Sandstone reservoir quality prediction: The state of the art

Joanna M. Ajdukiewicz and Robert H. Lander

INTRODUCTION

To guess is cheap; to guess wrongly is expensive (Chinese proverb).

Reservoir-quality predictive models will be a useful element of risk analysis until remote-sensing tools are invented that accurately measure effective porosity and permeability ahead of the bit. This issue of the *AAPG Bulletin* highlights recent advances in a new generation of reservoir quality models that have successfully predicted porosity and permeability in diverse siliclastic reservoirs under many different burial conditions.

Most previous attempts at predrill reservoir quality prediction have relied on empirical correlations or on first-principle geochemical simulations that incorporate laboratory-derived input parameters (Wood and Byrnes, 1994). The new reservoir quality models differ from previous approaches in that, although incorporating theory-inspired algorithms, they include terms with values that are explicitly designed to be calibrated by, and tested against, data sets of high-quality petrographic analyses that are linked to thermal and effective-stress histories. Petrographic observations therefore provide essential constraints in these models on the types, timing, and rates of key geologic processes affecting sandstone pore systems. This approach avoids the pitfalls inherent in predictions based on statistical correlations devoid of process interpretation (e.g., porosity-versus-depth trends) or on first-principle geochemical models that rely exclusively on laboratory-derived data to constrain the nature and rates of geochemical reactions.

Statistical correlations commonly fail to accurately predict reservoir quality in areas away from the observation data set because of changes in the relative significance of the controlling geologic processes. These changes reflect inevitable differences in sandstone compositions, textures, and burial histories that occur between the observation data set and the area of interest. For example, a porosity-depth trend driven by mechanical

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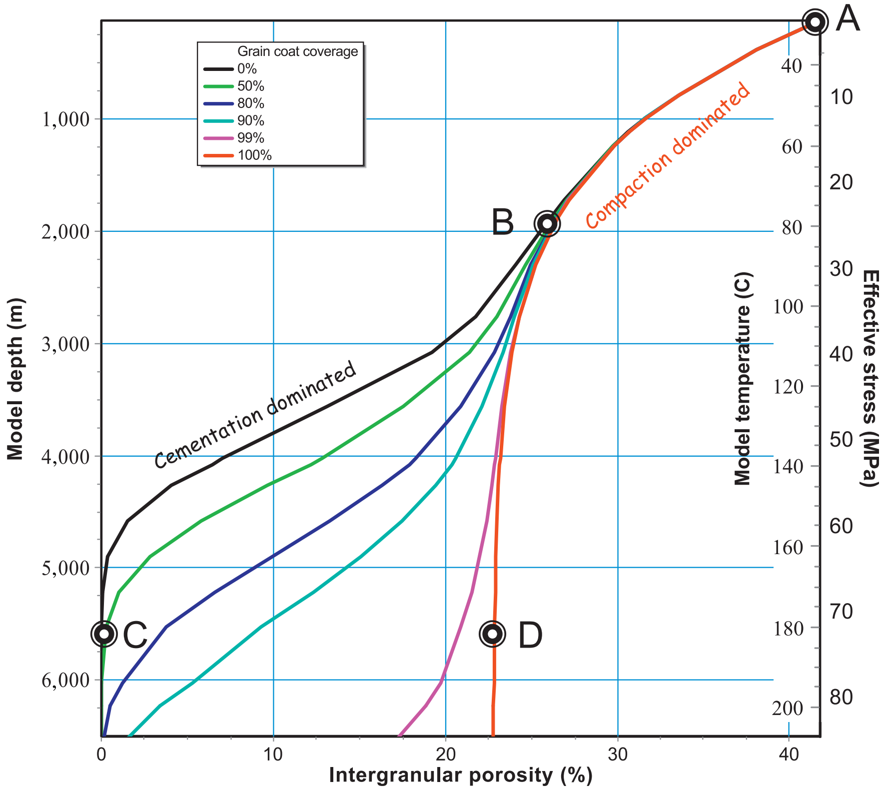

