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Building more realistic siliciclastic reservoir models through integration of depositional and diagenetic heterogeneities in a flow unit approach

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Abstract-It is presented an approach for reservoir characterization and development based on the analysis of depositional reservoir heterogeneities, their hierarchy, and how these heterogeneities should be addressed in a flow unit model. Genetic flow units, as used in this paper, are scale-dependent elements that correspond to sub-systems of deposition (association of architectural elements), part of fourth-order sequence-stratigraphic units. They are used to provide consistent geologic controls for reservoir quality correlation at oil-field scale, especially during IOR/EOR (improved or enhanced oil/gas recovery projects). This scale dependency contrasts with the previous flow unit models. The predictive capacity of such model based on genetic flow unit relies on the recognition of genetic flow units in wireline log patterns, within a high-resolution stratigraphical framework. Diagenesis, sometimes a pervasive process responsible for strong porosity and permeability changes, is also discussed in this article, with emphasis to the integration of this kind of analysis in the reservoir modeling process. In some cases, the diagenetic impact or a post-depositional process (fracturing, for instance) may compromise the applicability of the genetic flow unit approach as proposed here.
Key words: reservoir heterogeneities, diagenesis, flow units, reservoir quality.

Resumo - A CONSTRUÇÃO DE MODELOS REALÍSTICOS DE RESERVATÓRIOS SILICICLÁSTICOS ATRAVÉS DA INTEGRAÇÃO DE ESTUDOS DAS HETEROGENEIDADES DEPOSICIONAIS E DIAGENÉTICAS EM UMA ABORDAGEM DE UNIDADE DE FLUXO. Nesse artigo, é apresentada uma abordagem para caracterização e desenvolvimento de reservatórios baseada na análise de heterogeneidades deposicionais, suas hierarquias e como essas heterogeneidades devem ser focadas em um modelo de unidade de fluxo. O termo unidade de fluxo genética como utilizado nesse artigo representa um elemento que tem uma escala definida, correspondendo a um subsistema de deposição (associação de elementos arquiteturais), parte de uma unidade estratigráfica de quarta ordem. Essas unidades são utilizadas para prover controles geológicos consistentes para a análise da variabilidade da qualidade do reservatório, em escala de campo de petróleo, especialmente em projetos que estejam em estágios de melhoria avançada de recuperação de fluido. Essa necessidade de dependência de escala para a definição das unidades de fluxo contrasta com as definições anteriores. A capacidade preditiva de um modelo baseado em unidades de fluxo genéticas reside no reconhecimento dessas unidades em perfis elétricos, considerando um arcabouço de estratigrafia de alta resolução. O impacto dos processos diagenéticos nas variações entre porosidade e permeabilidade também é discutido nesse artigo, com ênfase na integração dessa análise ao processo de modelagem de reservatórios. Em alguns casos, o efeito da diagênese ou de outros processos pós-deposicionais (fraturamento, por exemplo) pode comprometer a aplicabilidade da abordagem por unidades de fluxo genéticas como é proposto aqui.
Palavras-chave: heterogeneidade de reservatório, diagênese, unidade de fluxo, qualidade de reservatório.

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1. Introduction

Reservoir characterization studies are increasing the interaction between reservoir geologists and engineers. These integrated studies aim to develop realistic models for dynamic simulations that are used for production strategies. It is well known that reservoir performance is the product of a complex equation that includes the relationship between static, geologically-defined units and dynamic, engineering constraints. Reservoir performance forecasts are very sensitive to the method that is used to represent the reservoir geology in the simulator (Guangming *et al.*, 1995).

Improved reservoir description and characterization certainly reduces the amount of hydrocarbons that is left behind in the reservoirs (Amaefule *et al*., 1993).

In such a context, the characterization of flow units may be considered to be the ultimate gap between the static and dynamic aspects of reservoir modeling. However, the conventional flow unit concept was essentially created by engineers as an independent approach, many times ignoring the role of geological attributes on reservoir performance (Lawal & Onyekonwu, 2005). This resulted in flow unit models without a comprehensive geological background and led to unreliable predictions in the numerical simulations. Consequently, some relatively recent literature (e.g., Mikes & Geel, 2006; Mikes and Bruining, 2006) has recognized that the engineering models that are based upon productive behavior alone are too simple to represent the geological complexity of true reservoirs.

Fortunately, there have been some visible, recent changes towards developing and using more consistent and realistic models. In 3D geocellular time, flow units are the materialization of a discrete framework of static models in a multiscale geological approach. Based on it, reservoir interpreters determine porosity, permeability (continuous parameters), characterizing pore throat distribution, capillarity curves and saturation values per flow unit. Although it may seem a paradox, the definition and spatial distribution of flow units, which have a dynamic connotation, may be considered to be the last geological (static-related) task before delivering the model for simulations. Thus, a flow unit model is clearly the best way to improve communication between geologists and engineers in integrated studies.

In this process, the static model that is defined by geologists must consider different aspects of reservoir heterogeneity on a working scale that is appropriate for the problem being addressed (Van de Graaff & Ealey, 1989; Slatt & Hopkins, 1990), such as exploration, appraisal, field development, and IOR/EOR projects. A consistent hierarchy analysis defines key heterogeneities that have a strong impact on fluid displacement within the reservoir, as well as less important heterogeneities that may be neglected for modeling purposes.

The objective of this paper is three-fold. The first objective is to present a hierarchical scale for depositional reservoir heterogeneities for field development, emphasizing IOR/EOR projects. We also present an attempt to clarify the relationship between reservoir heterogeneity and traditional sequence stratigraphy. The second objective is to discuss how the concepts that are used by geologists to define reservoir heterogeneity may be incorporated into flow unit models. Some previous flow unit definitions and their conceptual inconsistencies are analyzed, and new approaches are proposed. The genetic flow unit is used here as a modified term that is substantially based in robust sedimentologic and stratigraphic analysis. The third objective is to present a brief discussion on how diagenesis may be approached from a flow unit perspective and to examine particular cases that cause variations in the models.

2. Static model: geology

2.1. Importance of reservoir heterogeneity in hydrocarbon production units

Reservoir heterogeneity characterization is fundamental in the modern modeling process. The early recognition of compartments within the reservoir and the assessment of their impact on fluid flow define the most efficient strategies for reserve development (Tyler & Finley, 1991; Knox & Barton, 1999) through the improvement of the understanding of future reservoir performance (Gunter *et al*., 1997). Heterogeneities affect both the storage capacity of reservoir intervals (the original oil in place or OOIP), as well as the production rate. Other effects, such as system wettability and relative permeability, can also control the speed at which fluids move within the reservoir.

The characterization of heterogeneities is a geological task, which is a “static” approach that is used to understand the reservoir complexity. It is referred to as “static”, because the distribution of geological reservoir heterogeneities is unlikely to change during hydrocarbon production. Integration of data and information from different sources and scales is necessary to characterize reservoir heterogeneities, including core and outcrop description, wireline logs interpretation, petrophysical analysis, and the use of analogous reservoirs.

