Diagenesis and Depositional Heterogeneities: Reviewing a Complex Issue in Reservoir Modeling of Mature and Marginal Assets*

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Introduction

The construction of realistic geologic models that encompass the diagenetic impact on reservoir quality is one of the challenges these days. Depositional and/or stratigraphic architecture defines the main heterogeneities and frequently is the dominant control on quality distribution. However, diagenesis may substantially modify the distribution of porosity and permeability (Worden et al., 2000; Salem et al., 2000). In most cases, highly porous and permeable depositional facies tends to retain these qualities after burial, but they can also be affected by strong diagenetic changes, which could result in their even becoming flow barriers. Diagenesis may also enhance the reservoir heterogeneity by increasing the permeability contrast between adjacent facies (Hamilton et al., 1998). Thus, the present-day porosity and permeability distribution may or may not have direct relationship with the original depositional distribution (Primmer et al., 1997; Morad et al., 2000; Lee et al., 2002; Taylor et al., 2004). Besides porosity and permeability, diagenesis may also affect other petrophysical parameters, such as initial saturation, wettability, and capillarity. Although the oil industry recognizes this importance, only in a few cases is the diagenetic impact correctly addressed in modeling (Evans, 1987).

The objective of this article is to summarize how diagenesis should be addressed during the construction of a reservoir model (e.g., a flow-unit model). Reviewed is the hierarchy of the depositional heterogeneities in which the diagenetic model should be built. Many of these discussions are already known, but I think that a brief review of them is necessary to homogenize some concepts and “jargons” between geologists and engineers. For instance, geoscientific literature was not able to provide a simple and reasonable framework that combines depositional heterogeneity and sequence stratigraphy for modeling purposes. As a result, geologists may face problems in trying to explain to engineers the differences between the depositional and stratigraphic hierarchies as they were created to answer different questions.

This integrated analysis is especially important in mature projects where, although a higher detailed reservoir characterization is needed, economic constraints are also part of the reality. A better reservoir model built in a satisfactory scale is the objective that all modelers should pursue to make these marginal projects viable.

Hierarchy of Depositional Heterogeneities: Framework for Integrating Diagenetic Impact on Reservoir Quality

Realistic geologic models are fundamentally based on depositional heterogeneities and the spatial relationship between the sand bodies and non-reservoir rocks. This approach allows the interpreter to correctly define the most important discontinuities that are going to be considered in the model. As a consequence, the reservoir model, expressed by flow units, will capture the essential aspects that affect fluid flow displacement in subsurface. Diagenetic impact should be assessed, described, and integrated in the model but in many cases this is not what happens.

One of the main reasons for this failure in the process is determining the scale at which diagenesis becomes important. At what scale diagenesis can be neglected? A model should be scale-dependent especially in correctly translating what the geologist describes in terms the engineer will understand and ultimately add value. Thus, the depositional framework must be constructed on a working scale that is appropriate for the problem being addressed (Van de Graaff and Ealey, 1989; Slatt and Hopkins, 1990), such as exploration, appraisal, field development, and Improved Oil Recovery/Enhanced Oil Recovery (IOR/EOR) projects. A dependable hierarchical analysis defines key heterogeneities, as well as less important reservoir discontinuities that may be neglected for modeling purposes. Once this geologic framework is established, the interpreter must find the correct scale to address the diagenetic impact. Figure 1 shows a simplified hierarchy of depositional heterogeneities from individual lithofacies to basin-filling scale. The hierarchical relationship between these heterogeneities and traditional sequence stratigraphy may also be appreciated. Reservoir heterogeneities due to tectonic imprint are not addressed in this article.

In a practical view, diagenesis may modify reservoir quality in two ways (Figure 2): a) it promotes changes in the original distribution of the petrophysical parameters that follow the depositional architecture, including the depositional facies and stratigraphic framework, or b) it promotes changes that do not follow the depositional architecture, which creates a new reservoir-quality framework (as described subsequently).

The first type of modification seems to be common for many siliciclastic reservoirs. In those, eodiagenesis (sensu Morad et al., 2000) is the most important stage of the diagenetic evolution, and the diagenetic process is strongly controlled by physical, biological, and geochemical constraints that are defined by the depositional environment. In such a context, reservoir-quality distribution may be predictable through sequence stratigraphic analysis (Ryu and Niem, 1999; Ketzer et al., 2004; El-ghali et al., 2006). However, during the development stages of a reservoir, a higher-resolution analysis is needed to properly integrate the diagenesis. Thus, the diagenetic imprint on reservoir quality in such projects should be constrained at the fifth-order heterogeneity level (architectural element association or sub-environment of deposition, Figure 1); this may be taken as a proxy for “flow unit,” as commonly addressed by engineers. As a result, “flow unit,” if it follows these principles, is a scale-dependent component of a reservoir model.

