Explicit inclusion of connectivity in geostatistical facies modelling

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Abstract

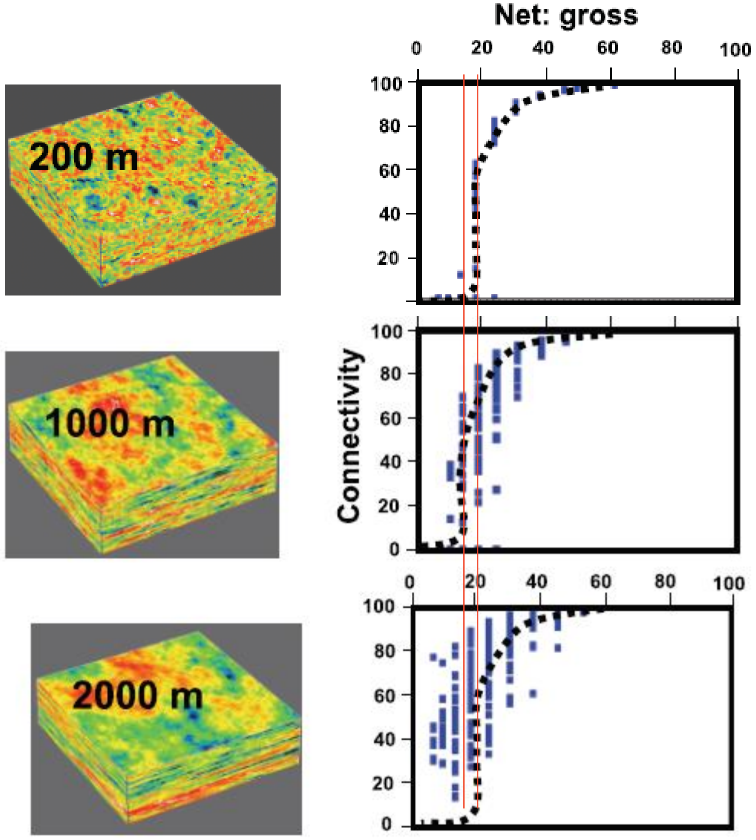
Irrespective of the specific technique (variogram-based, object-based or training image-based) applied, geostatistical facies models usually use facies proportions as the constraining input parameter to be honoured in the output model. The three-dimensional interconnectivity of the facies bodies in these models increases as the facies proportion increases, and the universal percolation thresholds that define the onset of macroscopic connectivity in idealized statistical physics models define also the connectivity of these facies models. Put simply, the bodies are well connected when the model net:gross ratio exceeds about 30%, and because of the similar behaviour of different geostatistical approaches, some researchers have concluded that the same thresholds apply to geological systems.

In this contribution we contend that connectivity in geological systems has more degrees of freedom than it does in conventional geostatistical facies models, and hence that geostatistical facies modelling should be constrained at input by a facies connectivity parameter as well as a facies proportion parameter. We have developed a method that decouples facies proportion from facies connectivity in the modelling process, and which allows systems to be generated in which both are defined independently at input. This so-called compression-based modelling approach applies the universal link between the connectivity and volume fraction in geostatistical modelling to first generate a model with the correct connectivity but incorrect volume fraction using a conventional geostatistical approach, and then applies a geometrical transform which scales the model to the correct facies proportions while maintaining the connectivity of the original model. The method is described and illustrated using examples representative of different geological systems. These include situations in which connectivity is both higher (e.g. fluid-driven injectite or karst networks) and lower (e.g. many depositional systems) than can be achieved in conventional geostatistical facies models.

Observation 1:

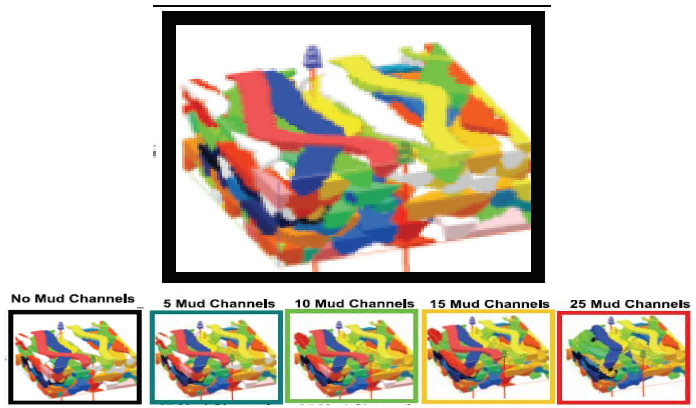
Facies in conventional geostatistical models become connected in 3D at a net:gross ratio of ca. 20 - 25%.

e.g. Variogram-based models (Larue and Hovadik, 2006)

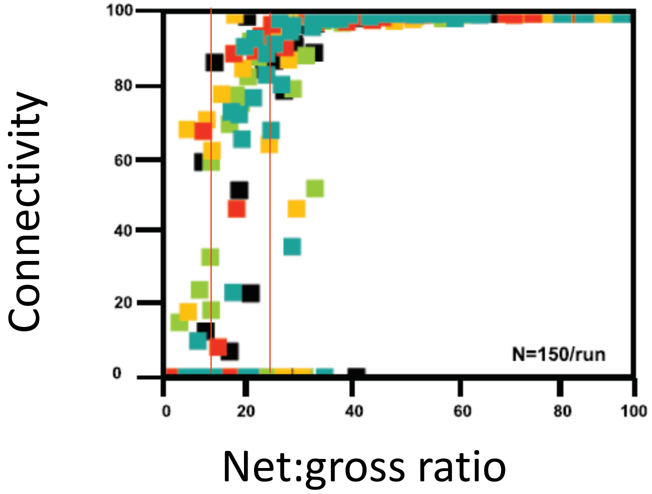


Critical net:gross ratio 15-20%

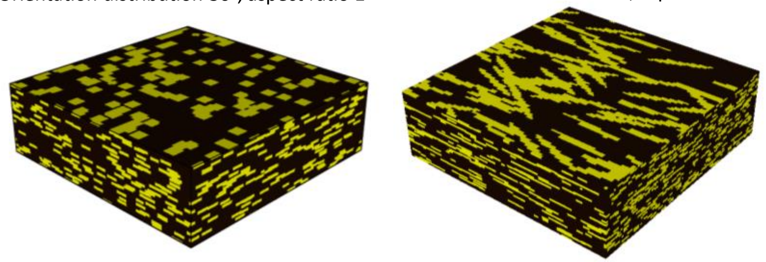
e.g. Object-based models of Sinuous channels (Larue and Hovadik 2006)