As suggested in many previous papers (Tyler & Finley, 1991; Moraes & Surdan, 1993; Hamilton *et al*., 1998, etc), reservoir heterogeneity represents everything that disrupts the fluid flow within a reservoir. Depositional heterogeneities may be inherent to any depositional system (Slatt & Galloway, 1992). The term “reservoir heterogeneity” is often imprecisely used, and without a clear hierarchical control. The genesis of such heterogeneities is related to sedimentology (facies and facies associations, depositional or architectural elements, etc), stratigraphy (key surfaces that are forming the stratigraphic framework, facies stacking patterns, etc), diagenesis (types and distribution of diagenetic components, different reservoir petrofacies associations, etc), tectonics (structural pattern, presence of faults, etc) or more commonly, a combination of some or all of them. Structural heterogeneities are not going to be fully addressed in this article although they are undoubtedly very important in some reservoirs (cf. Laubach *et al*., 2008). Faults and fractures may affect a reservoir during or after the diagenetic processes, by generating new storage and flow capacity that will be different from the quality distribution of original reservoir (Nelson, 2002).

Lately, the importance of studies that focus on the hierarchy of depositional heterogeneities has increased substantially, as they can define different reservoir compartments with different petrophysical properties or reservoir qualities. Several seminal works described depositional heterogeneities according to the importance of their bounding surfaces or the time lapse involved in their generation. The pioneering work of Jackson (1975) established formal differences between physical and time of bed formation scales, classifying them as microforms, mesoforms, and macroforms. Similar approaches were presented by Brookfield (1977) for eolian deposits and by Allen (1980, 1983) for fluvial successions. Both authors recognized that differences in scale might be preserved in bounding surfaces that separate different depositional units. This subject was further developed in the 1980´s by Miall, who proposed hierarchical models for fluvial deposits (the four-fold model of 1985, the six-fold model of 1988a and 1994, and the eight-fold model of 1996). Miall (1988b) also presented an excellent discussion on the identification of heterogeneities in outcrops, expressing the importance of proper characterization and hierarchization of bounding surfaces.

Some of the depositional heterogeneities recognized in those previous works do not have a significant impact during reservoir production. This issue may be approached from a twofold perspective: (a) what are the heterogeneities that really impact fluid flow within the reservoir and (b) what is the optimum detail of the geologic model considering the effectiveness of its results and the computational limitations. The main points under consideration here are "what heterogeneity to honor and how to describe it" (Srivastava, 1994). Computational limitations are evident when highly detailed geologic models become very difficult to be handled in simulators, which creates a need to simplify them. As a consequence, some of the small-scale heterogeneities that were described by Miall (e.g. first, second, and even third- orders in his models of 1985, 1988a and 1996), may be neglected. These heterogeneities show practically no impact on fluid flow during IOR/EOR projects, since they do not separate domains of different petrophysical properties. Additionally, some of these surfaces are rarely identifiable in wireline logs, and thus their definition is not practical during modeling.

Despite their lesser importance, studies on the impact of small-scale heterogeneities in fluid flow were not always neglected in the literature. Kortekaas (1985) showed that there might be some differences in recovery if specific directions of the cross bedding are considered. Following an approach similar to that of Weber (1982) and Evans (1985), Kortekaas (1985) demonstrated, through a conceptual simulation, that the parallel flow tends to be more effective in terms of oil displacement than the flow perpendicular to the foreset laminae. That author concludes that this is due to permeability variations that are observed in cross bedding. In this paper, this level of heterogeneity is disregarded, because it is believed that the flow will respond to major elements, as will be addressed in the following sections, especially where no significant grain size or sorting variations are presented. Small scale elements such foreset laminae are grouped in thicker units that may be defining a semi-regional or regional trend that will be more influential in the fluid flow.

Other interesting attempts to understanding the depositional heterogeneities in a hierarchical perspective were provided by Begg *et al.*, 1996; Kuchle & Holz, 2002; Bongiolo & Scherer, 2003, 2010; Slatt *et al.*, 2009;). For instance, Begg *et al.* (1996) presented an interesting model for reservoir characterization that included lithotypes grouped into major facies associations, elements that were used as proxies of genetic flow units. Kuchle & Holz (2002), working in the Paraná Basin, defined 5 levels of reservoir heterogeneity based on core descriptions that would be suitable for that aquifer exploitation. More recently, Slatt *et al.* (2009) presented a threefold hierarchical scale to exemplify how different levels of heterogeneity may impact or result in variability in acoustic and petrophysical properties. For different reasons, some of these examples failed to show a clear depositional-based scale of reservoir heterogeneity that encompass the building block perspective that is crucial for reservoir modeling (for instance, Slatt *et al.*, 2009). Others did not present a universal classification for reservoir heterogeneity, focusing on their specific reservoir or project (for instance, Bongiolo & Scherer, 2003, 2010).

2.2. Scales of building blocks

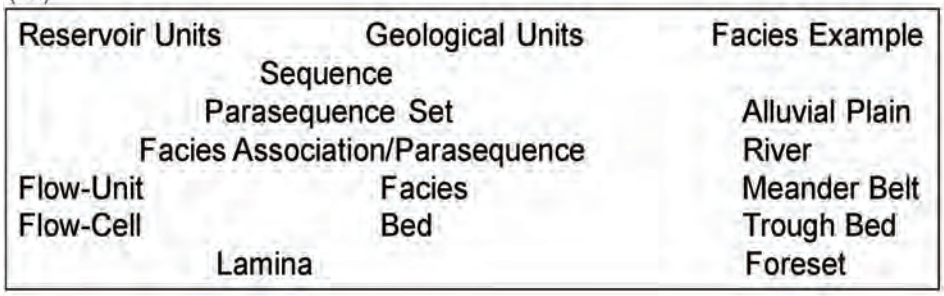
A hierarchical analysis of reservoir heterogeneity should be performed from the elemental heterogeneity (higher frequency heterogeneity) to large-scale, regional element (lower frequency heterogeneity). This approach supports the development of predictive models that allow the recognition of similar heterogeneities or compartments in new areas, or in situations with limited available data. Consequently, the flow unit framework will also be predictive in nature, which is a very useful characteristic for reservoir modeling.

In complex settings, the definition and hierarchization of heterogeneities is not always straightforward. Although complexity may imply in a large number of geological aspects, in general this term is related to the variability of the depositional systems, the stratigraphic organization, and the diagenetic impact on reservoir, which are all features that can affect and modify the porosity and permeability distribution (Slatt, 2006).

Another important concern of the petroleum industry is the need to perform upscaling of the geologic model due to the already mentioned computational limitations. Slatt & Hopkins (1990) argue that many geologic models are too detailed and are often not in an appropriate format for reservoir simulation. Conversely, in some cases, the geology complexity is oversimplified in the upscaling process (Mikes & Bruining, 2006), which can lead to some important heterogeneities being underestimated and becoming “technically invisible”. Incomplete stratigraphic analysis, incorrect definition of sand body geometry, simplification of the diagenetic imprint, a lack of a precise heterogeneity hierarchy, and even conceptual misuses can all create potential problems. Mikes *et al*. (2006) considered a six-fold model of heterogeneity as an approach for permeability upscaling (Fig 1A). In fact, the hierarchical framework that has been proposed in order to establish the basis for upscaling is somewhat questionable in terms of geological significance. In a stratigraphic sense, a facies association, or lithofacies association, is not a parasequence but rather represents an architectural element.

