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How to Interpret Turbidites: The Role of Relative Confinement in Understanding Reservoir Architectures

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Search and Discovery Article #51691 (2022)**
Posted August 3, 2022

*Adapted from extended abstract based on oral presentation given at 2020 AAPG Annual Convention and Exhibition.
DOI:10.1306/51691Stanbrook2022

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Abstract

Reservoir architecture is key in determining reservoir performance and 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 when architectures are sub-seismic.

Predictive architectural interpretations can be made by understanding the relative confinement of turbidity currents from which the reservoir is built. These predictions are made by observing patterns at the core and log scale and correlate through a relative confinement matrix to seismic-scale architecture. Variations in relative confinement are expressed through lateral bed continuity; vertical connectivity; amalgamation ratio; 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 etc.

A turbidity current is a combination of sediment and water kept in suspension through turbulence that flows down slope. The flow behaviour is a combination of the original volume of sediment, density of the flow, gradient of the slope, interaction with substrate and, critically, the ability for flows to expand (*sensu* Kneller, 1995) – i.e. the degree of confinement to which the flow is subjected by the container through which it is passing. There is a 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 of the flow and the size of the container into which it is flowing and / or depositing. Conceptually we can compare within a matrix a qualitative size of flow with a qualitative container size (Stanbrook et al, 2015). For example, the scale of the container may range from small scours to large basins. Similarly, the size of the flows may be vary considerably also. 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 as 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.

The careful analysis of the parameters described above allows the prediction of depositional architectures through the understanding of relative confinement. The architectural predictions in turn provide the basis for understanding permeability length-scales, kv/kh ratios and hence flow through these heterogeneous reservoirs.

Introduction

Reservoir architecture is a key determinant of reservoir performance and ultimate hydrocarbon recovery but varies greatly in deep-water clastic reservoir systems because of their intrinsic heterogeneity. 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 which typically flows down slope. The flow behaviour 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.

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 large or small. In this discussion the size of the flows considered are represented by the volume of the sediment in the observed depositional unit, i.e. the volume of the flow at the point of deposition. 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 and in this sense, there is a scale invariance between these controlling parameters and the resulting architectures.

Notionally the expression of the interaction of these two parameters is described for individual turbidity current deposits, however this can also be translated to the bed-set scale (or larger) in genetically similar packages. That is, while the statements regarding relative confinement apply to individual flows the overall architectural expression is a result of multiple events. While architecture is a product of multiple flows, with relative confinement varying through the interval, we distinguish between statements about one bed (which resides in one place in the matrix), and the reservoir interval of interest (which occupies a zone on the matrix).

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, expressed as low volume flows in a large container. As the axes 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 (relatively) wide channel. In principal, thin beds have a high degree of lateral continuity at the time of deposition, although continuity may be modified by pene-contemporaneous events such as slumping or erosion or later events such as faulting. Conversely, high-volume flows tend to be associated with areas of high confinement which prevents flow expansion beyond the walls of the container. The dominant force then becomes the interaction with the walls which promotes continued suspension and longitudinal transport. In Figure 1 highly confined flows occur where larger flows occur in relatively small containers; this may be very large volume event in a basin or a smaller scale event in a channelized system. 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 experience flow expansion and are therefore unlikely to be erosive. Therefore, the likely expression of the flows is to show preserved mud caps that were part of the original flow. In areas of low flow frequency there may also be intervening hemi-pelagic muds. Conversely, 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 (e.g. Stephen et al, 2001; Mattern, 2002). In areas of moderate confinement there is a variable amount of sand-on-sand bedding contacts within the bed-set. This relationship of bedding contact types is referred to as the 'amalgamation ratio' (Chapin et al, 1994) which is the proportion of the amalgamated bedding contacts as a percentage of the total number of bedding contacts within the interval of interest (Figure 3). The relative proportions of amalgamation relate to the degree of relative 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 depositing a 50m thick bed from a single flow is low, even in proximal areas (individual flow deposits over 3-4m in thickness are uncommon). Conversely in intervals of higher gamma ray response it follows that if sands are present, they have a higher probability of not being amalgamated and are possibly sub-log resolution (or may be averaged). Intermediate packages of variable gamma ray response may have a mixed amalgamation ratio signature. Image-logs, as a high-resolution resistivity tool have the advantage over standard logging tools in that the amalgamation ratio can be quantified by careful analysis of bed boundaries, though low contrast amalgamated contacts may still be difficult to discern.

