The Reservoir Architecture of Turbidite Channels: Models and Mysteries*

Tim McHargue[1]

Search and Discovery Article #51044 (2014)**
Posted November 24, 2014

*Adapted from 2013-2014 AAPG Foundation Distinguished Lecture

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Abstract

Petroleum exploration in deep-water settings is resulting in the discovery of many giant fields in reservoirs that accumulated in large channel systems on the continental slope. The architecture of these reservoirs is exceedingly complex. In the face of multi-billion dollar costs, it is more important than ever before to accurately characterize these reservoirs. Based on detailed examination of turbidite channel analogs as revealed in 3D seismic data, exposed in outcrops, or preserved on the modern sea floor, two principal models of channel architecture have emerged: a cut-and-fill model, and a lateral accretion model. Both models are appropriate in at least some cases, but debate continues as to which model is most applicable in any specific case. Furthermore, it is not apparent how to reconcile the preserved facies distributions of turbidite channel deposits and prevailing concepts of turbulent flow behavior. For example, when high levees are present, we know that flows are thick. Concentration of sand within sinuous channel elements confirms that turbulent flows are highly stratified. However, these architectures seem to require that the lower and upper portions of a single flow follow paths with markedly different sinuosities and divergent, even opposing, trajectories. How can that happen? Further debate concerns the transition from channel to fan architectures. Some high-resolution 3D seismic images suggest the presence

of distinct distributary systems on some submarine fans while others do not. Outcrop examples with the best continuous lateral exposures appear to be incompatible with seismic images of distributary systems. The few excellent outcrop examples of lobes arguably are strongly biased. Are our best images from 3D seismic also biased? High resolution images of modern submarine fans calibrated to sediment cores might provide the answer, but such data are lacking. This quandary is not just academic. It has become clear from recent drilling in the Gulf of Mexico that reservoir quality in submarine fans is highly variable, often containing good permeability within channels, in contrast to abundant argillaceous sands with low permeability in the lobes. With continued research, the issues discussed above will be resolved, but the path forward, like the channels themselves, will be long and sinuous.

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The Reservoir Architecture of Turbidite Channels: Models and Mysteries

Tim McHargue
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Stanford University

What is a turbidite?

Deposit of sediment transported by turbulence within a gravity flow

They can be thick bedded

What is a turbidite?

Or they can be thin bedded

Black Sea coast of Turkey

But usually they display:

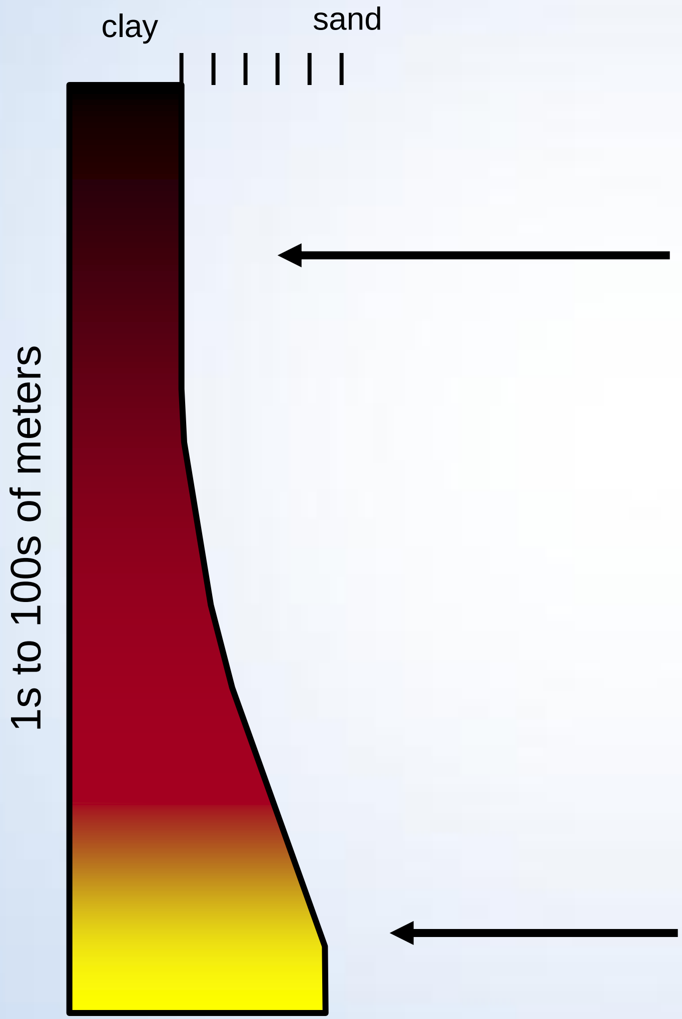
Graded Bed

Upward Fining

Decreasing Energy

Black Sea coast of Turkey

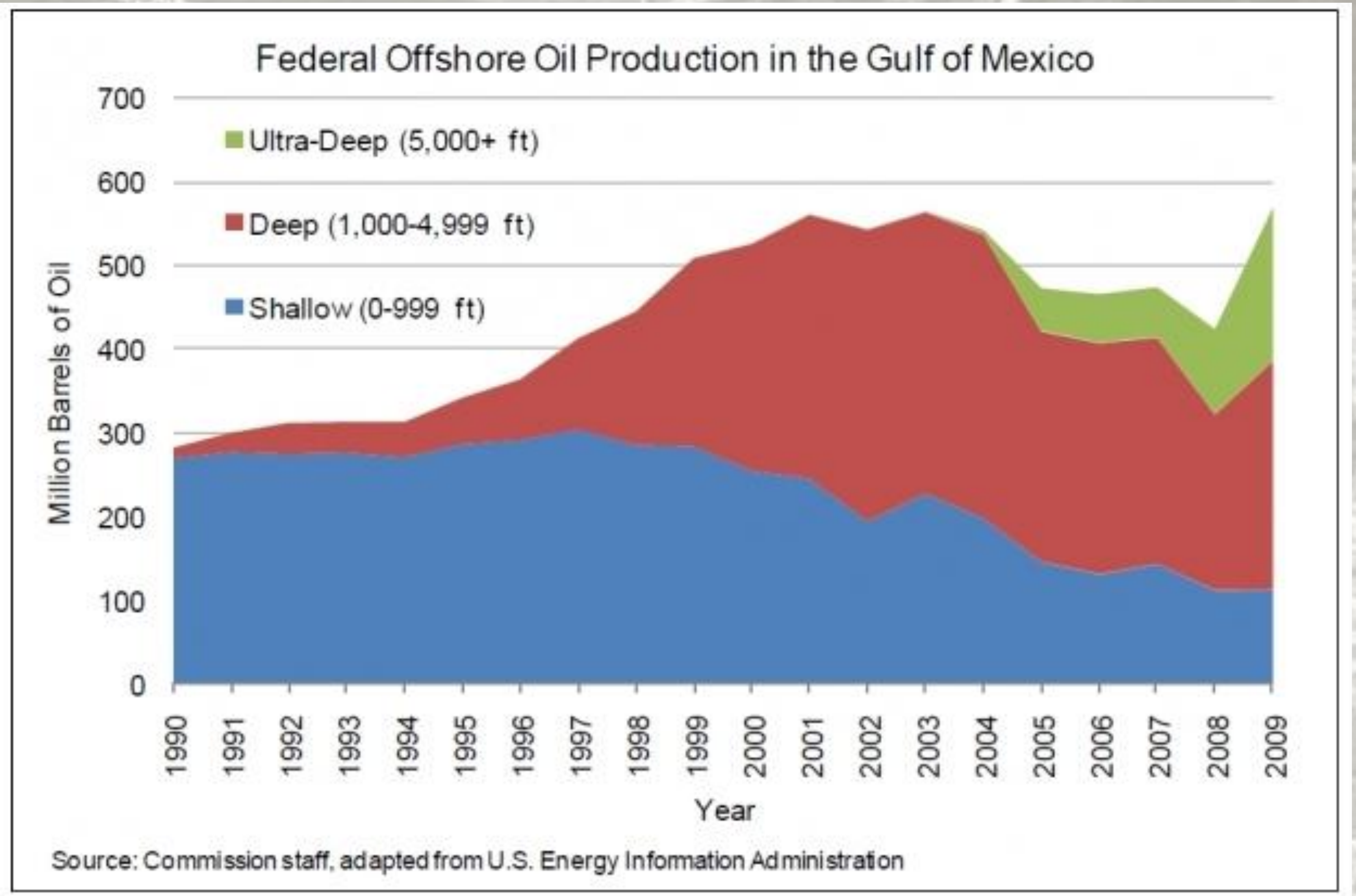
Density Stratification in a Turbulent Flow



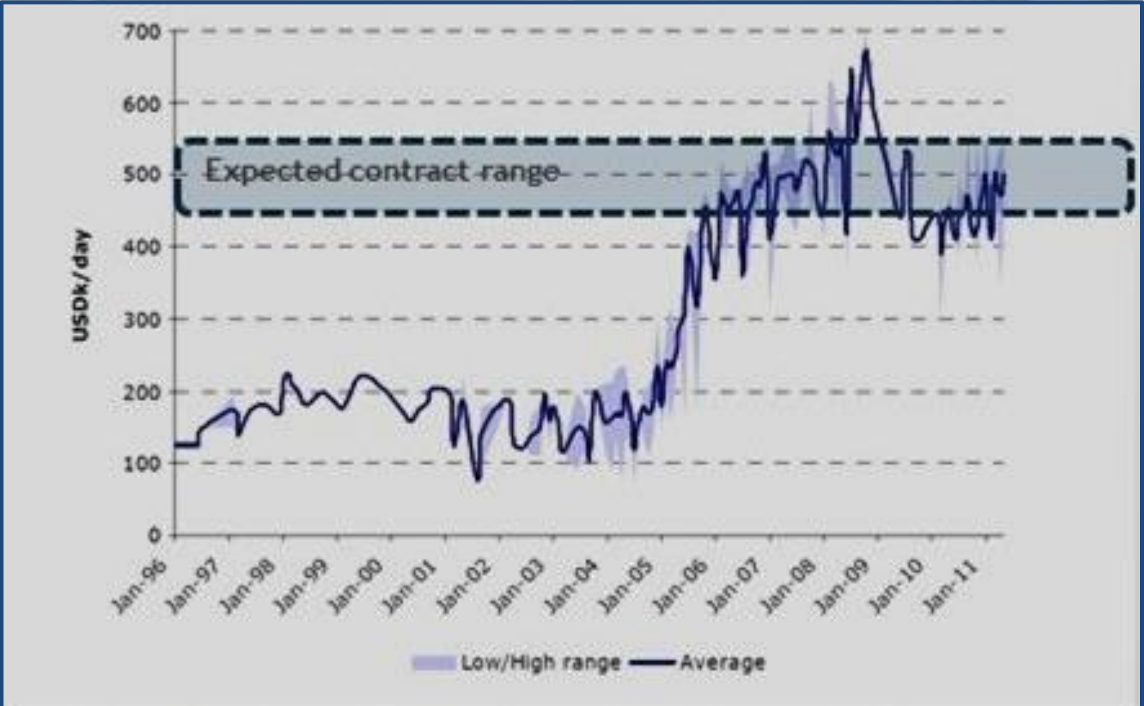
Mud Lost to:
Overspill,
Flow stripping and
Levee construction
Mud gained by erosion?

Sand Lost to Deposition
Sand gained by erosion?

Turbidites – Who Cares? Are they important?



Turbidites –
Who Cares?
Are they important?



Source: Saxo Bank and Seadrill, Energy-Power Conference presentation

Research Approach:

1. Gather examples
2. Determine and quantify common patterns, trends, and relationships to serve as rules
3. Construct rules-based forward modeling platform
4. Refine rules and improve modeling platform

Gather Examples

Data Types - Outcrops

Detailed facies relationships but limited architecture

Zerrissene Group, Namib Desert, Namibia

Observable Geometry: Channel bypass-drape

Tres Pasos Fm., Laguna Figueroa, Patagonia, Chile

Laterally extensive Submarine Fans, Tanqua Karoo, South Africa.

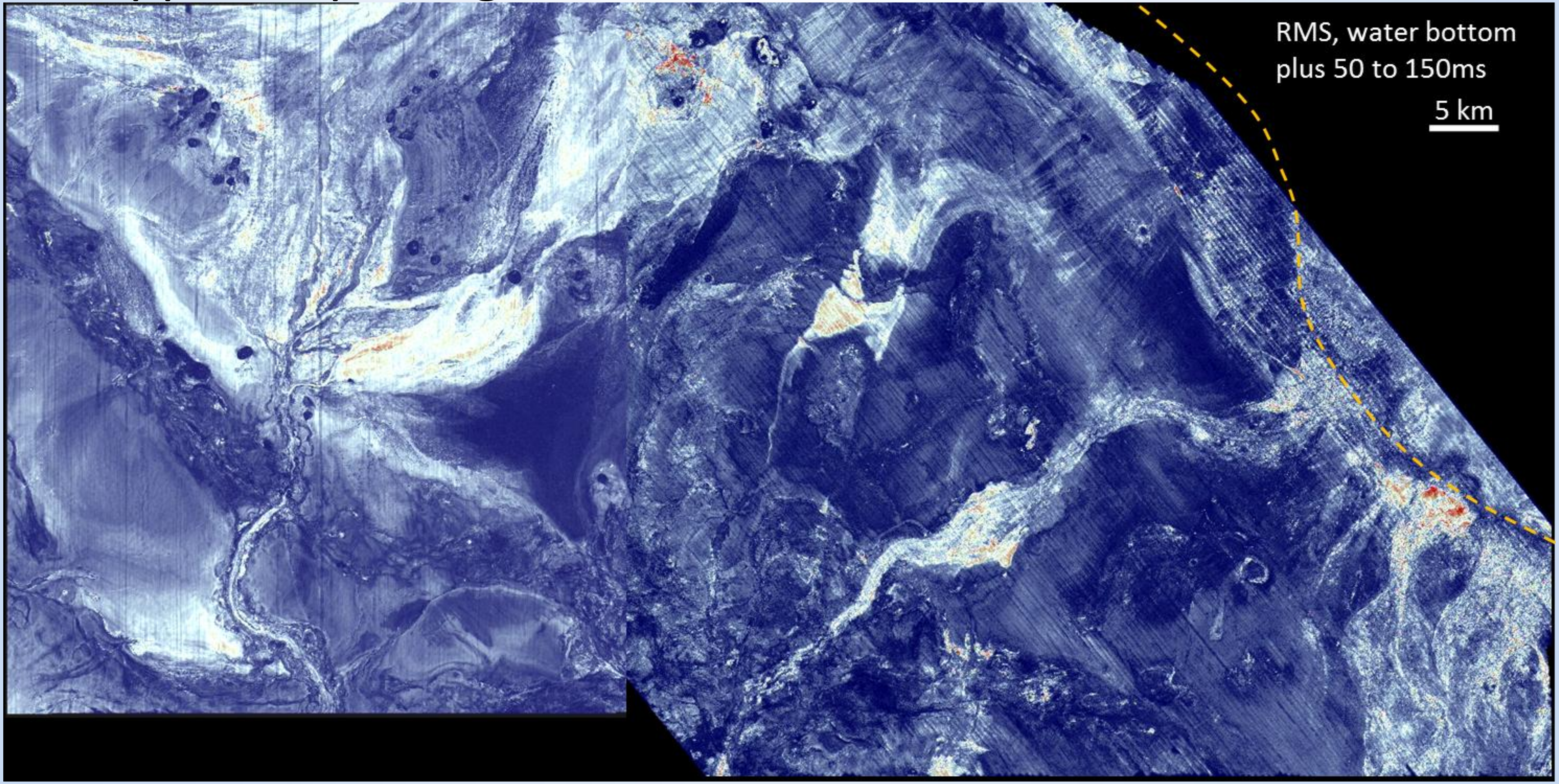
Laterally extensive Submarine Fans, Zerrissene Group, Namib Desert, Namibia

Data Types

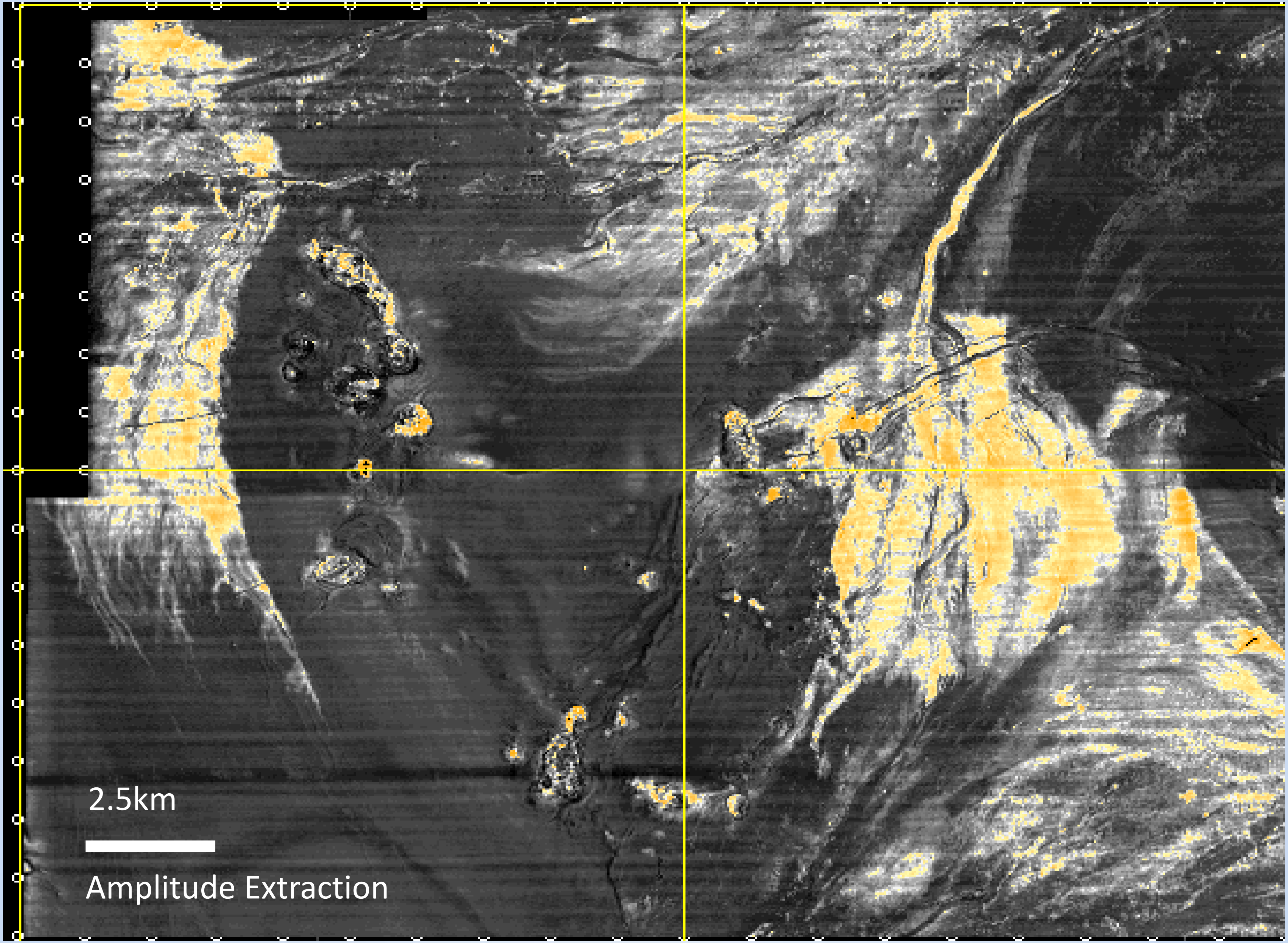
3D reflection seismic data (Courtesy of Chevron)

