Introduction

Reservoir architecture is a key determinant of reservoir performance and ultimate hydrocarbon productivity but varies greatly in deep-water clastic reservoir systems. The ability to predict reservoir architecture from limited log and core data is therefore of considerable value, particularly when much of the essential architecture is sub-seismic.

We propose that useful predictive architectural statements can be made based on an understanding of the relative confinement of turbidity currents from which the reservoir is built and that these predictions can be made based on observing patterns at the core and log scale. The objective of this paper is to outline the key characteristics of relative confinement in turbidite systems - focussing on lateral bed continuity, amalgamation ratio and net:gross as examples - and show how these can be used to predict reservoir architectures.

Central concept: relative confinement of turbidity current flows

A turbidity current is a combination of a volume of sediment and water kept in suspension through turbulence and flows down slope. The flow behavior is a combination of the original volume of sediment, the density of the flow, the gradient of the slope, interaction with the substrate and, critically, the ability for flow expansion (*sensu* Kneller, 1995) to occur – i.e. the degree of confinement to which the flow is subject by the container through which it is passing.

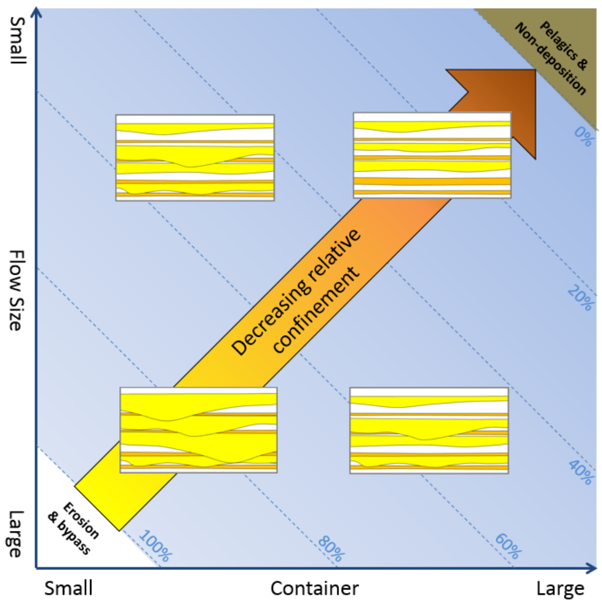

***Figure 1. A** matrix of qualitative size of flow and container derives the degree of relative confinement onto which quantitative parameters may be plotted. The expression of relative confinement may be linear (decreasing or increasing) or non-linear. Figure 2 shows the different expressions of relative confinement. Architectural cartoons and amalgamation ratio percentages are approximate.*

There is a clear relationship between relative flow confinement of a turbidity current and the depositional style and preserved expression of the flow deposits. The degree of relative confinement is a result of the size and composition of the flow and the size of the container into which it is flowing and / or depositing. In Figure 1 we use a comparison of the qualitative size of the flow (large to small) with a qualitative size of the container into which the turbidity currents are flowing (small to large). Quantitative dimensions are not shown on the axes as these may be scaled to the purpose of the user: for example the scale of the container may range from small sours to large basins. Similarly, the size of the flows may be considered to be the volume of sand within the originating flow. In this discussion the size of the flows considered are the volume of the flow at the point of the observed depositional unit. The purpose of this matrix is to derive a dimensionless comparison of flows and their container to express a degree of relative confinement. For example in terms of relative confinement there is much architectural similarity between a low volume flow in a small container and a large volume flow in a large container; each flow will be experiencing a similar degree of confinement. Notionally the expression of the interaction of these two dimensions is described for individual turbidity current deposits, however this can also be translated to the bed-set scale (or larger) in genetically similar units.

