The Problem of Paleotopography in Structurally Active Slope Basins*

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Abstract

Seafloor topography is an important control on turbidite reservoir distribution. However, there are major problems with techniques used to reconstruct seafloor topography in structurally active settings. We commonly assume that palaeobathymetry of a surface mirrors the isopach of the overlying interval (thicks = lows, thins = highs). But the present day seafloor within major sediment fairways commonly shows little or no evidence of the structures active beneath them, which are effectively swamped. Where sediment flux is lower, structures may have sea floor expression. Worse, the isopach approach is philosophically flawed – we assume that the upper surface of the interval was unstructured to deduce the topography of the lower surface, then we use the isopach of the interval above that to deduce the structure of the upper surface; but this invalidates our previous assumption! A way forward requires a deeper understanding of the structural and depositional history. Structure growth is typically continuous, whereas sedimentation tends to be pulsed. Forward modelling of these processes gives a synthetic stratigraphic architecture and predicted bathymetry. By adjusting the rates so that synthetic and observed stratal architectures match, we can derive a model for the paleobathymetry through time. This can be refined using seismic facies and images of depositional systems. Modelling results show that simple isopach-based bathymetry is a poor approximation. The shape of the seafloor changes through the depositional pulse; our models predict that during the peak of reservoir deposition, basins may have near-flat bottoms, a gently-dipping onlap/offlap fringe, and a more steeply-dipping perimeter.

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Apps, G.M., 1987, Evolution of the Grès d'Annot Basin, South West Alps: Ph.D. thesis, University of Liverpool, Liverpool, U.K., 352p.
Joseph et al., 2000

Hutton, J., 1788, The Theory of the Earth: Transactions of the Royal Society of Edinburgh, volume I. Image of Isle of Arran cross-section accessed January 4, 2015, http://www.educationscotland.gov.uk/scottishenlightenment/jameshutton/learnmore.asp.

Joseph, P., N. Babonneau, A. Bourgeois, G. Cotteret, et al., 2000, The Annot Sandstone outcrops (French Alps): Architecture description as input for quantification and 3D reservoir modeling, *in* P. Weimer, R.M. Slatt, J. Coleman, N.C. Rosen, et al., editors, Deep-Water Reservoirs of the World: Proceedings of the GCSSEPM Foundation 20th Annual Research Conference, Special Publication (SEPM CD-ROM) 28, p. 422-229.

Additional Reference

Joseph, P., Y. Callec, and M. Ford, 2012, Dynamic Controls on Sedimentology and Reservoir Architecture in the Alpine Foreland Basin: A Field Guide to the Eocene-Oligocene Grès d'Annot Turbidite System of SE France: IFP Energies nouvelles e-books, 128p. Website accessed January 4, 2015, http://books.ifpenergiesnouvelles.fr/ebooks/field_guide_to_the_eocene_oligocene_gres_annot_turbidite_system/doc/Field_Guide_to_the_Eocene_Oligocene_Gres_Annot_Turbidite_System.pdf.

The Problem of Paleotopography in structurally active slope basins

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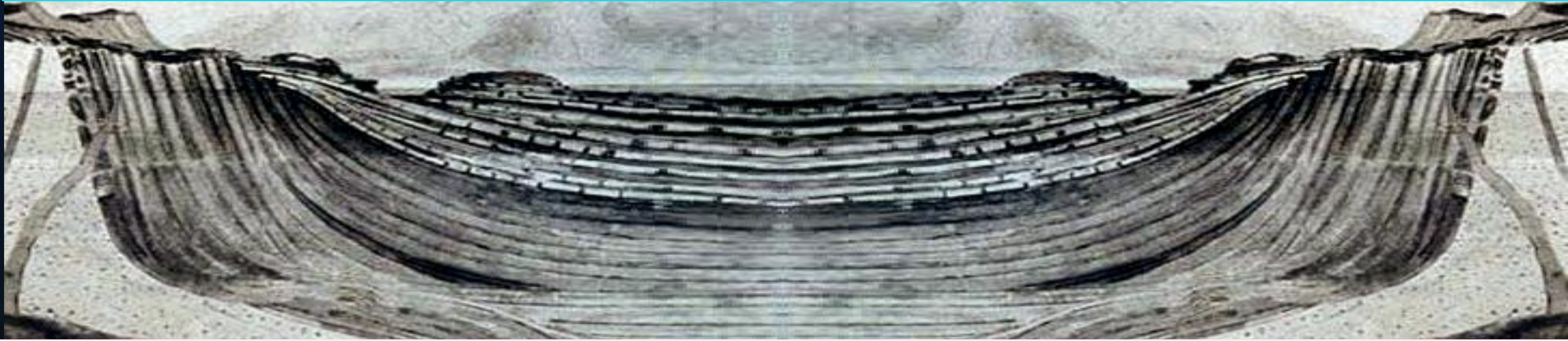
Oral presentation given at the AAPG ICE International meeting, Melbourne, Australia, 2015. This presentation has been modified from the original version. Written verbal description has been added, and animated gif files used in the original have ben replaced, where possible, with sequences of still frames captured from those animations. These sequences represent a small subset of the original simulations. Readers interested in seeing the full animations should contact the lead author, Frank Peel

James Hutton (1788): the first attempt to construct basin architecture in a structurally active setting? Hutton made a complete section in which he showed how sediment architecture could be controlled by onlap, offlap and erosion. If we mirror this section about one end, it has an interesting (unintended) resemblance to stratal patterns seen in deep water basins

Hutton (1788) cross section, Isle of Arran, Scotland.

Some common methods used by exploration geoscientists in the petroleum industry to approach a similar problem (modelling the evolution and paleobathymetry of the basin by approximating it to the gross isopach) may be reasoning without proper data. The apparent wisdom of the isopach approach lies in its apparent simplicity, widespread use, and apparent predictive power. But this may be deceptive, and the predictions it makes may be badly wrong in some circumstances.

In Hutton's own words: " We must not allow ourselves ever to reason without proper data, or to fabricate a system of apparent wisdom in the folly of a hypothetical delusion."



Hutton (1788) cross section, Isle of Arran, Scotland. (mirrored about end of original graphic)

Why does palaeotopography matter?

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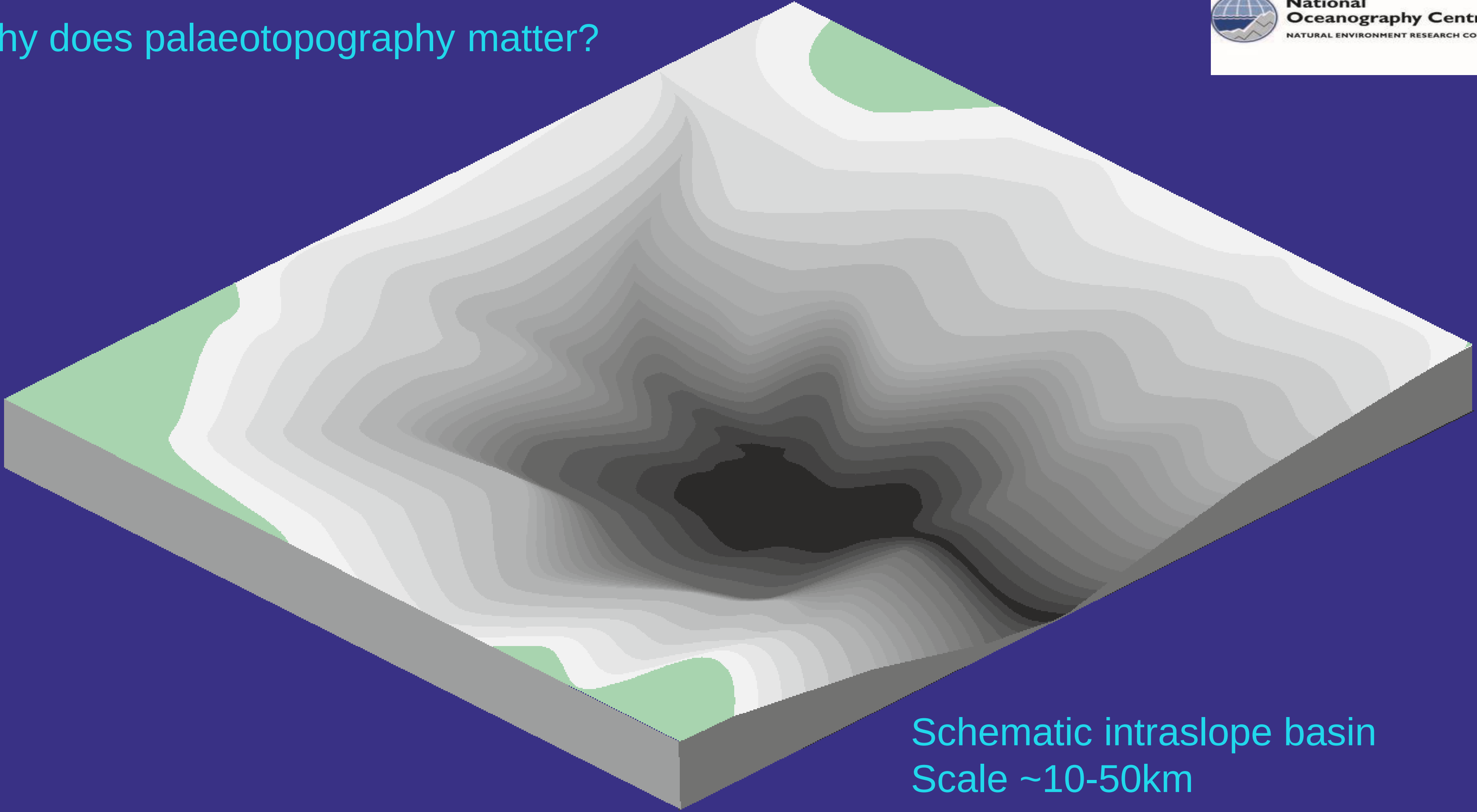
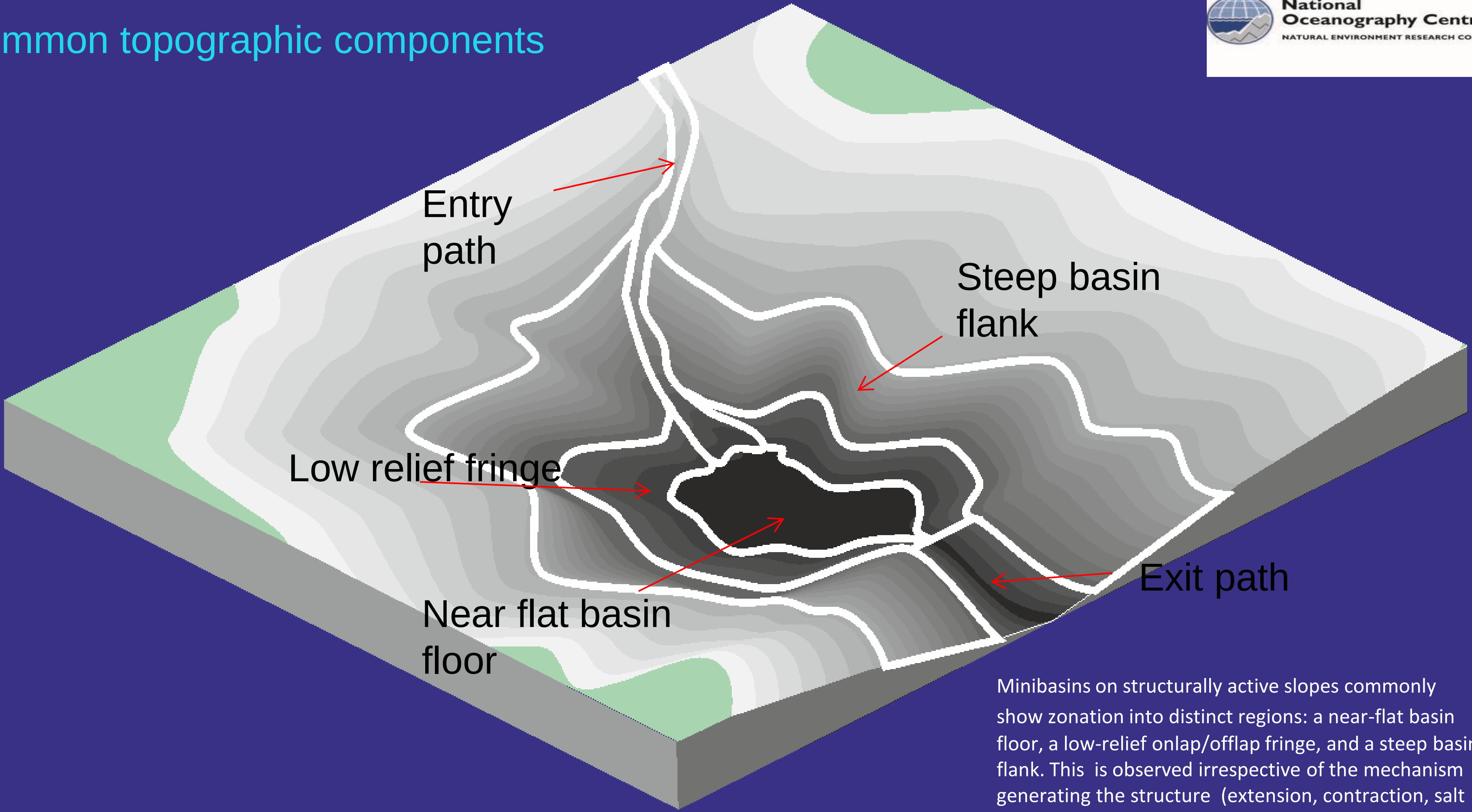


