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AN IMPROVED SONIC TRANSIT TIME-TO-POROSITY TRANSFORM

by

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ABSTRACT

Over the 20 years since acoustic velocity well logging was introduced, deficiencies have been noted in the transit time, Δt, to porosity, ϕ, transform (popularly referred to as the Wyllie time average equation). In particular, at the porosity extremes, 0 and 100%, the transit time seems to vary less than predicted. Furthermore, for unconsolidated sands, the transform must be modified using a so-called "lack of compaction" correction--an inconvenient, complicating factor.

Thus, a new empirical transform, based on extensive field observations of transit time versus porosity, is proposed. It provides superior transit time - porosity correlation over the entire porosity range, it suggests more consistent matrix velocities for given rock lithology, and it permits the determination of porosity in unconsolidated, low velocity sandstones without the need to determine a "lack of compaction," or similar, correction factor.

The proposed equation enables both the novice and experienced log analyst to utilize more easily acoustic velocity measurements for porosity evaluation over a wide range of rock situations; and it permits the inclusion of these velocity measurements into computer programs in a much more straight-forward manner.

PROBLEM

Commercial acoustic velocity (sonic) well logging, introduced over 20 years ago, helped usher in quantitative formation evaluation from well logs as we know it today. The Sonic Log was the first measurement permitting quantitative evaluation of formation porosity essentially independent of the saturating fluids.

Over the years, use of the Sonic Log for porosity determination has waned somewhat, but it remains an important measurement for evaluating porosity. A number of factors contributed to this decline in popularity, among them the introduction of other porosity-related measurements--such as the Compensated Formation Density Log and the Compensated Neutron Log--and the recognition of shortcomings in acoustic velocity as a porosity measurement.

As with most well logging measurements, the Sonic Log does not directly measure the parameter with which it has become associated (in this case, porosity). Instead, it measures the time required for a sound wave to traverse a given distance in a formation. This measured acoustic velocity, or travel time, or transit time, must then be translated into porosity. Various equations have been proposed to accomplish this. They have been based on theoretical developments, experimental data, or a combination of the two.

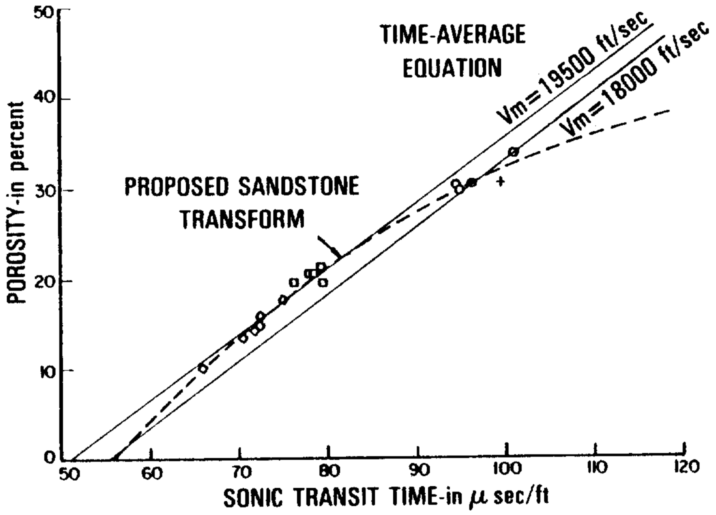


Fig. 1

Comparison of sonic transit time to core porosity from data collated by Meese and Walther (1967).

