log travel times (TPL) and log attenuations (EATT) for the effects of mudcakes on the tool responses. (Caution: Do not use TPPW and EAPW as inputs into these charts.) The charts also correct the log attenuations for spreading losses so that no further corrections are required. The chart outputs are the true formation travel times (t_{pl}) and attenuations (A_c), which are used to evaluate the flushed zone. For example, these latter quantities are the inputs to petrophysical models such as the Complex Refractive Index Method (CRIM).

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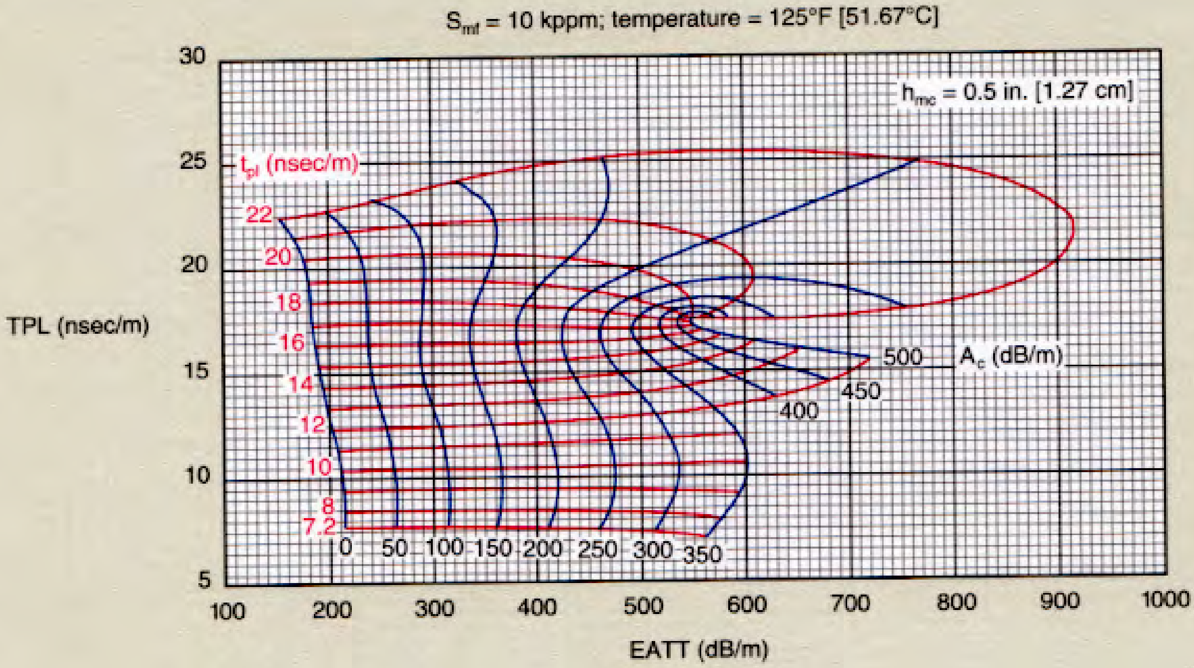
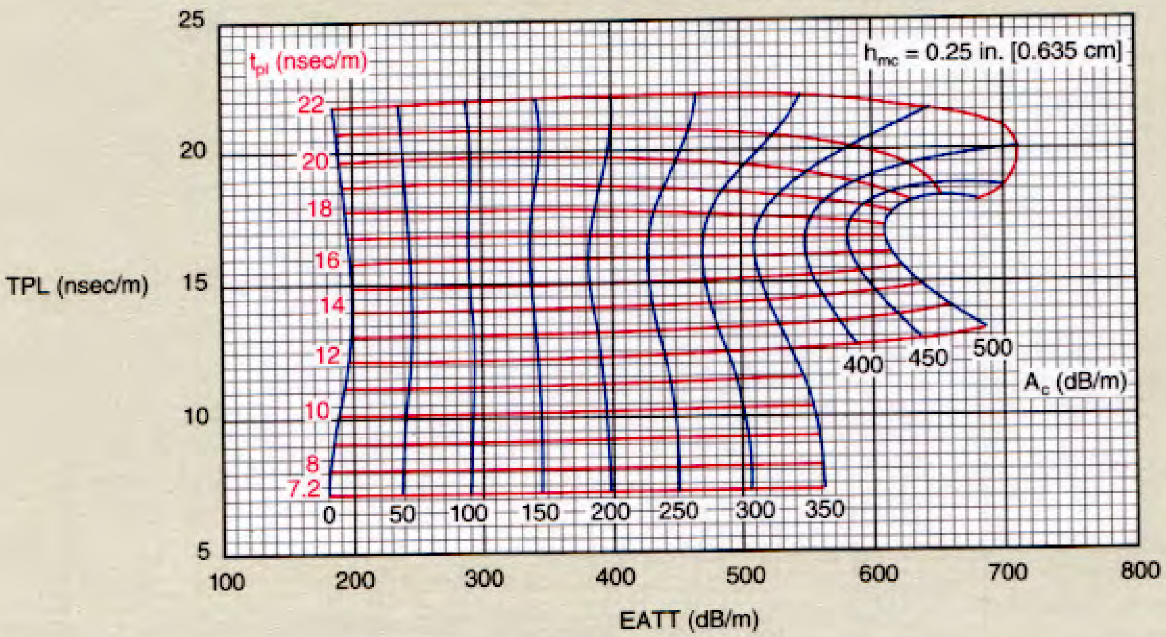
EPT-G Mudcake Correction Charts for Water-Base Mud

EMD-L (endfire array)





The true travel times, t_{pl}, can also be used in nomograms such as Sxo-1 to determine flushed-zone water saturations, S_{xo}. The charts displayed here are for water-base muds and are applicable, as indicated, for the EMD-L and BMD-S arrays. The charts are valid for the indicated mudcake thicknesses (h_{mc}), borehole temperatures and mud-filtrate salinities in kppm by weight NaCl (S_{mf}). The mudcake effects depend on h_{mc} and the contrast between the mudcake and formation dielectric properties.

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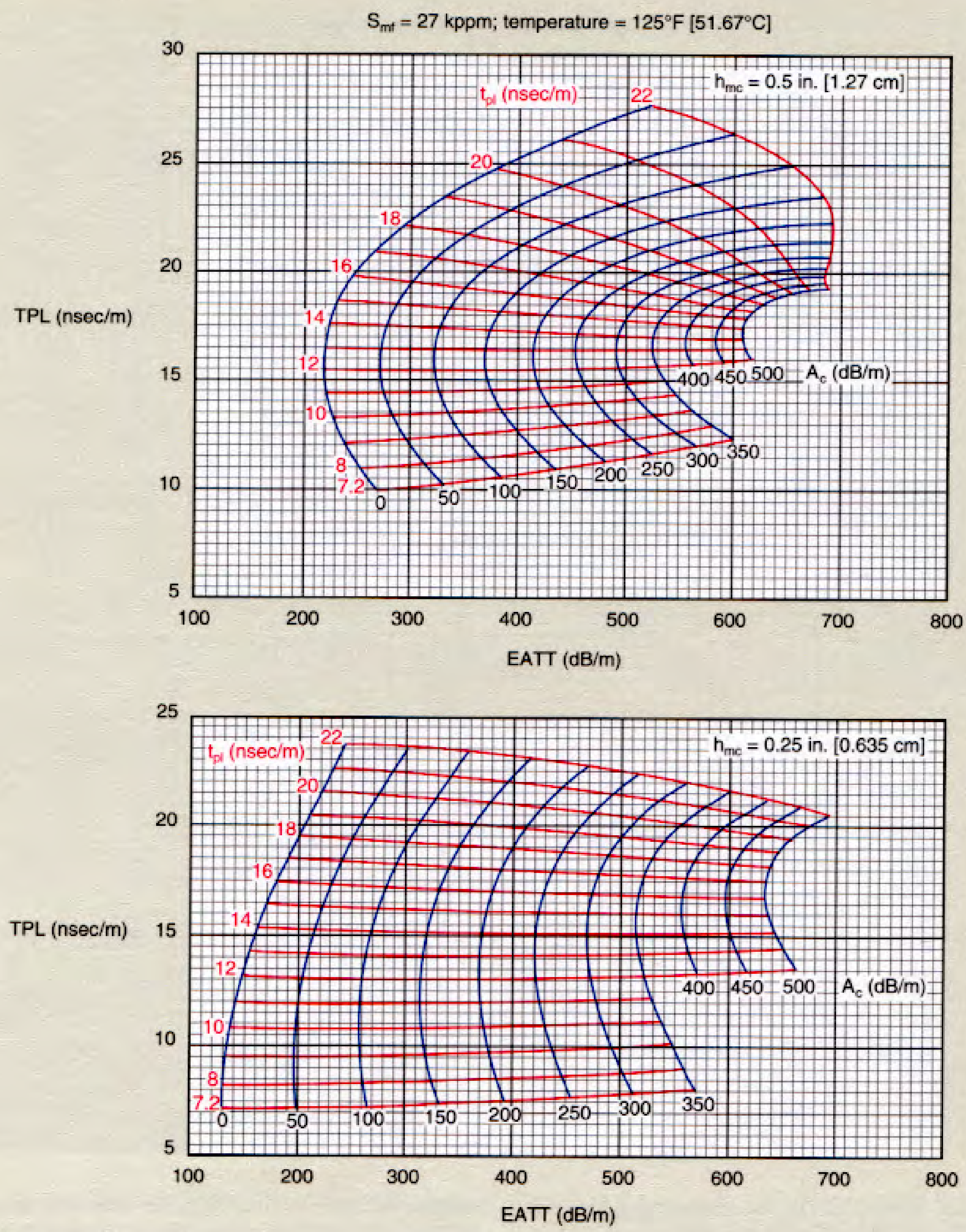
EPT-G Mudcake Correction Charts for Water-Base Mud

BMD-S (broadside array)



In general, low-conductivity muds produce the largest effects so that increases in temperature, mudcake porosity and salinity generally reduce the mudcake effects. The charts displayed here assume a mudcake porosity of 40 p.u. (For more information see Reference 31.) The mudcake thicknesses are estimated from a caliper or a Microlog using Chart Rxo-1.

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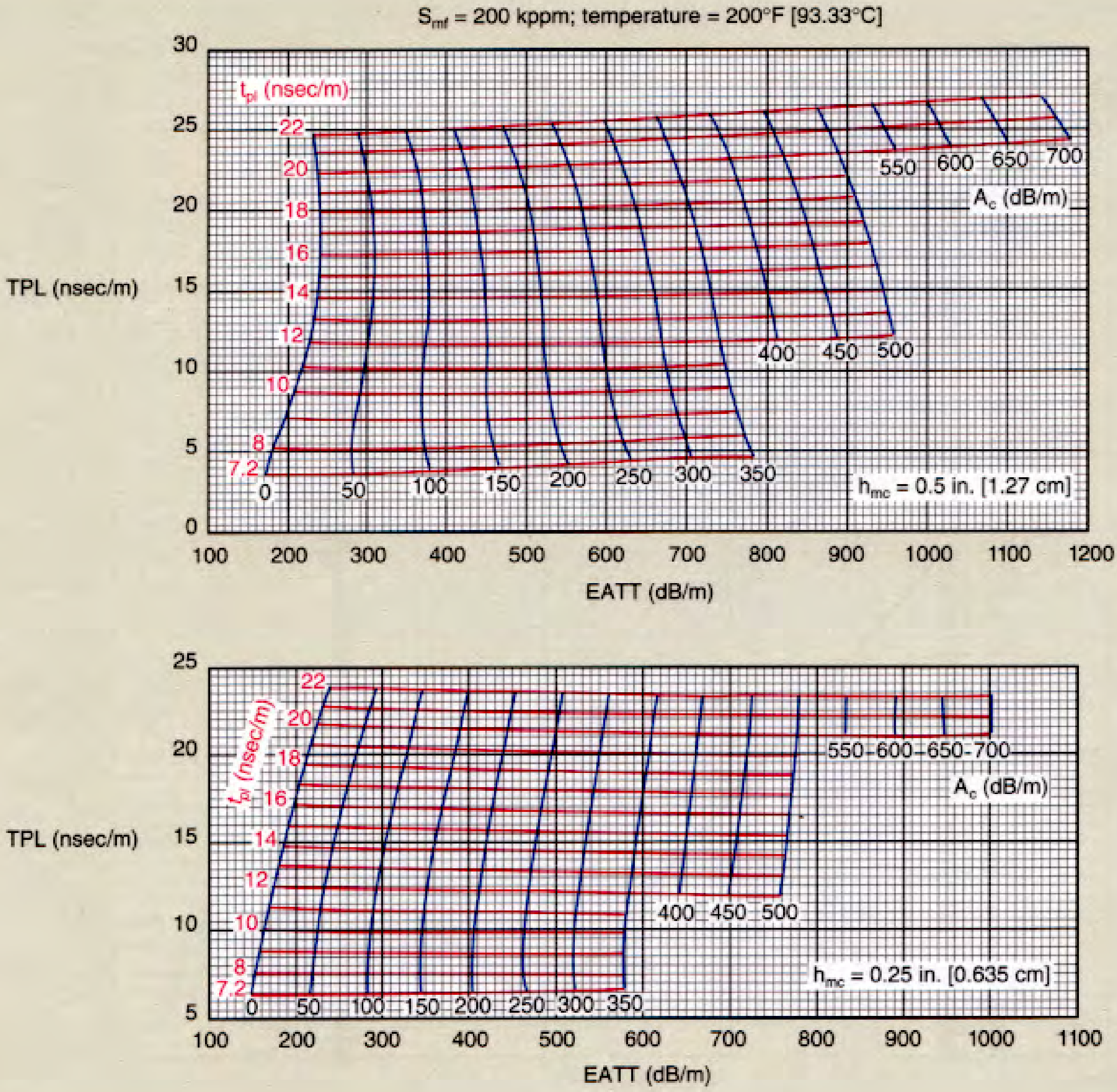
EPT-G Mudcake Correction Charts for Water-Base Mud

BMD-S (broadside array)



Example: EMD-L array

h_{mc} = 0.5 in. (estimated from bit size and caliper)

Borehole temperature = 125°F

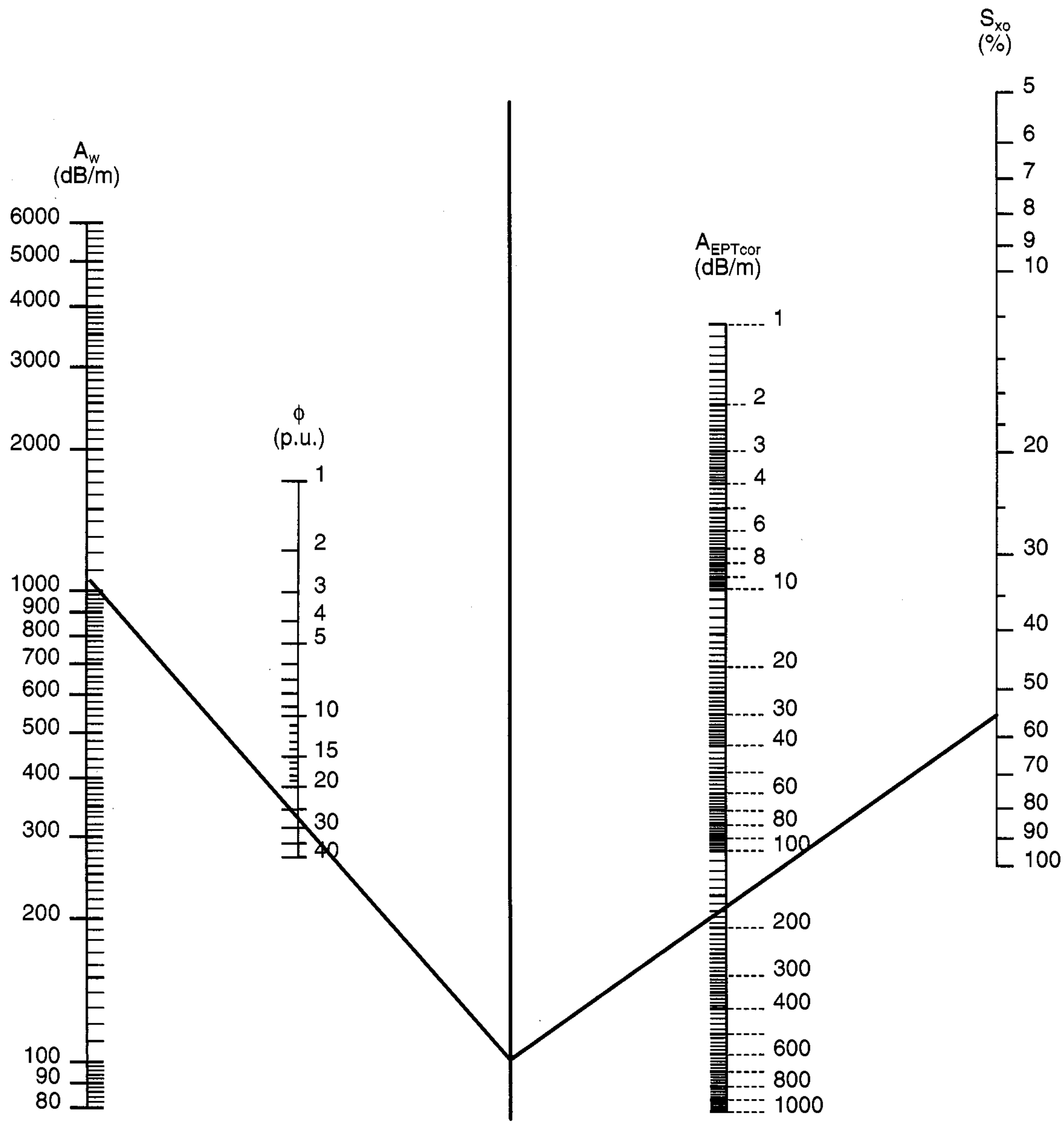
Mud filtrate salinity = 27,000 ppm NaCl

Log TPL = 20 nsec/m

Log EATT = 500 dB/m

Entering Chart EPTcor-3a with the above log values, one reads a true formation travel time, t_{pl} = 19.7 nsec/m, and true formation attenuation, A_c = 307 dB/m.

Flushed Zone Saturation from EPT* Attenuation



*Mark of Schlumberger

The nomograph defines water saturation in the rock immediately adjacent to the borehole, S_{xo}, using the EPT attenuation measurement. It requires knowledge of saturating fluid (usually mud filtrate) attenuation (A_w), porosity and the EPT attenuation (A_{EPTcor}) corrected for spreading loss.

Fluid attenuation (A_w) can be estimated from Chart EPTcor-2 by knowing the equivalent water salinity and formation temperature. EPT-D spreading loss is also determined from Chart EPTcor-2 based on the uncorrected EPT t_{pl} measurement. The spreading loss correction algebraically added to the EPT-D attenuation measurement gives the corrected EPT attenuation, A_{EPTcor}.

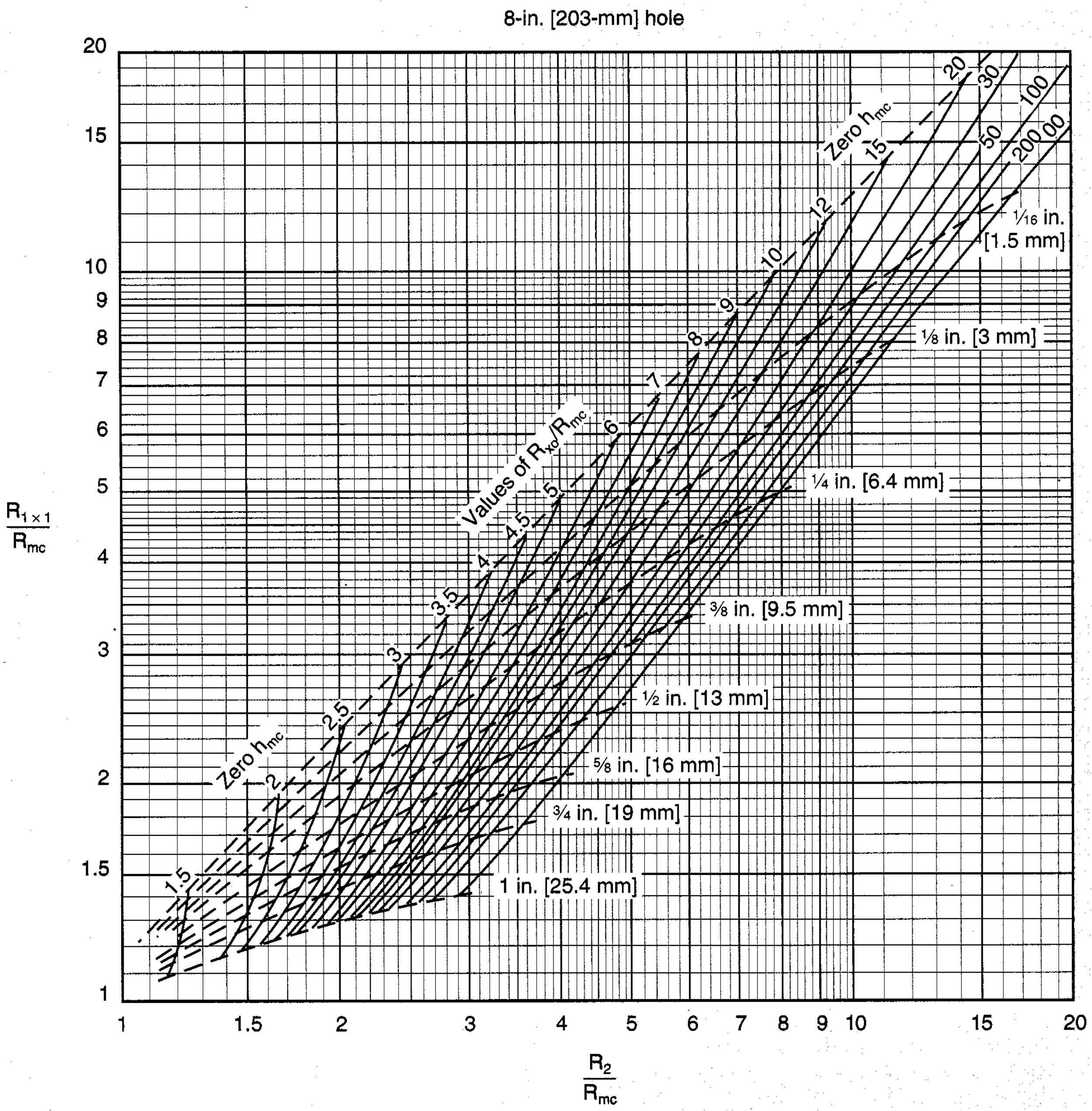
These values, together with porosity, inserted into the nomograph lead to the flushed zone water saturation, S_{xo}.

Example: A_{EPT} = 250 dB/m
t_{pl} = 10.9 nsec/m
ϕ = 28%
Water salinity = 20 kppm
BHT = 150°F

giving Spreading loss = –82 dB/m
A_{EPT} = 250 – 82 = 168 dB/m
A_w = 1100 dB/m

and S_{xo} = 56%

Microlog Interpretation Chart



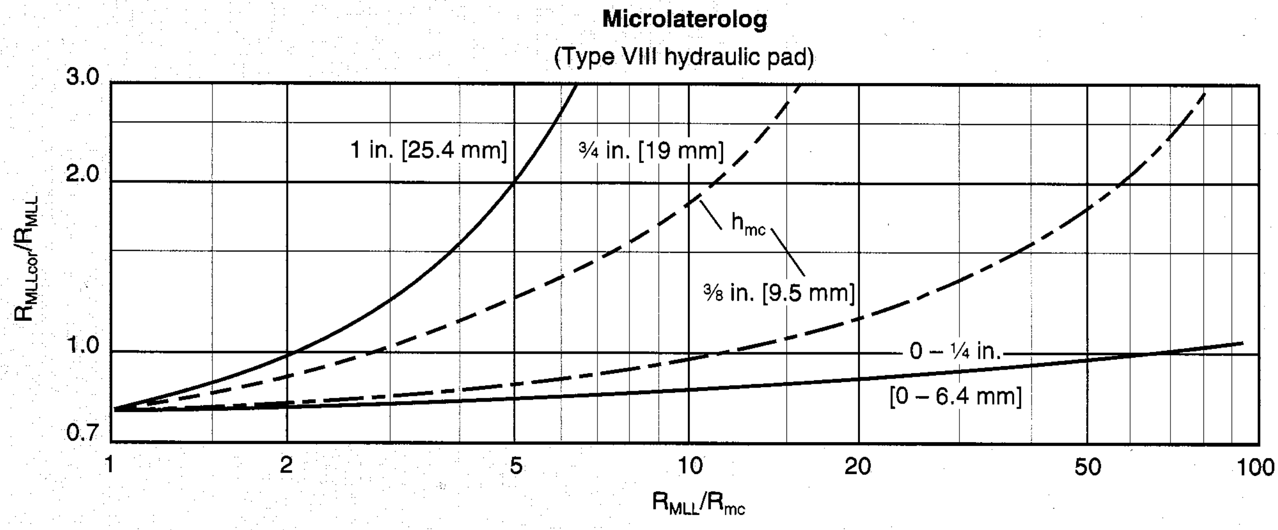
Enter the chart with the ratios $R_{1\times1}/R_{mc}$ and R_2/R_{mc}. The point of intersection defines the R_{xo}/R_{mc} ratio and the mudcake thickness, h_{mc}. Knowing R_{mc}, R_{xo} can be calculated.

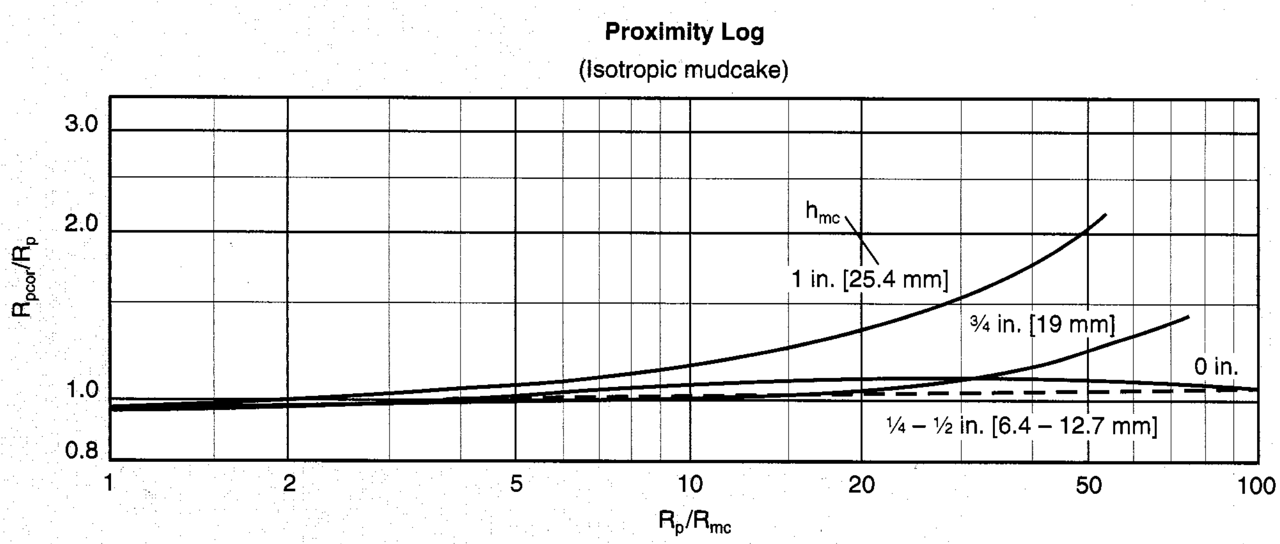
For hole sizes other than 8 in. [203 mm], multiply $R_{1\times1}/R_{mc}$ by the following factors before entering the chart: 1.15 for 4¾-in. [120-mm] hole, 1.05 for 6-in. [152-mm] hole, and 0.93 for 10-in. [254-mm] hole.

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 mudcake 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.

$$R_{xo} = R_2\left(\frac{R_{xo}/R_{mc}}{R_2/R_{mc}}\right)$$

Microlaterolog and Proximity Log Mudcake Correction





Charts Rxo-2 and Rxo-3 correct microresistivity measurements for mudcake effect. To use, enter the ratio of the microresistivity log reading divided by the mudcake resistivity into the abscissa of the appropriate chart. Go vertically to the mudcake thickness; the ratio of the corrected microresistivity value to the microresistivity log reading is then given on the ordinate. Multiplication of this ratio by the microresistivity log reading yields the corrected microresistivity.

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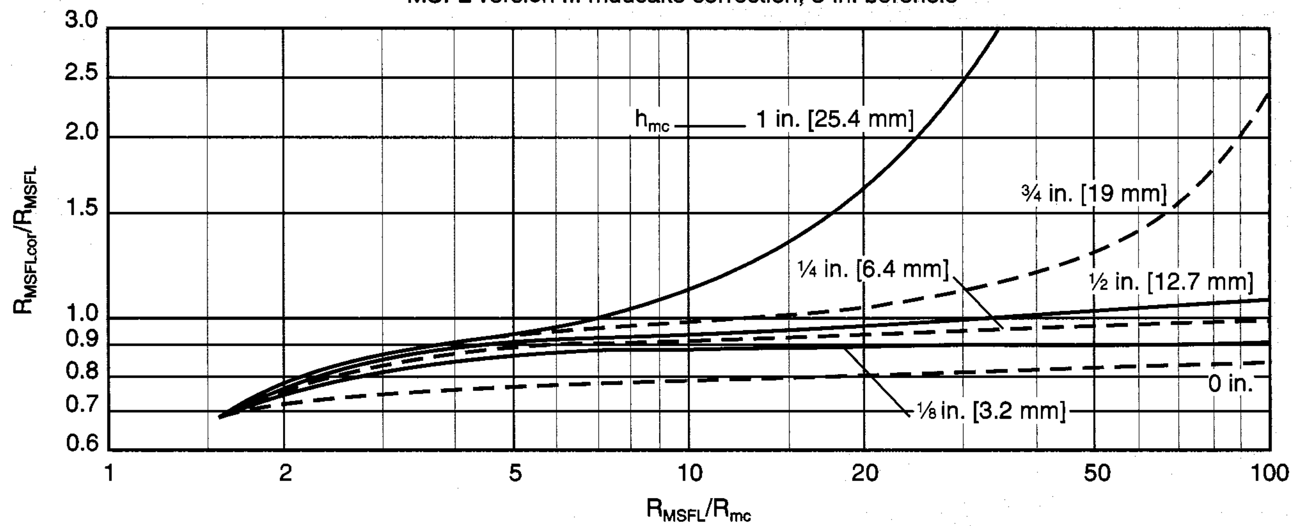
MicroSFL* Mudcake Correction

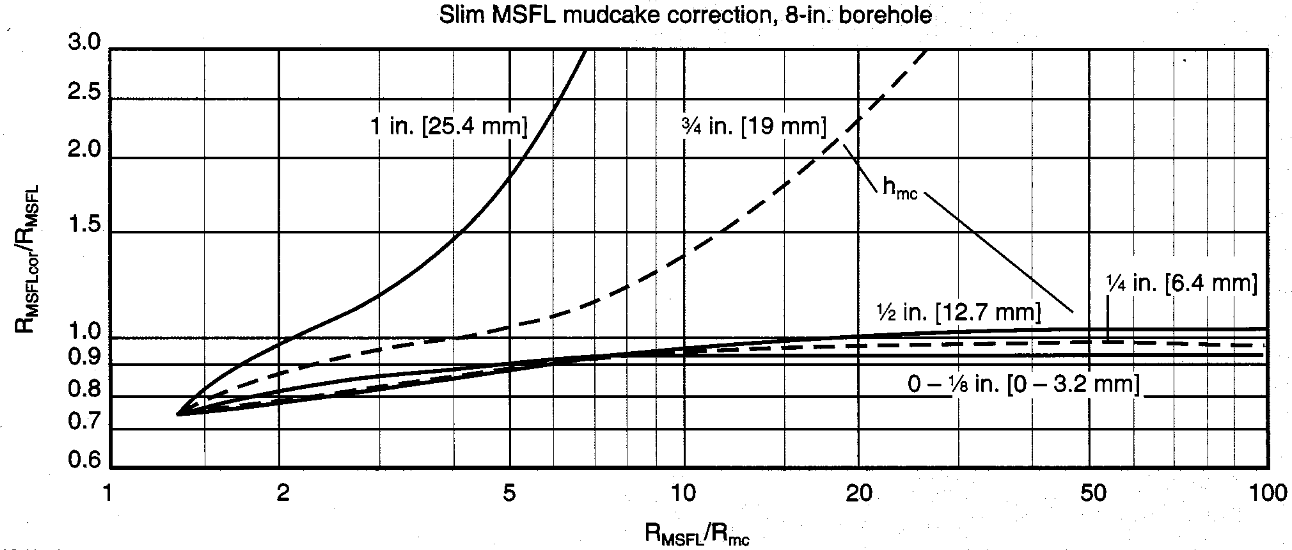
Standard MicroSFL

MSFL version III mudcake correction, 8-in. borehole



Slimhole MicroSFL

Slim MSFL mudcake correction, 8-in. borehole



Example: R_{MLL} = 9.0 ohm-m

R_{mc} = 0.15 ohm-m at formation temperature

h_{mc} = 9.5 mm

giving R_{MLL}/R_{mc} = 9.0/0.15 = 60

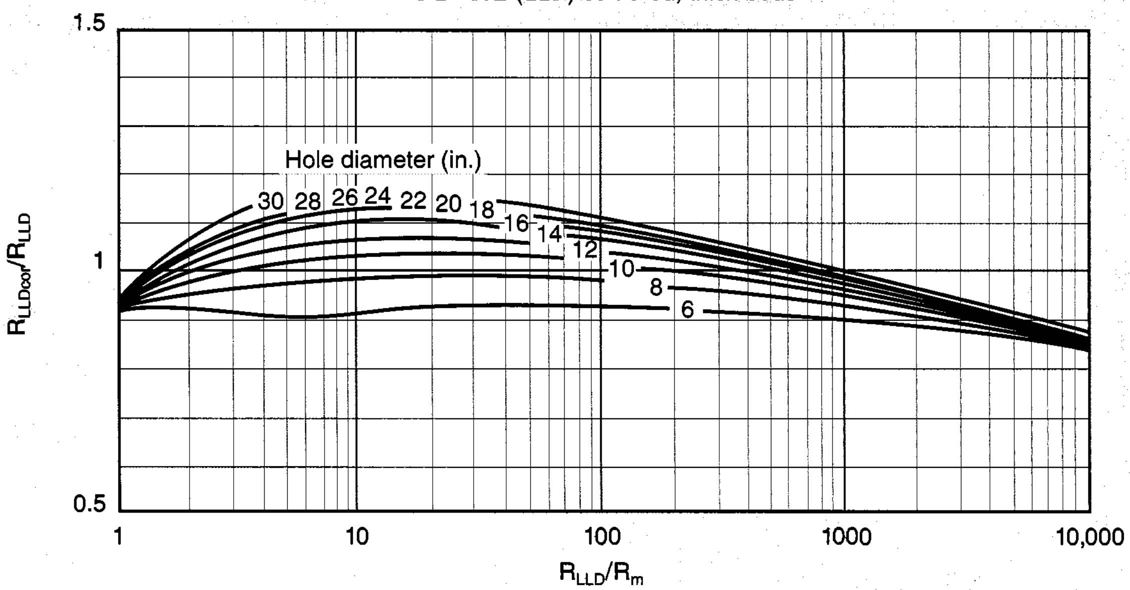
Therefore, R_{MLLcor}/R_{MLL} = 2

and R_{MLLcor} = 2(9.0) = 18 ohm-m

Dual Laterolog (D/E) Borehole Correction

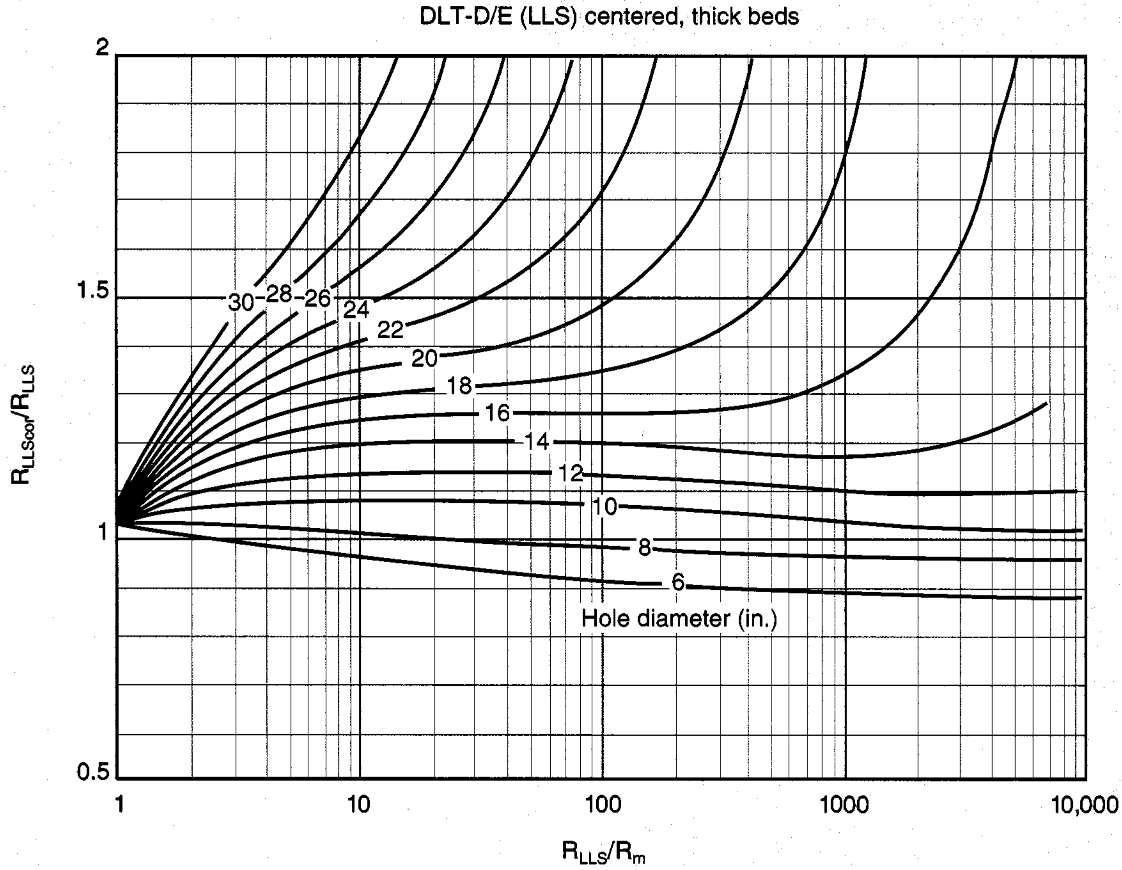
Deep Laterolog

DLT-D/E (LLD) centered, thick beds



Shallow Laterolog

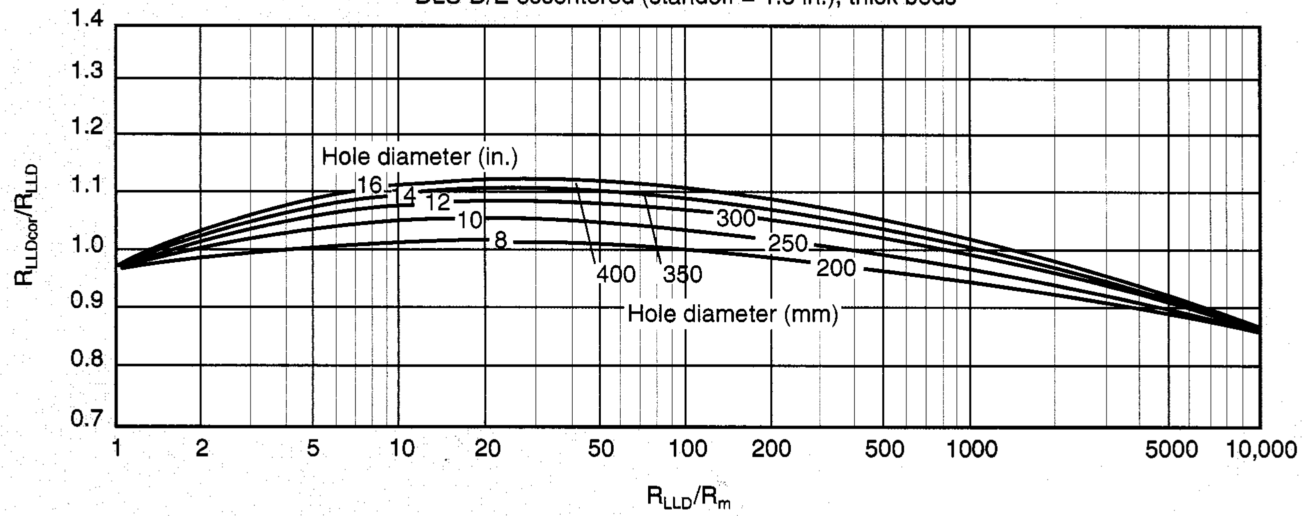
DLT-D/E (LLS) centered, thick beds



Dual Laterolog (D/E) Borehole Correction

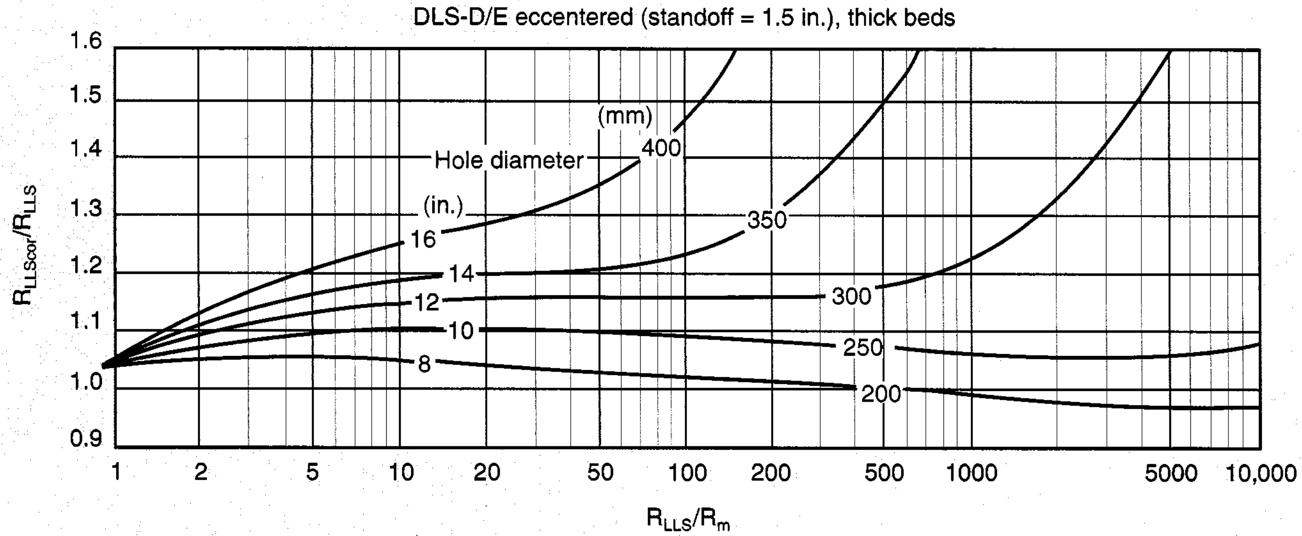
Deep Laterolog

DLS-D/E eccentered (standoff = 1.5 in.), thick beds



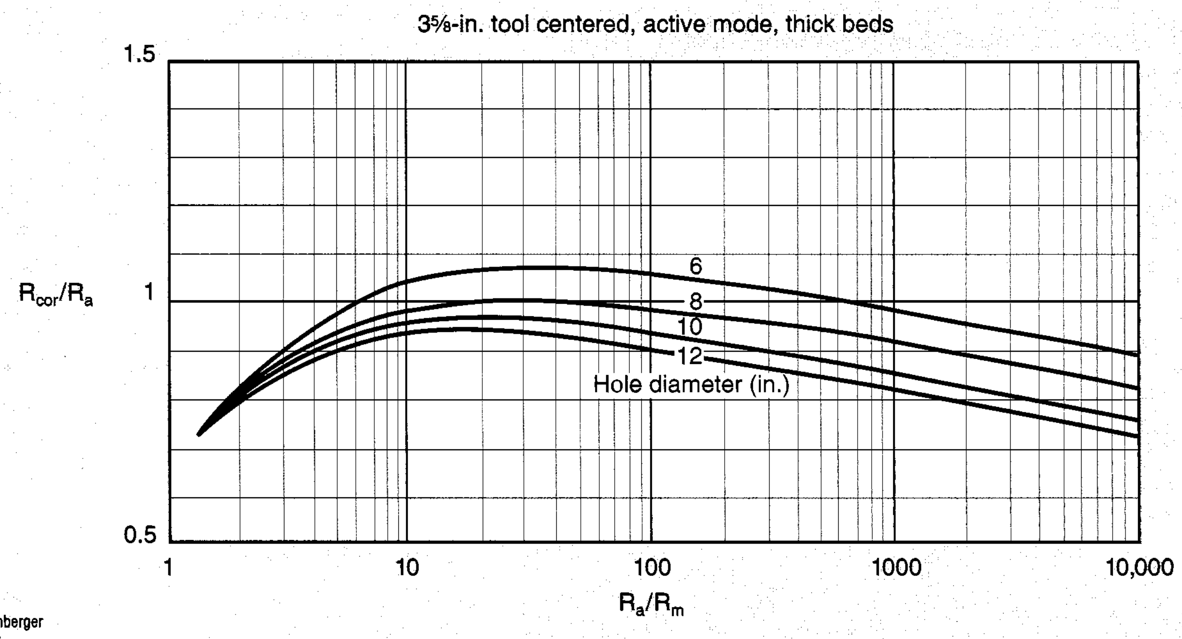
Shallow Laterolog

DLS-D/E eccentered (standoff = 1.5 in.), thick beds



ARI* Azimuthal Resistivity Imager Borehole Correction

For high-resolution LLhr curve



*Mark of Schlumberger

The high-resolution deep resistivity curve available from the ARI Azimuthal Resistivity Imager log is subject to borehole effects like any other laterolog measurement. Borehole correction is performed using Chart Rcor-14 in the same way as the deep and shallow laterolog borehole corrections and the microlog and MicroSFL* mudcake corrections (see Charts Rxo-2 and Rxo-3 for an explanation and illustration).

