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Impact of Sedimentological Hierarchy on Sandstone Connectivity in Deep-Water Lobes - An Object-Based Modelling Approach

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SUMMARY

Recent progress in understanding the internal architecture of deep-water lobes has benefited from high-resolution seismic and outcrop studies which have identified a 4-fold hierarchical geometrical arrangement (beds within lobe elements, within lobes, within lobe complexes). Our aim is to understand the influence on reservoir connectivity and performance of different sedimentological characteristics at different levels within this hierarchy. For this purpose, we have developed a novel object-based modelling tool designed not only to reproduce the detailed architecture within lobe complexes, but also to investigate the sandstone bed connectivity within and between different hierarchical components. We focus on the three-dimensional connectivity of sandstone beds within an idealised lobe, and show that models with statistically identical bed-scale properties (sizes, net:gross ratios, amalgamation ratios) can have vastly different lobe-scale connectivity, dependant on the quantitative sedimentological hierarchy. Hence it is important to test connectivity within different plausible parameterisations of lobe reservoirs of interest, since definition of the hierarchy is subtle and different workers can interpret the same systems in different ways.

Introduction

Connectivity of sandstone beds in lobe systems can be a fundamental control on eventual hydrocarbon recovery (e.g. King 1990). Recent modelling investigating the controls on sandstone connectivity in such systems have conceptualised the sedimentology as a binary system of permeable sandstones and impermeable shales, and have emphasised the importance of the net:gross ratio (i.e. the total volume fraction of sandstone) and amalgamation ratio (i.e. the fraction of sandstone bed bases that are amalgamated with a lower sandstone bed) in controlling overall sandstone connectivity (e.g. Hovadik and Larue 2007; Manzocchi et al. 2007). Although this work recognised the importance on connectivity of the scale of the beds with respect to overall scale of interest (e.g. the total dimension of the lobe, or the inter-well distances in a particular reservoir development scenario), it did not explore the effects that hierarchical sedimentology (e.g. Prélat et al. 2009) may have on sandstone connectivity. The objectives of this paper, therefore, are to examine systematically the differences in bed-scale connectivity within lobe models with identical bed-scale sedimentological characteristics (net:gross and amalgamation ratios, bed sizes and shape distributions), but different hierarchical arrangements. Results from new outcrop characterisation of the classic Ross Sandstone system in eastern Kilbaha Bay (Co Clare, Ireland) are used to contextualize our modelling, and highlight the difficulty in applying a single hierarchical model to a particular natural system.

Hierarchical lobe modelling

Recent outcrop characterisation has revealed that the internal structure of lobe complexes is arranged hierarchically (Gervais et al. 2006; Deptuck et al. 2008 ; Prélat et al. 2009; Fig 1a). It is, however, unclear as to the extent to which the details of the hierarchy control the sandstone bed connectivity. In this work we focus on an idealised lobe complex (Fig 1b), and measure connectivity in models employing different hierarchical definitions (conditioned to published datasets). The modelling is performed using a novel hierarchical object-based modelling tool in which the sedimentological properties (dimensions, shapes, orientations, drape characteristics) at each hierarchical level are conditioned to user-defined input values. An important feature of the tool is that the amalgamation ratio can be defined as input, allowing this important control on connectivity to be defined explicitly. This contrasts with conventional object-based modelling in which the amalgamation ratio is an unconstrained modelling outcome which depends primarily on the net:gross ratio (Manzocchi et al. 2007).

Bed-scale amalgamation ratio data indicate that different turbidite systems have different relationships between net:gross ratio and bed-scale connectivity (e.g. Fig 2a), however, to the best of our knowledge, no efforts have previously been made to measure amalgamation ratios at larger hierarchical levels (e.g. lobe elements, lobes). New data showing amalgamation ratios at different hierarchical levels collected from published literature (Fig 2b) shows that the degree of amalgamation decreases as scale increases (Fig 1b), an observation suggesting that different hierarchical interpretations of lobe sedimentology may result in different, large-scale sandstone connectivity.