Figure 1. Porosity-depth trends vary with dominant burial process and lithology. Shown is a modeled porosity evolution with burial for a well-sorted, fine-grained, quartzo-feldspathic (rigid-grained) eolian sandstone with variable grain coats formed near the surface. In this hypothetical example, the recently deposited sand (A) undergoes simple subsidence over more than 155 m.y., with no uplift or overpressure development, to burial depths of 6500 m (21,300 ft). Intergranular porosity evolves from 42% near the surface to a wide range of possible values depending on grain coat coverage at depth (e.g., C to D). During burial, porosity decreases, initially by mechanical compaction under increasing effective stress, to about 26% at 2 km (1.2 mi) depth (B). Below this point, compaction in rigid-grained sands stabilizes to very low rates (red curve). At 80°C, significant quartz cement begins to form. Below this point, as in many rigid-grained sands, most further intergranular porosity loss results from quartz cement filling pores. The amount of cement formed can be calculated as a function of time, temperature, grain size, and quartz-grain surface area available for cement precipitation. Quartz cement can be inhibited and porosity preserved by early formed grain coats, commonly of clays, that reduce available quartz surface area. With higher coat coverage, less quartz cement forms. Highest porosities are preserved at depth where compaction and cement are minimized (D), in this case, by rigid grains and well-developed grain coats.

compaction in shallow parts of a basin will not extrapolate successfully to deeper regions where high-temperature quartz cement begins to reduce porosity at very different rates from those associated with compaction. In addition, differences in textural and compositional attributes, some of them subtle, can significantly affect porosity-depth trends (Figure 1). Taylor et al. (2010, this issue) show geologic data sets with high-quality petrographic data, in which trends from shallow intervals break down with increasing burial depth. They also document how porosity-depth trends may vary significantly between basins even in shallow intervals, where compaction is the dominant control on porosity decline.

Most current first-principle geochemical models have limited predictive capabilities because they rely on laboratory-derived kinetic parameters and do not account for important changes in rock texture and pore-system surface area during the course of diagenetic alteration. These models sometimes ignore mechanical compaction, although that process is responsible for the greatest amount of porosity loss in most sandstones (Lundegard, 1991) and may significantly reduce reactive surface areas. In addition, such models do not consider the important impact that progressive development of overgrowth crystals can have on overall rates of reaction. For example, the results of Lander et al. (2008) imply that, other factors being constant, the average rate of quartz precipitation per surface area will decline by nearly an order of magnitude for quartzose sandstones as the cement reduces intergranular porosity (IGP) from 25 to 5%. This reduction in average rate arises because the proportion of nucleation area that is made up of slow-growing euhedral faces progressively increases as the overgrowth cementation proceeds.

Purely thermodynamic models are an inadequate basis for sandstone reservoir quality prediction because of the clear kinetic control on many important diagenetic processes such as quartz cementation (e.g., Walderhaug, 2000; Ajdukiewicz et al., 2010, this issue; Taylor et al., 2010, this issue; Tobin et al., 2010, this issue), plagioclase albitization (Perez and Boles, 2006), and fibrous illite formation (Franks and Zwingmann, 2010, this issue; Lander and Bonnell, 2010, this issue). Laboratory experiments that examine the kinetics of such geochemical reactions are an essential means for understanding the underlying processes. However, to our knowledge, geochemical models that rely on silicate reaction kinetics derived from laboratory experiments have yet to yield accurate predrill predictions for cement abundances. Compared with natural reactions in sandstone reservoirs, laboratory experiments typically occur at substantially higher temperatures during much shorter time intervals, involve conditions that are far from equilibrium, are undertaken on artificially cleaned materials, do not consider interactions among the full complement of phases typically present in reservoir sandstones, and ignore differences in euhedral and noneuhedral growth rates for overgrowth phases. These differences in conditions may profoundly alter experimental reaction kinetics compared with natural systems, resulting in reaction rates that are up to five orders of magnitude faster than those implied by constraints from geologic data sets, as discussed by Lander and Bonnell (2010, this issue).