Seismic may also be used to judge the degree of amalgamation within an interval but is of more 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 or poorly amalgamated. Vertical and lateral trends in seismic may also be used to infer the likely trends in amalgamation ratio through seismic-facies analysis– e.g. high-amplitude discontinuous reflectors are more likely to be amalgamated than low-amplitude continuous reflectors (e.g. Mitchum, 1985; Prather et al, 1998).

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 reservoir 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 (and hence the Kv/Kh ratio) 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, as opposed to net reservoir or net pay (*sensu* Worthington & Cosentino, 2005). The application of this interpretation of net:gross in this manner is relatively straightforward at outcrop and in 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 may 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 and therefore to underestimate sand content (Ringrose & Bentley, 2015) though with effort and special petrophysical analysis (e.g. Thomas & Stieber, 1977, Passey et al, 2006) greater resolution is possible. High resolution micro-resistivity (‘Image Log’) tools can break out thin-bedded intervals with good quality data though it is less able to determine amalgamation surfaces, particularly if there is little variation in grainsize, mineralogy or texture.

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.

Hemi-pelagics

In most deep-water settings there is ongoing sedimentation occurring in the basin in the form of hemi-pelagic fall-out within the water column. Unless remobilized after deposition this pelagic rain will be of a relatively constant thickness over extensive (basin scale) areas. It is the modification of the relative thicknesses of pelagics that can serve to infer the relative confinement of clastic flows into the same basin. Clastic turbidity currents entering a basin affect the distribution of pelagics in two main ways; by erosion and by non-deposition/dispersal.

As discussed above, there is variance in the probability of the preservation of muds between flows in areas of high confinement due to lack of flow expansion and increased erosion. This applies to the clastic mud associated with the turbidity current but also to intervening hemi-pelagics deposited between flows. In areas of low confinement and little erosion there is a much higher probability that these hemi-pelagic muds will not be eroded by the influx of turbidity currents.

The second interaction of hemi-pelagics and turbidites is vertical dispersal. Whereas the background hemi-pelagic sedimentation within a basin is continuous, the rate of accumulation is considerably slower than the clastic influx through turbidity processes by several orders of magnitude (e.g. Sadler, 1981). The deposition of the clastic flows interrupts the deposition of the pelagics and alters the relative proportions preserved in any given sequence. The volume of pelagic sediments has an inverse relationship to the presence of clastic materials with the basin and is therefore the inverse expression of the confinement of the flows entering a container. That is, large flows in a small container will displace the pelagic content within a given interval of accommodation space (even without erosion) whereas smaller flows in a large container will allow for a greater proportion of pelagic deposition in a comparable volume.

The presence of muds can be recognized in outcrop, core, petrophysical logs and even from seismic with enough resolution. However, it is important to differentiate pelagic muds from the presence of clastic derived (turbiditic) muds before their relative proportion with respect to the clastics can be established. In outcrop and in core (especially older core that has started to dry out) the difference between clastic and pelagic muds can be differentiated potentially by their colour but also their fracture pattern. Clastic and pelagic muds fracture in fissile and conchoidal ways, respectively, as a result of the more platy nature of the clastic muds compared to the pelagic (note, this does not apply in turbidite systems with carbonate rather than clastic sediment). Petrophysically, pelagic and clastic muds may be differentiated though the use of logs sensitive to subtle changes in porosity and bound water such as Nuclear Magnetic Resonance or other laboratory-based techniques such as X-ray diffraction or scanning electron microscopy (Ochoa, 2014). Also, dependent on bottom-water reducing conditions there will be a marked difference in the organic content of the two muds which should be readily established using simple biostratigraphic techniques such as total nannofossil or foraminiferal count (e.g. Crews et al, 2000). Seismically it is not possible to definitively determine the difference between the two from their inherent seismic character alone (though some subtle differences may conceivably be noted in very high resolution data), however their geometry may belie their nature as a result of their tendency to form widespread correlatable horizons (if resolvable), see section on lateral continuity.

Facies variation

Individual facies and facies associations are commonly used to infer depositional settings. In this paper we use the variation in facies types to infer the relative degree of confinement which can later be translated to more specific depositional environments. In areas of high-confinement, erosive processes are dominant and deposition occurring will tend to be quite uniform in that mostly the lower parts of beds are preserved; i.e. there is a high amalgamation ratio (see above) which only preserves the lower portion of beds, often Bouma (1962) Ta division / Lowe (1982) S1-S2 division dependent on the relative strength of the flows into the basin. Similarly, in areas of low confinement and low erosive activity most beds in a bed-set are preserved in their full original depositional style with full waning flow (*sensu* Kneller, 1995) structures preserved as a result of low amalgamation and the facies is similarly uniform.