LLD and LLS curves recorded with the ARI tool are identical to the curves recorded with a standard dual laterolog tool (type D or E) and may be corrected for borehole effects using Chart Rcor-2b or Rcor-2c.

Dual Laterolog (D/E) Bed-Thickness Corrections

Chart Rcor-10 corrects the Dual Laterolog (LLD and LLS) for bed thickness.

To use, laterolog readings should first be corrected for borehole effects (see Charts Rcor-2b and -2c). Then, enter Chart Rcor-10 with the bed thickness and proceed upward to the proper R_{LL}/R_s ratio (apparent laterolog reading corrected for borehole/adjacent-bed resistivity) curve. Read the ratio of the corrected laterolog value (R_{LLcor}) to the apparent laterolog value (R_{LL}) in ordinate.

Example: $R_{LLD} = 4.2$ ohm-m

$R_{LLS} = 3.0$ ohm-m

$R_S \approx 30$ ohm-m

Bed thickness = 6 ft

Given $$\frac{R_{LLD}}{R_S} = \frac{4.2}{30} = 0.14$$

$$\frac{R_{LLS}}{R_S} = \frac{3.0}{30} = 0.10$$

Therefore, $$\frac{R_{LLDcor}}{R_{LLD}} = 0.88$$

$$\frac{R_{LLScor}}{R_{LLS}} = 0.80$$

and $R_{LLDcor} = 3.7$ ohm-m

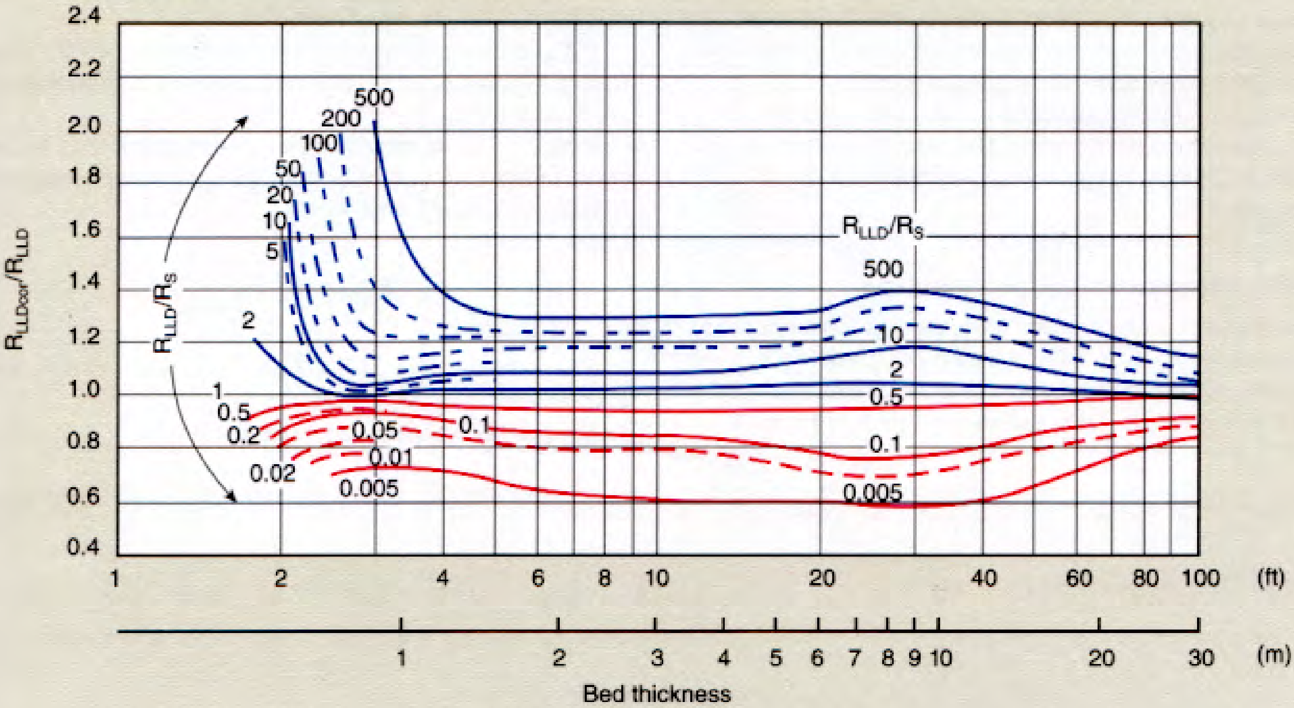
$R_{LLScor} = 2.4$ ohm-m

Dual Laterolog (D/E) Bed-Thickness Corrections

DLS-D/E

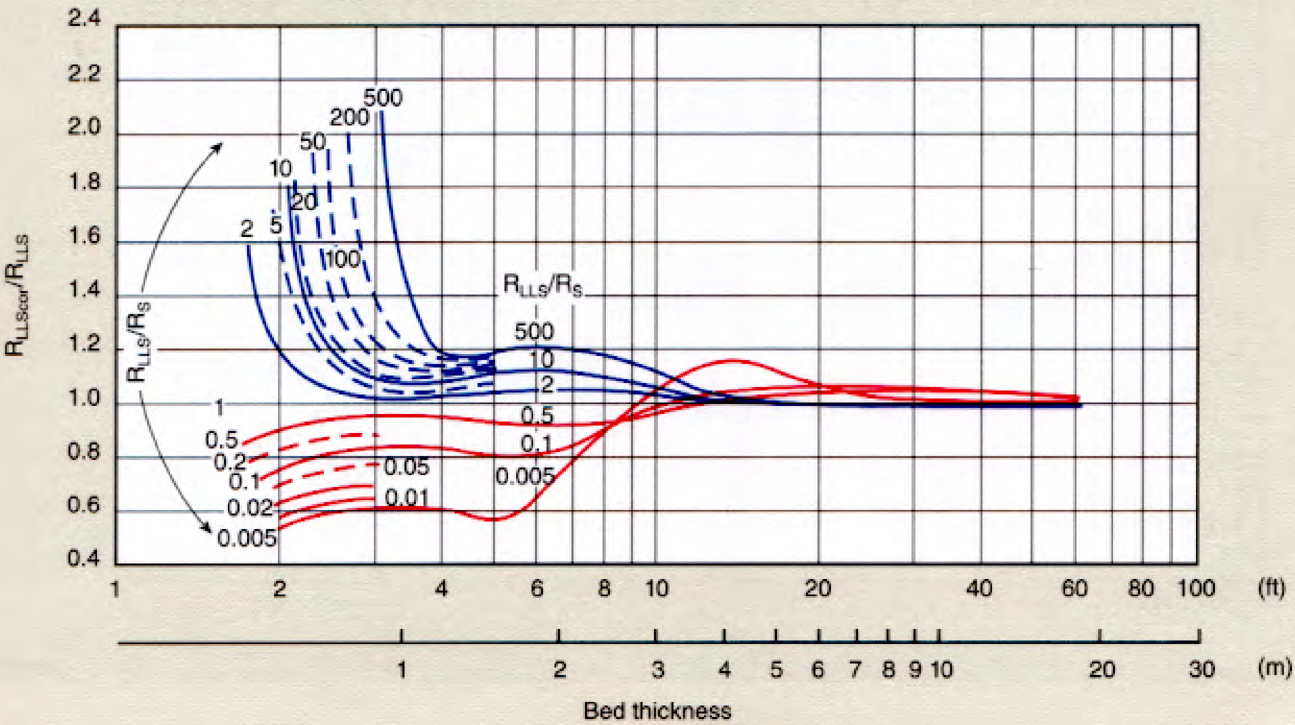
Deep Laterolog

No invasion, semi-infinite shoulder, 8-in. [203-mm] borehole, squeeze: $R_t/R_m \approx 30$, antisqueeze: $R_s/R_m \approx 30$



Shallow Laterolog

No invasion, semi-infinite shoulder, 8-in. [203-mm] borehole, squeeze: $R_t/R_m \approx 30$, antisqueeze: $R_s/R_m \approx 30$



Invasion Correction Charts

The invasion correction charts, sometimes referred to as "tornado" or "butterfly" charts, of the next several pages (labeled Rint-) are used to define the depth of invasion d_i, the R_{xo}/R_t ratio and the true resistivity R_t. All assume a step-contact profile of invasion and that all resistivity measurements have been corrected, where necessary, for borehole effect and bed thickness using the appropriate Rcor- chart, prior to entry.

To use any of these charts, enter the abscissa and ordinate with the required resistivity ratios. The point of intersection defines d_i, R_{xo}/R_t and R_t as a function of one resistivity measurement.

Saturation determination in clean formations

Either of the chart-derived values of R_t and R_{xo}/R_t 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.

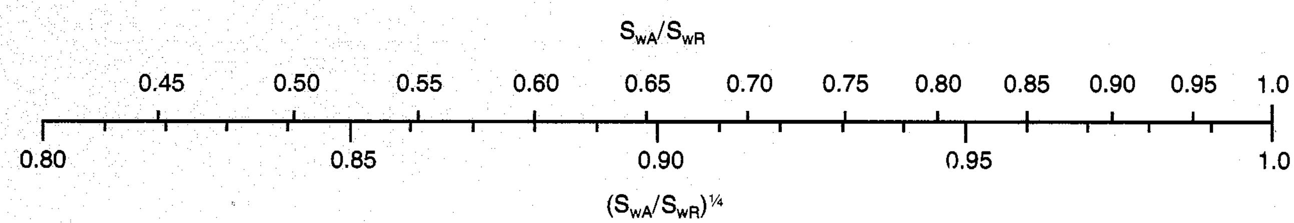
If $S_{wA} > S_{wR}$, either invasion is very shallow or a transition type of invasion profile is indicated, and S_{wA} is considered a good value for S_w.

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

$$S_{wcor} = S_{wA}\left(\frac{S_{wA}}{S_{wR}}\right)^{\frac{1}{4}}$$

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

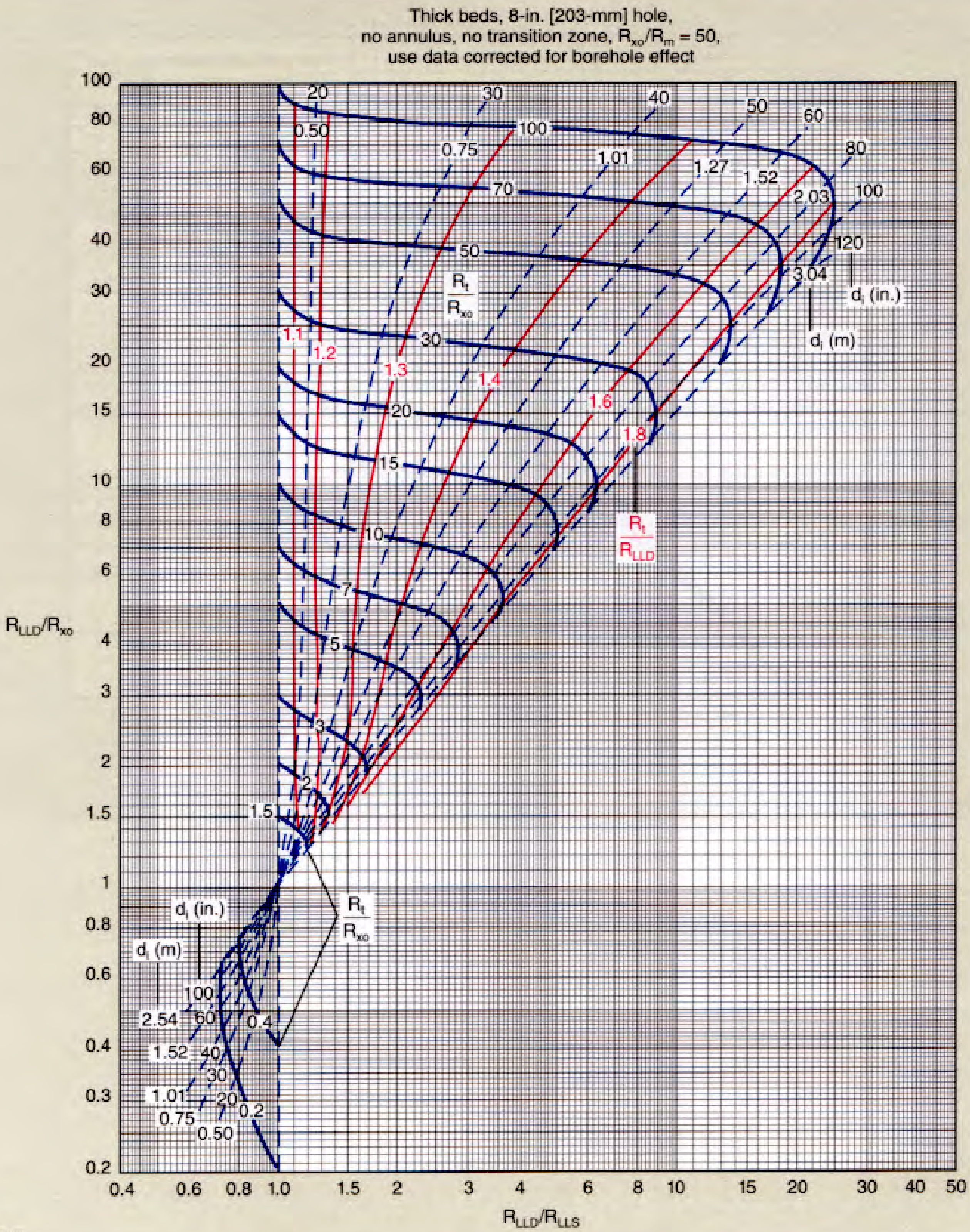
For more information see Reference 9.



Rint

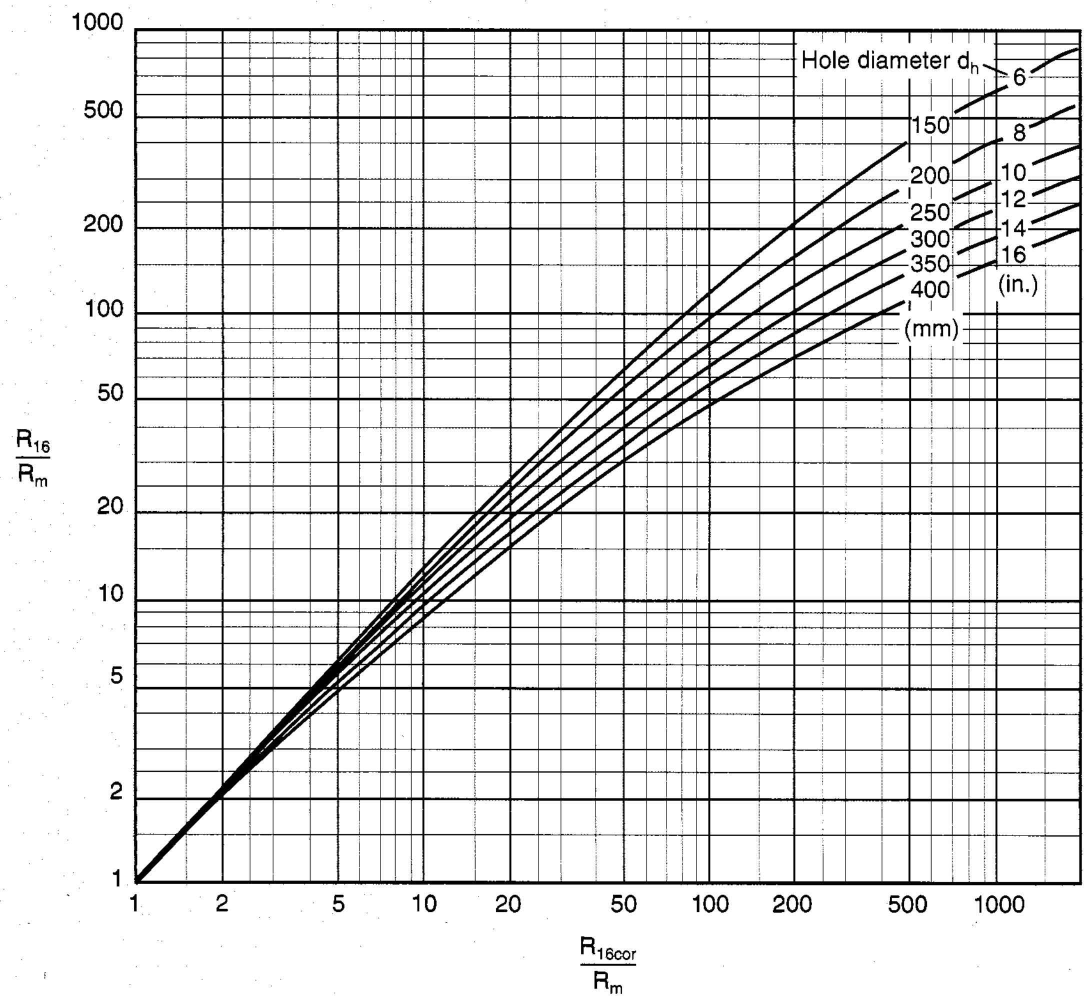
Dual Laterolog–R_{xo} Device

DLT-D/E LLD–LLS–R_{xo} device



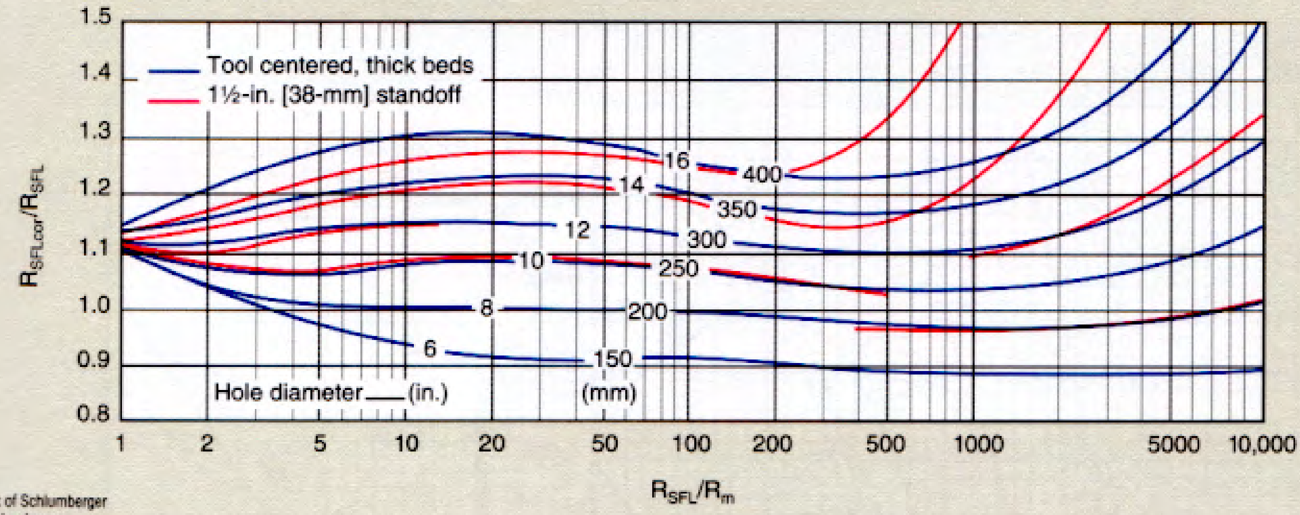
Borehole Correction for 16-in. Normal

Recorded with induction-electrical log



SFL* Spherically Focused Resistivity Borehole Correction

Recorded with DIS-DB, EA or equivalent



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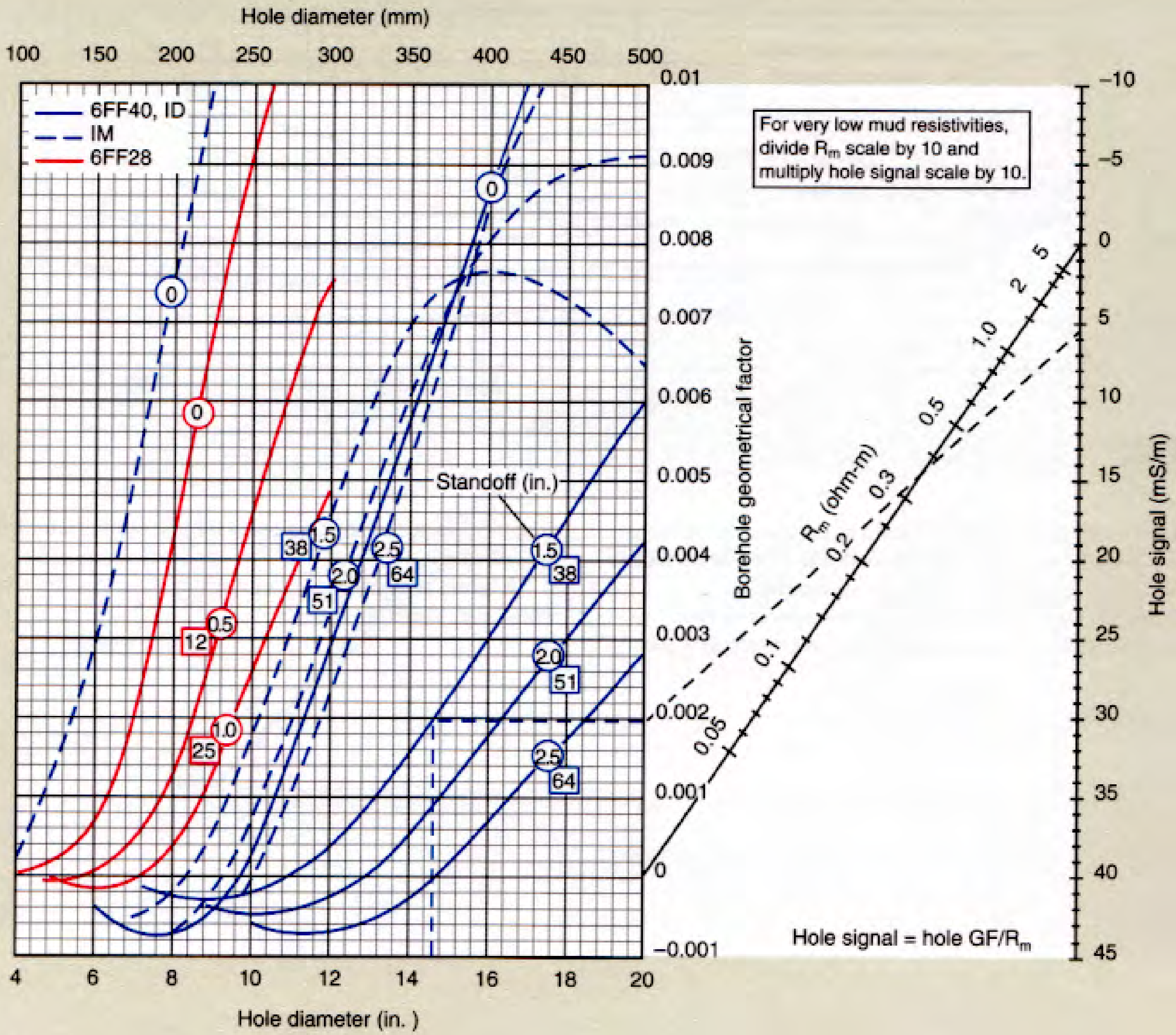
Most resistivity measurements should be corrected for borehole effect. Charts Rcor-1 and Rcor-8 provide the borehole correction for the 16-in. Normal and the SFL measurements.

To use, the ratio of the resistivity measurement divided by the mud resistivity, R_m, is entered in abscissa. Proceed to the proper borehole diameter, and read the correction factor from the ordinate.

The chart contains curves for a centered tool and for a tool with 1½-in. standoff.

Induction Log Borehole Correction



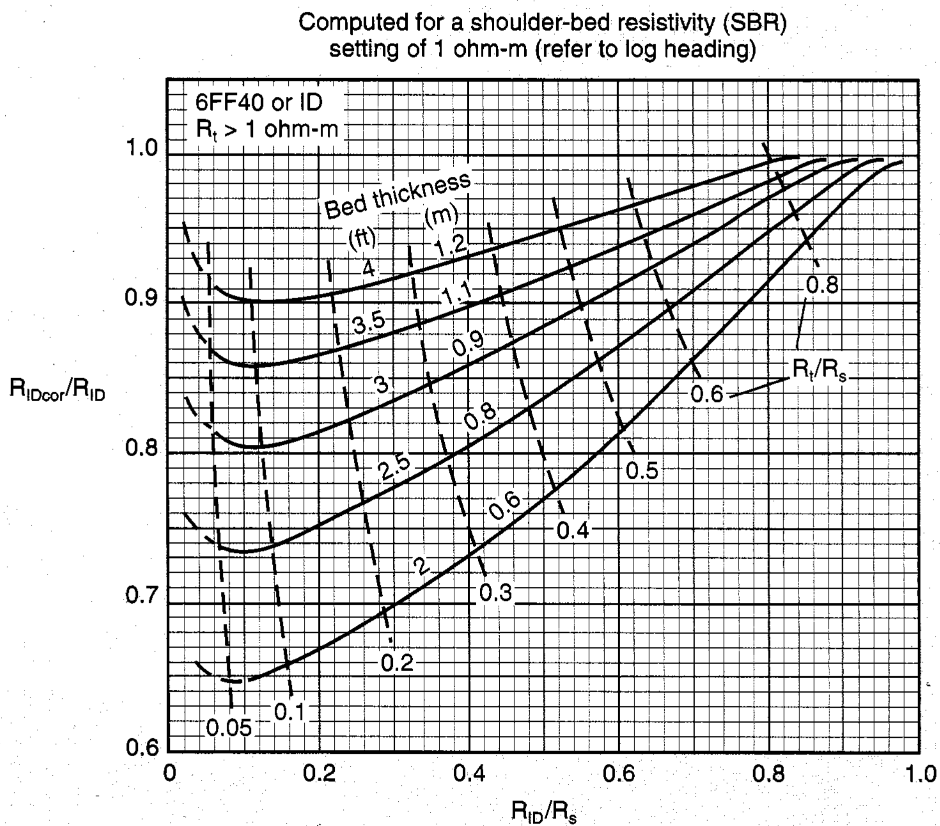
The hole-conductivity signal is to be subtracted, where necessary, from the induction log conductivity reading before other corrections are made.† This correction applies to all zones (including shoulder beds) having the same hole size and mud resistivity.

† 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 the log heading.

Rcor-4 gives corrections for 6FF40 or ID, IM and 6FF28 for various wall standoffs. Dashed lines illustrate the use of the chart for a 6FF40 sonde with a 1.5-in. standoff in a 14.6-in. borehole, and R_m = 0.35 ohm-m. The hole signal is found to be 5.5 mS/m. If the log reads R_I = 20 ohm-m, C_I (conductivity) = 50 mS/m. The corrected C_I is then (50 – 5.5) = 44.5 mS/m. R_I = 1000/44.5 = 22.4 ohm-m.

Induction Log Correction for Thin Conductive Beds

6FF40, ID, 6FF28



Charts Rcor-5, Rcor-6 and Rcor-7 correct the induction logs (6FF40, ID, 6FF28 and IM) for bed thickness. A skin-effect correction is included in these charts.

To use, select the chart appropriate for the tool type and for the adjacent bed resistivity (R_S). For Charts Rcor-5 and Rcor-6, enter the bed thickness and proceed upward to the proper R_a curve. Read the corrected resistivity value (R_t) in ordinate.

For Chart Rcor-7, enter the chart with the R_{ID}/R_S ratio (apparent ID reading/adjacent bed resistivity) and go upward to the bed thickness. Read the correction factor (R_{IDcor}/R_{ID}) in ordinate.

Example: R_{ID} = 4.2 ohm-m
R_{IM} = 6.0 ohm-m
R_S = 2.0 ohm-m
Bed thickness = 3 m

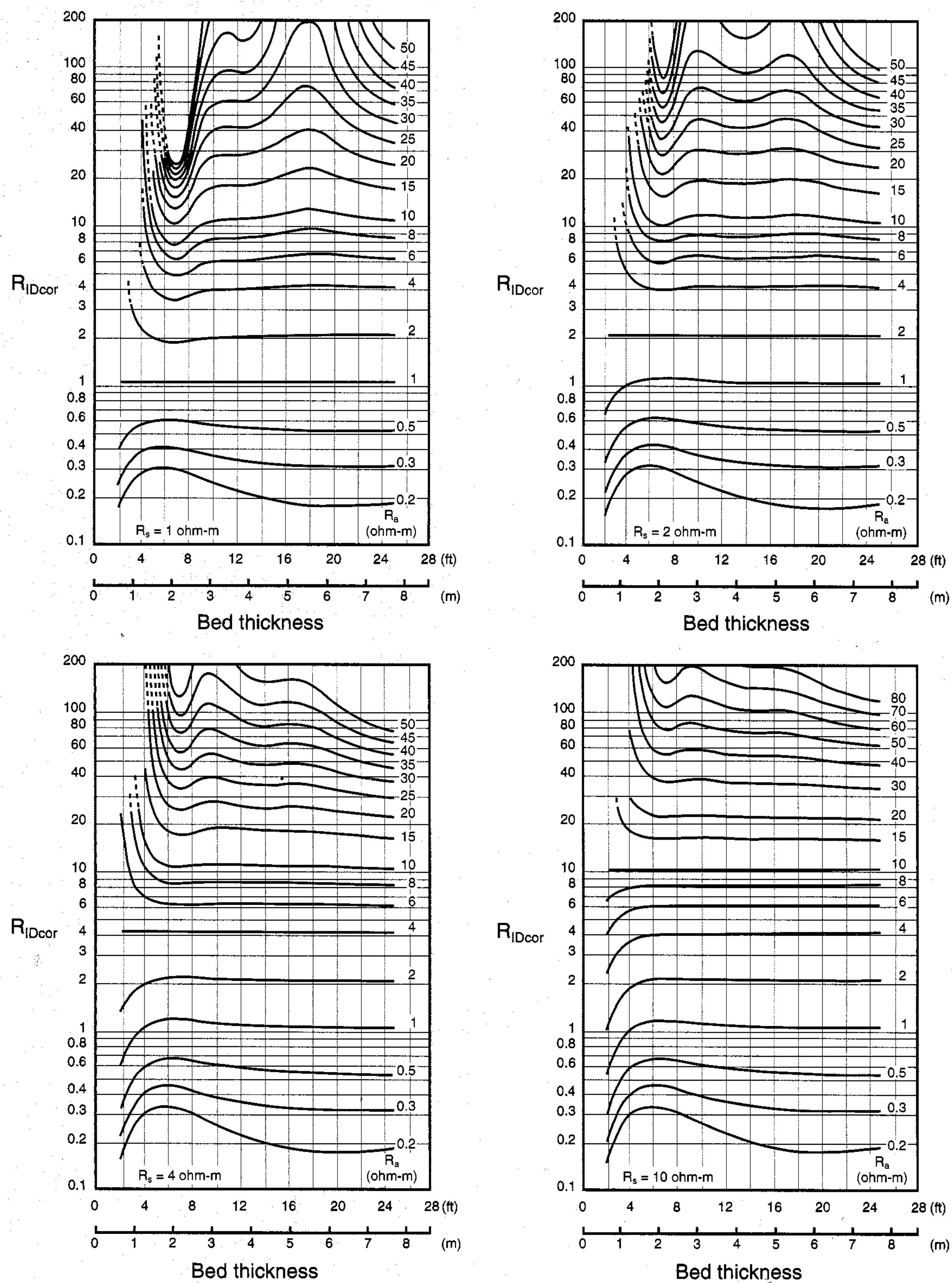
giving, from the R_S = 2 ohm-m charts,
R_{IDcor} = 4.5 ohm-m
R_{IMcor} = 6.2 ohm-m

For the small-diameter 6FF28, multiply the bed thickness by 1.43 before entering these correction charts. For example, in a 7-ft bed, the bed thickness used in correcting the 6FF28 reading is 10 ft (7 × 1.43 = 10).

Induction Log Bed-Thickness Correction

6FF40 (ID) and 6FF28

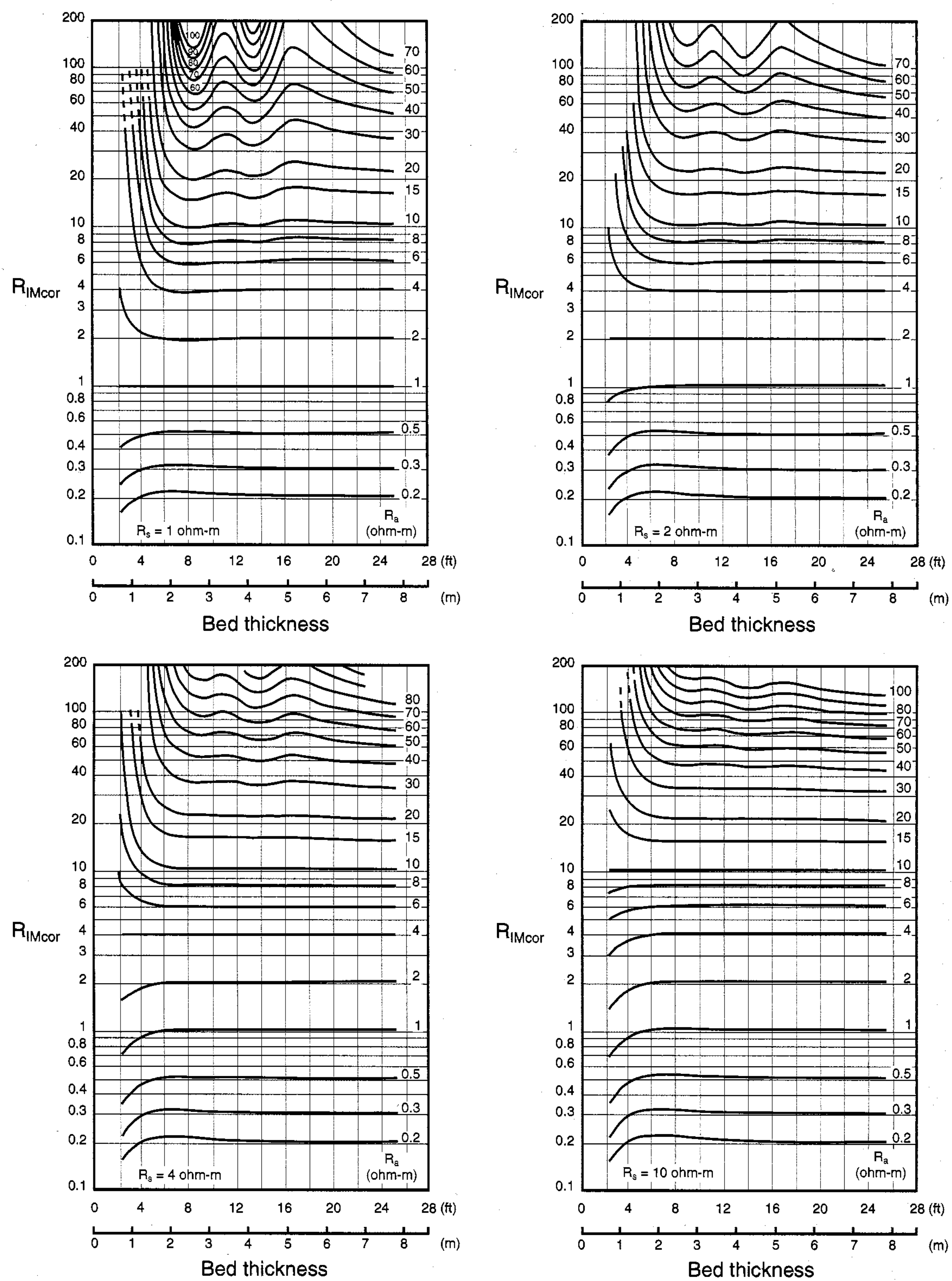
Computed for a shoulder-bed resistivity (SBR) setting of 1 ohm-m (refer to log heading)



For the small-diameter 6FF28 sonde, multiply the bed thickness by 1.43 before entering these correction charts. For example, in a 7-ft bed, the bed thickness used in correcting the 6FF28 reading is 10 ft (7 × 1.43 = 10).

Induction Log Bed-Thickness Correction

IM medium induction



Invasion Correction Charts

The invasion correction charts, sometimes referred to as "tornado" or "butterfly" charts, of the next several pages (labeled Rint-) are used to define the depth of invasion d_i, the R_{xo}/R_t ratio and the true resistivity R_t. All assume a step-contact profile of invasion and that all resistivity measurements have been corrected, where necessary, for borehole effect and bed thickness using the appropriate Rcor- chart, prior to entry.

To use any of these charts, enter the abscissa and ordinate with the required resistivity ratios. The point of intersection defines d_i, R_{xo}/R_t and R_t as a function of one resistivity measurement.

Example:

$$\left.\begin{array}{l} R_{SFL} = 25 \text{ ohm-m} \\ R_{IM} = 5.9 \text{ ohm-m} \\ R_{ID} = 4.8 \text{ ohm-m} \end{array}\right\} \begin{array}{l} \text{After correction} \\ \text{for borehole effect} \\ \text{and bed thickness} \end{array}$$

$R_m = 0.5$ ohm-m

Entering the $R_{xo}/R_m \approx 100$ chart (Chart Rint-2c) with

$R_{SFL}/R_{ID} = 25/4.8 = 5.2$

$R_{IM}/R_{ID} = 5.9/4.8 = 1.2$

yields $R_{xo}/R_t = 8$

$d_i = 39$ in. or 1 m

$R_t/R_{ID} = 0.97$

Therefore, $R_t = R_{ID}\,(R_t/R_{ID}) = 4.8 \times 0.97 = 4.7$ ohm-m

$R_{xo} = R_t\,(R_{xo}/R_t) = 4.7 \times 8 = 37.6$ ohm-m

Use of Chart Rint-2c is confirmed since $R_{xo}/R_m = 75$ (i.e., $R_{xo}/R_m \approx 100$).

Saturation determination in clean formations

Either of the chart-derived values of R_t and R_{xo}/R_t 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 as correct, and all values found (S_w, R_t, R_{xo} and d_i) are considered good.

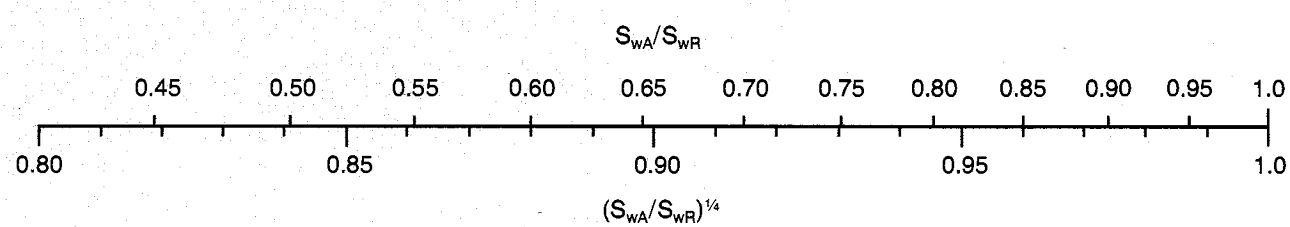
If $S_{wA} > S_{wR}$, either invasion is very shallow or a transition-type invasion profile is indicated, and S_{wA} is considered a good value for S_w.