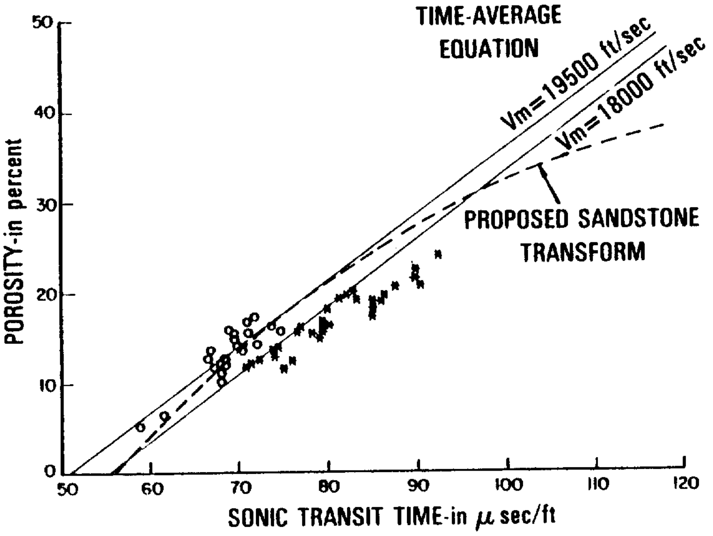
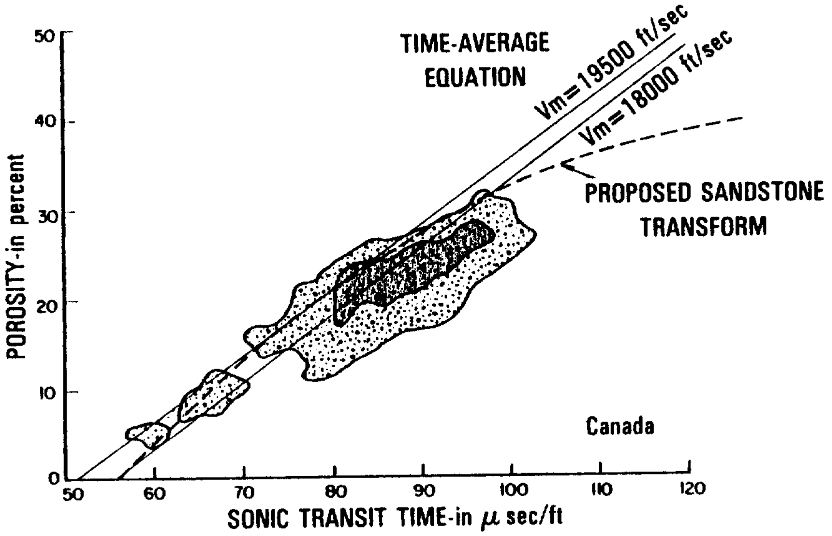


Fig. 2

Comparison of sonic transit time to core porosity from data collected by Millard (1960).

Fig. 3

Comparison of sonic transit time to porosity in low-to- medium porosity sandstones of a Canadian well.



The most popular by far has been a weighted-average transform developed by Wyllie, Gregory and Gardner. Commonly referred to as the Wyllie time-average equation, it is written in terms of sonic transit time, as,

$$\Delta t = \phi \Delta t_f + (1-\phi)\ \Delta t_{ma}$$

or, in terms of acoustic velocity, as,

$$\frac{1}{V} = \frac{\phi}{V_f} + \frac{(1-\phi)}{V_{ma}}$$

where Δt and V are, respectively, the sonic transit time (in μsec/ft) and acoustic velocity (in ft/sec) read from the log; Δt_f and V_f are the transit time and acoustic velocity of the interstitial fluid; and Δt_{ma} and V_{ma} are the transit time and acoustic velocity in the material constituting the rock matrix.

Generally, this time-average equation provides acceptable porosity values. And its simplicity certainly contributed to the early and continued acceptance of the Sonic Log in formation evaluation. Nevertheless, through the years, the shortcomings of the equation have become increasingly apparent. In many situations, either the transform does not quite yield the expected porosity value or it requires extensive modification to give an acceptable value.

Since the introduction of sonic logging, many comparisons have been made between porosity values derived from it and values obtained from other sources--such as core analysis. These studies generally indicate that at low porosities (less than, say, 15%), sonic transit time does not increase with increased porosity quite as rapidly as predicted by the time-average equation. Indeed, Wyllie et al noted this in the original measurements from which they proposed their time-average equation.

To illustrate this, Figure 1 reproduces data from Meese and Walther (1967) for four sandstones (Berea, Boise, Miocene and Page). Sonic transit time is compared with core porosity. For reference, the time-average response for V_m = 18000 and 19500 ft/sec and V_f = 5300 ft/sec is traced on the plot. Assuming that all these rocks possess a matrix velocity of 18000 ft/sec, the failure of the time-average equation to give an accurate description of the transit time - porosity relationship is obvious.

Figure 2 is a similar plot of Morrow sandstone data from Millard (1960). Sonic transit time measurements are compared with core analysis porosity measurements for both oil (liquid) and gas-bearing reservoir rock. Again, for ease of reference, the time-average equation is traced on the figure.

