# NEUTRON ABSORPTION EFFECTS ON DUAL-SPACED THERMAL NEUTRON LOGGING TOOLS

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## ABSTRACT

The ratio response of a dual-spaced thermal neutron logging tool is primarily controlled by neutron elastic scattering with formation and borehole nuclei during the slowing down process and secondarily by neutron absorption during diffusion at thermal energy. Neutron absorption cross sections at thermal energy (sigma) are functions not only of pure matrix materials and fluids present, but also of strong absorbers such as chlorine, boron, and rare earths that may be contained in both. Even trace amounts of these materials can have a significant effect on sigma matrix and sigma fluid, and thereby on tool response.

Although the dual-spaced ratio method is much less sensitive to sigma matrix and sigma fluid effects than older single detector methods, accurate porosity determination from ratio still requires correction for these effects both during ratio-porosity transform determination and during logging operations. This is true for all dual-spaced thermal neutron logging tools, but the amount of correction depends on source-to-detector spacings and the selection of shielding materials.

Dual-spaced thermal neutron porosity response is normally based on ratio and porosity measurements in limestone test formations. This paper details how this process can be made more accurate by also including matrix density and sigma data. A tool model uses basic nuclear cross sections and calculations of effective neutron migration lengths in order to correct measured ratios for observed matrix density and sigma values prior to obtaining the ratio-porosity transform. This results in significant improvement in porosity measurement accuracy at standard limestone conditions and in formations with known values of matrix density and sigma matrix.

Porosity response curves for field limestones, sandstones, and dolomites are presented for typical values of sigma matrix and sigma fluid. Corrections are also presented for logging in formations with known sigma matrix and sigma fluid. New test formation and logging data using these curves are presented. Corrections for sigma matrix are particularly significant in dolomites and limestones; however, even in sandstones, such corrections can be important. Neutron absorption effects are important for porosities above about 5%. Sigma matrix corrections are most important in low salinity environments and in hydrocarbon bearing formations.

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## INTRODUCTION

Dual-spaced neutron logs are a standard means for determining formation porosity.[1-3] Figure 1 shows the general features of a dual-spaced neutron logging tool that comprises a fast neutron source, shielding materials, and two thermal neutron detectors. Fast neutrons spread out and slow down by elastic scattering, approach thermal equilibrium, diffuse at thermal energy, and are absorbed by nuclei in the borehole/formation environment. During the thermal diffusion process, some neutrons are detected by either the near or the far detector and count rates are developed that become the primary logging input variables. A standard means for processing is to form the ratio of near count rate to far count rate and then to compute formation porosity from ratio measurements made in laboratory test formations and real earth formations. The data analyzed in this paper were obtained with DSN*-II, the dual-spaced thermal neutron tool of the Precision Logging System.*

Initial research and development focused on signal-to-noise enhancement through adjustment of near and far detector spacings and selection of shielding materials.[4] Considerable improvements in statistical precision, relative to the previous generation DSN* tool, have been reported for logging in very high porosity formations such as the diatomites found in California. Although DSN-II ratio response is primarily controlled by neutron elastic scattering, corrections must be applied for neutron absorption during the thermal diffusion process. Absorption properties of both the matrix and the fluids that comprise a formation must be considered. This paper details how neutron absorption can be corrected for during primary calibration of the standard tool in limestone formations saturated with freshwater, and during logging in both test pit and downhole formations with different lithologies and different fluids, both of which may contain materials with absorption properties different from primary calibration. These absorption corrections improve DSN-II porosity measurement accuracy.

Several difficulties are encountered in making corrections for neutron absorption. As noted in Figure 1, the industry standard specifies limestone and freshwater, but no mention is made of matrix absorption properties. A related problem is that matrix absorption data for the API Neutron Test Pit Facility at the University of Houston are unavailable. We have used the convention that the primary ratio-porosity transform describes limestone at a density of 2.71 g/cc and matrix absorption cross section of 7.1 capture units (cu). Although sigma matrix values as high as 33 cu have been reported,[5] the range of our data is more limited, thereby making direct experimental observation of matrix absorption effects very difficult. An excellent review article on measurement of neutron absorption properties of rocks and fluids is available.[5] Practical and accurate measurements of matrix neutron absorption cross sections remain a challenge.[5-7]

This paper examines the Direct Ratio Computation model for DSN-II and shows how neutron absorption can be successfully handled. Model performance is examined in 23 test formations with porosities that range from 1.4 to 41% in limestones, sandstones, and dolomites. Fluid sigma ranges from 22 to 112 cu and sigma matrix ranges from 7 to 12 cu. Compared with previous model verification efforts,[4] these 23 test formations include a significantly larger number with total absorption cross sections in the range 15 to 35 cu. This has resulted in use of effective neutron migration length (M*) in place of total neutron migration length (M) to model DSN-II response.

The model is then used to obtain correction curves in limestones, sandstones, and dolomites for sigma matrix values up to 30 cu, simultaneously with water salinities that range from 0 to 250,000 ppm NaCl. Finally, correction curves are presented for borated waters in which sigma fluid ranges from 22.2 to 120 cu, at a water density of 1.0 g/cc.

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## GENERAL FEATURES OF THE DIRECT RATIO COMPUTATION MODEL

An outstanding problem of dual-spaced neutron logging is obtaining tool response to formations with an extremely wide range of matrix and fluid components with only a limited number of test formations. (However, test formations do provide a mechanism for accurately handling changes in many borehole environmental conditions, such as borehole diameter, standoff, and fluid salinity.) The Direct Ratio Computation model (DRC) has been developed to facilitate primary calibration of a standard tool in limestones saturated with freshwater and to predict response in all other formations.[4] Accurate description of absorption effects is one example of using this model. It is equivalent to a five-group diffusion theory and includes special means for handling hydrogen. Actual DSN-II source-to-detector spacings are included, as well as their variation with formation properties. This model is driven by the chemical formulas, densities, and volume fractions of the elements contained in earth formations. Tables of neutron cross sections as functions of neutron energy for all elements found in earth formations are included in the model.

The DRC model is actually composed of two distinct levels of computation. LCALC supports calculation of characteristic lengths which describe the spatial distribution of neutrons as they slow down, thermalize, diffuse, and are absorbed in an infinite homogenous medium. DRC model computations use these lengths, together with selected limestone test data, to predict DSN-II ratios and porosities in all formations at standard borehole conditions (8 inch diameter, freshwater filled, and logging tool decentralized.) A key feature is that the selected data consist not only of measured ratios and porosities, but also measured values of matrix density and sigma matrix. The three point normalization procedure for the DRC model is discussed below. However, the exact details by which LCALC lengths and the normalizaton data are combined, as well as the actual ratio and porosity computations performed, are not given. Note that LCALC computations of characteristic lengths precede, and are independent of, DRC model predictions of DSN-II ratios and porosities.