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

$$S_{wcor} = S_{wA}\left(\frac{S_{wA}}{S_{wR}}\right)^{\frac{1}{4}}$$

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

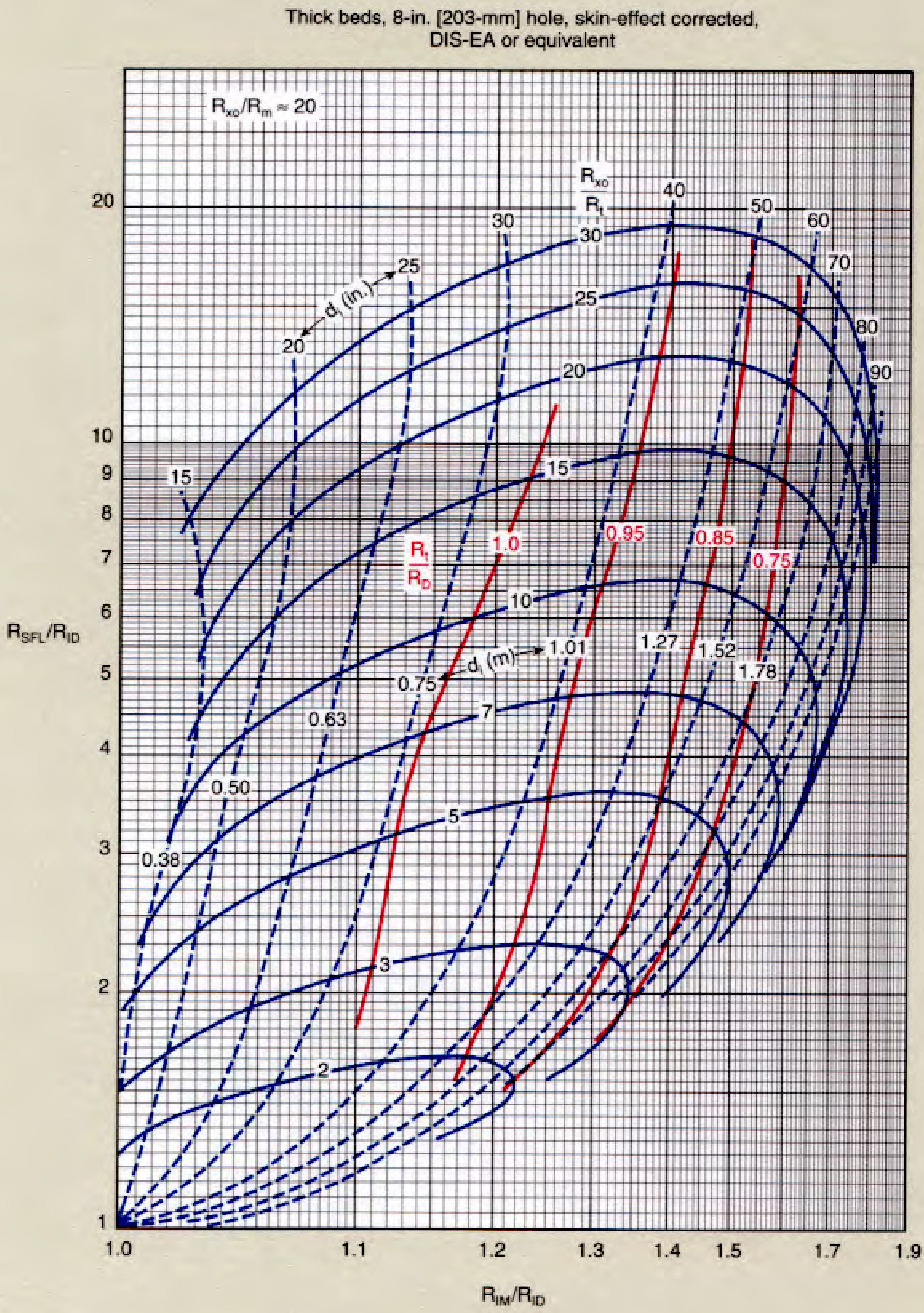
For more information see Reference 9.



Rint

DIL* Dual Induction–SFL* Spherically Focused Resistivity Log

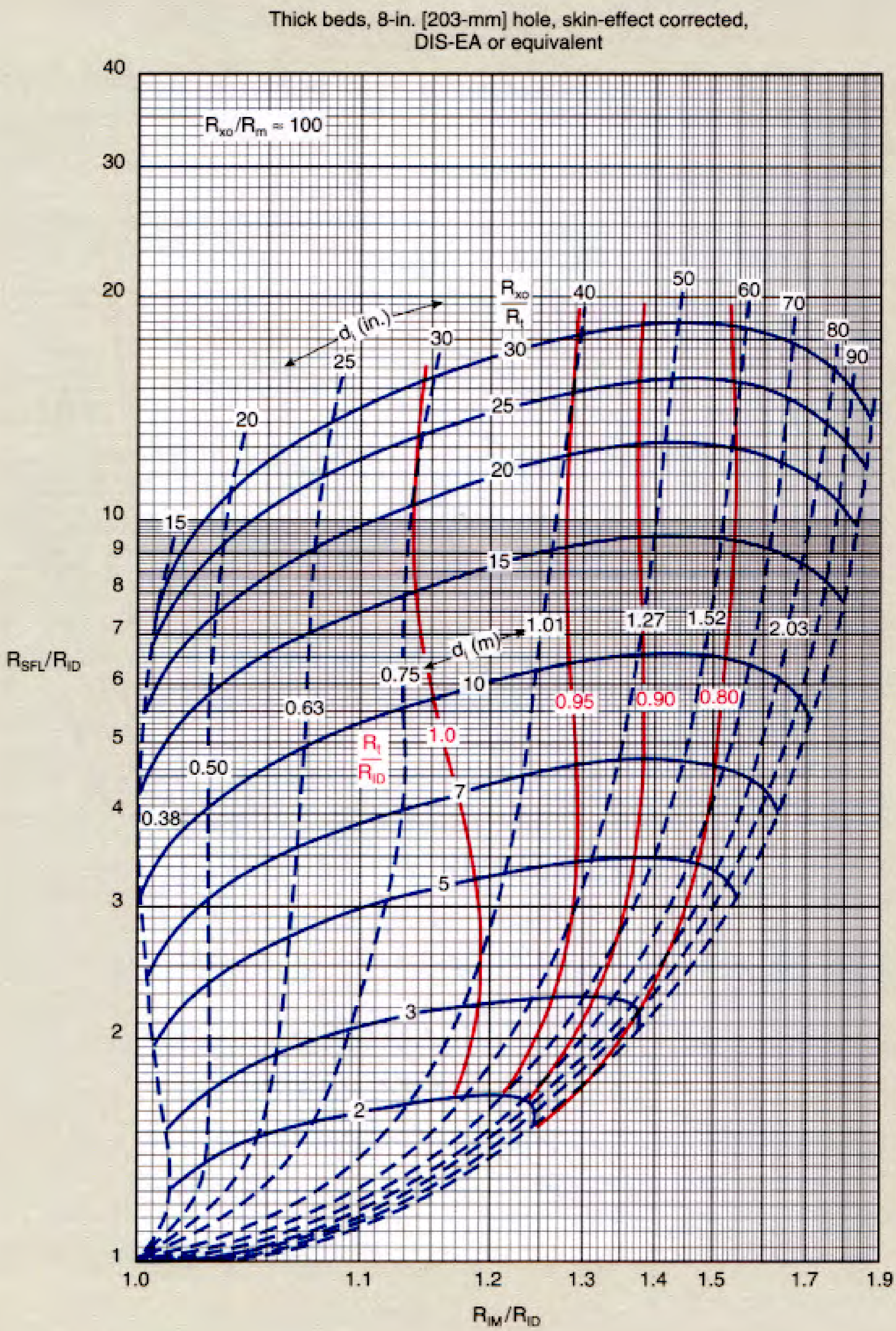
ID–IM–SFL



*Mark of Schlumberger

DIL* Dual Induction–SFL* Spherically Focused Resistivity Log

ID–IM–SFL

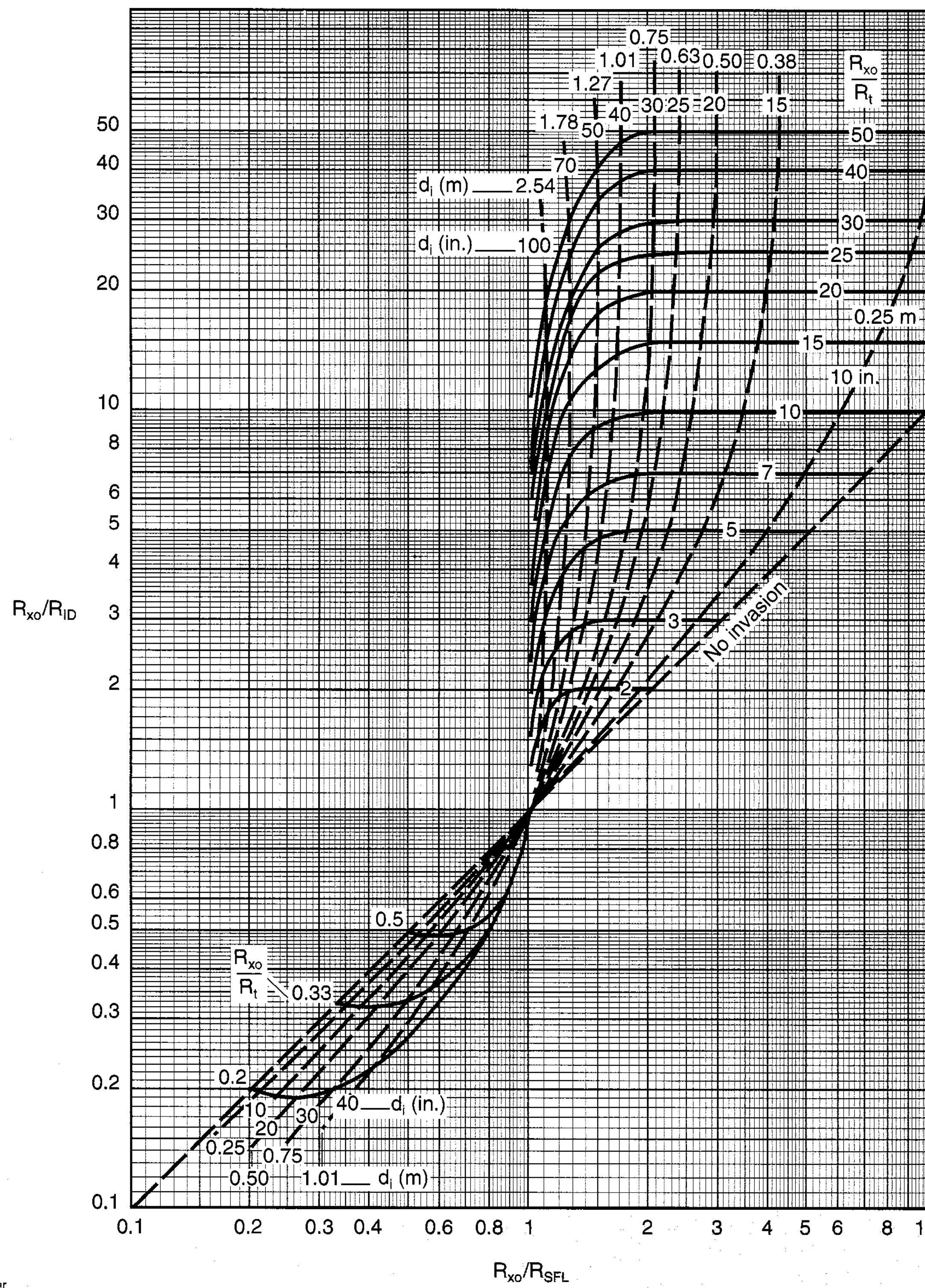


*Mark of Schlumberger

Deep Induction–SFL* Spherically Focused Resistivity Log–R_{xo} Device

ID–SFL–R_{xo} device

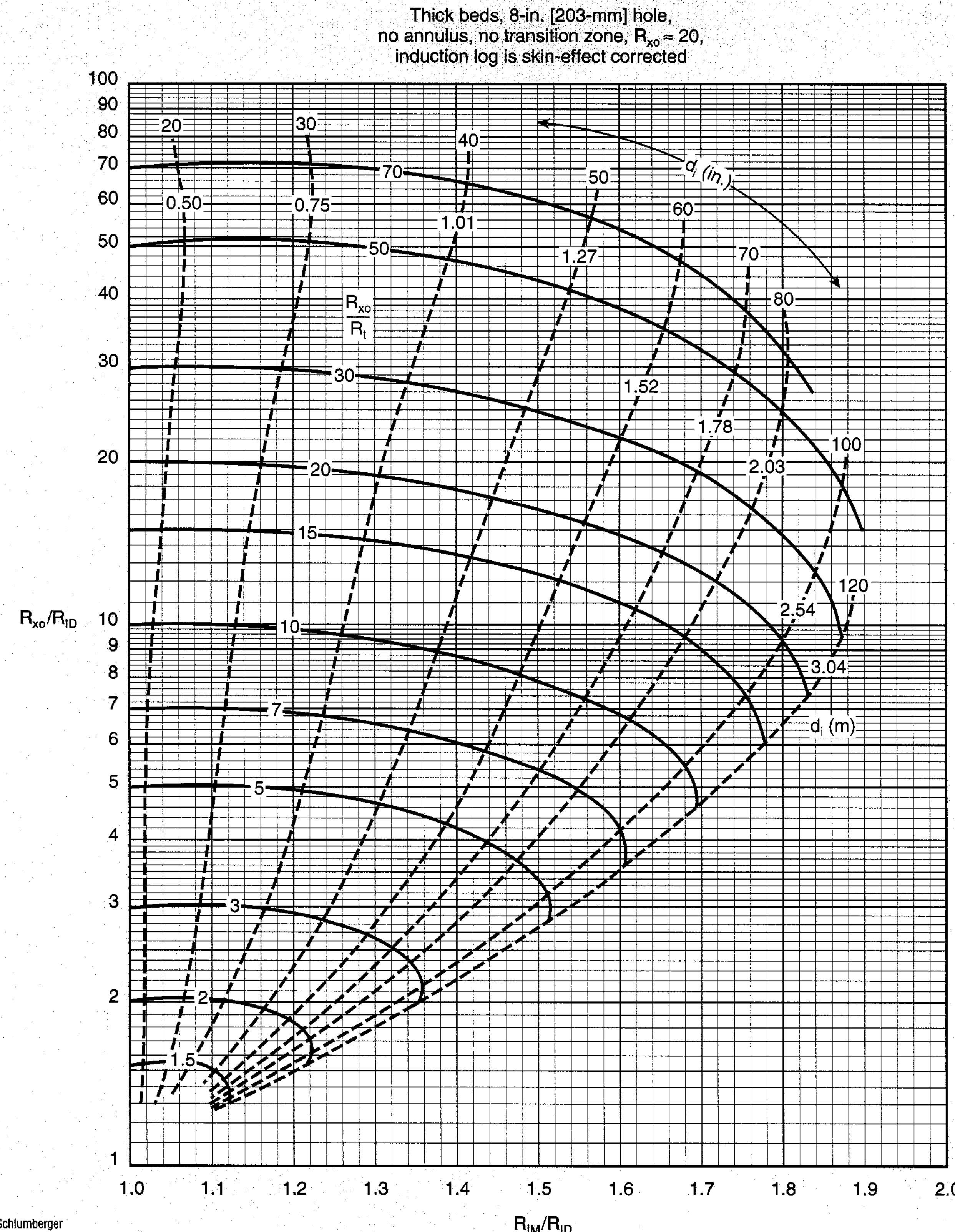
Thick beds, 8-in. [203-mm] hole,
no annulus, no transition zone,
induction log is skin-effect corrected



*Mark of Schlumberger

DIL* Dual Induction–R_{xo} Device

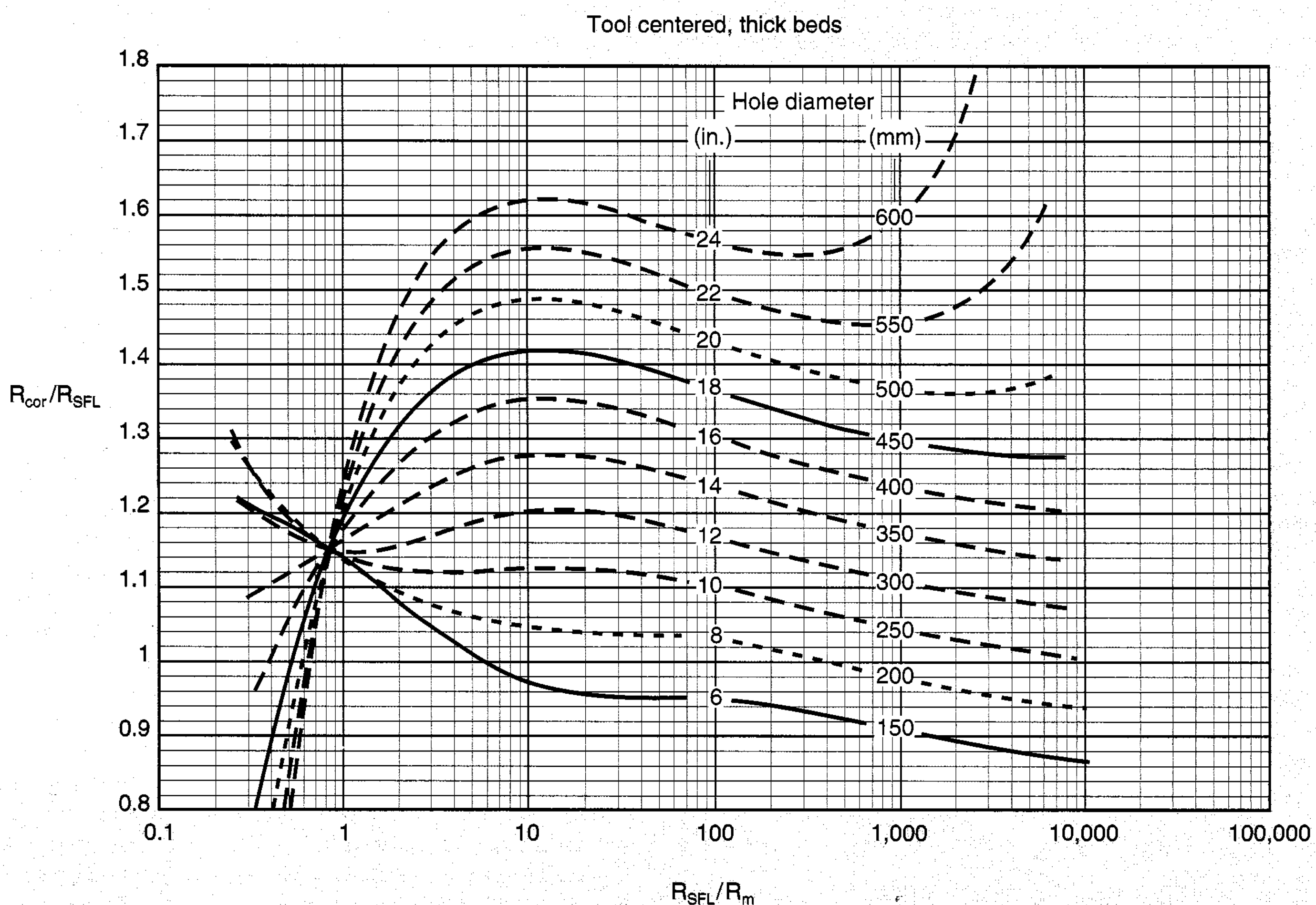
ID–IM–R_{xo} device



To use this chart in an oil-base mud environment, use synthetic R_{xo} calculated from EPT* or TDT* logs.

SFL* Borehole Correction

DIT-E Phasor* Induction tool



*Mark of Schlumberger

Phasor* Induction Borehole Correction

Borehole corrections can now be based on exact modeling as well as on traditional experiments. Borehole correction requires four inputs: borehole conductivity (C_B), formation conductivity (C_f), borehole diameter (D) and standoff (S). For smooth round holes, correction of Phasor Induction logs may be based on Charts Rcor-4b and Rcor-4c. For cases when $R_t/R_m > 100$, Chart Rcor-4b is used alone. For cases when $R_t/R_m < 100$, both Charts Rcor-4b and Rcor-4c are needed. Each chart gives the borehole geometrical factor (G_B) as a function of borehole diameter and standoff. G_B is used to get from apparent conductivity (C_a) to corrected conductivity (C_{cor}) through the correction formula

$$C_{cor} = \frac{C_a - C_B G_B}{1 - G_B} \quad (1)$$

G_B is obtained from the charts for the appropriate borehole and standoff. All conductivities are expressed in mS/m and are calculated through the formula

$$C = \frac{1000}{R} \quad (2)$$

where R is the resistivity in ohm-m.

When the formation-to-borehole contrast is low and the boreholes are large enough to warrant correction, the following formula for interpolation between charts gives the approximate borehole geometrical factor:

$$G_{B_{IM}} = A_M G_{B_{M4c}} + (1 - A_M) G_{B_{M4b}} \quad (3)$$

$$G_{B_{ID}} = A_D G_{B_{D4c}} + (1 - A_D) G_{B_{D4b}} \quad (4)$$

where $G_{B_{D4b}}$ is the ID GF from Chart Rcor-4b and $G_{B_{D4b}}$ is from Chart Rcor-4c (D refers to ID and M refers to IM). The parameter A_M is derived from the formation and mud conductivities through the formula

$$A_M = -2.58414 + 3.59087F - 1.49684F^2 \quad (5)$$

and

$$A_D = 0.994584 - 1.59245F + 0.663813F^2 \quad (6)$$

where

$$F = \frac{C_B - C_f}{C_B + C_F} \quad (7)$$

Since C_f represents the formation conductivity just inside the borehole, SFL is the best estimator of this conductivity. The interpolated borehole geometrical factor is used in Eq. 1.

Note: All resistivity logs are limited near 2000 ohm-m. Borehole conditions can cause legitimate negative conductivity readings in conditions such as very resistive formations. The conductivity channels CIDP and CIMP are not limited and are better choices for borehole correction.

All Phasor Induction borehole corrections are applicable to ERL* Enhanced Resolution Logging and ERA* Enhanced Resolution Analysis presentations.

Borehole corrections for the Phasor Induction tool are usually made in real time. These charts provide only approximate corrections for specific cases of R_t/R_m and unique hole diameters. Any discrepancy between real-time (or Data Services Center) and manual chart-based corrections should normally be resolved in favor of the real-time corrections.

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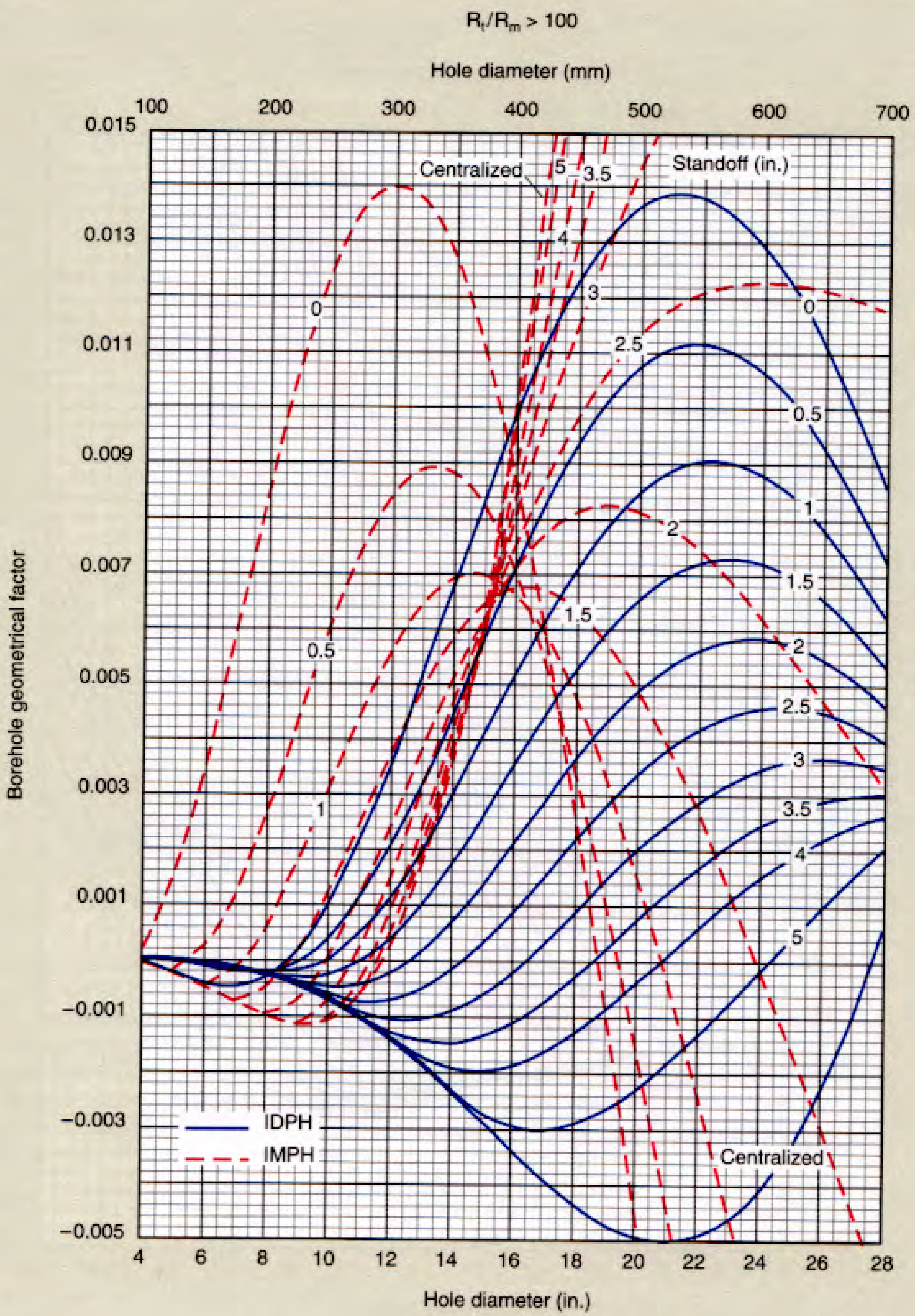
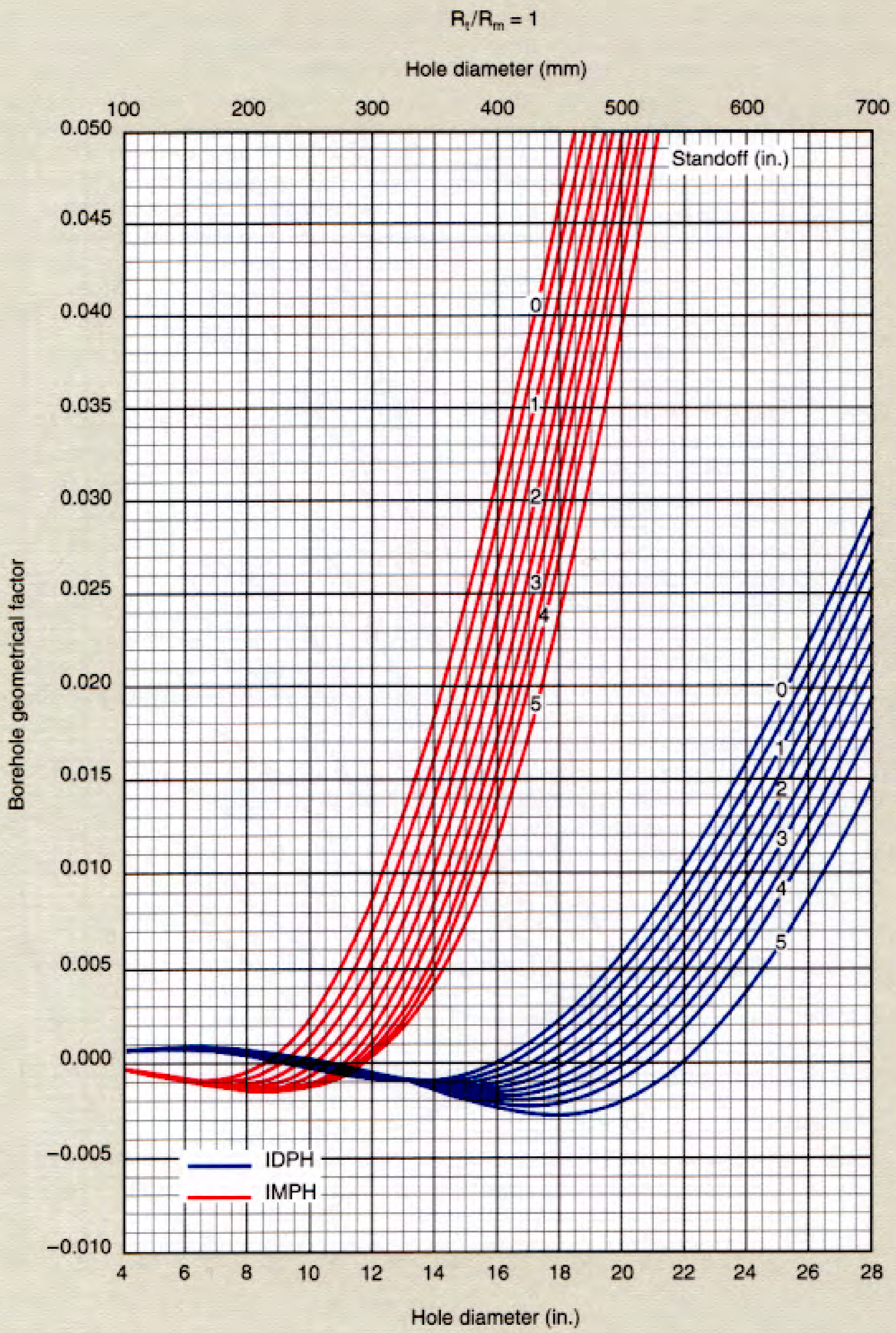
Phasor* Induction Borehole Correction



*Mark of Schlumberger

The borehole geometrical factor obtained from this chart or Chart Rcor-4c can be inserted into Nomograph Rcor-4a with the mud resistivity (R_m) to determine the hole signal (in mS/m).

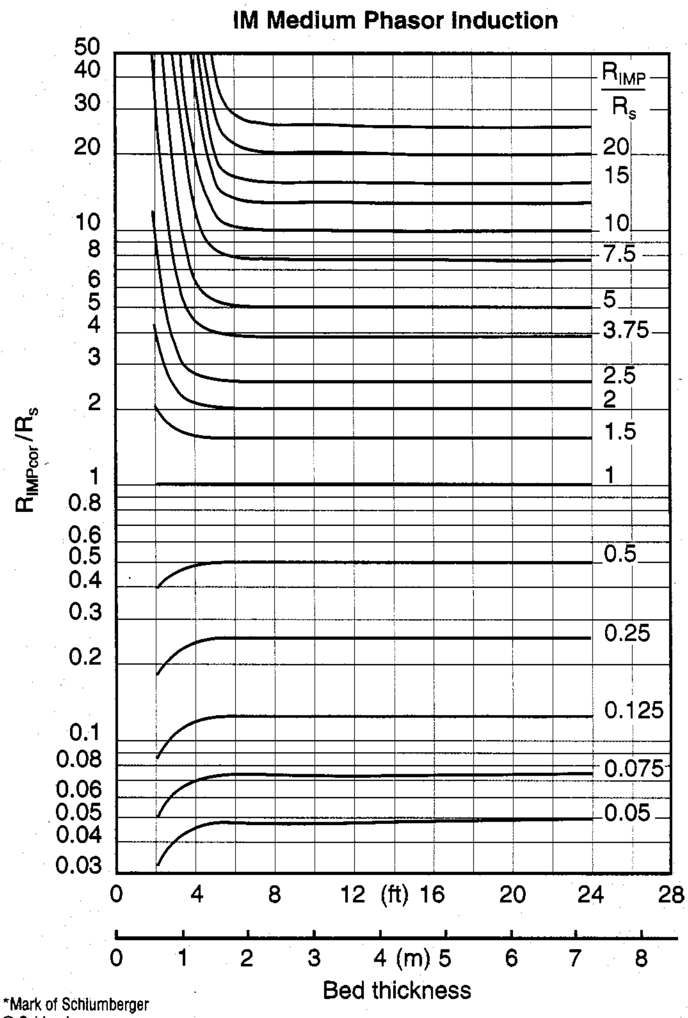
Phasor* Induction Borehole Correction

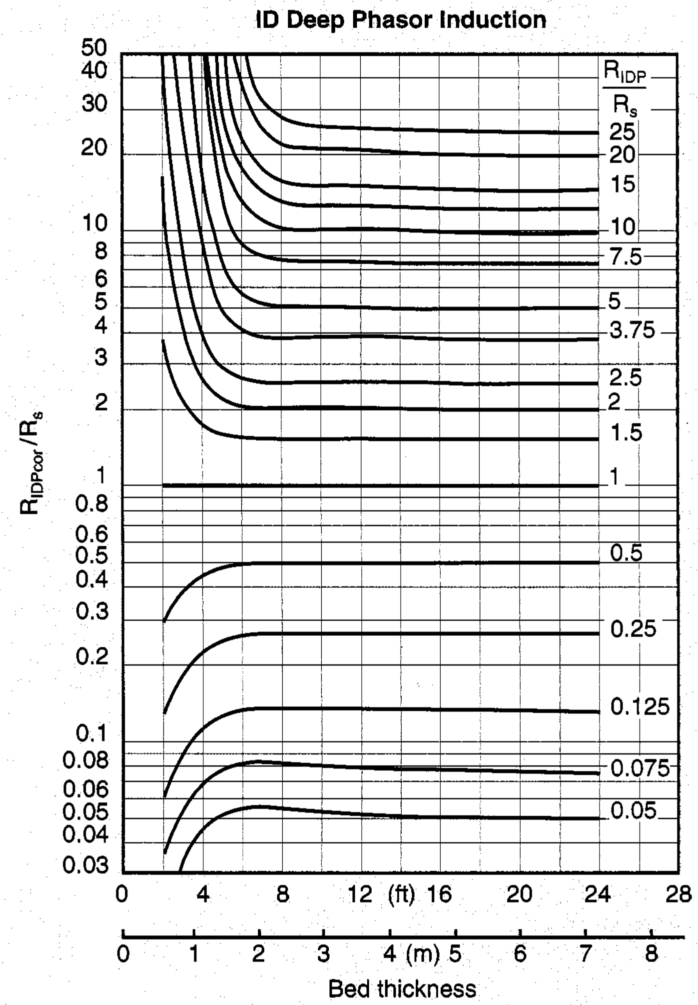


*Mark of Schlumberger

Phasor* Induction Bed-Thickness Correction

DIT-E Phasor Dual Induction–SFL





*Mark of Schlumberger

These charts (Rcor-9) correct the DIT-E Phasor Induction (IM and ID) measurements for bed thickness.

To use, enter the appropriate chart with the ratio of the apparent resistivity (R_{IMP} or R_{IDP}) divided by the adjacent bed resistivity (R_s) and the bed thickness. At this resulting intersection, the ratio of the corrected resistivity to the adjacent bed resistivity is read on the ordinate.

Example: $R_{IDP} = 7.5$ ohm-m
$R_{IMP} = 6$ ohm-m
$R_s = 2$ ohm-m
Bed thickness = 6 ft

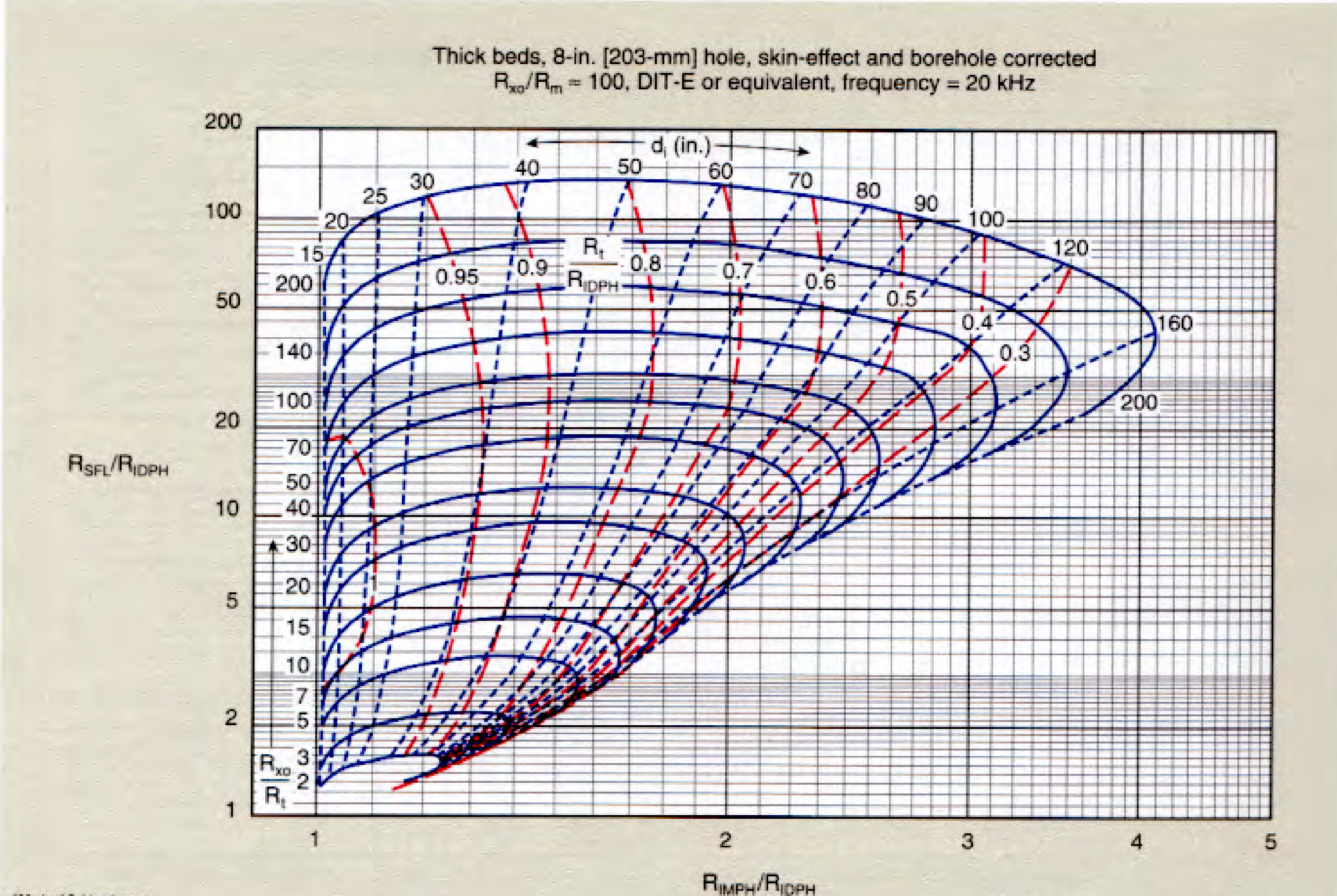
giving $R_{IDP}/R_s = 7.5/2 = 3.75$
$R_{IMP}/R_s = 6/2 = 3$

Therefore, $R_{IDPcor}/R_s = 4$
$R_{IMPcor}/R_s = 3.1$

and $R_{IDPcor} = 8$ ohm-m
$R_{IMPcor} = 6$ ohm-m

Phasor* Dual Induction–SFL* Spherically Focused Resistivity Log

ID Phasor–IM Phasor–SFL



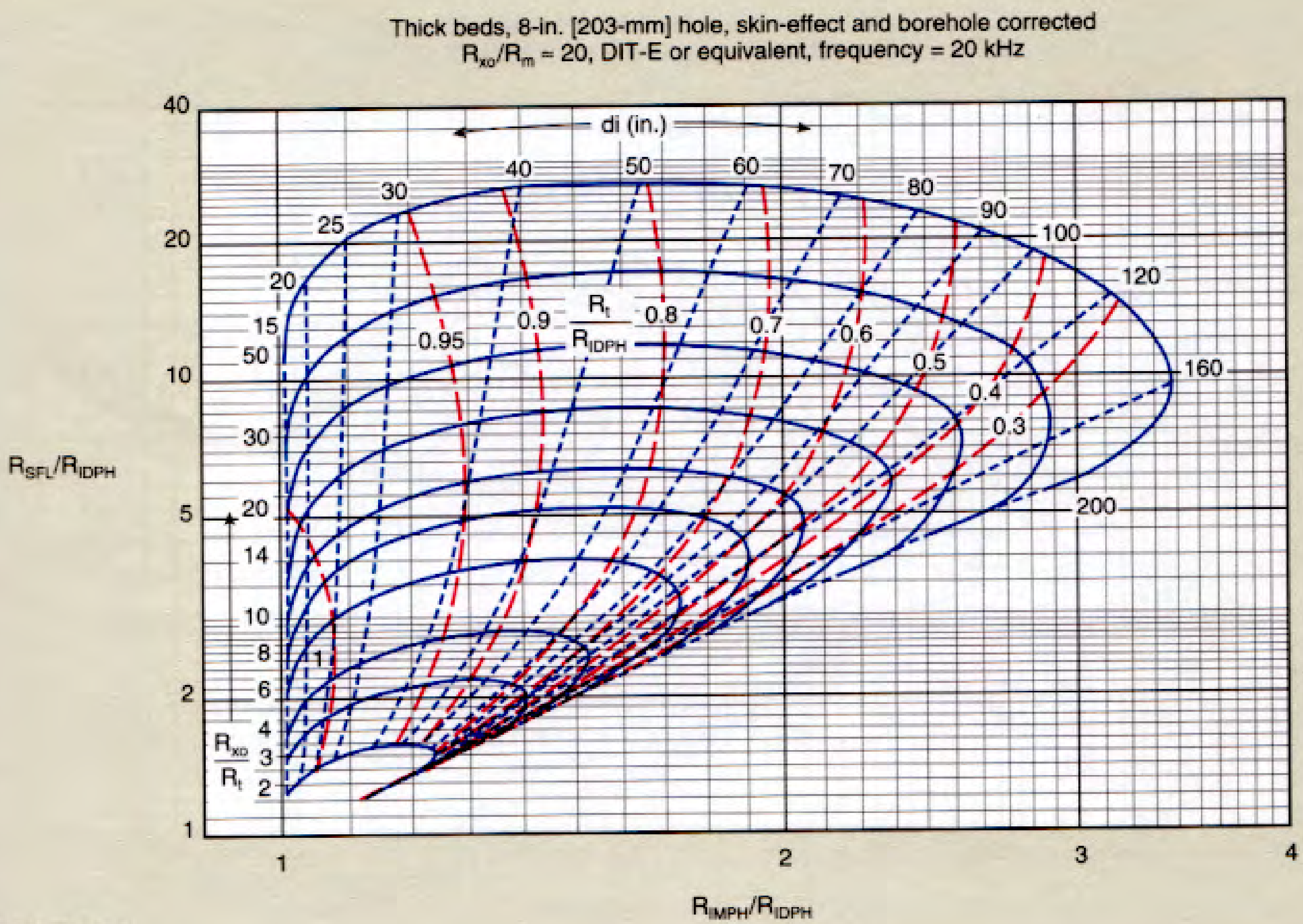
Charts Rint-11, Rint-12, Rint-13 and Rint-15 apply to the Phasor Induction tool when operated at a frequency of 20 kHz. Similar charts (not presented here) are available for tool operation at 10 kHz and 40 kHz.

