Carbonate Reservoir Characterization

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During the past 15 years, methods and technology for predicting the performance of carbonate reservoirs have improved dramatically. This advance occurred in response to the realization that more than half of the oil that could be swept by waterflooding is not contacted and remains in the reservoir. Attempts to simulate this performance and locate the remaining oil by use of simple reservoir models and newly developed flow-simulation computer programs have failed mainly because of the extreme heterogeneity that characterizes carbonate reservoirs. It is, in fact, the extreme geologic and petrophysical heterogeneity typical of carbonate reservoirs that distinguishes carbonate from siliciclastic reservoirs. Research programs focused on understanding the nature of the heterogeneity and developing methods to characterize carbonate reservoirs, together with improvements in computer capability and simulation programs, have led to more reliable predictions of reservoir performance and to methods for locating volumes of unswept oil in reservoirs under waterflood.

Reservoir characterization encompasses the understanding and methods used to characterize reservoir heterogeneity. It can be defined as the construction of realistic 3D images of petrophysical properties used to predict reservoir performance, and it is a multidisciplinary, integrated task involving expertise in reservoir geology, geophysics, petrophysics, well logging, geostatistics, and reservoir engineering. Three-dimensional images are obtained from geological models constructed with core, wireline-log, and geophysical data. Petrophysical properties, obtained from core, wireline-log, and production data, are distributed within the geological model by linking petrophysical properties to geologic fabrics and by use of advanced geostatistical and geophysical methods. Finally, the model is put into a numerical simulator for testing and predicting future performance.

The extreme petrophysical heterogeneity found in carbonate reservoirs is clearly demonstrated by the wide variability observed in porosity-permeability crossplots of core-analysis data. Research has shown that basic rock fabrics dominate control of petrophysical heterogeneity; within a rock-fabric facies, porosity and permeability have little spatial correlation and are widely variable at the scale of inches and feet. Permeability, in particular, can vary by a factor of 10 or more at the small scale and is nearly randomly distributed **(Fig. 1).**[1,2] This result suggests that much of the variability observed in core-analysis data is spatial noise and can be averaged within rock-fabric facies for the purposes of constructing a reservoir model. Only rock fabrics, not pore-throat size, permeability/porosity ratio, or flow-zone indicators, have vertical and lateral continuity. Therefore, rock-fabric facies are the basic elements for characterizing a carbonate reservoir.[3]

Rock fabrics are geologic descriptors that characterize pore size according to particle size and sorting, interparticle porosity, and various types of vuggy porosity. The main limestone rock fabrics are grainstone, grain-dominated packstone, and mud-dominated fabrics. Dolostone rock fabrics are similar but require a description of dolomite crystal size in mud-dominated dolostones as an added control on pore size. These basic fabrics are modified by the amount of fabric-selective vuggy pore space,[4] and many rock fabrics can be linked directly to depositional facies. However, some rock fabrics cannot be linked to depositional facies because extensive modifications to the fabric have occurred since deposition through a geologic process known as diagenesis. Constructing models of reservoirs comprising complex fabrics, such as fracture and karst fabrics, is difficult and is the subject of current research.

Each rock fabric has a specific porosity-permeability transform, and the vertical stacking of rock-fabric facies, together with interparticle porosity, provides the basis for estimating permeability in uncored wells. The wireline-log problem is determining interparticle porosity, as well as total porosity and rock fabric, for input into a general porosity-permeability transform. Porosity, acoustic velocity, resistivity, and saturation logs are used for this task, and calibrating wireline-log responses to core descriptions of rock fabrics is key to developing useful algorithms.[5]

Because rock-fabric and petrophysical data obtained from cores and wireline logs are one-dimensional, a geological framework is required to distribute the data in 3D space. In the past, geological models were constructed by identifying depositional facies from core data, then distributing those facies by use of depositional models on the basis of modern carbonate depositional processes. However, reservoirs described in this manner do not contain sufficient detail to capture basic reservoir heterogeneities, and facies correlations from well to well often are highly uncertain. Development of sequence stratigraphic methods greatly enhanced the accuracy of well-to-well correlations and provided the means of capturing basic scales of reservoir heterogeneity.