More recent, but similar, plots are shown in Figures 3 through 6. Frequency plots of transit time versus porosity from a variety of geographic and geologic provinces are represented. (The density of data points is proportional to the density of figure area "dotting".) Once again, the time-average equation for V_m = 18000 ft/sec and V_f = 5300 ft/sec has been traced on each figure for easy reference.

All these figures suggest the time-average equation to be overly conservative in the 5 to 25% porosity range. In other words, it predicts too low a porosity. Over the 25 to 30% porosity range, however, the time-average equation correctly predicts porosity. For porosities moderately in excess of 30%, the time-average equation is moderately optimistic; and for still higher porosities, it is highly optimistic.

Some measurements exist for very high porosity mixtures in which porosity is greater than 50%. These measurements have been made in the laboratory on slurries and in the field on ocean floor sediments. Figure 7 shows data from some measurements of marine sediments reported by Shumway (1960). The time-average equation bears little relation to the measured data. Indeed, the transit time for the slurries exhibiting a porosity greater than 60% is actually greater than the transit times of either the fluid (sea water) or the solids in suspension.

Another problem associated with the transformation of sonic transit time or acoustic velocity into porosity involves the selection of the proper matrix velocity value. Whereas, density measurements can usually be transformed into porosity values using a single characteristic value of grain density (for example, 2.65 gm/cc for sandstones, 2.71 gm/cc for limestones, or 2.87 gm/cc for dolomites), no single characteristic values for matrix velocity seem to exist. Sandstone matrix velocity may range from less

Fig. 4

Comparison of sonic transit time to porosity in low-porosity sandstones of a Colorado well.

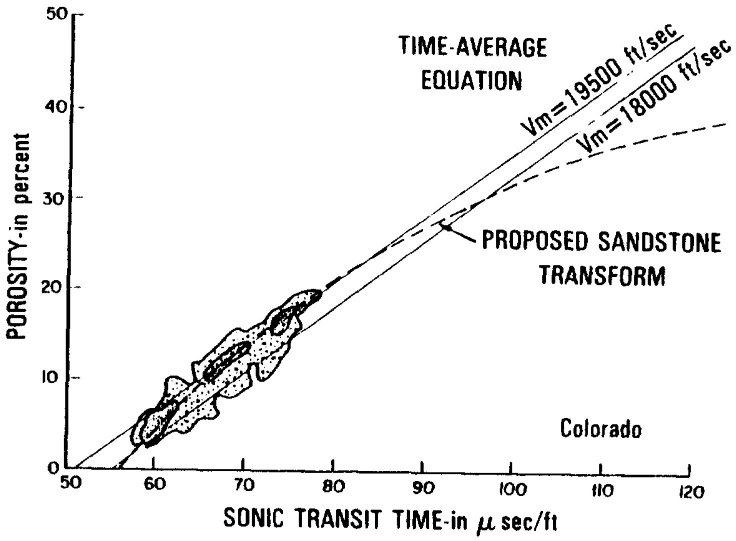


Fig. 5

Comparison of sonic transit time to porosity in medium-to-high porosity sandstones of a California well.