## CORRECTED RATIOS AND MODEL PREDICTIONS

In this paper, all count rate ratios have been corrected to standard borehole conditions, including corrections for any borehole liner. Correction of DSN-II raw ratios has been more accurately performed in comparison with previous efforts.[4] Figure 2 shows a plot of corrected ratio versus true formation porosity. Additional measurements are contained in Table 1. In all, 23 formations (including 100% freshwater) were analyzed, with 10 formations having elevated total thermal neutron absorption cross sections. Throughout the figures of this paper, open plot symbols indicate formations with low sigma fluid, half-filled symbols indicate formations with intermediate sigma fluid (55-80 cu), and filled symbols show formations with high sigma fluid. Examination of this data shows absorption corrections in the range 1-2 pu. Modeling accounts for variations in matrix density, matrix and fluid sigma, and porosity to accurately compute ratio and porosity for all the formations shown in Table 1. This also includes correcting the dolomites for illite and limestone, and the sandstones for kaolinite. An accurate prediction is also provided for the 23% porosity sandpack test formation saturated with freshwater and air, without using excavation effect mechanisms. Modeling thus provides an integrated, coherent description of all the test data. Sigma matrix values in Table 1 were obtained by neutron absorption measurements made in a nuclear reactor on core samples taken from the test formations. Equivalent amounts of boron are used to achieve desired values of sigma matrix.

## CHARACTERISTIC LENGTHS COMPARED WITH CORRECTED RATIOS

The total neutron migration length (M) is related to the slowing down length ($L_s$), thermalizing length ($L_e$), and thermal diffusion length (L) by

$$M^2 = L_s^2 + L_e^2 + L^2. \tag{1}$$

L is calculated from

$$L = \sqrt{\frac{D}{\Sigma_a}}, \tag{2}$$

where $\Sigma_a$ is the total thermal neutron absorption cross section and D is the thermal neutron diffusion coefficient given by

$$D = \frac{1}{3[\Sigma_a + \Sigma_s(1 - \bar{\mu})]}, \tag{3}$$

$\Sigma_s$ is the total thermal neutron scattering cross section, and $\bar{\mu}$ is the cosine of the mean scattering angle at thermal energy. Calculations of M, $L_s$, $L_e$, D, and L are in excellent agreement with the literature.[4,5,8-10]

Figure 3, in which corrected ratio is plotted versus neutron slowing down length ($L_s$), shows that DSN-II tool response is not completely controlled by $L_s$. That is, neutron absorption effects at thermal energies cannot be neglected because DSN-II detects thermal neutrons. Notice also that correlations between freshwater limestones, sandstones, and dolomites are only fair. Practical DSN-II spacings, originally chosen to optimize high porosity signal-to-noise ratio, are not long enough to realize or verify the original concept of Allen et al[1] to place both near and far detectors sufficiently far from the source to make ratio depend only on $L_s$.

Figure 4 shows corrected ratio versus total neutron migration length (M). It is evident that DSN-II tool response is also not exactly controlled by M. This agrees with previous observations by Scott, et al.[10] DSN-II model predictions based on M would show much larger salinity corrections than those actually observed. Also, no retrograde salinity effect (decrease in correction beyond about 100,000 ppm NaCl saltwater) is possible using M in the DRC model. Notice that poor correlation is mainly caused by formations with intermediate and higher neutron absorption. However, even the lower absorption freshwater limestone and sandstone formations near an M value of 14 cm do not correlate very well.

## EFFECTIVE THERMAL NEUTRON DIFFUSION AND MIGRATION LENGTHS

A careful analysis of all data from the 23 formations listed in Table 1 reveals that the judicious choices

$$L^* = 0.66L \tag{4}$$

and

$$M^{*2} = L_s^2 + L_e^2 + L^{*2} \tag{5}$$

lead to a very strong correlation between M* and DSN-II ratio. This is clearly indicated in Figure 5. This strong correlation is independent of fluid salinity, boron content, and lithology and suggests that M* is the formation migration length of physical interest in modeling tools which detect thermal neutrons. L* and M* are called the *effective thermal neutron diffusion* and *migration lengths*, respectively. Notice that use of M* in place of M is not merely a compressive data rescaling. M* lies between $L_s$ and M and indicates that the tool detects neutrons subsequent to slowing down, but before their absorption in the formation. In any event, M* best describes DSN-II ratio response for all test formations studied.

Figure 6 shows DRC model porosity predictions when $M^*$ is used in calculations of DSN-II ratio. Although correlation is not perfect, given the experimental errors in obtaining both true porosity and predicted porosity (via DSN-II corrected ratio), Figure 6 shows that modeling can quite adequately predict DSN-II ratio response. We are studying methods for more accurately obtaining the numerical factor of 0.66 that was used in equation (4). This may further improve model accuracy. We are also trying to attain a better understanding of the physics involved in this relationship, including effects of the thermal motion of the formation nuclei on thermal neutron diffusion.

## DRC MODEL NORMALIZATION

Previous modeling calculations have used total migration lengths supplied by LCALC, together with limited test formation data, to compute DSN-II ratios and porosities.[4] The above analysis of a much more extensive data set shows that DSN-II response is best characterized by the effective migration length $M^*$.

With reference to Figure 7 and Table 1, the model accepts values of $M^*$ and corrected ratios at limestone porosities of 13.0, 26.2, and 100%, together with measured matrix densities and matrix absorption cross sections, and computes three DSN-II tool constants for relative detector efficiencies, near detector streaming rate, and far detector streaming rate. These constants then permit the model to make predictions of DSN-II corrected ratios for all other combinations of rock matrix and fluid types. These same constants were used to obtain all the porosity values shown in Figures 6-12. Corrections are automatically made for variation in effective source-to-detector spacings with formation properties.

The standard DSN-II ratio-porosity transform curve shown in Figure 7 is the prediction for limestone and freshwater at a matrix density of 2.71 g/cc and matrix absorption cross section of 7.1 cu. Note that it is not necessary for this curve to pass through the measured ratio/porosity points, since it is generally not possible to realize standard limestones in actual test formations. However, in this case, our measured densities and absorption cross sections are very near standard conditions. Figure 8 shows predictions for sandstone and dolomite, at respective matrix densities of 2.65 and 2.87 g/cc; both have assumed matrix absorption cross sections of 10 cu. These results are for specific matrix density and sigma matrix values. They are not based on analyses of field data that often have poorly established matrix density and sigma values. Figures 9-12 show correction curves for fluid salinity and sigma matrix variations differing from these standard curves.

## SIMULTANEOUS FLUID SALINITY AND SIGMA MATRIX CORRECTIONS

The DRC model was used to obtain simultaneous fluid salinity and sigma matrix corrections for standard limestone, sandstone, and dolomite formations. An equivalent amount of boron was added to each matrix to achieve desired values for sigma matrix. Results are shown in Figures 9-11. Each correction chart must be entered with apparent (log) porosity at its proper lithology. As an example of using these charts, suppose that the DSN-II apparent limestone porosity of a formation is 32.8%. Suppose it is also known from analyses of water samples and a pulsed neutron log that this formation has a water salinity of 100 Kppm NaCl saltwater and a sigma matrix of 15 cu. Then, use of the middle grid in Figure 9 shows that the true limestone porosity of this formation, corrected for both salinity and sigma matrix, is 30%.