Between these two end members lies a zone of variable facies expression as a result of variable flow deposits juxtaposing different facies within differing architectures (e.g. proximal lobe locations). The confined expression of turbidity current deposits in confined areas will tend to be relatively uniform, become less uniform in less confined areas and once again uniform in unconfined areas.

Facies distribution and uniformity can be determined in outcrop and core through standard description techniques. Borehole evaluation is best with the use of careful image log analysis. Lower resolution standard logging tools such as gamma-ray can be used in combination with lithological data (core, sidewall core & cuttings) to infer facies associations; this is contextually driven but with assumptions about bed-thickness (see below) petrophysical facies can be derived. Seismic data is limited by vertical resolution though it can be used to infer facies associations (seismic facies) at a coarse scale (e.g. De Ruig et al, 2006; Prather, 2000, Booth et al, 2000).

Bed Thickness Frequency distribution

Bed thickness frequency distribution is the evaluation at the bed-set scale of the range and frequency of bed thickness and has a non-linear relationship to degree of confinement. In areas of high confinement where the system may be dominated by erosion the resultant bed thickness is an expression of successive amalgamated events giving rise to a relatively constant bed thickness expression. The distal expression or areas of unconfined flows turbidite distribution is by radial expansion of the flows and therefore relate to the original size of the flows more than other mechanisms. As such the representative depositional units will be dominated by the ‘normal’ size of the flows entering the basin or area of interest, i.e. typically of a relatively uniform size. That is to say that these areas will be dominated by the high-frequency and low volume events. It should be noted that depositional systems with a unimodal grain size may tend to have a constant bedding thickness; this may be due to autocyclic processes of build-up of sediment to a common critical failure point releasing similar volumes of material from up-dip staging areas.

Bed thickness distribution can be determined in outcrop and core through standard description techniques and plotted as a frequency distribution chart (see Sinclair and Tomasso, 2002 and Sinclair and Cowie, 2003 for examples). Borehole evaluation is best with the use of careful image log analysis. To a limited extent lower resolution standard logging tools such as gamma-ray can be used in combination with lithological data (core, sidewall core & cuttings) to infer facies bed-thickness distributions; this is contextually driven but with assumptions about bed-thickness (see below) bed-thickness distributions can be derived. Seismic data is of limited use due to lack of vertical resolution though liking of the seismic-facies expression (see above) can infer the likely lateral bed continuity and by association the likely bed thickness distribution.

Bioturbation style, diversity and intensity

Bioturbation style, diversity and intensity is the expression of the activity of organisms post-deposition in turbidity current deposits. The style and diversity of the organism traces are a response to the organisms living and feeding habits which are in turn controlled by their immediate environmental conditions (e.g. Pemberton et al, 2010). The expression of trace types may be diverse but fundamentally there are two end-member living patterns: dwelling and grazing. Typically, dwelling organisms live in relatively mobile sandy substrates and tend to form dominantly vertical to sub-vertical burrows that protect them from predation, often lining their burrows with mud to prevent collapse. Conversely grazing organisms live near to or at the sediment-water interface and are mostly horizontal or sub-horizontal in form. In turbidite systems the larger dwelling burrows (e.g. *Ophiomorpha*) tend to be found in sandy area such as channels or axial zones of lobes (*sensu* Prelat et al, 2010) and the smaller grazing traces (e.g. *Palaeodytion*) in areas area such as outer lobe setting in the relatively-unconfined zones where muds are preserved. See papers by Heard & Pickering (2007), Knaust et al (2014) & Callow et al (2014) for more examples of the distribution of trace fossils in deep-water settings.

In combination with this style of grazing is the diversity and intensity of the bioturbation. The diversity of the different types of traces is a function of the degree of environmental stress to which the organisms are subjected. In turbidite systems areas of high environmental stress may be in active areas such as channels and diversity in these areas is typically low as few organisms can thrive there (e.g. Heard and Pickering, 2007). Conversely, areas of lower environmental stress such as the outer lobe are less subject to erosion and bioturbation and diversity is typically much higher. Similarly, bioturbation intensity is linked to the frequency of depositional events. Long periods between flows that occur in areas distal to the flow axis allow time for multiple tiers of bioturbation to occur in deposited sediment. In areas of high sediment input, relatively little time is allowed for colonisation between flows.