Examination of natural lobe systems indicates that definition of the hierarchy is not straightforward, and many systems (including the Ross Sandstone at Kilbaha Bay, Co Clare, Ireland, where a new section of this classic outcrop has been examined to characterise the hierarchy) can be correlated both including and excluding the lobe element (Fig 1a) hierarchical level. The influence this may have on the connectivity of the sandstone beds is examined below.

Model construction

We discuss two sets of models, one including and one excluding the lobe element hierarchical level. The bed-scale characteristics are identical throughout, and a system with an 82% net:gross ratio and a 38% amalgamation ratio at the bed scale is considered (Fig 2a). In both sets of models, a particular realisation of lobes within a deterministic lobe element model defines the largest hierarchical scales (Fig 1b, 3a). The arrangement of lobes within the lobe complex follows the "Progradation-

Aggradation-Retrogradation" pattern proposed by Hodgson et al. (2005), with a 4% amalgamation ratio.

In the first set of models, lobe elements are modelled with a 15% amalgamation ratio within each lobe, and beds are subsequently placed within lobe elements. These hierarchical amalgamation ratio values used (30%, 15%, 4%) lie at the 70 percentile of the literature compilations (Fig 2b), an appropriate level for the high net:gross systems we are considering (Fig 1a). Figs 3a and 3b show cross-sections along the dip direction of the lobe complex in a realisation of the model, highlighting the locations of the amalgamation surfaces at the lobe element and bed hierarchical levels. In the second set of models, beds are placed directly within the lobes with no intervening lobe elements (Fig 3c). The cross-sections in Fig 3 are highly vertically exaggerated, but even so it is very difficult to recognise that they have different hierarchies. Fig 4 shows a 40m long, 6m high section through the centre of a lobe in the two models with no vertical exaggeration, demonstrating that the models have equivalent bed-scale characteristics and highlighting the difficulty of recognising the underlying hierarchical arrangement of beds at scales more characteristic of outcrops. Despite the apparent similarity of the models, however, we show below that they have very different bed-scale connectivity characteristics.

Model connectivity

Because an identical lobe complex / lobe hierarchical arrangement is assumed for both models, differences in bed connectivity in these models can only occur within lobes. Therefore we examine the bed-scale connectivity in 10 realisations of a single lobe (e.g. Fig 5). Connectivity is defined as the fractional volume of the largest cluster of mutually connected sandstone beds within the lobe (e.g. Manzocchi et al. 2007; Hovadik and Larue 2007) and has a value of 23 ± 6% for the hierarchies including lobe elements (e.g. Figs 3b, 5a), and 50 ± 14% if the lobe element hierarchical level is omitted (e.g. Figs 3c, 5b). As the bed-scale characteristics (net:gross ratio, amalgamation ratio, bed sizes) are identical in both models, the differences in connectivity clearly reflect the differences in hierarchical arrangement of the beds. Examination of the models including lobe elements (Fig 5a) indicates that the 38% amalgamation ratio at the bed-scale is sufficient to ensure that, at the lobe-element scale, the sandstone beds are well connected, but that the lobe element scale amalgamation ratio (15%) is too low to allow frequent inter-lobe element sandstone connectivity. In the less hierarchical model, however (Fig 5b), the bed-scale amalgamation ratio is applied throughout the lobe, and is sufficiently large to connect approximately 50% of the total sandstone within the lobe.

Given the internal hierarchical arrangements within deep-water lobes have been studied in detail only recently, quantitative description and analysis of hierarchical components of lobes is scarce. We believe future work on deepwater lobe deposits may benefit from more quantitative study (dimensions, amalgamation ratios) on each hierarchical component, since, as we have demonstrated, these data can be fundamental controls on sandstone connectivity.

Conclusions

The internal structure of lobe complexes is arranged hierarchically, and new data show a systematic decreases in amalgamation ratio at progressively larger hierarchical scales. Hierarchical object-based modelling of systems with identical bed-scale statistics but different hierarchical defintions has shown that the hierarchy used in a particular system, which can be subjective and hard to define, can have a significant influence on the overall connectivity of the sandstone beds.