Retrograde salinity behavior is predicted in Figures 9-11 due to competition between hydrogen content reduction and strong neutron absorption by chlorine as salinity increases. These corrections are always negative in limestone because sigma matrix for limestone was chosen as 7.1 cu, the minimum value for limestone. Corrections in sandstone and dolomite can be positive or negative because their standard responses were chosen with sigma matrix set to 10 cu. (Pure sandstone and dolomite can have values as low as 4.6 and 4.7 cu, respectively.) As expected, sigma matrix effects are strongest in low salinity formations and are also expected to be strong in hydrocarbon bearing formations. Note that the maximum amount of correction always increases as porosity increases and that, as sigma matrix increases, this maximum shifts to lower salinities.

Some insight into predicted salinity and sigma matrix corrections as functions of lithology and porosity can be provided by study of the $L_s$ and $L^*$ components of $M^*$. $L_s$ is smallest in dolomite and largest in sandstone. At a porosity of 30%, $L_s$ for dolomite is within 27% of its value in freshwater whereas for limestone and sandstone, these percentages are 31% and 45%. Thus, small decreases in $L^*$ caused by neutron absorption increases are accentuated in dolomites. We have observed (and the model predicts) negligible corrections for sigma matrix, sigma fluid, and fluid salinity at porosities below about 5%. Slowing down length variations with porosity dominate the behavior of $L^*$ at low porosities. $L^*/L_s$ ratios show a steady increase from 0 to 10% porosity, so that neutron absorption effects become stronger beyond porosities of about 5%. (Note that corrections for liner presence and borehole diameter are difficult to perform accurately in the very low porosity region and make direct experimental observation of these absorption effects difficult.)

These simultaneous salinity-sigma matrix corrections are somewhat larger than those in current use for the older DSN tool, which has different source-to-detector spacings and shielding materials than DSN-II. However, exact comparisons are difficult because previous DSN salinity corrections did not include a complete accounting of density and sigma effects.

The corrections for sandstone shown in Figure 10 can be used to estimate the "sigma effect" in shales.[3] Examination of the grid for 20 cu sandstone shows 1-2 pu of correction for a 10 cu elevation in sigma matrix at porosities above 35%. This is in good agreement with earlier work by Arnold et al.[3] Thus sigma matrix and salinity effects are small. The main reason why DSN-II reads high porosities in shales is likely due to bound water. This has been confirmed by DRC model calculations in chlorite, kaolinite, and montmorillonite.

## CORRECTIONS FOR BORATED WATER

Finally, the DRC model was used to predict corrections for borated water in standard limestone, sandstone, and dolomite. This situation occurs in California and other parts of the world; it is also common when boron is used in log-inject-log projects. Sigma fluid cannot be obtained by specific gravity measurements alone, but must be augmented by measurements involving neutron absorption directly, such as by using a sigma chamber.[11] Equivalent amounts of boron were added to freshwater in the model in order to achieve desired sigma fluid values. Results are shown in Figure 12. Again, each chart must be entered with apparent porosities and the correct lithology. No retrograde behavior occurs because, unlike saltwater, there is negligible hydrogen reduction with increasing fluid absorption cross section. Corrections are again larger for dolomite and smaller for sandstone, as discussed above.

## CONCLUSIONS

DSN-II data from 23 test formations, including 10 with intermediate to high neutron absorption cross sections have been carefully analyzed. DSN-II ratio response can best be described in terms of the effective thermal neutron diffusion length (L*) and effective migration length (M*) given by equations (4) and (5). Use of M* in the DRC model produces an accurate description of DSN-II ratio response and a more accurate accounting of neutron absorption effects in both matrix and fluid components. A more accurate ratio-porosity transform in limestone is achieved using modeling. A key feature of this model is its inclusion of measurements of both matrix densities and matrix absorption cross sections, in addition to ratios and porosities, to determine the basic ratio-porosity transform. This same model was used to generate curves that simultaneously correct for sigma matrix and sigma fluid in standard limestone, sandstone, and dolomite. With spacings that optimize statistical signal-to-noise ratio, these corrections are slightly larger than those in current use for the older DSN tool. Neutron absorption effects are important for porosities above about 5%. Sigma matrix effects are more significant in low salinity environments and in hydrocarbon bearing formations. Correction curves for borated waters are also presented for the same standard lithologies.

## ACKNOWLEDGMENTS

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# REFERENCES

1. Allen, L.S., Tittle, C.W., Mills, W.R., and Caldwell, R.L., "Dual-Spaced Neutron Logging for Porosity," *Geophysics*, Vol. 32, No.1, pp. 60-68, 1967.
2. Alger, R.P., Locke, S., Nagel, W.A., and Sherman, H., "The Dual-Spacing Neutron Log-CNL," Paper No. SPE 3565, 46th Annual Meeting of the Society of Petroleum Engineers, October, 1971.
3. Arnold, D.M., and Smith, H.D., Jr., "Experimental Determination of Environmental Corrections for a Dual-Spaced Neutron Porosity Log," SPWLA Twenty-Second Annual Logging Symposium, June, 1981.
4. Smith, M.P., "Calibration, Checking, and Physical Corrections for a New Dual-Spaced Neutron Porosity Tool," SPWLA Twenty-Seventh Annual Logging Symposium, June, 1986.
5. Czubek, J.A., "Measurement of Macroscopic Neutron Absorption Cross Sections and Other Macroparameters of Rocks," Institute of Nuclear Physics, Report No. 1281/AP, Krakow, 1985.
6. Tittle, C.W., and Crawford, G.W., "Measuring the Thermal Neutron Absorption Cross Section of Rocks," The Log Analyst, Vol. XXIV, No. 3, pp. 12-15, May-June, 1983.
7. Czubek,J.A., Drozdowicz, K., Krynica-Drozdowicz, E., Igielski, A., and Woznica, U., "Thermal Neutron Absorption Cross-Section Measurements on Rock Samples and Brines in the Institute of Nuclear Physics," Institute of Nuclear Physics, Report No. 1223/AP, Krakow, 1983.
8. Valente, F.A., and Sullivan, R.E., *Nuclear Science and Engineering*, Vol. 6, p. 162, 1959.
9. Kreft, A., "Calculation of the Neutron Slowing Down Length in Rocks and Soils," *Nukleonika*, Vol. XIX, pp. 145-156, 1974.
10. Scott, H.D., Flaum, C., and Sherman, H., "Dual Porosity CNL* Count Rate Processing," SPE 11146, September, 1982.
11. Schultz, W.E., Gold, R., and Zdunkawicz, J.A., "A Sigma Water Measurement System with Correction for Trace Elements," SPWLA Twenty-Sixth Annual Logging Symposium, June, 1985.