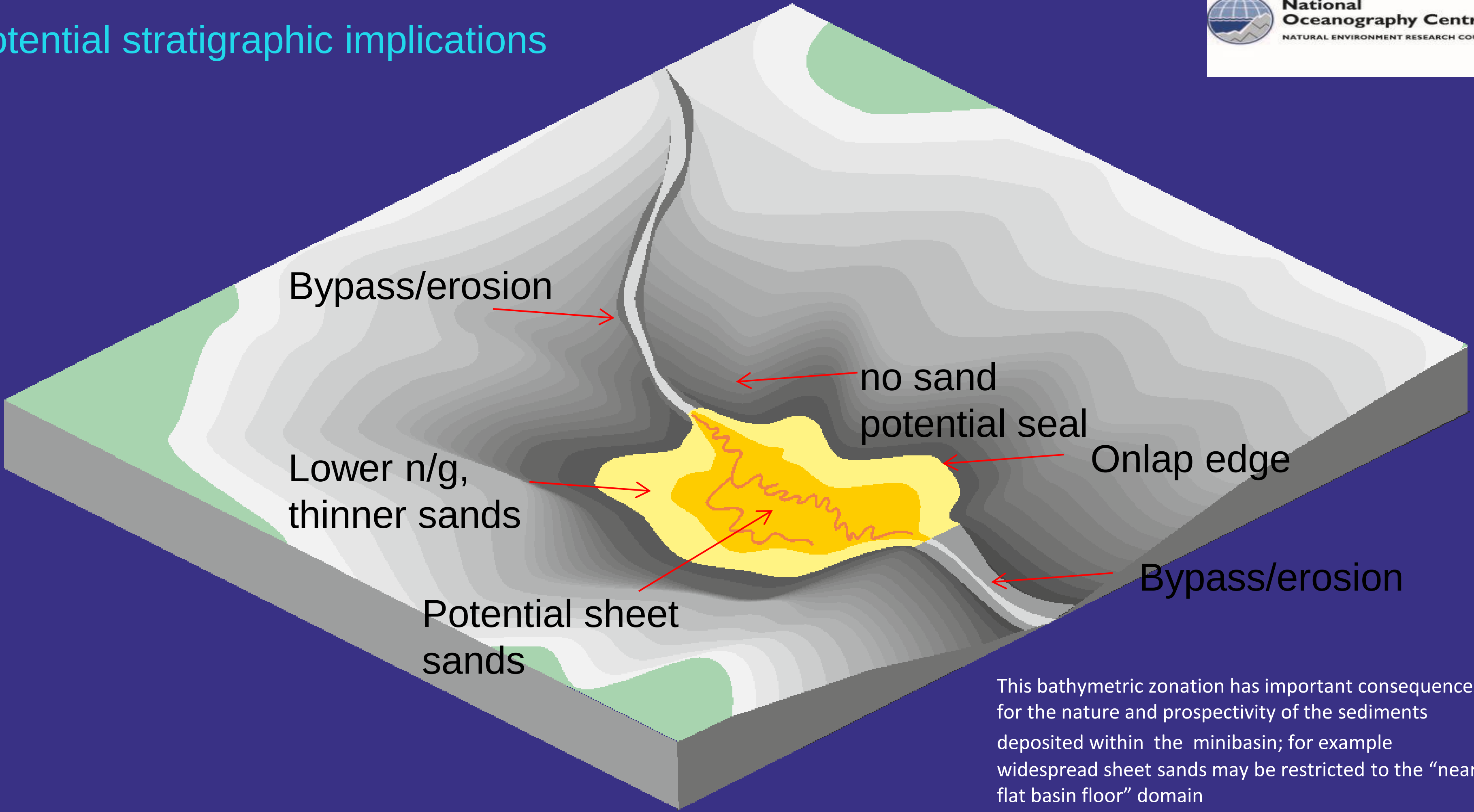
Schematic intraslope basin
Scale ~10-50km

common topographic components



Minibasins on structurally active slopes commonly show zonation into distinct regions: a near-flat basin floor, a low-relief onlap/offlap fringe, and a steep basin flank. This is observed irrespective of the mechanism generating the structure (extension, contraction, salt tectonics, etc.)

Potential stratigraphic implications



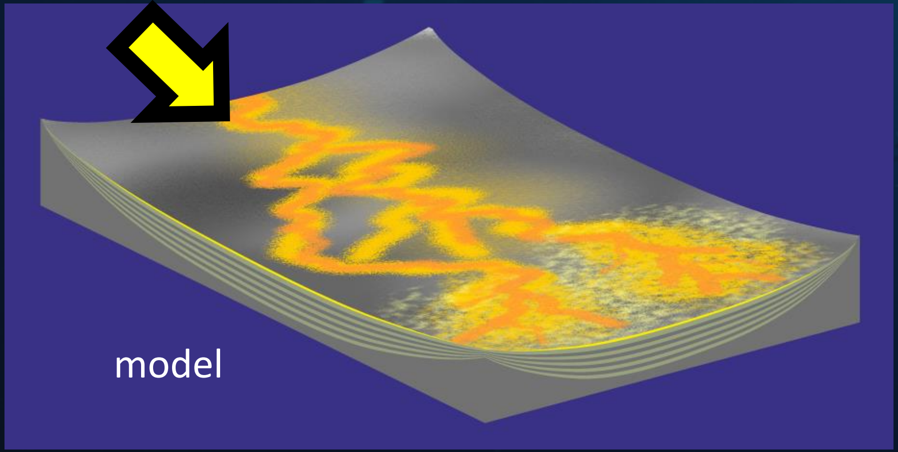
This bathymetric zonation has important consequences for the nature and prospectivity of the sediments deposited within the minibasin; for example widespread sheet sands may be restricted to the "near-flat basin floor" domain

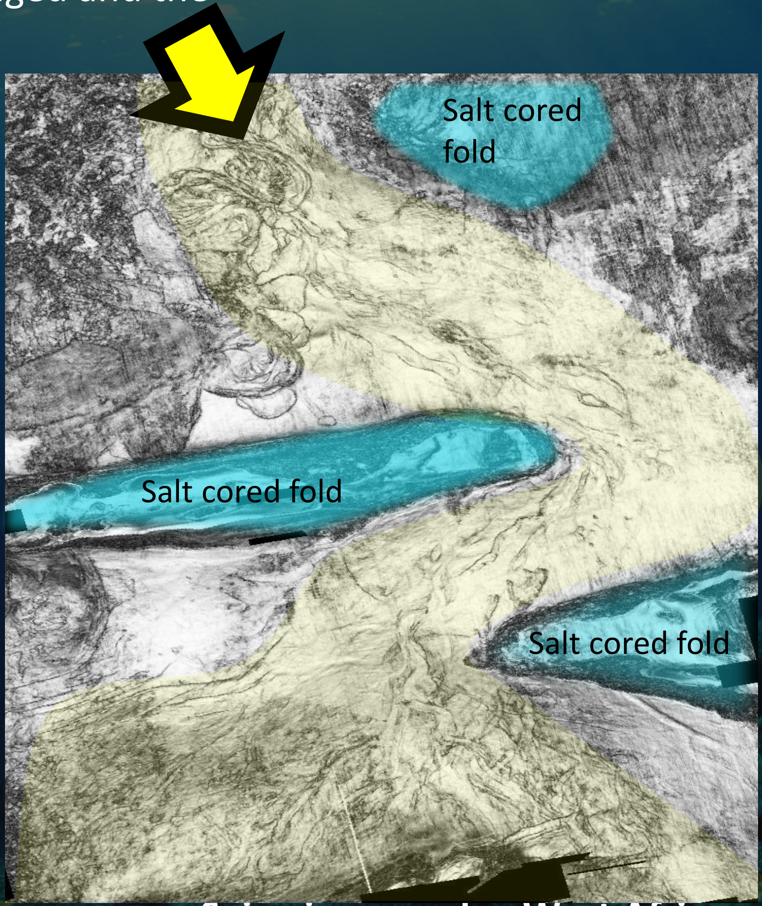
Strategies for estimating palaeotopography