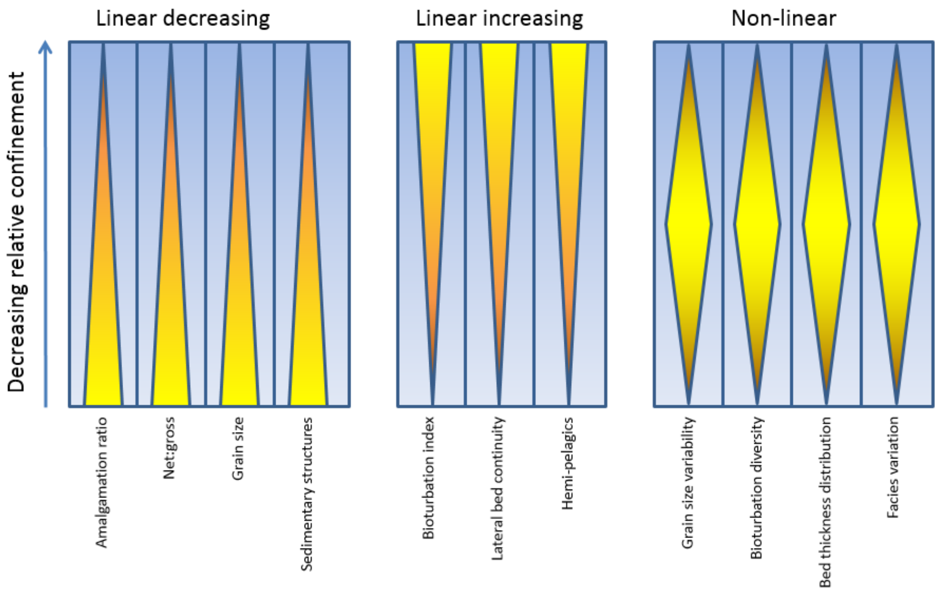

***Figure 2** Classes of character expression; linear decreasing value, linear increasing value and non-linear. Each parameter can be plotted on the relative confinement diagram (Figure 1). Key expressions are discussed in the text.*

Key expression of relative confinement: lateral bed continuity

Low volume turbidity currents are common in areas of low confinement because the lack margin control allows flows to expand across the available topography (*c.f.* 'depletive' of Kneller, 1995) with the dominant forces relating to the density contrast of the flow with the surrounding ambient fluid as opposed to interaction with the side of the container – i.e. they are unconfined. In Figure 1 therefore the position of low volume flows is placed in the area of low confinement as expressed as low volume flows in a large container. As the axis are dimensionless this could be distal flows in a large container such as a basin or low volume proximal flows in a smaller container such as a channel. In principal therefore thin beds have a high degree of lateral continuity at the time of deposition; continuity may be modified by pene-contemporaneous events such as slumping or erosion or later events such a fault throw. Conversely high volume flows occur mostly in areas of high confinement which prevents flow expansion beyond the walls of the container. The dominant force then becomes the interaction with the walls of the container which promotes continued suspension and longitudinal transport. In Figure 1 highly confined flows occur where larger flows occur in smaller containers; this may be very large volume event in a basin or more normal scale large event in a channel. Lateral continuity of beds (or lack of) can be deduced from outcrop (e.g. Stanbrook & Pringle, 2008), seismic (e.g. Prather *et al*, 1998) or inferred from other vertical parameters such as amalgamation ratio, grain size and bed thickness distribution.

Key expression of relative confinement: vertical connectivity / amalgamation ratio

At the bed-set scale the vertical continuity of sands within a series of beds in unconfined areas is likely to be low as the flows are experience flow expansion and therefore unlikely to be erosive. The likely expression of the flows therefore is to preserve the original mud caps that were part of the original flow. Also, in areas of low flow frequency there may be intervening hemi-pelagic muds. At the bed-set scale in areas of high confinement, flows that are unable to expand have a high probability to erode the substrate. In these areas the higher probability of erosion equates to a lower probability of the preservation of mudstones between sands due to their removal by erosion. In these areas therefore there is a high chance of sand on sand contacts; i.e. for sands to be amalgamated. In areas of moderate confinement there is a variable amount of sand on sand bedding contacts within the bed-set. This relationship is of bedding types is normally referred to as the amalgamation ratio which is the proportion of the amalgamated bedding contacts as a percentage of the total number of bedding contacts within the interval of interest. The relative proportions of amalgamation indicates the relative degree of confinement (Figure 1). The degree of amalgamation links directly to the effective vertical permeability in a reservoir, which has a significant impact on sweep efficiency during the producing life of fluids within a reservoir (Ringrose & Bentley, 2015)

The degree of vertical connectivity can be measured accurately in outcrop, in core and to a lesser degree with image-log tools and expressed as an amalgamation ratio. Standard logging tools may be used to infer the degree of amalgamation though this is subjective and more qualitative. For example a relatively stable low gamma-ray response over a 50m interval would indicate highly amalgamated sands as the probability of single deposit of 50m thickness is of a very low even in proximal areas (as individual flow deposits over 3-4m in thickness are uncommon). Conversely in intervals of low gamma ray response it follows that if sands are present they have a higher probability of not being amalgamated and possibly sub-log (i.e. averaged). Intermediate packages of variable gamma ray response may have a mixed signature of the amalgamation ratio.