3D architecture but limited facies information

Upper slope, Nigeria - Near Sea Floor



Transient Fans, upper slope, Nigeria - Near Sea Floor

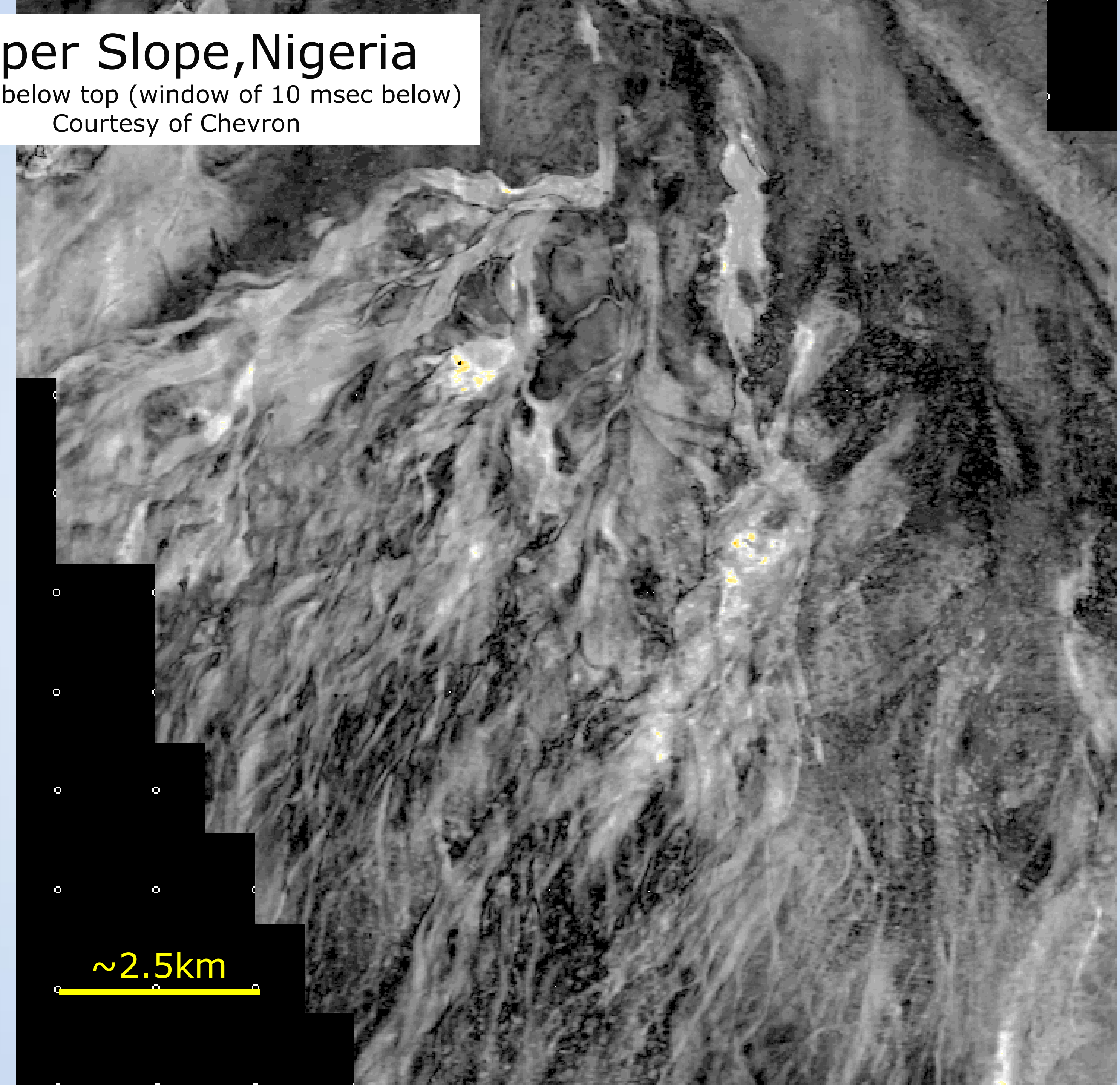


From Adeogba et al., 2005

Upper Slope,Nigeria

10 msec below top (window of 10 msec below)

Courtesy of Chevron

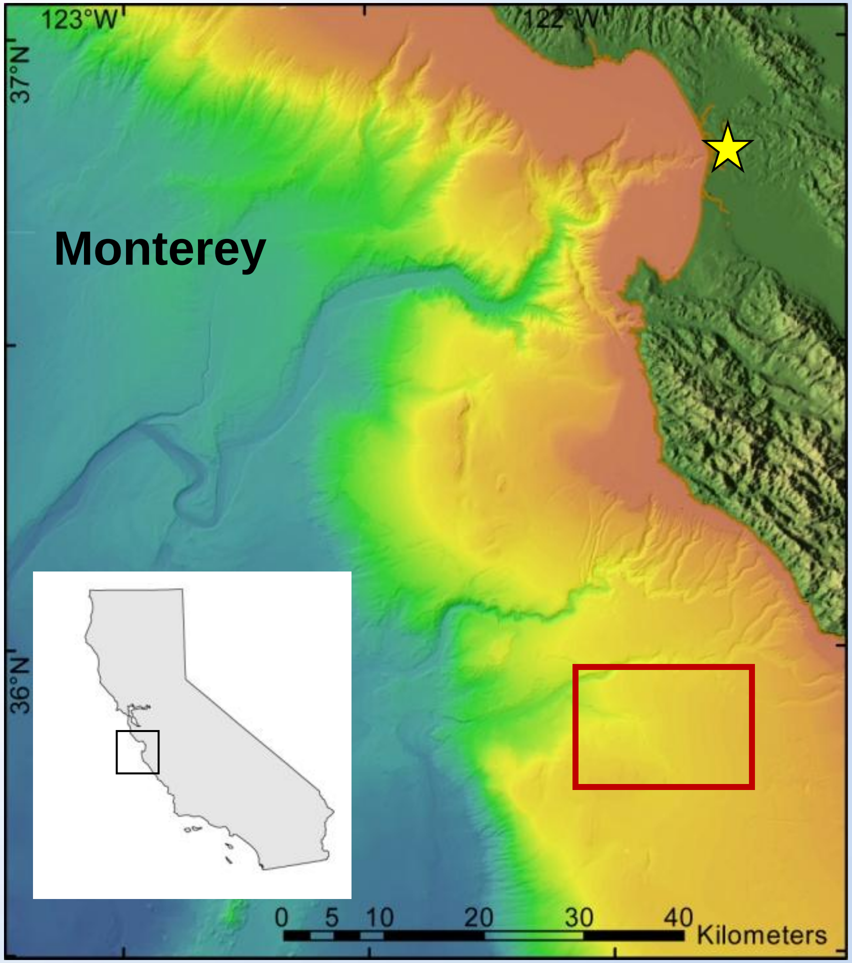


Data Types

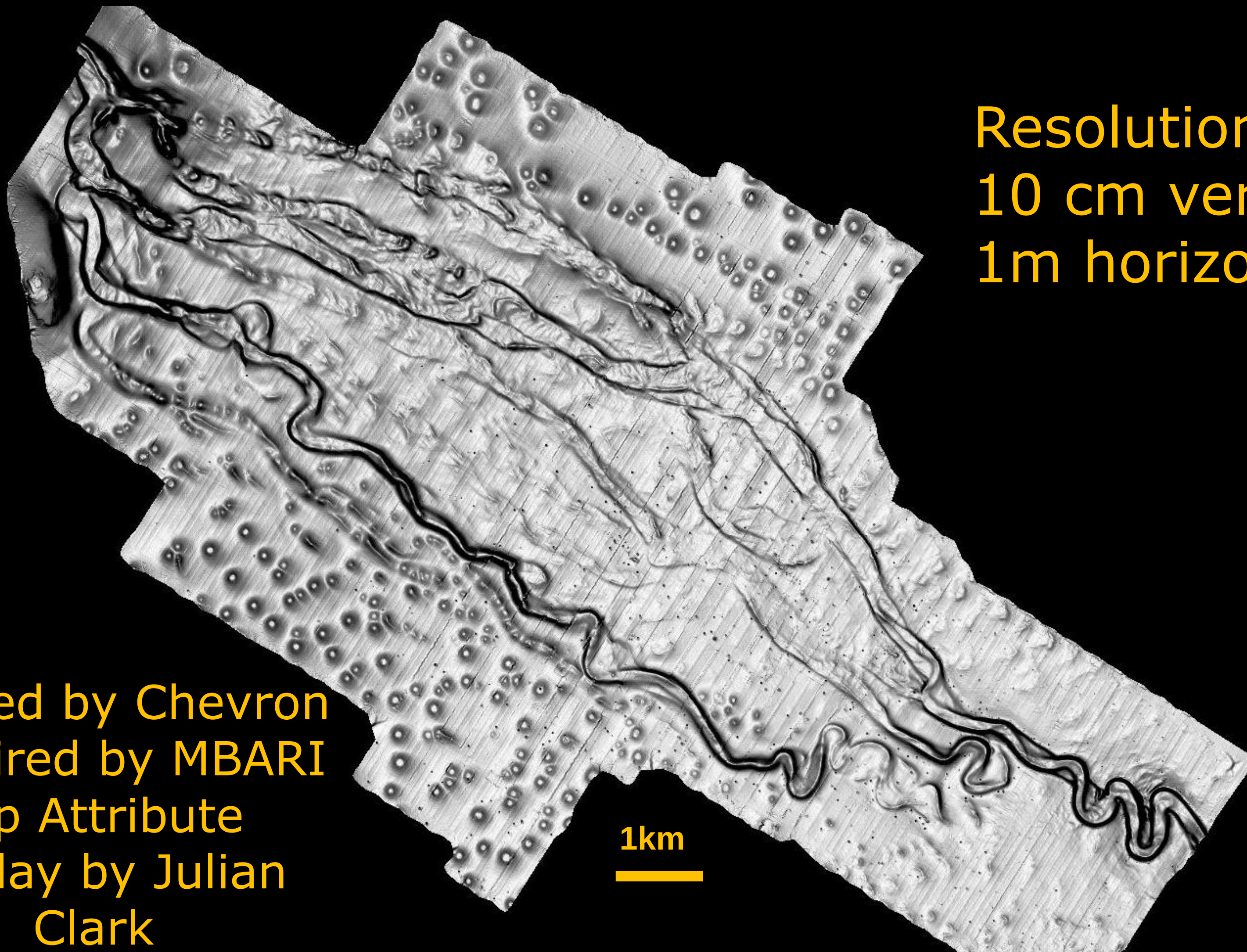
Oceanographic data from near-modern systems

Detailed 2D architecture, no lithology data

MBARI Zephyr and AUV



Lucia Chica, Central California
AUV multi beam bathymetry

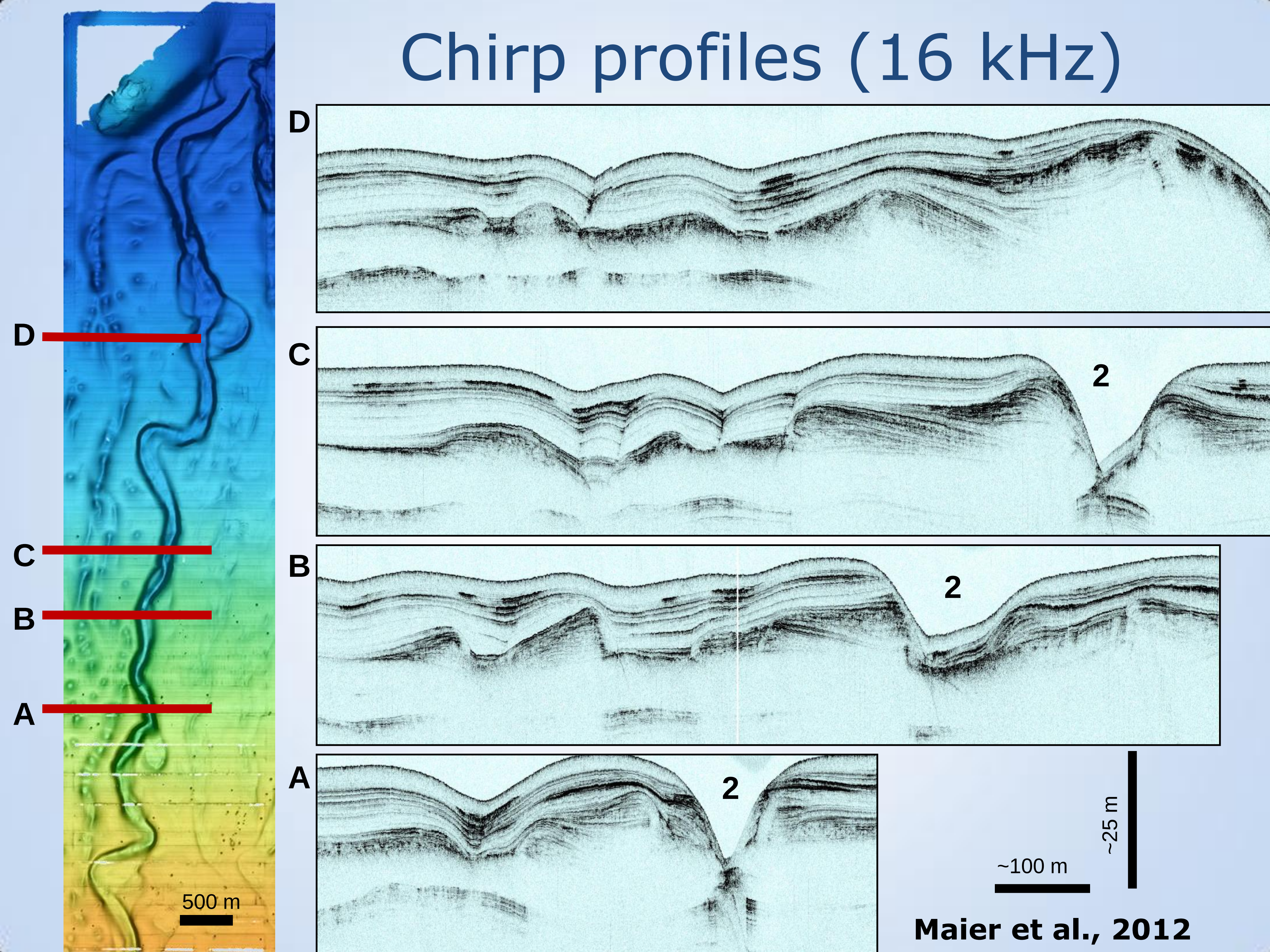


Resolution:
10 cm vertical
1m horizontal

Funded by Chevron
Acquired by MBARI
Dip Attribute
display by Julian
Clark

Maier et al., 2012

Chirp profiles (16 kHz)



Maier et al., 2012

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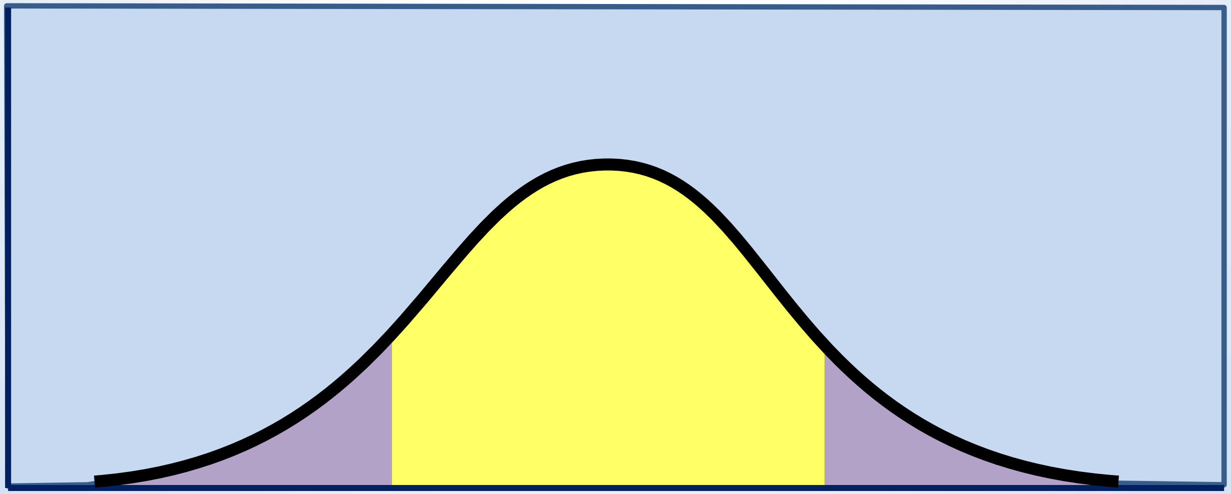
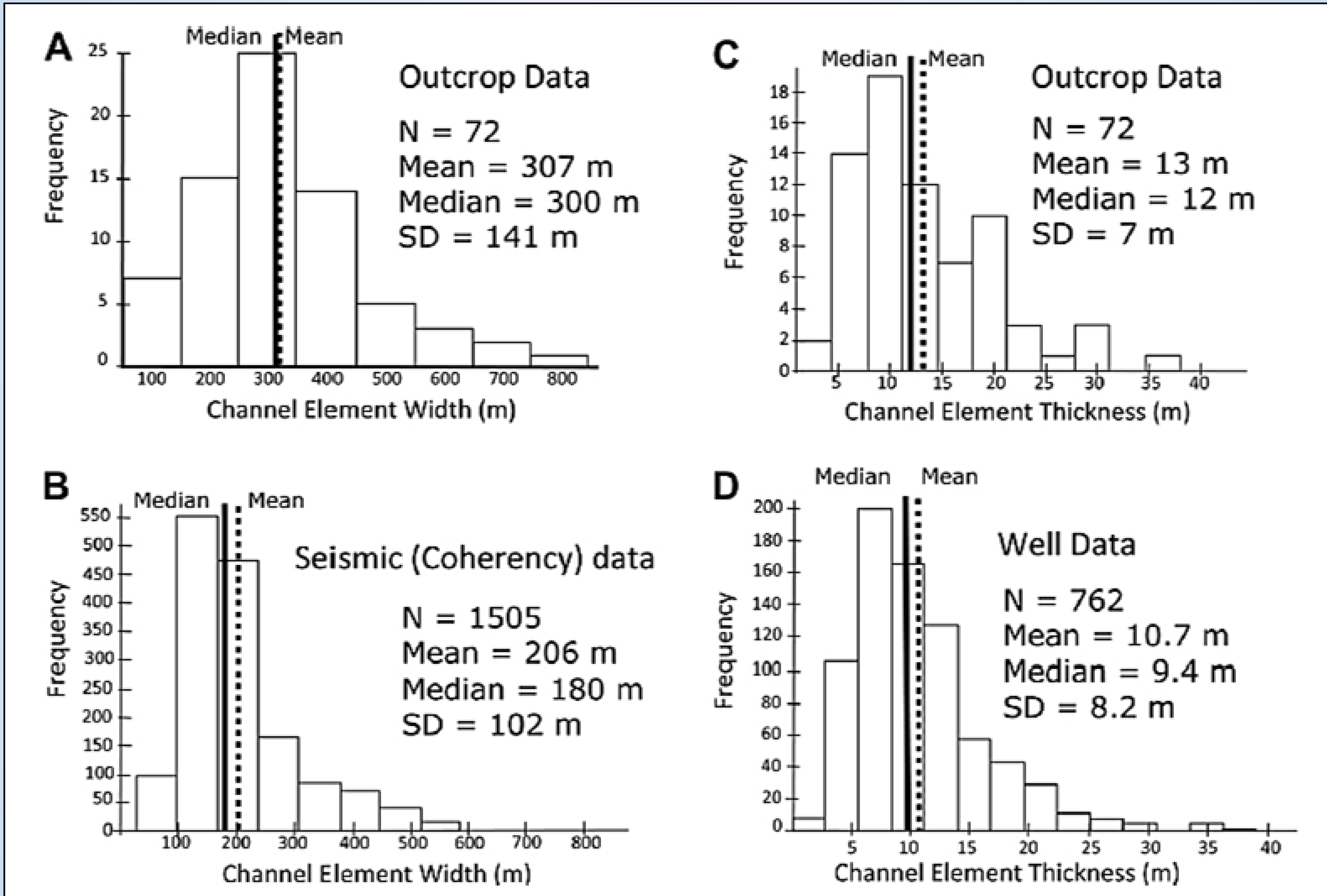
2. Determine and quantify common patterns, trends, and relation-ships to serve as rules



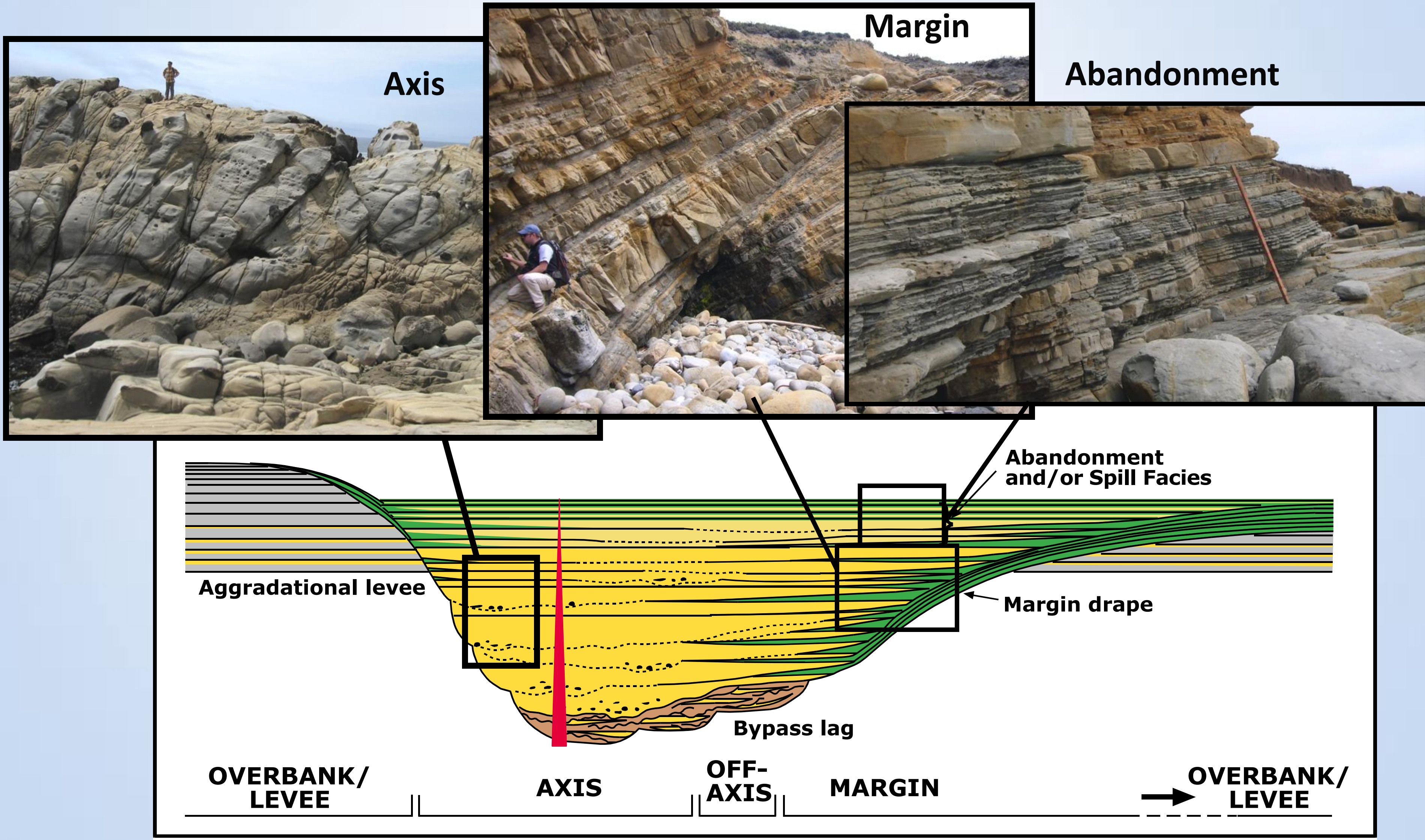
Channel Element Dimensions



McHargue et al., 2011, Marine and Petroleum Geology

Channel element lithofacies associations

Paleogene turbidites, Stump Beach, CA.