1. **Direct observational evidence:**
    - slope-sensitive depositional systems
2. **Secondary observational evidence: diagnostic features**
    - Onlaps and depositional edges
    - Evidence of seafloor slope (e.g. remobilisation)
3. **Forward modelling**

1. Direct observational evidence: slope-sensitive depositional systems

In some settings the reservoir systems are directly imaged and the topography can be directly inferred





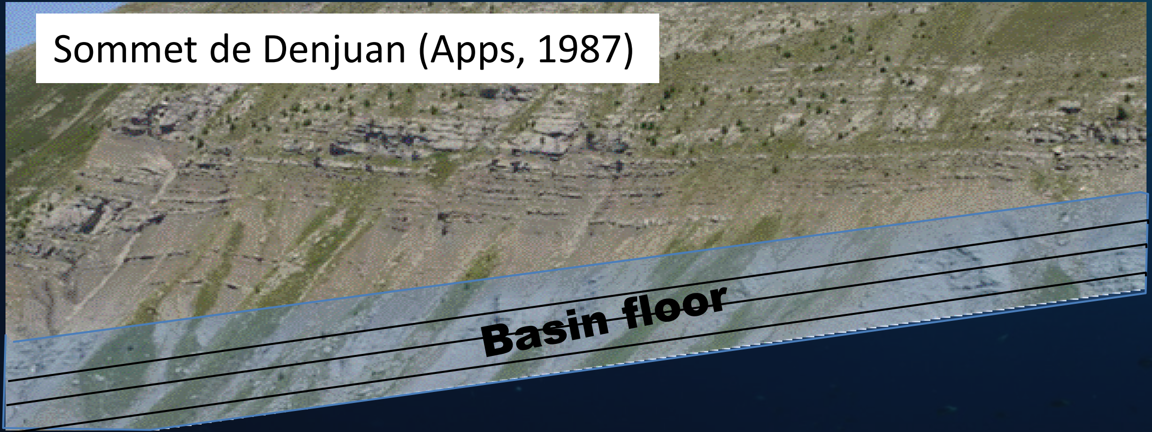
Seismic example : West Africa

in this ideal situation, seismic data alone would probably be sufficient to reveal most of the information you would be seeking from the paleotopography

2. Secondary observational evidence: diagnostic features

- Onlaps and depositional edges
- Evidence of seafloor slope (e.g. remobilisation)

Sommet de Denjuan (Apps, 1987)



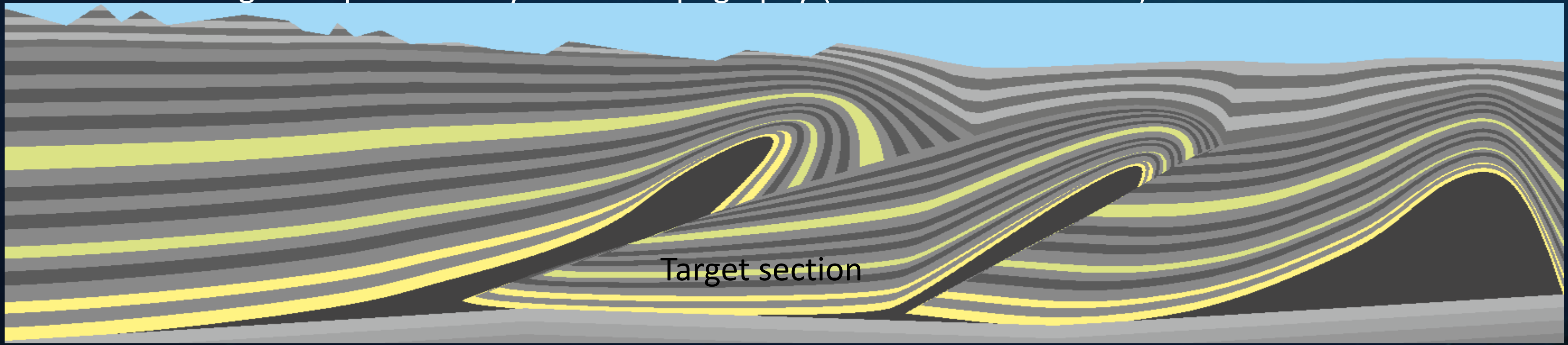
Chalufy (Apps, 1987)

1:1 v=h, after Joseph *et al.*, 2000

This is good for the basin flank slope, but not good enough for the subtle topography on the top of the turbidites, and rarely applicable in seismic data

There are situations where all we have to go on is basic horizon mapping, and we cannot see the fine-scale detail

Seismic image compromised by surface topography (thrust belt schematic)



In this schematic example, we need to know the reservoir distribution at a deep target level, but the structure is complex, and the seismic imaging is poor due to steep dips, surface topography, and complex structure

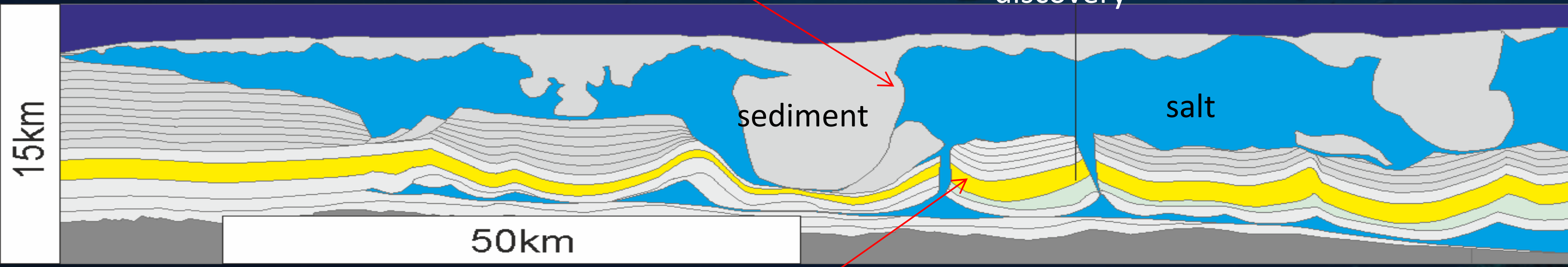
Seismic image compromised by complexity of overlying section (Gulf of Mexico example)

Complex salt body geometries

Steep and complex sediment geometries

Major oil discovery

S N



Target section:

Structurally complex; steep dips

Structurally active during deposition

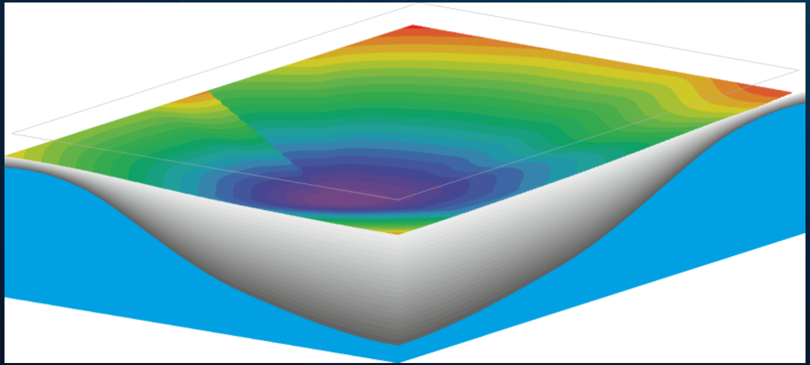
structure is not the same as at time of deposition:

Some paleo-lows are now structural highs

In this real-world example, from the US Gulf of Mexico, a very large hydrocarbon discovery lies in a minibasin beneath a complex salt (with steep salt/sediment interfaces) and suprasalt section. Seismic imaging is poor, and the target section has been tilted and restructured so that the present day low is not the paleolow. With well costs of a quarter-billion dollars each, we are strongly motivated to understand the controls on reservoir distribution!

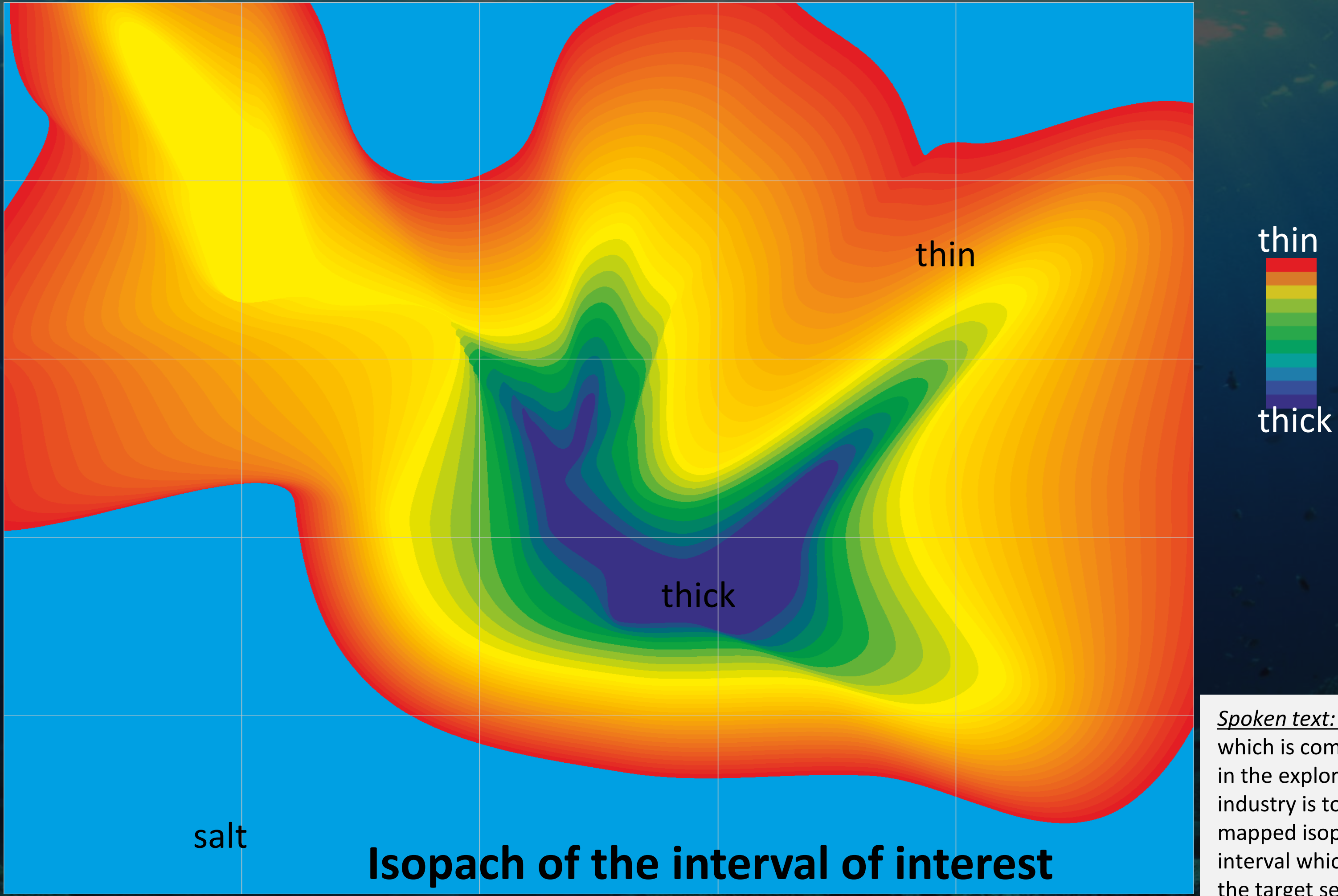
One very common pragmatic approach is to use the mapped surfaces to generate isopachs, and assume that these mirror the bathymetry