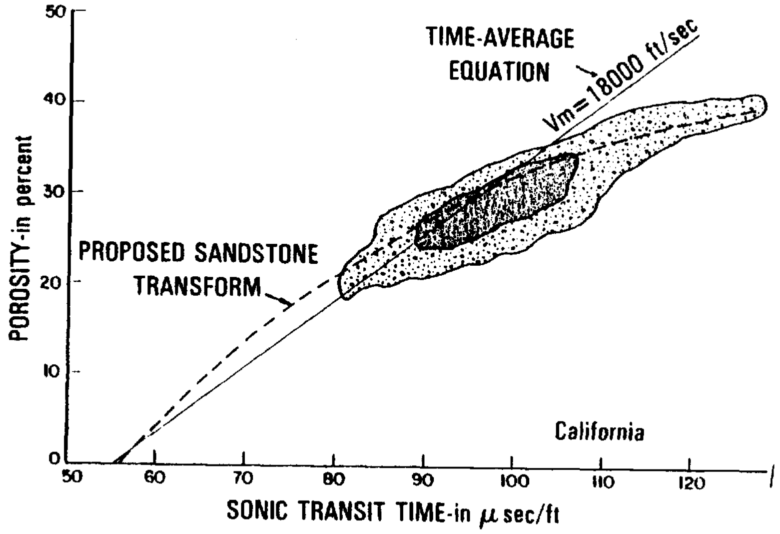
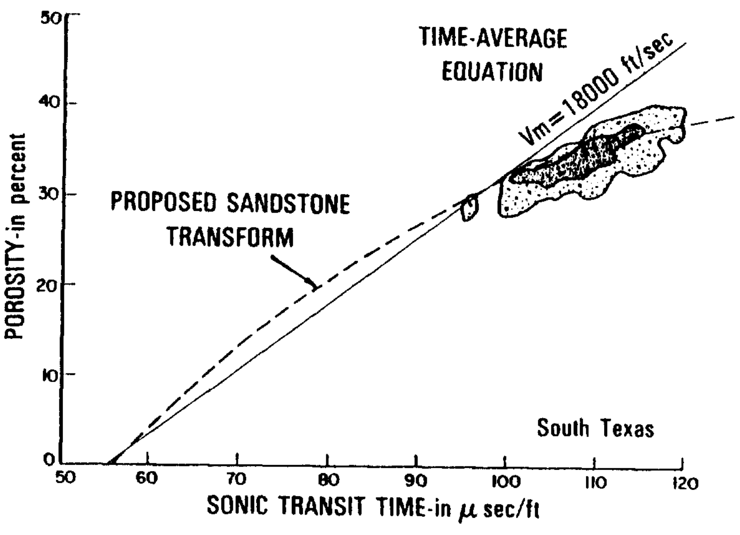


Fig. 6

Comparison of sonic transit time to porosity in high-porosity sandstones of a South Texas well.



than 18,000 ft/sec to more than 19,500 ft/sec, limestone matrix velocity from less than 21,000 ft/sec to more than 23,000 ft/sec, and dolomite matrix velocity from approximately 23,000 ft/sec to over 26,000 ft/sec.

Matrix mixtures could explain these apparent variations in matrix velocity. For example, a carbonate-cemented sandstone would be expected to exhibit a slightly greater matrix velocity than a pure quartz sandstone. Similarly, partially dolomitized limestone could explain the higher apparent limestone matrix velocities. It is somewhat more difficult to employ similar logic to explain the observed variation in the matrix velocity of dolomite. And in all cases, matrix velocities seem to be considerably more variable than their grain density counterparts. The need to resort to a matrix mixture to explain a grain-density anomaly is much less frequent than for a matrix velocity variation. The user of transit time data for porosity determination is almost placed in the position of having to know porosity in order to select the proper matrix velocity for porosity calculation.

But even greater difficulties arise when the time-average equation is applied to uncompacted, unconsolidated sands. It was recognized early that direct use of the time-average equation for porosity determination in unconsolidated sands gave porosity values which were much too high. This led to the introduction of a "lack of compaction" correction factor. First, porosity was calculated using the time-average equation,

$$\phi_a = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

Then this value was corrected by applying the "lack of compaction" correction factor,

$$\phi_c = \frac{\phi_a}{Cp}$$

where ϕ_a is the apparent porosity as given directly by the time-average equation, Cp is the "lack of compaction" correction factor, and ϕ_c is the corrected porosity.

Cp is always greater than unity. Values ranging from 1 to 1.3 are common, with values as high as 1.8 occasionally observed. A variety of methods are used to estimate Cp. The simplest is to use the sonic transit time observed in nearby shales divided by 100 (i.e., $Cp = \Delta t_{sh}/100$). A more accurate technique is to compare a recorded sonic transit time with a known porosity. In log analysis practice, this usually involves going to an obvious water-bearing clean sand. Knowing formation water resistivity (from the SP or other source), the formation factor can be computed from the recorded true resistivity of the electrical log (Induction or Laterolog). Formation factor is then converted to porosity using the appropriate transform. Comparison of this porosity with the sonic transit time, Δt, defines the "lack of compaction" correction needed to force the sonic transit time to yield the correct porosity value.