Seismic may also be used to judge the degree of amalgamation within an interval but is of limited use due to its low vertical resolution and is best used where there is a high contrast between sand and muddier sections (e.g. high impedance contrast) where the units can be inferred to be highly amalgamated and poorly amalgamated respectively. Vertical trends in seismic may also be used to infer the likely trends in amalgamation ratio. Well-test data may also be used to appraise the degree of amalgamation. Vertical connectivity can be inferred from well test pressure build up if the flowing interval is from a small section of the unit. Vertical connectivity would imply a 'spherical flow period' signature, i.e. -1/2 gradient of the transient derivative. This interpretation is not unique, since the same derivative signature may arise from increasing reservoir quality or fluid mobility; the latter for example in a viscous oil where pressure disturbance enters the water leg. Confirmation of vertical permeability is obtained in a vertical interference test, where a second pressure gauge measures the pressure disturbance in an offset interval. Combined analysis of the pressure pulse in the primary flowing and secondary intervals proves vertical connectivity and gives a measurement of the average horizontal and vertical permeability (effectively Kv/Kh) on the scale of the radius of investigation.

Key expression of relative confinement: net:gross

In this section we define net:gross as the amount of net sand as a percentage of the gross interval of interest (e.g. the bed-set scale). The application of this interpretation of net:gross in this manner is relatively straightforward at outcrop and core where the distinctions can be made visually, although there is a degree of interpretation even here. Petrophysically this can be more challenging as cut-offs need to be applied and these may not always have real-rock data to ground truth them. Regardless, it is a very common tendency in thin-bedded intervals not to recognize or underestimate net sand (Ringrose & Bentley, 2015). Net:gross values are inextricably linked to the amalgamation ratio (see above). In areas of low confinement the lesser degree of erosion leads to the preservation of clastic muds associated with the sandier parts of the turbidity currents. In areas of very low confinement the periodicity of flow events may be sufficiently low to allow the preservation of hemi-pelagic fall-out between flows as well. The overall effect is to lead to greater proportions of muddier intervals thereby reducing the overall net sand percentage. Conversely in area of high confinement there is a much greater probability of erosion of the associated muds leading to lower preservation potential and consequent higher net:gross.

Other expressions of relative confinement

Space does not permit the discussion of other characteristics of relative turbidity current confinement such as hemi-pelagics distribution; facies association distribution and uniformity; bed thickness frequency distribution; bioturbation style, diversity and intensity; distribution of sedimentary structures; mineralogical content, variability & textural maturity; grain size and grain size variability etc. Each expression can however be place on the relative confinement cross plot (Figure 1) and notional relationships for some of these characteristics are shown in Figure 2. The reader may also gain understanding of the likely expression by relating them to the discussed expressions of lateral bed continuity, vertical connectivity / amalgamation ratio and net:gross discussed above as all these characteristics are inter-linked.

Conclusions

There is a clear relationship between relative flow confinement of a turbidity current and the depositional style and preserved expression of the flows deposits. The degree of relative confinement and subsequent deposition is a complex interplay between sedimentary processes, depositional setting and gives rise to variable expressions in lateral bed continuity, vertical connectivity / amalgamation ratio and net:gross, hemi-pelagics distribution; facies association distribution and uniformity; bed thickness frequency distribution; bioturbation style, diversity and intensity; distribution of sedimentary structures; mineralogical content, variability & textural maturity; grain size and grain size variability. These key expressions can be plotted on a scheme to relate the expression of relative confinement of turbidity currents across a range of scales from core to seismic. Such a plot allows the comparison of expressions and also the ability to interpret probable architectures using the expression of relative confinement or by finding the expression of relative confinement predict likely architectures.

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