Basic method – “thicks = lows”

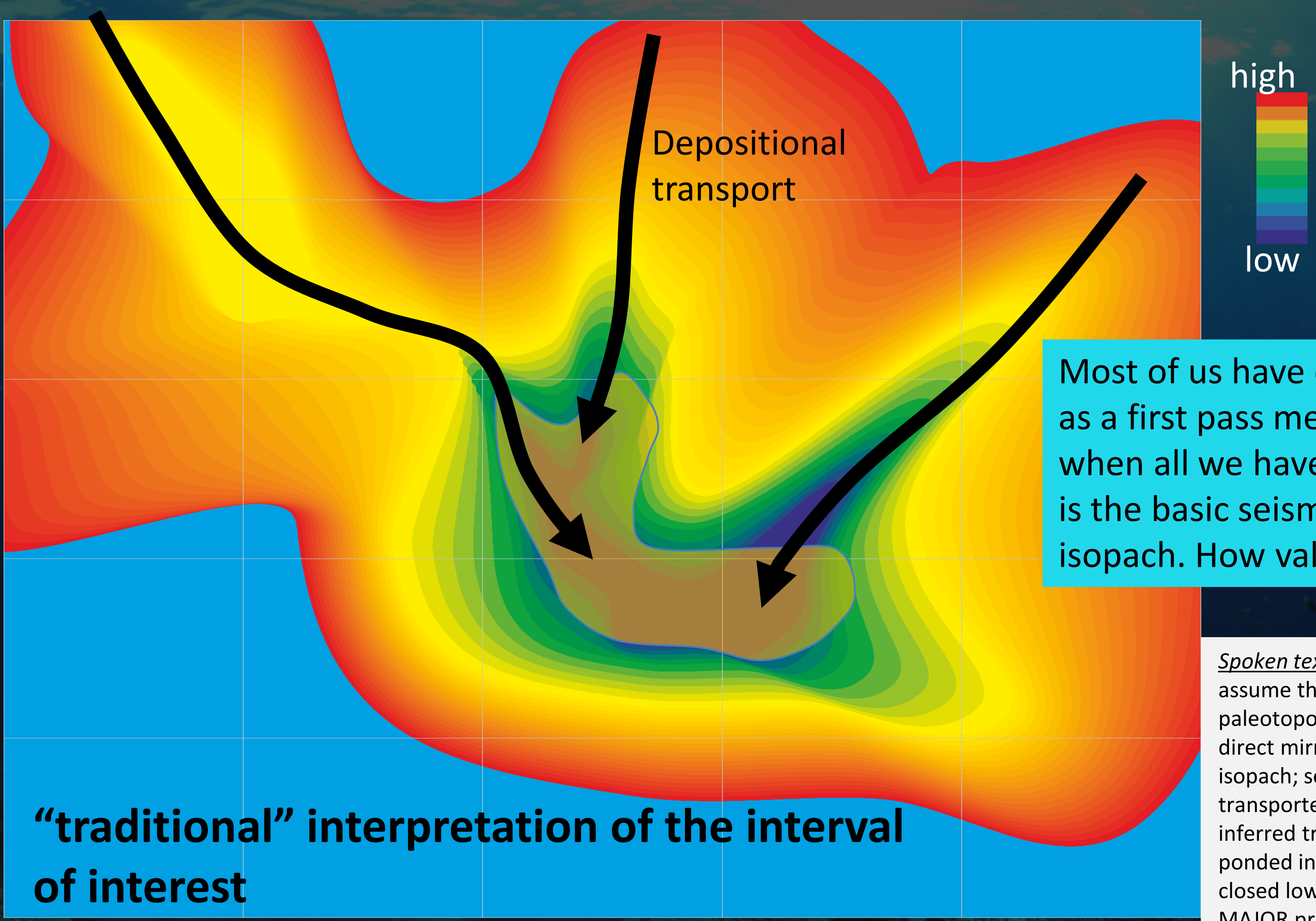


In many settings, the pattern of the isopach of recent sediment mirrors the present bathymetry

the isopach of a mapped subsurface interval is used as a ***guide*** to the relative topography, but we should not assume we know the absolute slopes or depths.



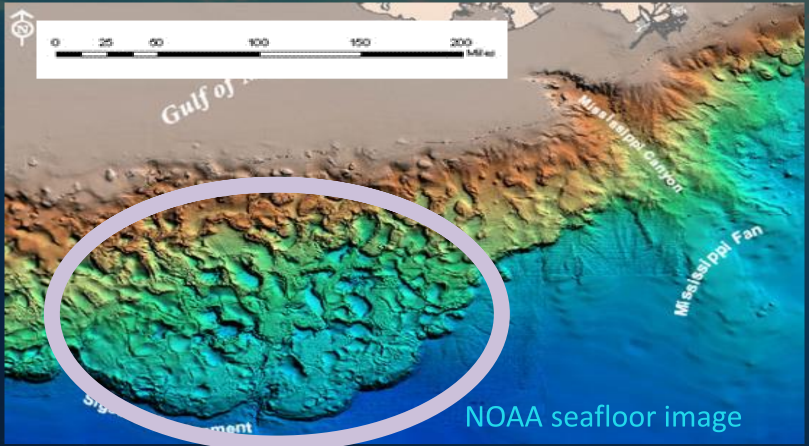
Spoken text: A method which is commonly used in the exploration industry is to take the mapped isopach of the interval which contains the target section, as shown schematically here

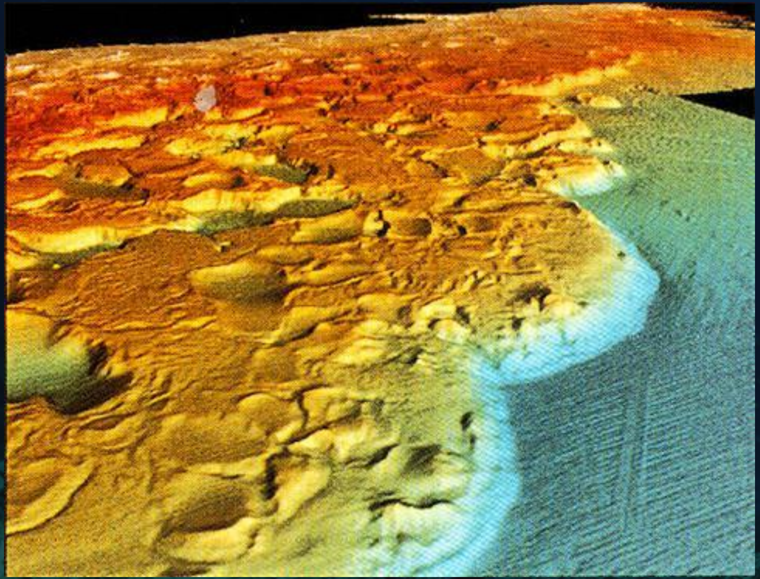


Most of us have done this as a first pass method, when all we have to go on is the basic seismic isopach. How valid is this?

Spoken text: Then to assume that the paleotopography was a direct mirror of the isopach; sediments are transported down the inferred troughs and ponded in the inferred closed lows . But there are MAJOR problems with this approach

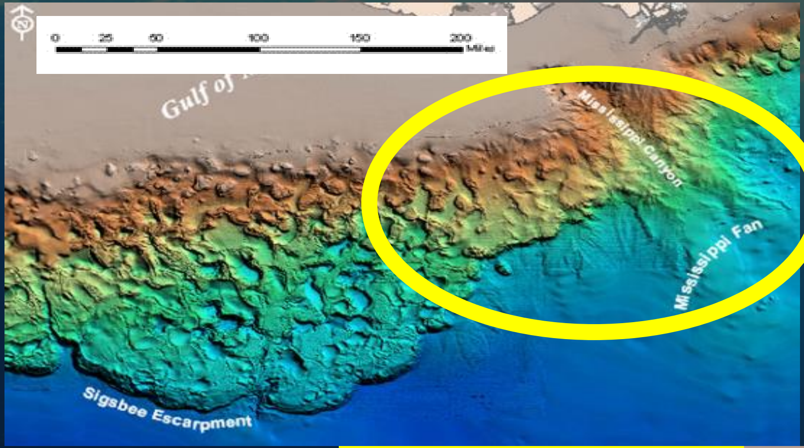
Northern Gulf of Mexico test case





In this region the sea floor has very strong expression of the subsurface isopach : **every low is a thick**

<u>Spoken text:</u> in the Central US Gulf of Mexico, there are large minibasins in which the isopach of the uppermost sediment layer does indeed mirror the present day bathymetry. But these are the minibasins which are not currently experiencing significant input of deepwater reservoir systems