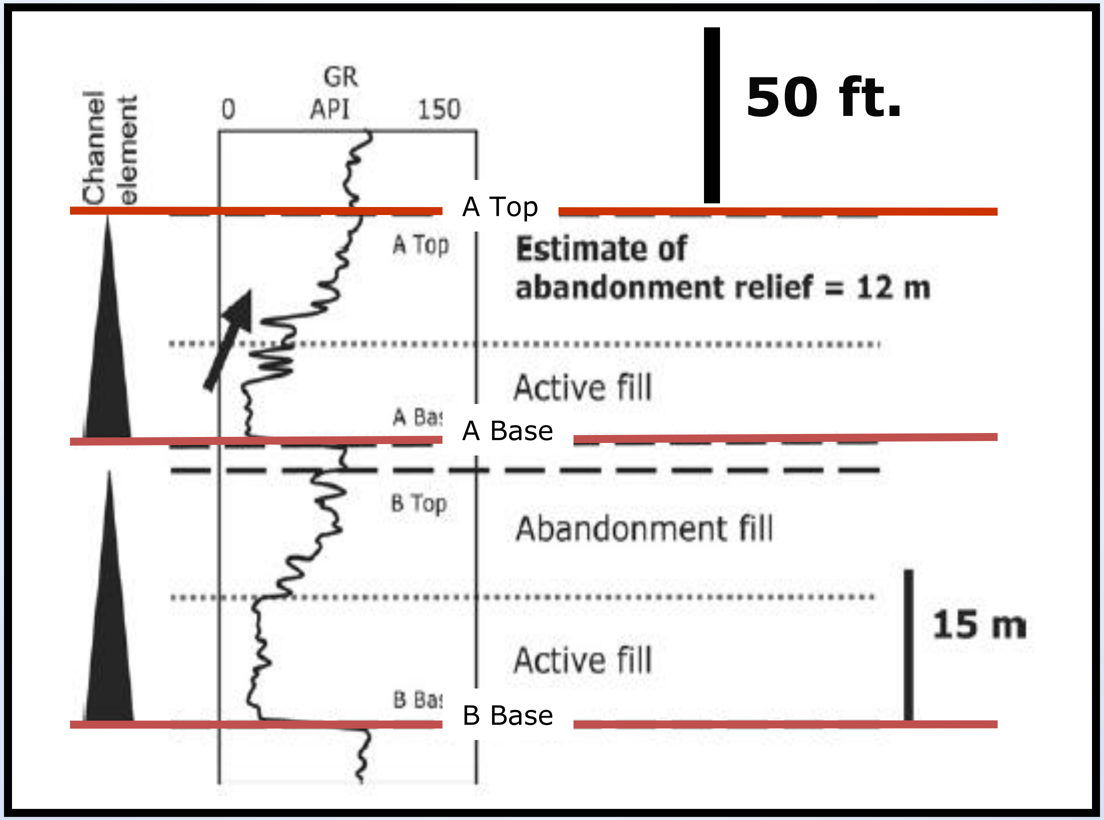


Abandonment facies –

Recognizing under-filled channels from logs

Channel abandonment-fill from logs:

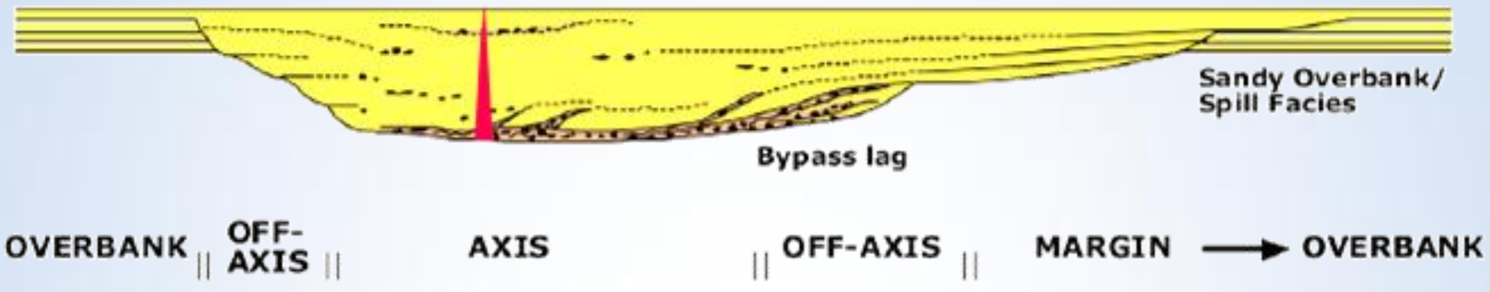
- Fine-grained,
- Upward thinning,
- upward increase in mud.



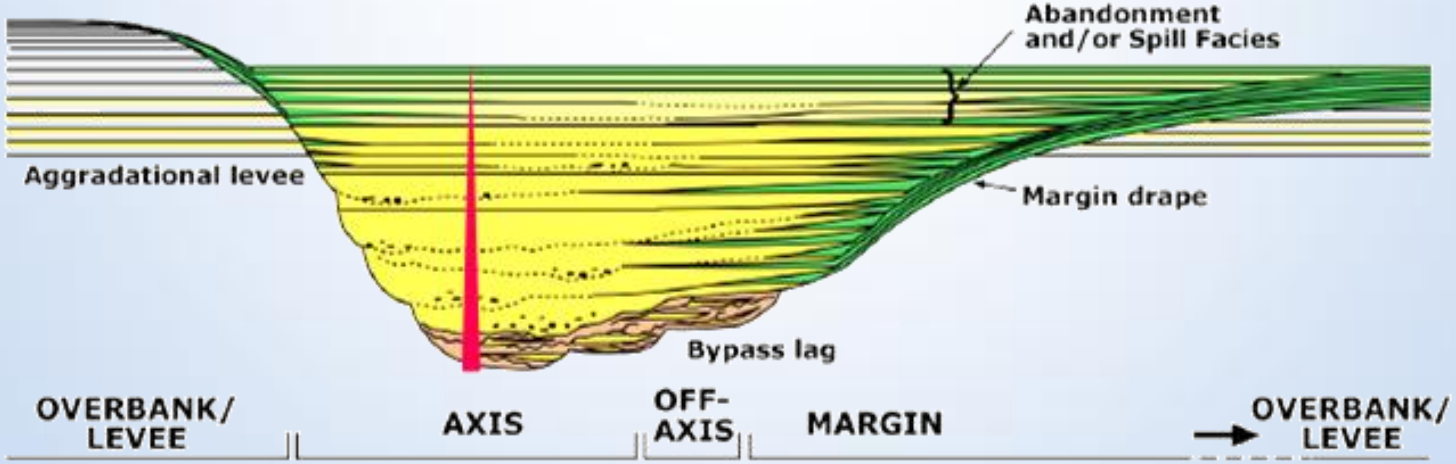
McHargue et al., 2011, Marine and Petroleum Geology

Filled Vs. Unfilled Channel Elements

Filled Channel Element

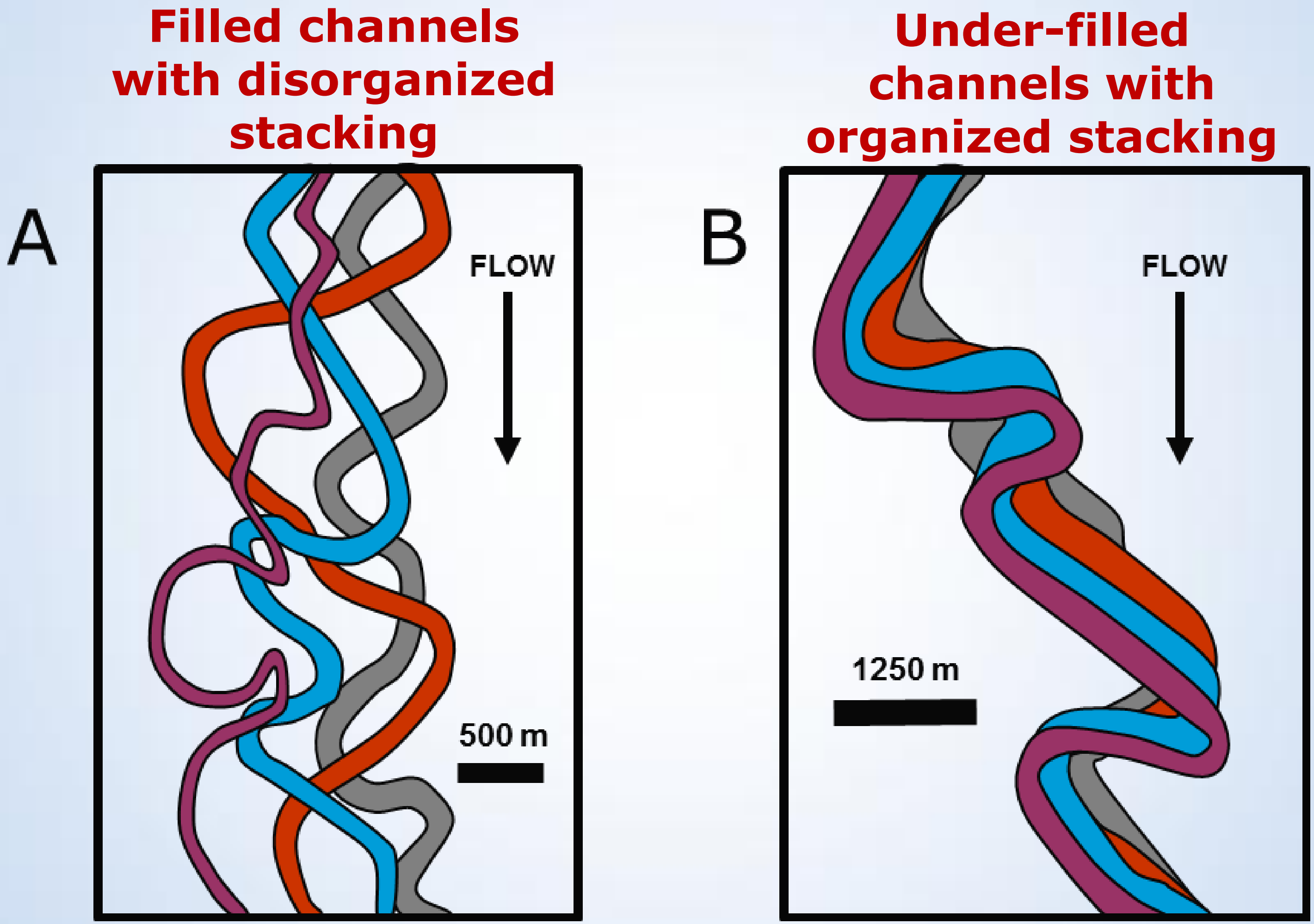


Unfilled Channel Element



McHargue et al., 2011, Marine and Petroleum Geology

Two-Channel Stacking Patterns



McHargue et al., 2011, Marine and Petroleum Geology

Research Approach:

1. **Gather examples**
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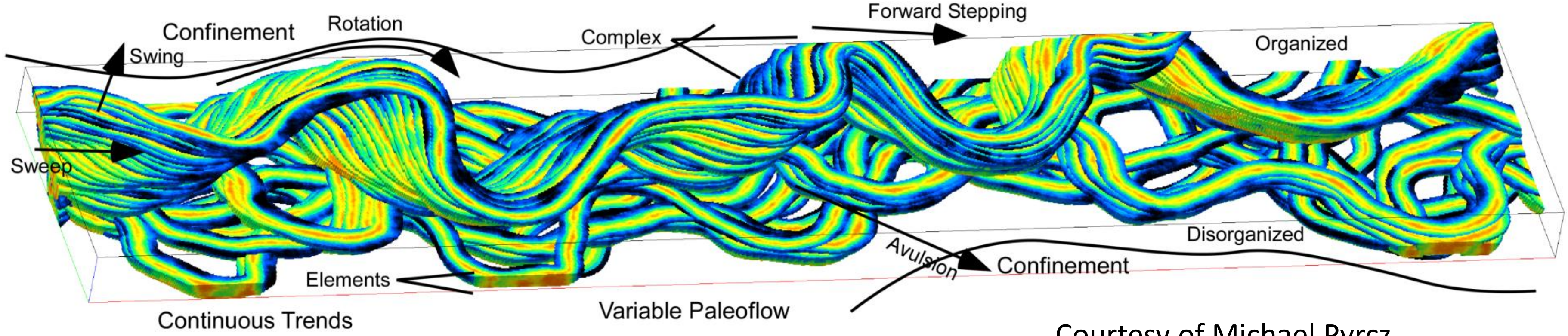
3. **Construct rules-based forward modeling platform**

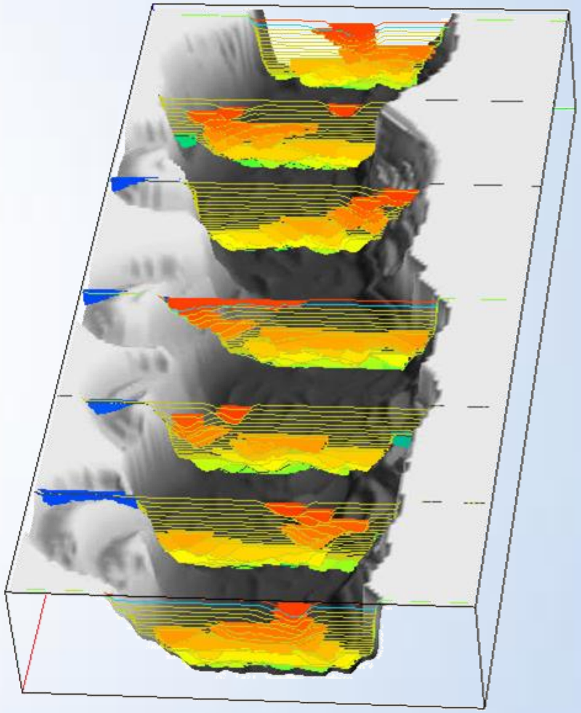


Courtesy of Michael Pyrcz

Event-based Modeling

(Pyrcz et al., 2012)

- Forward Model
  - simulate sequence of events
  - fill accommodation from base up
- Rule-based
  - depositional processes integrated through expert rules
- Architectural Element Basis
  - realistic centerline morphologies
  - attached element
- Produce "realistic", quantitative, and repeatable results

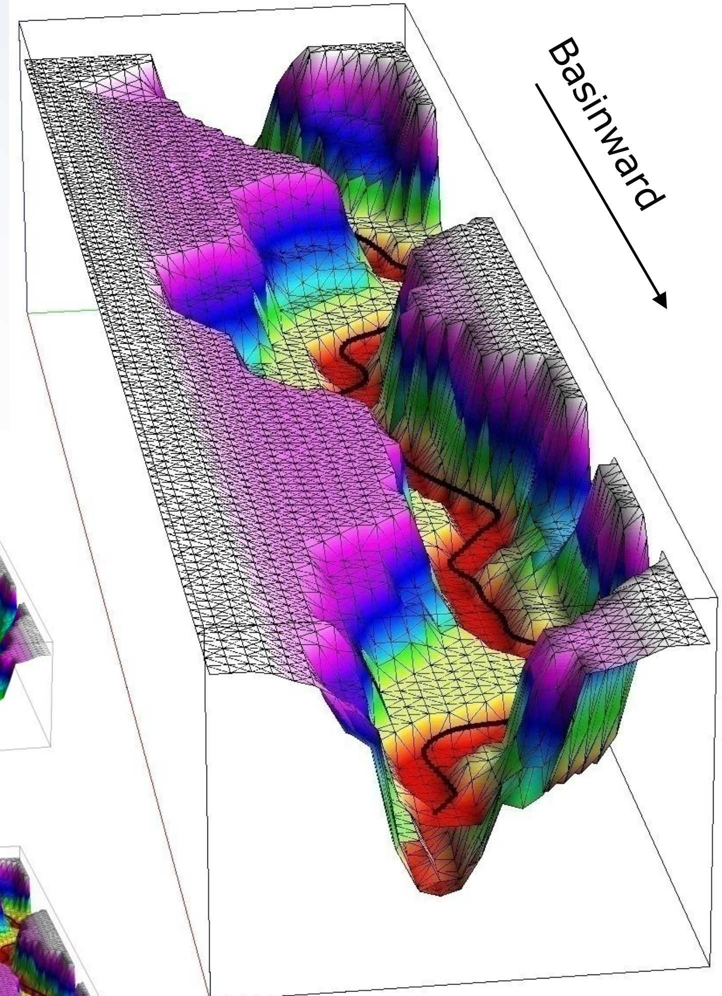


Integrating surfaces, well data and architectural information

(McHargue et al., 2011)

