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Dynamic impact and flow-based upscaling of the estuarine point-bar stratigraphic architecture

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ABSTRACT

The estuarine point-bar architecture – one of the main sub-depositional environments of tide-dominated shallow-marine and fluvial (SM&F) systems – constitutes one of the most shale-prone clastic reservoir architectures potentially posing risks to the production performance. A set of simulation-based sensitivity studies quantify the effects of a number of stratigraphic and reservoir engineering parameters on the dynamic connectivity of the confined estuarine point-bar architecture. Water injection recovery mechanism is utilized for polarizing the stratigraphic and reservoir engineering parameters in terms of their effects on hydrocarbon recovery.

The point-bar shale-drape architecture and abandonment channel attributes (e.g., permeability, facies composition, and shale-drape coverage) dominate the dynamic reservoir connectivity, hence the recovery factor and water breakthrough time/profile. In terms of reservoir engineering parameters, well spacing and, to some degree, relative mobility ratio constitute the factors of importance for the investigated model parameter ranges. The dynamic effects of intra-facies permeability heterogeneity are evaluated using a number of realizations comparing them to those stemming from facieswise-homogeneous realizations. Results indicate that intra-facies permeability heterogeneity influences the connectivity factor for low shale-drape coverage levels. For high coverage levels, presence of shale drapes almost completely overshadows the influences of intra-facies permeability heterogeneity.

A novel multiphase flow-based upscaling method, specifically developed for clastic reservoirs containing long-correlation-length permeability heterogeneity, is evaluated first-time on the scale-up of the estuarine point-bar architecture. Resulting coarse-scale models capture the fine-scale dynamic behavior with an accuracy level that is significantly higher than those obtained by use of single-phase flow-based upscaling.

1. Introduction

One of the most widely referred examples establishing a relationship between stratigraphy and reservoir performance is the study of Tyler et al. (1984) later updated by Tyler and Finley (1991). In this study, 450 major Texas petroleum reservoirs were evaluated (Galloway et al., 1983). Tyler et al. (1984) and Tyler and Finley (1991) demonstrated that average recovery efficiency could be linked closely to depositional environment and recovery mechanism. They also emphasized the importance of the drive mechanism on recovery efficiency.

1.1. Classification of the SM&F systems

SM&F systems are classified in a variety of ways. Here, we abide by the simple classification scheme described in Howell et al. (2008). The shoreline movement in SM&F systems is governed by the balance between the amount of sediment supplied (by rivers and longshore drift) to the depositional system and the amount of accommodation created by a combination of sea-level rise and subsidence. The shoreline will prograde if the amount of supplied sediment is greater than the available accommodation. The shoreline will migrate in a landward direction (retrograde) if the amount of accommodation created is larger than the amount of sediment that would be required to fill it. Sea-level rise (tectonic or eustatic) and reduction in sediment supply together or individually cause retrogradation, also called transgression.

In general, progradational successions are characterized by deltas while transgressive successions are characterized by estuaries (Dalrymple et al., 1992). The most volumetrically abundant transgressive deposits are laterally confined estuarine systems, which encompass complex stratigraphic architectures. Beyond estuarine settings, transgressive phases are typically represented by flooding surfaces and/or thin discontinuous shelf sandbodies that rarely preserve significant volumes of sediment. SM&F deposits are sub-classified based on the dominant depositional process,

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namely in the form of fluvial-, wave-, and tide-dominated deposits. It is important to emphasize that all SM&F systems are affected to some degree by fluvial (river), wave, and tidal processes. Thus, the process-driven classification of SM&F deposits is in fact a sliding scheme that can be described with a ternary diagram for deltas (Galloway, 1975) and estuaries (Dalrymple et al., 1992) (Fig. 1). Any point within the ternary triangle is defined by the relative importance of the three processes in controlling the resultant facies and ultimately the reservoir architecture.

1.2. Estuarine point-bar architecture

Macro-tidal estuaries display significant variability in morphology that cannot be attributed solely to tidal range. Estuaries characterized by fine grain size, low sediment flux, and low gradients tend to be dominated by accretionary point-bars. In contrast, estuaries characterized by coarse grain size, high sediment flux, and step gradients tend to be dominated by mid-channel or longitudinal bars. Tide-dominated progradational systems have not been commonly identified in subsurface settings but tend to form extremely heterogeneous intervals when found in subsurface hydrocarbon reservoirs (see, for example, Martinius et al. (2005)). Tide-dominated environments are more typically found in transgressive systems, where the amplification of the tide, required to suppress the other processes, is provided by the drowning of an incised topography. The estuarine point-bar architecture – the main subject of the work presented here – is one of the end-member architectures found in transgressive tide-dominated systems. The dynamic connectivity of coarser-grained, point-bar sand deposits separated by shale drapes along lateral accretion surfaces and mud-rich channel-abandonment fills can potentially exert a critical control on hydrocarbon volumes drained by individual wells.