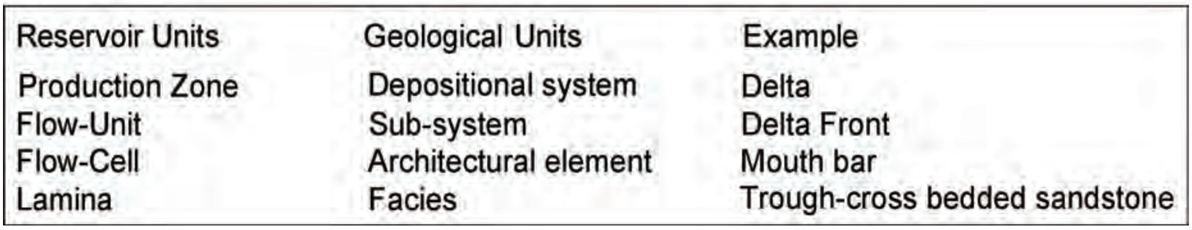
On the other hand, parasequences are defined by the association of several depositional sub-systems. Those authors also suggested that a facies (a geologic unit) may define a flow unit (a reservoir unit) and used a meander belt as an example. A meander belt is a deposit that is compounded by one or more point bars, which, in turn, are architectural elements. One architectural element is composed of several lithofacies, not just one. However, we agree that an association of architectural elements (their meander belt example) may define a flow unit, as will be discussed further on. Just for reference, our view of an approach with similar objective may be seen in figure 1B, where flow units may be combined to form “production zones”.

(1a)



Reservoir Units	Geological Units	Facies Example
	Sequence	
	Parasequence Set	Alluvial Plain
	Facies Association/Parasequence	River
Flow-Unit	Facies	Meander Belt
Flow-Cell	Bed	Trough Bed
	Lamina	Foreset

(1b)



Reservoir Units	Geological Units	Example
Production Zone	Depositional system	Delta
Flow-Unit	Sub-system	Delta Front
Flow-Cell	Architectural element	Mouth bar
Lamina	Facies	Trough-cross bedded sandstone

Figure 1. A) Six-fold model of reservoir heterogeneity proposed by Mikes *et al.* (2006). It is possible to identify some problems related to the correct definition of the geologic constrains, as well as depositional and stratigraphic hierarchies (see discussion in the text). B) Similar approach according to the authors of this article.

Although there are many published papers dealing with reservoir heterogeneity and hierarchization of it (Jackson, 1975; Brookfield, 1977; Weber, 1982; Evans, 1987; Miall, 1988b; Slatt & Hopkins, 1990; Tyler & Finley, 1991; Slatt & Galloway, 1992; Gosh & Lowe, 1993; Slatt *et al*., 2009, among others mentioned in this article), it seems that some updating and standardization is necessary. Our intention here is to provide and review a generalized structure for heterogeneity hierarchization, regardless the depositional environment and applicable to any field-scale management, emphasizing the use in IOR/EOR projects. Also, in this article we present the relationship between reservoir heterogeneity and traditional sequence stratigraphy, a link that many times is lost or misunderstood. In this framework, the first-order was considered the most important reservoir heterogeneity level, in contrast to the models that were presented by Miall (1985, 1988a, 1996) and by Ghosh & Lowe (1993). This approach seems to be more appropriate, as it follows the most widely used stratigraphic hierarchy (Vail *et al*., 1977; Duval *et al*., 1992). The proposed reservoir heterogeneity hierarchy is shown in figure 2**,** which also shows the genetic flow unit domain that will be discussed later.

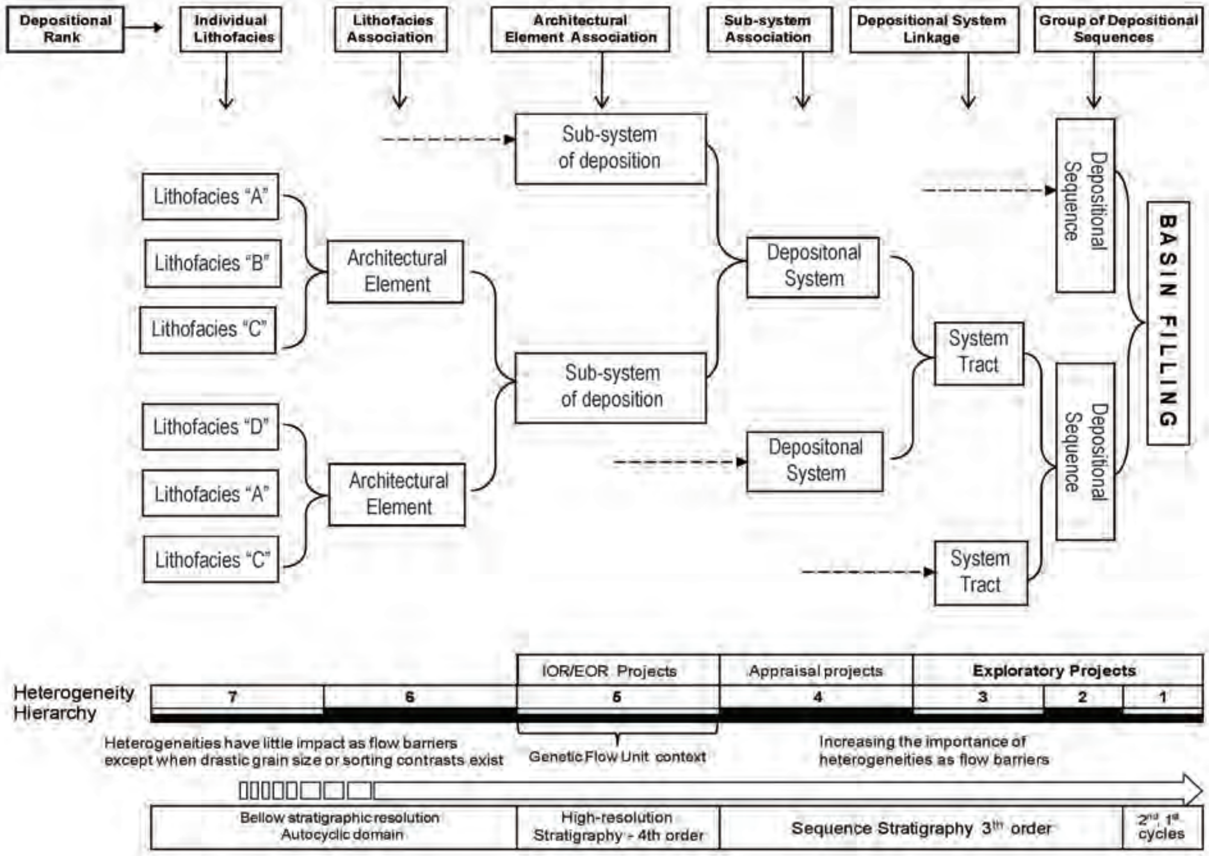


Figure 2. Hierarchy of depositional heterogeneities defined in this article. The genetic flow unit is related to the fifth-order of heterogeneity and corresponds to the fourth-order high-resolution sequence stratigraphic unit (modified from Daudt, 2011).