Slope Valley Complex Set

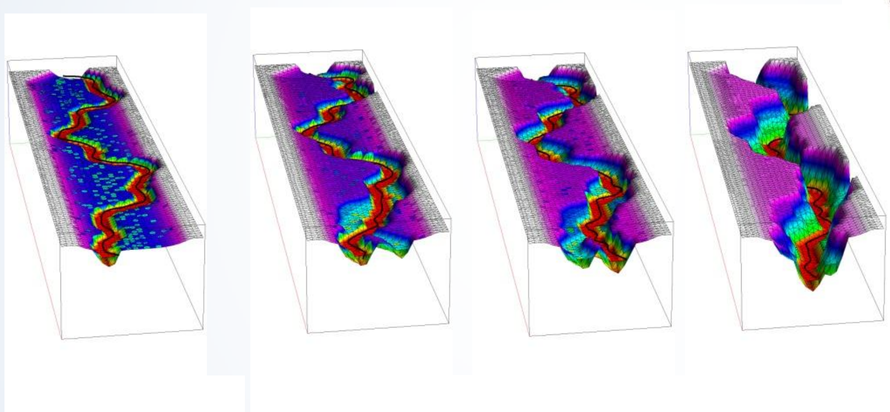
Events 1 - 15



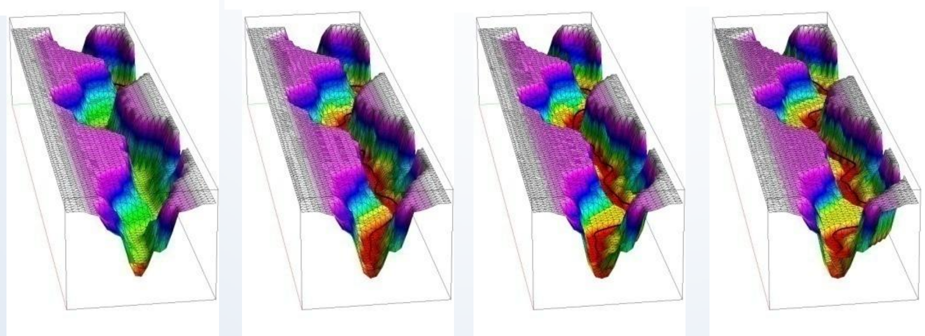
2 Stages

1. Incision
2. Amalgamation, Low Aggradation

Stage 1
events 1 -10

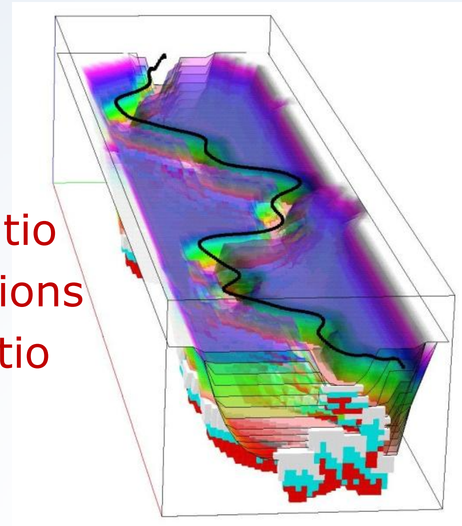


Stage 2
events 11 -15



Courtesy of Michael Pyrcz

Stacking Pattern Model
Slope Valley Fill

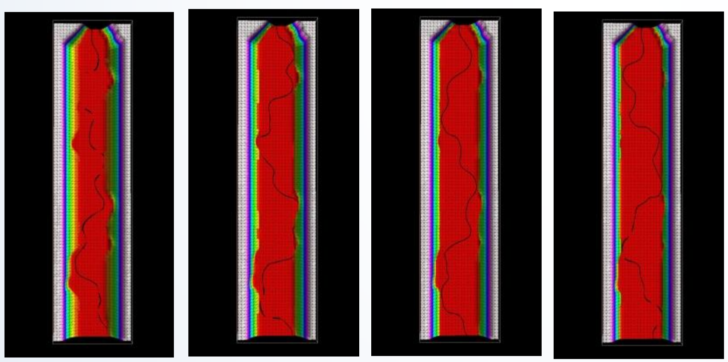


Stages 3 and 4

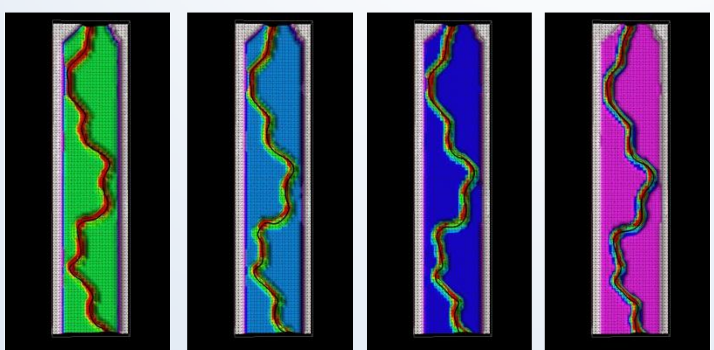
- 3. Low aggradation / high fill ratio
  disorganized / frequent avulsions
- 4. High aggradation / low fill ratio
  organized / sweep pattern

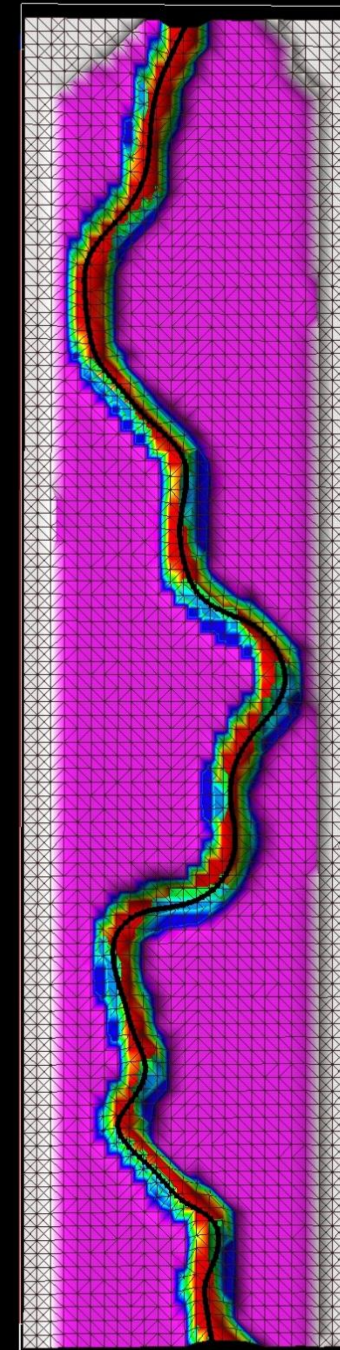
Courtesy of Michael Pyrcz

Stage 3

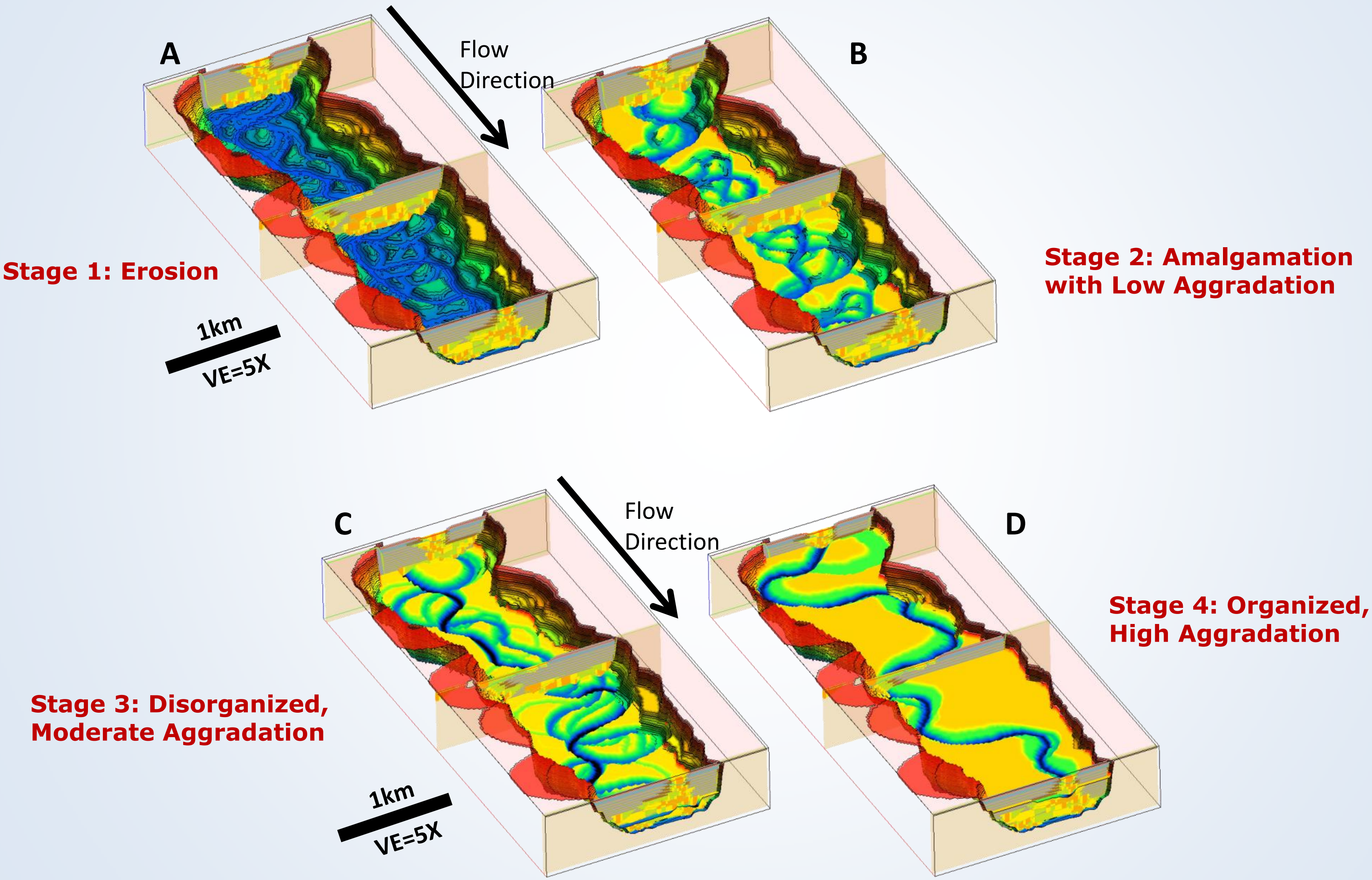


Stage 4



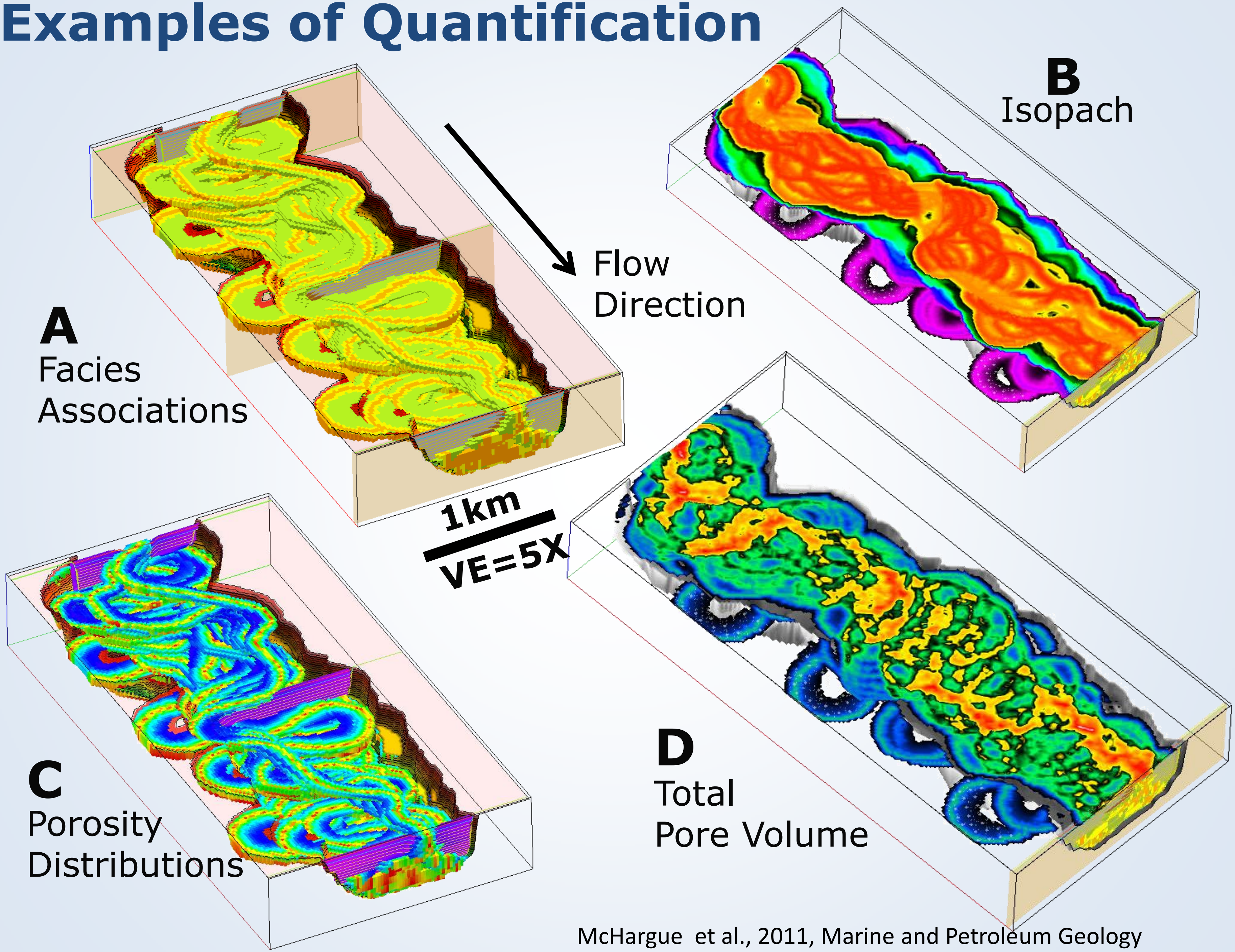


Common Sequence of Channel Stacking Patterns



McHargue et al., 2011, Marine and Petroleum Geology

Examples of Quantification



McHargue et al., 2011, Marine and Petroleum Geology

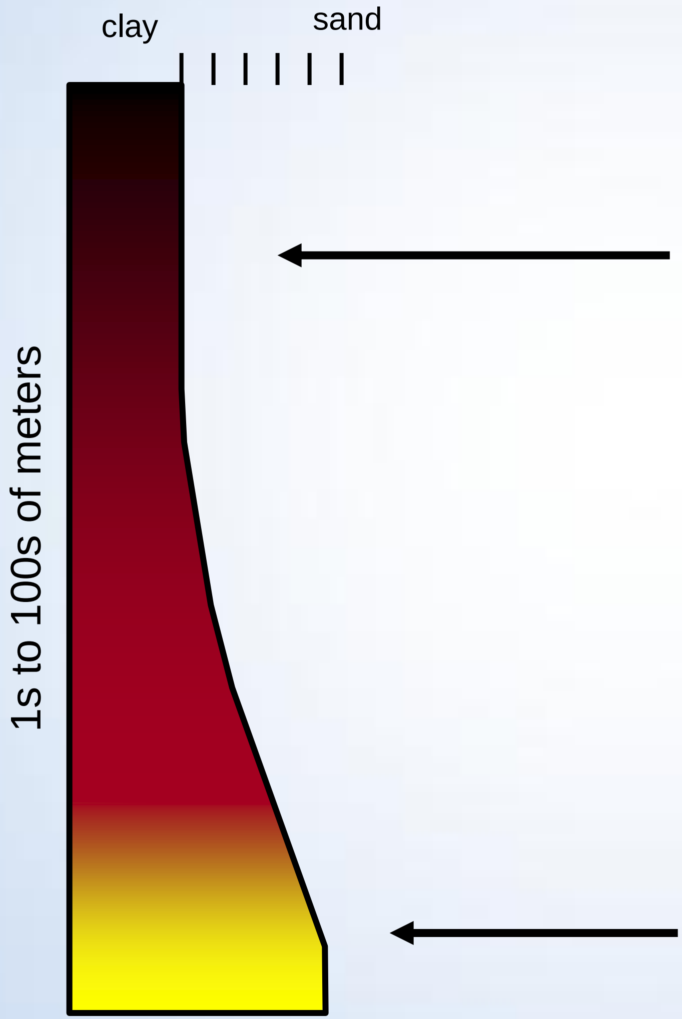
Research Approach:

1. **Gather examples**
2. **Determine and quantify common patterns, trends, and relation-ships to serve as rules**
3. **Construct rules-based forward modeling platform**
4. **Refine rules and improve modeling platform**

   (What problems remain?)

Problem 1:
Can a Single Turbidite Flow Decouple and Become Separate High and Low Concentration Flows?

Density Stratification in a Turbulent Flow



Mud Lost to:
Overspill,
Flow stripping and
Levee construction
Mud gained by erosion?

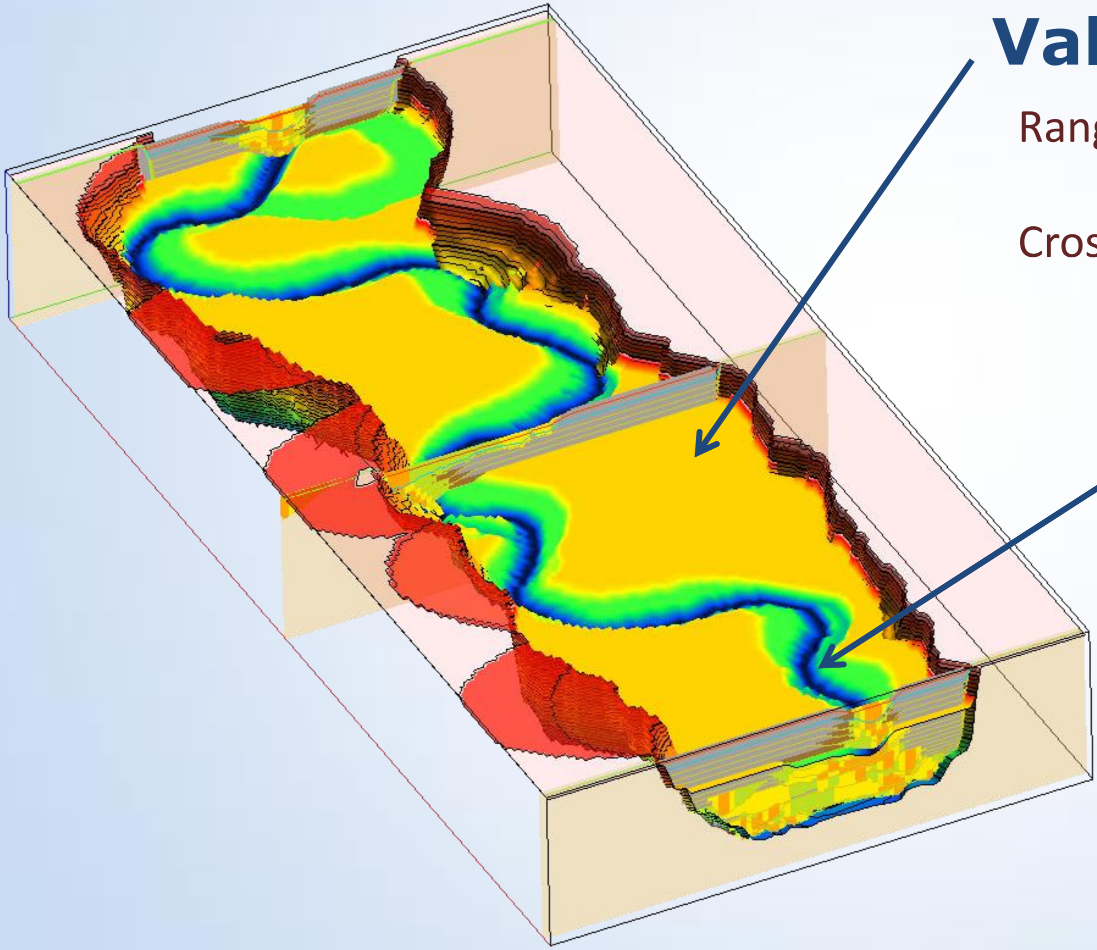
Sand Lost to Deposition
Sand gained by erosion?

Flow Stratification
Restricts Sand to Channel Elements

Tres Pasos Fm., Patagonia

Presenter's notes: Well logs and 3D seismic data from numerous channel systems confirm that turbidite sands typically are concentrated within the element-scale channel unless the confinement relief is thin, on the order of 10m or less. Therefore, collectively, architecture and sediment distribution imply that the turbidity currents traveling through these channel systems were stratified, and the higher concentration portion of these flows were restricted to the element-scale channels.

Valley cross-sectional area = 1 to 3.5 orders of magnitude larger than the channel element.