The 20-kHz charts provide reasonable approximations of R_{xo}/R_t and R_t/R_{IDPH} for tool operation at 10 kHz and 40 kHz when only moderately deep invasion exists (less than 100 in.).

All Phasor Induction invasion correction charts are applicable to ERL* Enhanced Resolution Logging and ERA* Enhanced Resolution Analysis presentations.

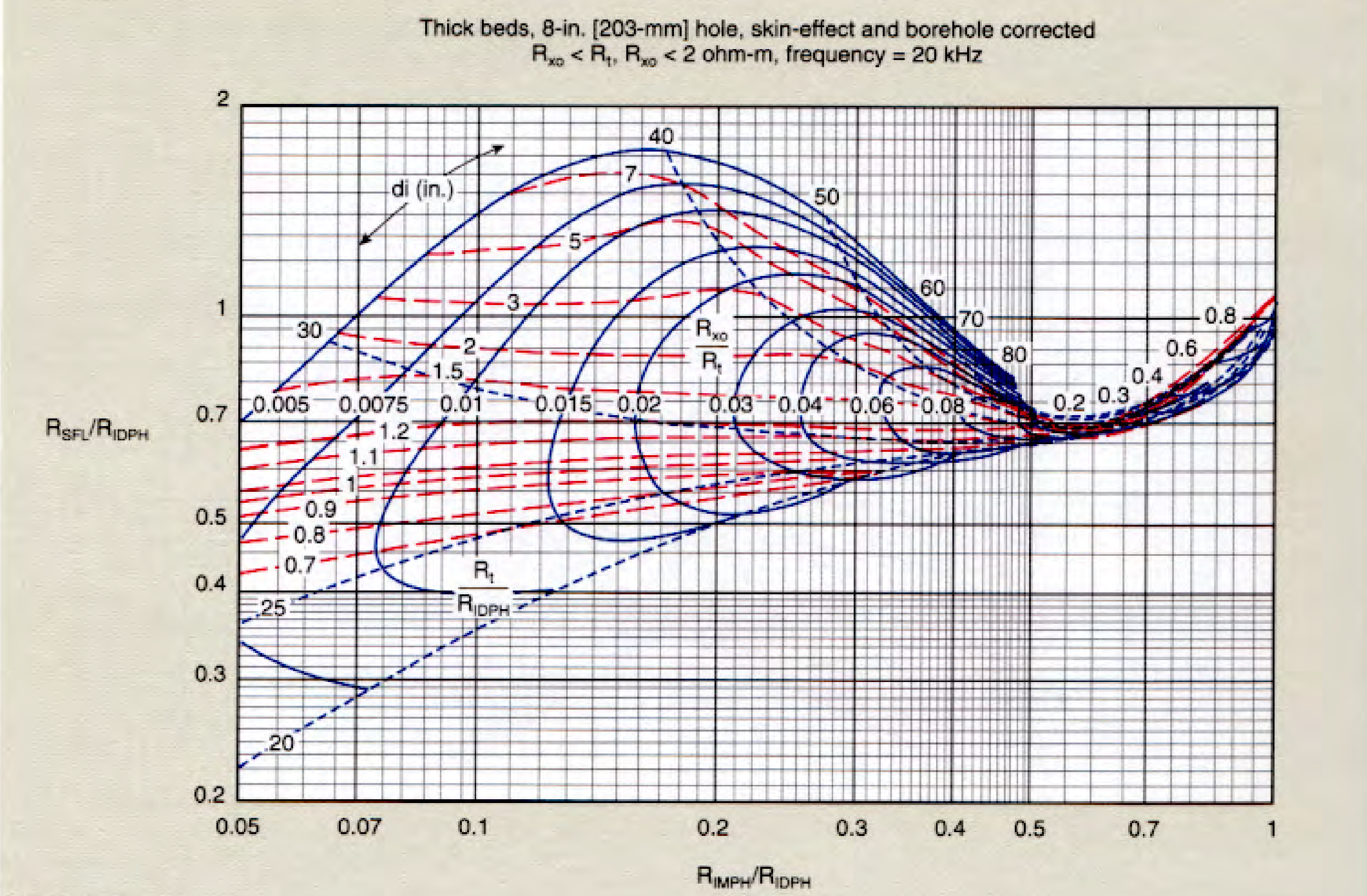
Phasor* Dual Induction–SFL* Spherically Focused Resistivity Log

ID Phasor–IM Phasor–SFL



Phasor* Dual Induction–SFL* Spherically Focused Resistivity Log

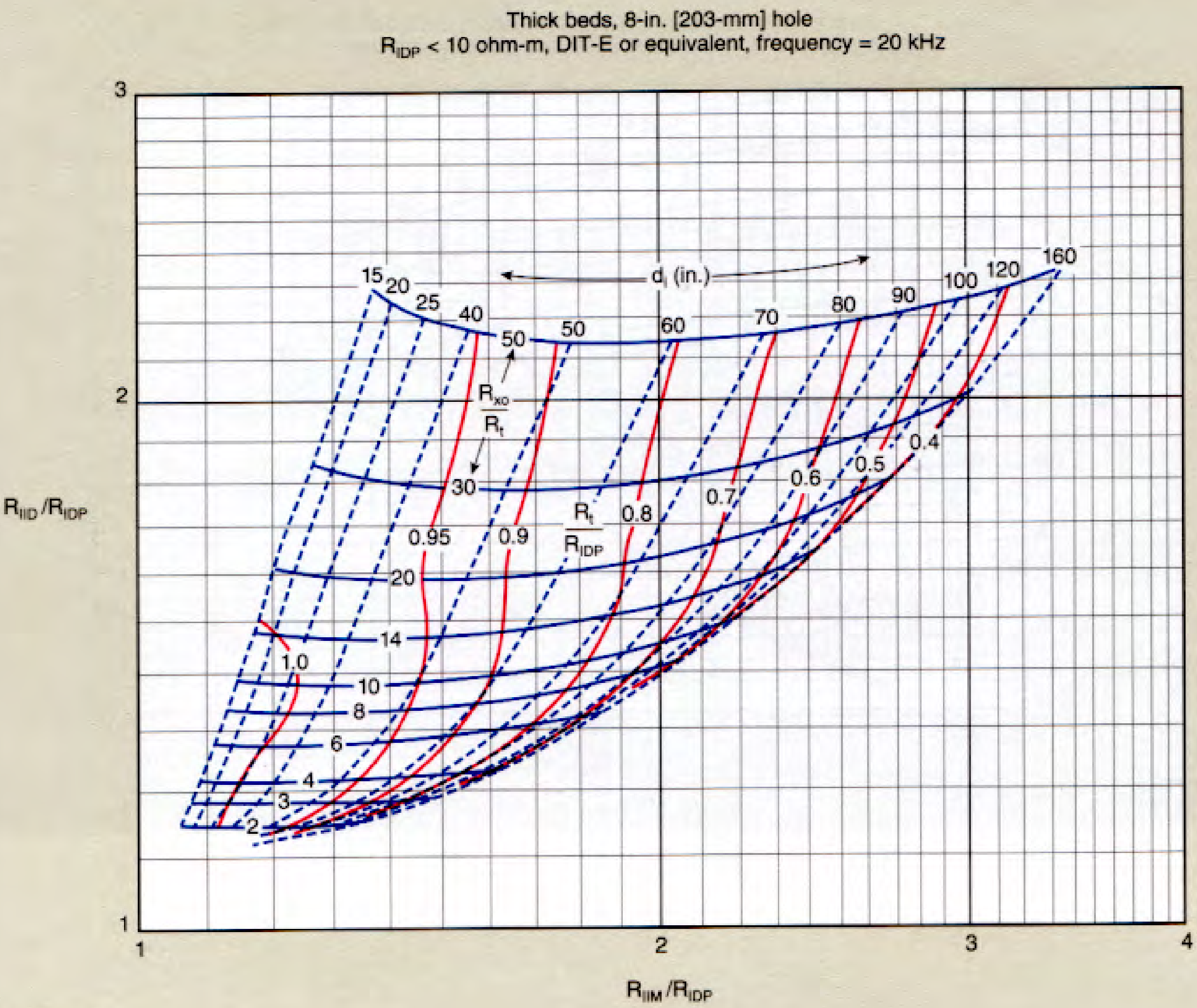
ID Phasor–IM Phasor–SFL



*Mark of Schlumberger

Phasor* Dual Induction in Oil-Base Mud

ID Phasor–IM Phasor–Raw, unboosted I signals



This chart uses the raw, unboosted induction signals and the ID Phasor value to define the invasion profile in a rock drilled with oil-base mud. To use the chart, the ratio of the raw, unboosted medium induction signal (IIM) and the deep Phasor induction (IDP) is entered in abscissa. The ratio of the raw, unboosted deep induction signal (IID) and the deep Phasor induction (IDP) is entered in ordinate. Their intersection defines d_i, R_{xo}/R_t and R_t/R_{IDP}.

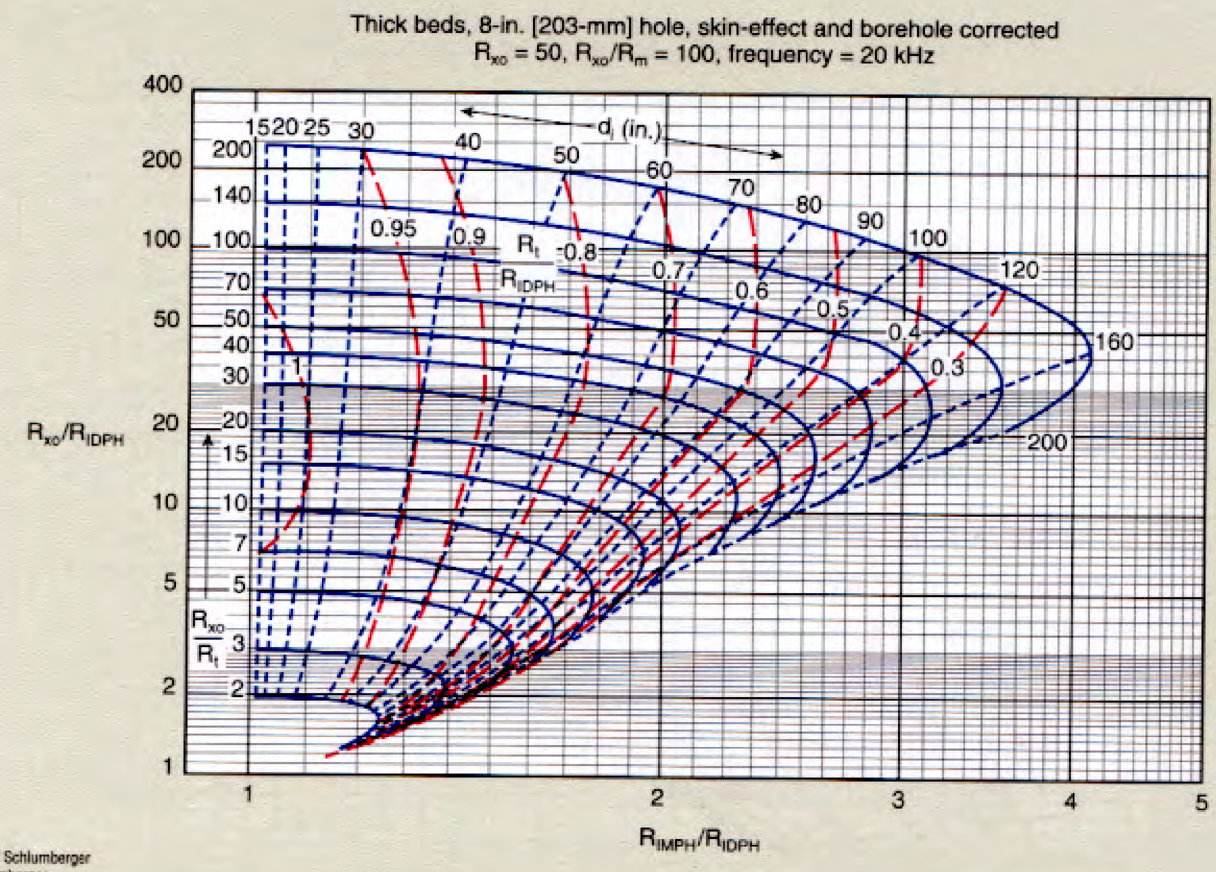
Example: R_{IDP} = 1.6 ohm-m
R_{IID} = 2.4 ohm-m
R_{IIM} = 2.4 ohm-m

giving R_{IID}/R_{IDP} = 2.4/1.6 = 1.5
R_{IIM}/R_{IDP} = 2.4/1.6 = 1.5

Therefore, d_i = 50 in.
R_{xo}/R_t = 15
R_t/R_{IDP} = 0.94
R_t = 0.94 (1.6) = 1.5 ohm-m

Phasor* Dual Induction–R_{xo} Device

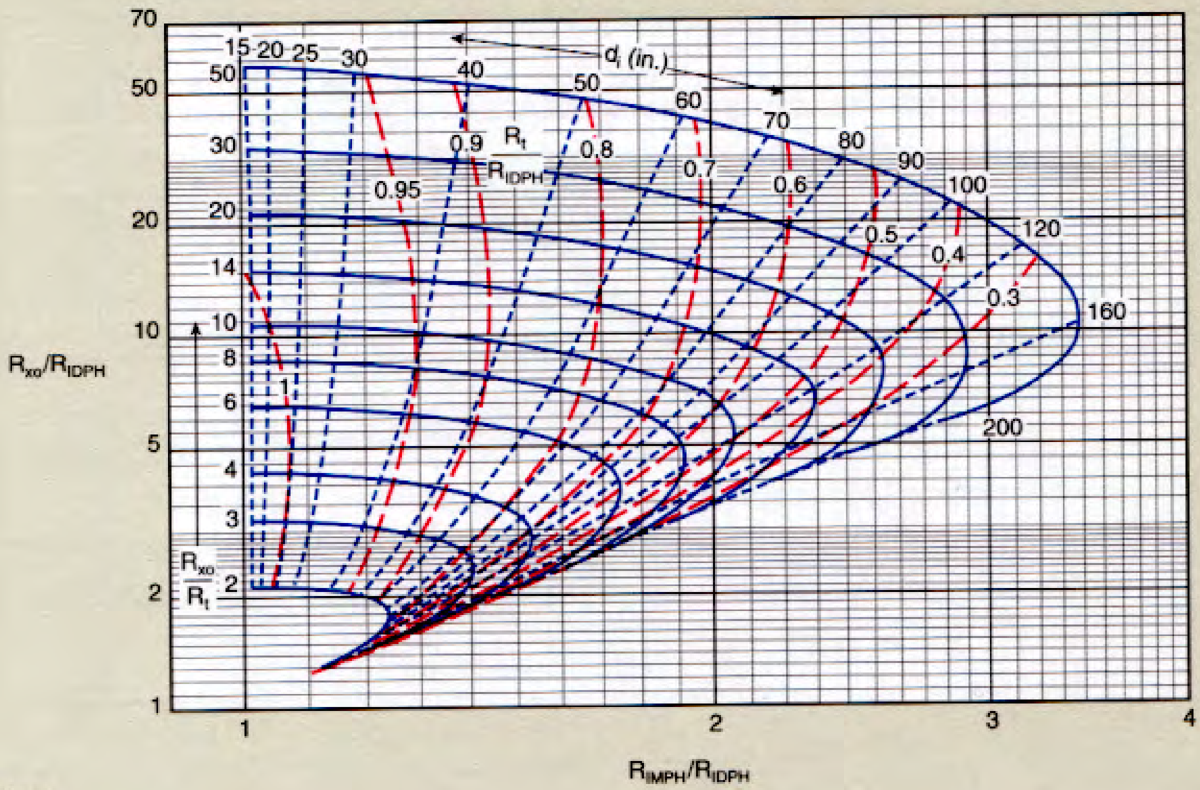
ID Phasor–IM Phasor–R_{xo} device



*Mark of Schlumberger

Phasor* Dual Induction–R_{xo} Device

ID Phasor–IM Phasor–R_{xo} device

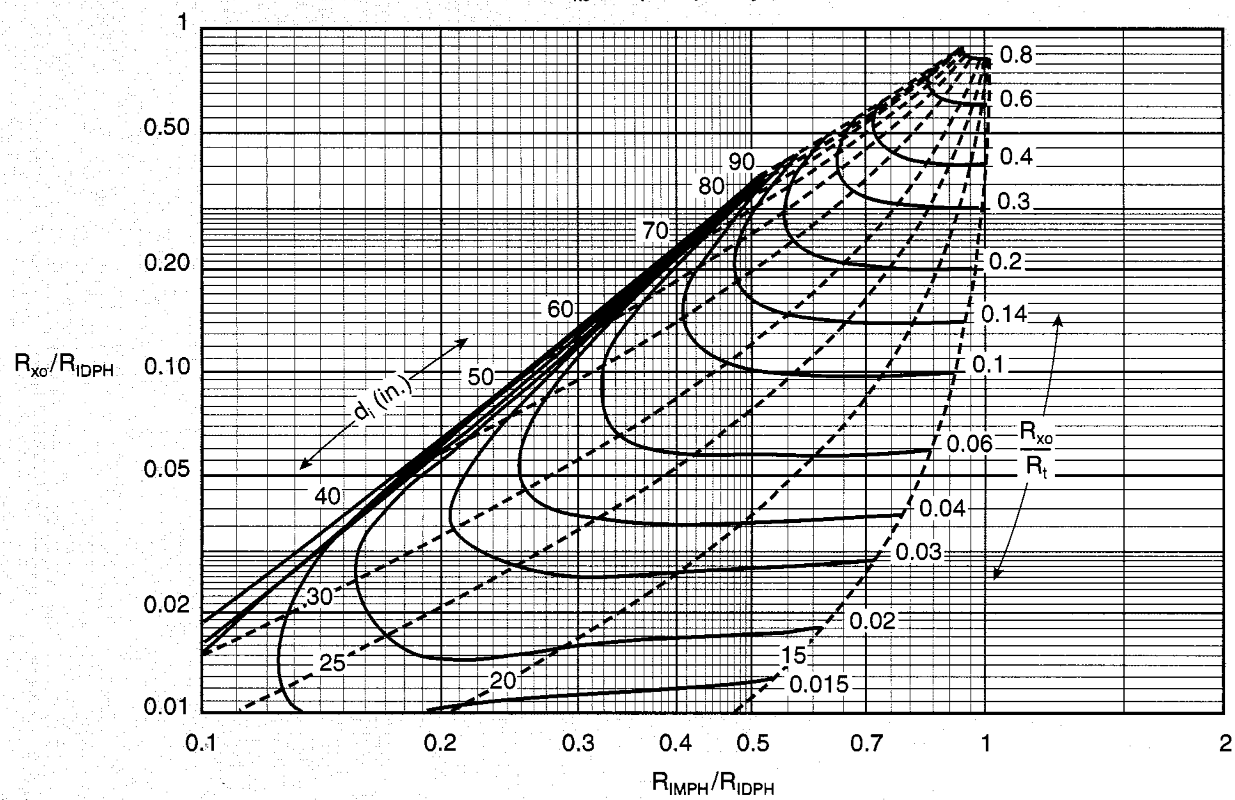


*Mark of Schlumberger

Phasor* Dual Induction–R_{xo} Device

ID Phasor–IM Phasor–R_{xo} device

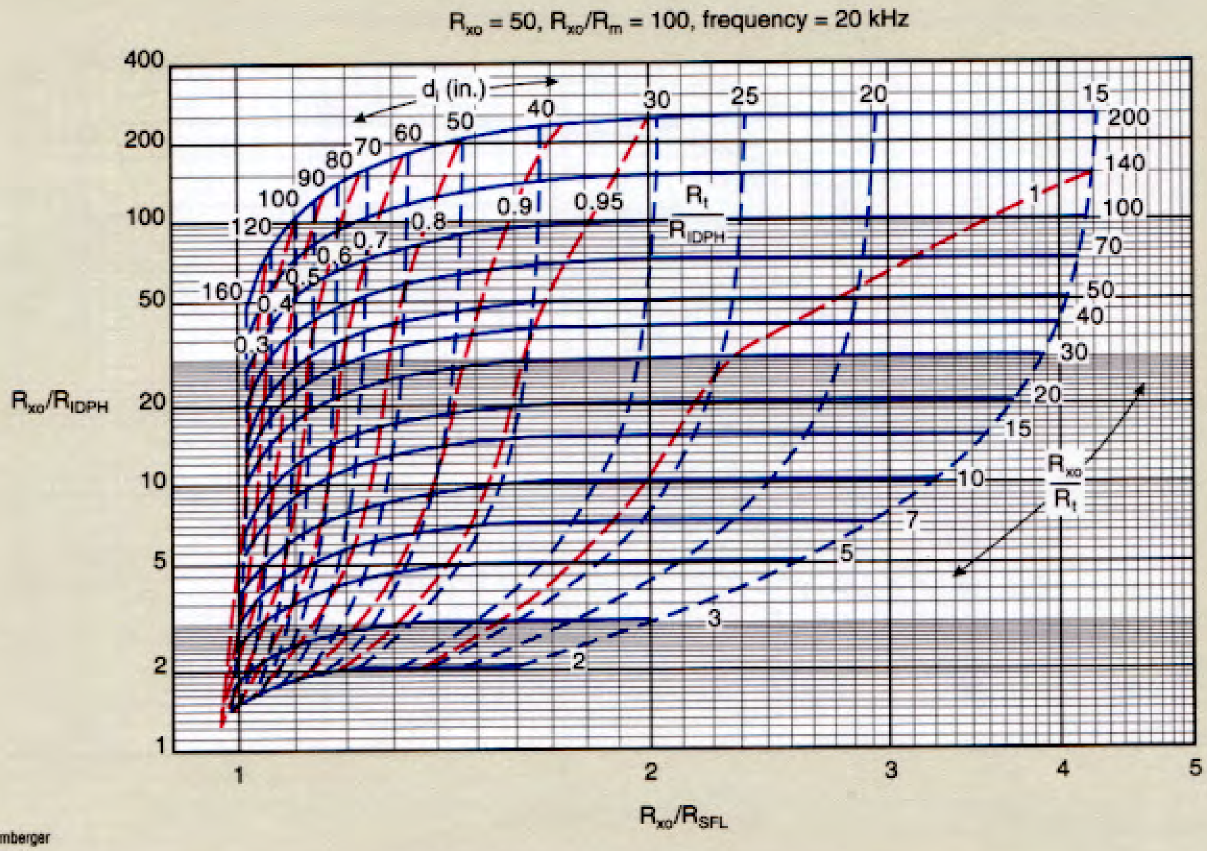
Thick beds, 8-in. [203-mm] hole, skin-effect and borehole corrected
$R_{xo} < R_t$, frequency = 20 kHz



*Mark of Schlumberger

Phasor* Dual Induction–SFL*–R_{xo} Device

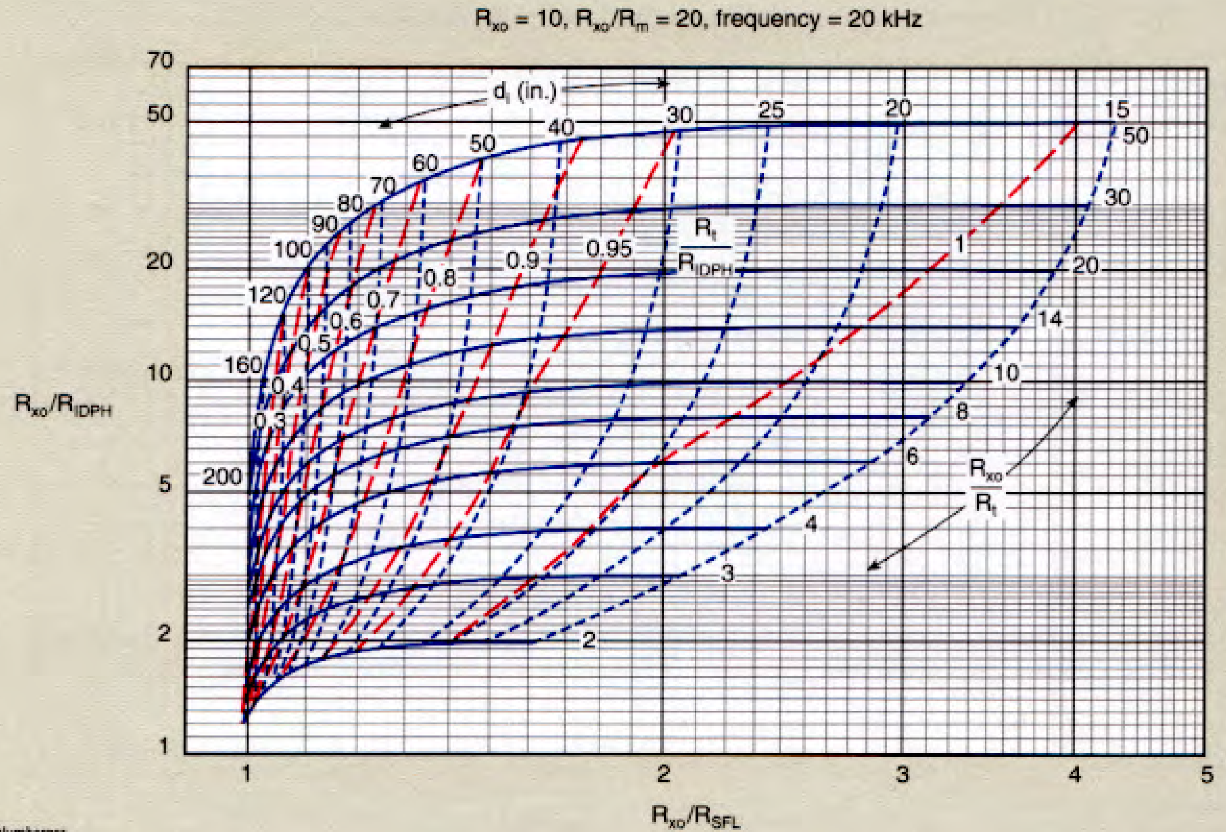
ID Phasor–SFL–R_{xo} device



*Mark of Schlumberger

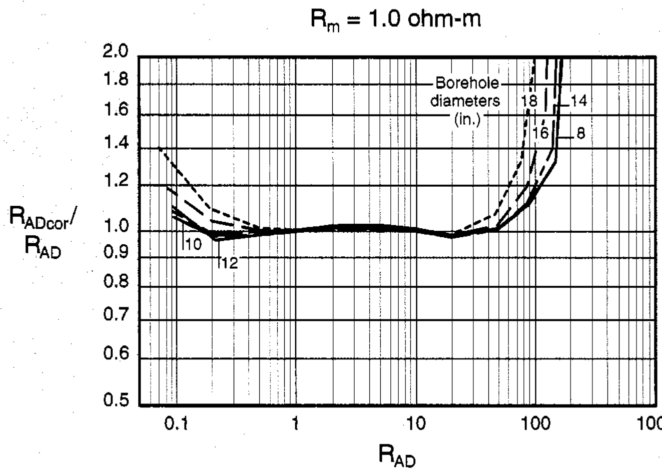
Phasor* Dual Induction–SFL*–R_{xo} Device

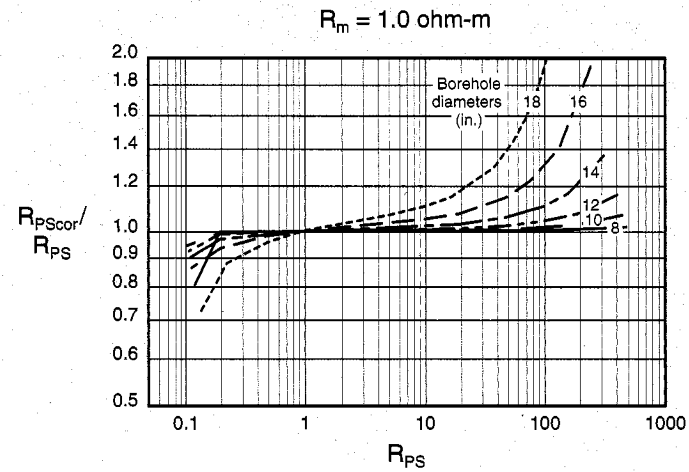
ID Phasor–SFL–R_{xo} device

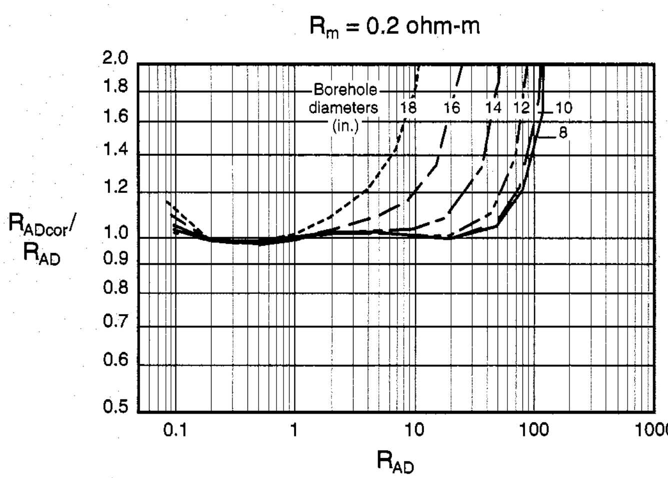


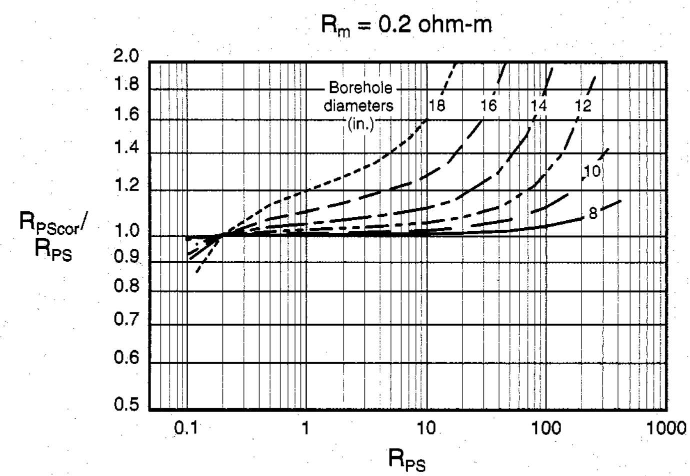
*Mark of Schlumberger

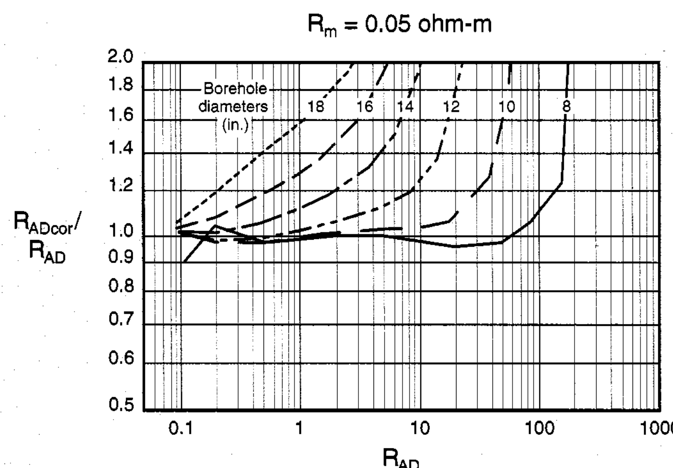
CDR* Compensated Dual Resistivity Borehole Correction for 6.5-in. Tool

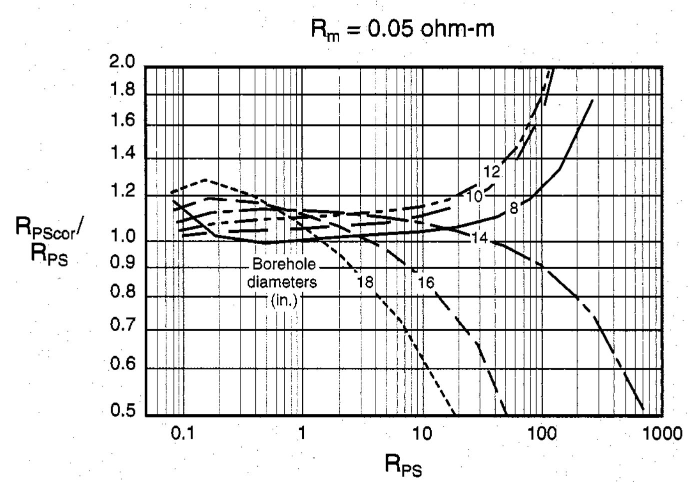












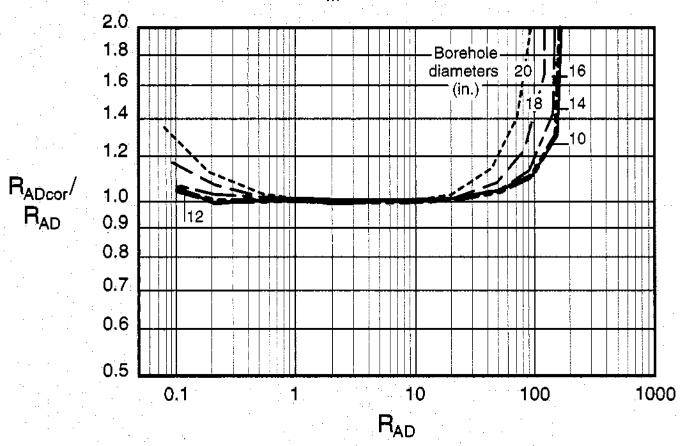
*Mark of Schlumberger

The CDR Compensated Dual Resistivity tool, a logging-while-drilling (LWD) electromagnetic propagation tool, provides measurements with similarities to the medium (IM) and deep (ID) wireline induction logs. The phase shift and attenuation of 2-MHz electromagnetic waves are independently transformed into two apparent resistivities—providing two depths of investigation.

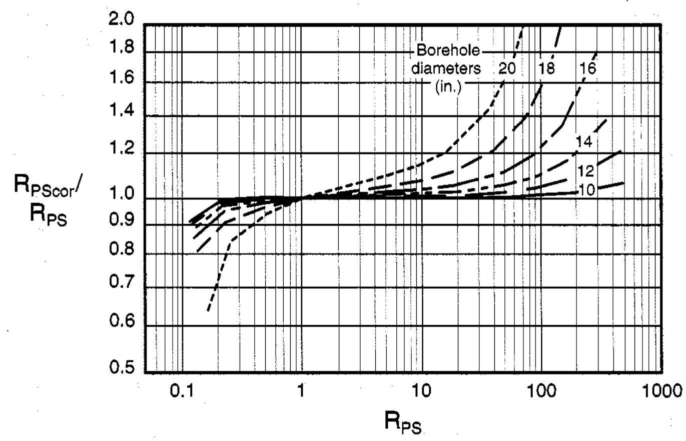
Continued on next page

CDR* Compensated Dual Resistivity Borehole Correction for 8-in. Tool

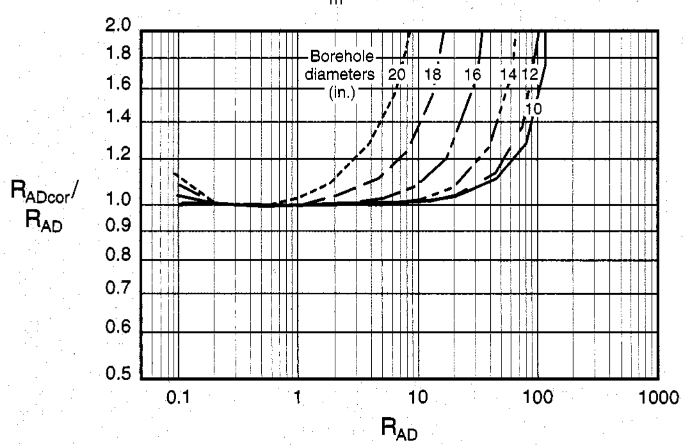
R_m = 1.0 ohm-m



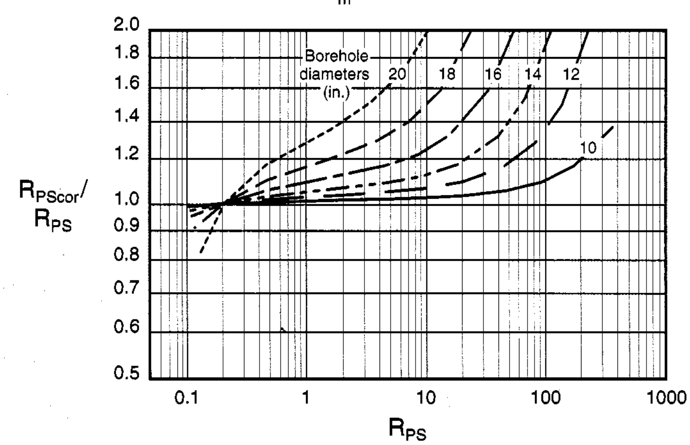
R_m = 1.0 ohm-m



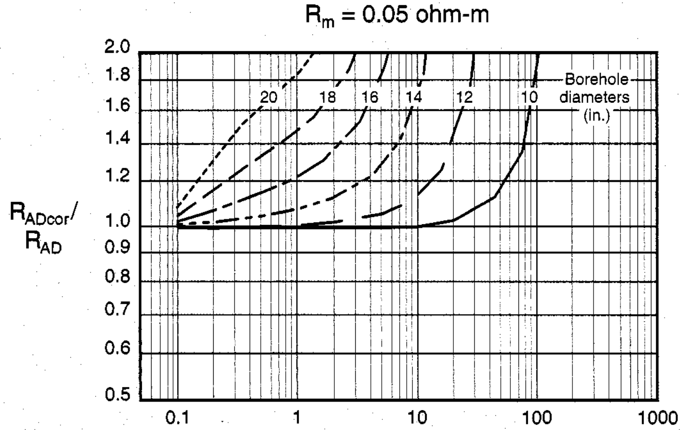
R_m = 0.2 ohm-m



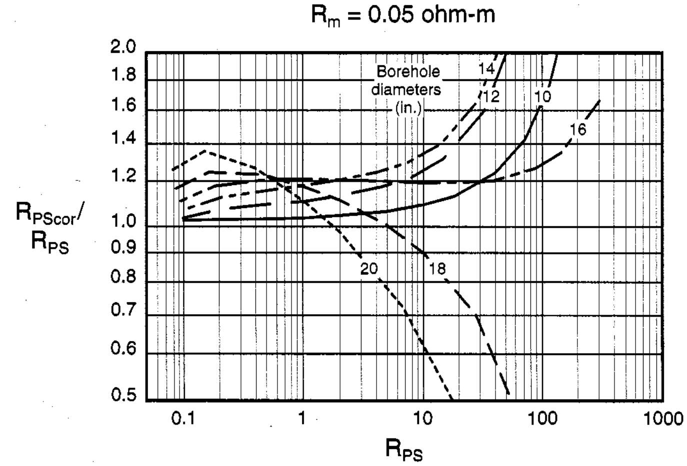
R_m = 0.2 ohm-m



R_m = 0.05 ohm-m



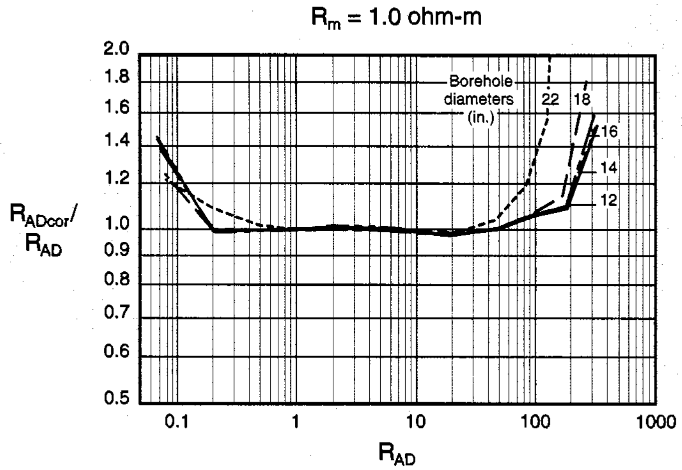
R_m = 0.05 ohm-m

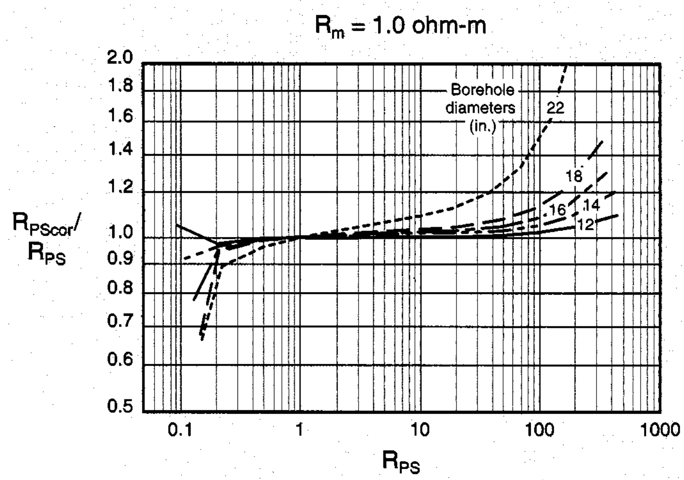


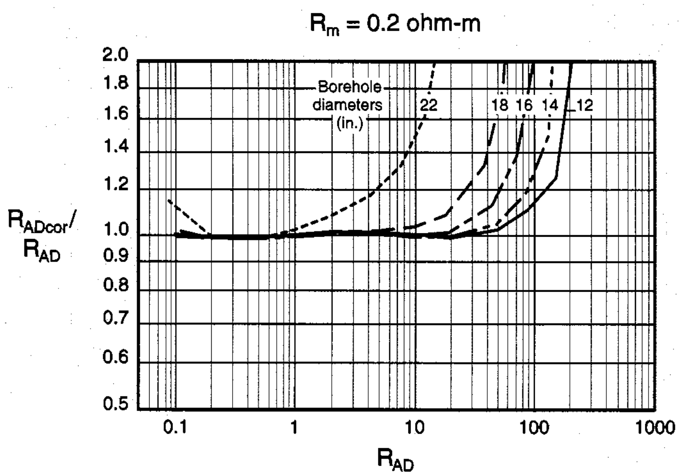
*Mark of Schlumberger

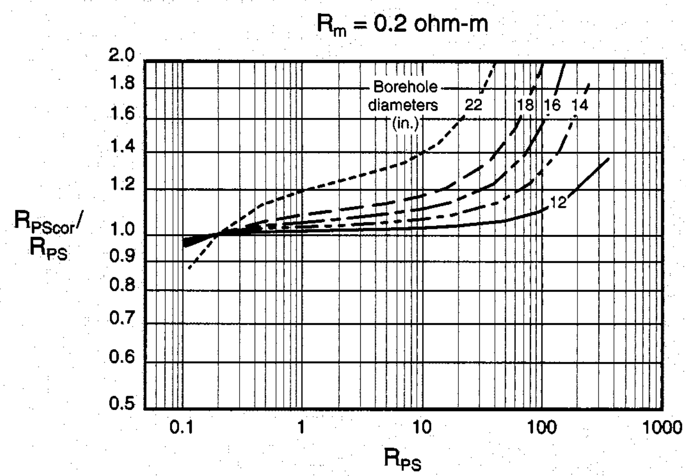
R_{PS} is the apparent resistivity from the phase shift-shallow, and R_{AD} is the apparent resistivity from the attenuation-deep. Charts Rcor-11a, -11b and -11c provide borehole corrections for the 6.5-, 8- and 9.5-in. CDR tools run in mud resistivities of 0.05, 0.2 and 1 ohm-m. To use, select the chart appropriate for the tool size, the measurement (R_{PS} or R_{AD}) and the proper mud resistivity. Enter the chart in abscissa with the apparent resistivity. Proceed upward to the proper hole diameter curve and read the correct/apparent resistivity value on the ordinate.