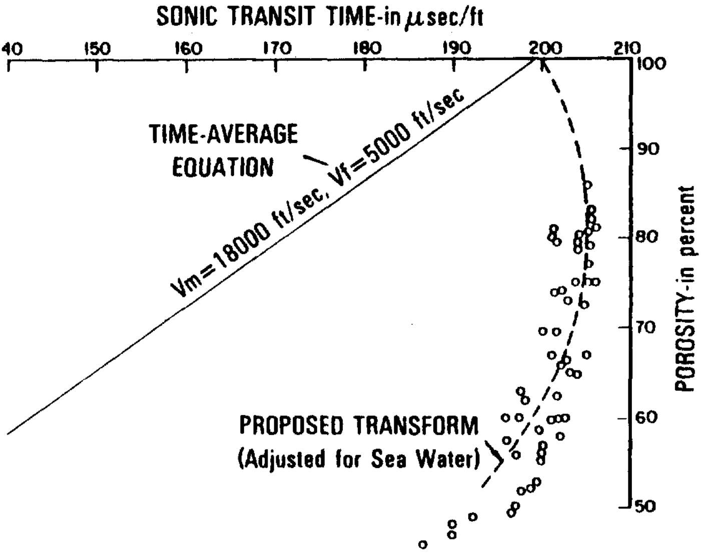
Although this procedure is certainly not overly complex, it does detract from the use of the time-average equation, and to a lesser degree the Sonic Log itself, for porosity determination. It is also a concept somewhat difficult to incorporate into automatic computer programs.

PROPOSED TRANSFORM

These long-standing problems with using the Wyllie time-average equation, coupled with numerous comparisons of sonic transit time versus porosity, lead us to propose a new empirical transit time-to-porosity transform. The transform, for a sandstone matrix, is shown in Figure 8. Although not germane to general well log interpretation, the transform is shown over the entire porosity range, from 0 to 100%. For comparison, the time-average equation for $V_m = 18{,}000$ ft/sec and $V_m = 19{,}500$ ft/sec

Fig. 7

Comparison of transit time to porosity in ocean floor sediments, from data published by Shumway (1960).