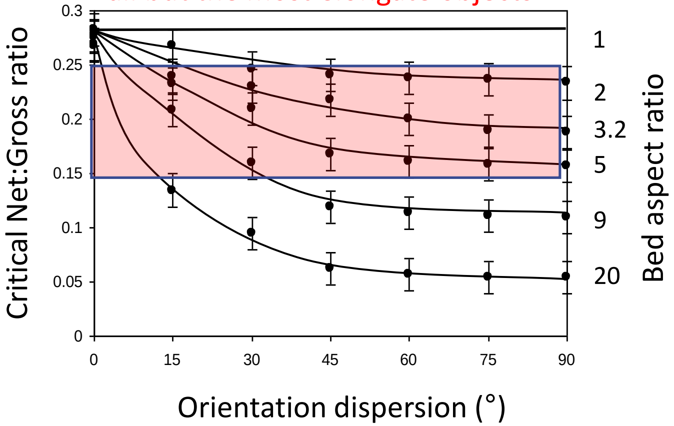
Critical net:gross ratio 15-25%



e.g. Object-base models of square, circular or elongate sheet-like objects (Manzocchi et al., 2007)



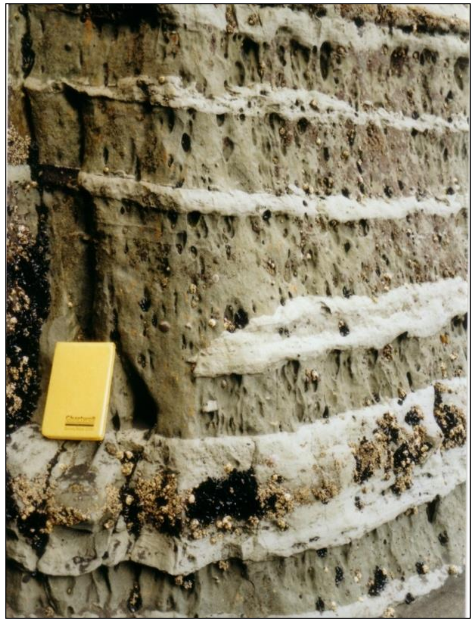
Critical net:gross ratio 15-25% for all but the most elongate objects



Observation 2: Geological systems have varied relationships between amalgamation ratio and net:gross ratio, but in conventional geostatistical facies models the two properties are approximately equal.

Connectivity in sand-shale systems can be measured using the Amalgamation Ratio, AR. This is defined as the the fraction of sandstone bed bases in contact with an underlying sandstone bed as opposed to a fine-grained inter-bed deposit.

Example: 80% NTG; 12.5% AR

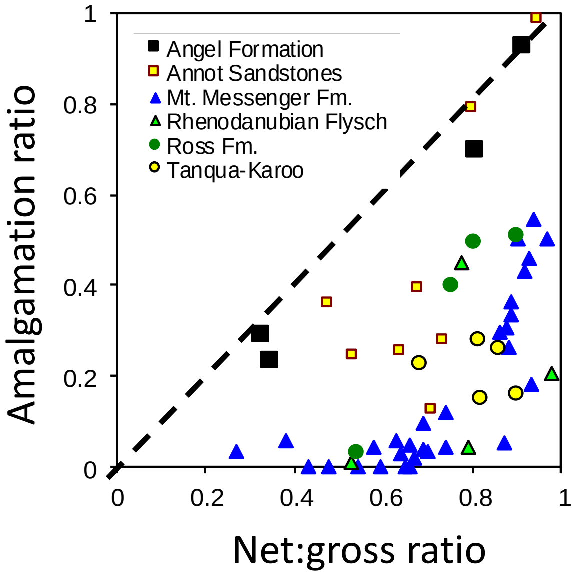


sand

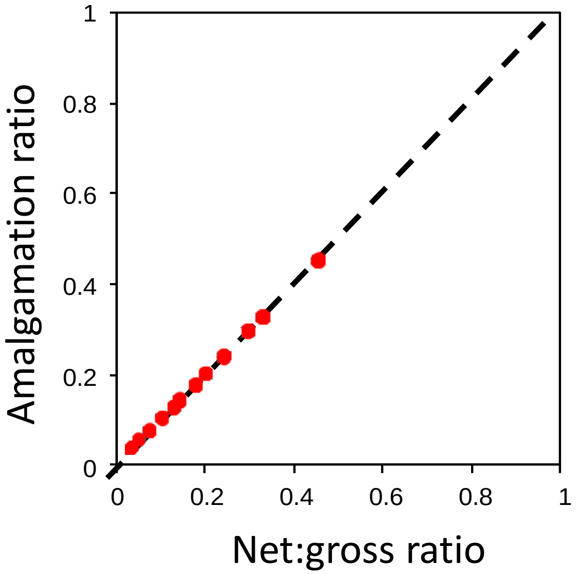
shale

Of the 4 sand bed bases in this photo, one is amalgamated over 50% of its length. Hence AR of these sands in this photo is 12.5%

Measurements from natural depositional geological systems:



Measurements from object-based models of square, circular or elongate sheet-like objects



Cross-plots of AR vs. NTG for models and natural system show that object-based facies models have AR = NTG, but natural systems consistently have AR < NTG, with different systems showing different trends.