2.2.1. *Seventh-order: unitary facies (lithofacies)*

In a hand-scale analysis, a single facies represents the smallest building block of the sedimentary record (Walker, 2006; Slatt *et al*., 2009). Thus, a single facies is potentially the most elemental reservoir heterogeneity that may affect the fluid flow within a reservoir (Galloway & Hobday, 1996).

In siliciclastic deposits, one facies may be the result, for instance, of the dynamics of sand movement and deposition, which generates a bed form. Ashley (1990) showed that the interaction between flow velocity and grain size produces different types of bed forms, which can range from ripple marks to 3D dunes.

The thickness of a single facies, which the product of a single, unitary surge-type event, is quite variable; it is limited to the point where the characteristics of the sedimentary process changes, which indicates the beginning of another sedimentary pulse of different characteristics. Post-depositional diagenetic processes may affect the porosity, the permeability, and other properties of these elemental depositional bodies (see discussion below).

This level of depositional heterogeneity may be negligible in successions that have very little grain size variation, but it can become important where significant grain size or sorting differences are present (Van de Graaff & Ealey, 1989). For instance, the presence of conglomeratic layers or residual conglomeratic lags may have a strong impact, since these lithologies normally show a much higher permeability than the underlying and overlying beds. There are some examples where fluid flow is driven, or at least strongly affected, by the presence of a single facies. Early water breakthrough during IOR/EOR projects is commonly related to the presence of thin layers of highly permeable conglomerates (Swan & Riley, 1962; Candido & Wardlaw, 1985; Wouterlood *et al*., 2002). In these cases, the fluid flow within the reservoir is controlled by the presence and distribution of specific facies, as single or stacked multi-events.

2.2.2. Sixth-order: facies associations (architectural elements)

Normally, a facies is associated with other facies or a set of facies within an element that represents the same genetic history. These facies associations have environmental significance (Collinson, 1969) as they reflect a continuous depositional process where there are no significant changes in the sedimentary controls (Walker, 1992). A combination of several bed forms (lithofacies) will form an architectural element.

This approach was introduced by Allen (1983) and further developed by Miall (1985, 1996). The facies association represents a cumulative effect of several dynamic events over a period that ranges from tens to hundreds of years (Miall, 1985), and occasionally thousands of years. An architectural element is defined not only by its internal association of facies but also by its external geometry, its nature and the hierarchy of its bounding surfaces. These surfaces, when separating similar stacked architectural elements, commonly have a very limited impact on fluid flow within the reservoir, except where they are affected by specific diagenetic processes.

The identification of architectural elements should be a systematic task for modeling geologists who work in reservoir development and on IOR/EOR projects. However, for most of these activities, only wireline logs, rather than cores and outcrops, are available. Thus, it is quite difficult to separate two or three similar, vertically stacked, architectural elements based only upon wireline logs. The integration with dynamic data, such as fluid pressure analysis, the use of radioactive tracers, and temperature logs, may provide some constraints on sand body geometry and areal distribution, but normally the definition of individual architectural element remains unreachable.

2.2.3. Fifth-order: architectural elements association (sub-systems of deposition)

An association of similar architectural elements constitutes a sub-system of deposition. The similar concept of "major facies association" was applied by Begg *et al*. (1996) and Daudt & Scherer (2006) for fluvio-deltaic successions. In case of a deltaic system, the delta plain, delta front, prodelta, and flood plain represent the sub-systems of deposition. Each of these intervals is formed by a variable number of architectural elements that are arranged in a specific style. Changes in these architectural elements or changes in their styles may represent base level changes in a predictable high-frequency order (the fourth-order of Raja Gabaglia *et al*., 2006).

The surfaces that bound these sub-systems are referred to as within trend surfaces or contacts (Catuneanu, 2006), and they may have a considerable impact on fluid flow. Although these surfaces do not represent sequence stratigraphic surfaces, they are boundaries that can constrain specific petrophysical signatures, being of great convenience for modeling purposes.

The association of architectural elements seems to be the perfect scale to integrate geological aspects of reservoir heterogeneity with petrophysics and production analysis, especially in advanced development or IOR/EOR projects. Fluid flow and drainage efficiency (vertical and horizontal sweep efficiency) are more evident at this scale than at the sixth-order. The diagenetic imprint may also be better constrained at this level (Daudt, 2009; see later discussion) to allow for reservoir quality analysis in a more integrated and predictive way, at least at oil-gas field scale.

2.2.4. Fourth-order: Depositional systems

The depositional system represents the assembly of all sub-systems that have a genetic relationship in space and time, which are defined as depositional domains. Deltas, for instance, are distinguished from any other system by a series of diagnostic features that may include architectural element associations, geometries, facies succession, and others. The early interpretation of the depositional systems and the identification of their bounding surfaces are important steps to establish initial development strategies for reservoirs that will be subjected to IOR/EOR projects in the future (see examples shown by Tyler & Finley, 1991). Genetic flow units should not be defined at this scale, because depositional systems are formed by a wide range of reservoir quality intervals, which makes the application of the genetic flow unit model useless.

The surfaces that bound these different genetic compartments are potentially important flow barriers. From this scale and up, the definition and mapping of all the bounding surfaces are vital steps to understand reservoir complexity. Once the fourth-order heterogeneity is defined, the interpreter should downsize the analysis as new data is being incorporated. The fourth-order heterogeneity level is extremely important, because it represents larger scale compartmentalization that can affect the general patterns of fluid flow and reservoir distribution.

2.2.5. Third-order: Systems tract

Systems tracts represent a linkage of contemporaneous depositional systems (Brown & Fisher, 1977). Fluvial, eolian, deltaic, and deep water systems may coexist in some part of a basin, during a certain time, if favorable conditions are established. At this level, large scale tri-dimensional relationships are defined among the different depositional systems. As a part of a depositional sequence, systems tracts are normally defined by their relative stratigraphic position within it, by the internal stacking pattern and geometric relationships (Van Wagoner *et al*., 1988). The tracts are bounded by surfaces that can be formed by different processes, such as maximum flooding, a ravinement process, and fluvial erosion (Catuneanu, 2006). These surfaces are potentially important flow barriers, and they may, at least, limit reservoirs by different sedimentological and/or facies architectural characteristics. An understanding of these features is normally applicable in exploration and appraisal approaches.

2.2.6. Second-order: Depositional sequence

Several different definitions of depositional sequence are found in the literature (Mitchum *et al.,* 1977; Vail *et al*., 1984; Posamentier *et al*., 1988; Hunt & Tucker, 1992, etc). In most cases, the contrast between these approaches resides on the definition of the sequence boundary. In this article we simply define depositional sequence as the most important unit in a third-order sequence stratigraphic framework. A depositional sequence represents a complete cycle of base level variation, which is limited at the top and the base by unconformities (Mitchum *et al*., 1977). As a practical matter, the scale of a depositional sequence is more related to the exploration than the reservoir development analysis. However, the sequence distribution is still important for determining field-wide production trends, as well as in-place hydrocarbon volume. This second-order may have little impact on IOR/EOR projects, as this type of heterogeneity is normally on a larger scale than the dimensions of these projects.