1.3. Motivation of the modeling study presented in this paper

Reservoir models of increasing complexity are being constructed for a wide spectrum of depositional environments. Such models do not always constitute a product of prior knowledge or a quantitative study demonstrating that volumetric or dynamic uncertainty is being defined better or reduced, or that predictions of recovery performance are more accurate. It is crucial that key heterogeneities in SM&F reservoirs are well understood and their impacts on reservoir performance are quantified in order to develop an efficient integrated reservoir modeling workflow. In summary, it is very important to know "what to model & what not to model" prior to building a static reservoir model. Such knowledge can only be developed through high-resolution simulations of detailed architectural models. In this context, the estuarine point-bar architecture constitutes an appropriate starting point for further studies of SM&F architectures. The main driver behind our estuarine point-bar architecture focus is that it is one of the most mud-prone architectures (Figs. 2 and 3). As such, dynamic modeling results open a window into the low-end of possibilities as far as recovery performance forecasts are concerned in SM&F reservoirs. Although geological studies about tide-dominated SM&F systems have been published in the literature (e.g., Dalrymple et al., 2003), the influence and relative importance of the hierarchy of depositional characteristics on subsurface fluid-flow remain poorly understood.

1.4. A brief literature survey on modeling studies for SM&F systems

Geological studies emphasizing 3D reservoir characterization and simulation have addressed specific relationships between stratigraphic architecture and recovery performance in SM&F reservoirs. For example, Kjønsvik et al. (1994) identified that parasequence thickness and stacking pattern has the largest influence

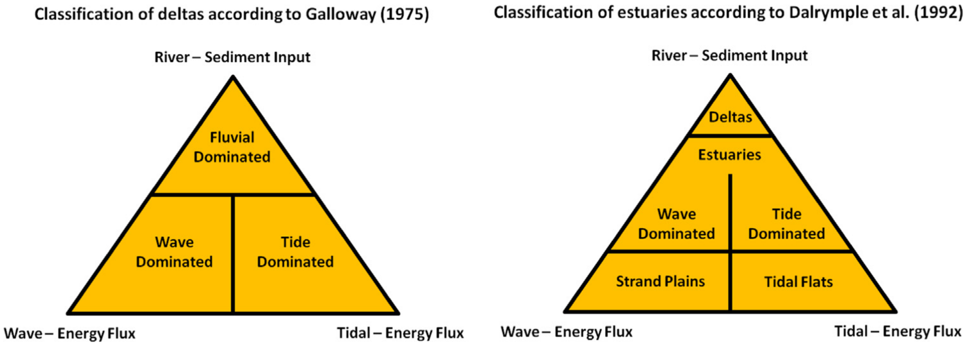

Fig. 1. Process-based sub-classification of deltas (Galloway, 1975) and estuaries (Dalrymple et al., 1992).

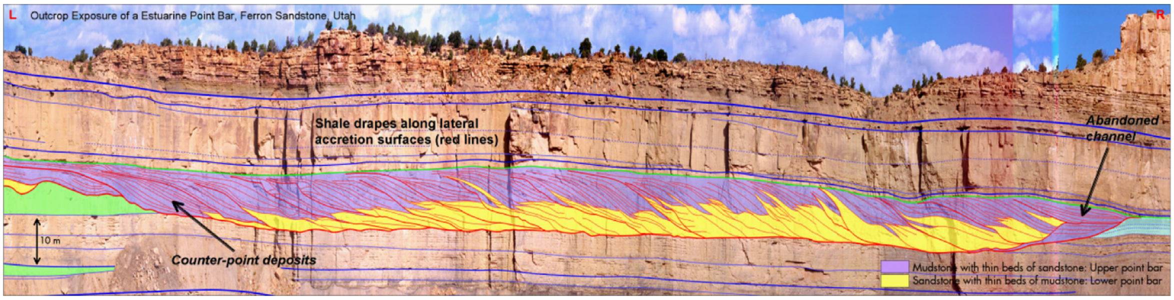

Fig. 2. Example of a cliff-face photomontage showing interpreted point-bar surfaces and facies boundaries. Bedding surfaces are highlighted by red lines. Bedding dips are as high as 20° with dip direction from left to right on the photo, representing the direction of channel migration. Shale drapes are common along most bedding surfaces and in many cases extend to the base of the channel. The yellow fill (lower point-bar) represents medium-grained, cross-bedded, and parallel laminated sandstones. The purple facies (upper point-bar) represents heterolithic fine-grained sandstones and mudstones. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)