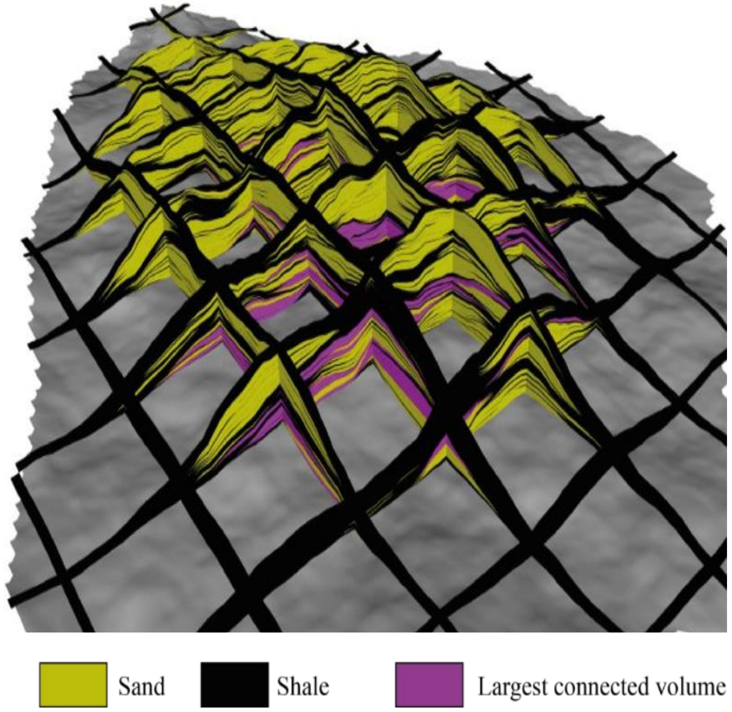
See Manzocchi et al. (2007) for details.

Observation 3:

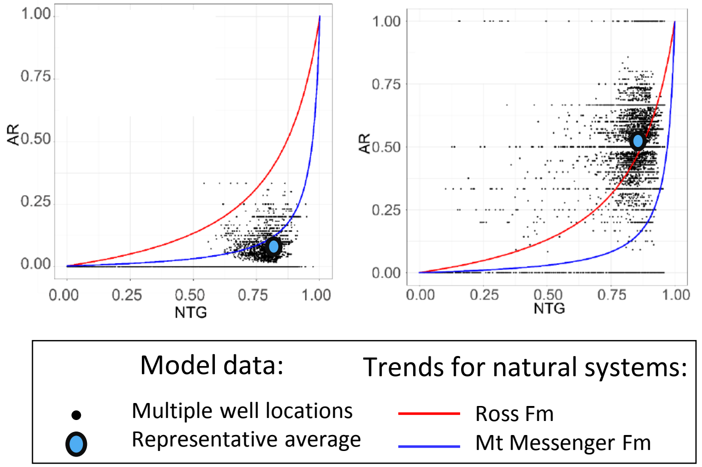
Facies in surface-based models become connected in 3D at an amalgamation ratio of ca. 20 - 25% irrespective of net:gross ratio

Objects in surface-based models are stacked in depositional order according to geological rules (aggradation, avulsion, erosion) and hence surface-based models are much more representative of natural systems than conventional geostatistical models. Different rules result in models with different amalgamation ratios for the same net:gross ratio, and bulk connectivity measured from a suite of models reveals a connectivity threshold at an amalgamation ratio of ca. 25%.

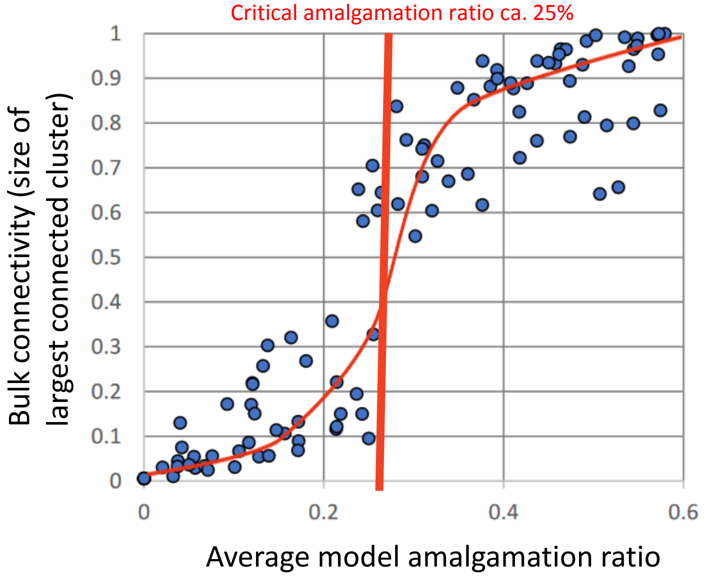
Example surface-based model showing sands in yellow and the sub-set of beds that form the largest connected cluster in purple



Measurements of AR and NTG in two different surface-based models generated according to different rules representative of different natural systems



Bulk connectivity vs. Amalgamation ratio of 100 models with approximately the same net:gross ratio generated with different rules



See López-Cabrera et al. (2019a, 2019b) for details.

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Observations:

1: Facies in conventional geostatistical models become connected in 3D at a net:gross ratio of ca. 20 - 25%.

2: Geological systems have varied relationships between amalgamation ratio and net:gross ratio, but in conventional geostatistical facies models the two properties are approximately equal.

3: Facies in surface-based models become connected in 3D at an amalgamation ratio of ca. 20 - 25% irrespective of net:gross ratio.