2.2.7. First-order: Basin filling

The basin-wide scale corresponds to the largest heterogeneity and is applicable to exploration analysis. Basins are created by extensional, compressional, or shearing stresses and represent dynamic loci of sediment accumulation. The main controls on sediment input and deposition result from the interaction between basin geometry, the rate of source area denudation, and base-level changes through time.

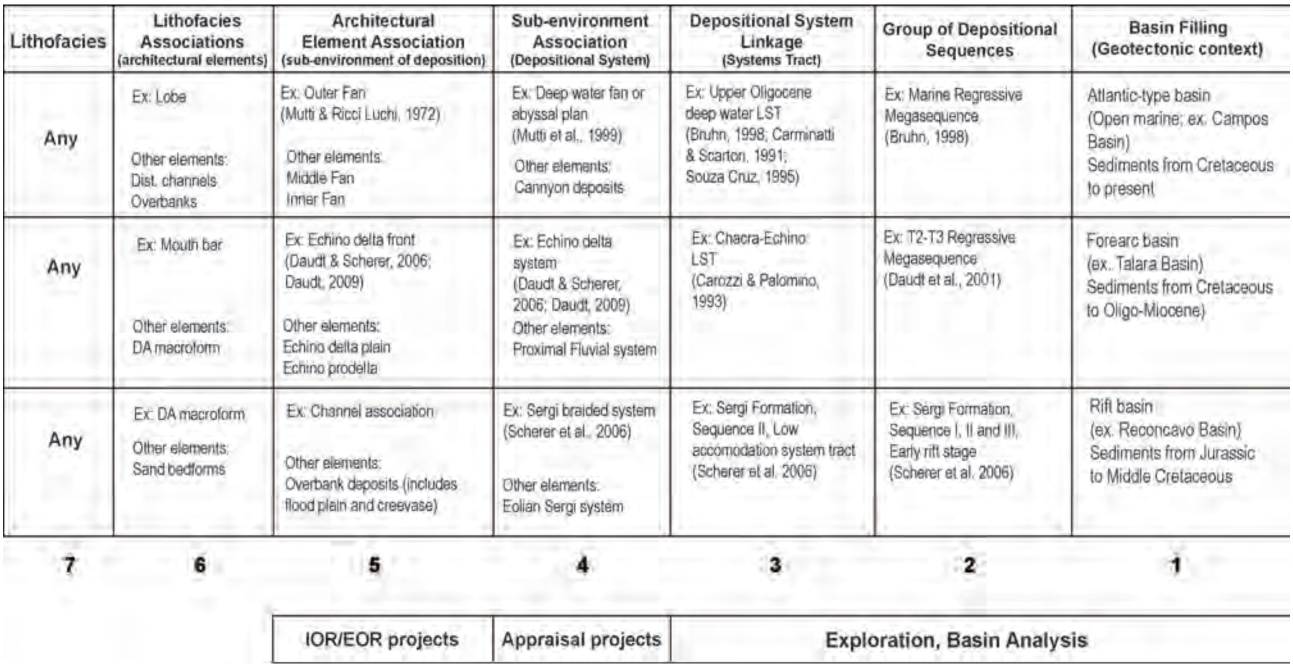
Examples of the use of this hierarchy are presented in figure 3, where several cases from three different geotectonic contexts (Atlantic-type, forearc and rift basins) were considered.

3. Flow units and geology

3.1. Flow unit: definitions and discussion of an integrated approach

The concept of flow unit was introduced by Hearn *et al*. (1984) to design rock packages with lateral and vertical continuity and similar geological and petrophysical characteristics, such as porosity and permeability. This concept led to an advance in reservoir characterization, since it allowed the transcription of detailed geology into mappable units. However, it has also triggered several discussions in recent years (Bhattacharya *et al*., 2008), particularly on the use of different techniques and methodologies for its definition. This wide range of possible approaches led to great discrepancies in the final results (Porras *et al*., 1999; Stolz & Graves, 2003; Svirsky *et al*., 2004; Lawal & Onyekonwu, 2005).

The first step in the understanding of flow unit significance should involve the characterization of reservoir heterogeneity, since the presence and distribution of geological discontinuities



Lithofacies	Lithofacies Associations (architectural elements)	Architectural Element Association (sub-environment of deposition)	Sub-environment Association (Depositional System)	Depositional System Linkage (Systems Tract)	Group of Depositional Sequences	Basin Filling (Geotectonic context)
Any	Ex: Lobe Other elements: Dist. channels Overbanks	Ex: Outer Fan (Mutti & Ricci Luchi, 1972) Other elements: Middle Fan Inner Fan	Ex: Deep water fan or abyssal plan (Mutti et al., 1999) Other elements: Cannyon deposits	Ex: Upper Oligocene deep water LST (Bruhn, 1998; Carminatti & Scarton, 1991; Souza Cruz, 1995)	Ex: Marine Regressive Megasequence (Bruhn, 1998)	Atlantic-type basin (Open marine; ex. Campos Basin) Sediments from Cretaceous to present
Any	Ex: Mouth bar Other elements: DA macroform	Ex: Echino delta front (Daudt & Scherer, 2006; Daudt, 2009) Other elements: Echino delta plain Echino prodella	Ex: Echino delta system (Daudt & Scherer, 2006; Daudt, 2009) Other elements: Proximal Fluvial system	Ex: Chacra-Echino LST (Carozzi & Palomino, 1993)	Ex: T2-T3 Regressive Megasequence (Daudt et al., 2001)	Forearc basin (ex. Talara Basin) Sediments from Cretaceous to Oligo-Miocene)
Any	Ex: DA macroform Other elements: Sand bedforms	Ex: Channel association Other elements: Overbank deposits (includes flood plain and creevase)	Ex: Sergi braided system (Scherer et al., 2006) Other elements: Eolian Sergi system	Ex: Sergi Formation, Sequence II, Low accomodation system tract (Scherer et al. 2006)	Ex: Sergi Formation, Sequence I, II and III, Early rift stage (Scherer et al. 2006)	Rift basin (ex. Reconcavo Basin) Sediments from Jurassic to Middle Cretaceous
7	6	5	4	3	2	1
		IOR/EOR projects	Appraisal projects	Exploration, Basin Analysis		

Figure 3. Application of the depositional heterogeneity hierarchy to three different geotectonic contexts, based on published articles.

strongly affects the vertical and horizontal fluid displacement within the reservoir (Eaton, 2006). Nonetheless, many models fail to incorporate geological controls in the definition of a flow unit due to different causes.

Some of these previous works defined flow units essentially through a direct connection between reservoir heterogeneity and vertical permeability distribution (Testerman, 1962; Kortekaas, 1985; Van de Graaf & Ealey, 1989; Mikes, 2006). Consequently, the flow units defined in these works represented exclusively an engineering concept that was associated only with the intrinsic hydraulic quality of the reservoir intervals (Amaefule *et al*., 1993) and disregarded the geological controls that were responsible for the quality variations.