Bioturbation style, diversity and intensity can be determined in outcrop and core through standard description techniques. Various recognition references are available to recognise types and diversity (see above references) which may be plotted as relative proportions of size and vertical to horizontal traces. Bioturbation intensity is referred to the ‘bioturbation index’ which is scaled from 0-6 (unbioturbated to completely-bioturbated), Taylor and Goldring (1993). Some very limited evaluation of bioturbation is possible with image-log tools if the organisms are sufficiently large and mud-line their burrows, though this method is intrinsically biased by its inability to recognise smaller organisms. Standard logging tools and seismic data play no role in the recognition of bioturbation type, diversity or intensity.

Sedimentary structures

The style and range of depositional structures is varied and relate to a combination of grain-size and flow velocities (Hjulström, 1935). However, if the grain size is known then it is possible to isolate the velocity component of the relationship which is directly linked to degree of confinement – i.e. more strongly confined regions experience higher flow velocities than less confined regions. The range of depositional sedimentary structures identified in the literature is covered mostly in the range of features described in the definitions of Lowe (1982) and

Bouma (1962). Their relationship to velocity is described in the flow regime experiments of Hjulström (1935). One sedimentary structure not described in is the ‘scour & fill’ feature found in an axial channel position indicating very high degrees of confinement (Elliott, 2000). Contemporaneous or immediately post-depositional de-watering attest to rapid deposition of sands coming out of high velocity suspension, e.g. Lowe (1982) type S1-S2 and their concentration and size attest to the rapidity of suspension fallout.

Upper flow regime sedimentary structures are therefore found in areas of high confinement with lower flow regime structures in areas of low confinement. Note, in areas of high confinement many structures may be lost due to erosion (see above section on amalgamation). De-watering structures tend to be a feature of highly confined areas such as axial lobes or channels. This range of sedimentary structures is readily recognised in outcrop and core (assuming the requisite grainsize distribution is present to form / preserve the feature). Side-wall cores and image logs may also be used but will be biased towards the smaller and larger scale features respectively; side-wall cores are also data limited.

Grain size and grain size variability

Grain size analysis in turbidite systems consists of measuring the modal grain size and the range and / or distribution of grain size. The use of grain size analysis is of limited use in systems where the originating depositional unit has been significantly pre-sorted in staging areas (such as shoreface systems) that result in narrow or unimodal grain size distributions.

In turbulent flows higher velocities are required to transport the coarser fractions of a sediment load than smaller grains (see above section). As higher velocities occur in regions of higher confinement there is a tendency to concentrate the larger grains into these areas such as channels (e.g. channel lag) or the axial zones of lobate systems. Conversely lighter grains will be ejected into less confined areas such as the sides and to the rear of flows where muddier units with platy materials such as mica and carbonaceous matter will deposit (e.g. Stanbrook & Clark, 2004). Areas of moderate confinement may contain a wide range of grain sizes.

Grain size data can be derived most accurately from outcrop, core and side-wall core data. Cuttings data can also be used with the understanding that coarser grain fractions above very coarse will likely not be represented and that there will be a depth uncertainty related to flow rate return. Use of modern Polycrystalline Diamond Compact (PDC) bits will reduce the range of grain sizes represented dramatically to the finer end of the spectrum, thereby limiting the application of the data. High resolution image log data can be used to determine grain size above circa gravel grade, but this similarly narrows the range of grain sizes represented to the coarse end of the spectrum. Log data can be of limited use through the density and gamma ray tools, but this entails many assumptions and is best used in conjunction with cuttings and core data. Seismic data plays no part in understanding grain size distribution.

Mineralogical content and variability / textural maturity

Mineralogical content and textural maturity are the expression of the degree of transport that has taken place to a load of sediment in single or multiple transport and depositional episodes. The transport of sediment has the effect of removing mechanically weaker mineralogies (such as feldspars) and rounding and sorting of the remaining materials. Its application in the deep-water realm is difficult as the original sediment load will probably have already undergone transport and reworking in the terrestrial and shallow marine settings (see above) - with the later particularly effective in changing the mineralogy and textural maturity. The transport of the sediment load in the turbidity currents themselves represent a very minor degree of the total transport of most sediment loads. However, where up-dip feeder systems are attached (e.g. Van der Merwe et al, 2014), interpreted, or have relatively little detachment to the deep-marine system, it may still be possible to infer some depositional information.

Conclusions

There is a clear relationship between the relative confinement of a turbidity current and the depositional style and preserved expression of the flow's 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 (Table 1).