Discussion:

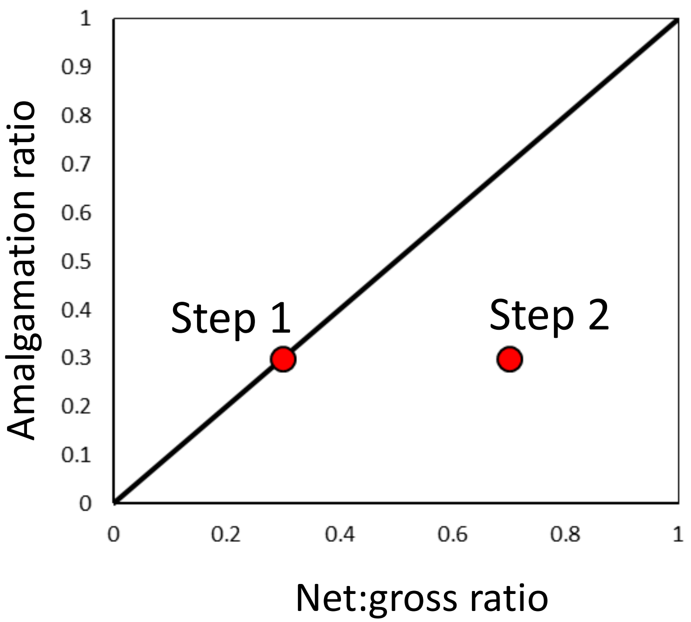
1: Connectivity in conventional geostatistical models is constrained by the artificial link between amalgamation ratio and net:gross ratio inherent in these models and hence is not necessarily representative of natural systems.

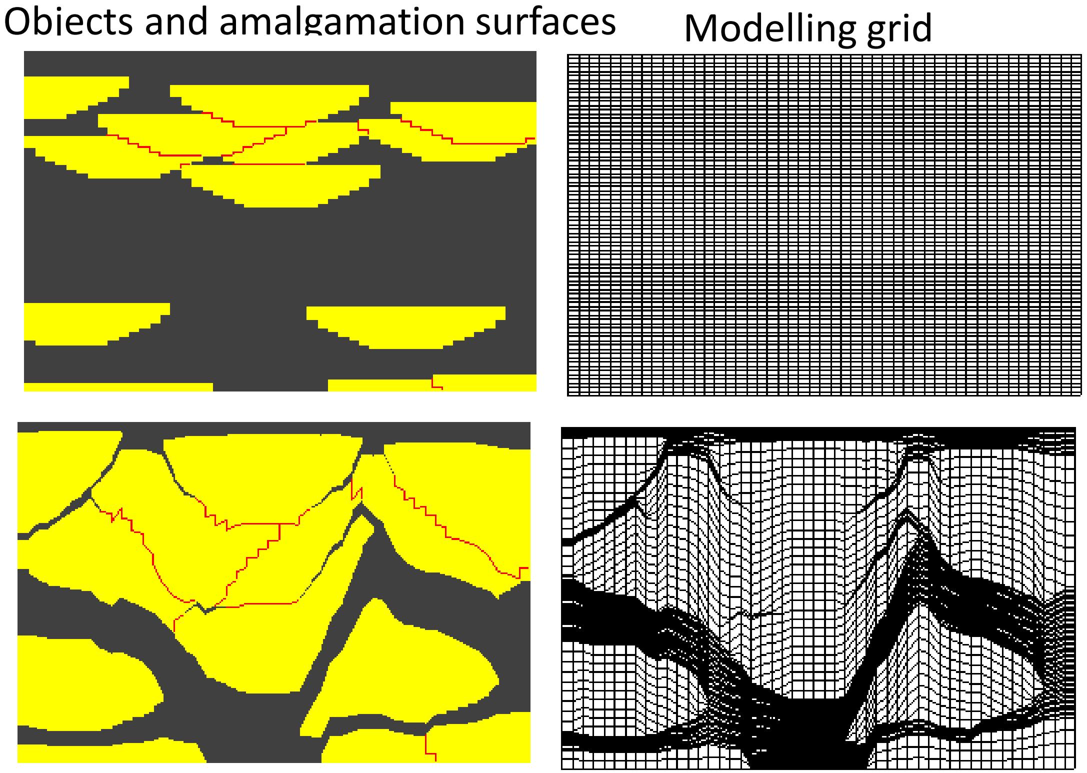
2: Connectivity in surface-based models is much more representative of natural systems than in geostatistical models, but geostatistical models are much easier to use in practical studies since it is possible to condition geostatistical models, but not surface-based models, to hard data (e.g observations at wells).

3: The compression algorithm has been devised to improve connectivity representation in conventional geostatistical models. The algorithm applies a geometrical grid transformation that allows amalgamation ratio and net:gross ratio to be defined independently of each other. The following slides show the basis of the method and some applications of if.

The compression-based modelling approach

The compression-based modelling approach allows amalgamation ratios and net:gross ratio to be defined as independent modelling input variables in geostatistical modelling workflows. The two steps in the process are shown below, to generate a model with AR < NTG. The approach can also generate models with AR > NTG.





Step 1: Generate a conventional geostatistical model in a regular grid using a net:gross ratio equal to the target amalgamation ratio and objects with appropriately scaled thickness

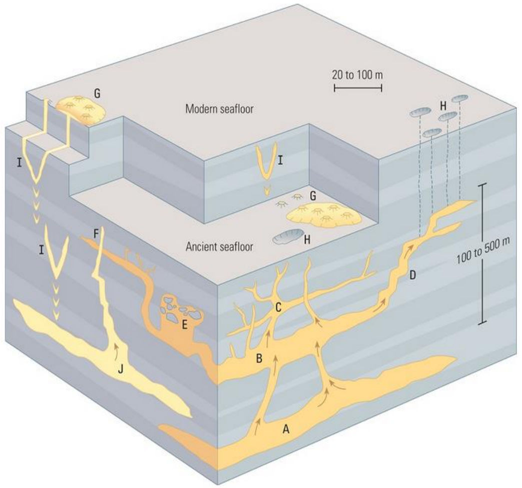
Step 2: Increase the thickness of grid cells in the target facies and decrease it in the background facies, to obtain the target NTG. This operation does not alter AR.