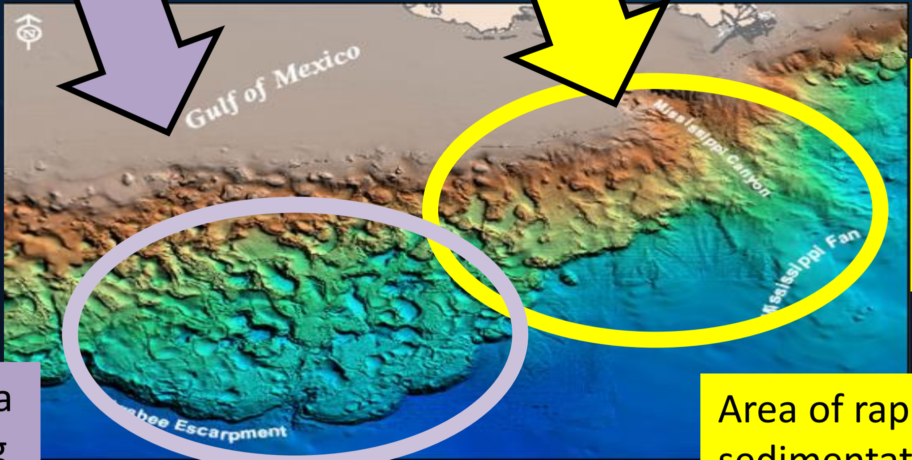
In this region the sea floor has **little** or **no** expression of the subsurface isopach

__Spoken text:__ in contrast, in the region of the present day Mississippi sediment input, we see that the seafloor expression of the underlying structure is partially or completely overwhelmed by the sediment flux. In these regions, where abundant reservoir-quality sand is being deposited, there is a weak (or even non-existent) relationship between the isopach of the near surface sediment layers and the present day bathymetry

The stronger the depositional system (hence most reservoir prone) the WEAKER the relationship between topography and bathymetry

minor sediment input

Major sediment input



In this region the sea floor has **little** or **no** expression of the subsurface isopach

Area of rapid sedimentation; major reservoir deposition

In this region the sea floor has very strong expression of the subsurface isopach : every low is a thick

Area of slow sedimentation; no major reservoir deposition

When there was **no reservoir input**, there should be a **strong relationship** between isopach and bathymetry.

When there was moderate sediment input, there may be some relationship. This will be strongest after a significant (3rd order or greater) depositional hiatus.

But for **major, long lived reservoir systems** (Pleistocene Mississippi, Wilcox, Tuscaloosa), if the section of interest lies significantly above the nearest hiatus, there may be only a **weak relationship** between isopach and bathymetry

We need a better way for estimating paleotopography:

a more rigorous, quantitative method

forward modelling may be the way forward

using all the information available from the architecture of the layers above and below the target section to create a model which matches the observations.

Introduction to the 2D model

We have created a simple 2D forward model of statal development in structurally active deep-water basins; it takes a basic structural profile, and allows it to grow with time according to a user-defined history (either constant rate, or variable rate).

Deepwater sedimentation is modelled in a very simple way. It is separated into two components:

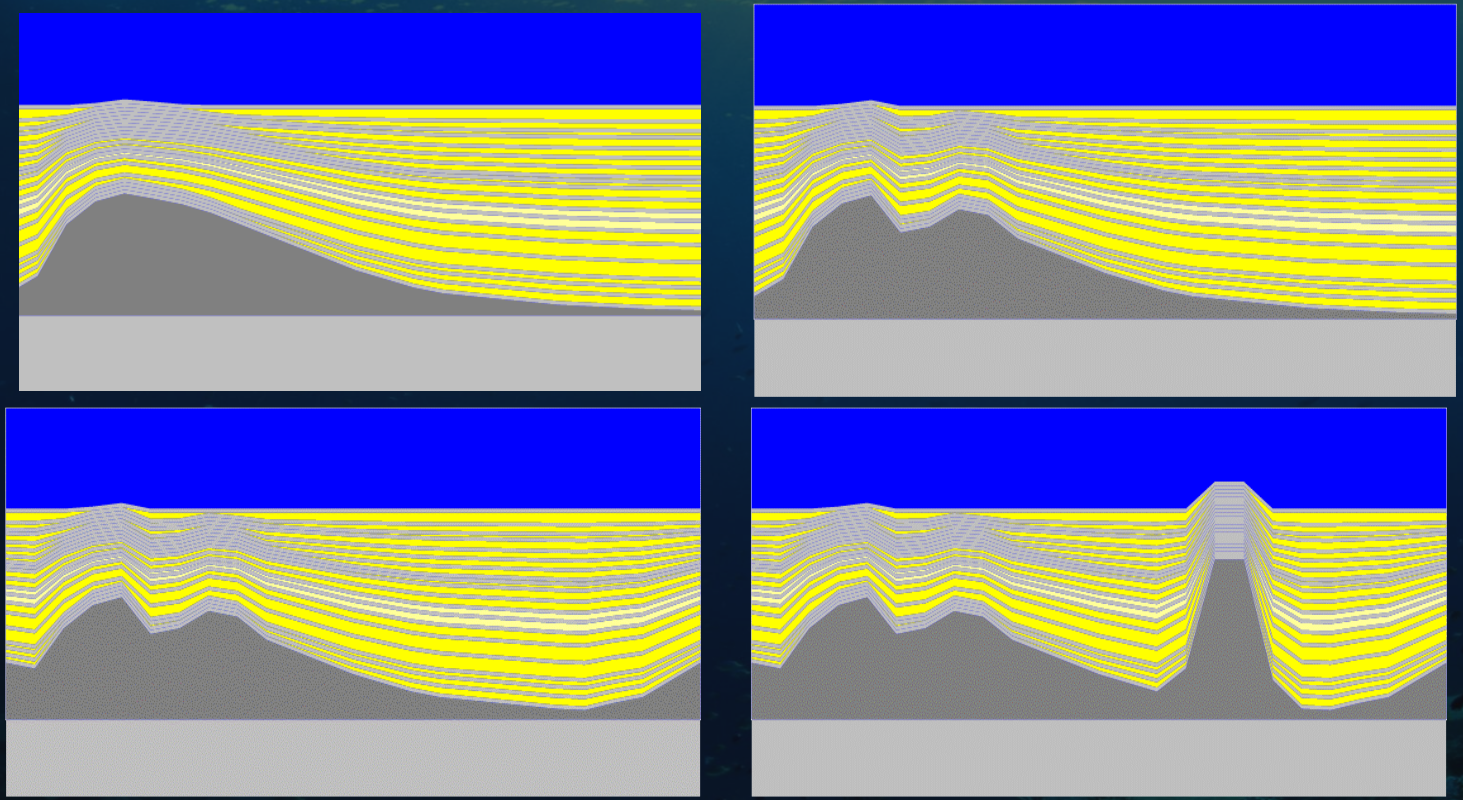
1. A pelagic component, which is deposited across the section at a rate which is uniform through the life of the model. This rate is user defined.
2. A turbiditic component, which is controlled by a user-defined base-level model. The equilibrium base level for turbidite deposition rises (or falls) through time. Any space below that level is filled by sediment; where the sea floor lies above that level, there is no deposition.

We recognize that the use of a simple equilibrium base level as the control on turbidite deposition is a very simplistic approximation of a very complex natural process. However, it is fit for purpose for delivering the sort of model we require. At this stage, it is not appropriate to use a more refined model (such as the numerical simulation of turbidity currents and their deposits); these are too sensitive to the major unknowns (such as sediment entry point location, overall seafloor gradient, etc.) and are likely to give an answer that is precise, but wrong. In a basin with poor initial constraint, it is better to start by using a simple model to get a first pass match. More refined methods can be used later.

Our basic 2D proof of concept model

The structural profile can be adjusted

Modeling software and underlying algorithm © patent pending



These models have the same depositional history model, and the same structural growth rate model; the shape of the structural template used in each case is different

Our basic 2D proof of concept model

Modeling software and underlying algorithm © patent pending

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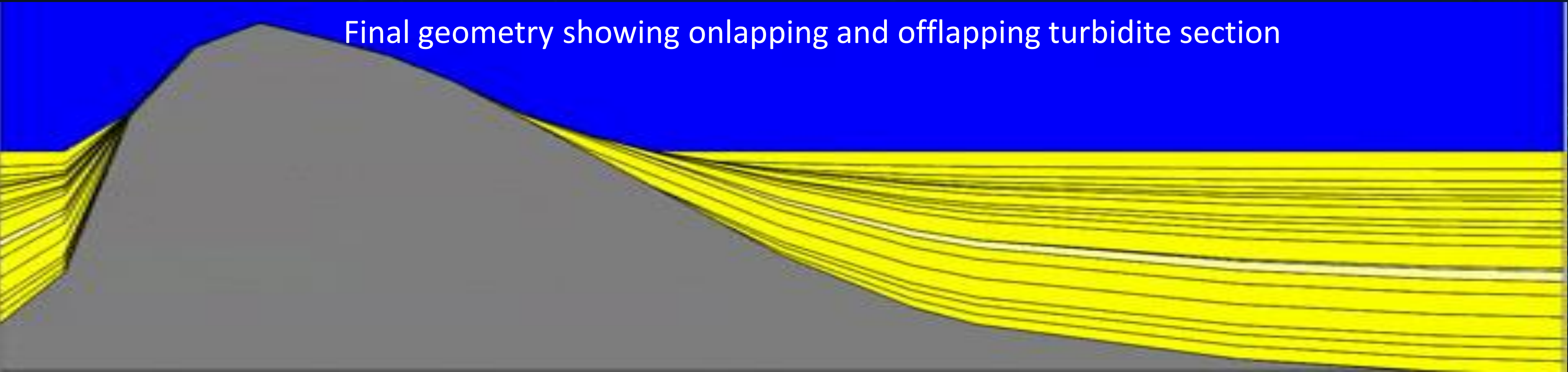
Evolution in time of a section **without pelagic sedimentation**