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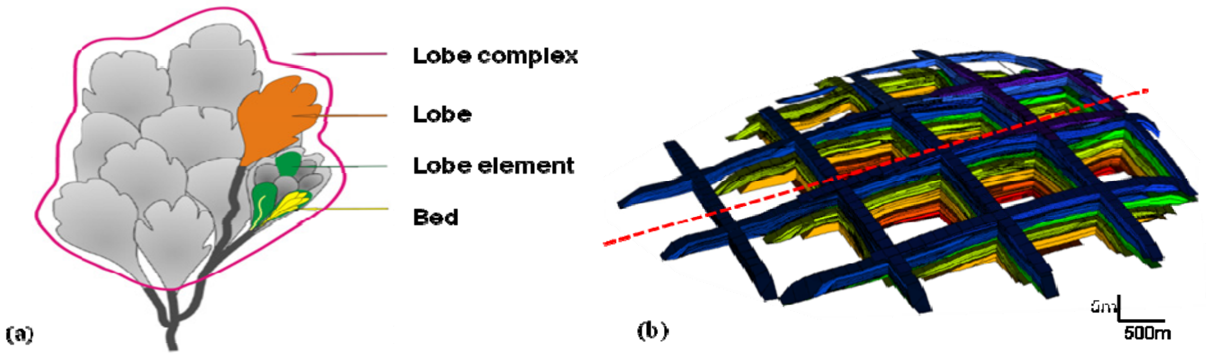

Figure 1 *(a) Cartoon showing a 4-fold hierarchy for lobe complexes, modified from Prélat et al. 2009. Note that the relative scale of objects at the different hierarchical levels is highly variable. (b) Fence diagram of the example lobe complex model. Beds are coloured according to the lobe they are contained in, and the model is 6km long, 3.5km wide and 30m thick. The dashed line shows the locations of the cross-section in Fig 3.*

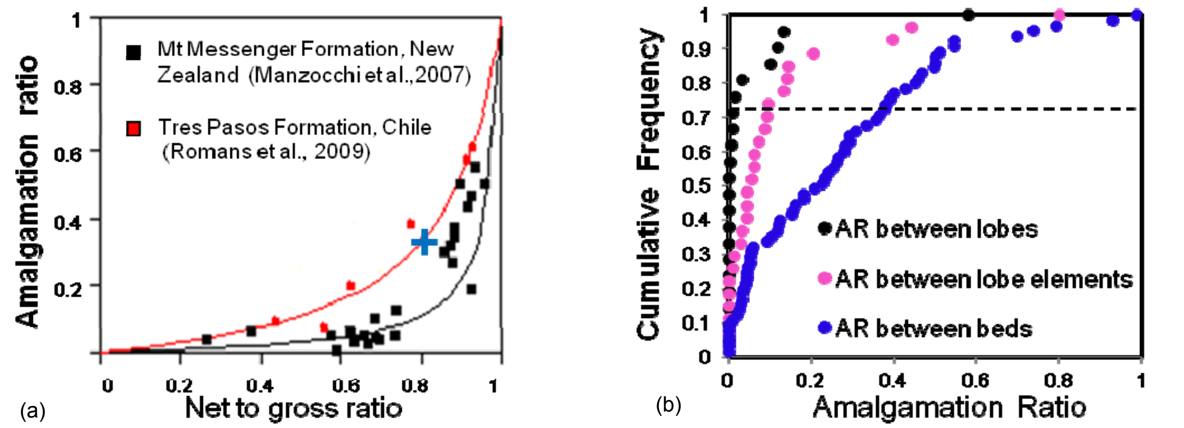

Figure 2 *(a) Bed-scale net:gross ratio vs. amalgamation ratio for the two turbidite systems. The cross shows the properties used in the modelling. (b) A global compilation of amalgamation ratios at different hierarchical levels compiled from published data. The dashed line shows the values used in the modelling.*