See Manzocchi et al. (2007, 2020) for details.

The compression-based modelling approach

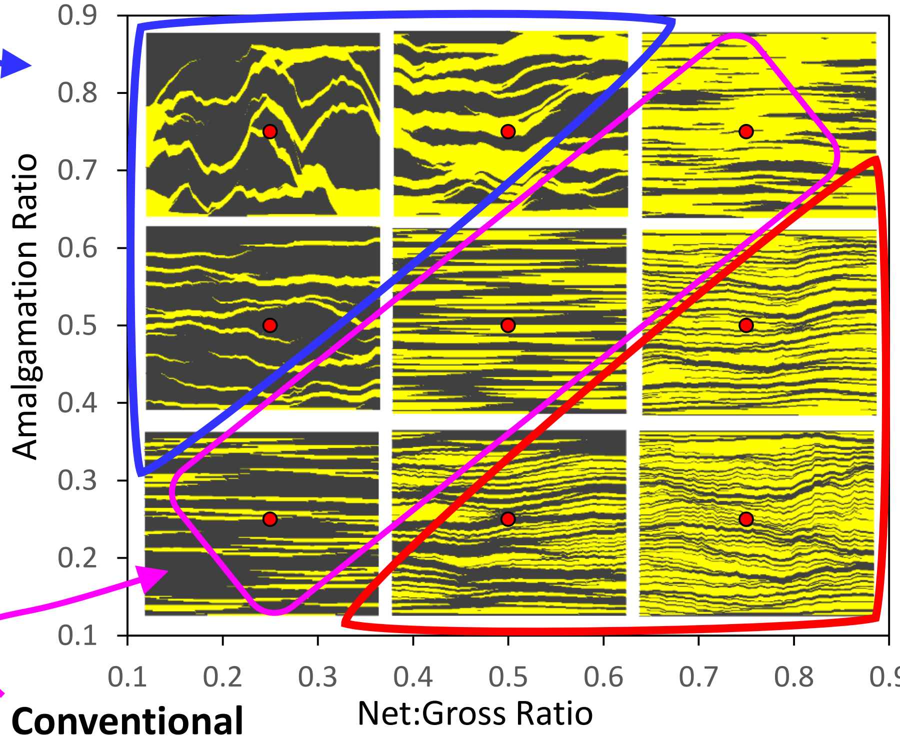
Different types of geological system have different associations between connectivity and net:gross ratio, with depositional systems less connected and fluid-driven systems more connected than random models. Our work to date has focused on the former type of system.

AR > NTG: Fluid-driven systems, e.g. sand injectites



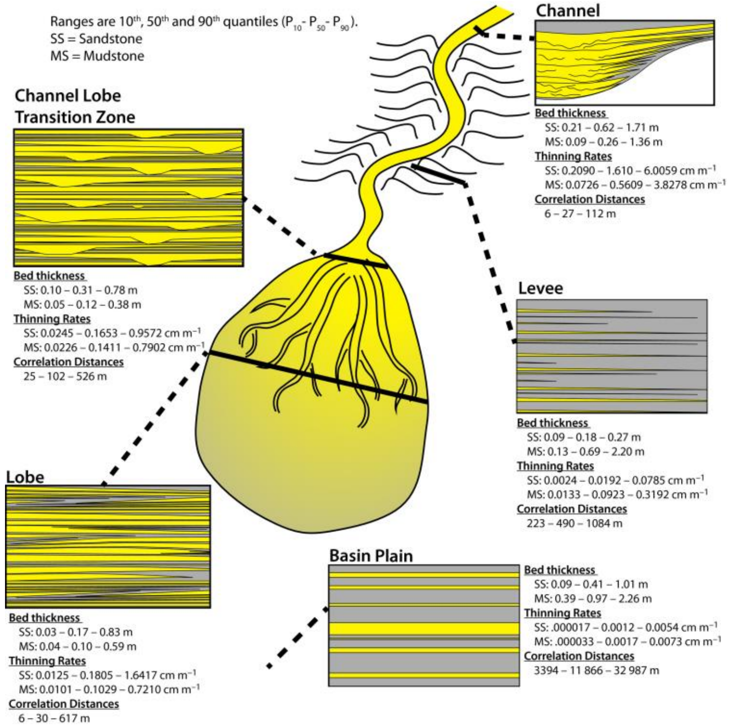
Conceptual model of sand injectites. From Schlumberger Oilfield Glossary, after Hurst and Cartwright (2007)

Cross-sectional object-based models built using the compression method, for combinations of Net:Gross and amalgamation ratio values of 0.25, 0.5 and 0.75. All models have the same sized yellow objects in a background black facies.



AR ≈ NTG: Conventional geostatistical models

AR < NTG: Depositional systems: e.g. deep-water lobe deposits

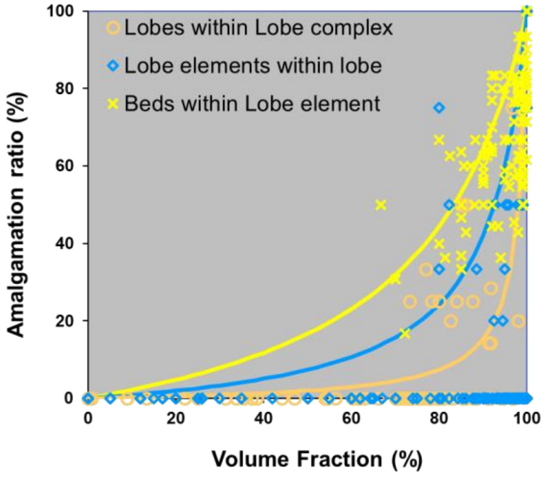


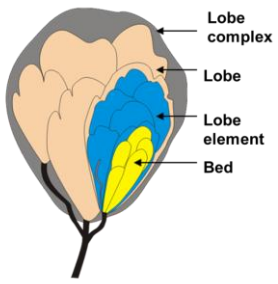
Conceptual model of beds in submarine depositional environments. From Fryer and Jobe (2019)