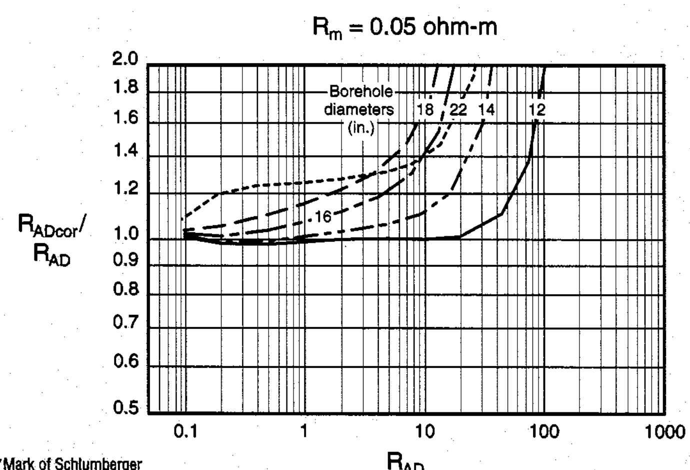
CDR* Compensated Dual Resistivity Borehole Correction for 9.5-in. Tool

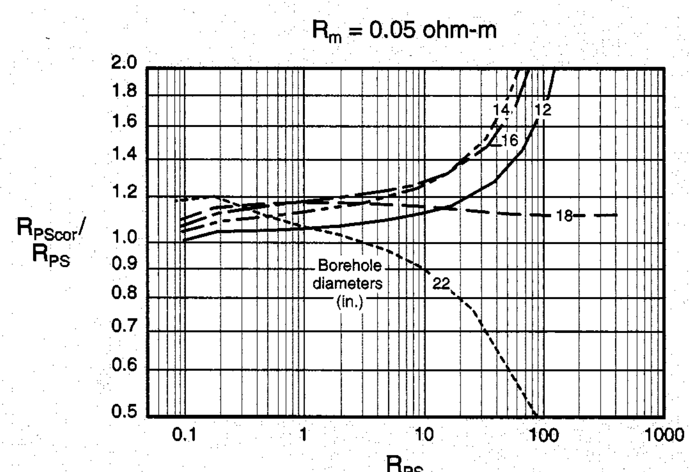






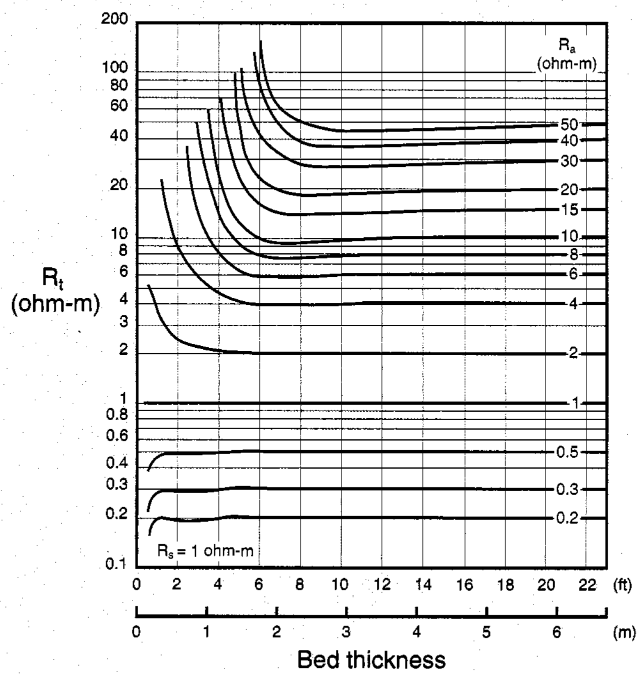


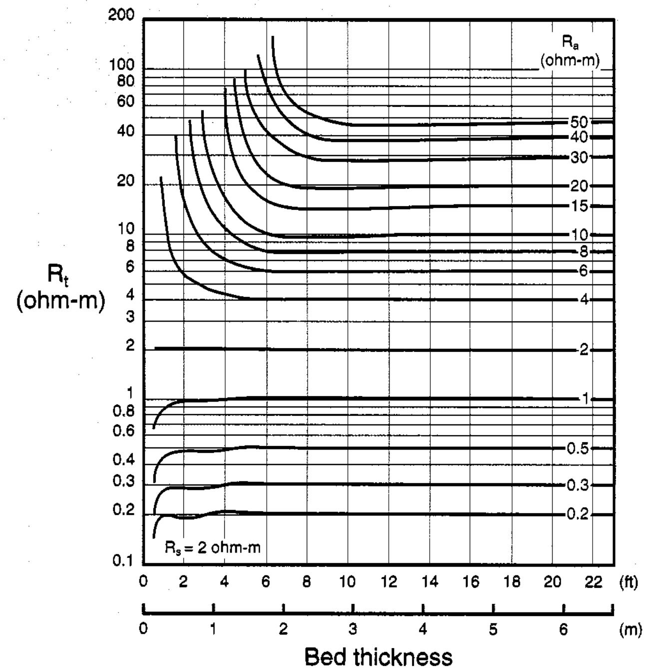


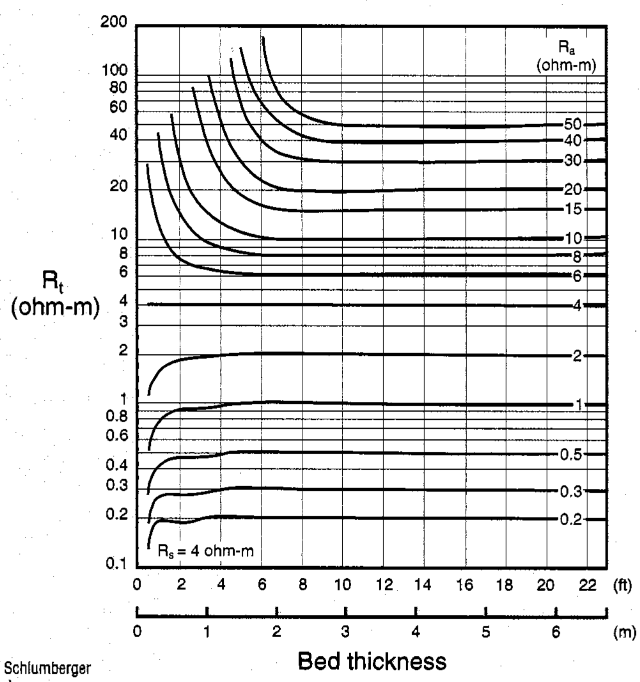


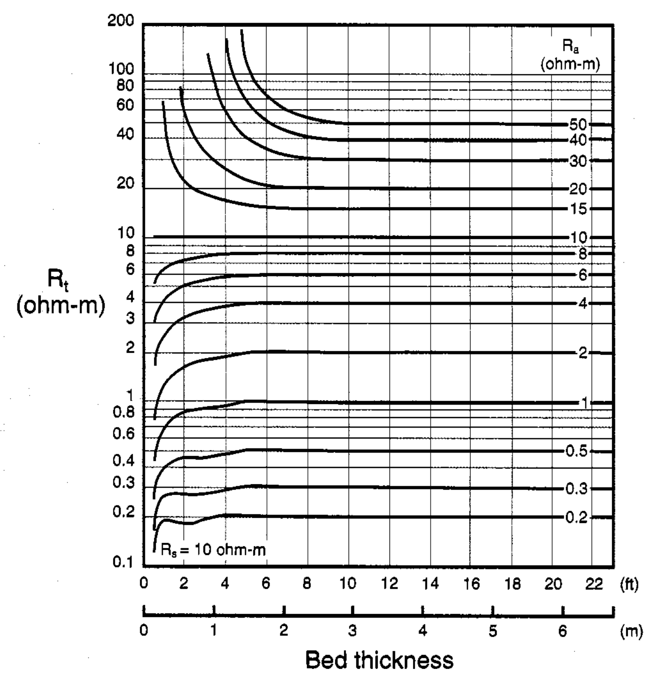
CDR* Bed-Thickness Correction

R_{PS}







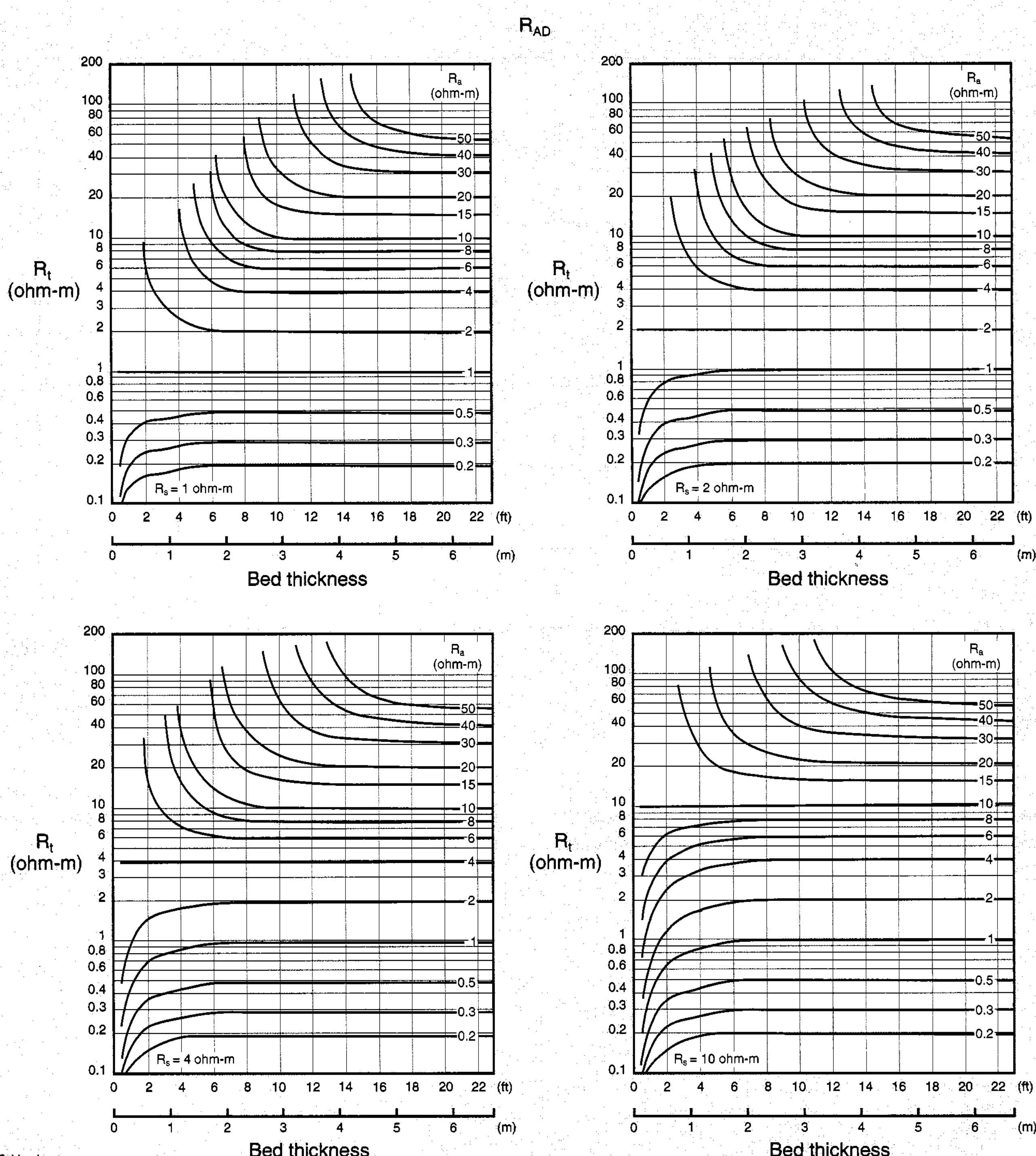


*Mark of Schlumberger

Charts Rcor-12 and Rcor-13 correct the CDR tool resistivities for bed thickness. To use, select the chart appropriate for the measurement (R_{PS} or R_{AD}) and for the adjacent bed resistivity (R_S). Enter the chart with the bed thickness, which can be determined from the distance between the crossovers of R_{PS} and R_{AD}. Proceed upward to the R_a curve corresponding to the center bed resistivity value. Read the corrected resistivity value (R_t) on the ordinate.

For more information see Reference 37.

CDR* Bed-Thickness Correction



RAB* Resistivity-at-the-Bit Borehole Correction for 6.75-in. Tool

8.5-in. borehole

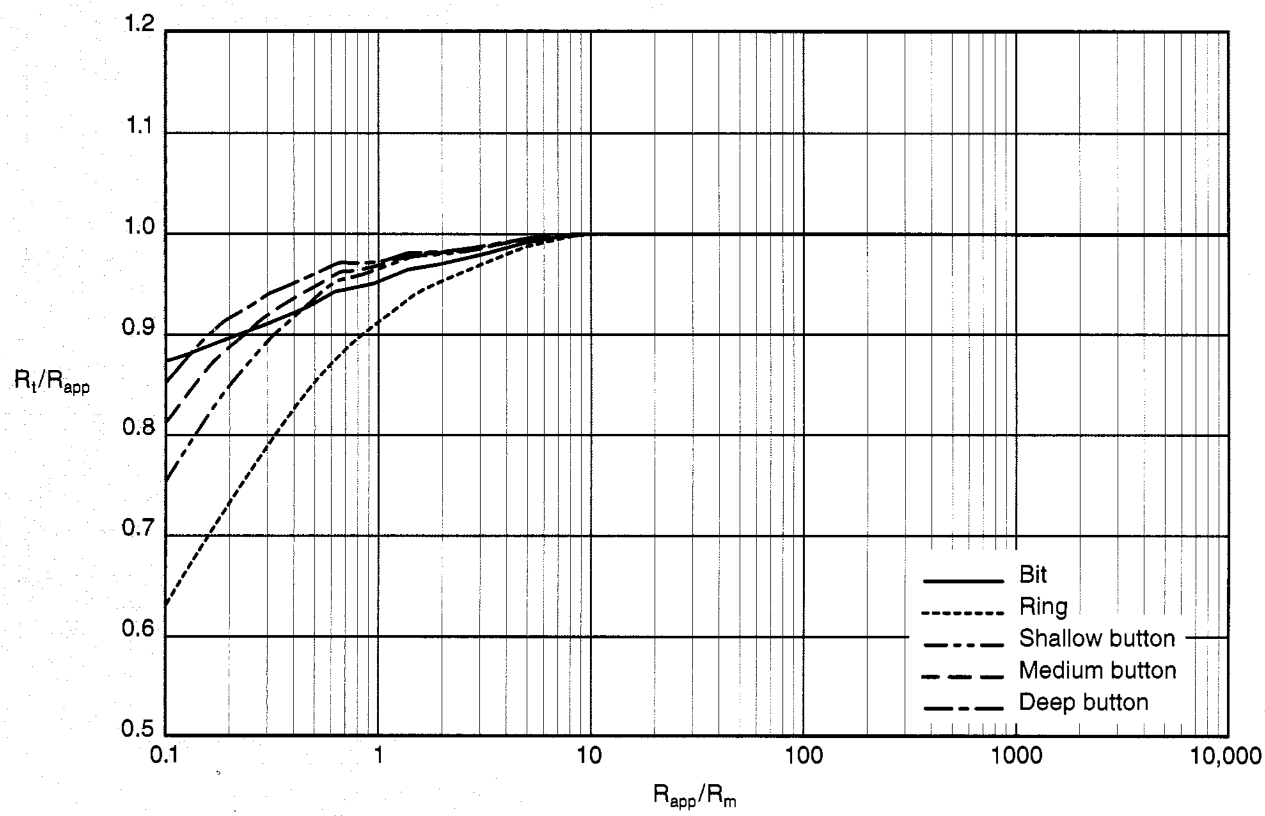
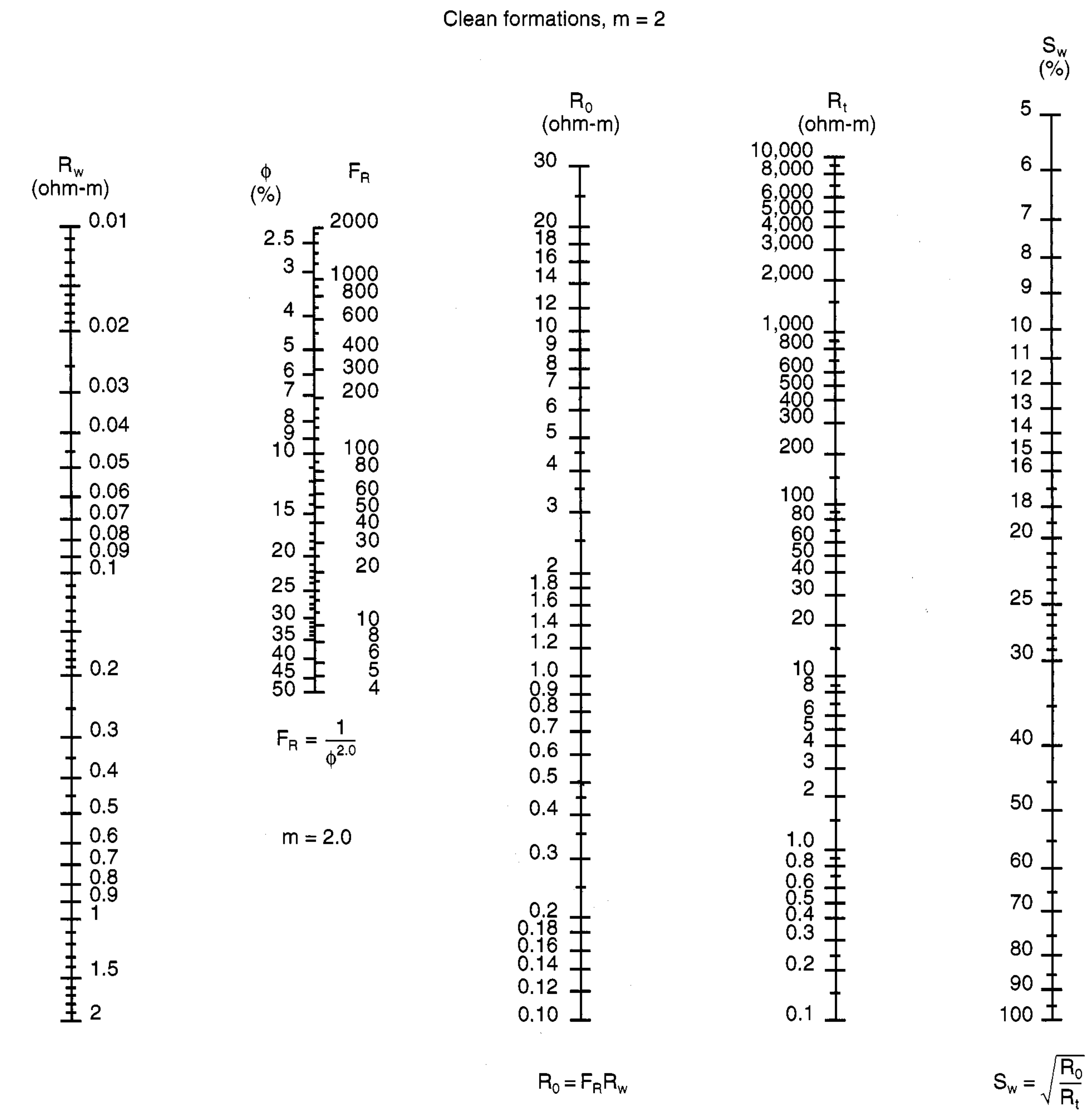


Chart Rcor-15 demonstrates the relative size of the borehole corrections for RAB measurements as a function of mud resistivity. This chart is for illustration purposes only. Borehole corrections are dependant upon the bottomhole assembly and are normally applied in the software. This example was generated for a RAB tool running behind a 12-in. bit.

Saturation Determination



This nomograph solves the Archie water saturation equation

$$S_w = \sqrt{\frac{R_0}{R_t}} = \sqrt{\frac{F_R R_w}{R_t}}$$

It should be used in clean (nonshaly) formations only. If R_0 (resistivity when 100% water saturated) is known, a straight line from the known R_0 value through the measured R_t value gives water saturation, S_w. If R_0 is unknown, it may be determined by connecting the formation water resistivity, R_w, with the formation resistivity factor, F_R, or porosity, ϕ.

Example: R_w = 0.05 ohm-m at formation temperature

ϕ = 20% (F_R = 25)

R_t = 10 ohm-m

Therefore, S_w = 35%

For other ϕ/F relations, the porosity scale should be changed according to Chart Por-1.

Saturation Determination

Ratio method

Chart Sw-2 (next page) is used to determine water saturation in shaly or clean formations when knowledge of porosity is unavailable. It may also be used to verify the water saturation determination from another interpretation method. The main chart assumes

$$S_{xo} = \sqrt[5]{S_w}$$

however, the small chart to the right provides an S_{xo} correction when S_{xo} is known. Note, too, that the SP portion of the chart does not provide for any water activity (Chart SP-2) correction.

For clean sands, plot the ratio R_{xo}/R_t against R_{mf}/R_w to find water saturation at average residual oil saturation. If R_{mf}/R_w is unknown, the chart may be entered with the SP value and the formation temperature. If S_{xo} is known, proceed diagonally upward, parallel to the constant S_{wa} lines, to the edge of the chart. Then, go horizontally to the known S_{xo} (or S_{or}) value to obtain the corrected water saturation S_w.

Example: $R_{xo} = 12$ ohm-m
$R_t = 2$ ohm-m
$R_{mf}/R_w = 20$
$S_{or} = 20\%$

Therefore, $S_w = 43\%$ (after ROS correction)

In shaly sands, plot R_{xo}/R_t against E_{pSP} (the SP in the shaly sand). This point gives an apparent water saturation. Draw a line from the chart's origin (the small circle located at $R_{xo}/R_t = R_{mf}/R_m = 1$) through this point. Extend this line to intersect with the value of E_{SSP} to obtain a value of R_{xo}/R_t corrected for shaliness. Plot this value of R_{xo}/R_t versus R_{mf}/R_w to find S_w. If R_{mf}/R_w is unknown, the point defined by R_{xo}/R_t and E_{SSP} is a reasonable approximation of S_w. Use the diagram at right to further refine S_w if S_{or} is known.

Example: $R_{xo}/R_t = 2.8$
$R_{mf}/R_w = 25$
$E_{pSP} = -75$ mV
$E_{SSP} = -120$ mV
$K = 80$ (formation temperature = 150°F)

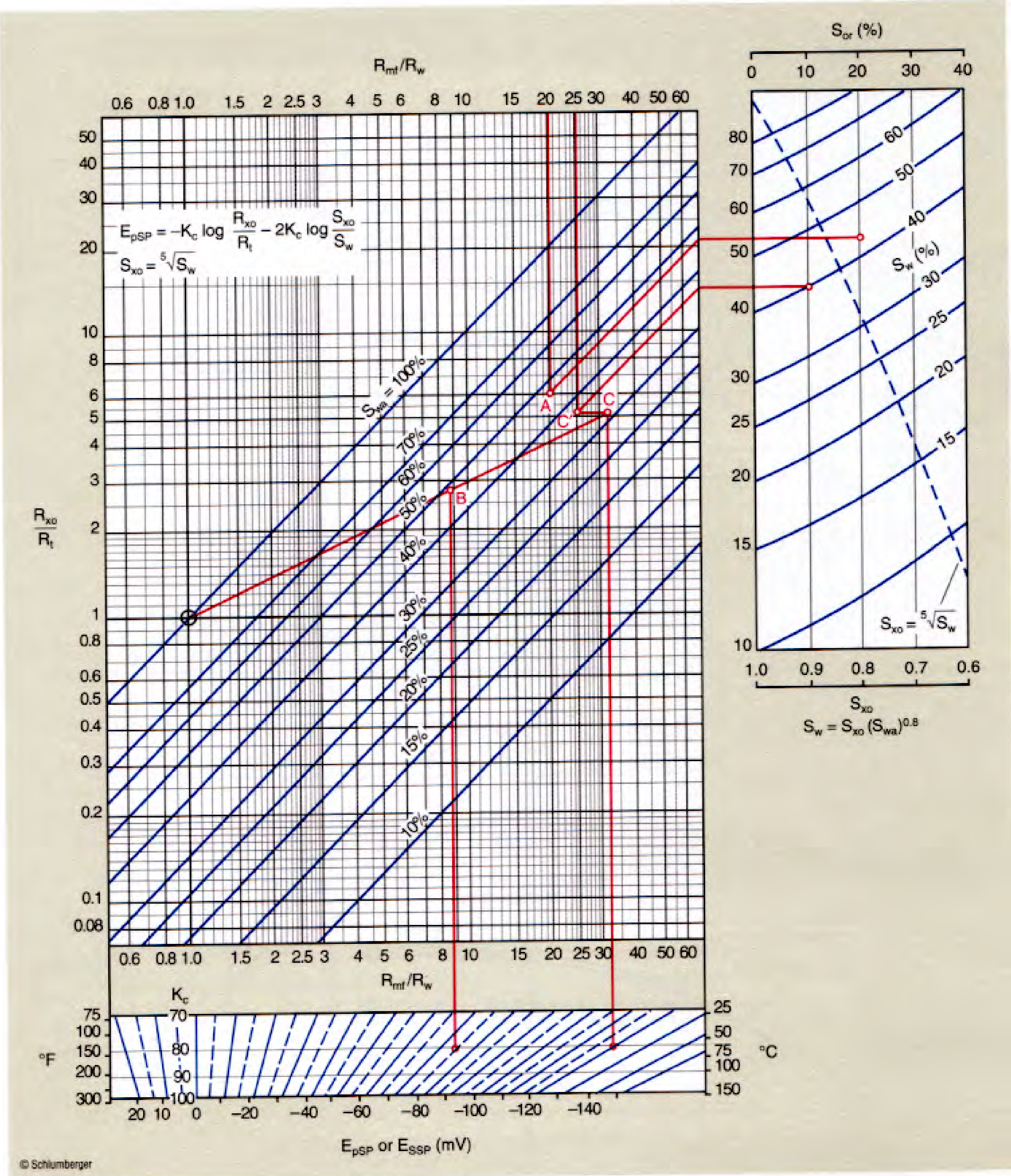
Therefore, $S_w = 38\%$
(If S_{or} were known to be 10%, $S_w = 40\%$)

For more information see Reference 12.

Sw

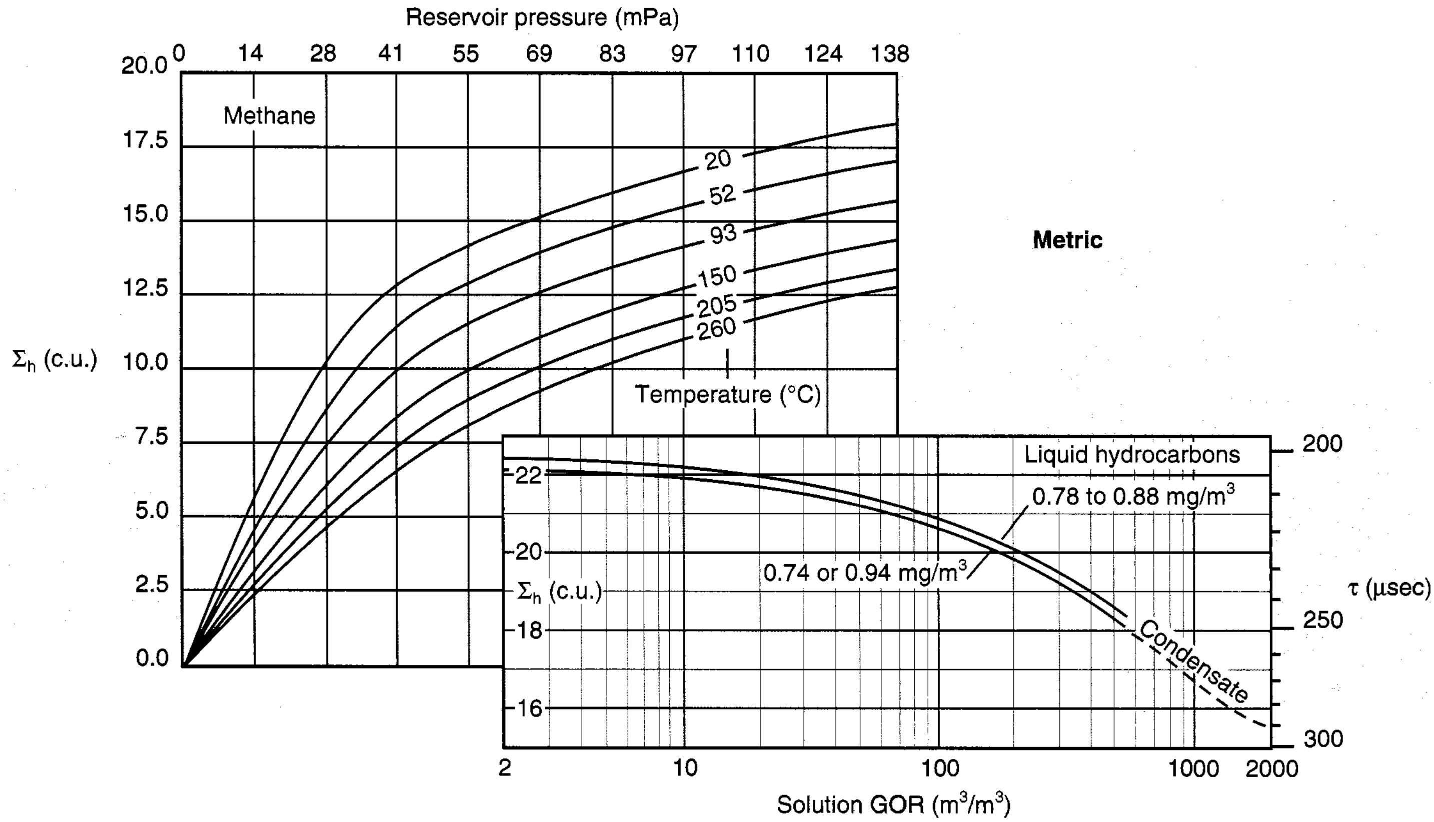
Saturation Determination

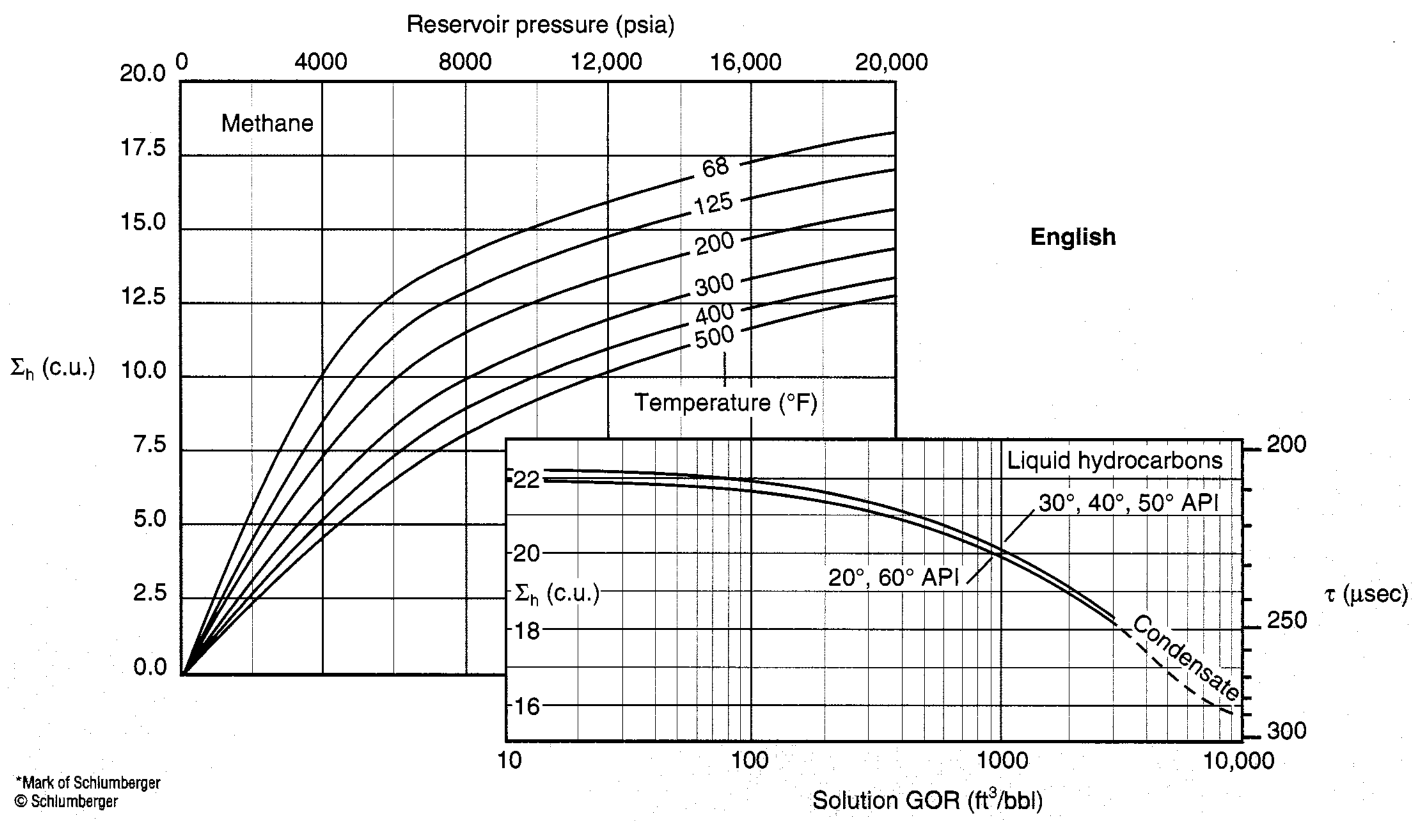
Ratio method



See instructions on previous page. For more information see Reference 12.

TDT* Thermal Decay Time Log Hydrocarbon Corrections





*Mark of Schlumberger

For more information see References 10 and 11.

TDT* Thermal Decay Time Log

Equivalent water salinity

Tcor-2a

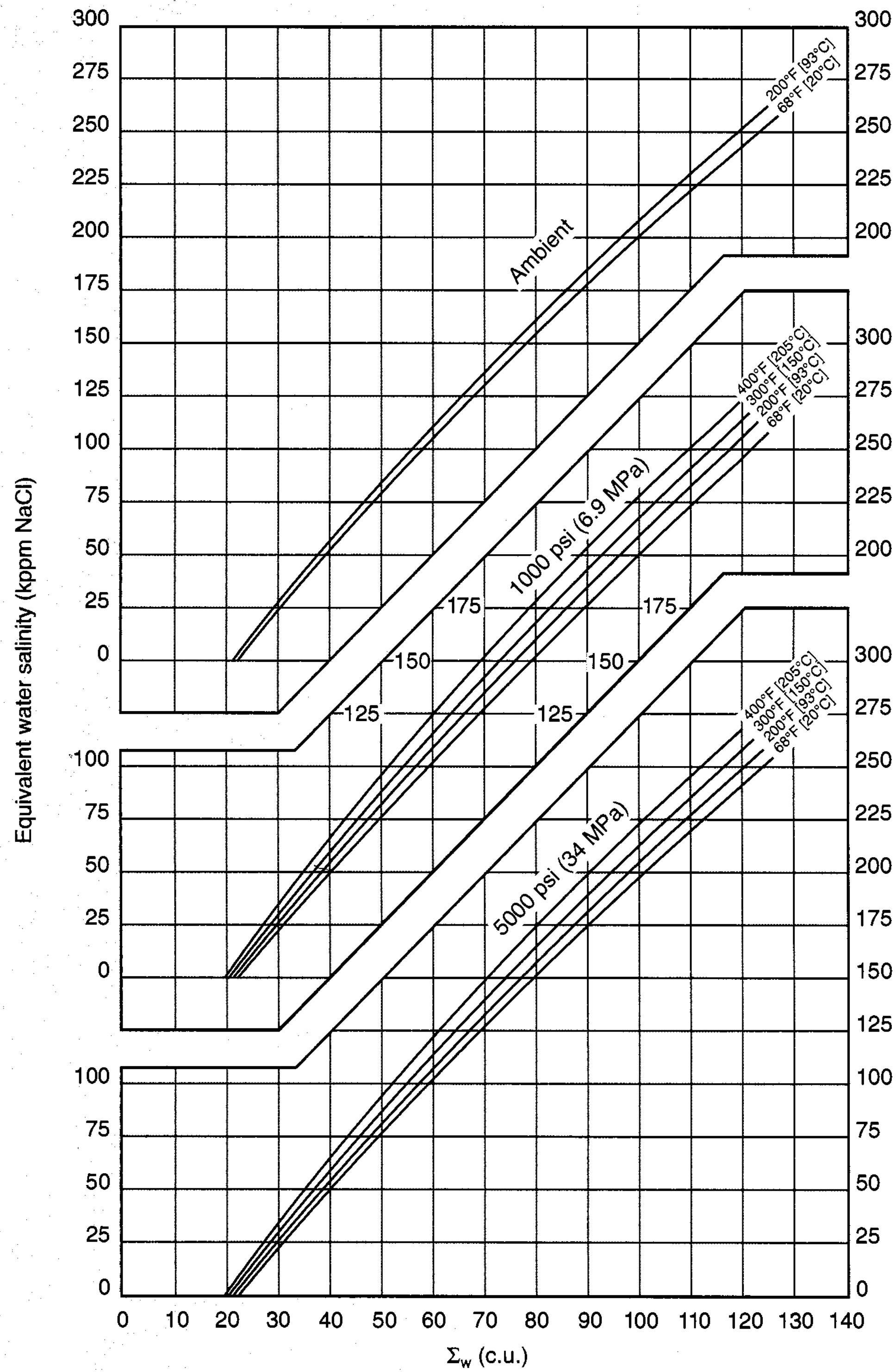


Chart Tcor-1 provides the capture cross section, Σ, for oil and methane, while Charts Tcor-2a and Tcor-2b give the Σ value for water salinity. These updated charts have an extended utility range to 500°F and 20,000 psia. Knowledge of water salinity, reservoir pressure, GOR and reservoir temperature is required.