## TABLE 1
## DSN-II TEST FORMATION DATA AND DRC MODEL COMPUTATIONS

| Formation Name | Plot Symbol | Matrix Density (g/cc) | Matrix Sigma (cu) | Fluid Type | Fluid Sigma (cu) | Corrected DSN-II Ratio | Thermal Diffusion Length (cm) | Total Migration Length (cm) | Effective Migration Length (cm) | True Porosity | Predicted Porosity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Limestone | □ | 2.68 | 9.6 | F | 22.2 | 1.740 | 9.44 | 21.87 | 20.69 | 0.018 | 0.024 |
| Limestone | □ | 2.69 | (8) | F | 22.2 | 1.906 | 10.06 | 21.20 | 19.80 | 0.020 | 0.031 |
| Limestone | ■ | 2.74 | 8.3 | S | 112.2 | 1.738 | 9.04 | 21.79 | 20.70 | 0.018 | 0.023 |
| Limestone | ⬓ | 2.74 | 8.4 | B | 60.2 | 1.656 | 9.73 | 22.43 | 21.21 | 0.014 | 0.018 |
| Limestone | □ | 2.70 | 7.7 | F | 22.2 | 4.035 | 8.03 | 15.64 | 14.43 | 0.130 | 0.130* |
| Limestone | □ | 2.69 | (8) | F | 22.2 | 5.466 | 6.99 | 13.90 | 12.87 | 0.189 | 0.192 |
| Limestone | ■ | 2.73 | 7.3 | S | 110 | 5.800 | 4.39 | 13.02 | 12.59 | 0.186 | 0.195 |
| Limestone | ⬓ | 2.73 | 7.8 | B | 58 | 5.650 | 5.62 | 13.40 | 12.71 | 0.176 | 0.180 |
| Limestone | □ | 2.69 | 7.7 | F | 22.2 | 6.942 | 6.26 | 12.68 | 11.77 | 0.262 | 0.262* |
| Limestone | □ | 2.71 | (8) | F | 22.2 | 6.645 | 6.38 | 12.90 | 11.98 | 0.255 | 0.244 |
| Limestone | ■ | 2.73 | 7.5 | S | 108.0 | 7.822 | 3.49 | 11.56 | 11.25 | 0.283 | 0.282 |
| Limestone | ⬓ | 2.73 | 7.6 | B | 55.5 | 7.673 | 4.67 | 11.87 | 11.34 | 0.283 | 0.263 |
| Sandstone | ○ | 2.66 | (10) | F | 22.2 | 2.232 | 8.72 | 19.54 | 18.41 | 0.061 | 0.073 |
| Dolomite | △ | 2.79 | 9.6 | F | 22.2 | 5.050 | 7.06 | 14.28 | 13.26 | 0.130 | 0.137 |
| Dolomite | ▲ | 2.79 | 9.6 | S | 78 | 5.225 | 5.47 | 13.72 | 13.09 | 0.130 | 0.137 |
| Sandstone | ○ | 2.66 | 10.3 | F | 22.2 | 5.423 | 6.27 | 13.74 | 12.91 | 0.202 | 0.206 |
| Sandstone | ◒ | 2.66 | 10.3 | S | 79.4 | 5.678 | 4.49 | 13.13 | 12.69 | 0.196 | 0.210 |
| Sand Pack | ○ | 2.64 | 11.9 | F | 22.2 | 8.734 | 4.73 | 11.35 | 10.78 | 0.41 | 0.405 |
| Sand Pack | ✡ | 2.64 | 8.1 | OIL | 22.8 | 8.410 | 5.19 | 11.62 | 10.94 | 0.366 | 0.356 |
| Dual Sand Pack | ◇ | 2.64 | 8.8 | F/AIR | 22.2 | 3.566 | 7.65 | 16.19 | 15.14 | 0.23 | 0.23 |
| Sand Pack | ◒ | 2.64 | 8.5 | S | 79.4 | 8.344 | 3.30 | 11.25 | 10.98 | 0.38 | 0.376 |
| Sand Pack | ◒ | 2.64 | 8.1 | S | 79.4 | 8.223 | 3.35 | 11.32 | 11.04 | 0.354 | 0.370 |
| Fresh Water | • | — | — | F | 22.2 | 15.824 | 2.84 | 8.29 | 8.01 | 1.00 | 1.000* |

F = Freshwater S = Saltwater B = Borated Water * = DRC Model Normalization Point

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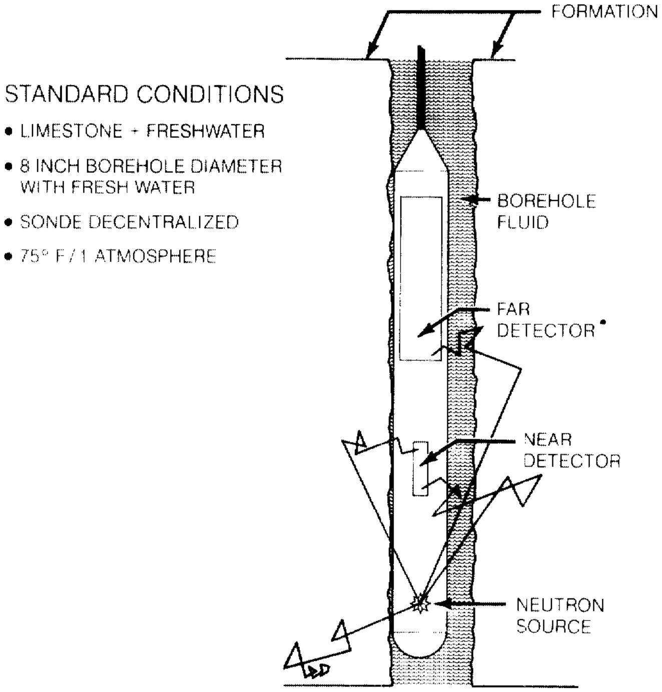

FIGURE 1. Schematic of dual-spaced neutron tool. Limestone at standard conditions has density 2.71 g/cc and matrix absorption cross section 7.1 cu.

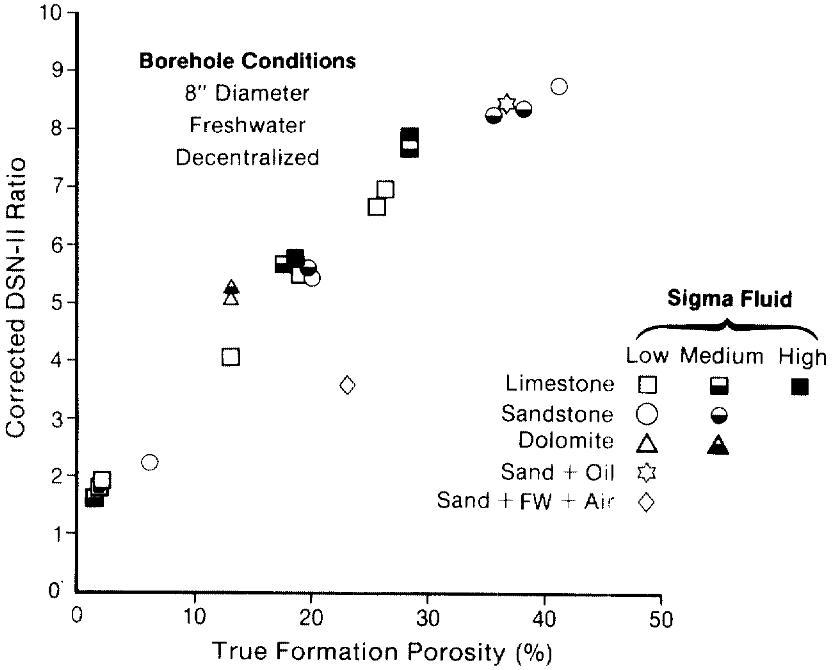

FIGURE 2. DSN-II ratios corrected to standard borehole conditions.