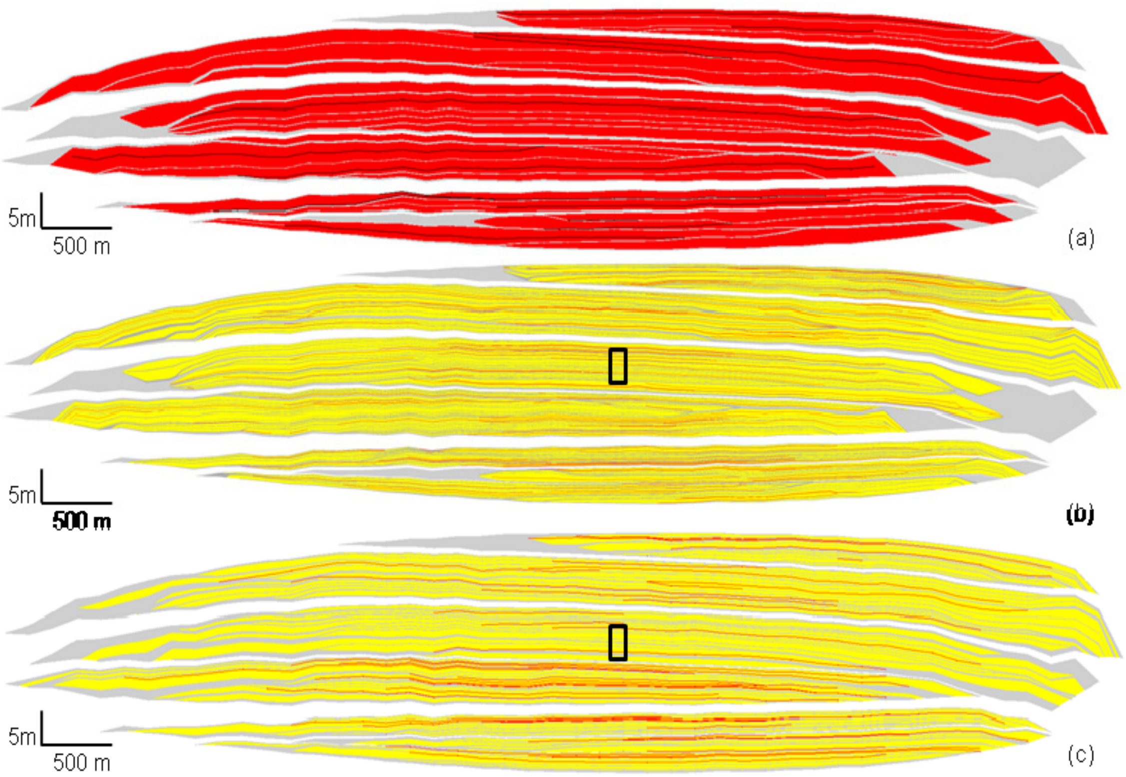

Figure 3 *Cross-sections through the long axis of the modelled lobe complex with vertical exaggeration 1:50. (a) lobe elements (red) placed within lobes (grey). Black lines are amalgamation surfaces. (b) Beds (yellow) placed within the lobe elements in (a). Lobes and lobe elements are both shown in grey. (c) Beds (yellow) placed directly within lobes (grey). The red lines in (b) and (c) show bed-scale amalgamation surfaces. Boxed parts are shown at natural scale (1:1) in Fig 4.*

Figure 4 *Natural scale (i.e. no vertical exaggeration) 40m long, 6m high sections through the centre of a lobe including (a) and excluding (b) the lobe element hierarchical level.*

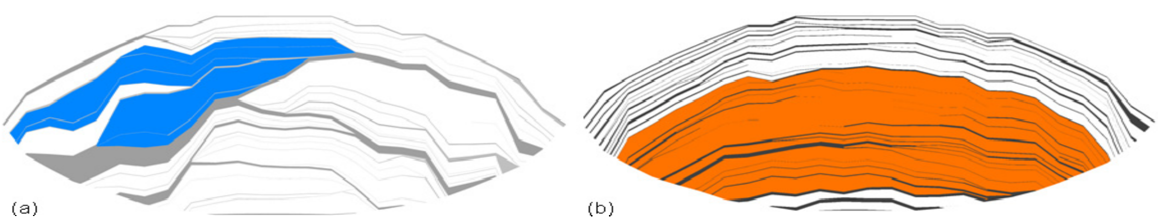

Figure 5 *Cross-sections of representative realisations of lobe models built including (a) and excluding (b) lobe elements, with the largest connected cluster of sandstone beds coloured in each case (other sandstone beds are white, and shales are grey). Note that these are sections through 3D models, and connectivity across continuous shales in these sections is achieved through vertical connection out of the plane of section.*