Input to the new reservoir quality prediction models includes petrographic data describing sediment texture, composition, and early cement attributes, as well as burial history reconstructions. These data are integrated to simulate compaction and cementation effects on pore systems under changing effective stress and temperature conditions through time. Model output includes single-site or mapped distributions of subsurface porosity and permeability for a given input lithology at any location or over any surface within the burial history model and can be linked to paleogeographic maps or facies models to integrate depositional variability with burial effects. Models have been applied to numerous reservoir-quality predictive studies (Bjørkum et al., 1998; Bonnell et al., 1998, 2000; Lander and Walderhaug, 1999; de Souza and McBride, 2000; Walderhaug et al., 2000; Bloch et al., 2002; Taylor et al., 2004; Thomas et al., 2005), have been used inversely to help constrain thermal histories (Awwiller and Summa, 1997, 1998; Lander et al., 1997a, b), and have proven useful for understanding the interactions between diagenesis and structural deformation (e.g., Lander et al., 2002; Fisher et al., 2003; Laubach et al., 2004; Perez and Boles, 2005; Laubach and Ward, 2006; Makowitz et al., 2006, in press; Solano et al., 2008; Laubach and Diaz-Tushman, 2009; Olson et al., 2009; Becker et al., 2010). Taylor et al. (2010, this issue) provide examples of single-site predrill reservoir quality predictions, and Tobin et al. (2010, this issue) provide map-based predictions.

Although these new models are a significant improvement on previous predictive methods, they are still evolving as research addresses current limitations. At present, the models work best in sandstones in which reservoir quality is dominantly controlled by some combination of compaction, quartz cementation, or fibrous illite formation. However, some sandstone reservoirs are strongly affected by other processes that are not yet well constrained. For example, early diagenetic features such as grain coats, carbonate cements, and secondary porosity are accounted for in the current reservoir quality models through observations or analogs, rather than by a priori predictions. Improved models for early diagenetic attributes will allow more accurate reservoir quality predictions ahead of the bit in exploration settings where few calibration data are available and more detailed field-scale predictions of reservoir quality distribution that will be useful for geologic models and development plans. Research on this front is underway. For example, Ajdukiewicz et al. (2010, this issue) propose a model for controls on grain-coat coverage and resulting deep reservoir quality distribution in the Norphlet, and Morad et al. (2010, this issue) review known links between reservoir quality and mappable geologic features.

RESERVOIR QUALITY CONTROLS: INTERACTION OF DEPOSITIONAL, EARLY DIAGENETIC, AND LATE DIAGENETIC PROCESSES

Deep reservoir quality in sandstones is the cumulative product of depositional, shallow diagenetic, and deep-burial diagenetic processes. Lithologic attributes created at each stage strongly influence subsequent pore-system evolution. Provenance, transport, and depositional environment determine initial sediment texture, composition, porosity, and permeability. These depositional characteristics evolve with early compaction and interact with shallow groundwater systems to control fluid flux and geochemical reactions, influencing the type and abundance of early diagenetic attributes. Early diagenesis may be fluid dominated and open system, resulting in the dissolution of unstable grains to form secondary porosity and the precipitation of early cements such as grain-coating clays and carbonates (e.g., Bjørlykke 1993; Morad et al., 2010, this issue). Vadose zone processes such as clay infiltration also can be an important part of early diagenesis, as can biologically related processes including bioturbation or microbially driven chemical reactions (Worden et al., 2006).

Combined depositional and early diagenetic attributes can significantly affect deep-burial diagenetic pathways. For example, deep porosity preservation may be critically linked to early clay or microquartz grain coats. Because almost all quartz cement nucleates syntaxially on a quartz-grain substrate, both infiltrated and diagenetic grain coats inhibit later quartz cement in proportion to the amount of grain surface they cover. The effect of such early diagenesis on deep reservoir quality can be substantial: deeply buried, well-sorted quartzose sandstones in the Norphlet Formation with very continuous early grain coats may have intergranular porosities of more than 20%; whereas depositionally comparable samples with less continuous coatings have porosities of less than 2% (Ajdukiewicz et al., 2010, this issue). In another example, the extent of early feldspar dissolution to form kaolinite has a direct control on late fibrous illite occurrence. High-temperature fibrous illite may reduce the permeability of a deeply buried sand by several orders of magnitude. Because fibrous illite typically forms by the reaction of kaolinite with K-feldspar, illite will tend not to form in (1) sandstones lacking feldspar at the time of deposition, (2) settings where no early feldspar alteration occurs, or (3) settings where all feldspar is altered during early diagenesis (Chuhan et al., 2000, 2001; Franks and Zwingmann, 2010, this issue; Ajdukiewicz et al., 2010, this issue; Lander and Bonnell, 2010, this issue). Morad et al. (2010, this issue) provide a comprehensive review of how initial sediment composition, depositional environment, and sequence-stratigraphic setting influence the early diagenesis of sandstones and subsequent late diagenetic pathways.