Diagenesis can be integrated through the use of reservoir-petrofacies concept (De Ros and Goldberg, 2007; Daudt, 2009). These descriptive elements are defined by a combination of attributes that control the porosity and permeability distribution in petroleum reservoirs (De Ros and Goldberg, 2007). Such attributes are a) depositional structures, textures, and composition; volume, b) intensity, habitats, and distribution of diagenetic processes and products (defined by Primmer et al., 1997 as diagenetic style), and c) the distribution of different pore types. Preliminary petrofacies are determined through the systematic attribute description in representative samples collected in each flow unit, followed by recognition of which attributes have larger impact on porosity and permeability. Petrofacies, now associated within each sub-environment of deposition, are then checked against petrophysical and petrographic quantitative parameters by using statistical tools. Threshold values for the influent textural and compositional attributes and ranges of porosity and permeability, per flow unit, may be subsequently defined (Lima and De Ros, 2002). For modeling purposes, the interpreter can assume that one flow unit is composed by a combination of reservoir petrofacies, and the statistical treatment of their petrophysical and diagenetic elements results in representative reservoir-quality indexes. This method guarantees consistency in terms of petrophysical properties, and wireline-log signatures (De Ros and Goldberg, 2007).

The use of the high-resolution stratigraphy and reservoir petrofacies combined (Goldberg et al., 2008; Daudt, 2009) constitute a powerful tool for reservoir characterization, as well as quality prediction, especially in complex settings. As sub-environments of deposition may be easily recognized in wireline logs, mapping these intervals will allow the recognition of reservoir-petrofacies association present within them. Dynamic data provided by engineering, such as production through time, flow tests, oil and water geochemistry, repeated formation surveys, injectivity logs, tracer surveys, and temperature logs, should be incorporated at this level to corroborate or adjust the geological model.

When diagenesis does not follow the depositional architecture, the distribution of reservoir quality may be far more difficult to predict. In such cases, a comprehensive understanding of the petroleum system is necessary, along with its evolution, in order to support a realistic flow-unit definition. One interesting example is presented by Taylor et al. (2004) for the complex diagenetic evolution of Norphlet sandstone (Jurassic, Gulf of Mexico), which resulted in a porous reservoir section (oil-bearing) that underlies a tight zone (gas-bearing). The reservoir-quality evolution, according to those authors, shows no relationship to the depositional facies distribution, but rather to the distribution of the vadose and phreatic zones during eodiagenesis. Thus, in this case, flow units are independent of the depositional framework.

Differences in timing in hydrocarbon emplacement are also responsible for diagenesis with no depositional control. Oil-bearing sandstones are normally less affected by diagenetic processes than the underlying aquifers (Yurkova, 1970; Bruhn et al., 1998; Worden and Burley, 2003). Early oil emplacement is believed to inhibit or even stop the diagenetic processes. Marchand et al. (2001) showed in a study on diagenesis in the Brae Formation, North Sea, that progressive oil-charging has slowed the rate of quartz cementation in these deep-water sandstones. In extreme cases, this deceleration could even completely halt the diagenetic process, favoring porosity preservation in the crestal part of deeply buried sandstones.

This discussion on the potential of early oil migration in terminating diagenesis and, thereby, preserving higher porosity and permeability is still a matter of considerable debate. Presently, the predominant interpretation is that oil emplacement does inhibit the diagenetic process, by reducing the flow of aqueous fluids and the amount of precipitation. However, this process cannot fully prevent diagenesis, except at very large oil-saturation values, because diagenesis cannot proceed in the thin, irreducible water films. This is well illustrated by the occurrence of oil inclusion within diagenetic minerals in some reservoirs (e.g., Saigal et al., 1992; Worden et al., 1998).

Final Comments

The integration of the diagenesis in a reservoir model is still an open question; there are lots of uncertainties and challenges to be overcome. This is especially true in mature assets, although they may still contain huge amounts of hydrocarbons, for which new technological and/or methodological solutions for their recovery are needed. In such projects, normally with strong economic constraints, a reasonable geologic model should be built at an architectural element-association level (hierarchy 5 in Figure 1), generating a reservoir model (flow unit) that is essentially scale-dependent. Diagenetic impact can be integrated at this level of heterogeneity, through the use of reservoir-petrofacies concept. This approach assumes that a flow unit is composed of an association of reservoir petrofacies from which reservoir-quality indexes can be obtained by statistical analysis. Dynamic data must be used to check and/or adjust the reservoir model in the phases that follow.