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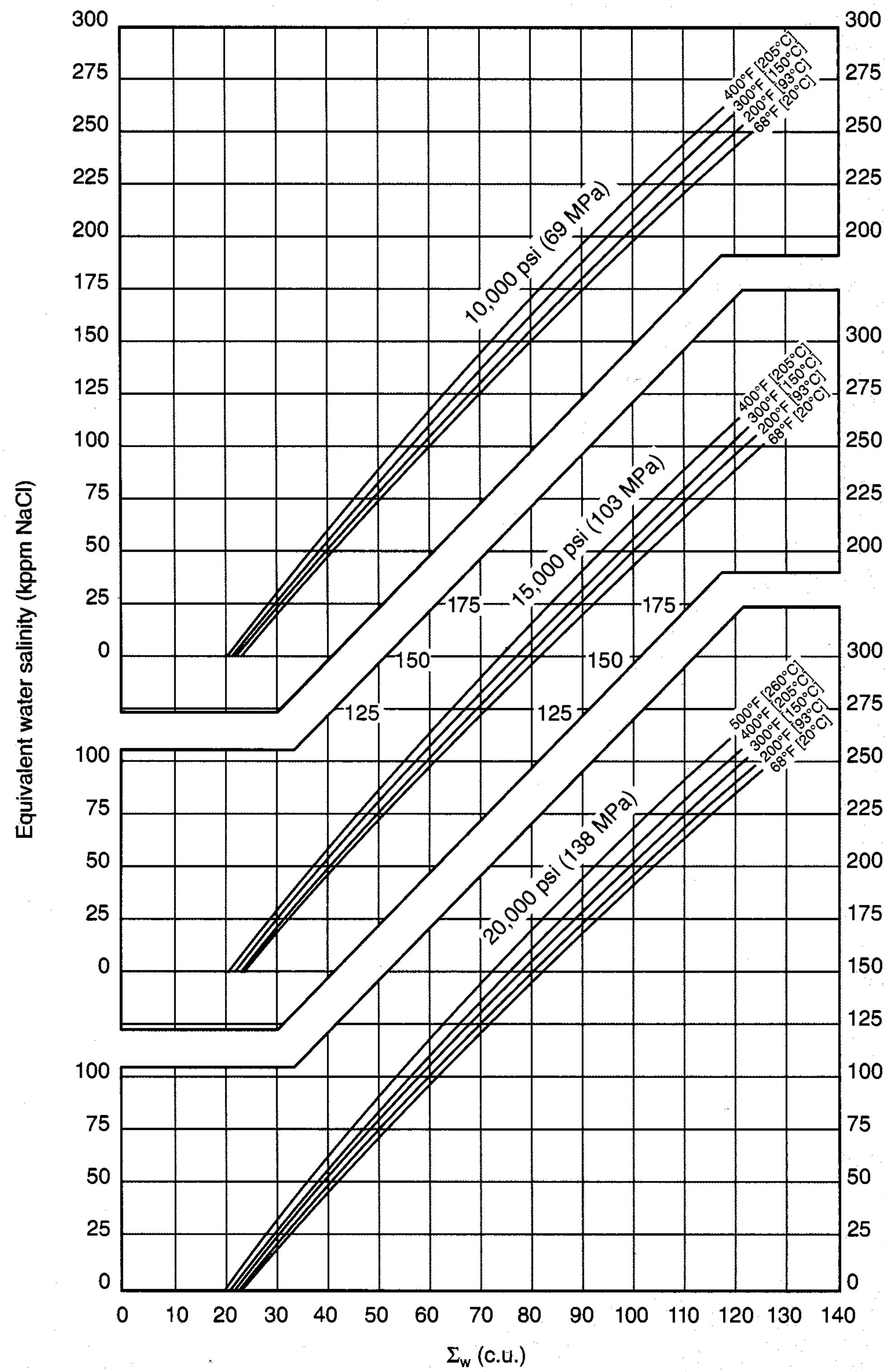
TDT* Thermal Decay Time Log

Equivalent water salinity

Tcor-2b



*Mark of Schlumberger

Example:

Given: A reservoir section at 90°C temperature and 25-MPa pressure contains water of 175,000-ppm (NaCl) salinity, 30° API oil with a gas/oil ratio of 2000 ft^3/bbl and methane gas.

Results: Σ_w = 87 c.u.

Σ_o = 19 c.u.

Σ_g = 6.9 c.u.

Tcor

Saturation Determination from TDT* Thermal Decay Time Logs

Neutron capture cross section, Σ, is expressed in capture units (c.u.). Σ is related to thermal decay time, τ (in μsec), by the formula $\Sigma = 4550/\tau$. A capture unit is equivalent to one-thousandth of a reciprocal centimeter (cm^{-1}).

Matrix capture cross section, Σ_{ma}, varies over a small range for each lithology. Practical values, empirically determined, are somewhat larger than those calculated for the pure rock minerals. Average values commonly used are sandstone, 8 c.u.; dolomite, 9 c.u.; and limestone, 11 to 12 c.u.

Σ_w, the capture cross section of the formation water, depends on the type and abundance of the elements in solution. The value of Σ_w corresponding to the NaCl concentration can be considered a minimum value; traces of certain elements in the water can increase Σ_w beyond the value indicated by the chemically equivalent concentration of NaCl.

For more information see Reference 11.

Description and use of Chart Sw-12

If Σ_{ma}, Σ_w and porosity are known, Chart Sw-12 may be used to determine water saturation. It may be used in shaly formations if porosity, ϕ, and the fraction of shale in the formation, V_{sh}, are known.

Clean formations

Information required:

Σ_{ma}	Matrix capture cross section, based on lithology
ϕ	Porosity
Σ_w	From NaCl salinity; see Tcor-2a or Tcor-2b
Σ_h	See Tcor-1

Procedure:

Enter the value of Σ_{ma} on Bar **B;** draw Matrix Line **a** from Σ_{ma} to Pivot Point **B.** Enter Σ_{LOG} on Bar **B;** draw Line **b** through the intersection of Line **a** and the value of ϕ to Σ_f on Bar **C.** Draw Line **5** from Σ_f through the intersection of Σ_h and Σ_w to the value of S_w.

Example:

Given: $\Sigma_{LOG} = 20$ c.u.
$\Sigma_{ma} = 8$ c.u. (sandstone)
$\Sigma_h = 21$ c.u. (oil)
$\Sigma_w = 80$ c.u. (150,000 ppm or mg/kg)
$\phi = 30$ p.u.

Solution: $S_w = 43\%$

Shaly formations

Information required:

Σ_{ma}	Based on lithology
Σ_{sh}	Read from TDT log in adjacent shale
Σ_w	From NaCl salinity; see Tcor-2a or Tcor-2b
Σ_h	See Tcor-1
V_{sh}	From porosity-log crossplot or gamma ray
ϕ_{sh}	Read from porosity log in adjacent shale
ϕ	From porosity log, corrected for shaliness; for neutron and density logs in liquid-filled formations, ϕ, $= \phi_{LOG} - V_{sh}\,\phi_{sh}$.

Procedure:

Enter the value of Σ_{ma} on Bar **B;** connect with Pivot Point **A** (Line **1**). From the value of Σ_{sh} on Bar **A,** draw Line **2** through the intersection of Line **1** and V_{sh} to determine Σ_{cor}. Draw Line **3** from Σ_{cor} to the value of Σ_{ma} on the scale at left of Bar **C.** Enter Σ_{LOG} on Bar **B;** draw Line **4** through the intersection of Line **3** and ϕ to Σ_f. From Σ_f draw Line **5** through Σ_h and Σ_w to S_w.

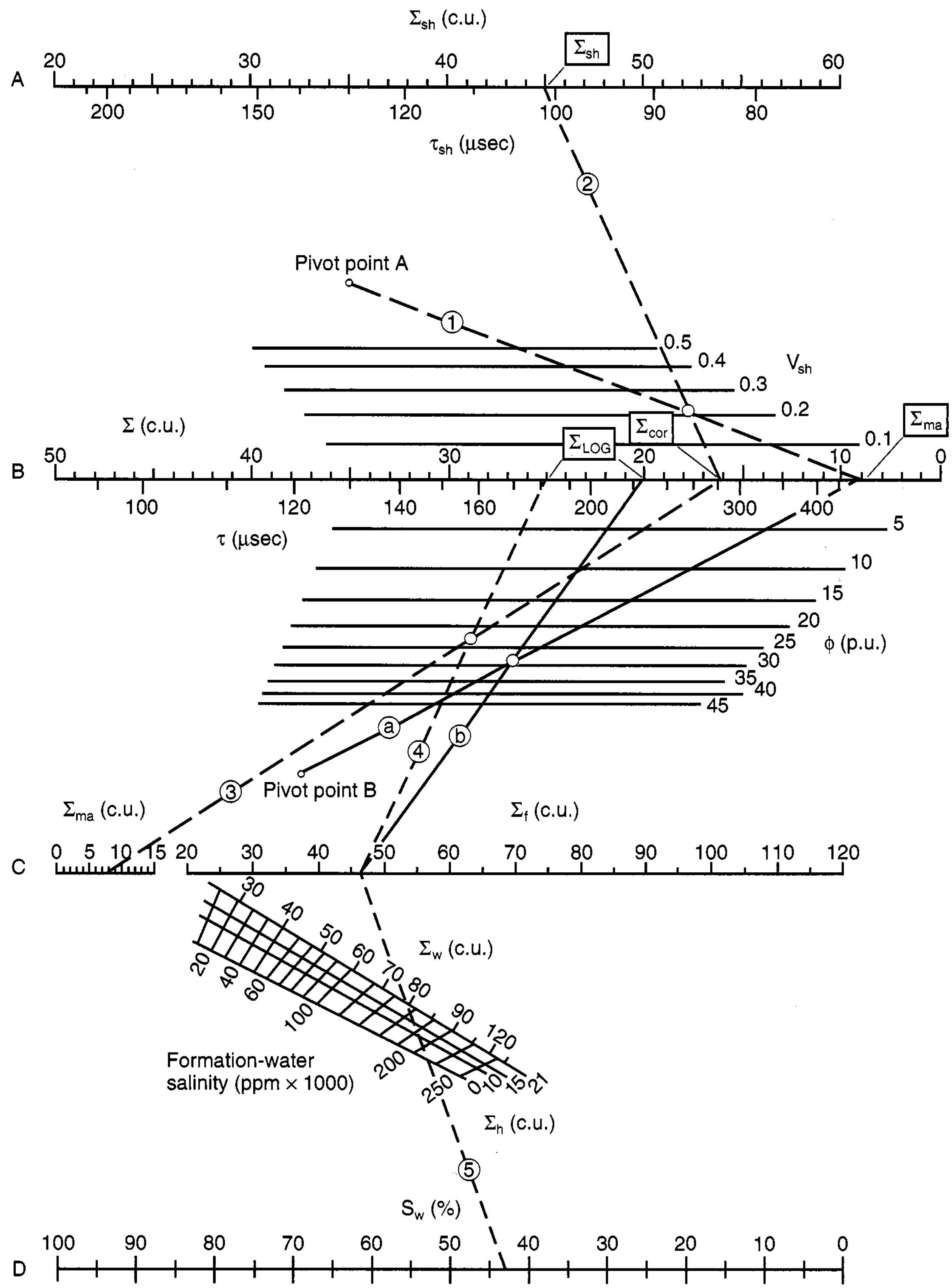
Example:

Given: $\Sigma_{LOG} = 25$ c.u.
$\Sigma_{ma} = 8$ c.u.
$\Sigma_h = 21$ c.u.
$\Sigma_w = 80$ c.u.
$\Sigma_{sh} = 45$ c.u.
$_{LOG} = 33$ p.u.
$\phi_{sh} = 45$ p.u.
$V_{sh} = 20\%$
$\phi = \phi_{LOG} - V_{sh}\,\phi_{sh}$
$\phi = 24$ p.u.

Solution: $S_w = 43\%$

*Mark of Schlumberger

S_W Determination from TDT* Thermal Decay Time Log



$$S_w = \frac{(\Sigma_{LOG} - \Sigma_{ma}) - \phi(\Sigma_h - \Sigma_{ma}) - V_{sh}\ (\Sigma_{sh} - \Sigma_{ma})}{\phi(\Sigma_w - \Sigma_h)}$$

*Mark of Schlumberger

Graphical Determination of Total Water Saturation (S_{wt}) from TDT* Thermal Decay Time Data

Grid Sw-17 can be used for graphical interpretation of the TDT Thermal Decay Time log. In one technique, applicable in shaly as well as clean sands, apparent water capture cross section, Σ_{wa}, is plotted versus bound water saturation on a specially constructed grid.

To construct this grid, refer to the chart on this page. Three fluid points must be located: a free water point, a hydrocarbon point and a bound water point. The free (or connate/formation) water point is located on the left edge of the grid and can be obtained from measurement of a formation water sample, from Chart Tcor-2 if water salinity is known, or from the TDT log in a clean water-bearing sand using the following equation:

$$\Sigma_{wa} = \frac{\Sigma_{log} - \Sigma_{ma}}{\phi} + \Sigma_{ma} \qquad (1)$$

The hydrocarbon point is also located on the left edge of the grid. It can be determined from Chart Tcor-1 based upon the known or expected hydrocarbon type.

The bound water point, Σ_{wb}, can be obtained from the TDT log in shale intervals using Eq. 1 above. It is located on the right edge of the grid.

The distance between the free water and hydrocarbon points is linearly divided into constant water saturation lines drawn parallel to a straight line connecting the free water and bound water points. The S_{wt} = 0% line originates from the hydrocarbon point, and the S_{wt} = 100% line originates from the free water point.

Apparent water capture cross section, Σ_{wa}, from Eq. 1, is then plotted versus bound water saturation, S_{wb}, to give the total water saturation. Bound water saturation can be estimated from the gamma ray or other bound water saturation estimator.

Knowing the total water saturation and the bound water saturation, the effective water saturation (water saturation of reservoir rock exclusive of shale) can be determined using Chart Sw-14.

Example (see chart on this page):

Free water point = 61 c.u.
(from TDT log in a water-bearing clean sand—Eq. 1, Chart Tcor-2 or measurement of a water sample)

Hydrocarbon point = 21 c.u.
(medium-gravity oil with modest gas/oil ratio—Chart Tcor-1)

Bound water point = 76 c.u.
(from TDT log in a shale interval—Eq. 1)

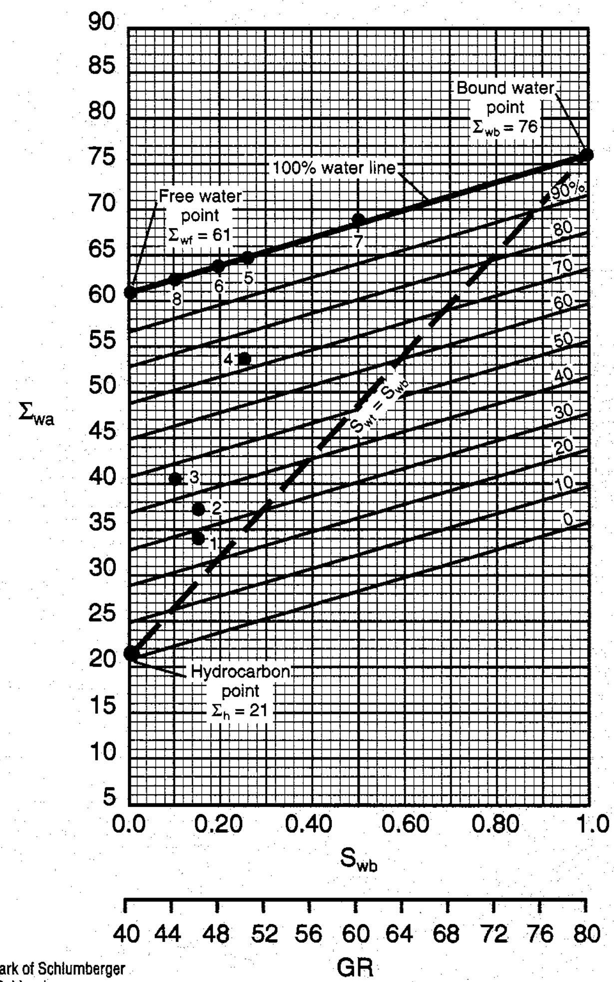
Analysis of Point 4:

Σ_{wa} = 54 c.u. (from Eq. 1)

S_{wb} = 25% (from gamma ray)

Therefore, S_{wt} = 72%

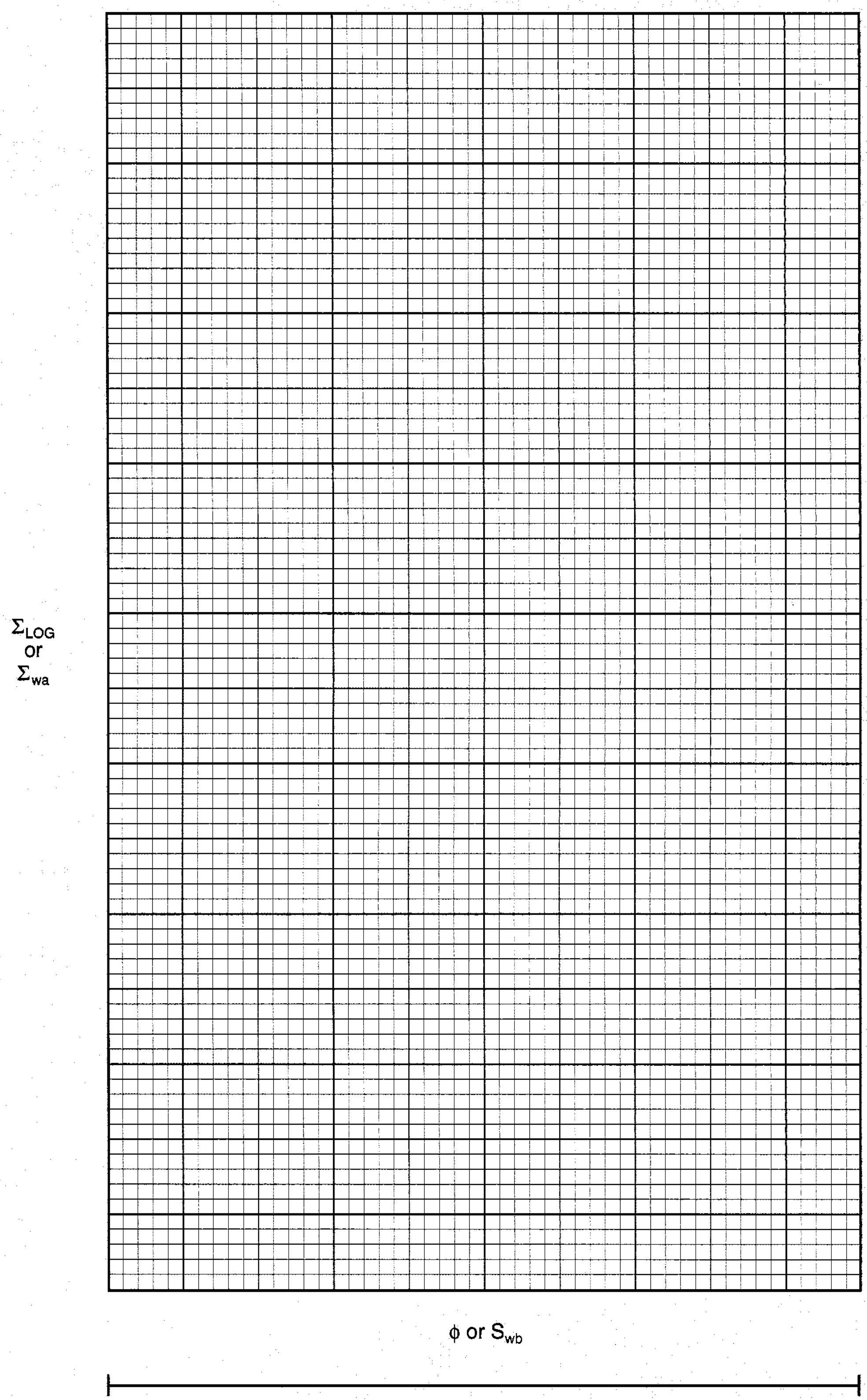
and S_w = 63% (from Chart Sw-14)



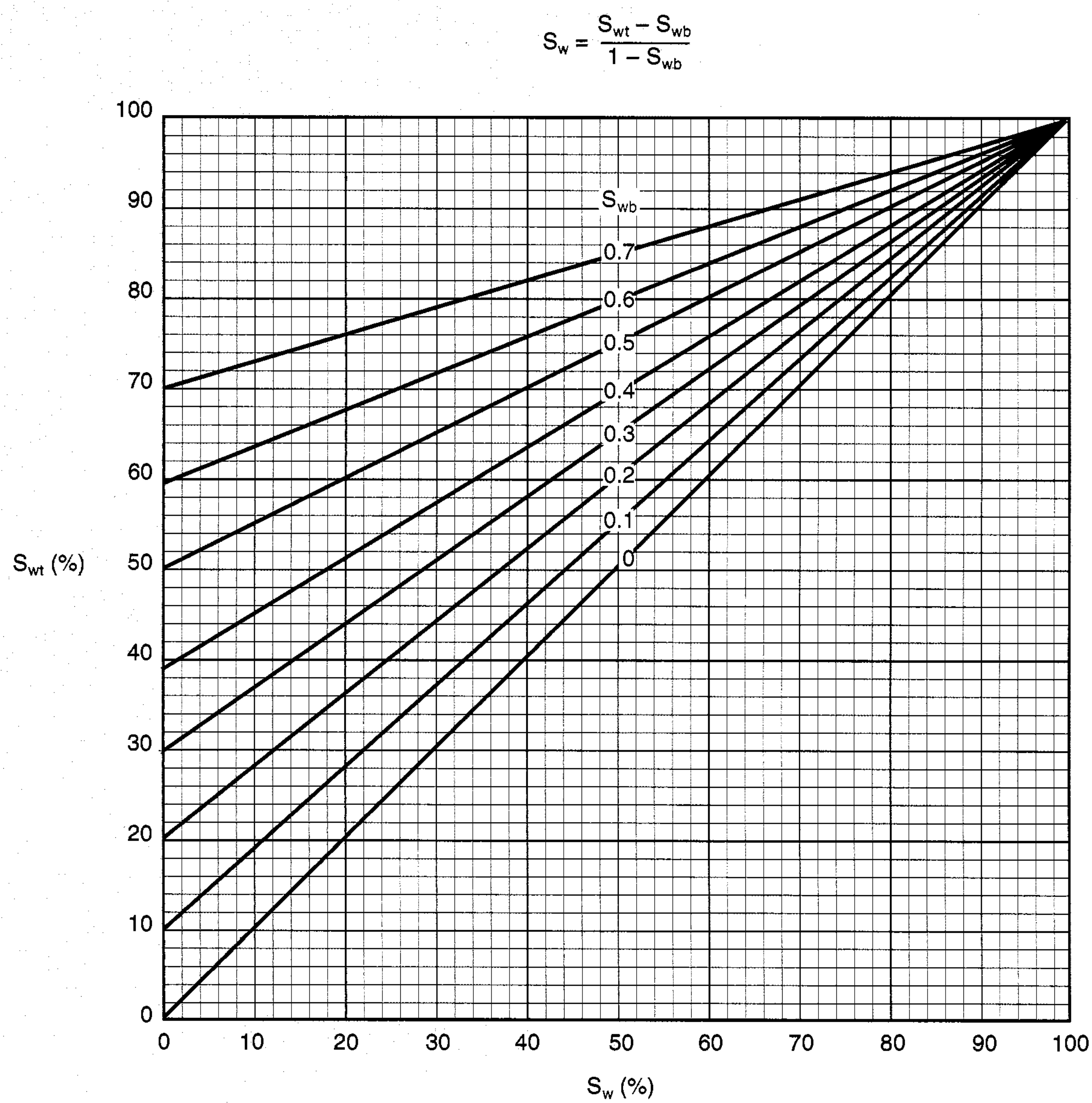
*Mark of Schlumberger

The grid can also be used to graphically determine water saturation, S_w, in clean formations by crossplotting Σ_{LOG} in ordinate versus porosity, ϕ, in abscissa. The matrix capture cross section, Σ_{ma}, and the formation water capture cross section, Σ_w, need not be known but must be constant over the interval studied. There must be some points from 100% water zones, and there must be a good variation in porosity. These water points define the S_w = 100% line; when extrapolated, this line intersects the zero-porosity axis at Σ_{ma}. The S_w = 0% line is drawn from Σ_{ma} at ϕ = 0 p.u. to $\Sigma = \Sigma_h$ at ϕ = 100 p.u. [or $\Sigma = \frac{1}{2}(\Sigma_{ma} + \Sigma_h)$ at ϕ = 50 p.u.]. The vertical distance from S_w = 0% to S_w = 100% is divided linearly to define lines of constant water saturation. The water saturation of any plotted point can thereby be determined.

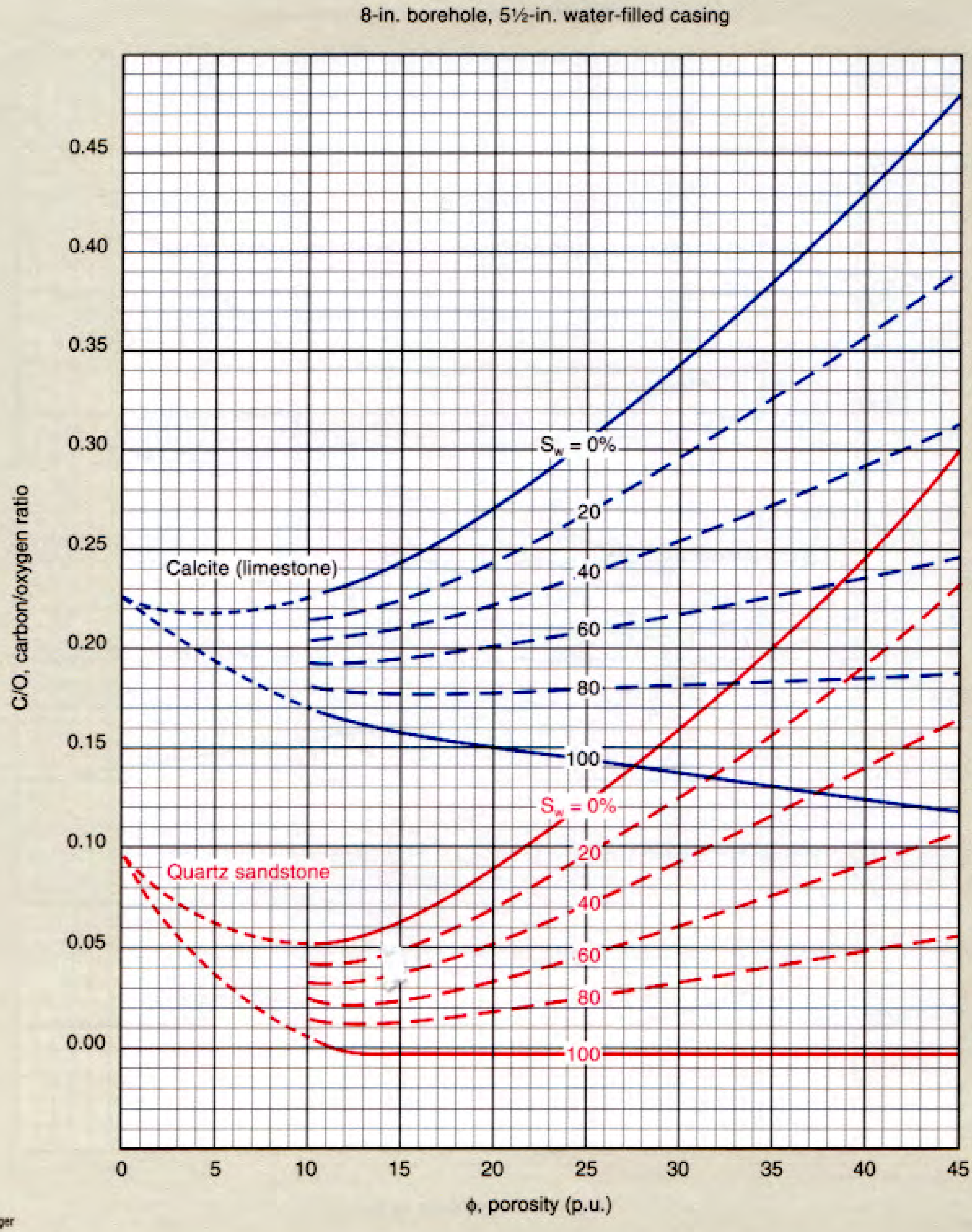
Graphical Determination of Water Saturation (S_w) or Total Water Saturation (S_{wt}) from TDT* Thermal Decay Time Log



Graphical Determination of S_w from S_{wt} and S_{wb}



Saturation Determination from GST* Induced Gamma Ray Spectrometry Log

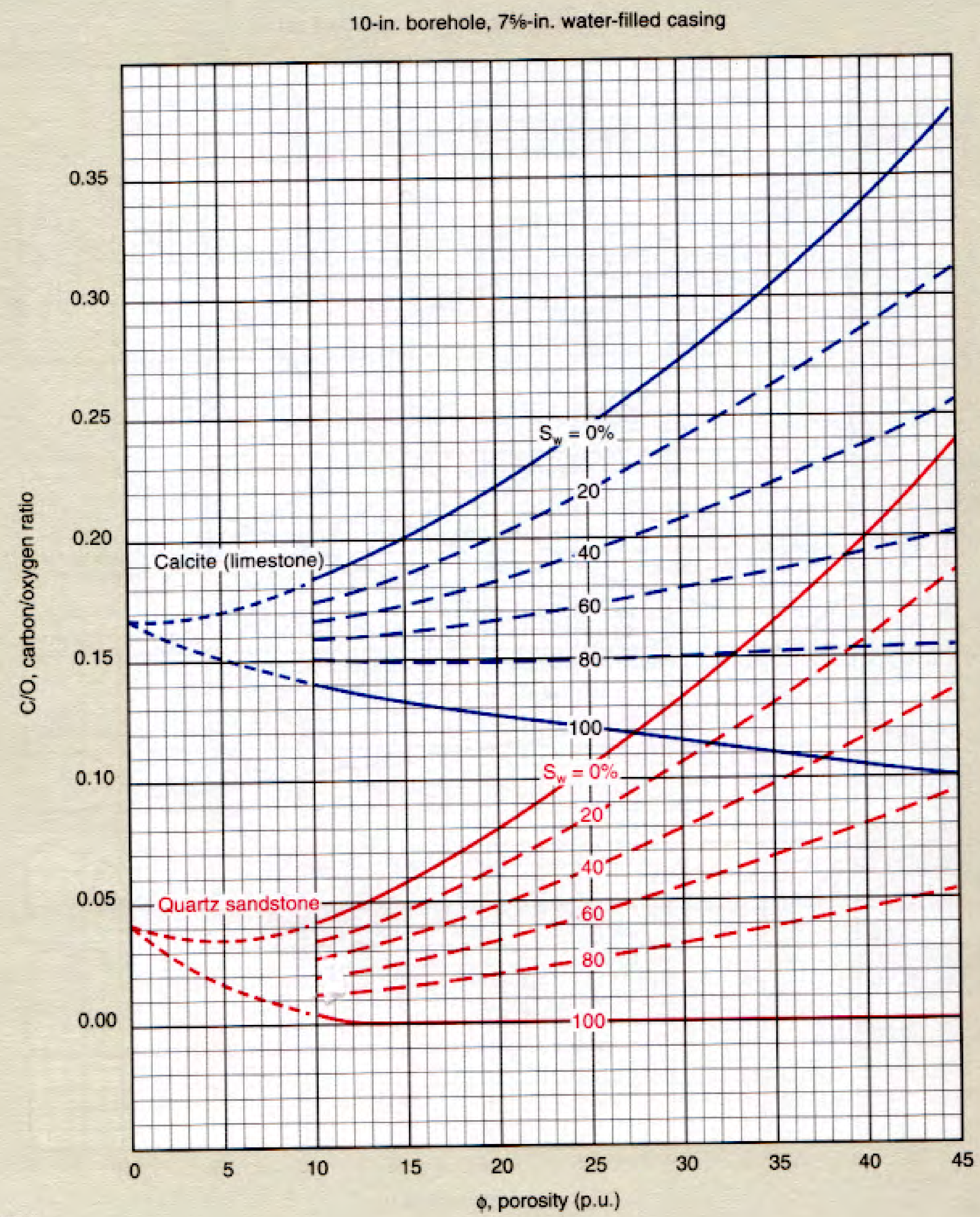


These charts permit the determination of water saturation from carbon/oxygen (C/O) ratio measurements made with the GST Induced Gamma Ray Spectrometry Tool in inelastic mode operation.

To use, the C/O ratio and the porosity, ϕ, are entered in ordinate and abscissa, respectively, on the appropriate chart (dependent upon borehole and casing size). Water saturation is defined by the location of the plotted point within the appropriate matrix "fan chart."

Continued on next page

Saturation Determination from GST* Induced Gamma Ray Spectrometry Log



*Mark of Schlumberger

Example: 5½-in. water-filled casing cemented in 7⅞-in. borehole (use Chart GST-1)

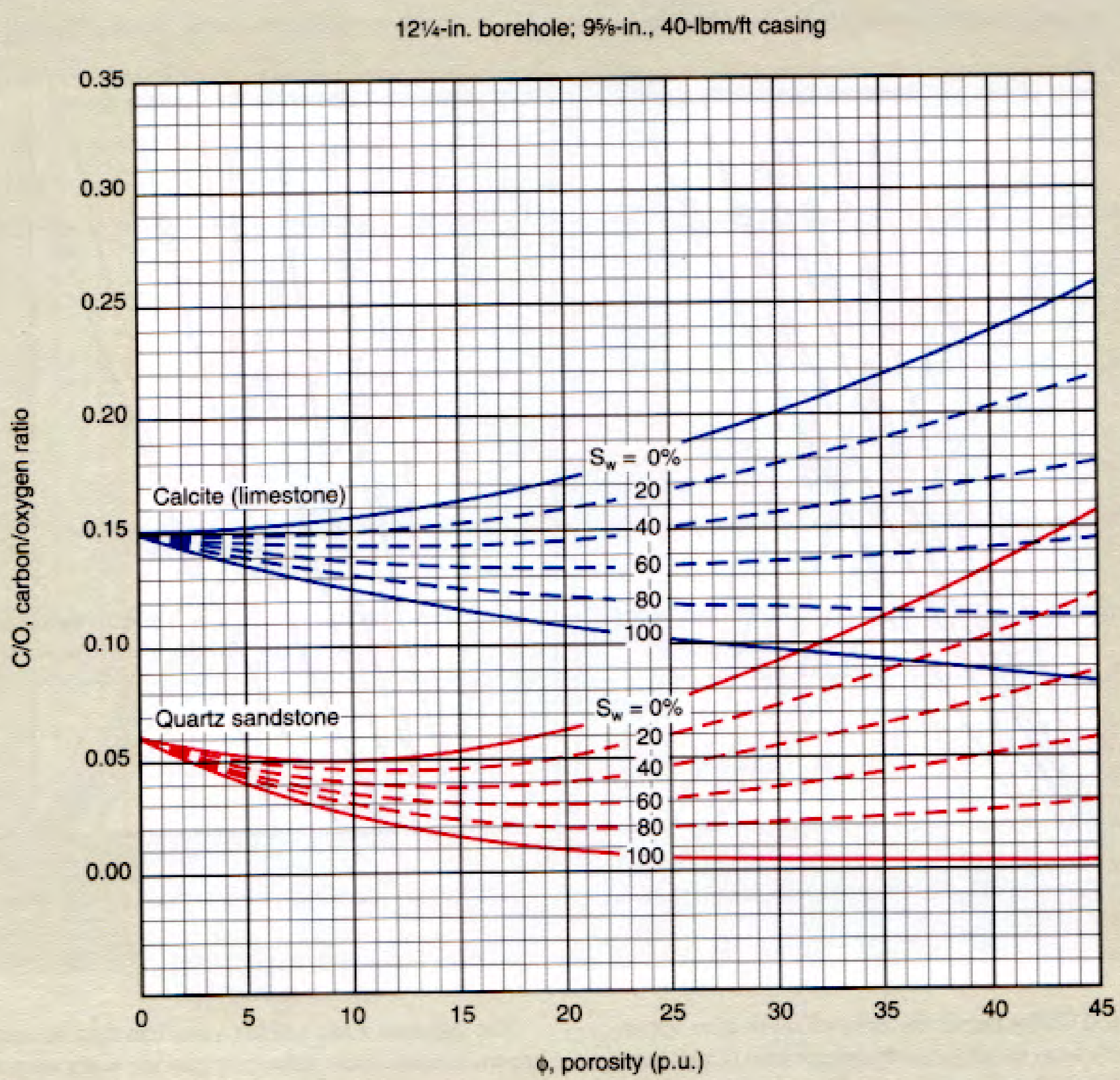
C/O ratio = 0.10

φ = 28 p.u.

Lithology is quartz sandstone

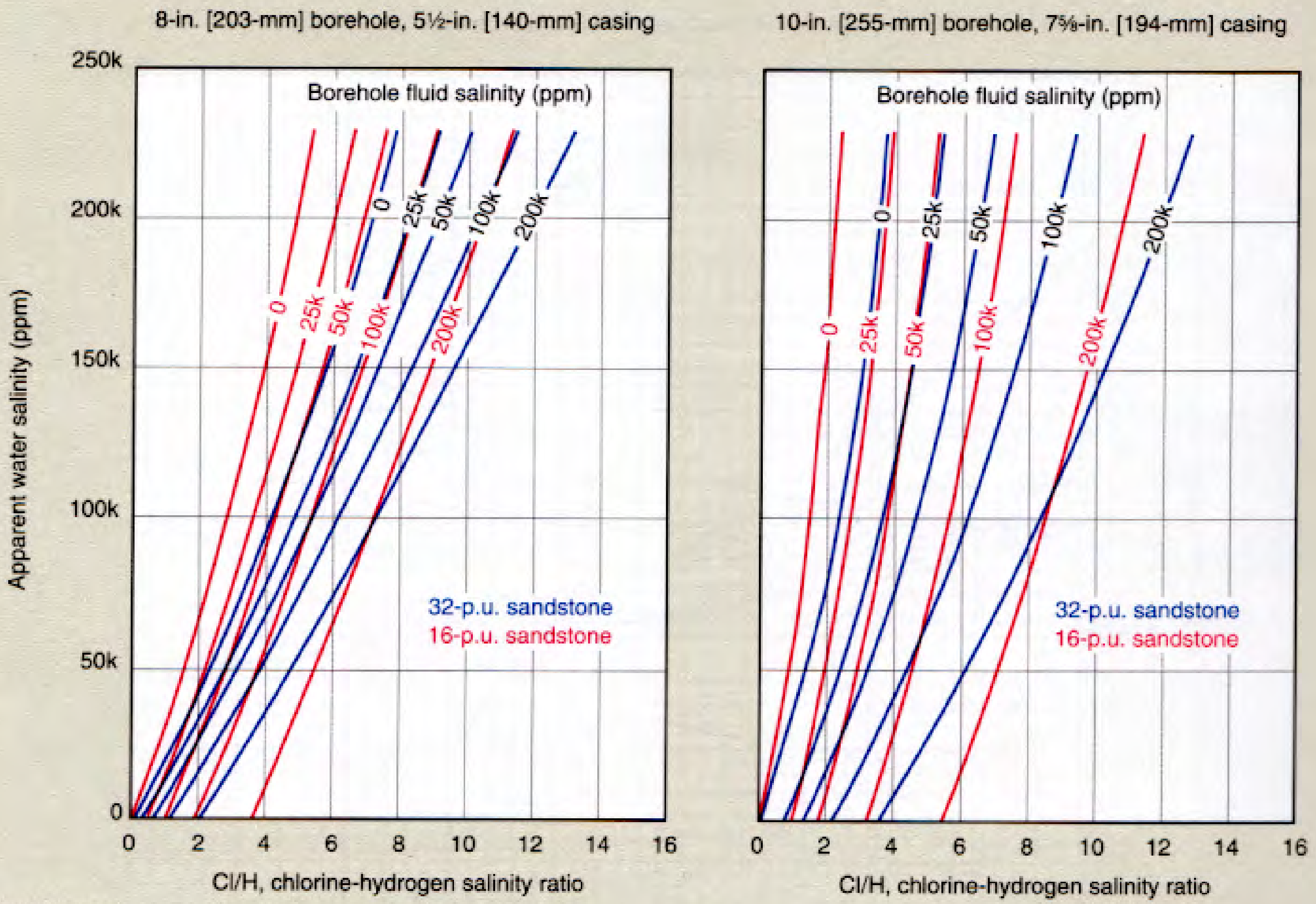
Therefore, S_w = 30%

Saturation Determination from GST* Induced Gamma Ray Spectrometry Log



Apparent Water Salinity Determination from GST* Induced Gamma Ray Spectrometry Log

Inelastic mode



*Mark of Schlumberger

Charts GST-3 and GST-4 permit the determination of an apparent water salinity from the chlorine-hydrogen ratio (Cl/H) as recorded with the GST Induced Gamma Ray Spectrometry Tool. Two sets of charts are presented. Chart GST-3 applies when the GST tool is operated in inelastic mode; Chart GST-4 applies when the tool is operated in capture-tau mode.

To use, enter the chlorine-hydrogen (Cl/H) ratio into the chart that most nearly matches the borehole and casing size conditions and matches the tool operating mode. Proceed upward to the appropriate combination of borehole fluid salinity and formation porosity conditions. Interpolation between curves may be necessary. The apparent water salinity is given in ordinate.

The apparent water salinity value can then be compared to the known connate water salinity to provide water saturation in clean formations.

Example: Cl/H ratio = 5

ϕ = 30%

Borehole fluid salinity ≈ 25,000 ppm

5½-in. casing in a 7⅞-in. borehole

Tool operating in capture-tau mode

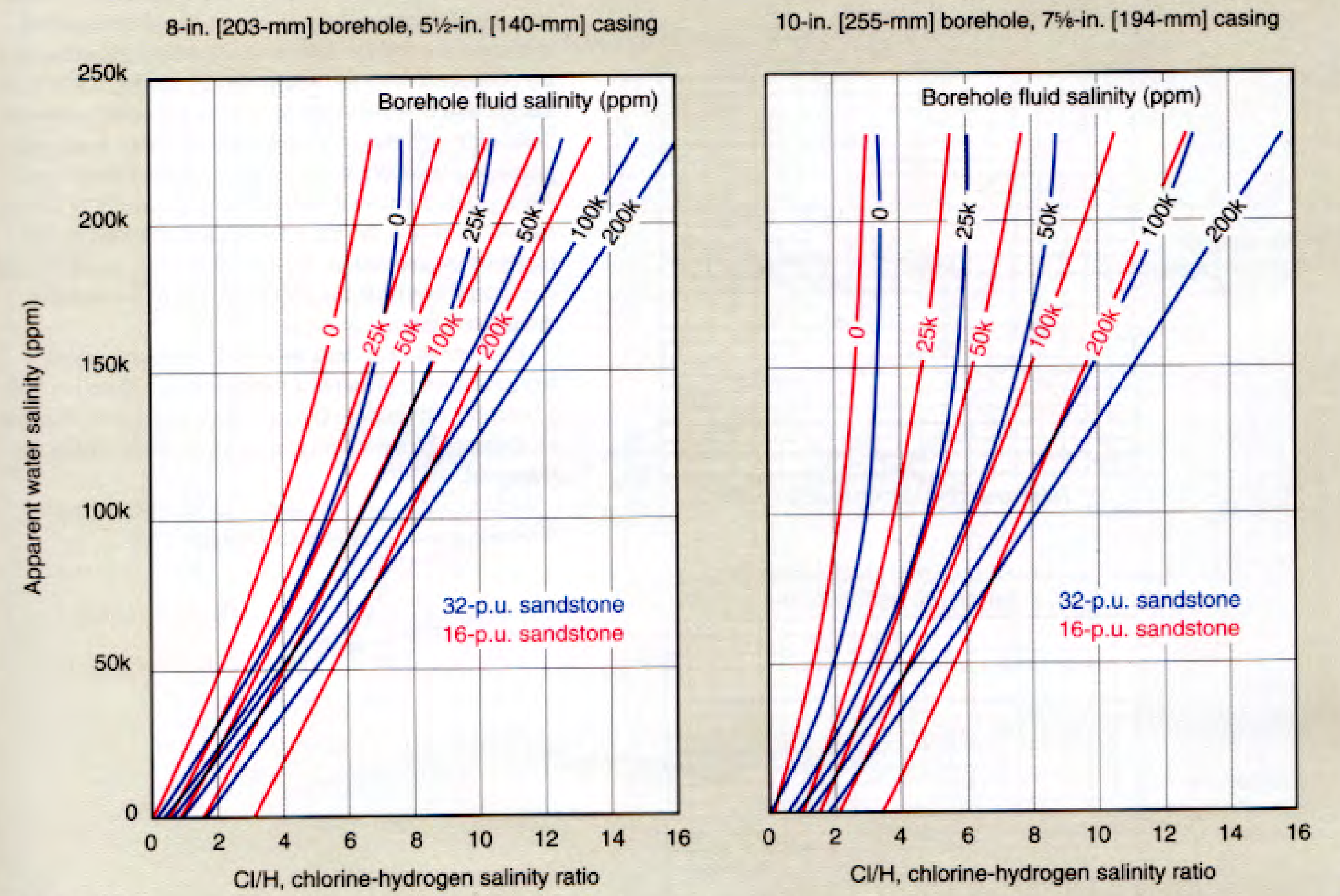
From Chart GST-4,

Apparent water salinity = 80,000 ppm

If the connate water salinity were 200,000 ppm, water saturation would be 40% (S_w = 80,000/200,000).