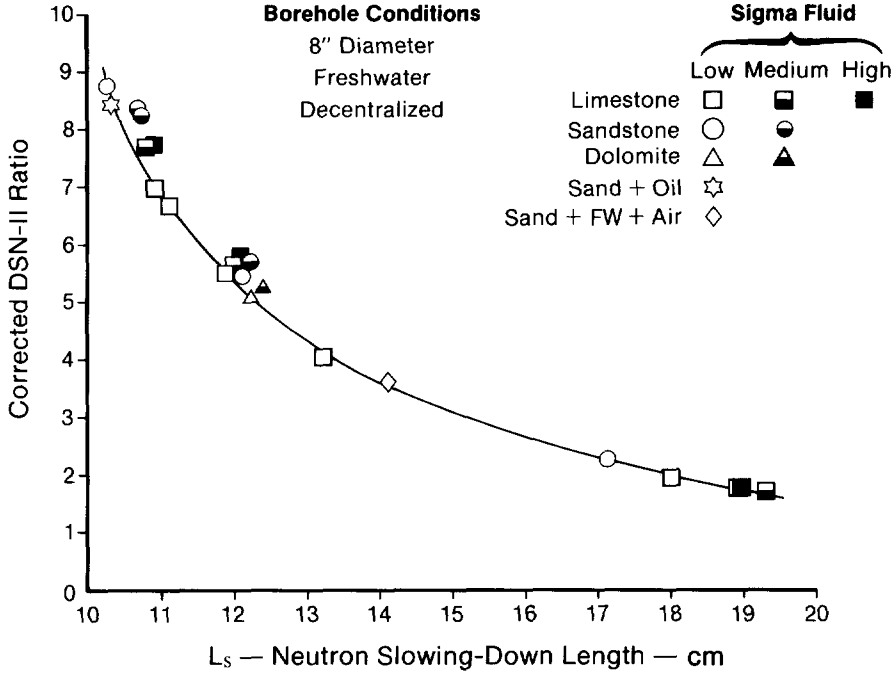

FIGURE 3. Correlation between DSN-II ratio and neutron slowing-down length.

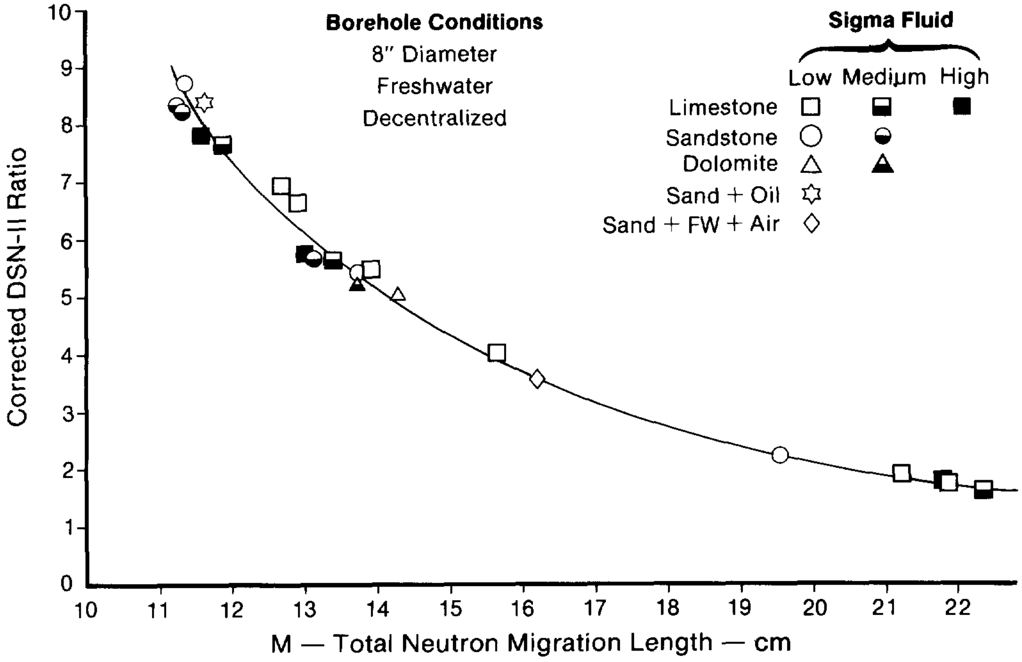

FIGURE 4. Correlation between DSN-II ratio and total neutron migration length.

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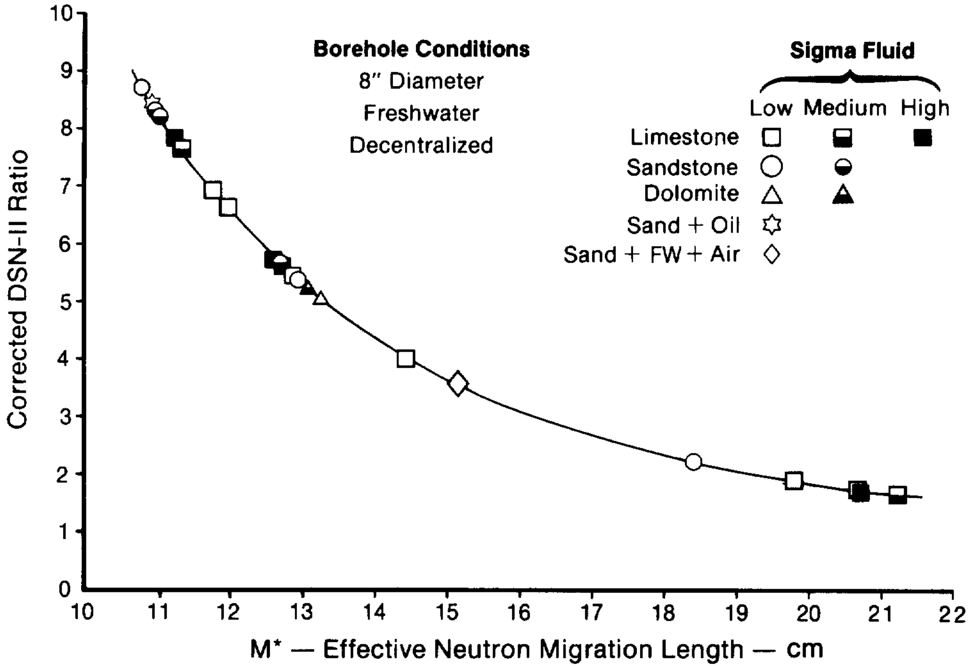


FIGURE 5. Correlation between DSN-II ratio and effective neutron migration length.