Application 1:

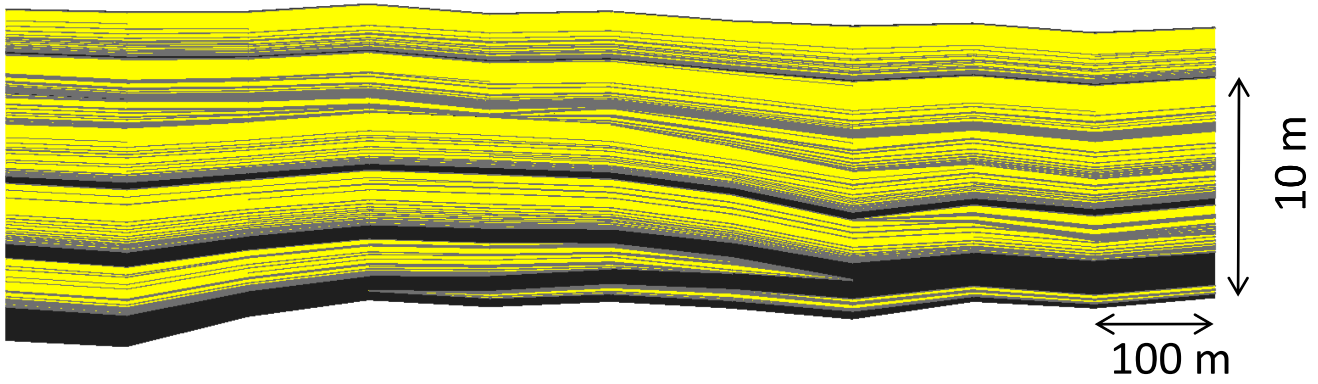
Hierarchical compression- and object-based modelling of deep-water lobe deposits

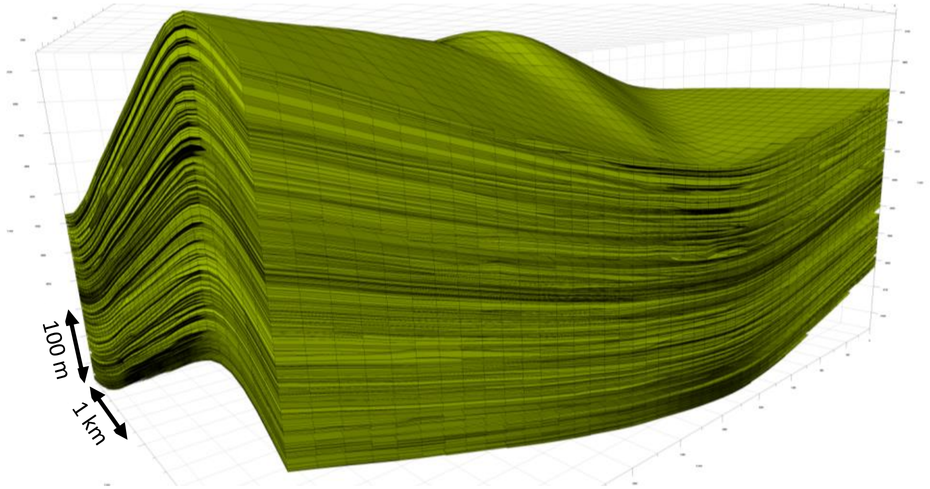
Hierarchical stacking data for lobe objects in the Ross Formation, W. Ireland



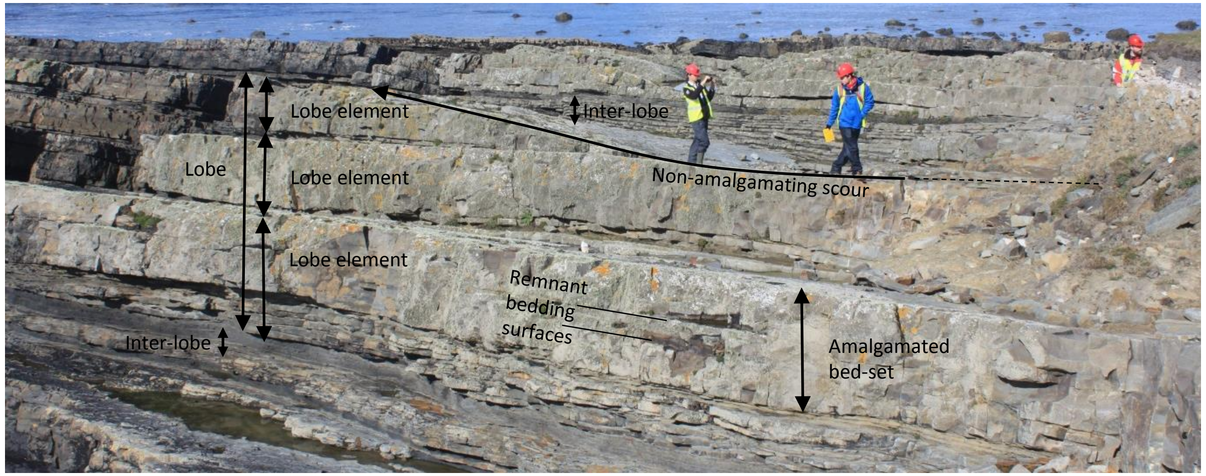


Detailed 2D model of beds in lobe elements in a lobe, based on Ross Formation data





Hierarchical 3D reservoir model build in stand-alone software according to these data.