Sequence stratigraphy is a method of identifying and correlating time surfaces (chronostratigraphic surfaces) from well to well. This method is of paramount importance to reservoir geology because a specific chronostratigraphic surface, by its very nature, must be present in every well in the reservoir. The same cannot be said for depositional

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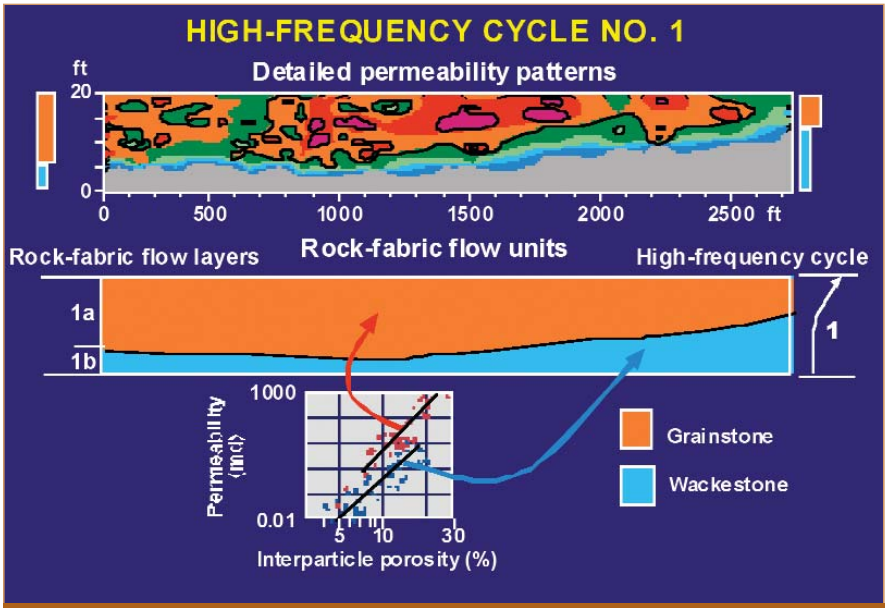

Fig. 1—Permeability map of a high-frequency cycle showing widely variable permeability in the grainstone and low permeability in the wackestone. The permeability shows little spatial correlation within either rock-fabric unit. The high-frequency cycle is divided into two flow layers: an upper grainstone flow layer and a lower wackestone flow layer to preserve high- and low-permeability values.

facies or lithology, and the assumption that facies and lithology are continuous has led to many inaccurate reservoir models.[6] Depositional facies are systematically packaged between time surfaces at a number of scales, referred to as sequences, systems tracts, and cycles. Correlation of the larger time-stratigraphic packages, called sequences, is aided by seismic data. Correlation of smaller packages (typically 3- to 30-ft-thick units), called cycles, is based on core and wireline-log data. All scales are important in the development of the geological model.

The most important scale for characterizing reservoir heterogeneity is the cycle scale.[5,6] Typically, a cycle comprises a vertical succession of fabrics from a basal, mud-dominated fabric (wackestone and mud-dominated packstone) grading upward into a grain-dominated fabric (grain-dominated packstone and grainstone). To build a reservoir model, rock fabrics are grouped into flow layers within the cyclic framework of the geological model, typically two rock-fabric flow layers per cycle (Fig. 1). These flow layers are the basic elements of the reservoir model. Geostatistical methods are required to populate the flow layers with petrophysical properties, which often are spatially correlated at a scale smaller than that of well spacing. Modern geostatistical methods for quanitifying and modeling the variability in 3D, called variography and stochastic simulation, respectively, are used for this purpose.