development through time

Representative frames from the evolution of the section



Our basic 2D proof of concept model

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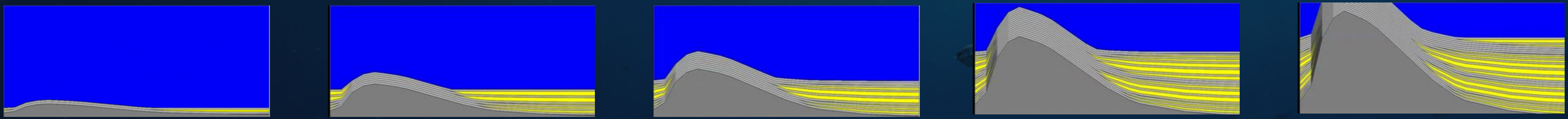
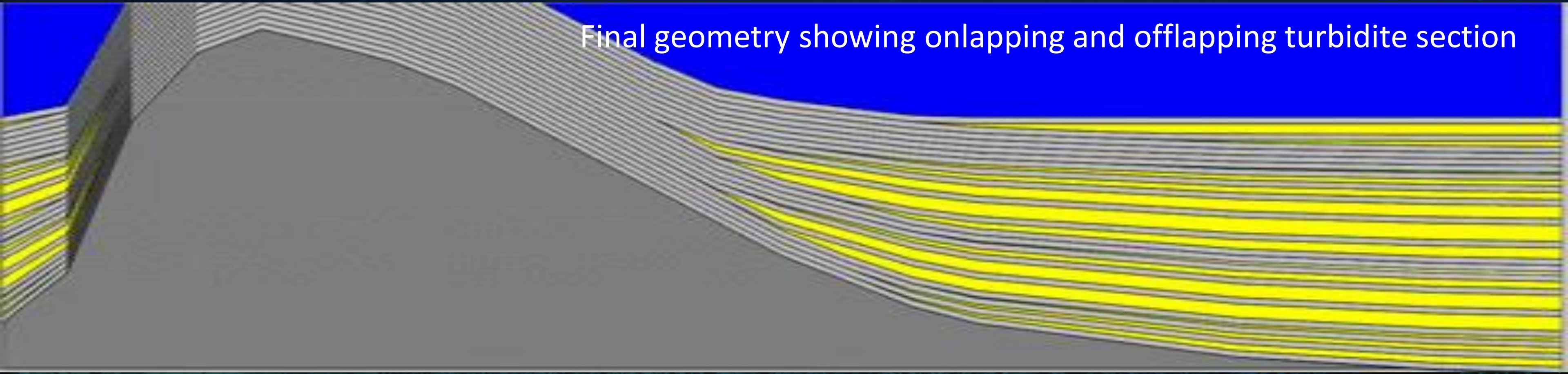
Evolution in time of a section **with pelagic sedimentation**

The only difference between this and the previous slide is the addition of pelagic/hemipelagic deposition at a constant rate

development through time



Representative frames from the evolution of the section



Our basic 2D proof of concept model

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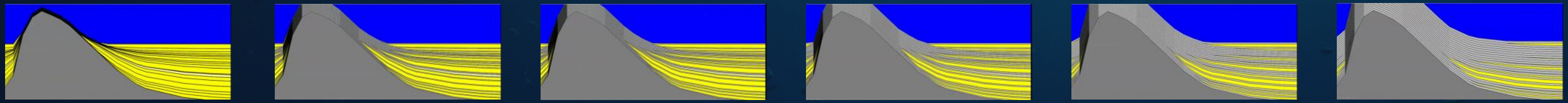
Effect of changing the rate of **pelagic sedimentation**

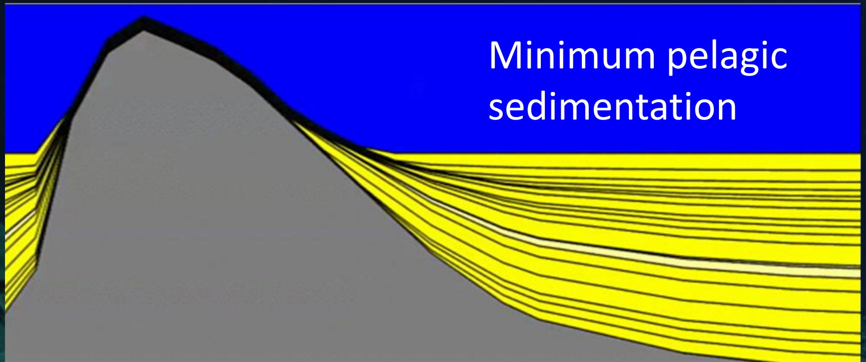
these simulations all have the same rate of structure growth, and the same history of sediment base level rise

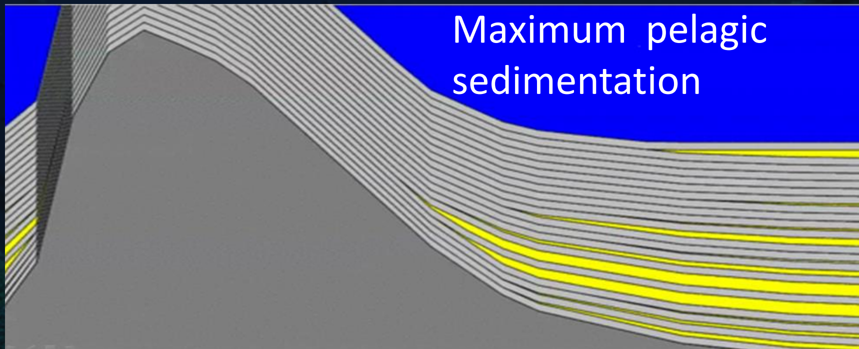
Increasing rate of pelagic sedimentation



These sections represent different final states, given different rates of pelagic sedimentation

Final geometry showing onlapping and offlapping turbidite section





Our basic 2D proof of concept model

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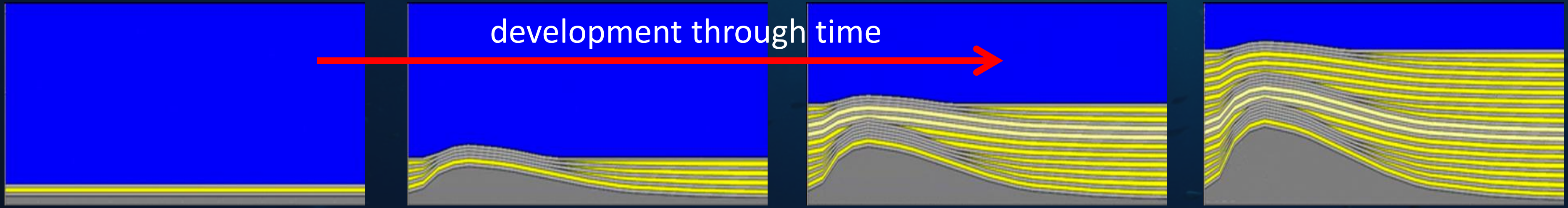
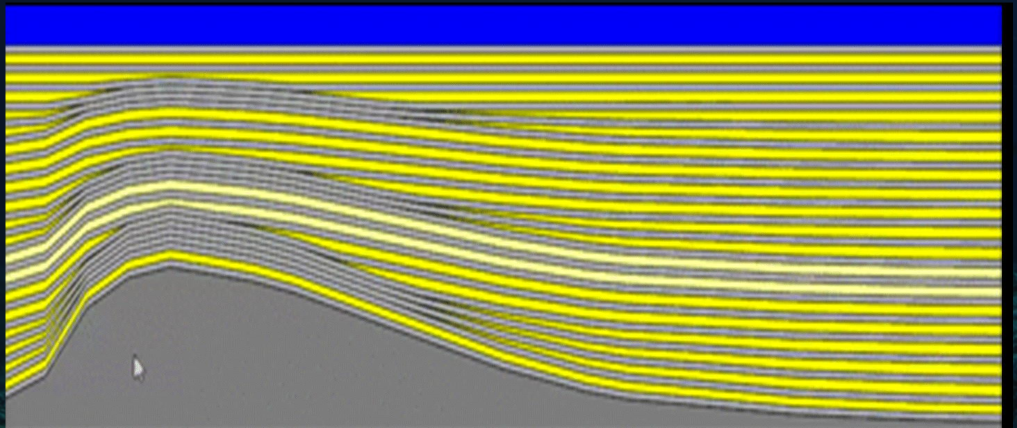
Evolution in time of a section with VARIABLE structure growth rate

The rate of structural growth can be variable through time, or constant in time (we adjust the rate of growth, but it applies uniformly). In this example, the rate of rise of the sediment base level is held constant, but the rate of structure growth is pulsed, with two phases of movement



Frames from the evolution of the section.



Our basic 2D proof of concept model

Modeling software and underlying algorithm © patent pending

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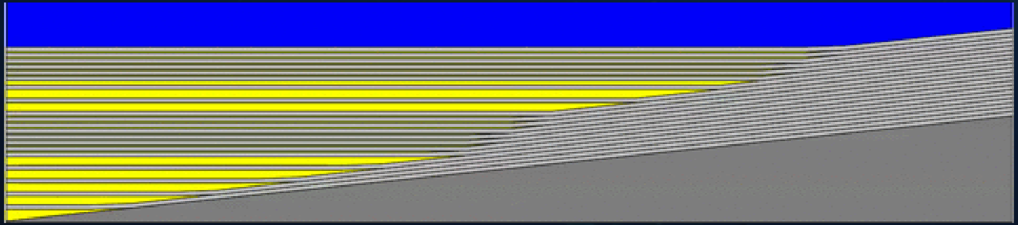
Evolution in time of a section with fixed structure

We can model the stratigraphic evolution of a basin floor in which the structure growth is static or very slow relative to the rate of deposition.

Frames from the evolution of the section.



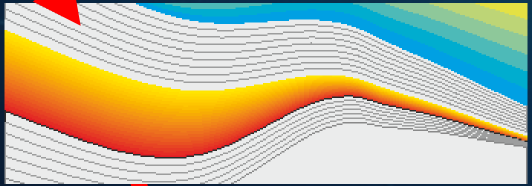
Final model showing a turbidite sequence onlapping a basin-floor slope

Comparison with the outcrop of Gres d’Annot onlaps at Chalufy (French Alps)

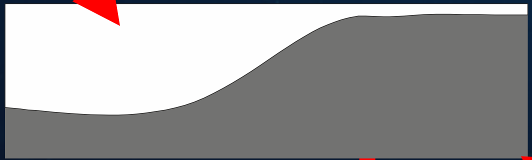
How the model may be used for estimating paleotopography

Strategy for using synthetic stratigraphic models to give a full-basin topography and stratal architecture

Basic horizon mapping

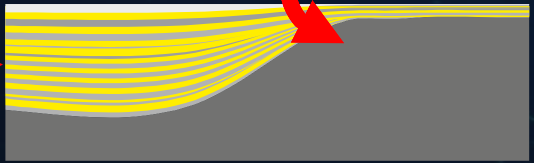


Isopach



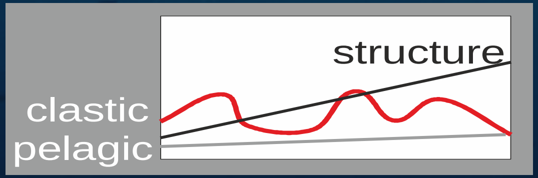
Structural profile

Initial depo model



Simulated basin fill

Modelled rates of processes

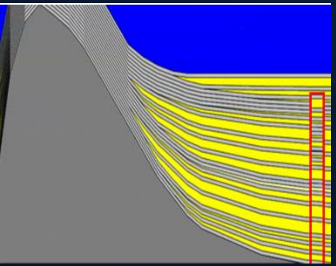


Compare real world data

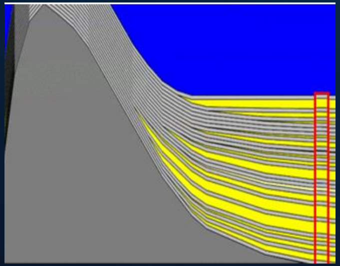
Best fit model:
Sediment architecture
Bathymetry through time

In order to use the simulation to derive a model of the bathymetric and stratal development of the section, we start by getting the structural template (shape of the structure) about right, using information such as the present day structure, the isopach, etc. We create a rough match of the gross stratigraphy to a data control point, such as a well log. Then the detailed depositional history is fine-tuned, starting at the bottom upwards, to achieve an acceptable match between the simulation and the well log.