Valley Dimensions

Range from 1km to 10km wide
by 100 to 500m deep
Cross-sectional area =
100 - 5000 km^2

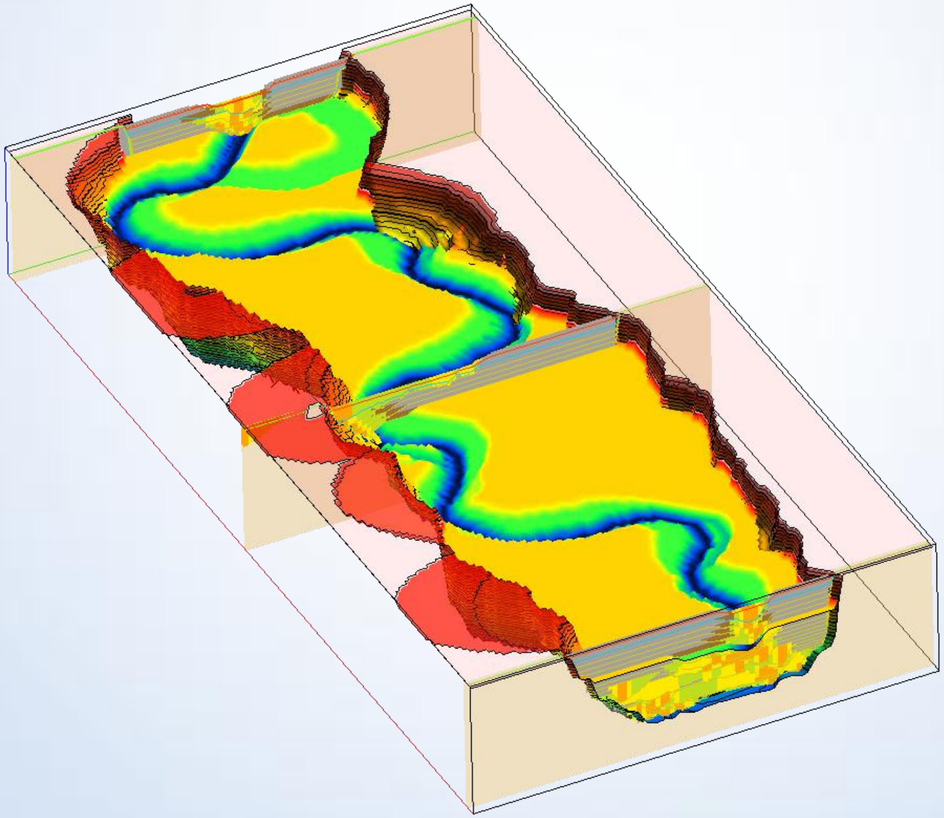
Channel element

Average 13m X 307m
Cross-sectional area = 1- 9 km^2

modified from
McHargue et al., 2011

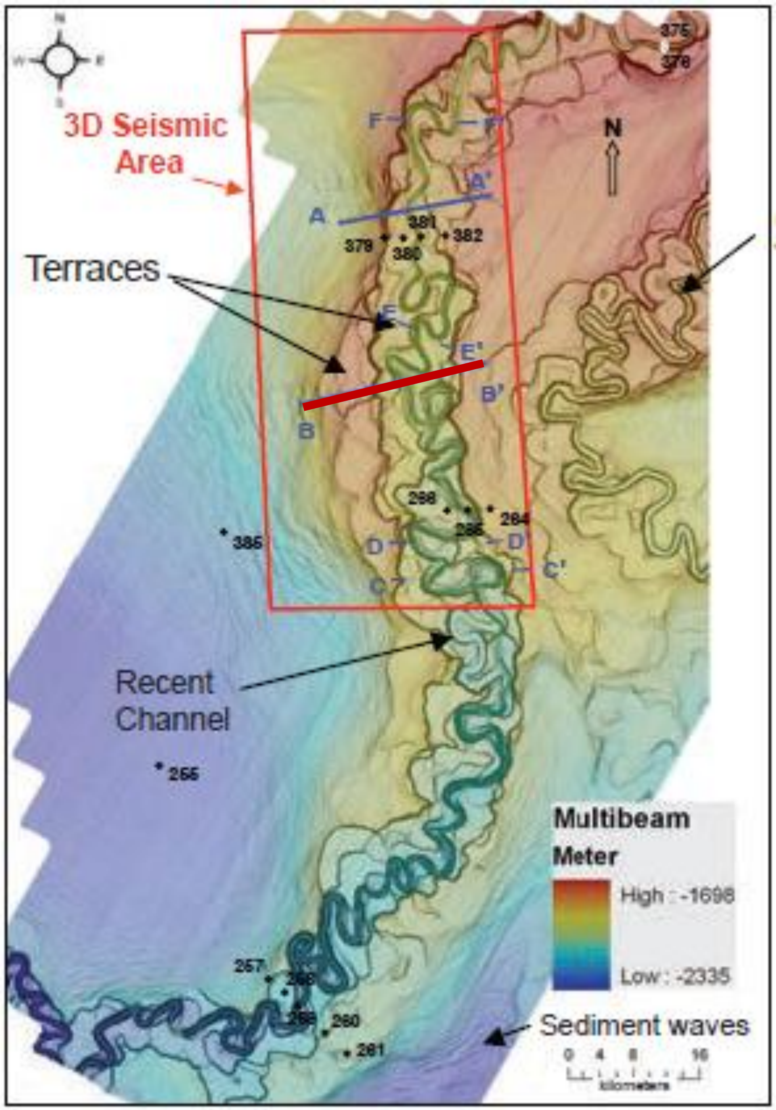
By assuming that a single flow fills this morphology, we are assuming the sandy, high-density portion of the flow typically is:

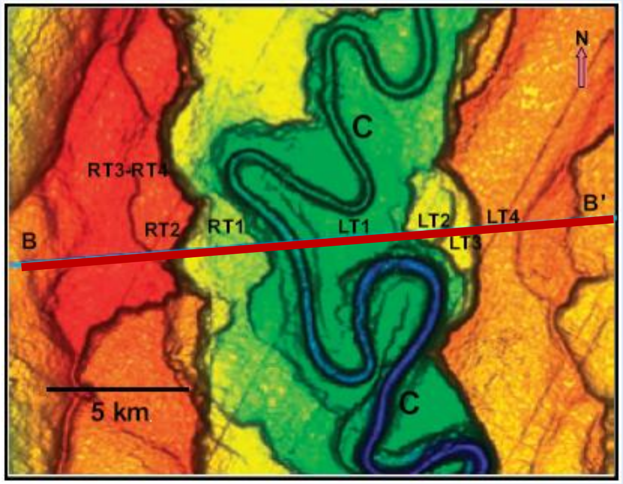
less than 10% of the flow height
less than 1% of the flow volume.

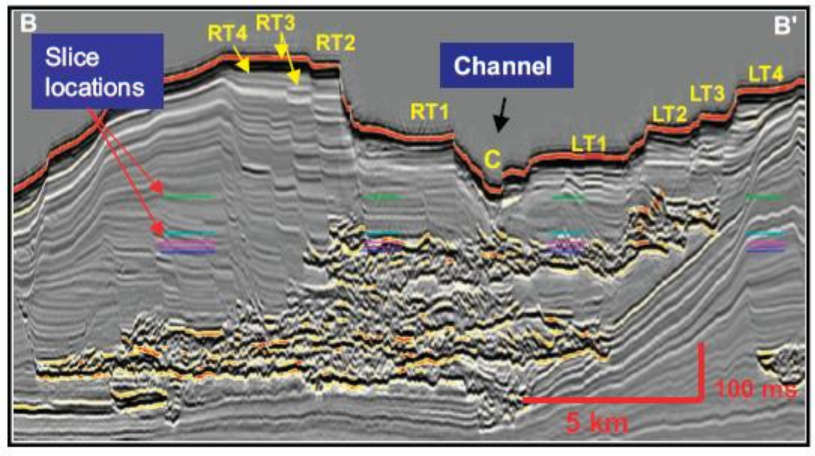


modified from
McHargue et al., 2011

Proximal Bengal Fan Channel



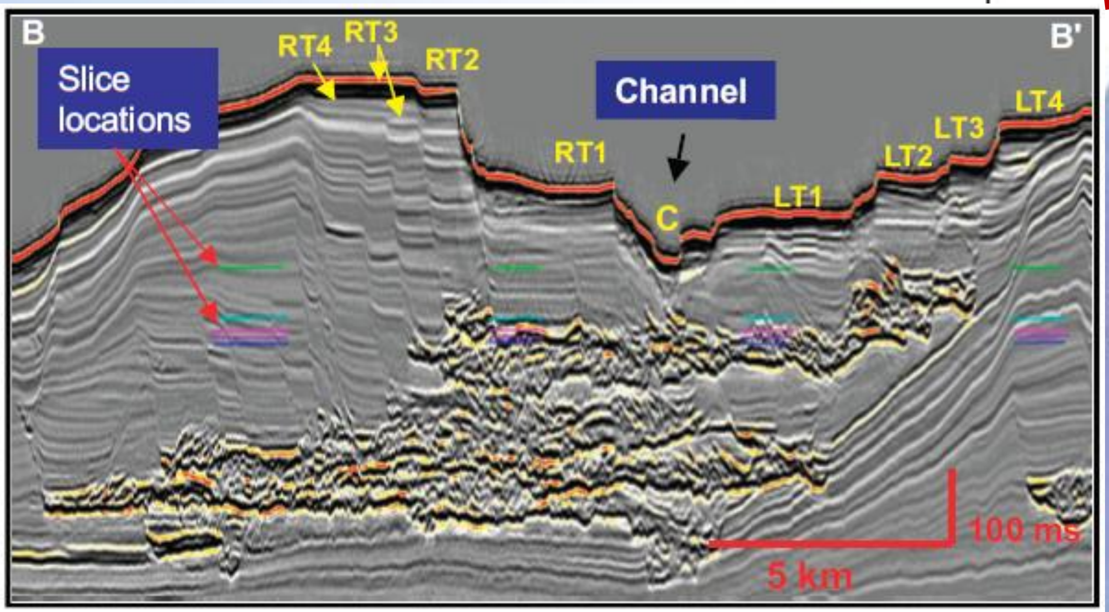


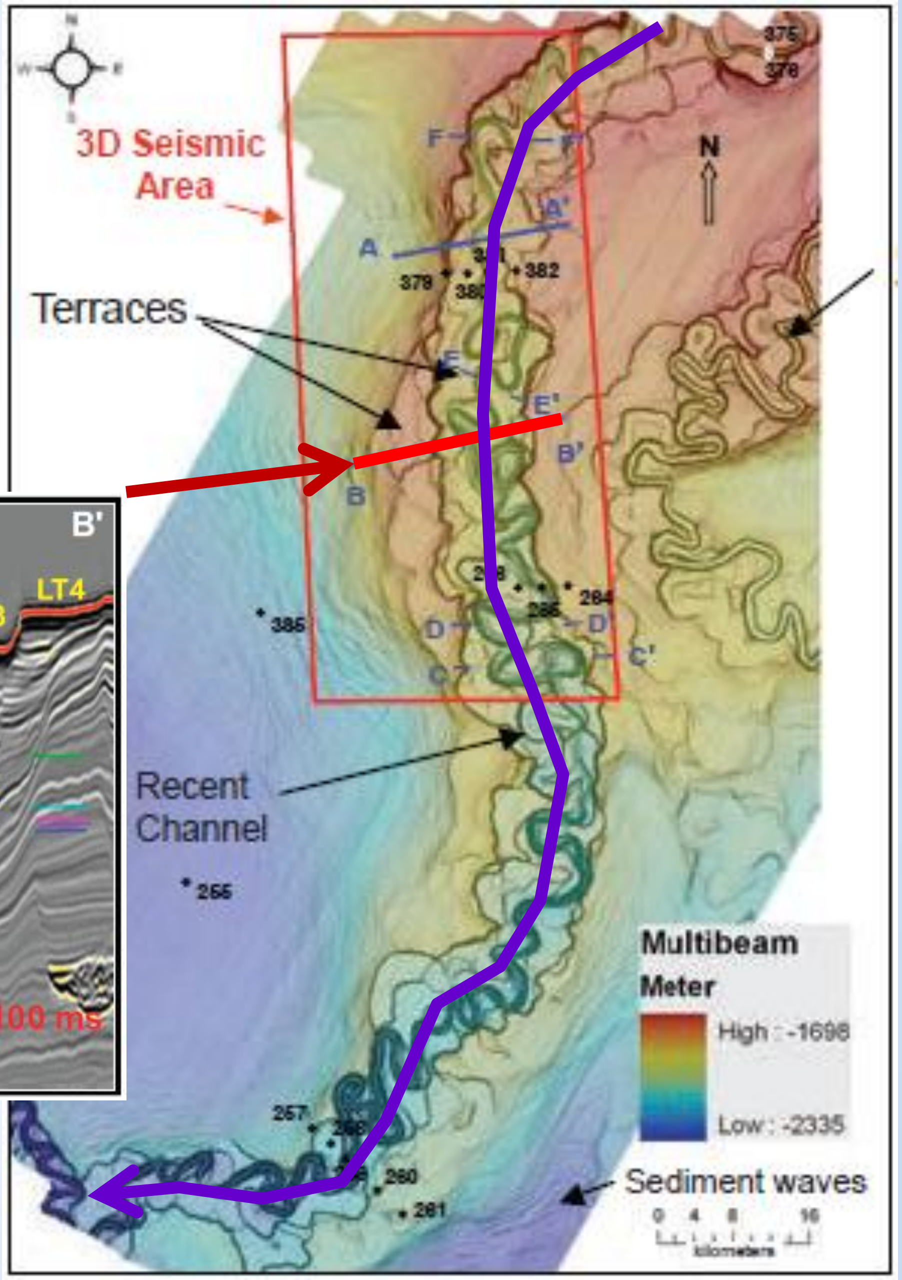


Kolla et al., 2012

We are also assuming:

- The upper, dilute layer is confined by large levees and follows a low-sinuosity path.

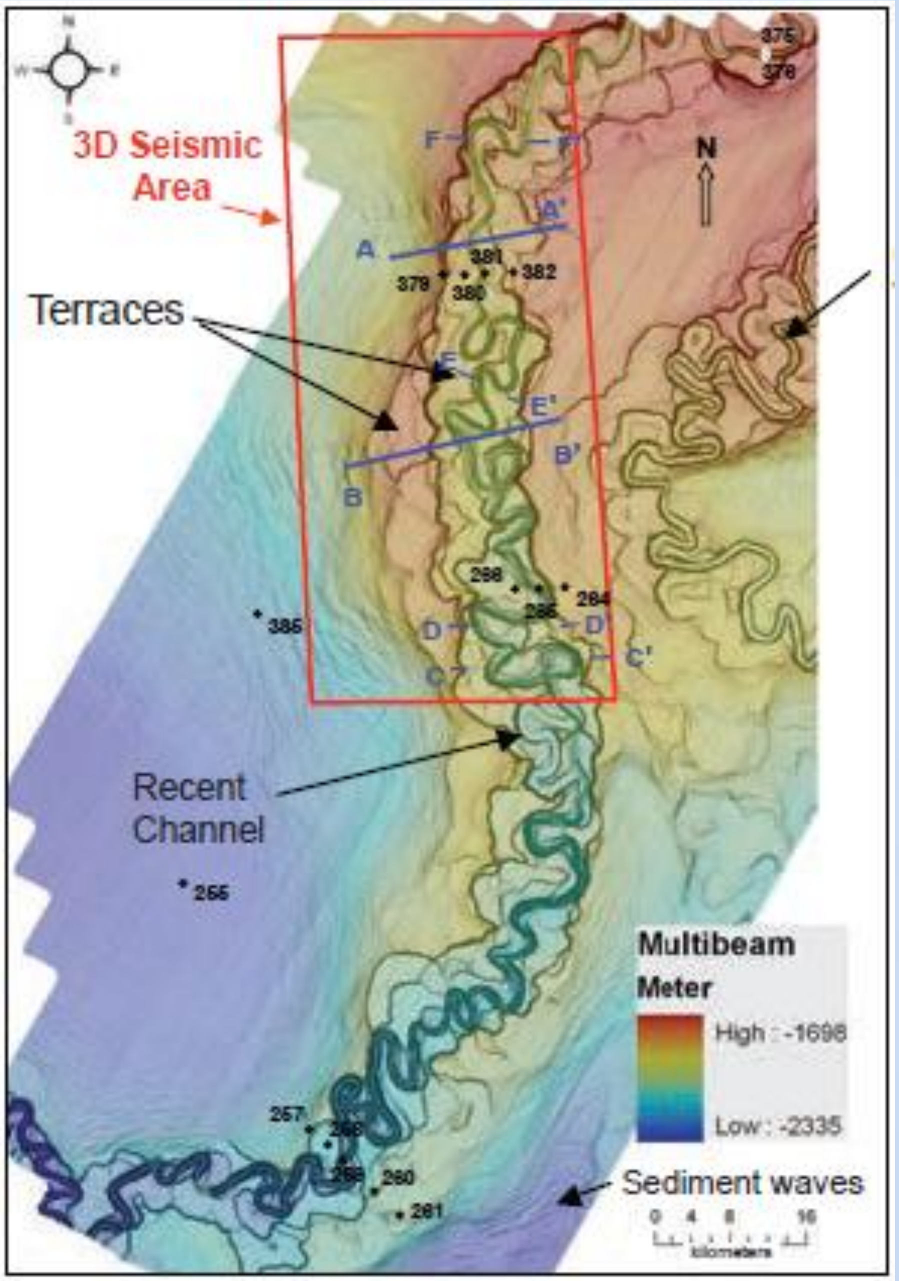




Proximal Bengal Fan, Kolla et al., 2012

We are also assuming:

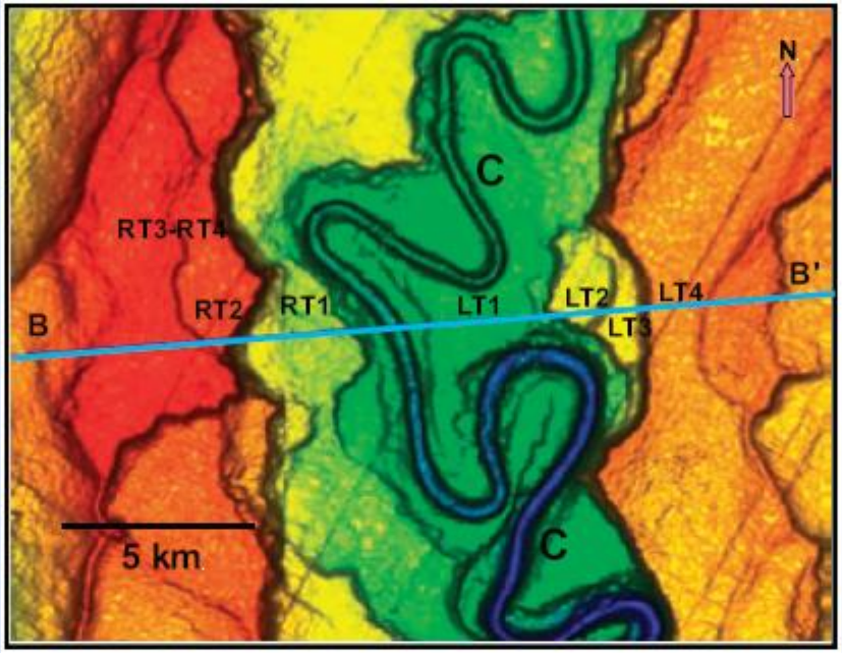
- The upper, dilute layer is confined by large levees and follows a low-sinuosity path.
- For 60% to >90% of its width the dilute layer is in contact with the valley floor, rather than the underlying sinuous channel.

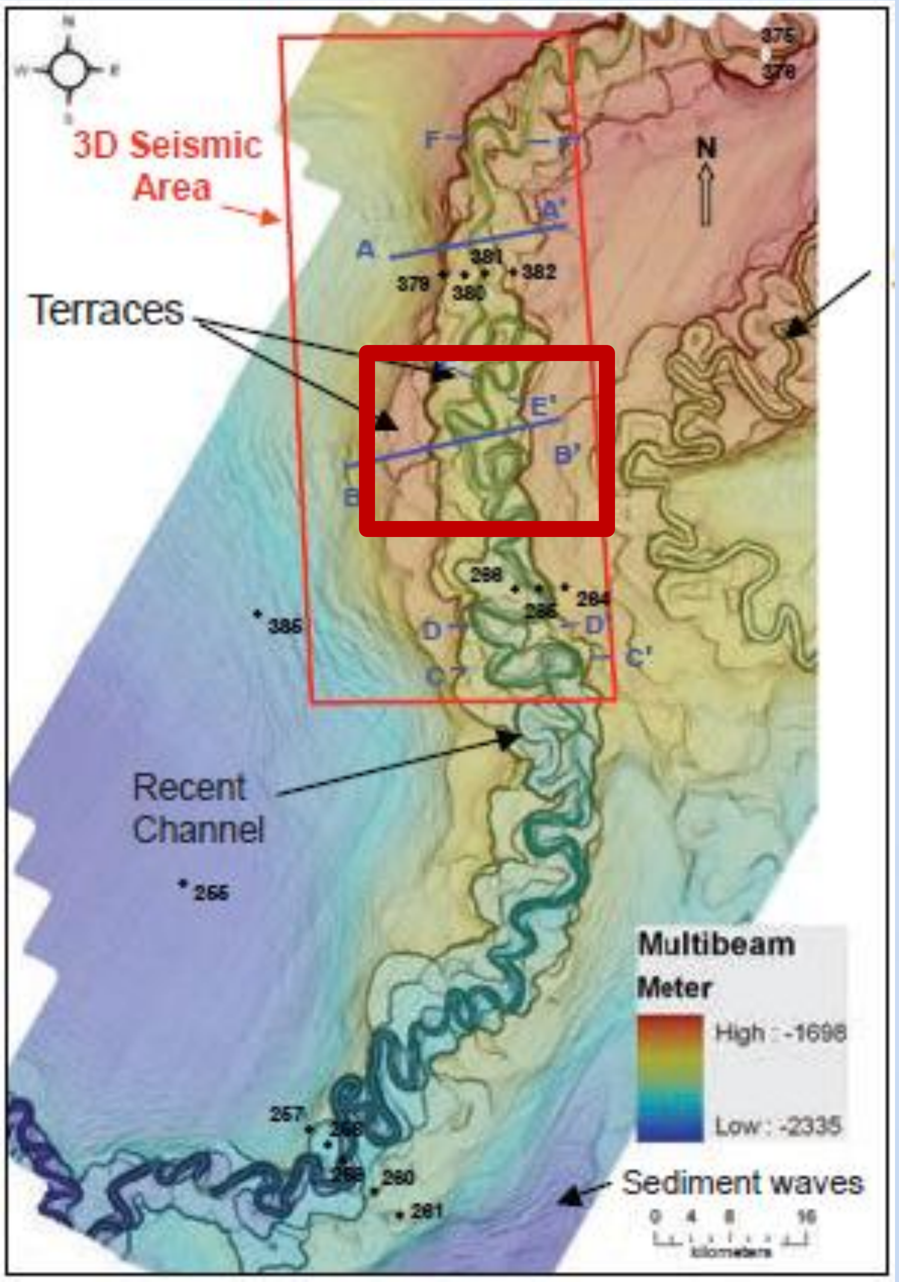


Proximal Bengal Fan, Kolla et al., 2012

We are also assuming:

The underlying, high-density layer may erode a confining channel element that follows a high-sinuosity path.