As **Fig. 2** shows, the final South Wassen Clear Fork (SWCF) reservoir model comprises a series of rock-fabric flow layers constrained by petrophysical properties derived from wireline logs and the sequence stratigraphic framework. The advantages of this model over models in which layers are defined arbitrarily are that the layered nature of the geologic architecture is maintained, high- and low-permeability layers are preserved, the necessity of arbitrary increases in horizontal permeability is significantly reduced, and the necessity of using unrealistically low vertical/horizontal permeability ratios is minimized.[7]

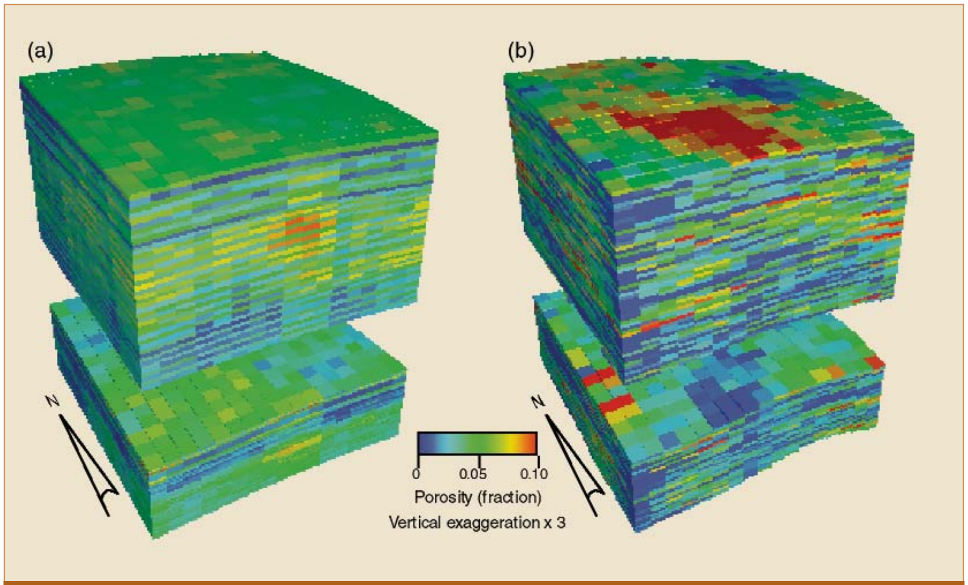

Fig. 2—Conditional stochastic simulation of (a) SWCF grid-block averaged porosity and (b) traditional geostatistical simulation of SWCF porosity.[7] The model layers in (a) are rock-fabric layers and faithfully reproduce the stratigraphy. The model layers in (b) are arbitrary and the model is less organized, but with statistically homogeneous variability.

The final test of the reservoir model is a comparison of the model to outcrop analogs, because a true image of interwell space can be observed only in well-exposed outcrops. The reservoir model is constructed with powerful imaging software that can display the data in 3D. These images are used to make reservoir-management decisions and as input for numerical simulators. Because these models normally are too detailed to enter directly into flow simulators, scaleup methods must be applied that reduce the complexity while retaining the overall geologic architecture and production characteristics. A field-production profile is simulated, and results are compared with history. When a satisfactory history match is obtained, the model is used to predict performance of future development operations and to make economic decisions.

A workflow that integrates key technical disciplines is fundamental to the success of a reservoir-characterization project. Geologists, geophysicists, petrophysicists, geostatisticians, and reservoir engineers must work together closely on all phases of the project, not just their principal phase. It is the geologist's task to build a sequence stratigraphic framework that will be populated by petrophysical data. The reservoir engineer, however, must be involved to advise the geologist regarding the kinds of data that will and will not be useful for numerical simulation. The petrophysicist's task is to collect accurate petrophysical data and work with geologists to link the data to rock fabrics that can be systematically distributed within the stratigraphic framework. Reservoir engineers define flow layers or units on the basis of the rock-fabric facies provided by the geologist and petrophysicist. The geologist and petrophysicist, however, must be involved to provide geologic constraints on the location of flow layers. It is the geophysicist's task to invert the seismic data to porosity using stratigraphic information supplied by the geologist and petrophysical data provided by the petrophysicist. The geostatistician's and reservoir engineer's task is to fill the interwell space with petrophysical properties using geological, petrophysical, and seismic data. Then the reservoir engineer constructs the final reservoir model showing the 3D distribution of these petrophysical properties. If the key technical disciplines are involved in each step, the final product will be a superior 3D image of the reservoir suitable for accurate performance predictions. JPT

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