Poor match



Best match



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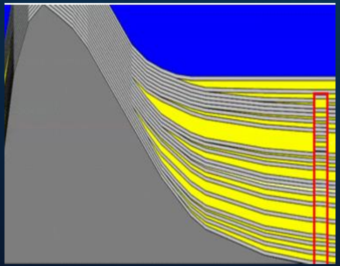

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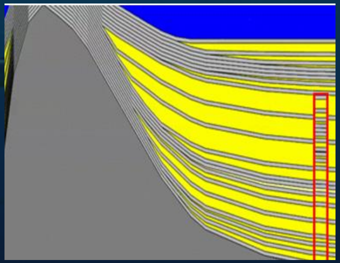
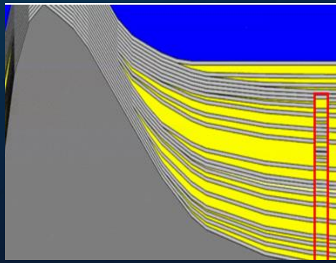
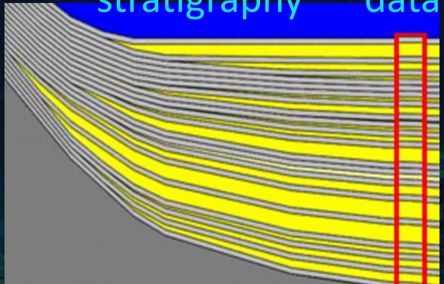


Poor match



Synthetic stratigraphy

Well data



Best match model

The model we have at present is only 2D

But it demonstrates that applying a similar approach in 3D should not be a problem

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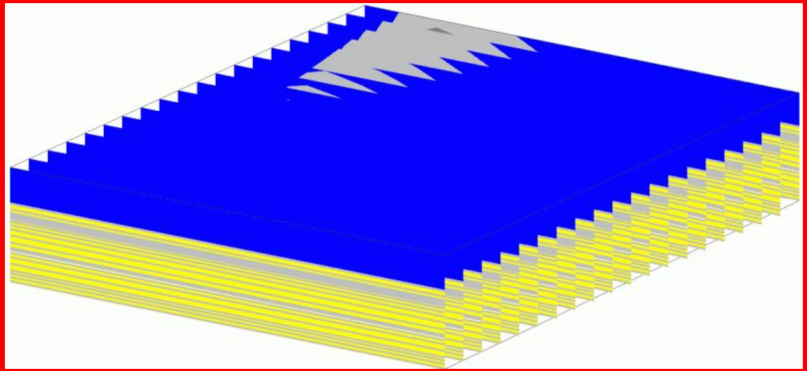
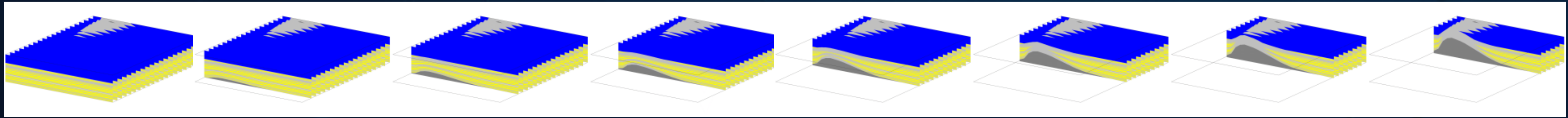
We can create a pseudo-3D model by creating a set of closely spaced 2D slices; although the modelling in each slice is in 2D, the set of 2D sections builds a representative 3D model



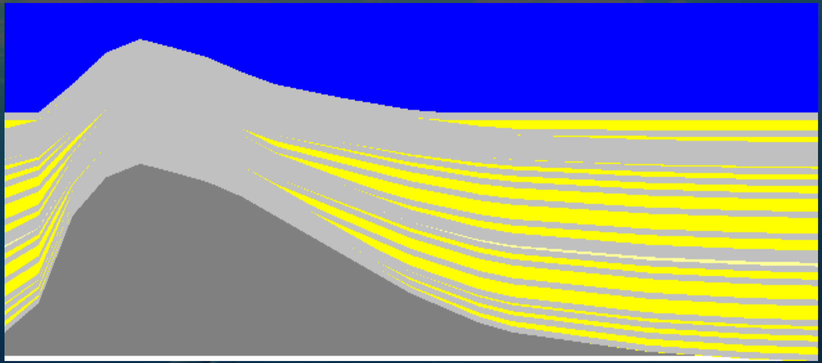


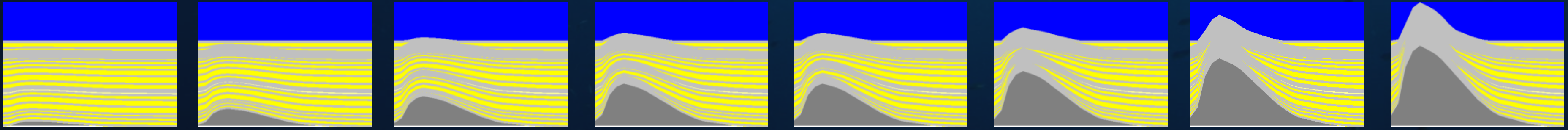
Sequential slices through the model

Frames from the original animation show how a set of closely spaced 2D sections is used to create a "two-and-a-half-D" model representing a three dimensional geometry

The original file is an animated gif which does not reproduce in this format. This slide has therefore has been modified from the original presentation

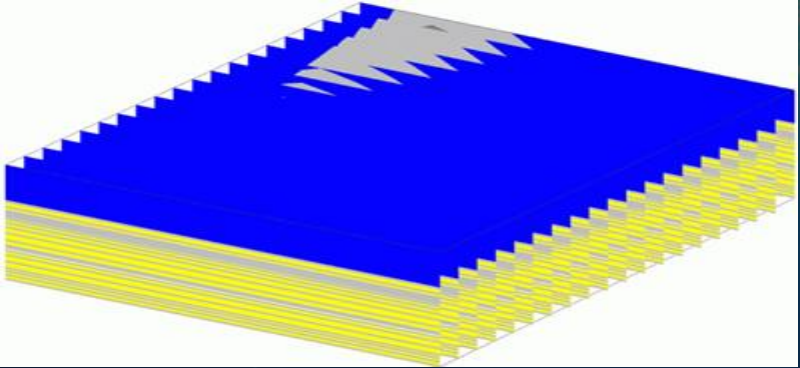
On each 2D slice we obtain the full history of bathymetry, and the complete stratal architecture

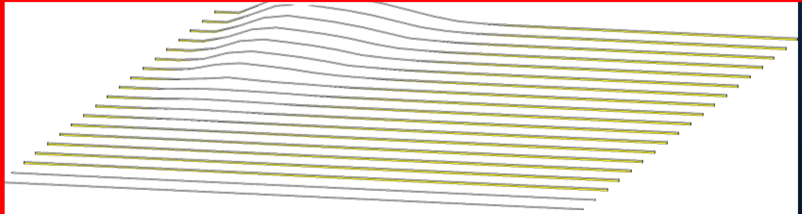




Sequential slices through the model

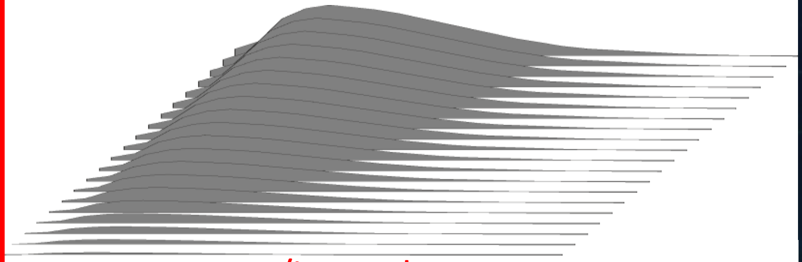
Frames from the original animation show how a set of closely spaced 2D sections is used to create a "two-and-a-half-D" model representing a three dimensional geometry





