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.
References Cited

Joseph et al., 2000


Additional Reference

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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 been 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.
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.”
Why does palaeotopography matter?

Schematic intraslope basin
Scale ~10-50km
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.

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

Seismic example: West Africa
2. Secondary observational evidence: diagnostic features

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

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.

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.
Major oil discovery

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

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

Complex salt body geometries
Steep and complex sediment geometries

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

Basic method – “thicks = lows”

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

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.
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.
“traditional” interpretation of the interval of interest

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

*Spoken text:* 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.
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.

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

Area of rapid sedimentation; major reservoir deposition.

In this region the sea floor has little or no expression of the subsurface isopach.
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.
We have created a simple 2D forward model of statistical 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.
The structural profile can be adjusted

Our basic 2D proof of concept model

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

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

Development through time

Representative frames from the evolution of the section

Final geometry showing onlapping and offlapping turbidite section
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

Representative frames from the evolution of the section

Final geometry showing onlapping and offlapping turbidite section
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.

Minimum pelagic sedimentation

Maximum pelagic sedimentation
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.

Development through time

Frames from the evolution of the section.
Our basic 2D proof of concept model

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.

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

- clastic structure
- pelagic structure

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.
The model we have at present is only 2D

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