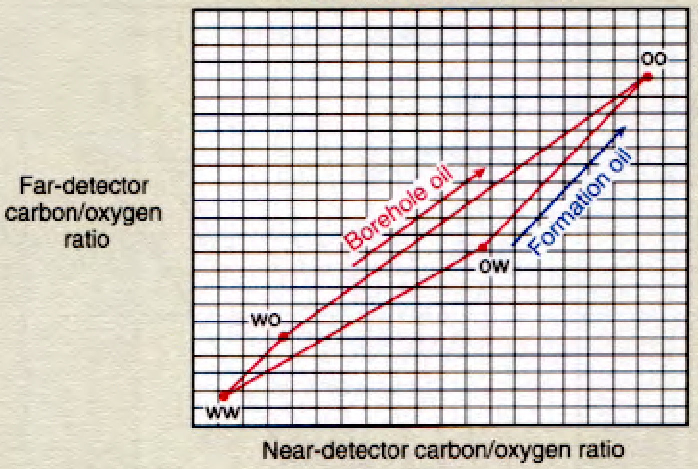
Apparent Water Salinity Determination from GST* Induced Gamma Ray Spectrometry Log

Capture-Tau mode

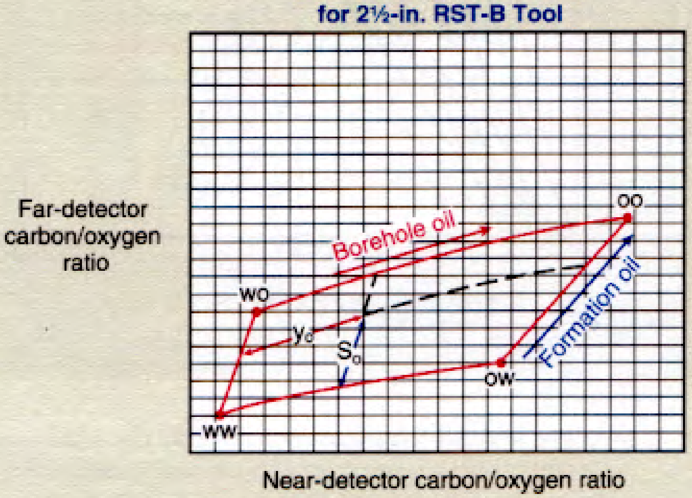


RST* Reservoir Saturation Tool Carbon/Oxygen Ratio Response

Dual-Detector COR Model for 1¹¹⁄₁₆-in. RST-A Tool



Dual-Detector COR Model for 2½-in. RST-B Tool



WW: water in borehole, water in formation
OW: oil in borehole, water in formation
OO: oil in borehole, oil in formation
WO: water in borehole, oil in formation

*Mark of Schlumberger

Charts RST-1, -2 and -3, drawn for specific cased hole and openhole cases, help to ensure that the measured near-detector and far-detector carbon/oxygen ratio data are consistent with the interpretation model. Known formation and borehole data define the expected values of carbon/oxygen ratio for each detector using water saturation and borehole holdup values ranging from 0 to 1. All log data for levels with porosity greater than 10 p.u. should lie within the trapezoidal area bounded by the limits on oil saturation, S_o, and oil holdup, y_o. If data fall consistently outside the trapezoid, the interpretation model may require revision.

Each set of near-detector and far-detector carbon/oxygen ratios represents a formation oil saturation and a borehole oil holdup. Oil saturation and oil holdup can be estimated for each level by interpolation within the trapezoid.

Additional trapezoid charts can be constructed for alternative casing and borehole sizes.

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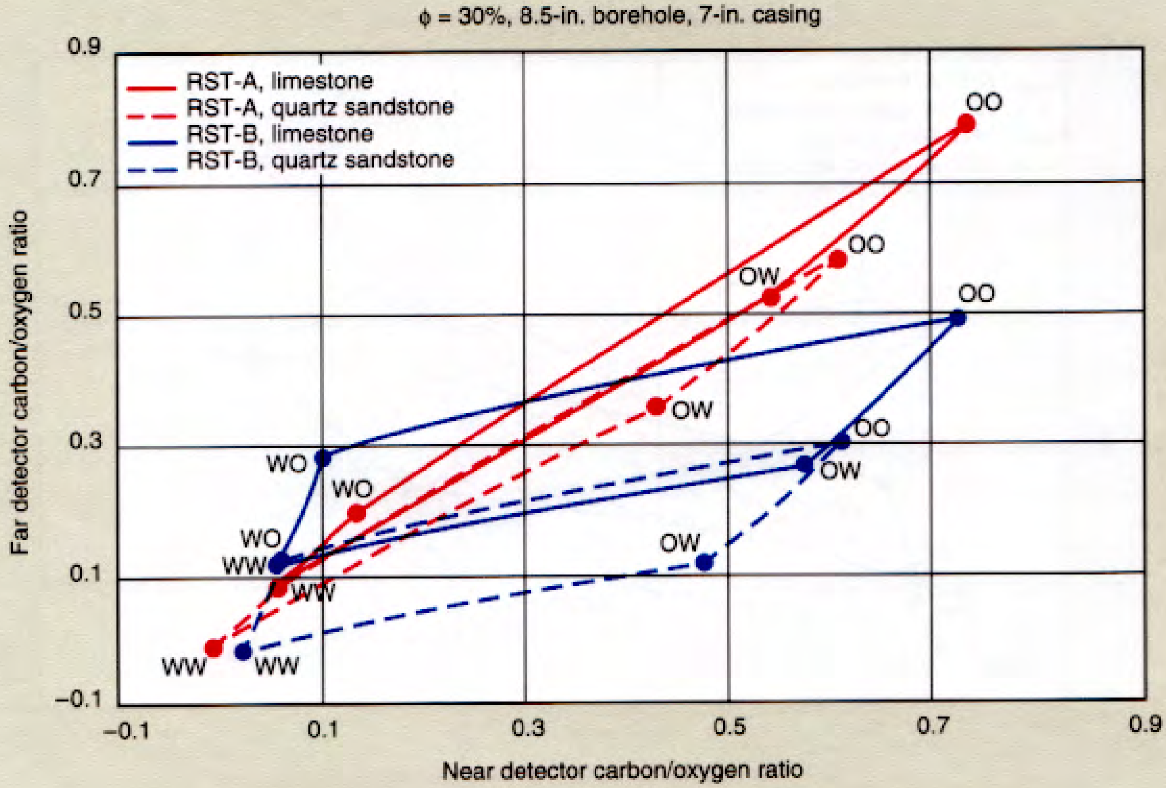
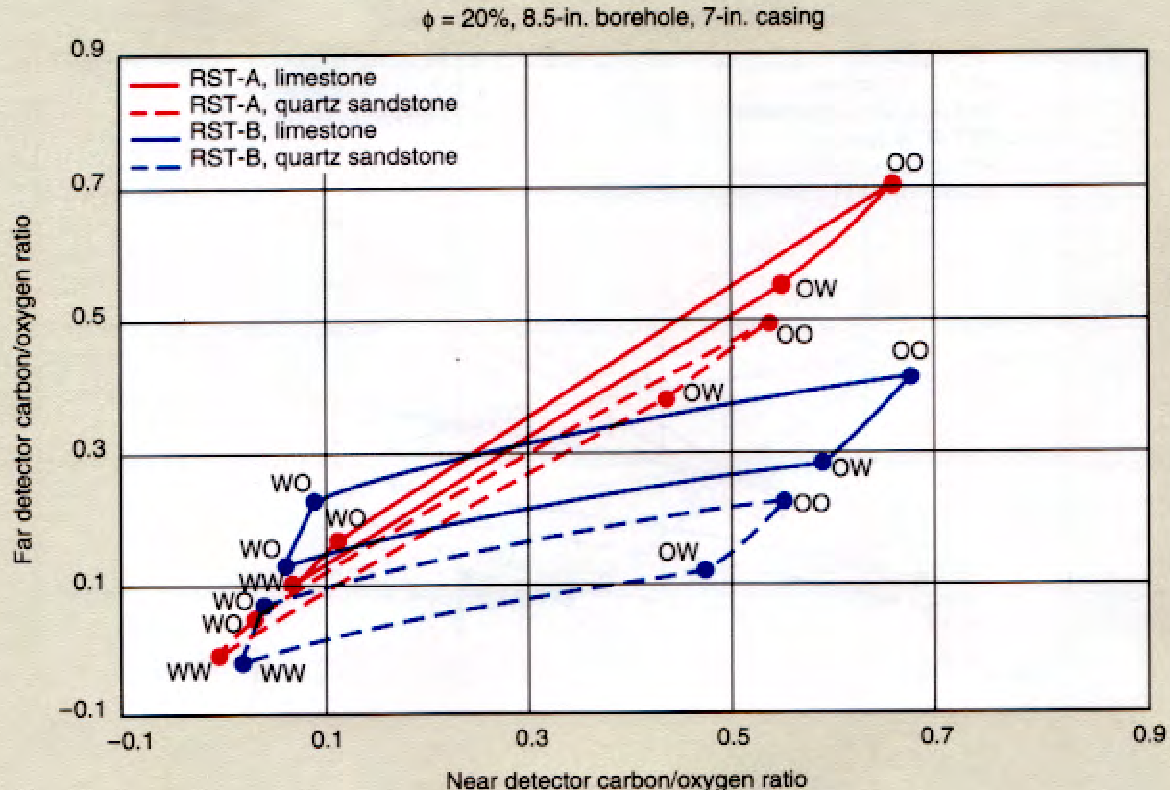
RST* Reservoir Saturation Tool Carbon/Oxygen Ratio Response

RST-A and RST-B in cased holes

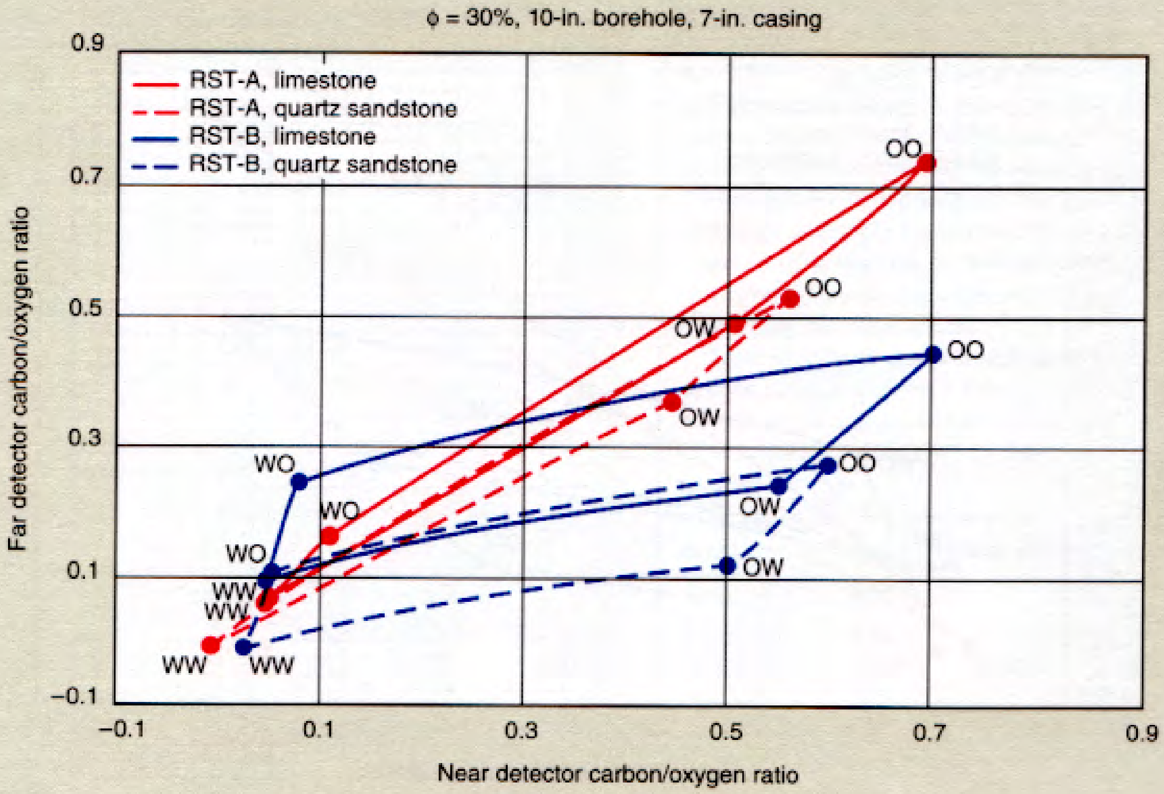


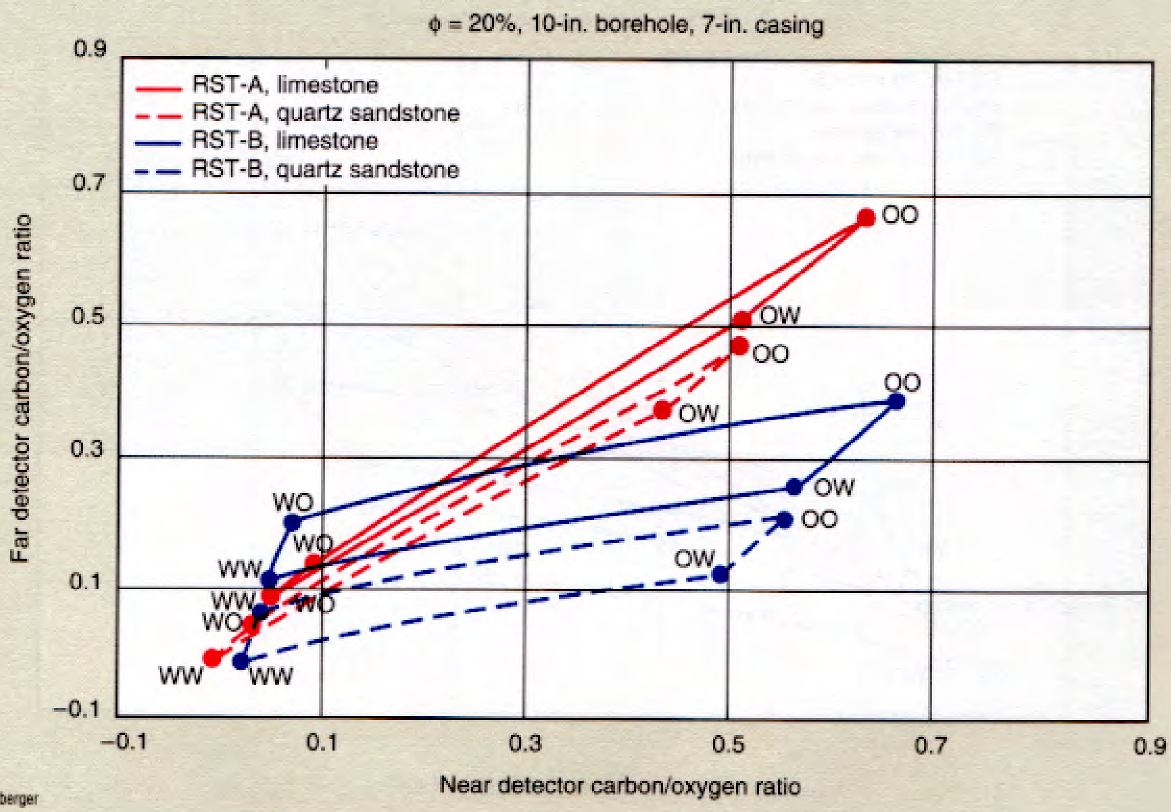


RST

RST* Reservoir Saturation Tool Carbon/Oxygen Ratio Response

RST-A and RST-B in cased holes

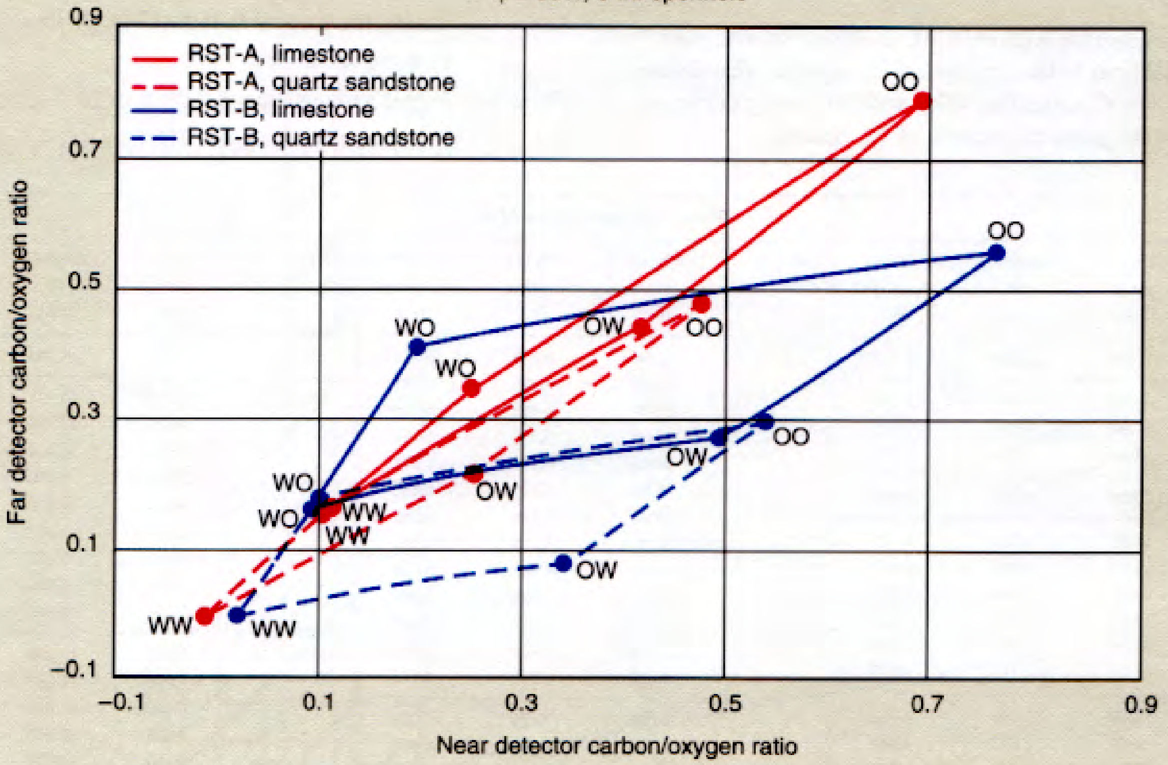




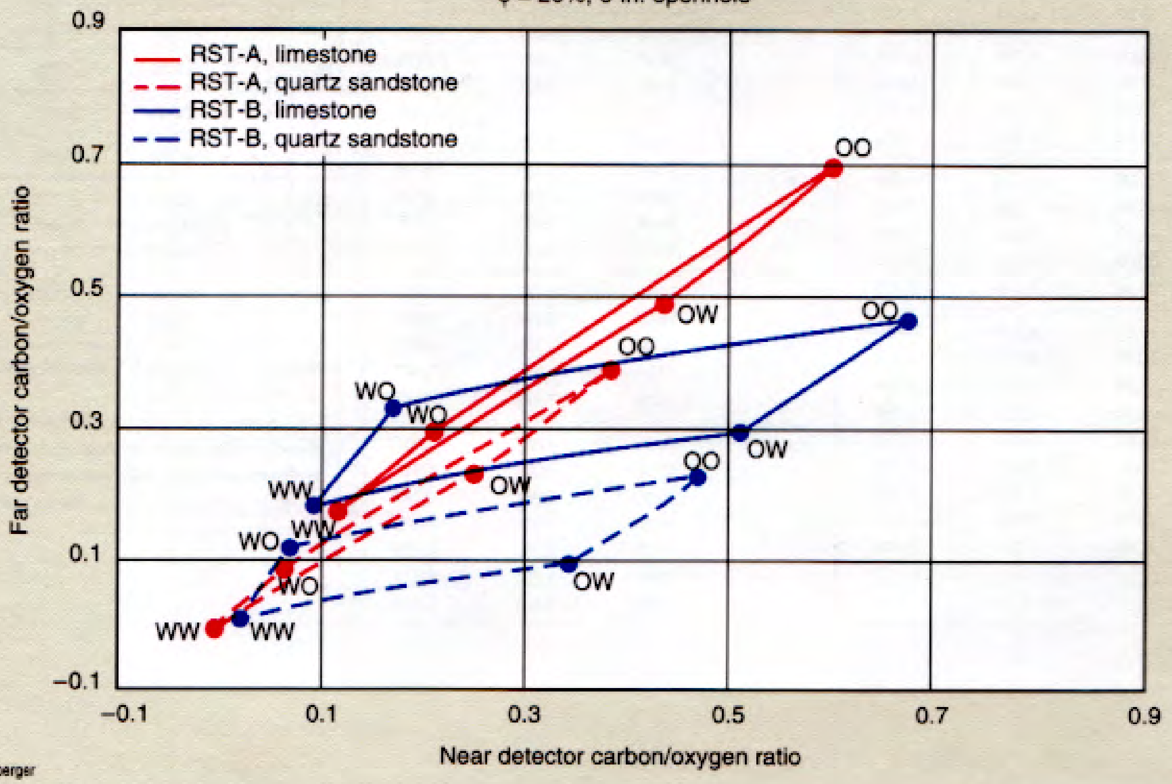
RST* Reservoir Saturation Tool
Carbon/Oxygen Ratio Response

RST-A and RST-B in openholes

ϕ = 30%, 6-in. openhole



ϕ = 20%, 6-in. openhole



CBL Interpretation—Casing Data

The compressive strength of bonded cement (either standard or foamed) can be estimated from the CBL amplitude recording using Chart M-1.

Enter the nomograph with the CBL amplitude in mV; then follow diagonal lines to the appropriate casing size. This defines signal attenuation. Connect this value with the casing thickness to estimate the compressive strength of the cement.

Example:	CBL amplitude = 3.5 mV
	Casing size = 7 in.
	Casing thickness = 0.41 in. (7 in. 29 lbm)
	Cement is standard
Therefore,	Signal attenuation = 8.9 dB/ft or 29.2 dB/m
and	Compressive strength = 2100 psi or 14.5 mPa

Data for Threaded Nonupset Casing

OD (in.)	Weight† per ft (lbm)	Nominal ID (in.)	Drift Diameter‡ (in.)
4	11.60	3.428	3.303
4½	9.50	4.090	3.965
	11.60	4.000	3.875
	13.50	3.920	3.795
4¾	16.00	4.082	3.957
5	11.50	4.560	4.435
	13.00	4.494	4.369
	15.00	4.408	4.283
	17.70	4.300	4.175
	18.00	4.276	4.151
	21.00	4.154	4.029
5½	13.00	5.044	4.919
	14.00	5.012	4.887
	15.00	4.974	4.849
	15.50	4.950	4.825
	17.00	4.892	4.767
	20.00	4.778	4.653
	23.00	4.670	4.545
5¾	14.00	5.290	5.165
	17.00	5.190	5.065
	19.50	5.090	4.965
	22.50	4.990	4.865
6	15.00	5.524	5.399
	16.00	5.500	5.375
	18.00	5.424	5.299
	20.00	5.352	5.227
	23.00	5.240	5.115
6⅝	17.00	6.135	6.010
	20.00	6.049	5.924
	22.00	5.989	5.864
	24.00	5.921	5.796
	26.00	5.855	5.730
	26.80	5.837	5.712
	28.00	5.791	5.666
	29.00	5.761	5.636
	32.00	5.675	5.550

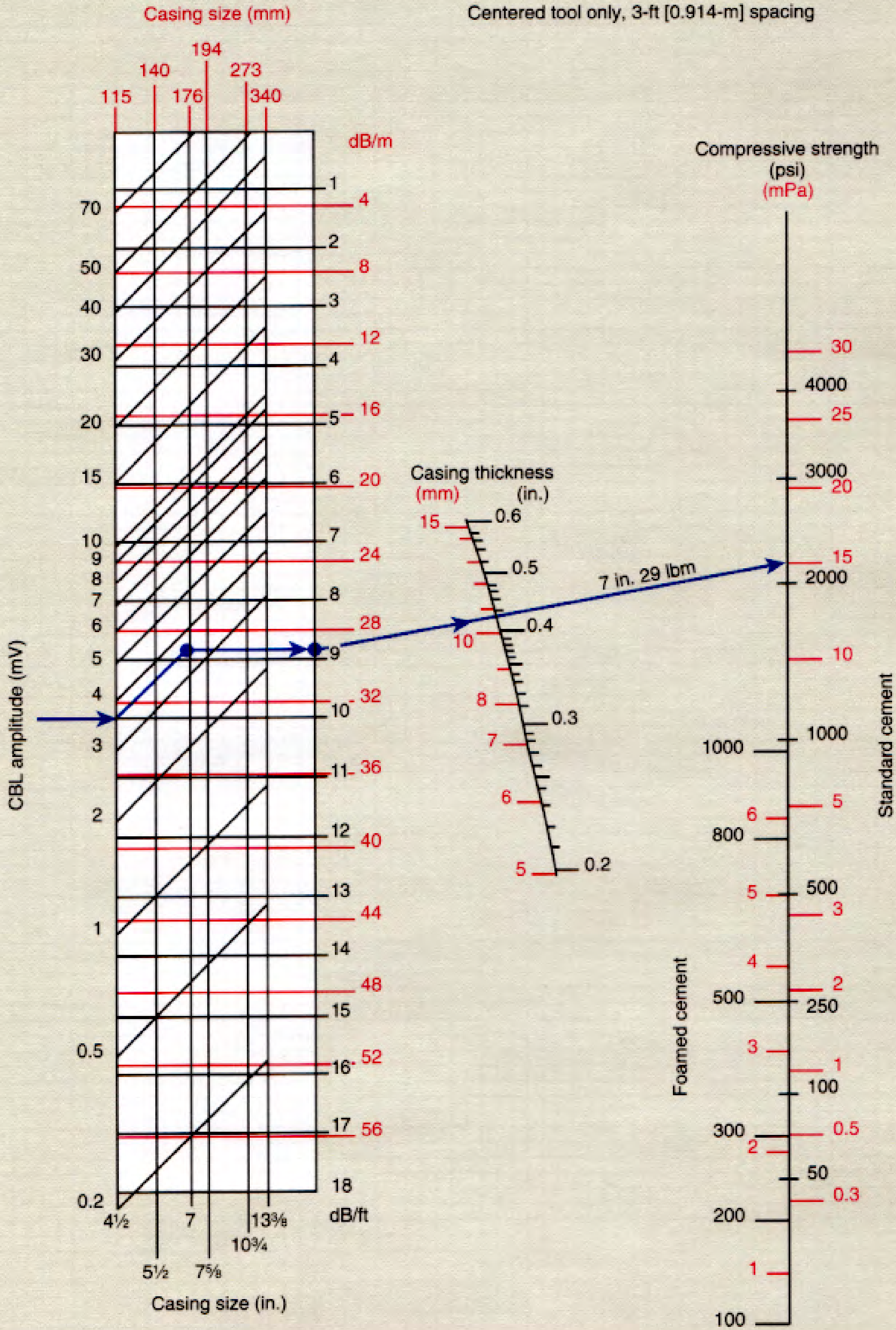
OD (in.)	Weight† per ft (lbm)	Nominal ID (in.)	Drift Diameter‡ (in.)
7	17.00	6.538	6.413
	20.00	6.456	6.331
	22.00	6.398	6.273
	23.00	6.366	6.241
	24.00	6.336	6.211
	26.00	6.276	6.151
	28.00	6.214	6.089
	29.00	6.184	6.059
	30.00	6.154	6.029
	32.00	6.094	5.969
	35.00	6.004	5.879
	38.00	5.920	5.795
	40.00	5.836	5.711
7⅝	20.00	7.125	7.000
	24.00	7.025	6.900
	26.40	6.969	6.844
	29.70	6.875	6.750
	33.70	6.765	6.640
	39.00	6.625	6.500
8⅝	24.00	8.097	7.972
	28.00	8.017	7.892
	32.00	7.921	7.796
	36.00	7.825	7.700
	38.00	7.775	7.650
	40.00	7.725	7.600
	43.00	7.651	7.526
	44.00	7.625	7.500
	49.00	7.511	7.386
9	34.00	8.290	8.165
	38.00	8.196	8.071
	40.00	8.150	8.025
	45.00	8.032	7.907
	55.00	7.812	7.687
9⅝	29.30	9.063	8.907
	32.30	9.001	8.845
	36.00	8.921	8.765
	40.00	8.835	8.679
	43.50	8.755	8.599
	47.00	8.681	8.525
	53.50	8.535	8.379

OD (in.)	Weight† per ft (lbm)	Nominal ID (in.)	Drift Diameter‡ (in.)
10	33.00	9.384	9.228
10¾	32.75	10.192	10.036
	40.00	10.054	9.898
	40.50	10.050	9.894
	45.00	9.960	9.804
	45.50	9.950	9.794
	48.00	9.902	9.746
	51.00	9.850	9.694
	54.00	9.784	9.628
	55.50	9.760	9.604
11¾	38.00	11.150	10.994
	42.00	11.084	10.928
	47.00	11.000	10.844
	54.00	10.880	10.724
	60.00	10.772	10.616
12	40.00	11.384	11.228
13	40.00	12.438	12.282
13⅜	48.00	12.715	12.559
16	55.00	15.375	15.187
18⅝	78.00	17.855	17.667
20	90.00	19.190	19.002
21½	92.50	20.710	20.522
	103.00	20.610	20.422
	114.00	20.510	20.322
24½	100.50	23.750	23.562
	113.00	23.650	23.462

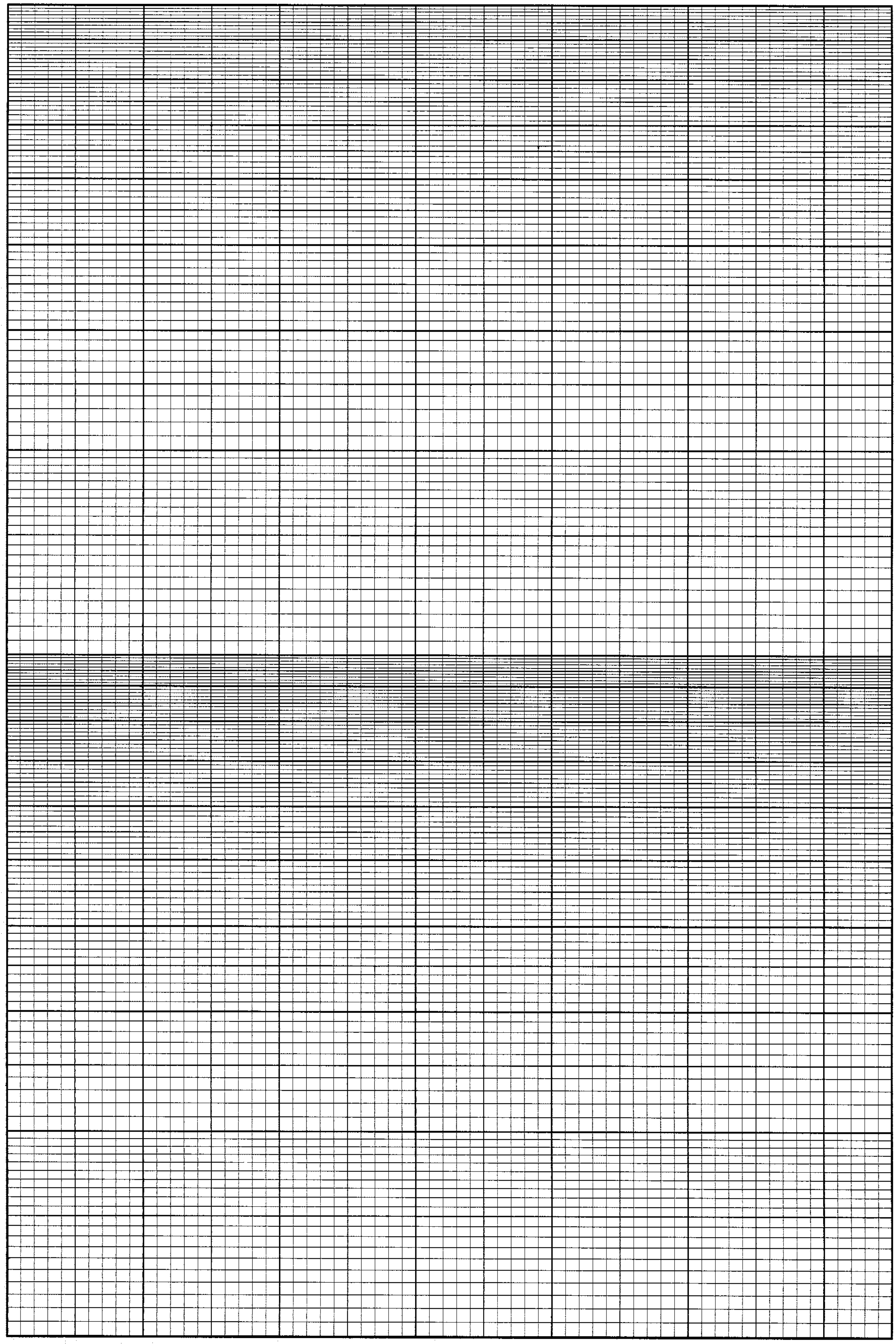
† Weight per foot in pounds is given for plain pipe (no threads or coupling).

‡ Drift diameter is the guaranteed minimum internal diameter of any part of the casing. Use drift diameter to determine the largest-diameter equipment that can be safely run inside the casing. Use internal diameter for volume capacity calculations.

CBL Interpretation Chart



See opposite page for instructions.


9
8
7
6
5
4
3
2
1
9
8
7
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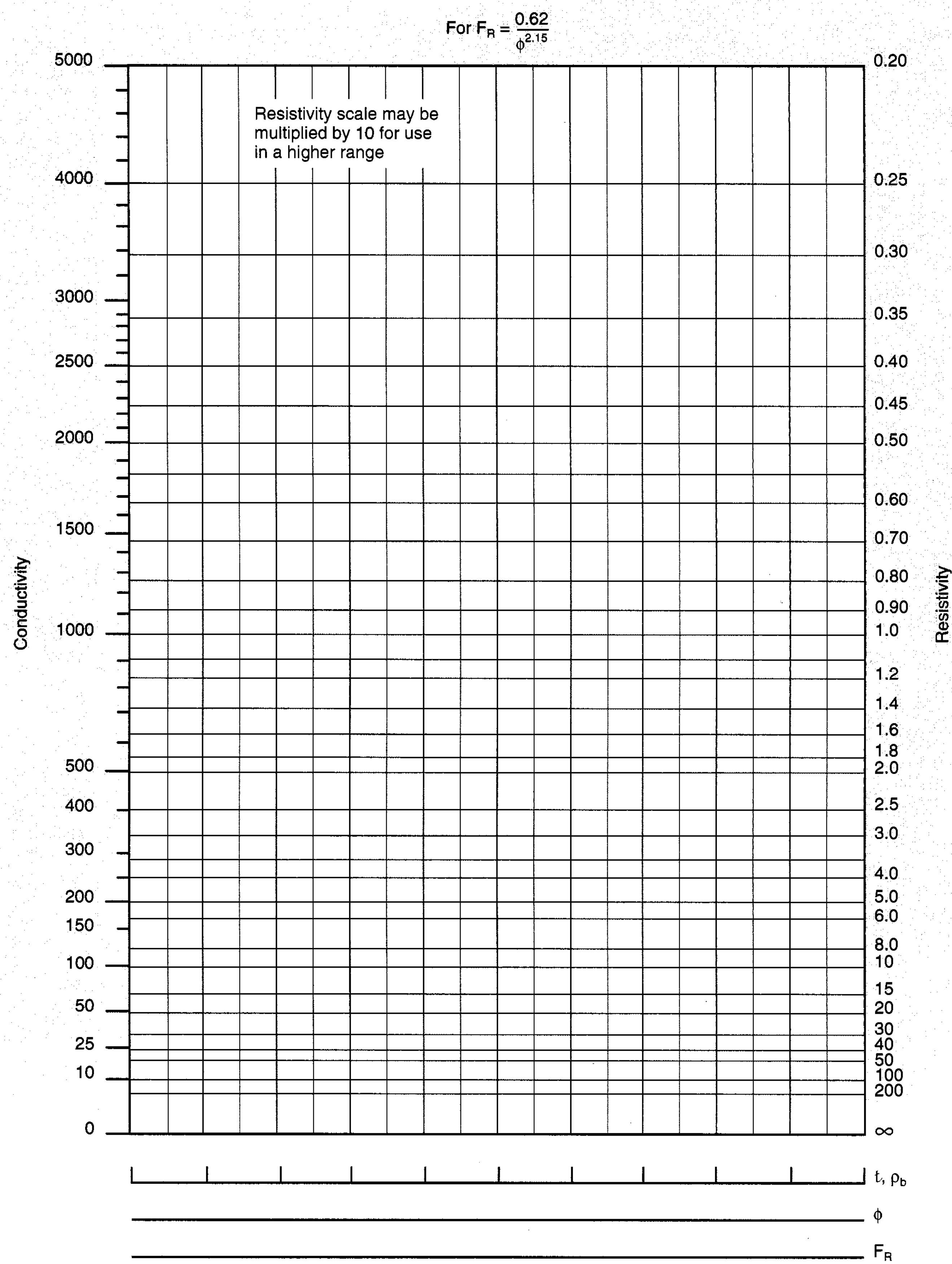
5
4
3
2
1


For $F_R = \frac{0.62}{\phi^{2.15}}$
Resistivity scale may be multiplied by 10 for use in a higher range
Conductivity
5000
4000
3000
2500
2000
1500
1000
500
400
300
200
150
100
50
25
10
0
Resistivity
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.60
0.70
0.80
0.90
1.0
1.2
1.4
1.6
1.8
2.0
2.5
3.0
4.0
5.0
6.0
8.0
10
15
20
30
40
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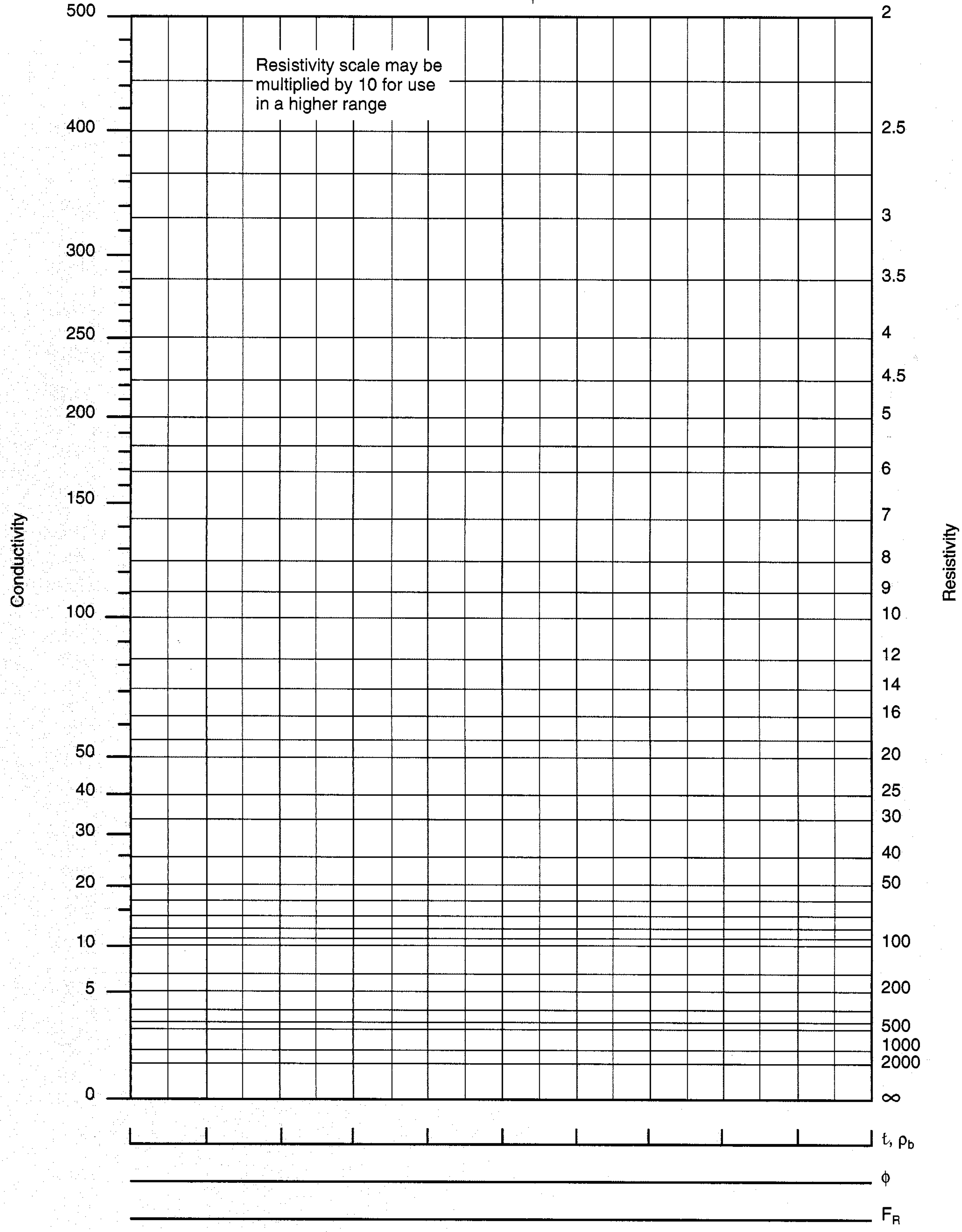
100
200
∞
t, ρ_b
ϕ
F_R

For $F_R = \frac{1}{\phi^2}$



Name	Formula	ρ_{LOG} (g/cm^3)	ϕ_{SNP} (p.u.)	ϕ_{CNL} (p.u.)	ϕ_{APS}† (p.u.)	t_c (μsec/ft)	t_s (μsec/ft)	P_e	U	ε (farad/m)	t_p (nsec/m)	GR (API units)	Σ (c.u.)
Silicates													
Quartz	SiO_2	2.64	−1	−2	−1	56.0	88.0	1.8	4.8	4.65	7.2		4.3
β-Cristobalite	SiO_2	2.15	−2	−3				1.8	3.9				3.5
Opal (3.5% H_2O)	$SiO_2(H_2O)_{.1209}$	2.13	4	2		58		1.8	3.7				5.0
Garnet‡	$Fe_3Al_2(SiO_4)_3$	4.31	3	7				11	48				45
Hornblende‡	$Ca_2NaMg_2Fe_2AlSi_8O_{22}(O,OH)_2$	3.20	4	8		43.8	81.5	6.0	19				18
Tourmaline	$NaMg_3Al_6B_3Si_6O_2(OH)_4$	3.02	16	22				2.1	6.5				7450
Zircon	$ZrSiO_4$	4.50	−1	−3				69	311				6.9
Carbonates													
Calcite	$CaCO_3$	2.71	0	0	0	49.0	88.4	5.1	13.8	7.5	9.1		7.1
Dolomite	$CaCO_3MgCO_3$	2.85	2	1	1	44.0	72	3.1	9.0	6.8	8.7		4.7
Ankerite	$Ca(Mg,Fe)(CO_3)_2$	2.86	0	1				9.3	27				22
Siderite	$FeCO_3$	3.89	5	12	3	47		15	57	6.8–7.5	8.8–9.1		52
Oxidates													
Hematite	Fe_2O_3	5.18	4	11		42.9	79.3	21	111				101
Magnetite	Fe_3O_4	5.08	3	9		73		22	113				103
Geothite	$FeO(OH)$	4.34	50+	60+				19	83				85
Limonite‡	$FeO(OH)(H_2O)_{2.05}$	3.59	50+	60+		56.9	102.6	13	47	9.9–10.9	10.5–11.0		71
Gibbsite	$Al(OH)_3$	2.49	50+	60+				1.1					23
Phosphates													
Hydroxyapatite	$Ca_5(PO_4)_3OH$	3.17	5	8		42		5.8	18				9.6
Chlorapatite	$Ca_5(PO_4)_3CL$	3.18	−1	−1		42		6.1	19				130
Fluorapatite	$Ca_5(PO_4)_3F$	3.21	−1	−2		42		5.8	19				8.5
Carbonapatite	$(Ca_5(PO_4)_3)_2CO_3H_2O$	3.13	5	8				5.6	17				9.1
Feldspars—Alkali‡													
Orthoclase	$KAlSi_3O_8$	2.52	−2	−3		69		2.9	7.2	4.4–6.0	7.0–8.2	~220	16
Anorthoclase	$KAlSi_3O_8$	2.59	−2	−2				2.9	7.4	4.4–6.0	7.0–8.2	~220	16
Microcline	$KAlSi_3O_8$	2.53	−2	−3				2.9	7.2	4.4–6.0	7.0–8.2	~220	16
Feldspars—Plagioclase‡													
Albite	$NaAlSi_3O_8$	2.59	−1	−2	−2	49	85	1.7	4.4	4.4–6.0	7.0–8.2		7.5
Anorthite	$CaAl_2Si_2O_8$	2.74	−1	−2		45		3.1	8.6	4.4–6.0	7.0–8.2		7.2
Micas‡													
Muscovite	$KAl_2(Si_3AlO_{10})(OH)_2$	2.82	12	~20	~13	49	149	2.4	6.7	6.2–7.9	8.3–9.4	~270	17
Glauconite	$K_{0.7}(Mg,Fe_2,Al)(Si_4,Al_{10})O_2(OH)$	2.86		~38	~15			4.8	14				21
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	~2.99	~11	~21	~11	50.8	224	6.3	19	4.8–6.0	7.2–8.1	~275	30
Phlogopite	$KMg_3(AlSi_3O_{10})(OH)_2$					50	207						33

†APS porosity derived from near-to-array ratio (APLC)

‡Mean value, which may vary for individual samples

For more information see Reference 41.