Final bathymetry

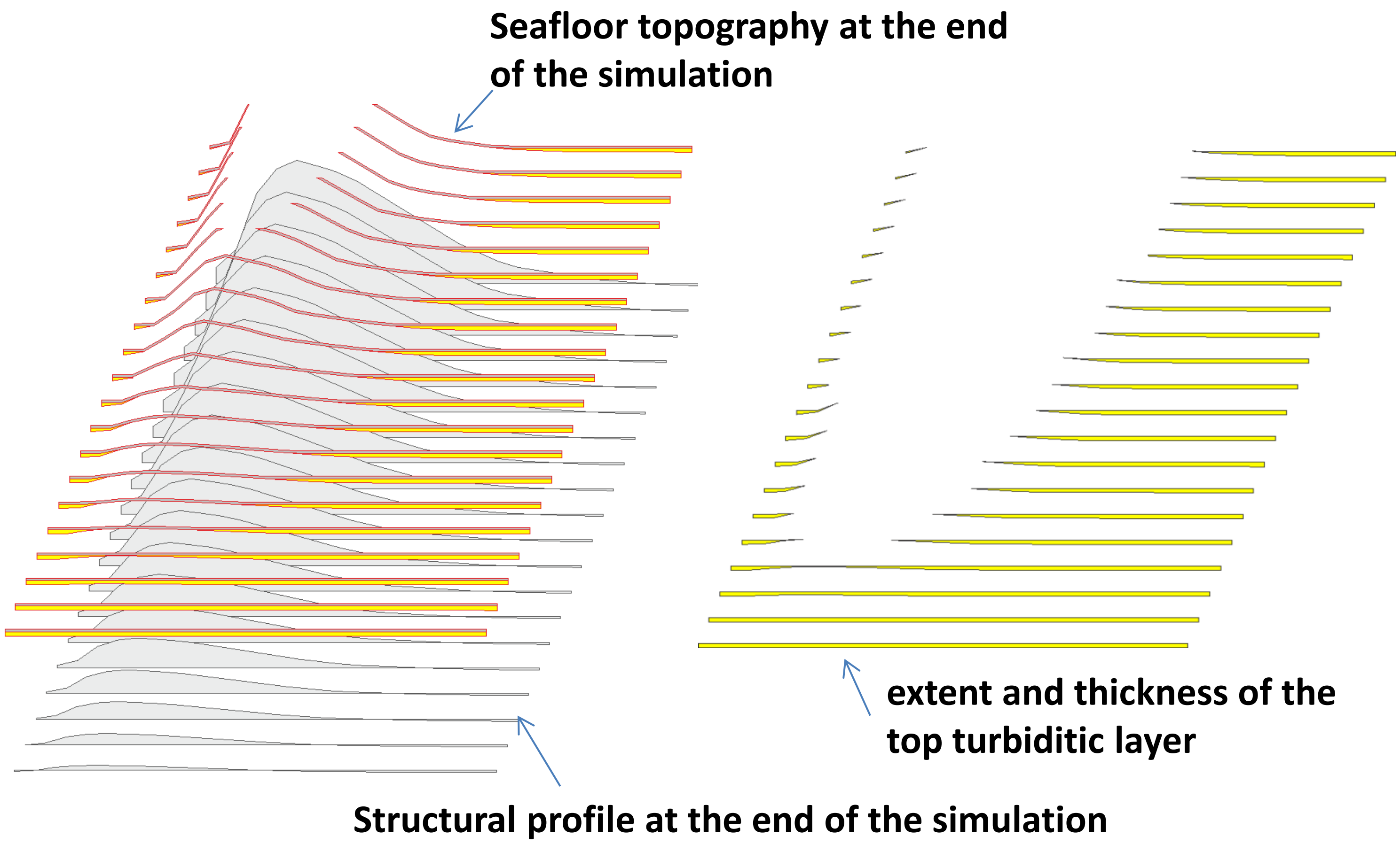
Architecture of final turbidite interval



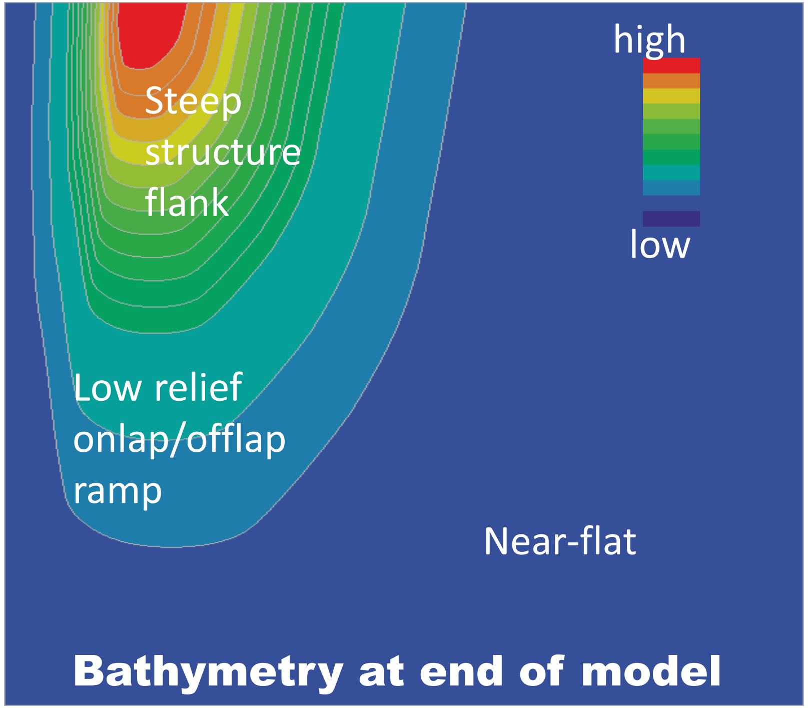
Deep structure/isopach

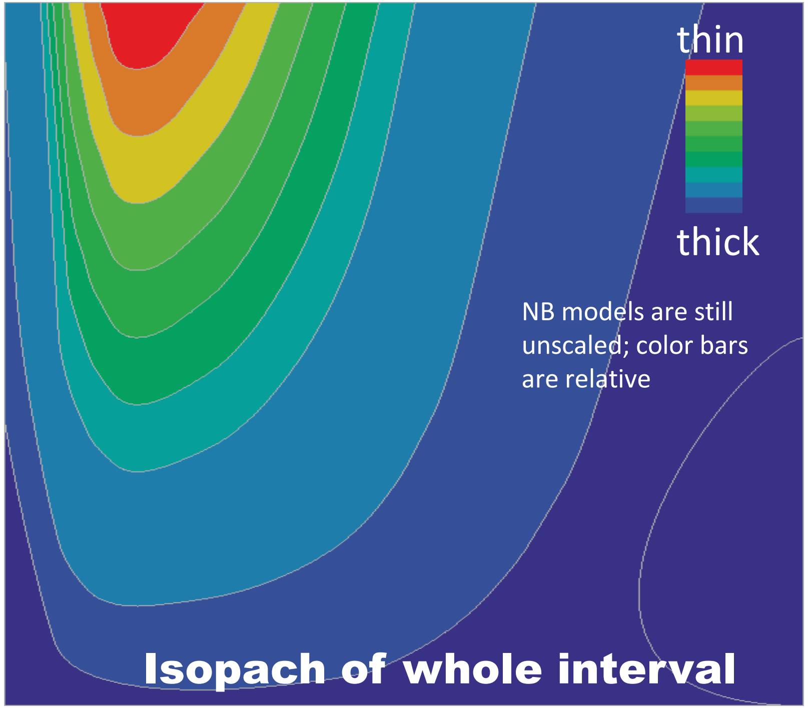
This gives a 3D model of the gross architecture, the bathymetry, and the evolution through time

Putting these together, we can see how the forward model creates a well defined seafloor topography and stratal architecture. This exploded block diagram shows the shape of the top layer only



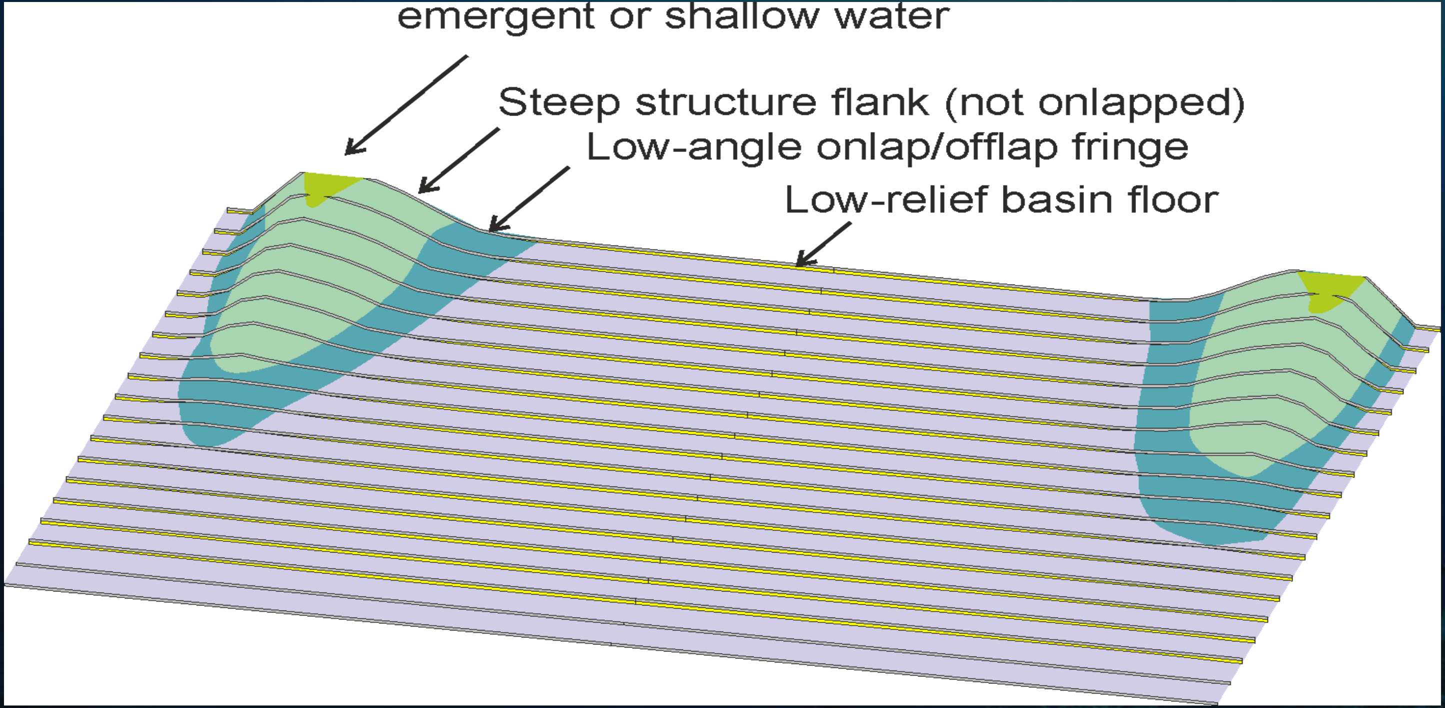
Representing this in map form, we can see how the simulation has succeeded in creating a basin whose seafloor shape (left) is representative of what we see in nature: relatively flat mid-basin floor, a low relief onlap/offlap fringe, and a steep structure flank. The overall isopach of the sediment (right) shows the more gradational form which we also observe in natural examples.





This comes back to our original starting observation. Relative bathymetry and total isopach are related but significantly different. ISOPACH IS NOT BATHYMETRY and should not be used a proxy for it.

Models are still unscaled but they prove the concept: we can produce a realistic simulation of bathymetry and stratal architecture that works in 2D and appears to be scalable up to 3D. The results are geologically reasonable.



Conclusions

Simple 2D modelling creates paleotopography and architecture

Iteration to match observed well/seismic observations results in a valid model which predicts topography through time

This is a major improvement on the crude isopach method

there is no problem extending this into 3D

Way forward:

We need funding and industry collaboration to advance the next step! Develop true 3D code – follow the logic of the 2D code, but completely rewrite it to make a user-friendly tool for use in exploration

Use real-world isopachs from well and seismic data to generate the structural template (input as grids)

Test against well and seismic data, adjusting the sedimentation model to generate valid stratal architecture.

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