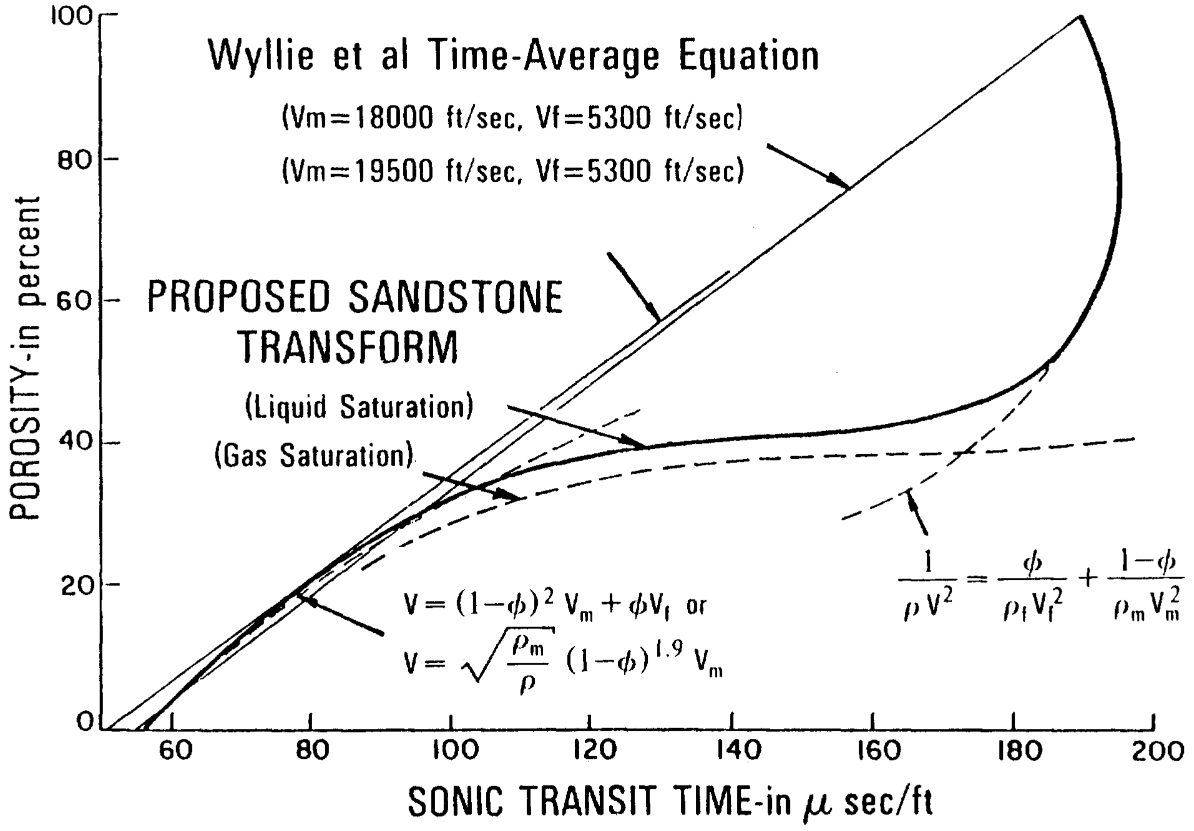


Fig. 8

The proposed sonic transit time-to-porosity transform, showing comparison to Wyllie time-average equation (1956) and to suggested algorithms.

is also shown. The transform is totally empirical, being based entirely on comparisons (both within and outside the literature) of sonic transit time versus an independent porosity measurement.

The proposed transform exhibits several salient features. First, it appears that all pure quartz sandstones may be characterized by a unique matrix velocity, slightly less than 18,000 ft/sec. A value of 17,850 ft/sec (or $\Delta t_{ma} = 56\ \mu sec/ft$) is suggested. Limestone and dolomite also seem to each exhibit unique matrix velocities: 20,500 ft/sec (or $\Delta t_{ma} = 49\ \mu sec/ft$) for limestone, and 22,750 ft/sec (or $\Delta t_{ma} = 44\ \mu sec/ft$) for dolomite.

Next, the transform yields slightly greater porosity values over the low to medium porosity range (i.e., the 5% to 25% porosity range) than does the time-average equation using an 18,000 ft/sec matrix velocity. In fact, at 15% porosity, the transform indicates a porosity similar to that given by the time-average equation using a matrix velocity of 19,500 ft/sec. Thus, it appears the higher matrix velocities employed in sonic interpretation in the past have been selected to force the time-average equation to yield a truer porosity over the low to medium range; this is true for both carbonates and sandstones.

For moderately high porosities (around 30%), the proposed transform generally corresponds to the time-average equation using $V_m = 18{,}000$ ft/sec. Above 35% porosity, however, sonic transit time increases much more rapidly than porosity, and its response quickly departs from that predicted by the time-average equation. This is the region in which present sonic interpretation would require a "lack of compaction" correction. Use of the new transform eliminates the need for the "lack of compaction" correction factor. Using the proposed transform, sonic transit time yields porosity directly.

Finally, in the very high porosity range (above 50%), transit time is relatively independent of porosity, exhibiting, instead, a value close to that of the fluid.

For the case of gas-saturated sandstone, a special transit time-to-porosity transform is given. It should be used when the portion of reservoir rock investigated by the sonic measurement contains an appreciable amount of hydrocarbon in the gassy (vapor) phase. Normally, because of the very shallow depth of investigation of the sonic measurement, this condition exists only in higher porosity sandstones (porosity greater than 30%). However, it is occasionally observed in rocks of lower porosity. Figure 2 is an example. Measured transit times in the gas-bearing portion of these Morrow sandstones are clearly greater than those in the oil-bearing portion.

For comparison, the proposed transit time-to-porosity transform for sandstone has been sketched on Figure 1 through 7. Its agreement with the data, over the rather extensive range in porosity, geography and geology represented by these data, is quite good.

ALGORITHMS

It is not our objective here to explain or to justify the proposed transit time-to-porosity transform in terms of acoustic wave propagation in a porous medium. Extensive excellent work has been published on that subject over the past 25 years, although, unfortunately, no single theory completely describes the process over the entire porosity range.

Our objective is simply to report our observations, presented in the form of a transit time-to-porosity curve in Figure 8. Figure 9 is the expanded response over the practical porosity for the three common reservoir rocks--sandstone, limestone and dolomite.

It would, however, be convenient to have an algorithm of these curves in order to program the transform into the computer. We could not, unfortunately, find a single algorithm which accurately described our transit time-to-porosity transform over the entire porosity range. The response curve was, therefore, divided into three segments. Algorithms for each of these segments follow:

0% to 37% Porosity Range

Over the 0% to 37% porosity range ($\phi<37\%$), either of two algorithms reasonably duplicate the observed response.

$$V_l = \sqrt{\frac{\rho_{ma}}{\rho}}(1-\phi)^{1.9}V_{ma} \qquad (1)$$

where, ρ and ρ_{ma} are, of course, the bulk density of the mixture and the grain density of the matrix component, respectively, or

$$V_l = (1-\phi)^2 V_{ma} + \phi V_f \qquad (2)$$

and

$$\Delta t_l = \frac{10^6}{V_l}$$

The first algorithm can be used when the saturating fluid in the zone investigated by the sonic log is water. The second equation can be used regardless of the nature of the saturating fluid; of course, the proper value for fluid velocity is required.