Name	Formula	ρ_{LOG} (g/cm³)	ϕ_{SNP} (p.u.)	ϕ_{CNL} (p.u.)	ϕ_{APS}† (p.u.)	t_c (μsec/ft)	t_s (μsec/ft)	P_e	U	ε (farad/m)	t_p (nsec/m)	GR (API units)	Σ (c.u.)
Clays‡													
Kaolinite	$Al_4Si_4O_{10}(OH)_8$	2.41	34	~37	~34			1.8	4.4	~5.8	~8.0	80–130	14
Chlorite	$(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$	2.76	37	~52	~35			6.3	17	~5.8	~8.0	180–250	25
Illite	$K_{1-1.5}Al_4(Si_{7-6.5},Al_{1-1.5})O_{20}(OH)_4$	2.52	20	~30	~17			3.5	8.7	~5.8	~8.0	250–300	18
Montmorillonite	$(Ca,Na)_7(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4(H_2O)_n$	2.12		~60	~60			2.0	4.0	~5.8	~8.0	150–200	14
Evaporites													
Halite	$NaCl$	2.04	−2	−3	21	67.0	120	4.7	9.5	5.6–6.3	7.9–8.4		754
Anhydrite	$CaSO_4$	2.98	−1	−2	2	50		5.1	15	6.3	8.4		12
Gypsum	$CaSO_4(H_2O)_2$	2.35	50+	60+	60	52		4.0	9.4	4.1	6.8		19
Trona	$Na_2CO_3NaHCO_3H_2O$	2.08	24	35		65		0.71	1.5				16
Tachhydrite	$CaCl_2(MgCl_2)_2(H_2O)_{12}$	1.66	50+	60+		92		3.8	6.4				406
Sylvite	KCl	1.86	−2	−3				8.5	16	4.6–4.8	7.2–7.3	500+	565
Carnalite	$KClMgCl_2(H_2O)_6$	1.57	41	60+				4.1	6.4			~220	369
Langbeinite	$K_2SO_4(MgSO_4)_2$	2.82	−1	−2				3.6	10			~290	24
Polyhalite	$K_2SO_4MgSO_4(CaSO_4)_2(H_2O)_2$	2.79	14	25				4.3	12			~200	24
Kainite	$MgSO_4KCl(H_2O)_3$	2.12	40	60+				3.5	7.4			~245	195
Kieserite	$MgSO_4H_2)$	2.59	38	43				1.8	4.7				14
Epsomite	$MgSO_4(H_2O)_7$	1.71	50+	60+				1.2	2.0				21
Bischofite	$MgCl_2(H_2O)_6$	1.54	50+	60+		100		2.6	4.0				323
Barite	$BaSO_4$	4.09	−1	−2				267	1090				6.8
Celestite	$SrSO_4$	3.79	−1	−1				55	209				7.9
Sulfides													
Pyrite	FeS_2	4.99	−2	−3		39.2	62.1	17	85				90
Marcasite	FeS_2	4.87	−2	−3				17	83				88
Pyrrhotite	Fe_7S_8	4.53	−2	−3				21	93				94
Sphalerite	ZnS	3.85	−3	−3				36	138	7.8–8.1	9.3–9.5		25
Chalopyrite	$CuFeS_2$	4.07	−2	−3				27	109				102
Galena	PbS	6.39	−3	−3				1630	10,400				13
Sulfur	S	2.02	−2	−3		122		5.4	11				20
Coals													
Anthracite	$CH_{.358}N_{.009}O_{.022}$	1.47	37	38		105		0.16	0.23				8.7
Bituminous	$CH_{.793}N_{.015}O_{.078}$	1.24	50+	60+		120		0.17	0.21				14
Lignite	$CH_{.849}N_{.015}O_{.211}$	1.19	47	52		160		0.20	0.24				13

†APS porosity derived from near-to-array ratio (APLC)
‡Mean value, which may vary for individual samples

For more information see Reference 41.

Multiply Number of / to Obtain by	Centimeters	Feet	Inches	Kilometers	Nautical miles	Meters	Mils	Miles	Millimeters	Yards
Centimeters	1	30.48	2.540	10^5	1.853×10^5	100	2.540×10^{-3}	1.609×10^5	0.1	91.44
Feet	3.281×10^{-2}	1	8.333×10^{-2}	3281	6080.27	3.281	8.333×10^{-5}	5280	3.281×10^{-3}	3
Inches	0.3937	12	1	3.937×10^4	7.296×10^4	39.37	0.001	6.336×10^4	3.937×10^{-2}	36
Kilometers	10^{-5}	3.048×10^{-4}	2.540×10^{-5}	1	1.853	0.001	2.540×10^{-8}	1.609	10^{-6}	9.144×10^{-4}
Nautical miles		1.645×10^{-4}		0.5396	1	5.396×10^{-4}		0.8684		4.934×10^{-4}
Meters	0.01	0.3048	2.540×10^{-2}	1000	1853	1		1609	0.001	0.9144
Mils	393.7	1.2×10^4	1000	3.937×10^7		3.937×10^4	1		39.37	3.6×10^4
Miles	6.214×10^{-6}	1.894×10^{-4}	1.578×10^{-5}	0.6214	1.1516	6.214×10^{-4}		1	6.214×10^{-7}	5.682×10^{-4}
Millimeters	10	304.8	25.40	10^5		1000	2.540×10^{-2}		1	914.4
Yards	1.094×10^{-2}	0.3333	2.778×10^{-2}	1094	2027	1.094	2.778×10^{-5}	1760	1.094×10^{-3}	1

Area

Multiply Number of / to Obtain by	Acres	Circular mils	Square centimeters	Square feet	Square inches	Square kilometers	Square meters	Square miles	Square millimeters	Square yards
Acres	1			2.296×10^{-5}		247.1	2.471×10^{-4}	640		2.066×10^{-4}
Circular mils		1	1.973×10^5	1.833×10^8	1.273×10^6		1.973×10^9		1973	
Square centimeters		5.067×10^{-6}	1	929.0	6.452	10^{10}	10^4	2.590×10^{10}	0.01	8361
Square feet	4.356×10^4		1.076×10^{-3}	1	6.944×10^{-3}	1.076×10^7	10.76	2.788×10^7	1.076×10^{-5}	9
Square inches	6,272,640	7.854×10^{-7}	0.1550	144	1	1.550×10^9	1550	4.015×10^9	1.550×10^{-3}	1296
Square kilometers	4.047×10^{-3}		10^{-10}	9.290×10^{-8}	6.452×10^{-10}	1	10^{-6}	2.590	10^{-12}	8.361×10^{-7}
Square meters	4047		0.0001	9.290×10^{-2}	6.452×10^{-4}	10^6	1	2.590×10^6	10^{-6}	0.8361
Square miles	1.562×10^{-3}		3.861×10^{-11}	3.587×10^{-8}		0.3861	3.861×10^{-7}	1	3.861×10^{-13}	3.228×10^{-7}
Square millimeters		5.067×10^{-4}	100	9.290×10^4	645.2	10^{12}	10^6		1	8.361×10^5
Square yards	4840		1.196×10^{-4}	0.1111	7.716×10^{-4}	1.196×10^6	1.196	3.098×10^6	1.196×10^{-6}	1

Volume

Multiply Number of ↘ by, to Obtain	Bushels (dry)	Cubic centimeters	Cubic feet	Cubic inches	Cubic meters	Cubic yards	Gallons (liquid)	Liters	Pints (liquid)	Quarts (liquid)
Bushels (dry)	1		0.8036	4.651×10^{-4}	28.38			2.838×10^{-2}		
Cubic centimeters	3.524×10^{4}	1	2.832×10^{4}	16.39	10^{6}	7.646×10^{5}	3785	1000	473.2	946.4
Cubic feet	1.2445	3.531×10^{-5}	1	5.787×10^{-4}	35.31	27	0.1337	3.531×10^{-2}	1.671×10^{-2}	3.342×10^{-2}
Cubic inches	2150.4	6.102×10^{-2}	1728	1	6.102×10^{4}	46,656	231	61.02	28.87	57.75
Cubic meters	3.524×10^{-2}	10^{-6}	2.832×10^{-2}	1.639×10^{-5}	1	0.7646	3.785×10^{-3}	0.001	4.732×10^{-4}	9.464×10^{-4}
Cubic yards		1.308×10^{-6}	3.704×10^{-2}	2.143×10^{-5}	1.308	1	4.951×10^{-3}	1.308×10^{-3}	6.189×10^{-4}	1.238×10^{-3}
Gallons (liquid)		2.642×10^{-4}	7.481	4.329×10^{-3}	264.2	202.0	1	0.2642	0.125	0.25
Liters	35.24	0.001	28.32	1.639×10^{-2}	1000	764.6	3.785	1	0.4732	0.9464
Pints (liquid)		2.113×10^{-3}	59.84	3.463×10^{-2}	2113	1616	8	2.113	1	2
Quarts (liquid)		1.057×10^{-3}	29.92	1.732×10^{-2}	1057	807.9	4	1.057	0.5	1

Mass and Weight

Multiply Number of ↘ by, to Obtain	Grains	Grams	Kilograms	Milligrams	Ounces†	Pounds†	Tons (long)	Tons (metric)	Tons (short)
Grains	1	15.43	1.543×10^{4}	1.543×10^{-2}	437.5	7000			
Grams	6.481×10^{-2}	1	1000	0.001	28.35	453.6	1.016×10^{6}	10^{6}	9.072×10^{5}
Kilograms	6.481×10^{-5}	0.001	1	10^{-6}	2.835×10^{-2}	0.4536	1016	1000	907.2
Milligrams	64.81	1000	10^{6}	1	2.835×10^{4}	4.536×10^{5}	1.016×10^{9}	10^{9}	9.072×10^{8}
Ounces†	2.286×10^{-3}	3.527×10^{-2}	35.27	3.527×10^{-5}	1	16	3.584×10^{4}	3.527×10^{4}	3.2×10^{4}
Pounds†	1.429×10^{-4}	2.205×10^{-3}	2.205	2.205×10^{-6}	6.250×10^{-2}	1	2240	2205	2000
Tons (long)		9.842×10^{-7}	9.842×10^{-4}	9.842×10^{-10}	2.790×10^{-5}	4.464×10^{-4}	1	0.9842	0.8929
Tons (metric)		10^{-6}	0.001	10^{-9}	2.835×10^{-5}	4.536×10^{-4}	1.016	1	0.9072
Tons (short)		1.102×10^{-6}	1.102×10^{-3}	1.102×10^{-9}	3.125×10^{-5}	0.0005	1.120	1.102	1

†Avoirdupois pounds and ounces

Pressure or Force per Unit Area

Multiply Number of → to Obtain ↓ by	Atmospheres†	Bayres or dynes per square centimeter‡	Centimeters of mercury at 0°C§	Inches of mercury at 0°C§	Inches of water at 4°C	Kilograms per square meter††	Pounds per square foot	Pounds per square inch‡‡	Tons (short) per square foot	Pascals
Atmospheres†	1	9.869×10^{-7}	1.316×10^{-2}	3.342×10^{-2}	2.458×10^{-3}	9.678×10^{-5}	4.725×10^{-4}	6.804×10^{-2}	0.9450	9.869×10^{-6}
Bayres or dynes per square centimeter‡	1.013×10^{6}	1	1.333×10^{4}	3.386×10^{4}	2.491×10^{-3}	98.07	478.8	6.895×10^{4}	9.576×10^{5}	10
Centimeters of mercury at 0°C§	76.00	7.501×10^{-5}	1	2.540	0.1868	7.356×10^{-3}	3.591×10^{-2}	5.171	71.83	7.501×10^{-4}
Inches of mercury at 0°C§	29.92	2.953×10^{-5}	0.3937	1	7.355×10^{-2}	2.896×10^{-3}	1.414×10^{-2}	2.036	28.28	2.953×10^{-4}
Inches of water at 4°C	406.8	4.015×10^{-4}	5.354	13.60	1	3.937×10^{-2}	0.1922	27.68	384.5	4.015×10^{-3}
Kilograms per square meter††	1.033×10^{4}	1.020×10^{-2}	136.0	345.3	25.40	1	4.882	703.1	9765	0.1020
Pounds per square foot	2117	2.089×10^{-3}	27.85	70.73	5.204	0.2048	1	144	2000	2.089×10^{-2}
Pounds per square inch‡‡	14.70	1.450×10^{-5}	0.1934	0.4912	3.613×10^{-2}	1.422×10^{-3}	6.944×10^{-3}	1	13.89	1.450×10^{-4}
Tons (short) per square foot	1.058	1.044×10^{-5}	1.392×10^{-2}	3.536×10^{-2}	2.601×10^{-3}	1.024×10^{-4}	0.0005	0.072	1	1.044×10^{-5}
Pascals	1.013×10^{5}	10^{-1}	1.333×10^{3}	3.386×10^{3}	2.491×10^{-4}	9.807	47.88	6.895×10^{3}	9.576×10^{4}	1

† One atmosphere (standard) = 76 cm of mercury at 0°C

‡ Bar

§ To convert height h of a column of mercury at t°C to the equivalent height h_0 at 0°C, use $h_0 = h\,\{1 - [(m - l)\,t / 1 + mt]\}$, where $m = 0.0001818$ and $l = 18.4 \times 10^{-6}$ if the scale is engraved on brass; $l = 8.5 \times 10^{-6}$ if on glass. This assumes the scale is correct at 0°C; for other cases (any liquid) see *International Critical Tables,* Vol. 1, 68.

†† 1 gram per square centimeter = 10 kilograms per square meter

‡‡ psi = MPa × 145.038
psi/ft = 0.433 × g/cm³ = lb/ft³/144 = lb/gal/19.27

Density or Mass per Unit Volume

Multiply Number of → to Obtain ↓ by	Grams per cubic centimeter	Kilograms per cubic meter	Pounds per cubic foot	Pounds per cubic inch	Pounds per gallon
Grams per cubic centimeter	1	0.001	1.602×10^{-2}	27.68	0.1198
Kilograms per cubic meter	1000	1	16.02	2.768×10^{4}	119.8
Pounds per cubic foot	62.43	6.243×10^{-2}	1	1728	7.479
Pounds per cubic inch	3.613×10^{-2}	3.613×10^{-5}	5.787×10^{-4}	1	4.329×10^{-3}
Pounds per gallon	8.347	8.3×10^{-3}	13.37×10^{-2}	231.0	1

Temperature

°F	1.8°C + 32
°C	5⁄9 (°F – 32)
°R	°F + 459.69
K	°C + 273.16

Traditional symbol	Standard SPE and SPWLA[a]	Standard computer symbol[a]	Description	Customary unit or relation	Standard reserve symbol[b]
a	a	ACT	electrochemical activity	equivalents/liter, moles/liter	
a	K_R	COER	coefficient in $F_R - \phi$ relation	$F_R = K_R/\phi^m$	M_R, a, C
A	A	AWT	atomic weight	amu	
C	C	ECN	conductivity (electrical logging)	millimho per meter (mmho/m)	σ
C_p	B_{cp}	CORCP	sonic compaction correction factor	$\phi_{SVcor} = B_{cp}\ \phi_{SV}$	C_{cp}
D	D	DPH	depth	ft, m	y, H
d	d	DIA	diameter	in.	D
E	E	EMF	electromotive force	mV	V
F	F_R	FACHR	formation resistivity factor	$F_R = K_R/\phi^m$	
G	G	GMF	geometrical factor (multiplier)		f_G
H	I_H	HYX	hydrogen index		i_H
h	h	THK	bed thickness, individual	ft, m, in.	d, e
I	I	–X	index		i
FFI	I_{Ff}	FFX	free fluid index		i_{Ff}
SI	I_{sl}	SLX	silt index		I_{slt}, i_{sl}, i_{slt}
	I_ϕ	PRX	porosity index		i_ϕ
SPI	$I_{\phi 2}$	PRXSE	secondary porosity index		$i_{\phi 2}$
J	G_p	GMFP	pseudogeometrical factor		f_{Gp}
K	K_c	COEC	electrochemical SP coefficient	$E_c = K_c \log (a_w/a_{mf})$	M_c, K_{ec}
k	k	PRM	permeability, absolute (fluid flow)	md	K
L	L	LTH	length, path length	ft, m, in.	s, ℓ
M	M	SAD	slope, sonic interval transit time versus density × 0.01, in M-N plot	$M = [(t_f - t_{LOG})/(\rho_b - \rho_f)] \times 0.01$	$m_{\theta D}$
m	m	MXP	porosity (cementation) exponent	$F_R = K_R/\phi^m$	
N	N	SND	slope, neutron porosity versus density, in M-N Plot	$N = (\phi_{Nf} - \phi_N)/(\rho_b - \rho_f)$	$m_{\phi ND}$
n	n	SXP	saturation exponent	$S_w{}^n = F_R R_w/R_t$	
P	C	CNC	salinity	g/g, ppm	c, n
p	p	PRS	pressure	psi, kg/cm2[c], atm	P
P_c	P_c	PRSCP	capillary pressure	psi, kg/cm2[c], atm	P_c, p_c
P_e			photoelectric cross section		

a References: "SPE Letter and Computer Symbols Standard," 1986.

b Reserve symbols are to be used only if conflict arises between standard symbols used in the same paper.

c The unit, kilograms per square centimeter, is to be replaced in use by the SI metric unit, the pascal.

d "DEL" is in the operator field. "RAD" is in the main-quantity field.

e Suggested computer symbol.

Traditional symbol	Standard SPE and SPWLA[a]	Standard computer symbol[a]	Description	Customary unit or relation	Standard reserve symbol[b]
Q_v			shaliness (CEC per ml water)	meq/ml	
q	$f_{\phi shd}$	FIMSHD	dispersed-shale volume fraction of intermatrix porosity		ϕ_{imfshd}, q
R	R	RES	resistivity (electrical)	ohm-m	ρ, r
r	r	RAD	radial distance from hole axis	in.	R
S	S	SAT	saturation	fraction or percent of pore volume	ρ, s
T	T	TEM	temperature	°F, °C, K	θ
BHT, T_{bh}	T_{bh}	TEMBH	bottomhole temperature	°F, °C, K	θ_{BH}
FT, T_{fm}	T_f	TEMF	formation temperature	°F, °C, K	
t	t	TIM	time	μsec, sec, min	t
t	t	TAC	interval transit time		Δt
U			volumetric cross section	$barns/cm^3$	
v	v	VAC	velocity (acoustic)	ft/sec, m/sec	V, u
V	V	VOL	volume	cm^3, ft^3, etc.	v
V	V	VLF	volume fraction		f_v, F_v
Z	Z	ANM	atomic number		
α	α_{SP}	REDSP	SP reduction factor		
γ	γ	SPG	specific gravity (ρ/ρ_w or ρ_g/ρ_{air})		s, F_s
φ	φ	POR	porosity	fraction or percentage of bulk volume, p.u.	f, ε
	ϕ_1	PORPR	primary porosity	fraction or percentage of bulk volume, p.u.	f_1, e_1
	ϕ_2	PORSE	secondary porosity	fraction or percentage of bulk volume, p.u.	f_2, e_2
	ϕ_{ig}	PORIG	intergranular porosity	$\phi_{ig} = (V_b - V_{gr})/V_b$	f_{ig}, ε_{ig}
ϕ_z, ϕ_{im}	ϕ_{im}	PORIM	intermatrix porosity	$\phi_{im} = (V_b - V_{ma})/V_b$	f_{im}, ε_{im}
Δr	Δr	DELRAD[d]	radial distance (increment)	in.	ΔR
Δt	t	TAC	sonic interval transit time	μsec/ft	Δt
$\Delta\phi_{Nex}$		DELPORNX[e]	excavation effect	p.u.	
λ	K_{ani}	COEANI	coefficient of anisotropy		M_{ani}
ρ	ρ	DEN	density	g/cm^3	D
Σ	Σ	XST XSTMAC	neutron capture cross section macroscopic	c.u., cm^{-1}	S
τ	τ_{dN}	TIMDN	thermal neutron decay time	μsec	t_{dn}

a References: "SPE Letter and Computer Symbols Standard," 1986.
b Reserve symbols are to be used only if conflict arises between standard symbols used in the same paper.
c The unit, kilograms per square centimeter, is to be replaced in use by the SI metric unit, the pascal.
d "DEL" is in the operator field. "RAD" is in the main-quantity field.
e Suggested computer symbol.

Traditional subscript	Standard SPE and SPWLA[a]	Standard computer subscript[a]	Explanation	Example	Standard reserve subscript[b]
a	LOG	L	apparent from log reading (or use tool description subscript)	R_{LOG}, R_{LL}	log
a	a	A	apparent (general)	R_a	ap
abs	cap	C	absorption, capture	Σ_{cap}	
anh	anh	AH	anhydrite		
b	b	B	bulk	ρ_b	B, t
bh	bh	BH	bottomhole	T_{bh}	w, BH
clay	cl	CL	clay	V_{cl}	cla
cor, c	cor	COR	corrected	t_{cor}	
c	c	C	electrochemical	E_c	ec
cp	cp	CP	compaction	B_{cp}	
D	D	D	density log		d
dis	shd	SHD	dispersed shale	V_{shd}	
dol	dol	DL	dolomite	t_{dol}	
e, eq	eq	EV	equivalent	R_{weq}, R_{mfeq}	EV
f, fluid	f	F	fluid	ρ_f	fl
fm	f	F	formation (rock)	T_f	fm
g, gas	g	G	gas	S_g	G
	gr	GR	grain	ρ_{gr}	
gxo	gxo	GXO	gas in flushed zone	S_{gxo}	GXO
gyp	gyp	GY	gypsum	ρ_{gyp}	
h	h	H	hole	d_h	H
h	h	H	hydrocarbon	ρ_h	H
hr	hr	HR	residual hydrocarbon	S_{hr}	
i	i	I	invaded zone (inner boundary)	d_i	I
ig	ig	IG	intergranular (incl. disp. and str. shale)	ϕ_{ig}	
im, z	im	IM	intermatrix (incl. disp. shale)	ϕ_{im}	
int	int	I	intrinsic (as opposed to log value)	Σ_{int}	
irr	i	IR	irreducible	S_{wi}	ir, ι
J	j	J	liquid junction	E_j	ι
k	k	K	electrokinetic	E_k	ek
l		L	log	t_{pl}	log
lam	ℓ	LAM	lamination, laminated	$V_{sh\ell}$	L
lim	lim	LM	limiting value	ϕ_{lim}	
liq	L	L	liquid	ρ_L	ℓ

a References: "SPE Letter and Computer Symbols Standard," 1986.

b Reserve symbols are to be used only if conflict arises between standard symbols used in the same paper.

Traditional subscript	Standard SPE and SPWLA[a]	Standard computer subscript[a]	Explanation	Example	Standard reserve subscript[b]
log	LOG	L	log values	t_{LOG}	log
ls	ls	LS	limestone	t_{ls}	1st
m	m	M	mud	R_m	
max	max	MX	maximum	ϕ_{max}	
ma	ma	MA	matrix	t_{ma}	
mc	mc	MC	mudcake	R_{mc}	
mf	mf	MF	mud filtrate	R_{mf}	
mfa	mfa	MFA	mud filtrate, apparent	R_{mfa}	
min	min	MN	minimum value		
ni			noninvaded zone	R_{ni}	
o	o	O	oil (except with resistivity)	S_o	N
or	or	OR	residual oil	S_{or}	
o, 0 (zero)	0 (zero)	ZR	100-percent water saturated	F_0	zr
p			propagation	t_{pw}	
PSP	pSP	PSP	pseudostatic SP	E_{pSP}	
pri	1 (one)	PR	primary	ϕ_1	p, pri
r	r	R	relative	k_{ro}, k_{rw}	R
r	r	R	residual	S_{or}, S_{hr}	R
s	s	S	adjacent (surrounding) formation	R_s	
sd	sd	SD	sand		sa
ss	ss	SS	sandstone		sst
sec	2	SE	secondary	ϕ_2	s, sec
sh	sh	SH	shale	V_{sh}	sha
silt	sl	SL	silt	I_{sl}	slt
SP	SP	SP	spontaneous potential	E_{SP}	sp
SSP	SSP	SSP	static spontaneous potential	E_{SSP}	
str	sh st	SH ST	structural shale	V_{shst}	s
t, ni	t	T	true (as opposed to apparent)	R_t	tr
T	t	T	total	C_t	T
w	w	W	water, formation water	S_w	W
wa	wa	WA	formation water, apparent	R_{wa}	Wap
wf	wf	WF	well flowing conditions	p_{wf}	f
ws	ws	WS	well static conditions	p_{ws}	s
xo	xo	XO	flushed zone	R_{xo}	
z, im	im	IM	intermatrix	ϕ_{im}	

a References: “SPE Letter and Computer Symbols Standard,” 1986.

b Reserve symbols are to be used only if conflict arises between standard symbols used in the same paper.

Traditional subscript	Standard SPE and SPWLA[a]	Standard computer subscript[a]	Explanation	Example	Standard reserve subscript[b]
0 (zero)	0 (zero)	ZR	100 percent water saturated	R_0	zr
AD		RAD	from CDR* attenuation deep	R_{AD}	
D	D	D	from density log	ϕ_D	d
	GG	GG	from gamma-gamma log	ϕ_{GG}	gg
IL	I	I	from induction log	R_I	i
ILD	ID	ID	from deep induction log	R_{ID}	id
ILM	IM	IM	from medium induction log	R_{IM}	im
LL	LL (also LL3, LL8, etc.)	LL	from laterolog (also LL3, LL7, LL8, LLD, LLS)	R_{LL}	$\ell\ell$
N	N	N	from normal resistivity log	R_N	n
N	N	N	from neutron log	ϕ_N	n
PS		RPS	from CDR phase shift shallow	R_{PS}	
16", 16"N			from 16-in. normal Log	$R_{16"}$	
1" × 1"			from 1-in. by 1-in. microinverse (MI)	$R_{1" \times 1"}$	
2"			from 2-in. micronormal (MN)	$R_{2"}$	

a References: “SPE Letter and Computer Symbols Standard,” 1986.

b Reserve symbols are to be used only if conflict arises between standard symbols used in the same paper.

These unit abbreviations, which have been adopted by the Society for Petroleum Engineers (SPE), are appropriate for most publications. However, an accepted industry standard may be used instead. For instance, in the drilling field, *ppg* may be more common than *lbm/gal* when referring to pounds per gallon.

Unit abbreviations are followed by a period only when the abbreviation forms a word (for example, *in.* for *inch*).

acre	spell out
acre-foot	acre-ft
alternating-current (adj.)	AC
ampere	A
ampere-hour	amp-hr
angstrom unit (10^{-8} cm)	A
atmosphere	atm
atomic mass unit	amu
average	avg
barrel	bbl
barrels of fluid per day	BFPD
barrels of liquid per day	BLPD
barrels of oil per day	BOPD
barrels of water per day	BWPD
barrels per day	B/D
barrels per minute	bbl/min
billion cubic feet (billion = 10^9)	Bcf
billion cubic feet per day	Bcf/D
billion standard cubic feet per day	Bscf/D
bits per inch	bpi
bits per second	bps
bottomhole pressure	BHP
bottomhole temperature	BHT
British thermal unit	Btu
capture unit	c.u.
centimeter	cm
centipoise	cp
centistoke	cstk
coulomb	C
counts per second	cps
cubic centimeter	cm^3
cubic foot	ft^3
cubic feet per barrel	ft^3/bbl
cubic feet per day	ft^3/D
cubic feet per minute	ft^3/min
cubic feet per pound	ft^3/lbm
cubic feet per second	ft^3/sec
cubic inch	$in.^3$
cubic meter	m^3
cubic millimeter	mm^3
cubic yard	yd^3
Curie	Ci
darcy, darcies	spell out
day	spell out
dead-weight ton	DWT
decibel	dB
degree (American Petroleum Institute)	°API
degree Celsius	°C
degree Fahrenheit	°F
degree Kelvin	(see "kelvin")
degree Rankine	°R
direct-current (as adjective)	DC
dots per inch	dpi
electromotive force	emf
electron volt	eV
farad	F
feet per minute	ft/min
feet per second	ft/sec
foot	ft
foot-pound	ft-lbf
gallon	gal
gallons per minute	gal/min
gallons per day	gal/D
gigabyte	Gbyte
gigahertz	GHz
gigaPascal	gPa
gigawatt	GW
gram	g
hertz	Hz
horsepower	hp
horsepower-hour	hp-hr
hour	hr
hyperbolic sine, cosine, etc.	sinh, cosh, etc.
inch	in.
inches per second	in./sec
kelvin	K
kilobyte	kbyte
kilogram	kg
kilogram-meter	kg-m
kilohertz	kHz
kilometer	km
kilopond (1000 lbf)	lbf

kilovolt	kV
kilowatt	kW
kilowatt-hour	kW-hr
kips per square inch	ksi
lines per inch	lpi
lines per minute	lpm
lines per second	lps
liter	spell out
megabyte	Mbyte
megahertz	MHz
meter	m
mho per meter	℧/m
microsecond	μsec
mile	spell out
miles per hour	mph
milliamperes	milliamp
milliCurie	mCi
millidarcy, millidarcies	md
milliequivalent	meq
milligram	mg
milliliter	mL
millimeter	mm
millimho	mmho
million cubic feet (million = 10^6)	MMcf
million cubic feet per day	MMcf/D
million electron volts	MeV
million Pascals	MPa
million standard cubic feet per day	MMscf/D
millisecond	msec
millisiemen	mS
millivolt	mV
mils per year	mil/yr
minute	min
mole	mol
nanosecond	nsec
newton	N
ohm	ohm
ohm-centimeter	ohm-cm
ohm-meter	ohm-m
ounce	oz
parts per million	ppm
picofarad	pF
pint	pt
pore volume	PV
porosity unit	p.u.
pound (force)	lbf
pound (mass)	lbm
pound per cubic foot	lbm/ft^3
pound per gallon	lbm/gal
pounds per square inch	psi
pounds per square inch absolute	psia
pounds per square inch gauge	psig
quart	qt
reservoir barrel	res bbl
reservoir barrel per day	RB/D
revolutions per minute	rpm
saturation unit	s.u.
second	sec
self-potential	SP
shots per foot	spf
specific productivity index	SPI
square	sq
square centimeter	cm^2
square foot	ft^2
square inch	$in.^2$
square meter	m^2
square millimeter	mm^2
standard	std
standard cubic feet per day	scf/D
standard cubic foot	scf
stock-tank barrel	STB
stock-tank barrels per day	STB/D
stoke	St
teragram	Tg
thousand cubic feet	Mcf
thousand cubic feet per day	Mcf/D
thousand pounds per square inch	kpsi
thousand standard cubic feet per day	Mscf/D
tonne (metric ton)	t
trillion cubic feet (trillion = 10^{-12})	Tcf
trillion cubic feet per day	Tcf/D
volt	V
volume per volume	vol/vol
watt	W
yard	yd
year	yr

References

1. Overton HL and Lipson LB: "A Correlation of the Electrical Properties of Drilling Fluids with Solids Content," *Transactions,* AIME (1958) **213.**
2. Desai KP and Moore EJ: "Equivalent NaCl Concentrations from Ionic Concentrations," *The Log Analyst* (May–June 1969).
3. Gondouin M, Tixier MP and Simard GL: "An Experimental Study on the Influence of the Chemical Composition of Electrolytes on the SP Curve," *JPT* (February 1957).
4. Segesman FF: "New SP Correction Charts," *Geophysics* (December 1962) **27,** No. 6, PI.
5. Alger RP, Locke S, Nagel WA and Sherman H: "The Dual Spacing Neutron Log–CNL," paper SPE 3565, presented at the 46th SPE Annual Meeting, New Orleans, Louisiana, USA (1971).
6. Segesman FF and Liu OYH: "The Excavation Effect," *Transactions of the SPWLA 12th Annual Logging Symposium* (1971).
7. Burke JA, Campbell RL Jr and Schmidt AW: "The Litho-Porosity Crossplot," *Transactions of the SPWLA 10th Annual Logging Symposium* (1969), paper Y.
8. Clavier C and Rust DH: "MID-PLOT: A New Lithology Technique," *The Log Analyst* (November–December 1976).
9. Tixier MP, Alger RP, Biggs WP and Carpenter BN: "Dual Induction-Laterolog: A New Tool for Resistivity Analysis," paper 713, presented at the 38th SPE Annual Meeting, New Orleans, Louisiana, USA (1963).
10. Wahl JS, Nelligan WB, Frentrop AH, Johnstone CW and Schwartz RJ: "The Thermal Neutron Decay Time Log," *SPEJ* (December 1970).
11. Clavier C, Hoyle WR and Meunier D:" Quantitative Interpretation of Thermal Neutron Decay Time Logs, Part I and II," *JPT* (June 1971).
12. Poupon A, Loy ME and Tixier MP: "A Contribution to Electrical Log Interpretation in Shaly Sands," *JPT* (June 1954).
13. Tixier MP, Alger RP and Tanguy DR: "New Developments in Induction and Sonic Logging," paper 1300G, presented at the 34th SPE Annual Meeting, Dallas, Texas, USA (1959).
14. Rodermund CG, Alger RP and Tittman J: "Logging Empty Holes," *OGJ* (June 1961).
15. Tixier MP: "Evaluation of Permeability from Electric Log Resistivity Gradients," *OGJ* (June 1949).
16. Morris RL and Biggs WP: "Using Log-Derived Values of Water Saturation and Porosity," *Transactions of the SPWLA 8th Annual Logging Symposium* (1967).
17. Timur A: "An Investigation of Permeability, Porosity, and Residual Water Saturation Relationships for Sandstone Reservoirs," *The Log Analyst* (July–August 1968).
18. Wyllie MRJ, Gregory AR and Gardner GHF: "Elastic Wave Velocities in Heterogeneous and Porous Media," *Geophysics* (January 1956) **21,** No. 1.
19. Tixier MP, Alger RP and Doh CA: "Sonic Logging," *JPT* (May 1959) **11,** No. 5.
20. Raymer LL, Hunt ER and Gardner JS: "An Improved Sonic Transit Time-to-Porosity Transform," *Transactions of the SPWLA 21st Annual Logging Symposium* (1980).
21. Coates GR and Dumanoir JR: "A New Approach to Improved Log-Derived Permeability," *The Log Analyst* (January–February 1974).
22. Raymer LL: "Elevation and Hydrocarbon Density Correction for Log-Derived Permeability Relationships," *The Log Analyst* (May–June 1981).
23. Westaway P, Hertzog R and Plasic RE: "The Gamma Spectrometer Tool, Inelastic and Capture Gamma Ray Spectroscopy for Reservoir Analysis," paper SPE 9461, presented at the 55th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA (1980).
24. Quirein JA, Gardner JS and Watson JT: "Combined Natural Gamma Ray Spectral/Litho-Density Measurements Applied to Complex Lithologies," paper SPE 11143, presented at the 57th SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA (1982).
25. Harton RP, Hazen GA, Rau RN and Best DL: "Electromagnetic Propagation Logging: Advances in Technique and Interpretation," paper SPE 9267, presented at the 55th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA (1980).
26. Serra O, Baldwin JL and Quirein JA: "Theory and Practical Application of Natural Gamma Ray Spectrometry," *Transactions of the SPWLA 21st Annual Logging Symposium* (1980).
27. Gardner JS and Dumanoir JL: "Litho-Density Log Interpretation," *Transactions of the SPWLA 21st Annual Logging Symposium* (1980).
28. Edmondson H and Raymer LL: "Radioactivity Logging Parameters for Common Minerals," *Transactions of the SPWLA 20th Annual Logging Symposium* (1979).
29. Barber TD: "Real-Time Environmental Corrections for the Phasor Dual Induction Tool," *Transactions of the SPWLA 26th Annual Logging Symposium* (1985).
30. Roscoe BA and Grau J: "Response of the Carbon-Oxygen Measurement for an Inelastic Gamma Ray Spectroscopy Tool," paper SPE 14460, presented at the 60th SPE Annual Technical Conference and Exhibition, Las Vegas, Nevada, USA (1985).

31. Freedman R and Grove G: "Interpretation of EPT-G Logs in the Presence of Mudcakes," paper presented at the 63rd SPE Annual Technical Conference and Exhibition, Houston, Texas, USA (1988).
32. Gilchrist WA Jr, Galford JE, Flaum C, Soran PD and Gardner JS: "Improved Environmental Corrections for Compensated Neutron Logs," paper SPE 15540, presented at the 61st SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA (1986).
33. Tabanou JR, Glowinski R and Rouault GF: "SP Deconvolution and Quantitative Interpretation in Shaly Sands," *Transactions of the SPWLA 28th Annual Logging Symposium* (1987).
34. Kienitz C, Flaum C, Olesen J-R and Barber T: "Accurate Logging in Large Boreholes," *Transactions of the SPWLA 27th Annual Logging Symposium* (1986).
35. Galford JE, Flaum C, Gilchrist WA Jr and Duckett SW: "Enhanced Resolution Processing of Compensated Neutron Logs, paper SPE 15541, presented at the 61st SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA (1986).
36. Lowe TA and Dunlap HF: "Estimation of Mud Filtrate Resistivity in Fresh Water Drilling Muds," *The Log Analyst* (March–April 1986).
37. Clark B, Luling MG, Jundt J, Ross M and Best D: "A Dual Depth Resistivity for FEWD," *Transactions of the SPWLA 29th Annual Logging Symposium* (1988).
38. Ellis DV, Flaum C, Galford JE and Scott HD: "The Effect of Formation Absorption on the Thermal Neutron Porosity Measurement," paper presented at the 62nd SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA (1987).
39. Watfa M and Nurmi R: "Calculation of Saturation, Secondary Porosity and Producibility in Complex Middle East Carbonate Reservoirs," *Transactions of the SPWLA 28th Annual Logging Symposium* (1987).
40. Brie A, Johnson DL and Nurmi RD: "Effect of Spherical Pores on Sonic and Resistivity Measurements," *Transactions of the SPWLA 26th Annual Logging Symposium* (1985).
41. Serra O: *Element Mineral Rock Catalog,* Schlumberger (1990).