Other studies may have overlooked the role of some geological features in the definition of flow units for other reasons. For instance, Mijnssen *et al*. (1990) defined their elementary flow unit as "a volume of rock which is homogeneously heterogeneous", which is an expression that may be useful for engineering but is rather confusing for geological characterization. Testerman (1962) and Gill (1970) used a statistical technique to divide the reservoir into several zones defined by minimum internal permeability variation and maximum variation between zones, without any geological control. Although they did not use the term "flow unit", the final product was very similar to a flow unit framework. Very little geological characterization was also observed in Bishop (1960), who used a slice technique to subdivide the reservoir into slices of arbitrary thickness that were taken as operationally defined units, without any consideration to lithofacies or stratigraphic complexity.

In another example, Guangming *et al*. (1995) argued that the utility of sequence stratigraphic analysis was limited for reservoir engineering purposes, since these sequences may cut across lithologic boundaries. Altunbay *et al*. (1994) encountered similar conceptual limitations, as their flow units were supposed to "occur as layers within lithofacies", which they called "sub-lithofacies". These are only a few examples of how flow units have been defined by unrealistic models, confusing expressions, or complicated approaches.

Ebanks (1987) and Ebanks *et al*. (1992) provided a good geological approach for flow unit characterization, presenting the most commonly used definition of this term. Flow unit, in those articles, represents "a specific volume of a reservoir, which is composed of one or more reservoir quality lithologies and any non-reservoir quality rock types within that same volume, as well as the fluids they contain". Gunter *et al*. (1997) proposed that a flow unit is a "stratigraphically continuous interval of similar reservoir process speed that honors the geologic framework and maintains characteristics of rock types". A flow unit also has to be "correlative and mappable at the inter-well scale", as well as "recognizable on wireline logs" (Ebanks *et al*., 1992). However, although such definitions carry some "intrinsic" geology with them, they fail to mention that depositional heterogeneities should be used to describe the geologic complexity and its relationships to the fluid flow through the reservoir. Moreover, the controls exerted by diagenesis on reservoir quality and heterogeneity are overlooked or used as a merely "decorative" information quite difficult to integrate in the modeling process.

In this paper, the term "genetic flow unit" was used to describe specific intervals that are constrained by surfaces generated as a result of considerable depositional and/or post-depositional changes. "Considerable", in this sense, refers to depositional changes that are reflected in the texture, structures, and/or architecture of the units, as well as to the distribution of major diagenetic processes and products that can be mapped in a wireline log scale, and are potentially predictable within a high-resolution stratigraphic framework. The term genetic flow unit was previously used by Mijnssen *et al*. (1990) to characterize architectural elements in deltaic successions from a flow unit perspective, but our definition is much more precise and comprehensive in terms of geologic modeling.

Therefore, we propose an alternative approach to the traditional flow unit model. The flow unit presented herein is a discrete element that is defined by depositional heterogeneities and their hierarchy as well as by the distribution of significant diagenetic processes affecting reservoir quality. A genetic flow unit model should be applied at the level of architectural element associations or sub-systems of deposition (hierarchy 5 in fig 2), and they may have their petrophysical properties modified by diagenesis. Occasionally, the definition of flow units may correspond to the level of an individual architectural element (hierarchy 6 in fig. 2), for which the eolian system is a good example. Genetic flow units that are defined at the depositional system scale (heterogeneity 4 in fig. 2 or third-order sequence stratigraphy) are not useful for IOR/EOR projects, because depositional systems are characteristically comprised of several rock volumes, corresponding to facies of different reservoir qualities. Nevertheless, units at the third-order sequence stratigraphic scale are important for the definition of the large scale reservoir quality controls and distribution.

The recognition of the fifth level of hierarchy is vital to constrain the distribution of petrophysical properties, even if these properties are similar between two adjacent genetic units. In such cases, the units are constrained by bounding surfaces that are at least discrete elements that act as flow barriers or deflectors. These discrete elements may compartmentalize the reservoir and must be considered in the modeling process.

When comparing this integrated approach with some classical flow unit definitions (Ebanks *et al*., 1992; Amaefule *et al*., 1993; Gunter *et al*., 1997), some similarities and differences can be identified:

a) The proposed model resulted in flow units that are composed of reservoir and non-reservoir lithologies which are constrained by fifth-order heterogeneity surfaces. Consequently, the distribution of petrophysical properties is likely to show some dispersion, as it represents variable original textures of the reservoir lithologies, which are, in many cases, influenced by diagenesis, and may include thin muddy layers as well. This approach is similar to what Ebanks *et al*. (1992) used to define flow units (their point "a");

b) Given that the proposed model is based upon the recognition of different depositional compartments, mapping these intervals within a tridimensional space will allow the correlation of flow units. Ebanks *et al*. (1992) proposed that a flow unit is "correlative and mappable at the interwell scale". This characteristic depends on the maturity of the project, because well spacing tends to decrease as the development reaches an advanced stage. Thus, the flow unit framework may change "with infill drilling and changes in production mechanism", according to those authors. Considering this, a flow unit may be not correlatable between wells due to two factors, the immaturity of the field (well spacing is too large to intercept some flow units), and the intrinsic depositional geometry of the unit (wells drilled along the strike line of a narrow channel system, for instance). However, the genetic flow unit that is introduced here represents a scale-dependent approach that is based on pure depositional characteristics. Our approach clearly constrains the use of this term to the scale of the architectural element associations or the subsystems of deposition, regardless of the average distance between wells. In conclusion, reducing well spacing will change our perception of the geology but it will not change the geology itself;

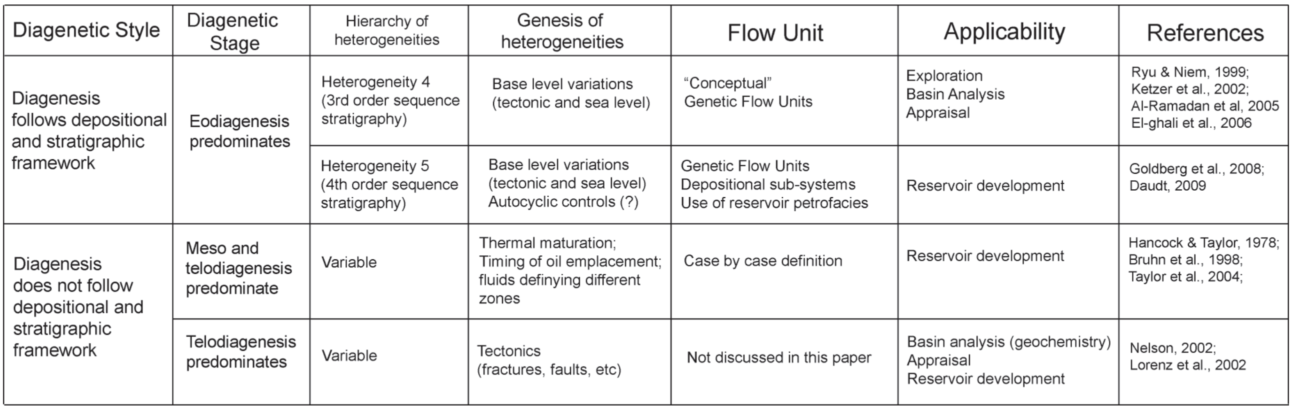
c) There is a general sense that a flow unit should be recognizable in wireline logs (Ebanks *et al*., 1992), which is an essential aspect of the practical applicability of the model. For this reason, the recognition of key depositional surfaces and, in some cases, the concentration of diagenetic effects in wireline logs is a key step for the definition of genetic flow units. The distribution of these surfaces is likely to be predictable within a high-resolution sequence stratigraphic framework. The fifth-order is the most appropriate in this regard. Heterogeneities at the sixth-order (architectural element level) may be recognizable if enough dynamic or core data is available;