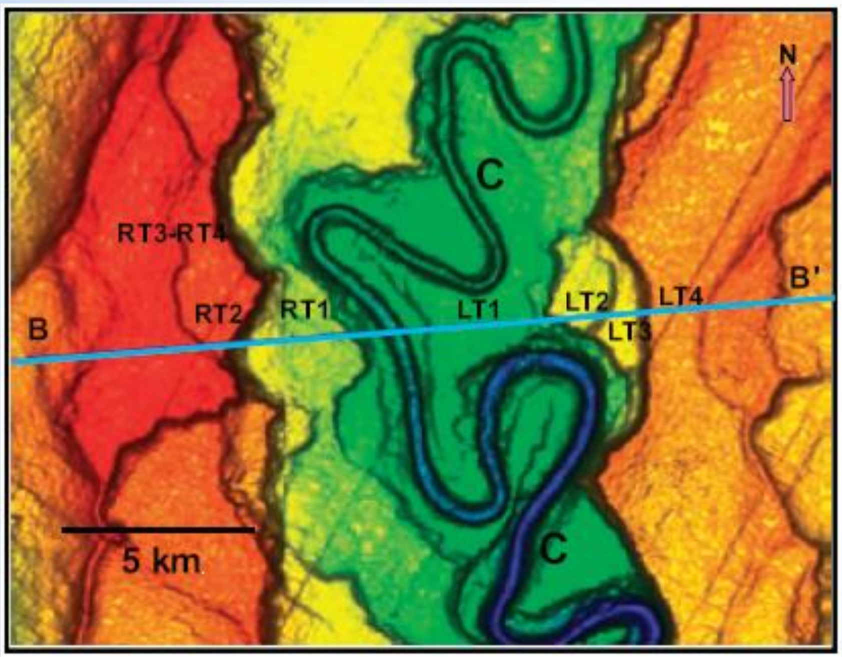


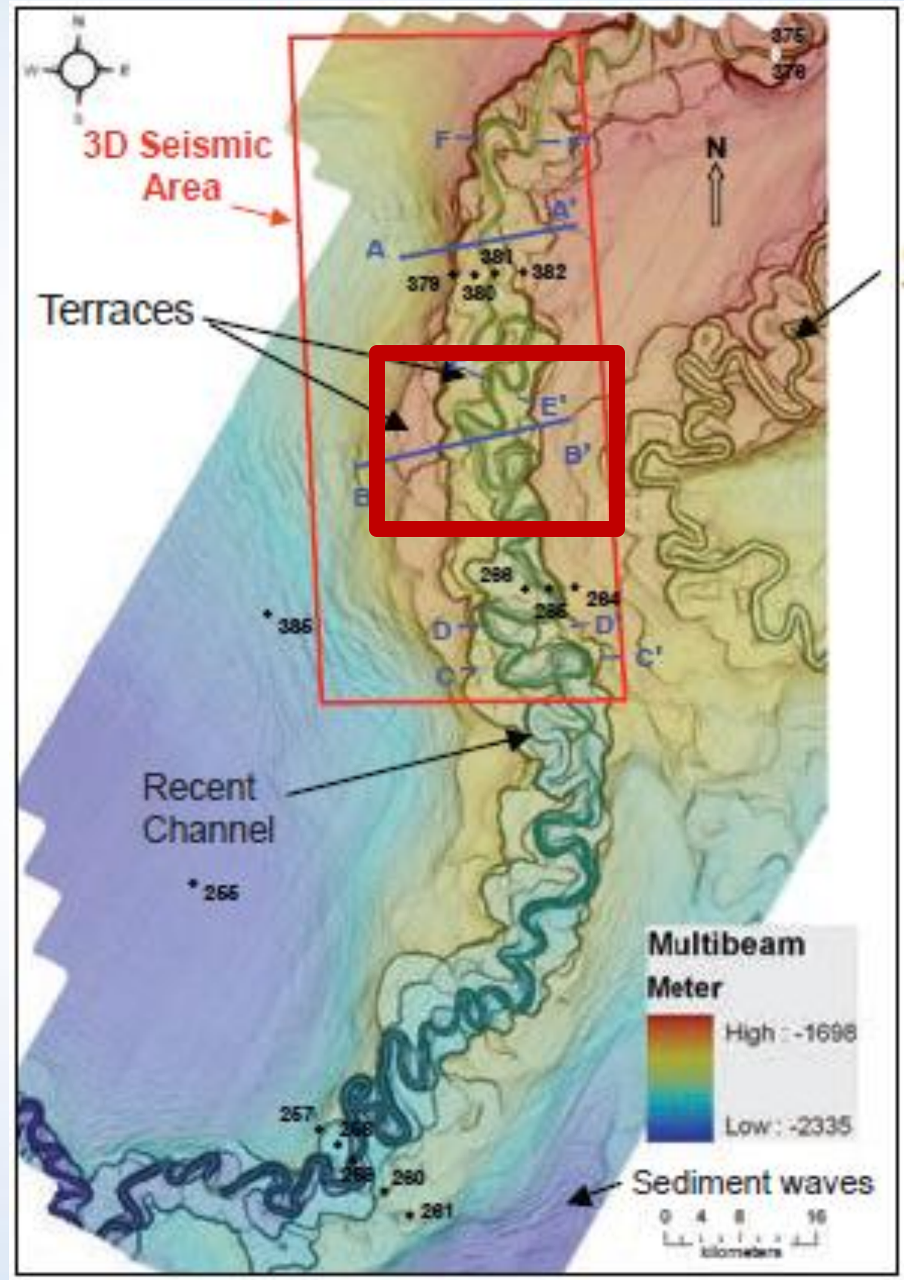


Proximal Bengal Fan,
Kolla et al., 2012

We are also assuming:

The underlying, high-density layer may build its own inner levees around the sinuous channel elements.

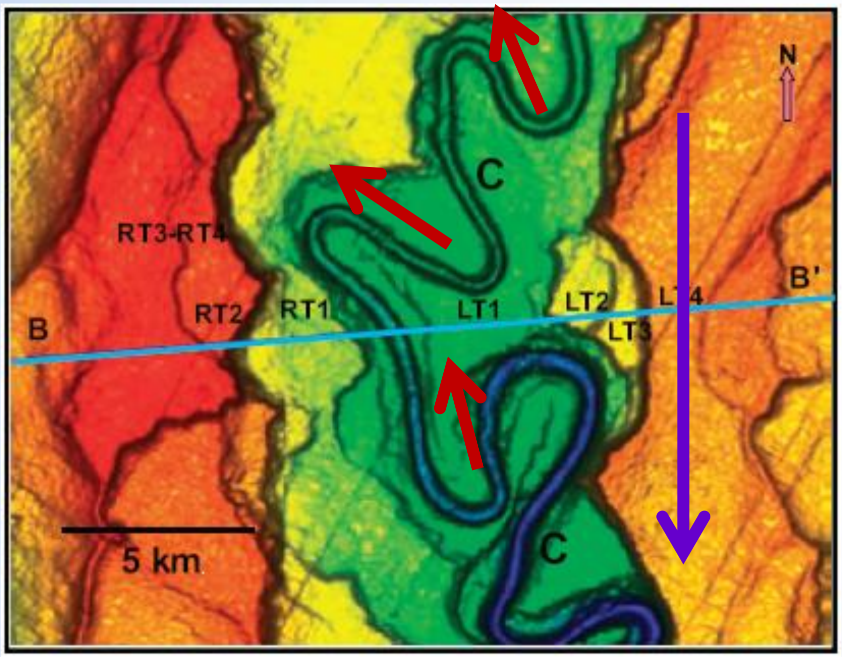


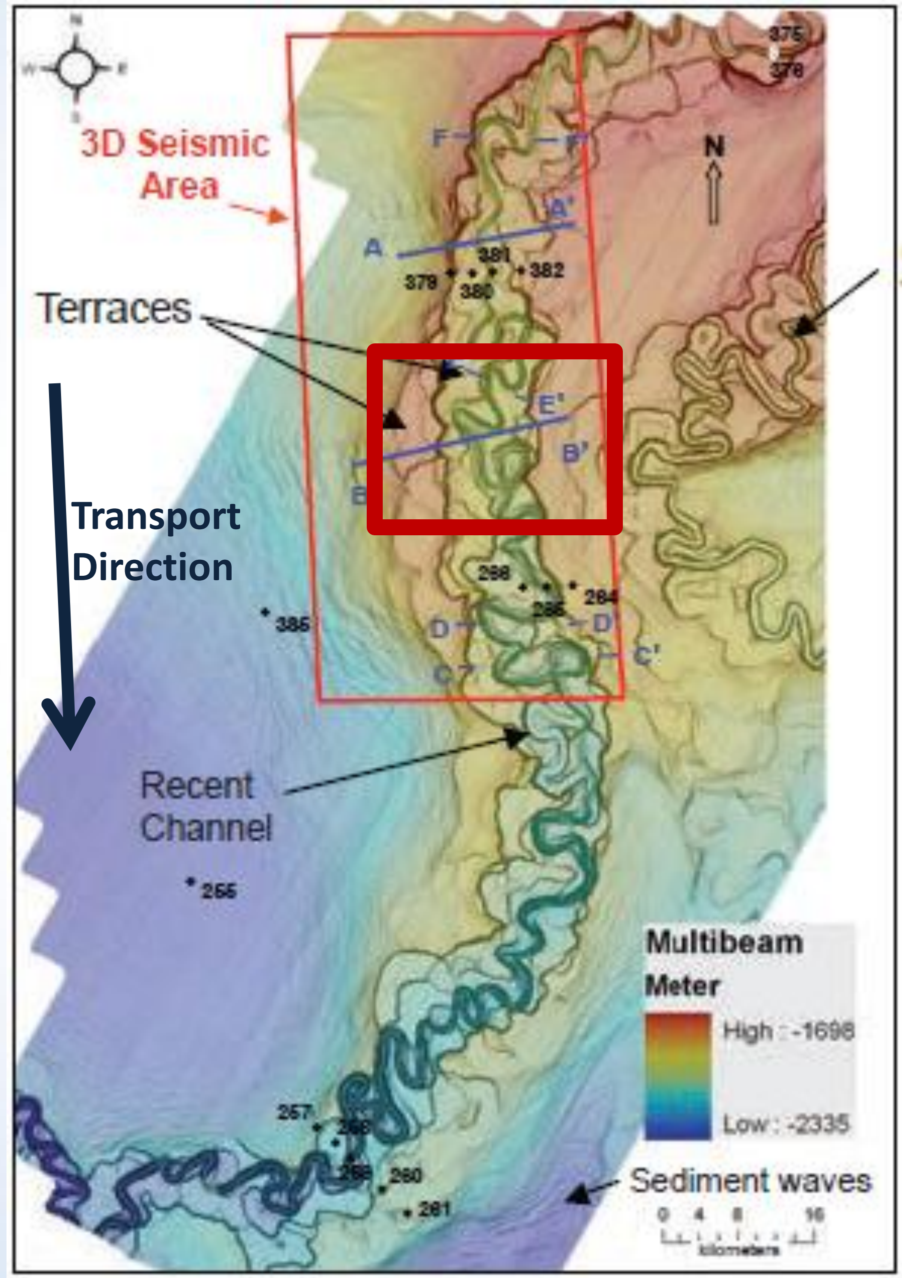


Proximal Bengal Fan, Kolla et al., 2012

We are also assuming:

The high-density layer can even flow in the opposite direction to the dilute layer for kilometers at a time.





Proximal Bengal Fan,
Kolla et al., 2012

Single Flow Model Requires:

A single flow has two layers that can have

- ✓ different concentrations,
- ✓ markedly different volumes,
- ✓ limited vertical contact
- ✓ separate pathways with different sinuosities
- ✓ separate pathways with different patterns of erosion/deposition
- ✓ separate pathways that may be in opposite directions

Hypothesis

It is reasonable to consider that a large, thick, stratified gravity flow can decouple to become two distinct flows, one high density and one low density. Despite confinement by the same large valley, the two flows separate, travel at different velocities, and cause distinctly different depositional/erosional architectures.

However……..

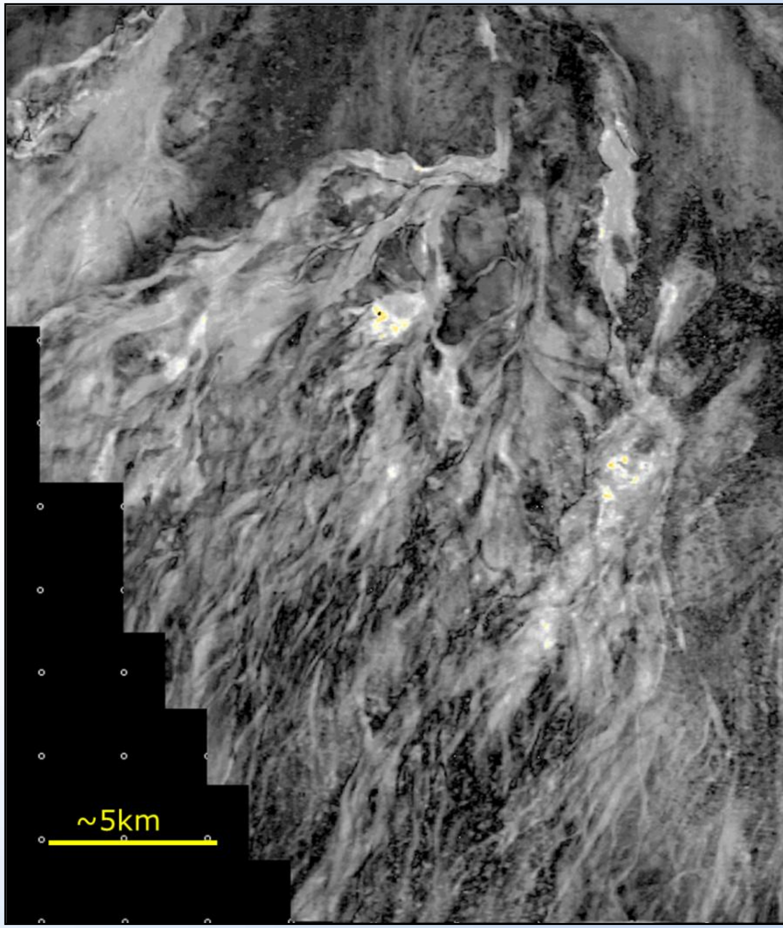
There is no known mechanism for sustaining transport of sediment in such a high-density flow. The flow should collapse.

Problem 2:
A Turbidite Fan
Without Distributary Channels

Importance of
Dispersed Line Source?
Littoral Drift?

Common Models of Submarine Fans (or Lobes)

Share the following characteristics:

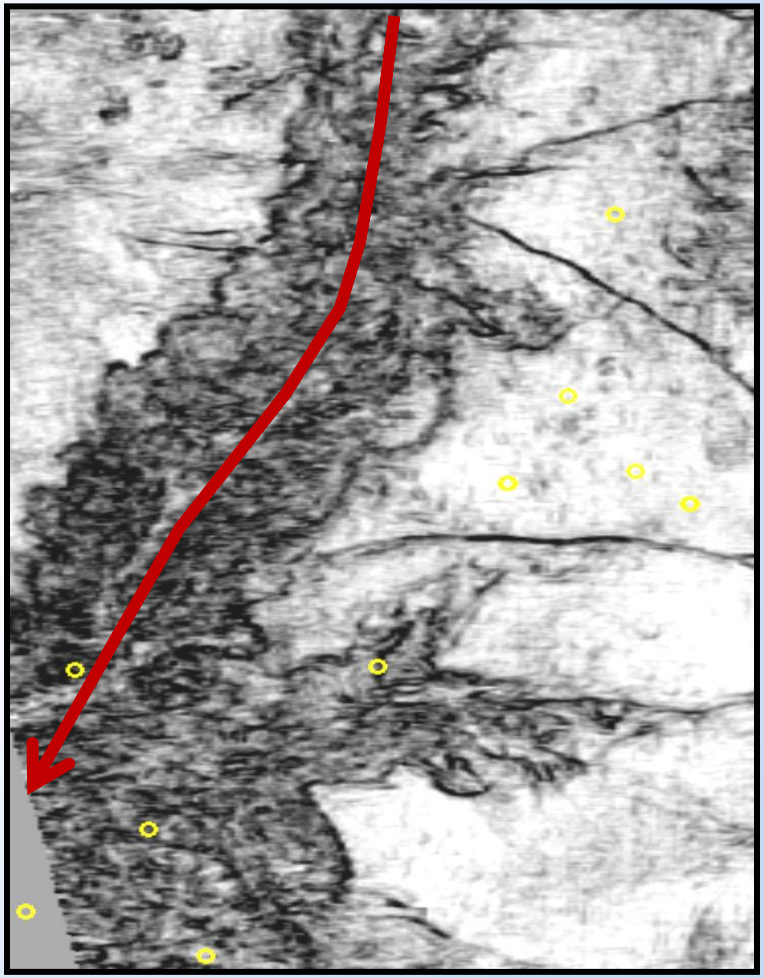


Seismic images courtesy of Chevron

Common Models of Submarine Fans (or Lobes)

Share the following characteristics:

(1)Sediments are funneled into deep water via a submarine canyon

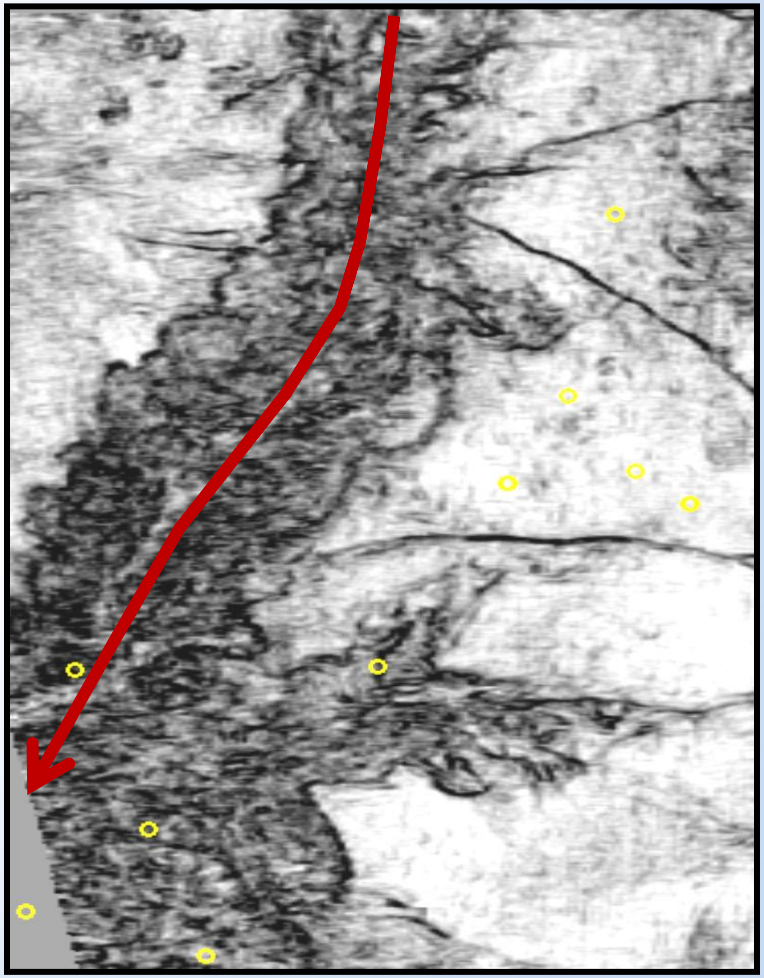


Seismic images courtesy of Chevron

Common Models of Submarine Fans (or Lobes)

Share the following characteristics:

(1) Sediments are funneled into deep water via a submarine canyon
(2) Sediments are delivered to the canyon via a fluvial or deltaic system