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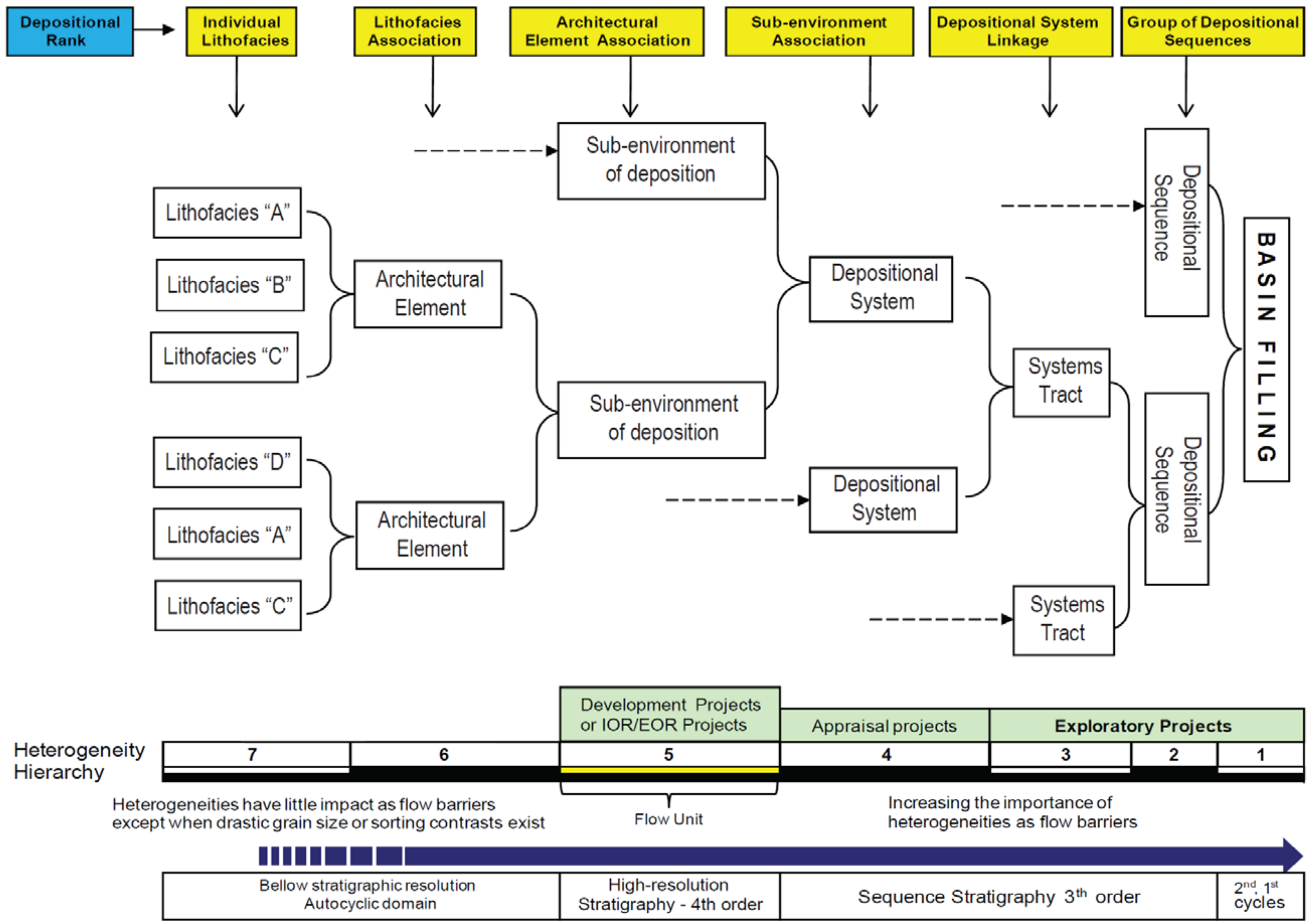

Figure 1. Hierarchy of depositional heterogeneities defined in this article. The flow unit "level" is related to the 5th order of heterogeneity and corresponds to the 4th-order high-resolution sequence stratigraphic unit.

Diagenetic Style	Diagenetic Stage	Hierarchy of heterogeneities	Genesis of heterogeneities	Flow Unit	Applicability	References
Diagenesis follows depositional and stratigraphic framework	Eodiagenesis predominates	Heterogeneity 4 (3rd order sequence stratigraphy)	Base-level variations (tectonic and sea level)	"Conceptual" Flow Units Regional approach.	Exploration Basin Analysis Appraisal	Ryu & Niem, 1999; Ketzer et al., 2004; El-ghali et al., 2006
		Heterogeneity 5 (4th order sequence stratigraphy)	Base-level variations (tectonic and sea level) Autocyclic controls (?)	Flow Units for modeling. Architectural element assoc. Use of reservoir petrofacies	Reservoir development	Goldberg et al., 2008; Daudt, 2009
Diagenesis does not follow depositional and stratigraphic framework	Meso- and telodiagenesis predominate	Variable	Thermal maturation; Timing of oil emplacement; fluids defining different zones	Case by case definition	Reservoir development	Bruhn et al., 1998; Taylor et al., 2004;
	Telodiagenesis predominates	Variable	Tectonics (fractures, faults, etc)	Not discussed in this paper	Basin analysis (geochemistry) Appraisal Reservoir development	Nelson, 2002; Lorenz et al., 2002

Figure 2. Differences in diagenetic style and consequences in the flow unit model.