47% to 100% Porosity Range

Over the 47% to 100% porosity range ($\phi > 47\%$),

$$\Delta t_2 = \sqrt{\frac{\rho\phi\Delta t_f^2}{\rho_f} + \frac{\rho(1-\phi)\Delta t_{ma}^2}{\rho_{ma}}}$$

37% to 47% Porosity Range

Over the 37% to 47% porosity range ($37\% < \phi < 47\%$), a linear interpolation between the above two results provides a reasonable duplication of the observed response,

$$\Delta t = \frac{0.47-\phi}{0.1}\Delta t_l + \frac{\phi-0.37}{0.1}\Delta t_2 \qquad (1)$$

or a slightly simpler algorithm,

$$\Delta t = \frac{0.47-\phi}{0.1}\Delta t_l + \frac{\phi-0.37}{0.1}\Delta t_f \qquad (2)$$

The latter equation eliminates the need to ever actually calculate Δt_2.

These algorithms are shown on Figure 8 for easy comparison with the response curve they attempt to duplicate.

The algorithms do provide some insight into acoustic propagation in a porous medium. Over the higher porosity interval. ($\phi > 50\%$), the suspended solid particles tend to float within the fluid. The fluid, therefore, represents the continuous material with the solid particles as isolated inclusions. In this situation, the compressibility of the fluid-solid mixture seems to be well predicted by the simple addition of fluid and suspended particle compressibilities,

$$c = \phi c_f + (1 - \phi)\, c_{ma}$$

or in terms of bulk modulus,

$$\frac{1}{K} = \frac{\phi}{K_f} + \frac{1 \phi}{K_{ma}}$$

or in terms of densities and acoustic velocities for materials exhibiting little rigidity,

$$\frac{1}{\rho V^2} = \frac{\phi}{\rho_f V_f^2} + \frac{1 - \phi}{\rho_{ma} V_{ma}^2}$$

and, hence, the algorithm presented above.

Over the lower porosity range ($\phi < 35\%$), the rock matrix also becomes continuous. Thus, the rock matrix and the fluid-filled pores present a more parallel network for acoustic transmission. In terms of bulk modulus, this model would take the form

$$K = \phi K_f + (1 - \phi) K_{ma}$$

The algorithms presented above for the lower porosity case, although significantly modified, do exhibit this form. The modification could be explained as a tortuosity effect, similar to the tortuosity effects commonly observed in electrical resistivity or conductivity mixtures.

Over the intermediate porosity range ($35\% < \phi < 50\%$), the effective acoustic propagation network rapidly changes from a more-or-less parallel one into a series network. In other words, the rock matrix lattice, which is continuous at lower porosity, breaks down into individual solid particles suspended in the fluid as the mixture porosity increases. This considerable change in the form, or continuity, of the matrix material greatly affects the transmission characteristics of the mixture. The mixture acoustic velocity decreases rapidly for rather modest porosity increases within this intermediate porosity range.

SUMMARY

A new sonic transit time-to-porosity transform has been proposed. It is based on numerous comparisons of transit time versus porosity observed over many years of log interpretative experience. Although totally empirical in origin, the transform does not contradict theoretical acoustic wave propagation considerations.

The transform offers the following advantages:

1. It applies over the entire porosity range--from 0% to 100%.
2. Porosity is provided directly; no special corrections, such as the "lack of compaction" correction factor, are required.
3. Matrix velocities, for pure minerals, are single valued--for sandstone, V_m = 17,850 ft/sec; for limestone, V_m = 20,500 ft/sec; and for dolomite, V_m = 22,750 ft/sec.
4. The transform can be applied to saturating fluids other than water, provided fluid velocity and density are known.

