Use of Wet Shale and Effective Porosity in a Petrophysical Velocity Model

Sonic logs can be improved by use of a petrophysical model to create theoretical compressional and shear waves. The measured sonic logs are used only as a guide. Measured sonic logs are subject to serious error resulting from borehole conditions and invasion. When the results of a petrophysical velocity model are used to compare wells to seismic or to build a rock-strength model for pore-pressure prediction or a well completion, the results usually are better than with the measured data alone. One debate is about how to add porosity and what porosity to use. Many petrophysicists prefer to use total porosity and volume of dry clay to build models. This author prefers to use effective porosity and wet-shale volume.

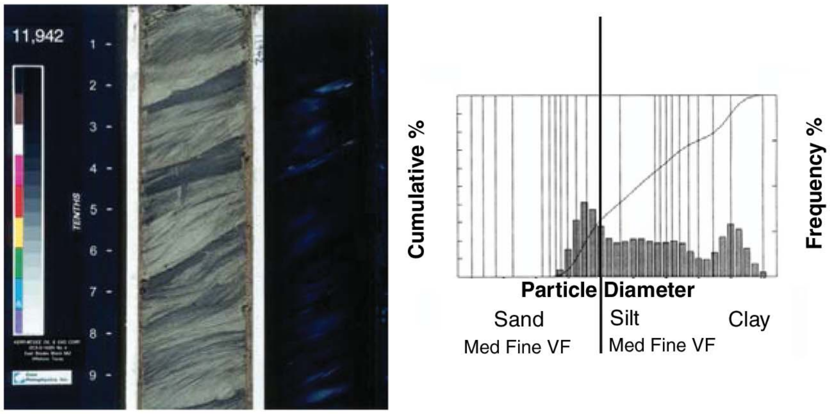

Fig. 1—Example of a 1-ft section of a sandstone reservoir having shale (dark) and fine-grained sand (light) streaks. The image on the right shows the particle-size distribution.

Introduction

Petrophysical velocity modeling, to improve sonic logs and create better well ties to seismic sections, is important today for both amplitude-variation-with-offset studies and seismic inversions. These petrophysical velocity models begin with a petrophysical interpretation that describes the rock components. The interpretation provides the volumes of sand, shale, carbonate, and other components in the solid matrix, as well as the porosity of the rock and a description of the fluids filling the rock's pores. This description is used to compute compressional sonic velocity and shear sonic velocity. Various methods can be used to make these calculations, but great care must be taken to make certain that the volume definitions used in the petrophysical interpretation are the same as those used in the velocity model. This admonition is particularly important for the definitions of shale and porosity.

This article, written by Technology Editor Dennis Denney, contains highlights of paper OTC 17643, "Using Wet Shale and Effective Porosity in a Petrophysical Velocity Model," by ***A. May,*** *Kerr-McGee Corp., prepared for the 2005 Offshore Technology Conference, Houston, 2–5 May.*

Wet Shale

The techniques for producing and presenting petrophysical interpretations fall into two categories, the wet-shale/effective-porosity method and the dry-clay/total-porosity method. In both models, total porosity is the same. The wet-shale model, which also can be called a rock model, divides the rock into two components: sand and shale. These are not minerals, but rock components. In this model, the shale has bound water associated with it according to a shale porosity determined by the log response of a "type shale" chosen by the analyst. The effective porosity is the porosity in excess of the shale porosity. The effective-porosity portion of the rock contains irreducible water associated with the sand and silt that depends on the height above the hydrocarbon/water contact, or capillary pressure.

The dry-clay/total-porosity method divides the rock into mineralogic clay (e.g., illite and kaolinite), quartz, and other sand-grain-forming minerals such as feldspars. Clay- and silt-sized quartz are lumped in with sand-sized quartz in this model. They are part of the shale in the wet-shale model. The amount of clay-bound water computed in this model must be estimated by calculating or assuming a clay-mineral composition and the amount of bound water that the particular clays can hold. Then, using an assumed or computed grain-size distribution, an amount of capillary-bound water must be determined because the volume of clay-bound water will be less than that of the total irreducible water in the rock. This estimate of capillary-bound water is higher than the amount in the wet-shale model in proportion to the amount of clay and silt-sized quartz, feldspar, and other sand-forming grains.

Both methods can work, given the appropriate data and interpretation. Neither method is invalid. However, the wet-shale model requires fewer data and results in a more accurate interpretation in most cases because the most important data (shale volume and shale porosity) are more readily available to the analyst. **Fig. 1** shows a portion of the top of a reservoir sandstone.

The darker streaks are shale, and lighter streaks are fine sand. A 1-ft section of rock is shown. These streaks of sand and shale are below the resolution of density and resistivity logs, so the shale and sand streaks are effectively averaged together. Using normal logs, such as gamma ray and density/neutron, calibrated to core or sidewall-core laser-particle-size measurements, the amount of shale can be computed accurately. The laser-particle-size distribution of a plug from the core is shown beside the photograph. The sand is separated from shale with the conventional cutoff of 31 mm as shown by the line through the histogram.