CURRENT RESERVOIR QUALITY MODEL CONCEPTS

The new generation of reservoir quality models are based on burial diagenesis concepts developed since 1990. As discussed by Taylor et al. (2010, this issue), earlier concepts prevalent in the 1980s held that (1) the extent of porosity loss with depth is controlled by the influence of compaction, with intergranular quartz pressure solution linked to quartz cementation at depth; and (2) deep porosity, where it occurs, mainly results from the dissolution of unstable grains or early nonquartz cements as a result of interaction with migrating organic acids.

By contrast, the current paradigm, built on thousands of petrographic observations from reservoirs around the world is that (1) most deep porosity in conventional sandstone reservoirs is preserved primary, with maximum porosity preserved where compaction and quartz cementation are most limited; and (2) most deep quartz cement forms in a slow continuous process related to burial temperature rather than to in situ grain-to-grain pressure solution or to episodic fluid flux. Two sets of conceptual breakthroughs, one related to compaction and the other to quartz cementation, led to the development of this new view, as discussed below.

Compaction

Grain size, sorting, shape, and matrix content determine the initial space among the sand grains, measured as the intergranular volume (IGV) of the sediment (Weller, 1959; Houseknecht, 1987; Paxton et al., 1990, 2002). In clean sands with no matrix or cement, IGV equals IGP. With burial, IGV and IGP decrease, initially as a function of mechanical compaction under overburden, during which grains become more closely packed. A breakthrough concept for current models was derived from the observation that in clean, well-sorted, quartz-rich sandstones with little early cement, mechanical compaction does not lead necessarily to chemical compaction but can stabilize at values approximating closest packing (26% IGV), commonly achieved by 2 km (1.2 mi) burial depth (Szabo and Paxton, 1991; Lander and Walderhaug, 1999; Paxton et al., 2002). Sandstones with ductile grains such as shale clasts or lithic fragments experience more extensive compaction and lower IGVs and IGPs than their rigid-grained counterparts under the same burial conditions (Rittenhouse, 1971). The influence of ductile grains on compaction is a function of their mechanical properties and abundances, as well as effective stress (e.g., Pittman and Larese, 1991). Overpressure can inhibit compaction by reducing effective stress, but only if introduced before extensive mechanical compaction has occurred (Paxton et al., 2002; Bloch et al., 2002).

Cementation

The second major conceptual breakthrough for the new paradigm was the idea that in sandstones at temperatures in excess of 60 to 80°C, quartz cement overcomes kinetic inhibitions and begins to precipitate on available quartz grain surfaces as a predictable function of time, temperature, quartz grain surface area (Walderhaug, 1994a, b; 1996; 2000), and nucleation domain size (Heald and Renton, 1966; Makowitz and Sibley, 2001; Lander et al., 2008). Various factors can inhibit quartz cement growth. The most widespread of these are early formed grain coats, most commonly of infiltrated or diagenetic clays (Heald and Larese, 1974; Pittman et al., 1992), as previously discussed.

These two concepts lie at the core of the new reservoir quality–predictive tools. Intergranular porosity is predicted as a function of calculated IGV minus calculated cement abundance (Lander and Walderhaug, 1999). Over the years, the application of these tools to a range of lithologies and burial conditions has allowed the concepts underlying the models to be tested against alternative hypotheses for deep reservoir quality controls (e.g., Aase and Walderhaug, 2005; Bonnell et al., 2006; Makowitz and Sibley, 2001). Myths and realities associated with various proposed deep porosity controls, such as late dissolution of early cements and cement inhibition by early emplaced hydrocarbons, framework grain dissolution, decreased thermal exposure, and grain coatings are discussed by Taylor et al. (2010, this issue).

FUTURE DIRECTIONS

In the future, we expect that reservoir quality models may be extended to consider the impact of additional diagenetic processes, linked to depositional models, integrated with petrophysical and geophysical formation characterization and geomechanical models, and applied to the exploration and production of tight gas sandstones.