ACKNOWLEDGMENT

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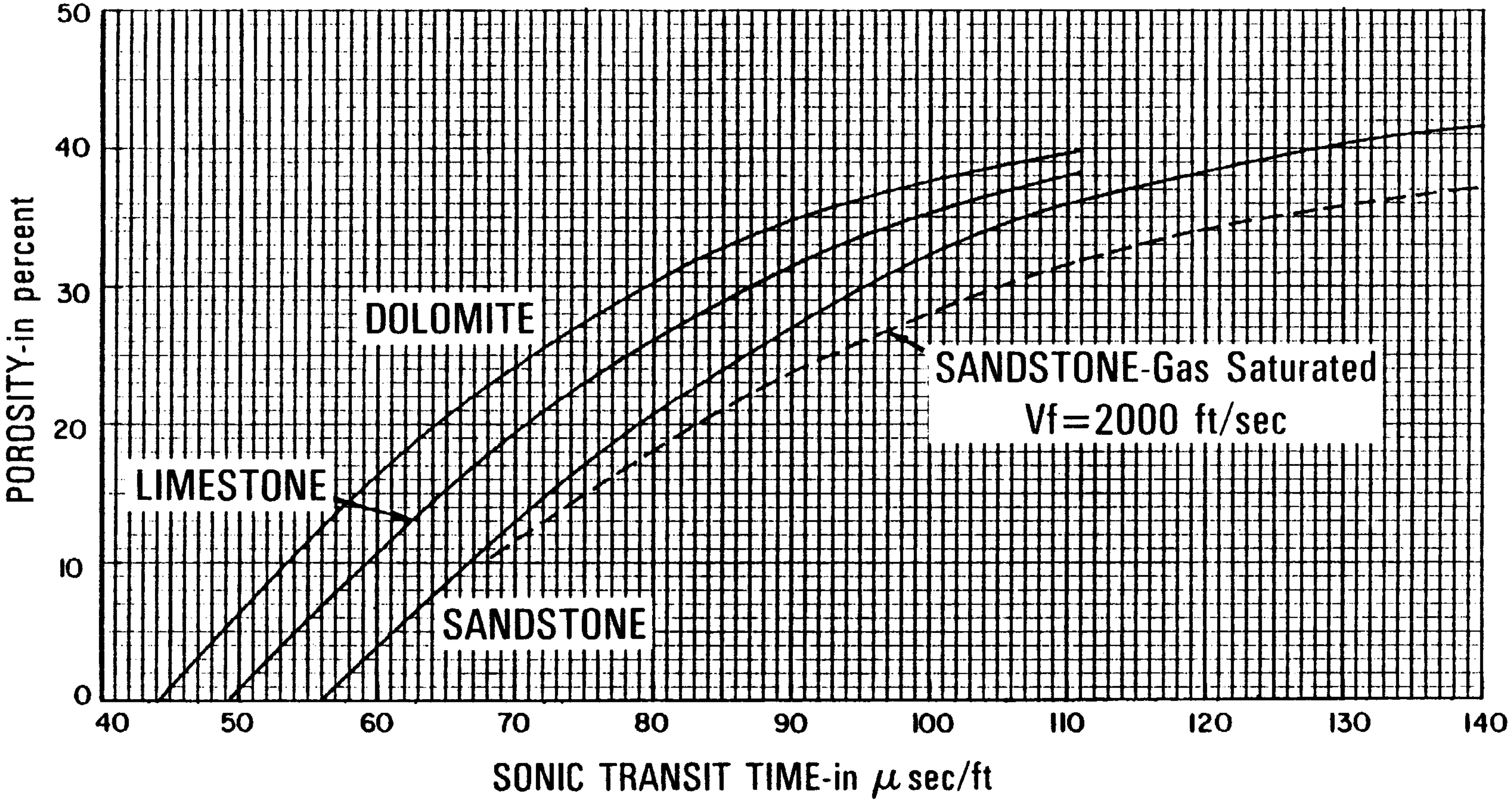

Fig. 9

The proposed sonic transit time-to-porosity transform, showing response in sandstone, limestone, and dolomite.

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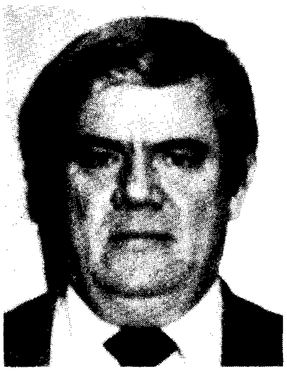

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