d) Several controversial characteristics have been used to define flow unit concept, including those that indicate that a flow unit "may be in communication with other flow units" (Ebanks *et al.*, 1992), "may cross-cut sedimentary facies boundaries" (Slatt & Hopkins, 1990; Ebanks *et al.*, 1992; Danielli, 1996; Bhattacharya *et al.*, 2008) and "may be defined without any facies control" (Gunter *et al.*, 1997). These definitions are inadequate if a genetic model is considered. Heterogeneous surfaces (Fig. 2) are typically sites of facies changes or of specific diagenetic features that are potentially effective barriers or deflectors to fluid flow within the reservoirs. These surfaces are, therefore, likely to cause some effect on the hydrocarbon displacement efficiency and prevent the communication between adjacent units. Faults and fractures may create pathways that disrupt this typical model.

The important aspect of defining flow units seems to be that some geological features, including the structural, stratigraphic, sedimentologic, and diagenetic aspects, initially plays the main role as the basis for the construction of reservoir models. Geologic models, however, should be developed with a level of detail that is compatible with time and computational constrains. As discussed below, diagenesis must always be accounted in the models due to its importance as a modifier of reservoir quality.

3.2. Inclusion of the diagenesis in the flow unit model

A reservoir is the product of depositional and post-depositional processes that transform sediments into sedimentary rocks during burial. Although the depositional and/or stratigraphic architecture usually defines the main heterogeneities and frequently is the dominant control of reservoir quality, diagenesis, in many cases, substantially modifies the distribution of porosity and permeability, as well as their relationships (Hamilton *et al.*, 1998; Moraes & Surdam, 1993; Altunbay *et al.*, 1994; Salem *et al.*, 2000; Worden *et al.*, 2000). Depositional facies that were highly porous and permeable may retain these qualities after burial and diagenesis or be affected by cementation and/or compaction, which could even result in them becoming flow barriers, as in some fluvial or turbiditic cycle-base conglomerates. 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 not have any relationship with the original, depositional distribution (Primmer *et al.*, 1997; Morad *et al.*, 2000; Hartmann *et al.*, 2000; Lee *et al.*, 2002; Taylor *et al.*, 2004). Besides porosity and permeability, diagenesis may also affect wireline signatures and other petrophysical parameters, such as initial saturation, wettability, and capillarity. The combination of all these effects is important when estimating the original hydrocarbon in place and the recoverable volumes. As a consequence, although in many situations diagenesis causes a strong impact on reservoir quality, only in a few cases this impact is correctly addressed in modeling (Evans, 1987).



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" Genetic Flow Units	Exploration Basin Analysis Appraisal	Ryu & Niem, 1999; Ketzer et al., 2002; Al-Ramadan et al, 2005 El-ghali et al., 2006
		Heterogeneity 5 (4th order sequence stratigraphy)	Base level variations (tectonic and sea level) Autocyclic controls (?)	Genetic Flow Units Depositional sub-systems 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 definying different zones	Case by case definition	Reservoir development	Hancock & Taylor, 1978; 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 4. Differences in diagenetic style and consequences in the flow unit model (based on Daudt, 2011).

In a practical view, diagenesis may modify reservoir quality in two ways (Daudt, 2011): 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 (Fig. 4).

The first situation 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 & Niem, 1999; Ketzer *et al*., 2002, 2003, 2004; Al-Ramadan *et al*., 2005; El-ghali *et al*., 2006). However, during the development stage of a reservoir, a higher resolution approach is needed to properly address the diagenetic issue. We propose that this analysis should include the genetic flow unit model built at fifth-order heterogeneity level (architectural element association, fig. 2).

This high-resolution approach will be adequately achieved through the use of the reservoir petrofacies analysis (De Ros & Goldberg, 2007), constrained by the sub-systems of deposition (genetic flow unit model, cf. Goldberg *et al*., 2008, Daudt, 2009). The term reservoir petrofacies is similar to the reservoir facies of Langton & Chin (1968), although the first is more precise because its definition is based on systematic petrographic analysis (see below). Reservoir facies, on the other hand, is a less precise term that was proposed for hand-scale analysis of outcrops or cores.

The analysis used to define reservoir petrofacies is based on the characterization of the petrographic attributes as texture, composition, volume, intensity, habits and distribution of diagenetic processes and products, combined with the analysis of the distribution of different pore types (Lima & De Ros, 2002; De Ros & Goldberg, 2007). Preliminary petrofacies are determined through a systematic attribute description in representative samples collected in each genetic flow unit, followed by recognition of which attributes have larger impact on porosity and permeability. These preliminary petrofacies are then checked against petrophysical and petrographic quantitative parameters by using statistical or neural network tools. Threshold values for the influent textural and compositional attributes and ranges of porosity and permeability, per individual petrofacies, may be defined (Lima & De Ros, 2002; Goldberg *et al*., 2008). For modeling purposes, the interpreter can assume that one genetic flow unit is composed by combination of reservoir petrofacies, and the statistical treatment of their petrophysical and diagenetic elements result in representative reservoir quality indexes. This method guarantees consistency in terms of petrophysical properties, and wireline log signatures (De Ros & Goldberg, 2007).

The use of the high-resolution stratigraphy and reservoir petrofacies combined (c.f. Goldberg *et al*., 2008; Daudt, 2009) constitute a powerful tool for reservoir characterization, as well as quality prediction, especially in complex diagenetic settings. As sub-systems of deposition may be easily recognized in wireline logs, mapping these elements allows 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.

In situations where diagenesis does not follow the depositional architecture, the distribution of reservoir quality is far more complicated and difficult to predict. In some cases, only a comprehensive understanding of the petroleum system and its evolution will supply the elements to support a realistic flow unit definition. An excellent example of such an integrated study is presented by Taylor *et al*. (2004) for the complex diagenetic evolution of Norphlet sandstone (Jurassic, Gulf of Mexico), which resulted in a porous oil-bearing reservoir section that underlies a tight gas-bearing zone. According to these authors, early wetting and drying cycles promoted anhydrite cementation above the water table, which prevented the formation of continuous chlorite coatings in this interval. During deep burial and high temperature, anhydrite cements were dissolved, and the uncoated quartz surfaces were exposed to quartz cementation. Meanwhile, continuous chlorite coatings preserved much of the original porosity in the lower interval. The reservoir quality evolution, as proposed by the authors, shows no relationship with the depositional facies distribution but rather to the distribution of the vadose and phreatic zones during eodiagenesis. Consequently, in this case, flow units are independent of the depositional framework.