Seismic images courtesy of Chevron

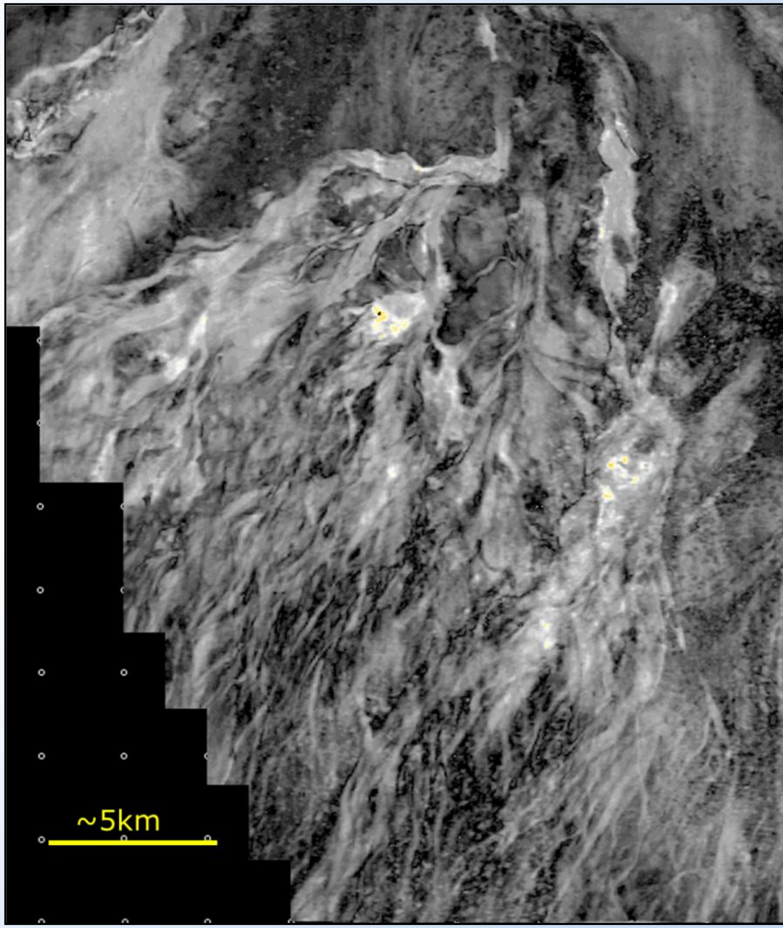
Common Models of Submarine Fans (or Lobes)

Share the following characteristics:

(1) Sediments are funneled into deep water via a submarine canyon

(2) Sediments are delivered to the canyon via a fluvial or deltaic system

(3) The delivered sediments are heterolithic, consisting of clay-rich mud to coarse sand or gravel

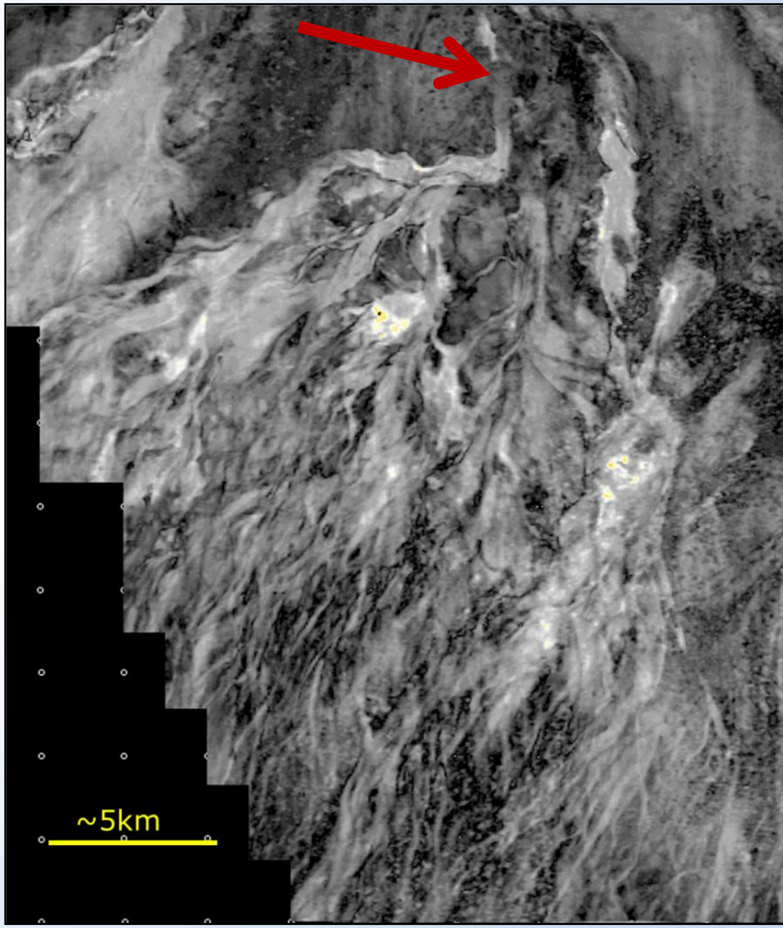


Seismic images courtesy of Chevron

Common Models of Submarine Fans (or Lobes)

Share the following characteristics:

(1) Sediments are funneled into deep water via a submarine canyon
(2) Sediments are delivered to the canyon via a fluvial or deltaic system
(3) The delivered sediments are heterolithic, consisting of clay-rich mud to coarse sand or gravel
(4) Sediments are transported to the depositional fan via a single channel complex



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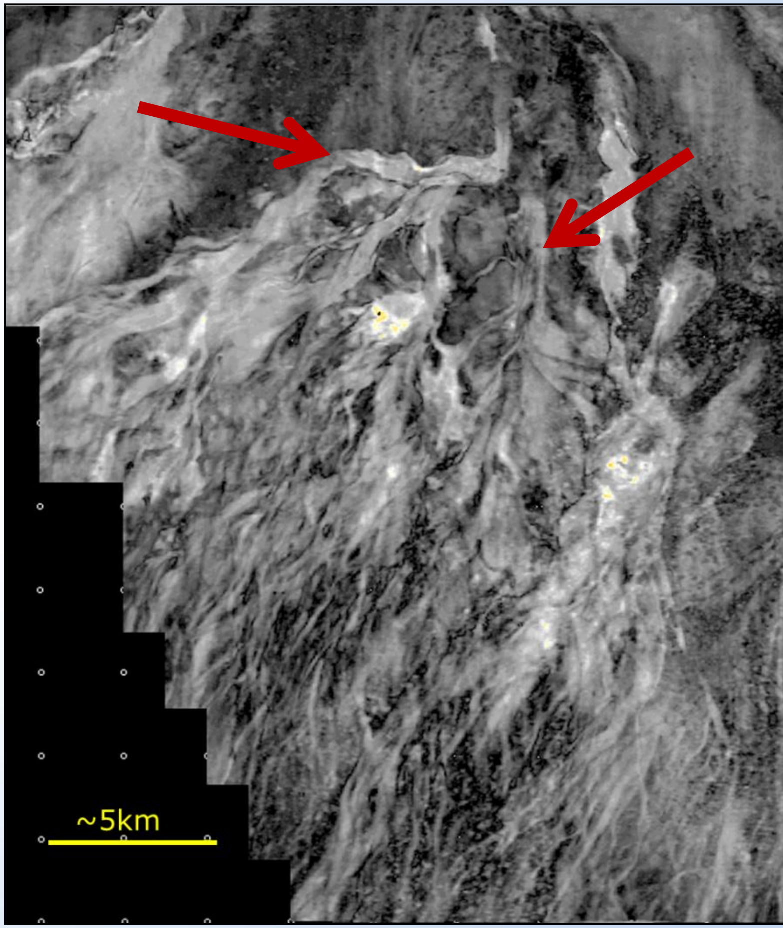
(5) Sediments are dispersed across the fan via distributary channels



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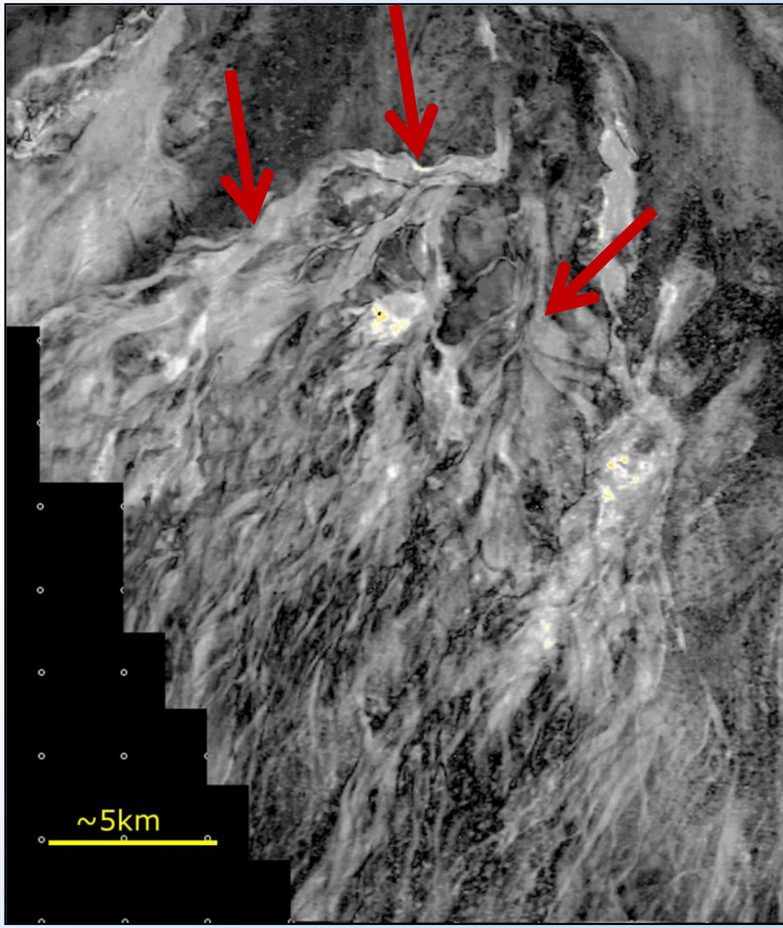
(5) Sediments are dispersed across the fan via distributary channels
(6) The fan grows as a result of avulsions or bifurcations at diverse positions along the distributary channel pathways



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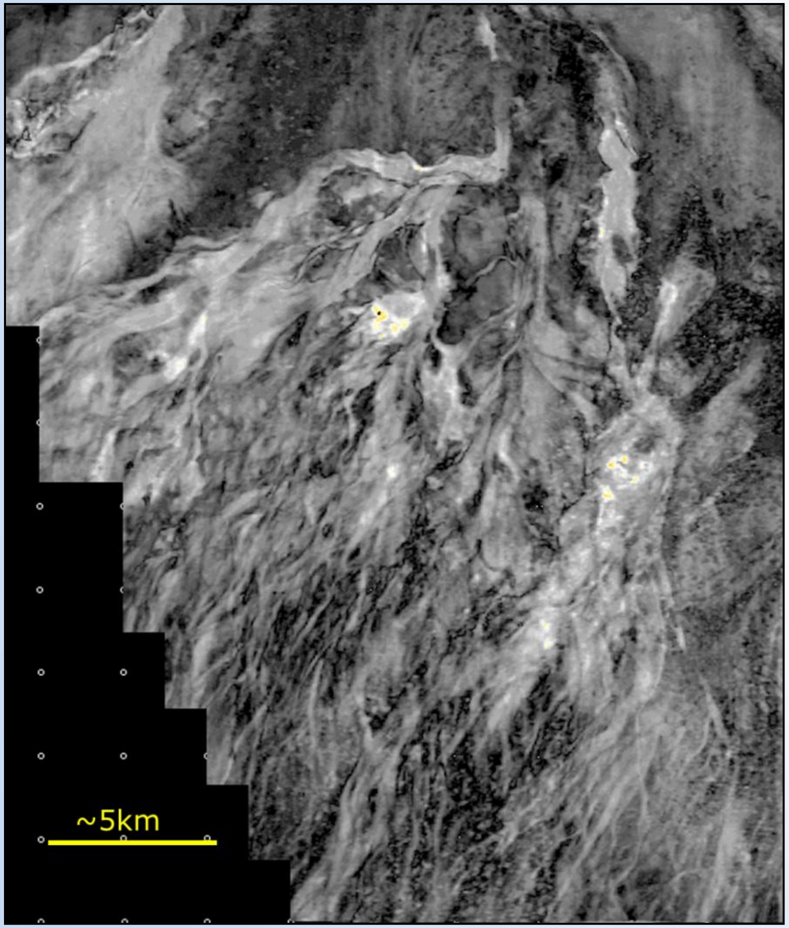
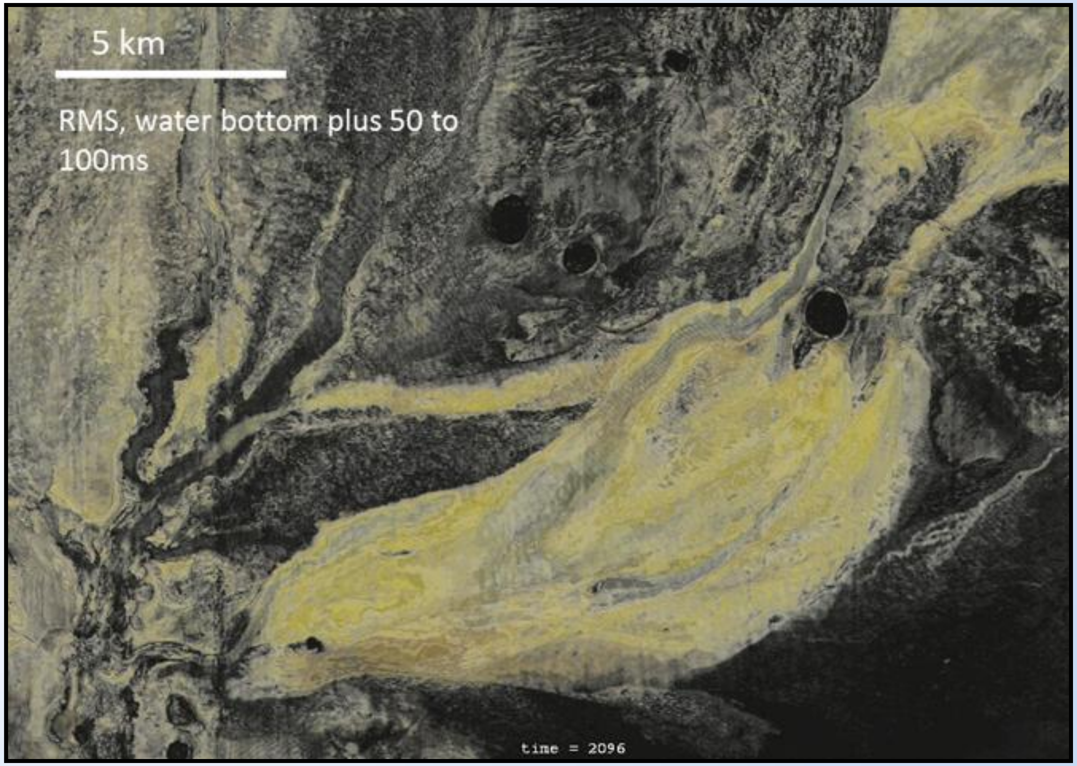
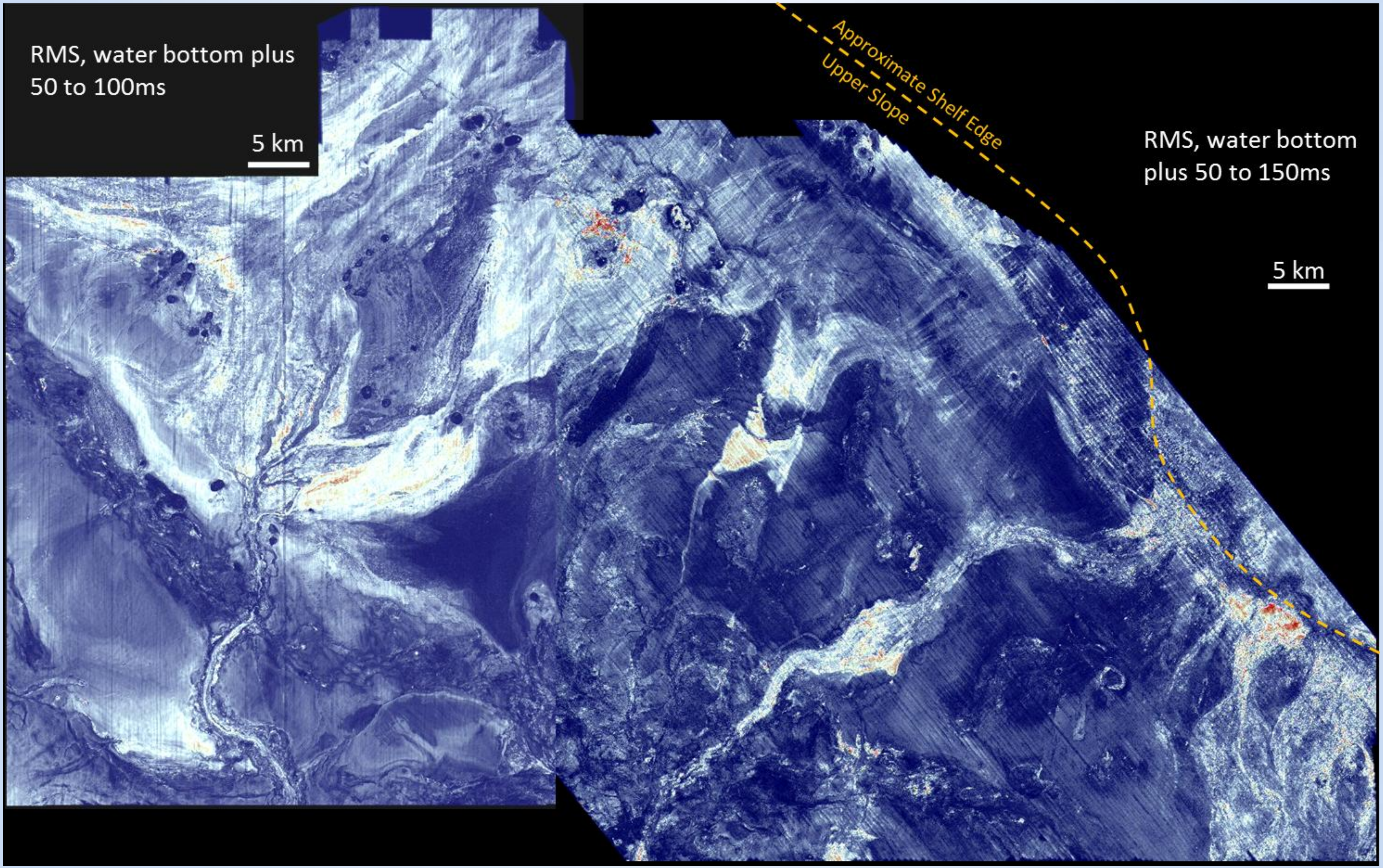
Some Submarine Fans Don't Fit That Description





Seismic images courtesy of Chevron

Upper Slope of the Niger Delta



Seismic images courtesy of Chevron

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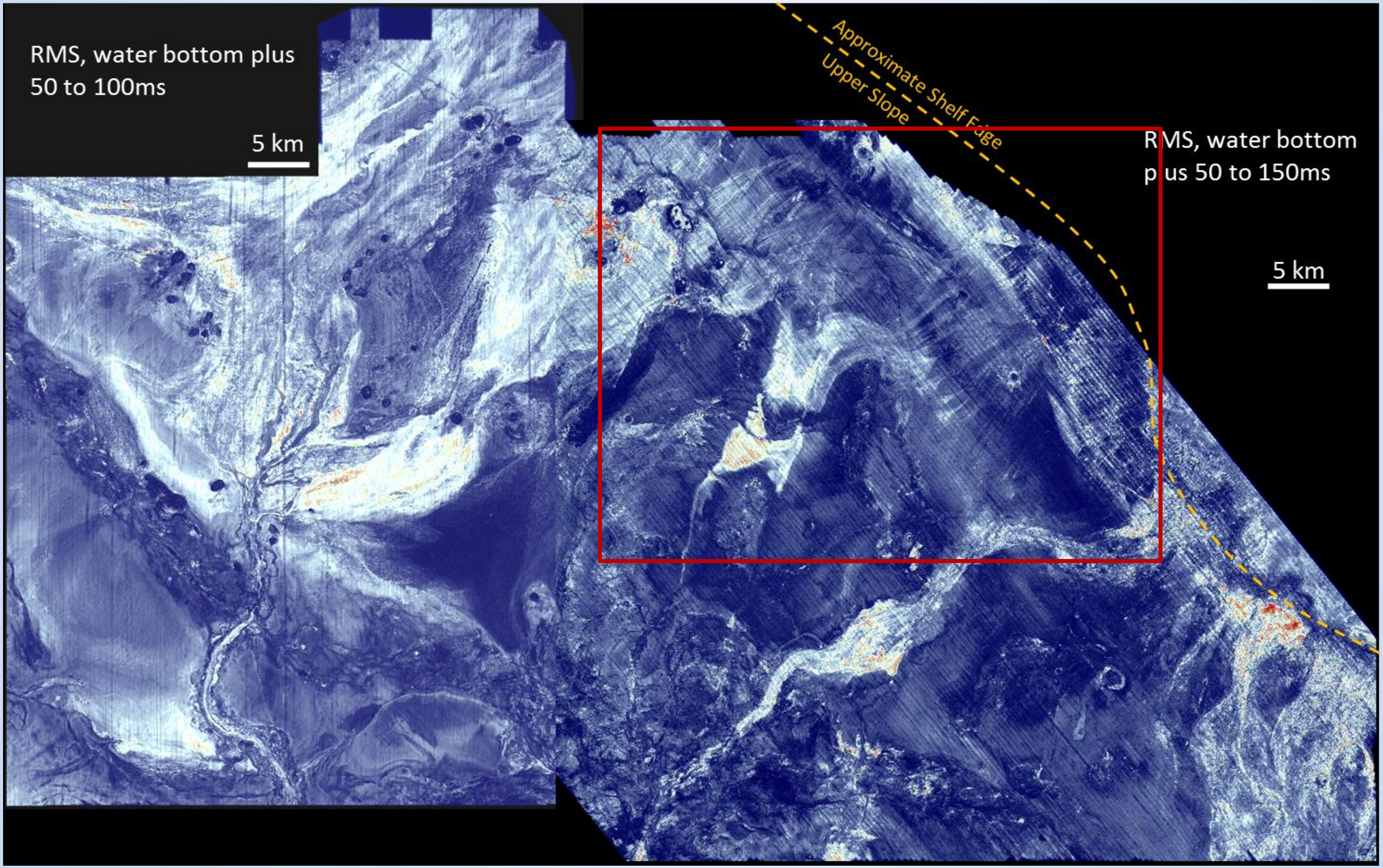