Outcrop photo of Ross Formations: Beds in lobe elements in a lobe

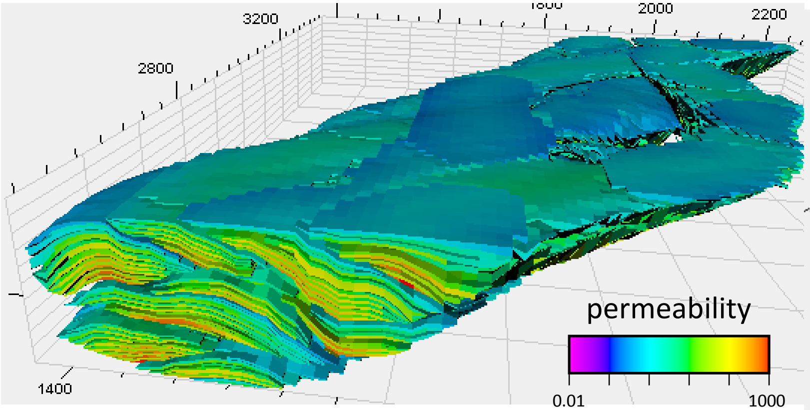
See Zhang et al. (2015) and Manzocchi et al. (2020) for details.

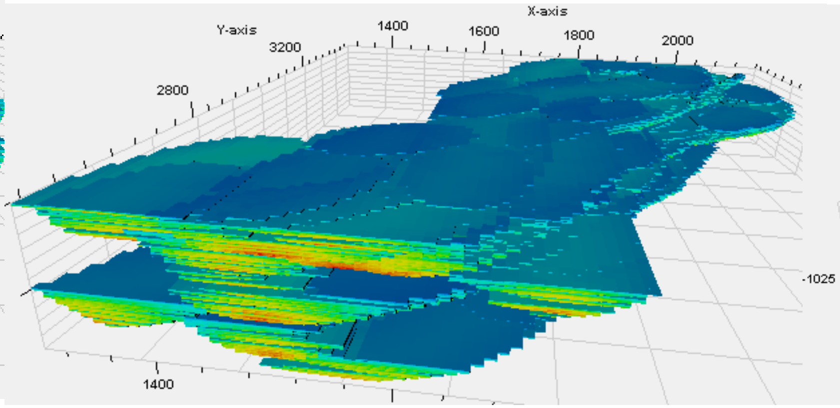
Application 2: Hierarchical compression- and object-based modelling of deep-water channel deposits

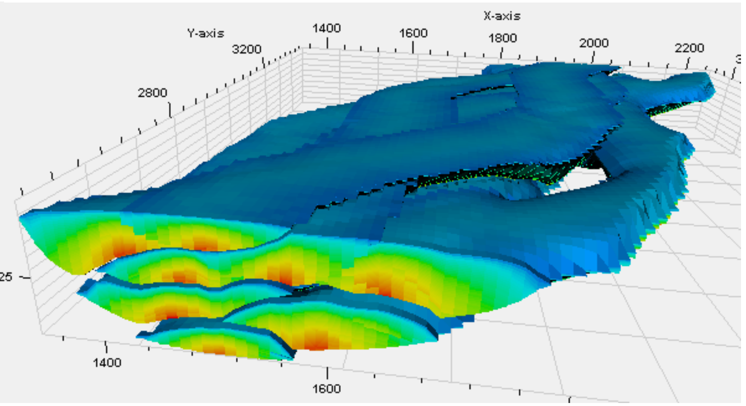
Set A: Base-case: beds in channel elements in channel complex, representative hierarchical amalgamation ratios

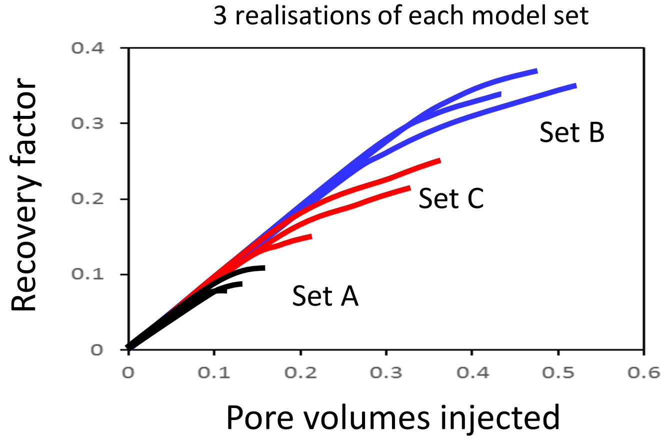
Set B: Same hierarchy and object dimensions but unconstrained amalgamations (i.e. conventional object-based modelling)

Set C: Base-case channel elements but no bed-scale heterogeneity









Suites of hierarchical reservoir-scale models of a generic deep-marine channel complex were built using the compression algorithm implemented as a plugin in industry-standard software. Cases were generated using different modelling assumptions and analysed using a production flow simulation model. Results indicate a factor-of-three decrease in recovery at water breakthrough in the most realistic models (Set A), compared to a models with identical properties but unconstrained connectivity (Set B).

See Carneiro and Manzocchi (2017) and Soni et al. (2018)