These key expressions can be used to interpret the relative confinement of turbidity currents and hence to predict the architectural characteristics from sparse data gathered from a range of scales from core to seismic. This can be summarised on a simple cross-plot on which, by definition, all deposits of deep marine systems must be located somewhere. Locating an interval of interest on the spectrum of relative confinement allows predictions to be made of likely sand distribution and connectivity, permeability architecture and hence fluid flow properties in deep marine sedimentary deposits that are preserved as reservoirs in the subsurface.

Acknowledgements

The authors which to acknowledge the successive participants of Nautilus training course 'Characterisation, Modelling Simulation and Development Planning in Deepwater Clastic Reservoirs' who have been the test bed of the concept of relative confinement over many years.

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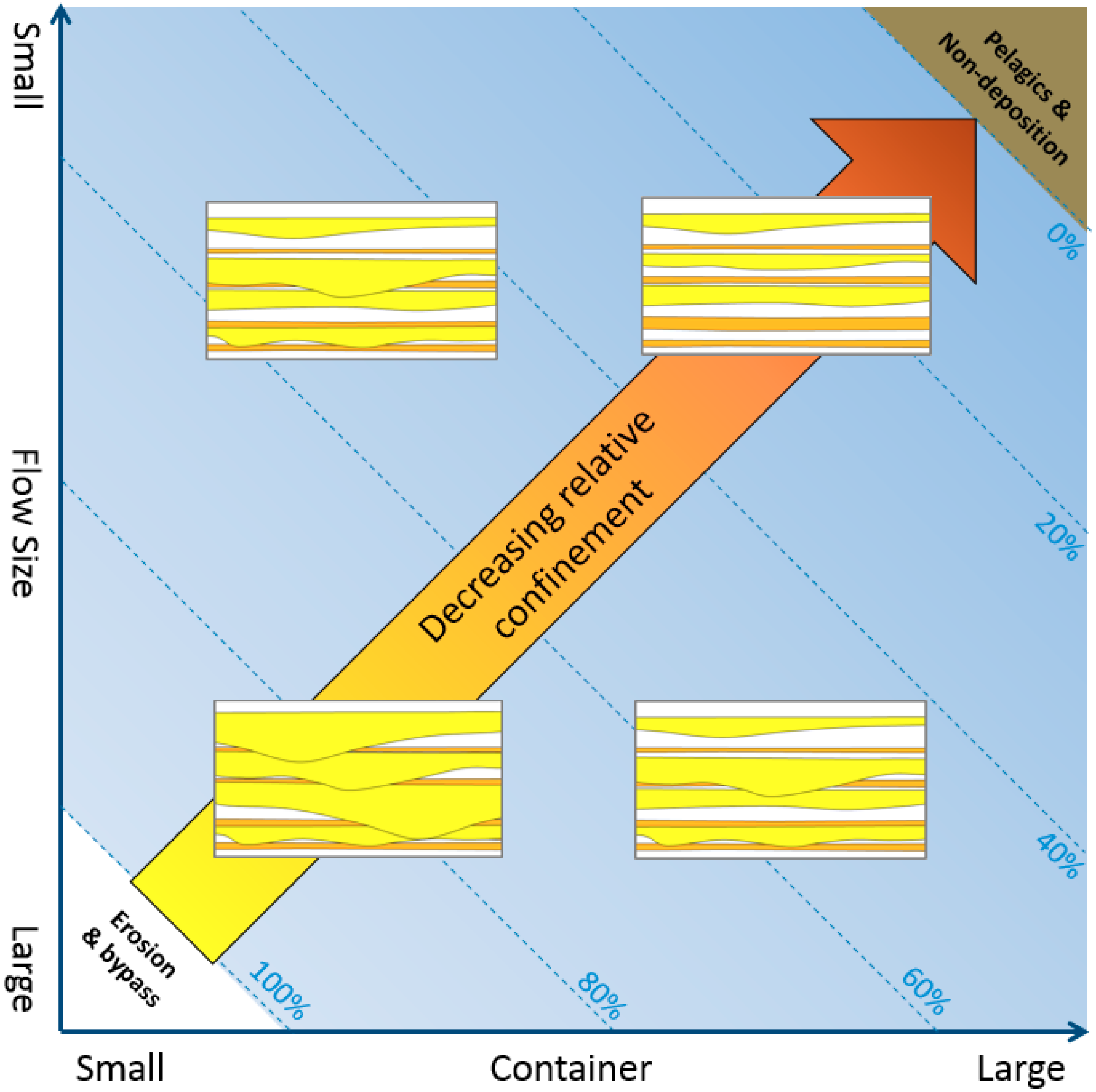