Another example of mesodiagenetic control on reservoir quality that is independent of the depositional architecture is given by Hancock & Taylor (1978). They presented a case where illite diagenesis, and the consequent reduction in permeability, took place in a water zone, synchronously with oil migration. With its evolution, differential oil saturation allowed the preservation of early diagenetic stages, which are represented by kaolinite, in the upper part of the reservoir, again, without depositional control. The inhibiting effect of oil migration upon illite authigenesis has been discussed by Hamilton *et al*. (1992) for several reservoirs of the Brent Group (Jurassic) in the North Sea.

Oil-bearing sandstones are normally less affected by diagenetic processes than the underlying aquifers (Yurkova, 1970; Bruhn *et al*., 1998; Worden & Morad, 2000; Worden & Burley, 2003). Early oil emplacement is believed to inhibit or even stop the diagenetic processes. Bruhn *et al*. (1998) described important differences in the diagenesis of the oil and water zones in the Upper Albian Namorado Sandstones in the Albacora Field, Campos Basin, Brazil. In those turbidite deposits, coarse poikilotopic calcite cement is much more abundant in the interval below oil/water contact, which indicates the influence of oil emplacement on the diagenetic history of these reservoirs. 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, favouring porosity preservation in the crestal part of deeply buried sandstones.

This discussion on the potential of early oil migration in stopping 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, since 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).

There are, of course, "hybrid" cases, where the timing of oil emplacement prevented the diagenetic reactions that were responsible for the reduction of porosity and permeability but some depositional control was followed. Hawkins (1978) showed that early oil emplacement inhibited mesodiagenetic quartz cementation in the channel facies of the Bothamsall Field (late Carboniferous, North Sea), which preserved much of the depositional porosity only in the axial position of the system.

Differential or focused dissolution is another diagenetic process that may create flow units that are not necessarily controlled by the depositional system. Porosity enhancement due to dissolution during burial is very well known (Wilkinson & Haszeldine, 1996; Wilkinson *et al*., 2001; Worden & Burley, 2003), although none of the examples include a discussion on the flow unit framework. Grains may be dissolved by meteoric water infiltration through exposure surfaces, faults or fractures during telodiagenesis or by fluid percolation with some degree of depositional control during eodiagenesis (KulenDare, 2007). Secondary porosity that is developed in the early diagenetic stages has, however, little preservation potential, as it tends to be strongly reduced during mechanical compaction, while secondary porosity that is developed during telodiagenesis has a better potential for preservation. Intermediate conditions, with secondary porosity generation controlled by a combination of depositional characteristics, such as provenance and facies distribution, and hydrodynamics (e.g. meteoric water percolation through fractures) may also occur (Bermudez *et al*., 2006).

As mentioned earlier, a discussion on the influence of tectonics on the flow unit model is beyond the scope of this article. However, it is necessary to comment that, in some siliciclastic reservoirs, the fractures and smaller scale discontinuities are critical points in the definition of flow units. This is particularly true in areas where strong diagenesis resulted in reservoirs with very low "bulk" or "matrix" porosity and where permeability is provided by faults and fractures. The flow unit framework, in these cases, is the product of a complex equation that is related to all the possible aspects that were mentioned before, plus the post-depositional tectonics. A good example of that is the Spraberry Formation (Midland Basin, Texas), in which flow units are defined based on differences in diagenetic styles that promoted differences in fracturing patterns (Lorenz *et al*., 2002). These authors created a new term ("mechanical stratigraphy") to express this variability. The excellent text book by Nelson (2002) offers significant help for the understanding of fractured reservoirs.

4. Implications of these concepts for reservoir modeling in mature assets

Mature and over-mature assets may still contain huge amounts of hydrocarbons, which awaits new technological and/or methodological solutions for their recovery. These assets are commonly affected by economic constraints, since the productivity per well is normally low. In IOR/EOR projects, the understanding of the nature and hierarchy of heterogeneities will be of key importance for the determination of the best procedures that can be used to improve the recovery of these remaining reserves. Heterogeneity characterization will also bring a better understanding of how fluids flow within the reservoir (fluid displacement efficiency). Thus, a better control on the geology of the reservoir, its heterogeneities, and the assessment of the impact of these heterogeneities on fluid flow is a fundamental step to optimize production and investments. The genetic flow unit approach, which integrates depositional reservoir heterogeneity, high-resolution stratigraphy, and diagenesis, represents a methodological process that offers the solutions for bridging the gap between reservoir geology and engineering in the form of more realistic and operational modeling.

5. Conclusions

In this article, we reviewed the hierarchical scheme based upon building blocks of different levels of heterogeneity for siliciclastic reservoirs. Upon this framework, flow units model should be built to realistically represent geological complexity in the dynamic simulation.

Genetic flow units as proposed here are discrete elements that correspond to sub-systems of deposition and to fourth-order sequence stratigraphic units. These units provide consistent geologic controls for reservoir quality correlation at the oil/gas field scale. They represent different rock volumes that, according to their petrophysical properties, determine the static conditions for fluid flow within the reservoirs. Genetic flow units are recognizable in wireline logs as tri-dimensional volumes and are bounded by depositional, stratigraphic, structural, or diagenetic surfaces, which can function as potential flow barriers or deflectors. These characteristic prevent one genetic flow unit from being in free communication with another, which conflicts with previous definitions.

In contrast to conventional flow units or reservoir zones, genetic flow units are scale-dependent to be represented at the architectural element association level (fifth-order heterogeneity hierarchy), which is normally the scale that is used in IOR/EOR projects. Flow units that are defined at the fourth-order of heterogeneity, or the traditional third-order of sequence stratigraphy, may be useful just as a first approach to define regional reservoir quality distribution. However, the genetic flow unit approach is not applicable at these scales, since depositional systems (fourth heterogeneity level) and depositional systems associations (third-order heterogeneity level) represent a wide spectrum of facies with different reservoir quality.

The diagenetic processes that are responsible for porosity and permeability modification can be constrained by depositional or stratigraphic surfaces, at the fifth heterogeneity level, which are the sub-systems of deposition. As a consequence, reservoir quality assessment, which is represented quantitatively by the distribution of petrophysical properties, can also be constrained by these surfaces. Reservoir petrofacies, which are defined by the combination of depositional and diagenetic parameters that control the intrinsic porosity and permeability of the reservoir rocks, are adequate tool for modeling the impact of diagenesis on reservoir quality and heterogeneity. Statistical methods allow modeling the proportions of different reservoir petrofacies within each flow unit.

Regarding reservoir quality and heterogeneity, the predictive potential of the genetic flow unit approach is provided by the recognition of the genetic flow units in the wireline log patterns, within a high-resolution stratigraphical framework. However, burial diagenetic processes may define flow units that have no relationship with the depositional architecture. In such cases, an integrated burial-thermal-generation-migration analysis must be coupled with the concepts of reservoir petrofacies and genetic flow unit for reservoir modeling.

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