Continued Model Improvements

An important extension of the new reservoir quality modeling approach will be the incorporation of reaction transfer models (Taylor et al., 2010, this issue). Key differences compared with existing reaction transport models will be (1) the integration of the more sophisticated compaction, quartz cementation, fibrous illite formation, microporosity, and permeability models from reservoir quality models; (2) the use of geologic data sets rather than laboratory data to constrain reaction kinetics; and (3) the greater emphasis on predicting not only bulk mineralogical composition, but also sandstone texture and the impact that this texture has on reactive surfaces and bulk rock properties. This combined approach will improve predictive capabilities in geologic settings with significant material fluxes. Such settings include shallow groundwater, soil, and vadose zones (e.g., Ajdukiewicz et al., 2010, this issue); regimes with substantial topographic drive for flow; fault-related flow (as discussed by Taylor et al., 2010, this issue); diffusive transfer associated with interbedded lithologies (e.g., Thyne et al., 2001); and thermohaline circulation near salt structures (e.g., Hanor, 1987). This modeling approach may be augmented by incorporation of models of biogeochemical processes for use in predicting the occurrence and distribution of early grain coats, carbonate cementation and dissolution, secondary porosity development, and the occurrence of some types of diagenetic kaolinite and chlorite.

Several kinetically controlled silicate reactions have yet to be accounted for in reservoir quality prediction models. Although a model has recently been published describing the kinetics of plagioclase albitization in natural sandstones (Perez and Boles, 2006), no comparable model has been developed for the albitization of K-feldspar. In addition, predictive kinetic models are still lacking for the occurrence of zeolites such as clinoptilolite, analcime, and laumontite in sandstones and the extent of compaction associated with illitic grain coatings (e.g., Bjørkum, 1996).

Improvements to Models That Predict the Spatial Distribution, Texture, and Framework Grain Composition of Sandstones

Sandstone depositional composition and texture are essential input for the current generation of diagenesis/reservoir quality models. Reservoir quality prediction models in the broader sense, therefore, should encompass those processes that control lithologic character at deposition. Forward depositional models provide a rigorous means for predicting the spatial distributions and textures of sandstones (e.g., Granjeon and Joseph, 1999; Griffiths et al., 2001; Sømme et al., 2009). A shortcoming in the current generation of such models, however, is that they do not predict framework grain compositions and textures at the level of detail required for diagenetic modeling. One potential means of addressing this problem would be the incorporation of a promising new approach developed by Heins and Kairo (2007) for predicting framework grain compositions based on sediment provenance, climate, transport distance, and other factors into depositional models.

Use of Reservoir Quality Model Predictions As Input for Rock Physics and Petrophysics Models

Integrated reservoir quality/rock property models may provide an important means for improving reservoir characterization by predicting log and seismic properties. In addition, such models could provide a unique method for reconstructing geomechanical properties through geologic time. The present-day characteristics of sandstone reservoirs may differ substantially from the rock characteristics during the time of reservoir deformation. Thus, integrated reservoir quality and rock property models could constrain input for geomechanical models that aim to predict fault or natural fracture characteristics (Laubach et al., 2009).

Application of Reservoir Quality Models to Unconventional Reservoirs

The methods and tools developed for conventional reservoir quality prediction can be extended to prediction of sweet spots related to porosity in, and hydraulic fracture behavior of, unconventional reservoirs as discussed by Tobin et al. (2010, this issue). In addition, this modeling approach provides a means to improve the understanding of the origin of petroleum systems in tight gas plays by reconstructing reservoir properties at the time of hydrocarbon incursion (Tobin et al., 2010, this issue).

CONCLUSIONS

Advances in the understanding of diagenetic processes have led to substantial improvements in the prediction of sandstone reservoir quality. The integration of high-quality petrographic data with burial history reconstructions to construct and calibrate predictive models has been crucial to successful prediction. A principal conclusion from the application of the new models to multiple reservoirs under varied burial conditions is that the commonly applied term "anomalous porosity" is a flawed concept, apart from the narrow statistical sense of the term. All observed values of reservoir porosity should be predictable as a logical consequence of depositional, early diagenetic, and late diagenetic processes. What has been described as anomalous porosity is in fact the high end of the range of possible outcomes, where a particular combination of grain size, sorting, composition, early diagenesis, and burial history have acted together to minimize the effects of compaction and cementation and preserve the greatest amount of porosity and permeability at depth.

APPENDIX

Articles in this issue

Ajdukiewicz, J. M., P. H. Nicholson, and W. L. Esch, 2010, Prediction of deep reservoir quality using early diagenetic processes in the Jurassic Norphlet Formation, Gulf of Mexico: AAPG Bulletin, v. 94, p. 1189–1227, doi:10.1306/04211009152.

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