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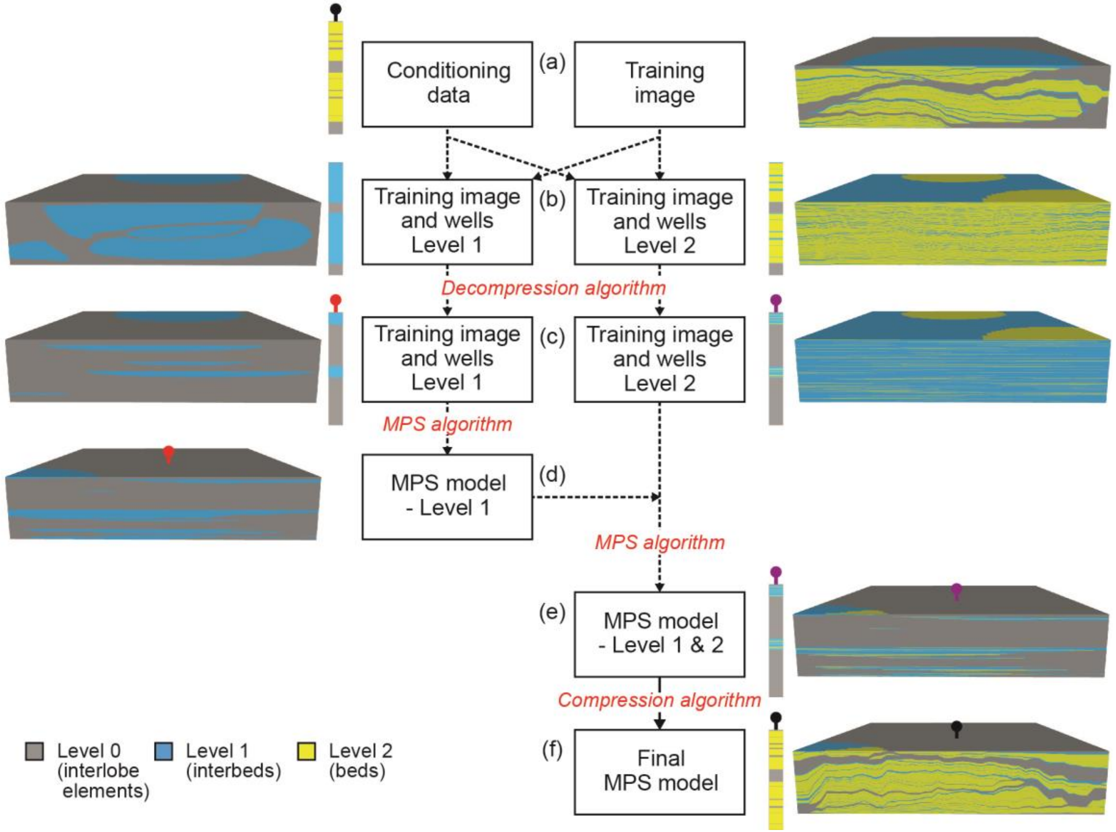
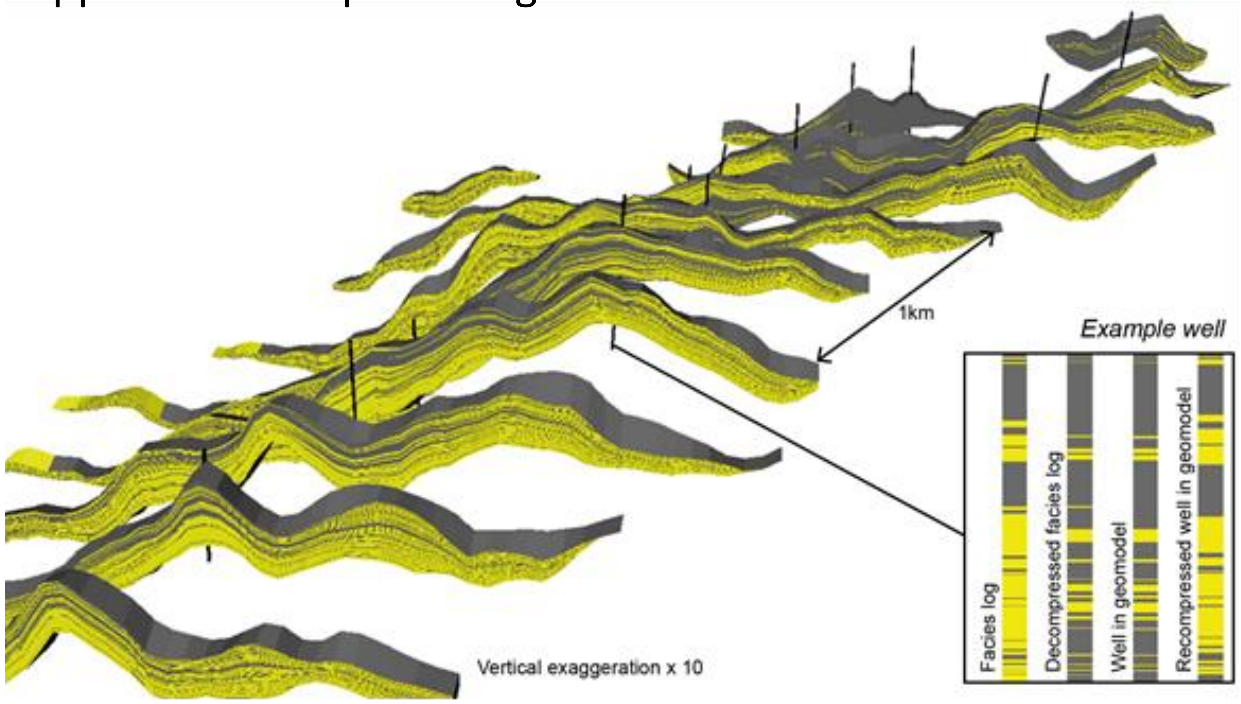
Application 3: Hierarchical compression-based MPS modelling conditioned to wells.

A benefit of Multiple-Points Statistics (MPS) over other geostatistical methods is that it allows both object shapes and well data to be honoured. Pixel-based MPS models, however, have similar percolation threshold to other geostatistical models, and therefore the compression method is needed to generate MPS models with the target sandstone connectivity.

Summary of workflow



Application to a producing oilfield



See Walsh and Manzocchi (2016, 2019) for details.

Conclusions

The amalgamation ratio in conventional geostatistical facies models is an unconstrained output property that is approximately equal to the model net:gross ratio.

Natural geological systems and more realistic facies models (e.g. surface-based models) have varied relationships between amalgamation ratio and net:gross ratio.

The compression algorithm is a geometrical grid transformation that allows conventional geostatistical models to be constrained independently to amalgamation ratio as well as net:gross ratio.

Models in which AR < NTG are representative of many depositional systems, while models with AR > NTG are representative of fluid-driven systems.

We have focused on streamlining the compression algorithm and implementing it within standard workflows for modelling depositional systems using industry-standard modelling software.

References and acknowledgements

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