Figure 1. A matrix of qualitative size of flow and container derives the degree of relative confinement onto which quantitative parameters may be plotted. The expression of relative confinement may be linear (decreasing or increasing) or non-linear. Figure 2 shows the different expressions of relative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

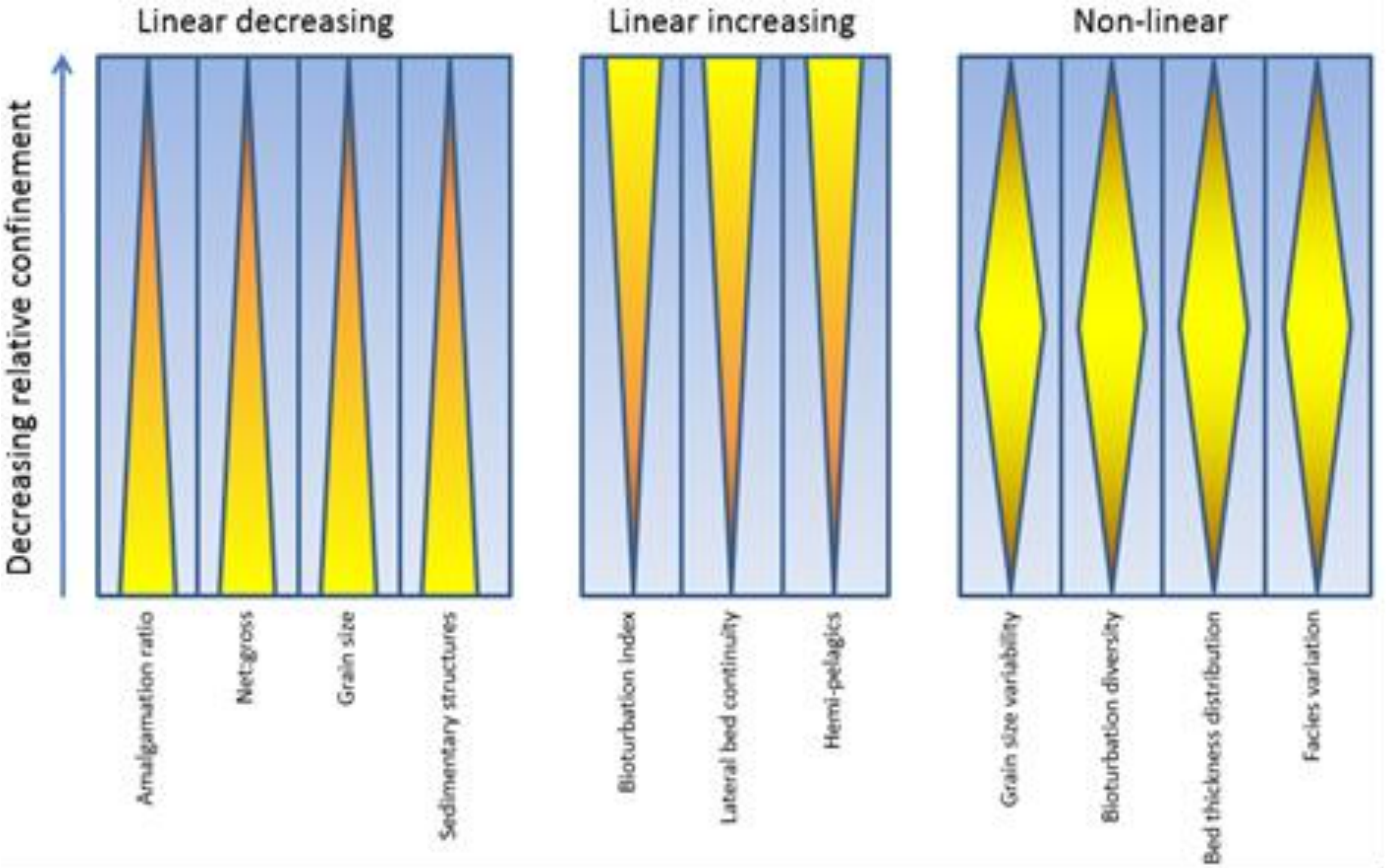


Figure 2. Classes of character expression; linear decreasing value, linear increasing value and non-linear. Each parameter can be plotted on the relative confinement diagram (Figure 1). Key expressions are discussed in the text.