Dry Clay

Some petrophysicists prefer to estimate clay volume in the rock by use of logs and core data, and then estimate the amount of bound water associated with the clay. This method has some advantages. Clay is responsible for holding most of the shale-bound water because of its electrical properties. Most sand and silt grains are composed of the relatively inert quartz, feldspar, and miscellaneous rock fragments. These latter rock components bind to much less water as a percent of pore volume than most clay minerals.

There is considerable research describing the petrophysical properties, especially the cation-exchange capacity, of various clay minerals in the laboratory. Also, obtaining sidewall cores and performing X-ray analysis of the fines fraction enable defining clay minerals in the reservoir sands fairly accurately. Compare two equations relating effective to total porosity.

- Wet-shale method:

Total porosity=effective porosity+(shale porosity×shale volume).

- Volume-of-dry-clay method:

Total porosity=effective porosity+(clay porosity×clay volume).

The value of total porosity is the same in both equations. The clay volume is a much smaller value than shale volume, but clay porosity can be quite large compared with shale porosity, depending on the clay type and its capacity to hold water, its distribution in the rock, and other factors.

It is common in the literature and in practice for some petrophysicists to use the phrase "volume of clay" but actually mean shale volume. So in practice, the wet-shale model often is used, while the terminology is from the dry-clay model. The result can be problems in petrophysical velocity modeling because, typically, the petrophysical evaluation is done in one computer program, and the sonic modeling is done in another. If the values computed in the petrophysical model are in clay-volume terms and the values entered into the sonic modeling are supposed to be in shale-volume terms, considerable errors in the velocity-model output are possible.

Comparing the Methods

When building a petrophysical velocity model, especially in a loosely consolidated rock, the shale is very important. The water bound to the clays and other minerals in the shale provides most of the strength of typical reservoir rocks. Small changes in the shale volume computed in the petrophysical analysis make a large difference in the velocity-model results. Likewise, small changes in the selection of the density of the shale and the sonic-interval transit time of the shale make a large difference.

The wet-shale/effective-porosity method uses critical parameters in the analysis that are selected downhole, near the rocks being modeled. However, rock is very rarely composed of 100% clay minerals; therefore, parameters for the dry-clay model can rarely, if ever, be selected downhole. The shale-volume quantity has properties that can be measured in a native environment.

An estimate of the percent dry clay and the mineral composition of the dry clay are fairly easily obtained in the laboratory, but measuring these values in a wellbore is very difficult. Often, there are several minerals having more than trace amounts, and some usually are clay minerals. Also, there could be a significant amount of mixed-layer illite and smectite. These particular minerals have a substantial variability in their electrical properties (water-binding power) depending on the actual percentage of the two end members present and their distribution in the rock. To make the estimation of clay-bound water (clay porosity×clay volume) even more difficult, the petrophysical and acoustic properties of clay minerals vary with temperature, pressure, and salinity.

Computing the Acoustic Properties

Currently, the Hill Average method is used to compute the solid bulk modulus. Effective porosity is added to the solid bulk and shear moduli by use of an approximation to the Kuster-Toksoz algorithm. To compute shale porosity, the same matrix density used for the nonshale portion of the rock is used. Therefore, a matrix density of 2.65 g/cm^3 normally is used to compute shale porosity in sand/shale sequences. This value is not precise in all cases, but it is a good approximation. In all cases, effective porosity is distributed between the rock components in proportion to their solid-rock volume. The pores in the shale and the pores in the nonshale rock are treated differently; they are assumed to have different pore aspect ratios.

Impermeable rock with effective porosity contains small, isolated sandstones and siltstones that are not interconnected. In conventional petrophysics, these rocks typically are ignored because the free fluid that they contain cannot be produced. When creating a petrophysical velocity model, the effective porosity, even if unconnected, must be taken into account. The effective porosity remaining in these shales, whether associated with siltstones or isolated sandstones, affects the rock's strength and, thus, its acoustic properties. See the full-length paper for examples of the wet-shale/effective-porosity method.

Conclusions

Use of a petrophysical interpretation to build a petrophysical velocity model, if done with a wet-shale model and effective porosity, is a valid and useful tool. Compressional sonic logs and density logs are subject to error from borehole effects and drilling-fluid invasion. Most shear logs, as measured by dipole sonic logs, have serious errors. These errors probably are the result of borehole effects and invasion, but are more common than errors in the other two logs. These effects can be corrected with successful petrophysical velocity modeling.

The wet-shale/effective-porosity method uses the shale-volume and -porosity parameters measured in the wellbore under the appropriate conditions. The parameters used to compute the amount of clay-bound water must be derived from laboratory data that were not measured in situ. Clay minerals have acoustic properties that vary with temperature, salinity of the surrounding brine, and pressure. For these reasons, translating the laboratory properties to the rocks in the well is a very difficult task.

Very good sonic and density data are required for well ties to seismic data and for rock-mechanical-properties calculations. While sonic and density logs provide the ground-truth data for model calibration, sonic and density logs are reliable only in good sections of the borehole and in tight, uninvaded rocks. In invaded sandstones (especially hydrocarbon-bearing sands) or rugose boreholes, sonic and density logs often are bad. In these sections of rock, the petrophysical-velocity-model results are the best data to use. JPT