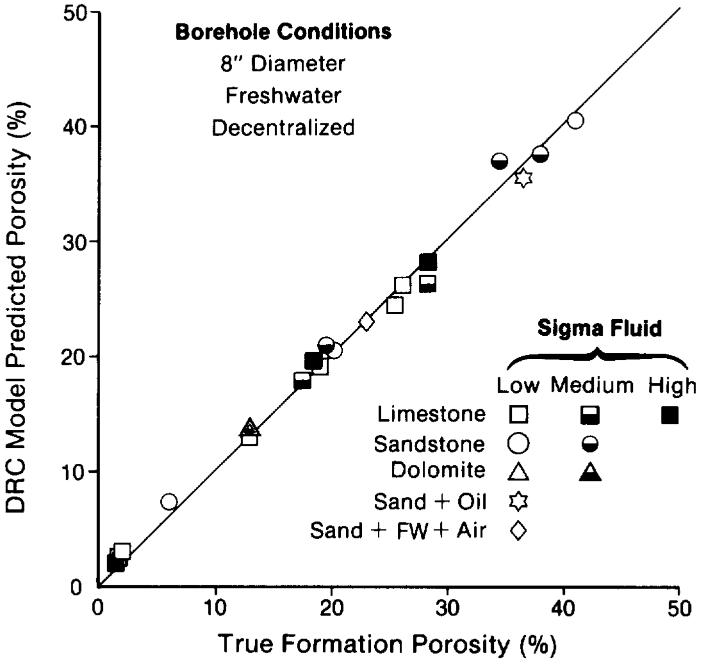


FIGURE 6. Correlation between DRC model predicted porosity and true formation porosity.

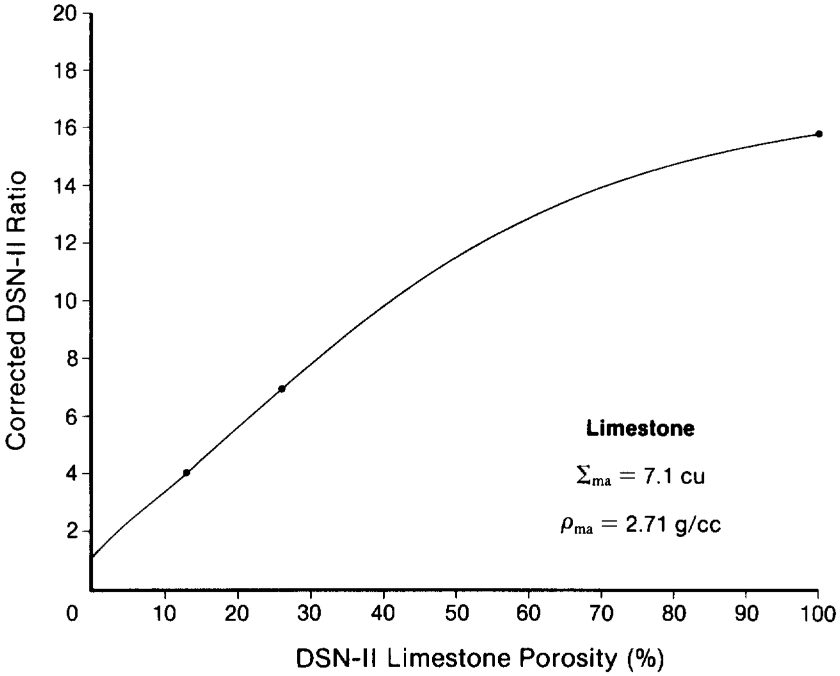
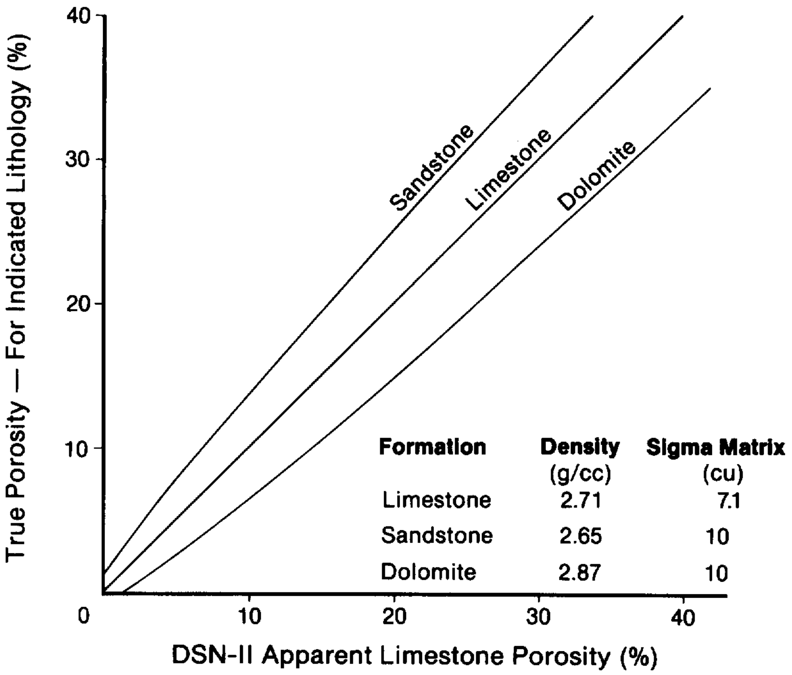


FIGURE 7. Determination of ratio-porosity transform in limestone, using both test data and the DRC model.



| Formation | Density (g/cc) | Sigma Matrix (cu) |
|---|---|---|
| Limestone | 2.71 | 7.1 |
| Sandstone | 2.65 | 10 |
| Dolomite | 2.87 | 10 |

FIGURE 8. DRC model predictions for standard lithologies.