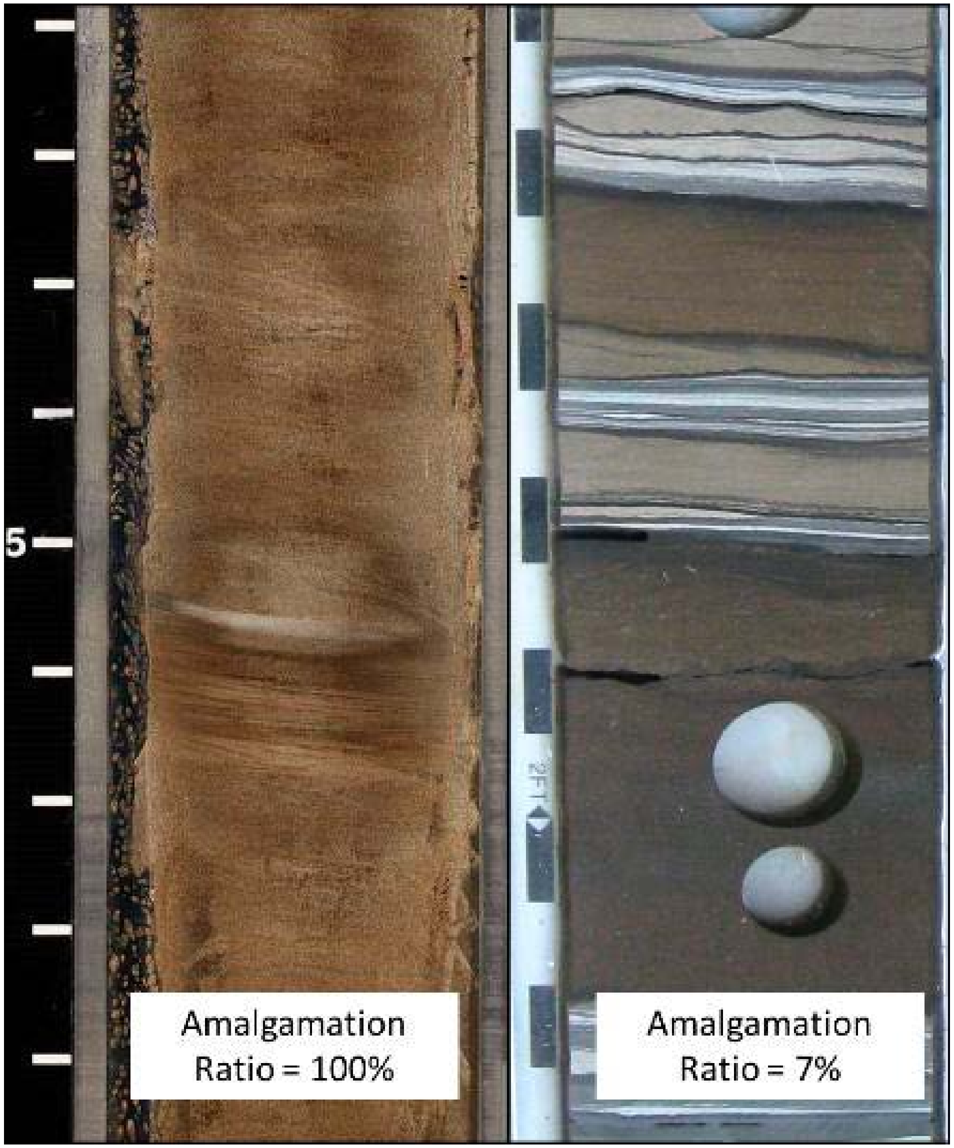
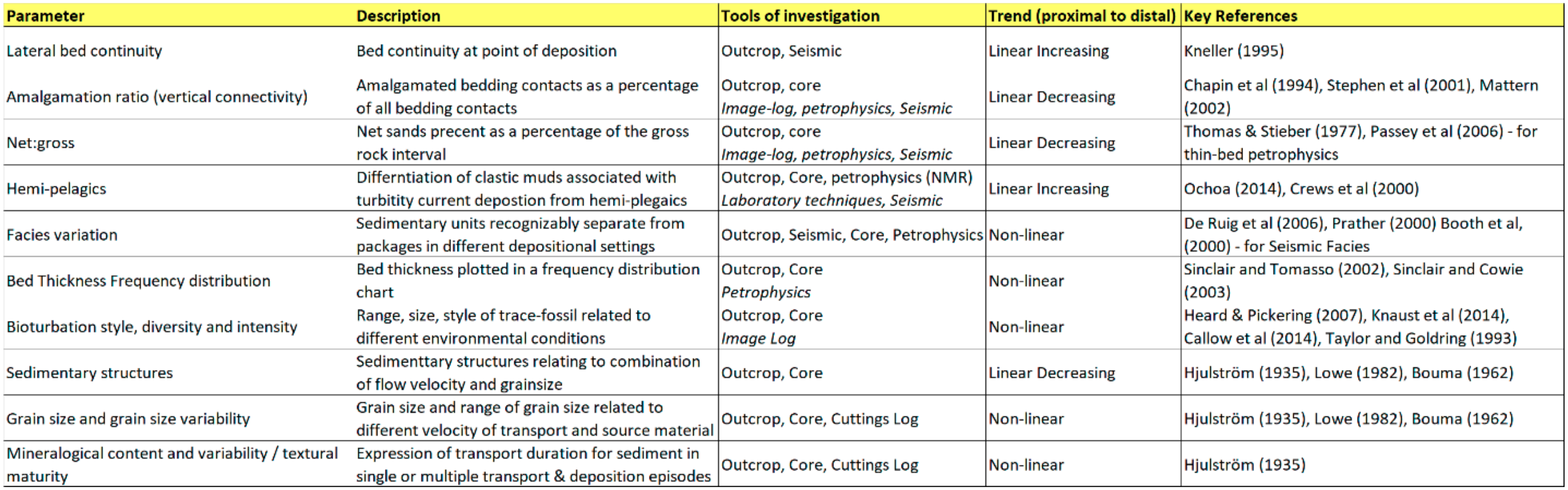