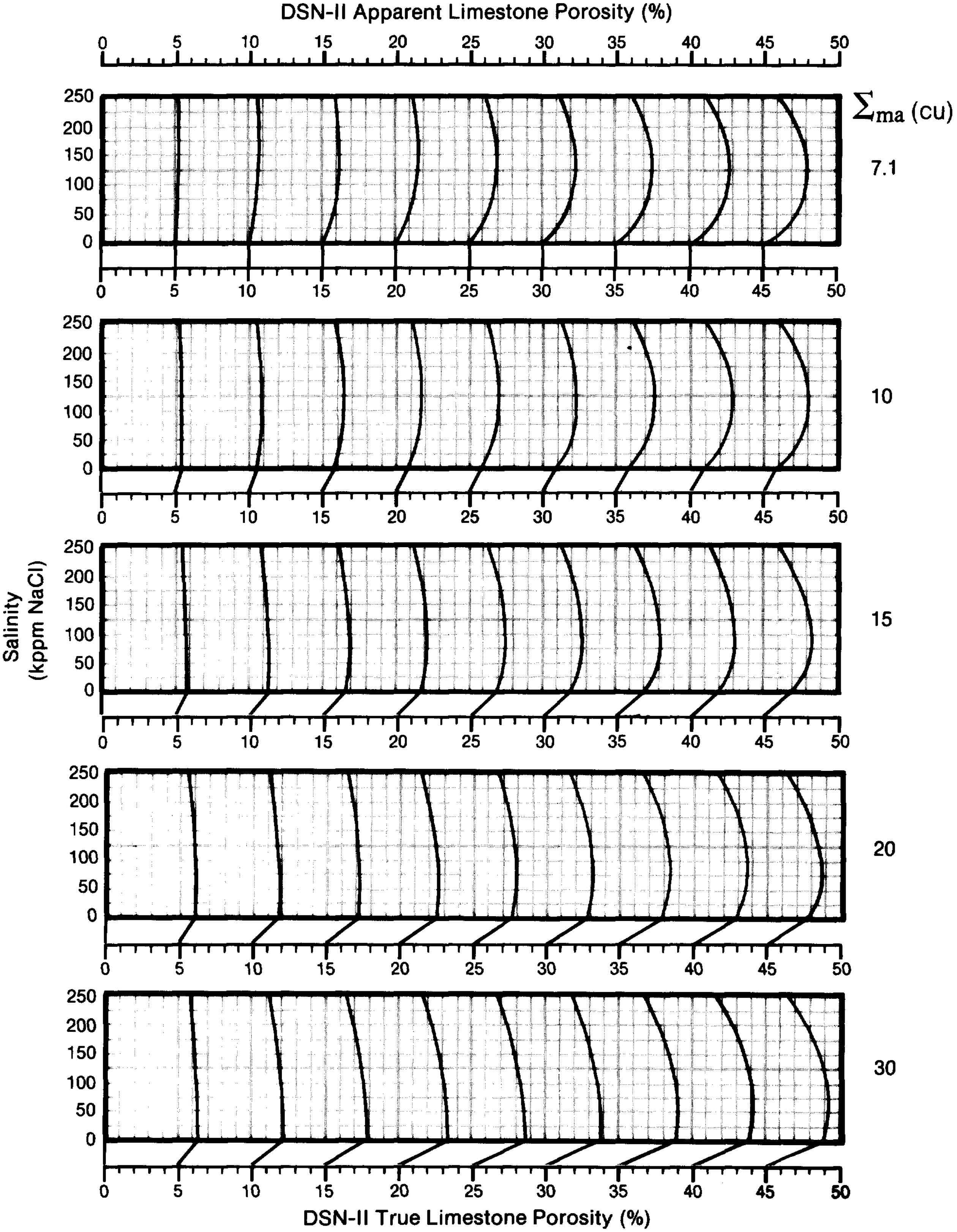


FIGURE 9. Simultaneous salinity/sigma matrix corrections for DSN-II in limestone. Sigma matrix is 7.1 cu for standard limestone.

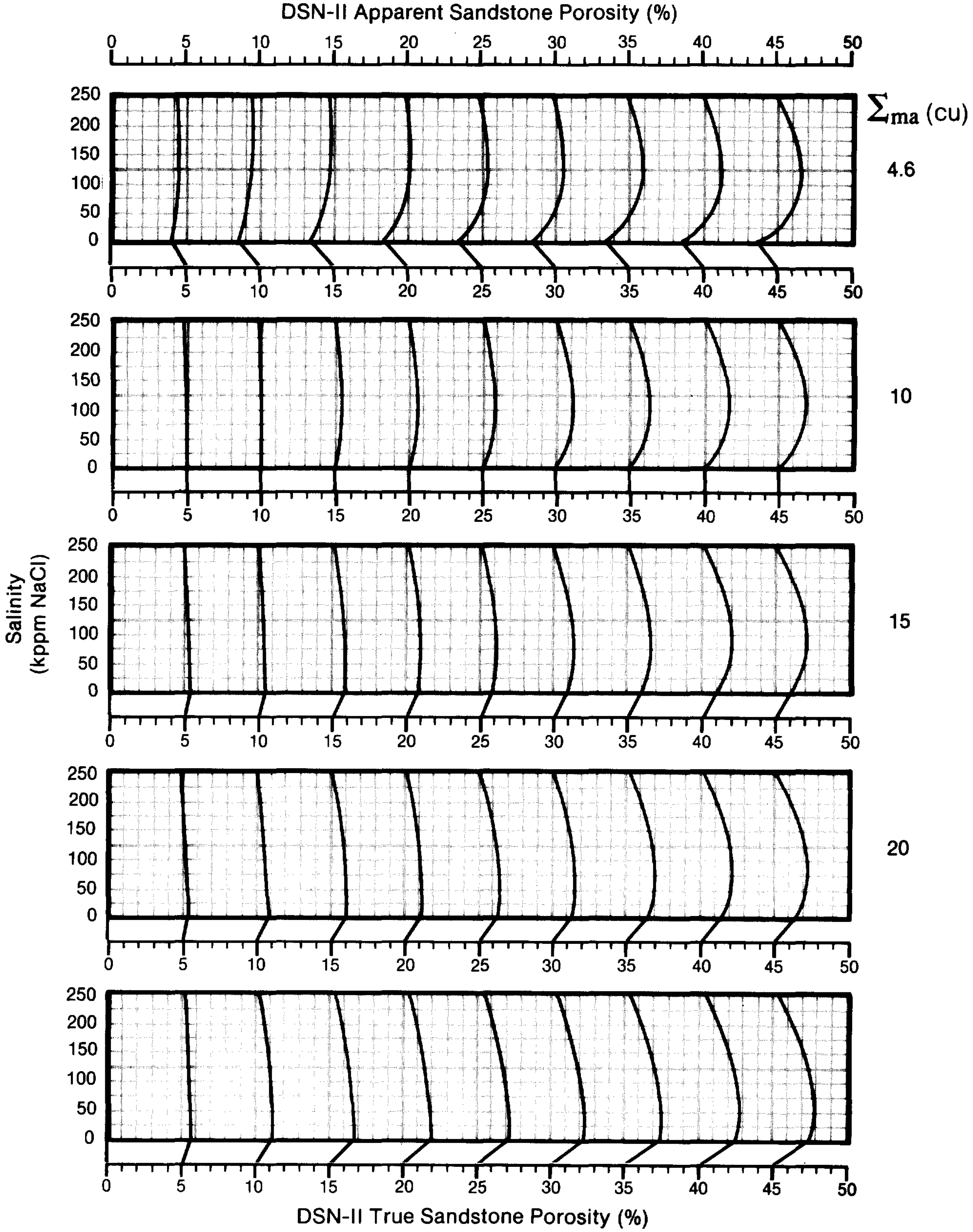


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FIGURE 10. Simultaneous salinity/sigma matrix corrections for DSN-II in sandstone. Sigma matrix is 10 cu for standard sandstone.