Figure 3. Amalgamation ratio is a function of the number of amalgamated (sand on sand bedding contacts as a result of erosion) as a percentage of all bedding contacts. In this example the core on the left has one bedding contact which is amalgamated making an amalgamation ratio of 100%. The core on the right has thirteen bedding contacts with one being amalgamated, making an amalgamation ratio of seven percent.



Parameter	Description	Tools of investigation	Trend (proximal to distal)	Key References
Lateral bed continuity	Bed continuity at point of deposition	Outcrop, Seismic	Linear Increasing	Kneller (1995)
Amalgamation ratio (vertical connectivity)	Amalgamated bedding contacts as a percentage of all bedding contacts	Outcrop, core *Image-log, petrophysics, Seismic*	Linear Decreasing	Chapin et al (1994), Stephen et al (2001), Mattern (2002)
Net:gross	Net sands precent as a percentage of the gross rock interval	Outcrop, core *Image-log, petrophysics, Seismic*	Linear Decreasing	Thomas & Stieber (1977), Passey et al (2006) - for thin-bed petrophysics
Hemi-pelagics	Differntiation of clastic muds associated with turbitity current depostion from hemi-plegaics	Outcrop, Core, petrophysics (NMR) *Laboratory techniques, Seismic*	Linear Increasing	Ochoa (2014), Crews et al (2000)
Facies variation	Sedimentary units recognizably separate from packages in different depositional settings	Outcrop, Seismic, Core, Petrophysics	Non-linear	De Ruig et al (2006), Prather (2000) Booth et al, (2000) - for Seismic Facies
Bed Thickness Frequency distribution	Bed thickness plotted in a frequency distribution chart	Outcrop, Core *Petrophysics*	Non-linear	Sinclair and Tomasso (2002), Sinclair and Cowie (2003)
Bioturbation style, diversity and intensity	Range, size, style of trace-fossil related to different environmental conditions	Outcrop, Core *Image Log*	Non-linear	Heard & Pickering (2007), Knaust et al (2014), Callow et al (2014), Taylor and Goldring (1993)
Sedimentary structures	Sedimenttary structures relating to combination of flow velocity and grainsize	Outcrop, Core	Linear Decreasing	Hjulström (1935), Lowe (1982), Bouma (1962)
Grain size and grain size variability	Grain size and range of grain size related to different velocity of transport and source material	Outcrop, Core, Cuttings Log	Non-linear	Hjulström (1935), Lowe (1982), Bouma (1962)
Mineralogical content and variability / textural maturity	Expression of transport duration for sediment in single or multiple transport & deposition episodes	Outcrop, Core, Cuttings Log	Non-linear	Hjulström (1935)

Table 1. Different parameters that can be used to derive sense of relative confinement and their utility in the sub-surface; tools of investigation in *italics* less reliable and / or usable. Compare with Figures 1 & 2.