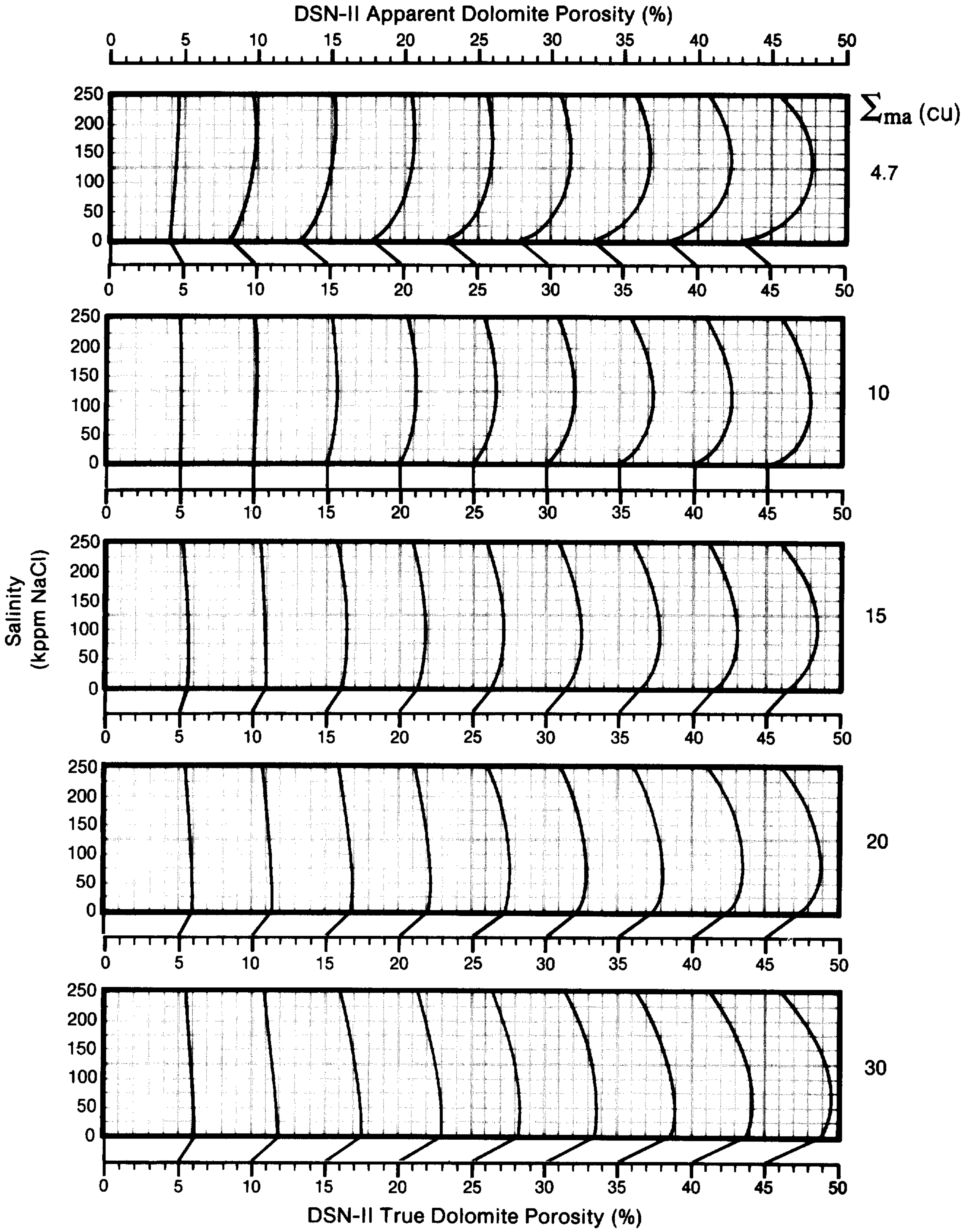

FIGURE 11. Simultaneous salinity/sigma matrix corrections for DSN-II in dolomite. Sigma matrix is 10 cu for standard dolomite.

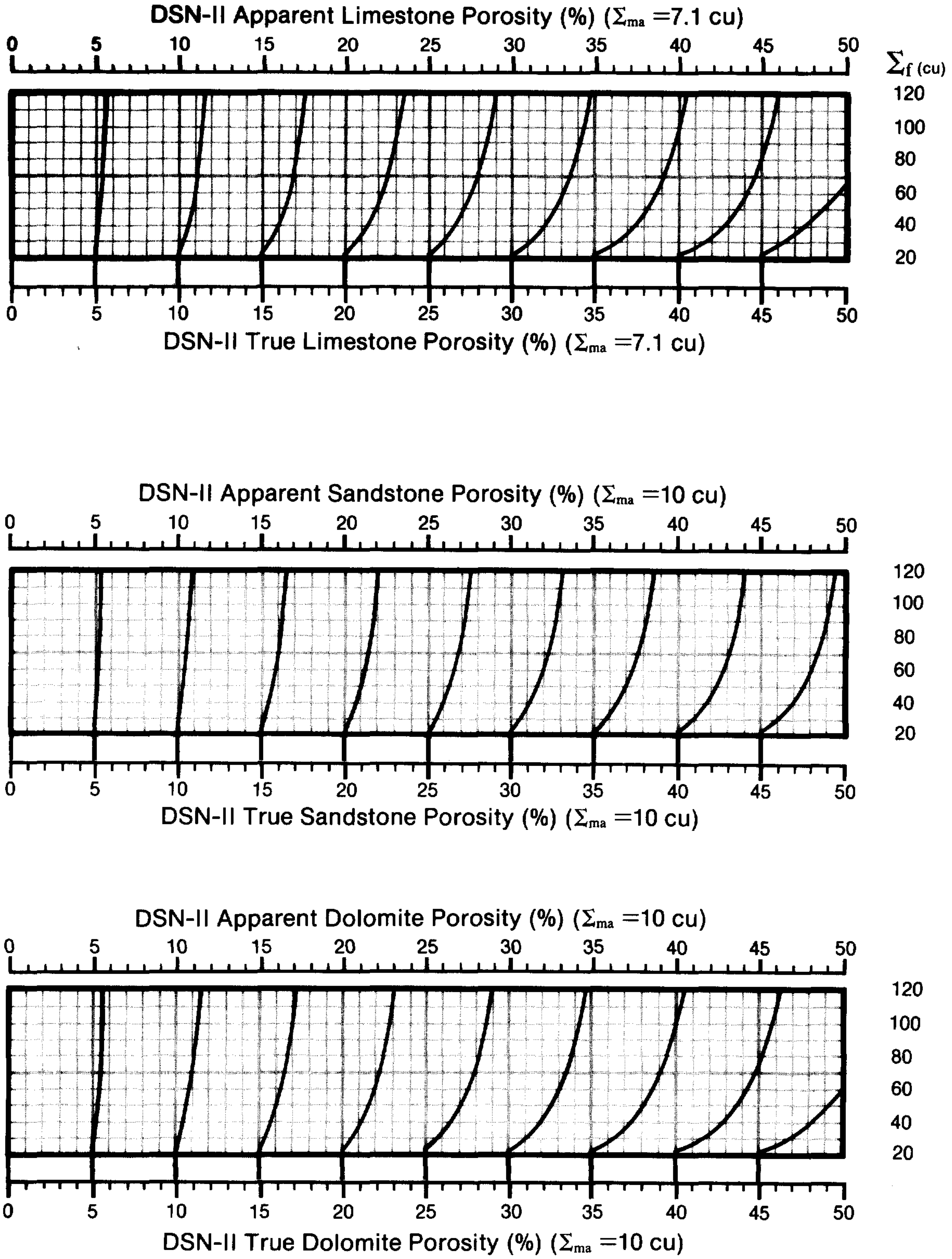

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FIGURE 12. Corrections for borated water in standard limestone, sandstone, and dolomite with respective sigma matrix values of 7.1, 10, and 10 cu.

## BIOGRAPHY

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