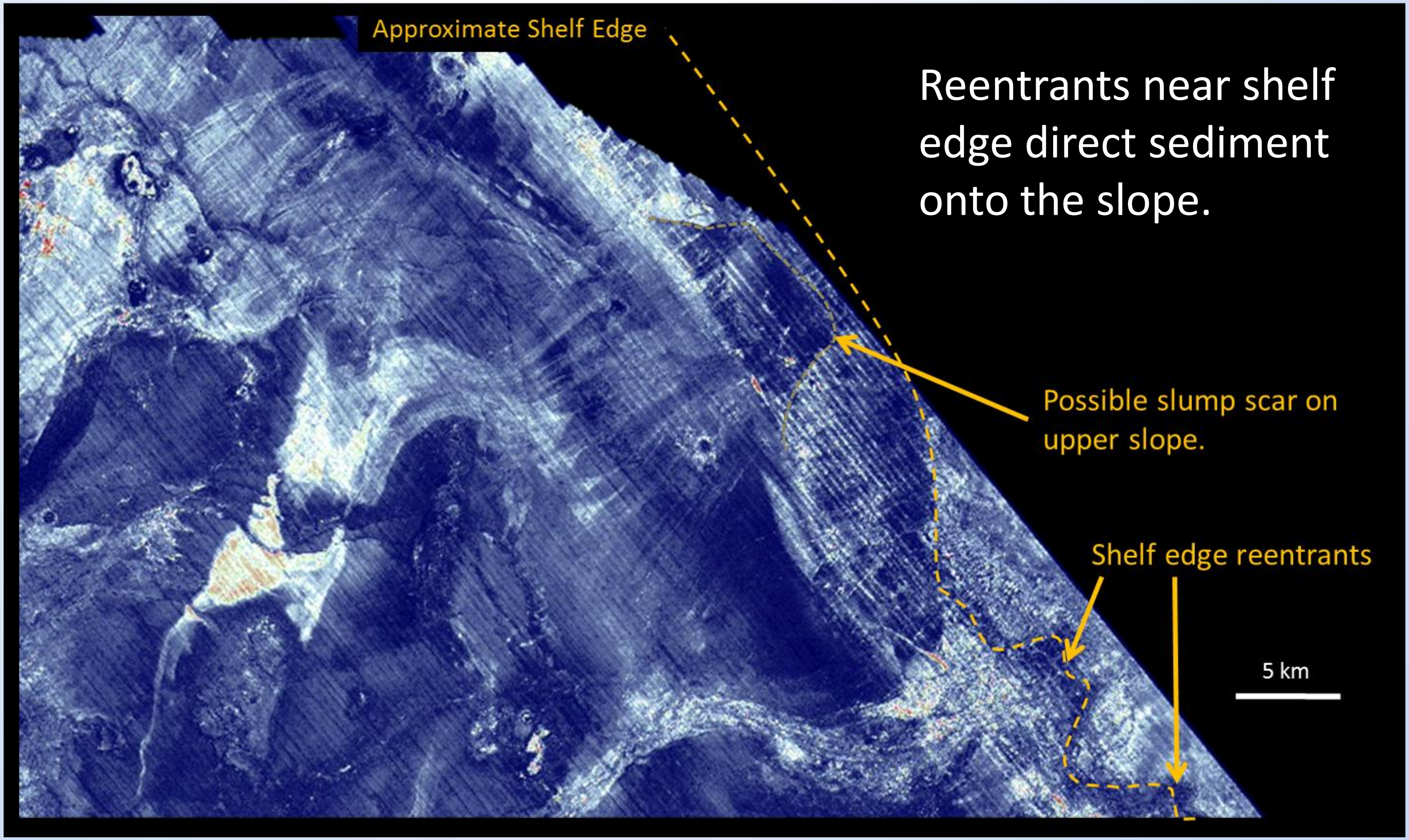
Seismic images courtesy of Chevron

Anomalous Submarine Fans

Have the following characteristics:

(1) Constructed of sediments from a line source at the shelf edge without evidence of a submarine canyon

Seismic images courtesy of Chevron



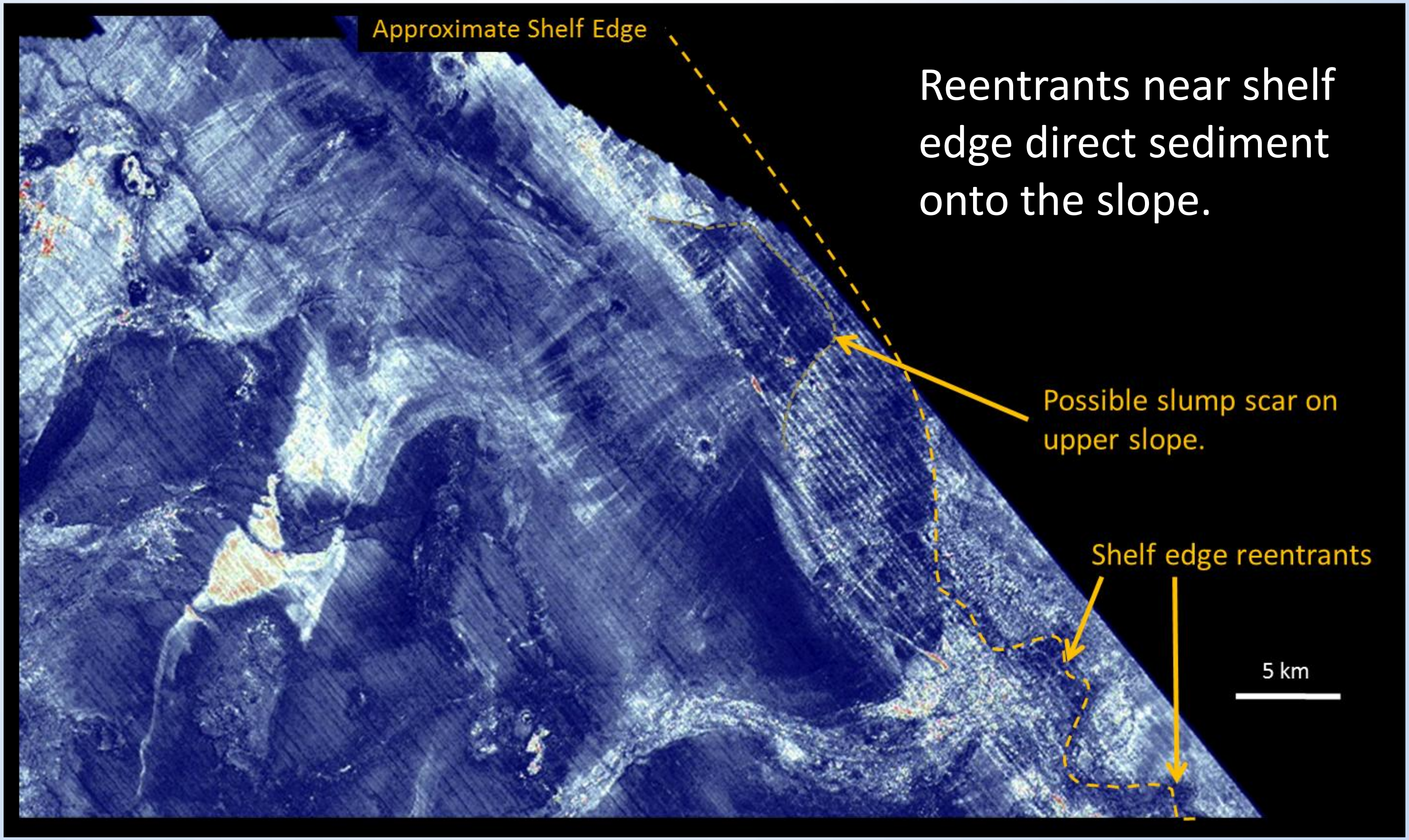
Anomalous Submarine Fans

Have the following characteristics:

(1) **Constructed of sediments from a line source at the shelf edge without evidence of a submarine canyon**

(2) **The line source is interpreted to reflect transport by littoral drift**

Seismic images courtesy of Chevron



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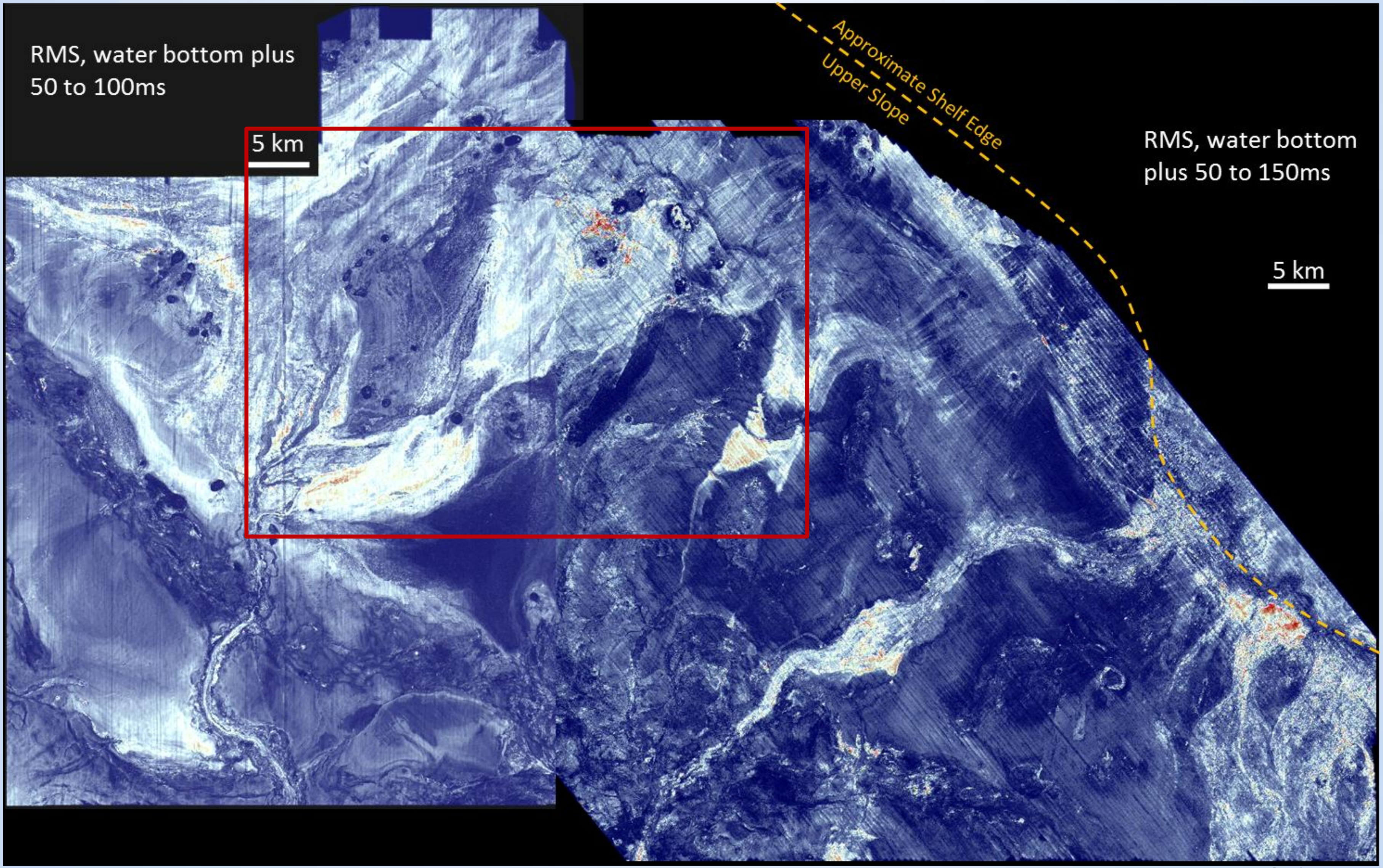
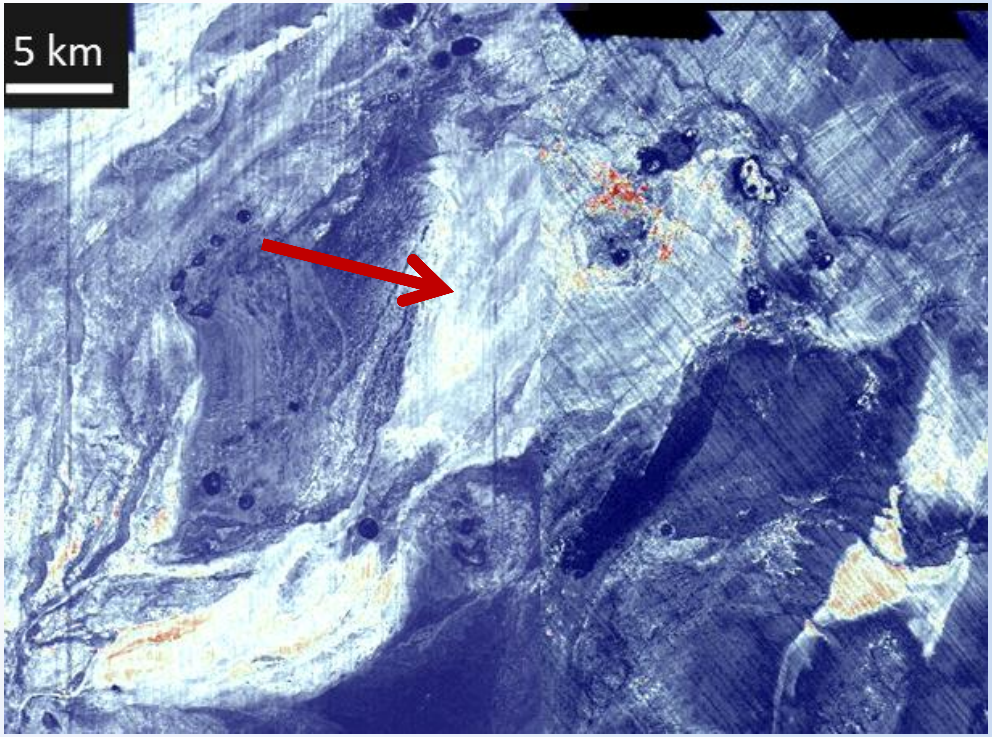


Seismic images courtesy of Chevron

Anomalous Submarine Fans

Have the following characteristics:

(1) Constructed of sediments from a line source at the shelf edge without evidence of a submarine canyon
(2) The line source is interpreted to reflect transport by littoral drift
(3) Sediments are transported via multiple channel complexes



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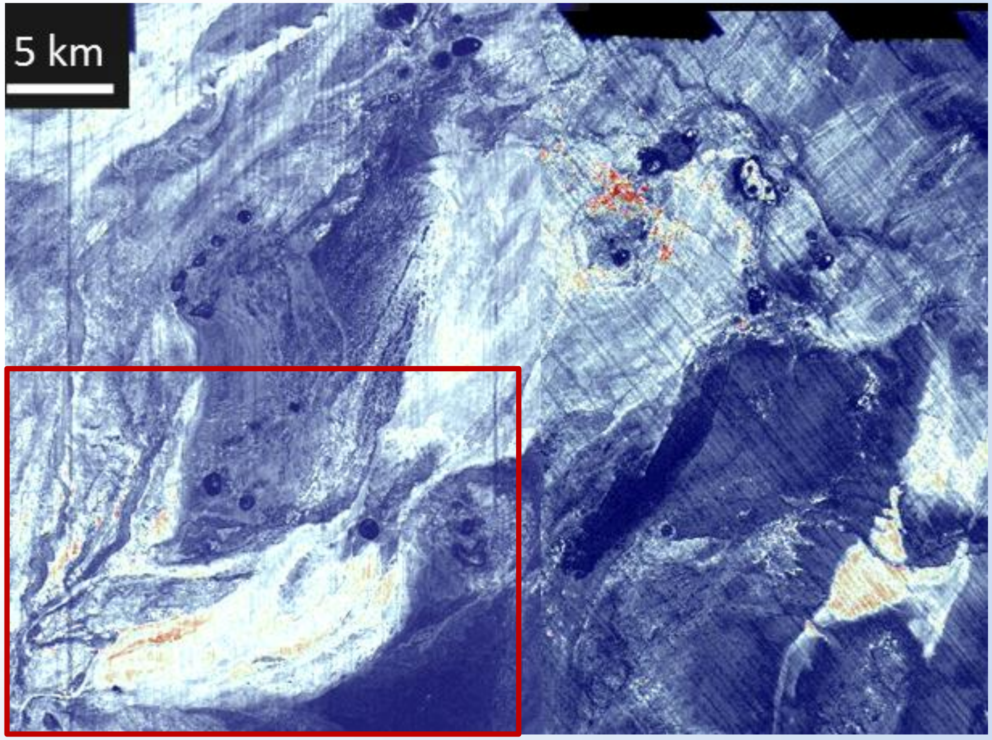

Seismic images courtesy of Chevron

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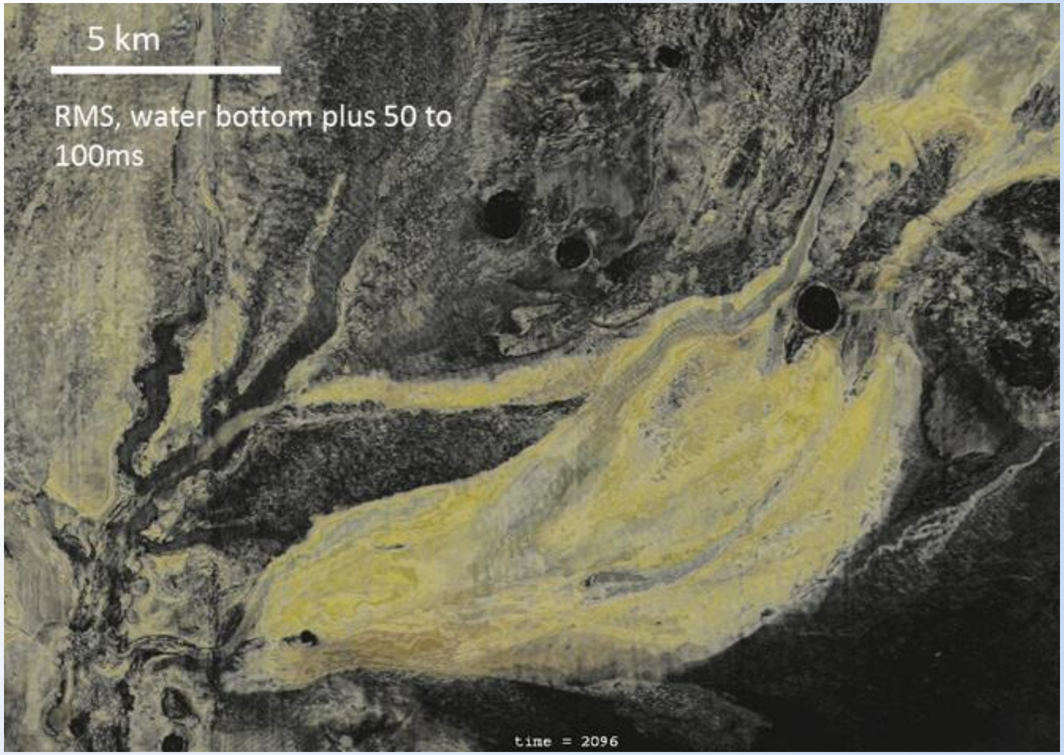
(3) Sediments are transported via multiple channel complexes

(4) No distributary channel system is visible within the fan



Seismic images courtesy of Chevron

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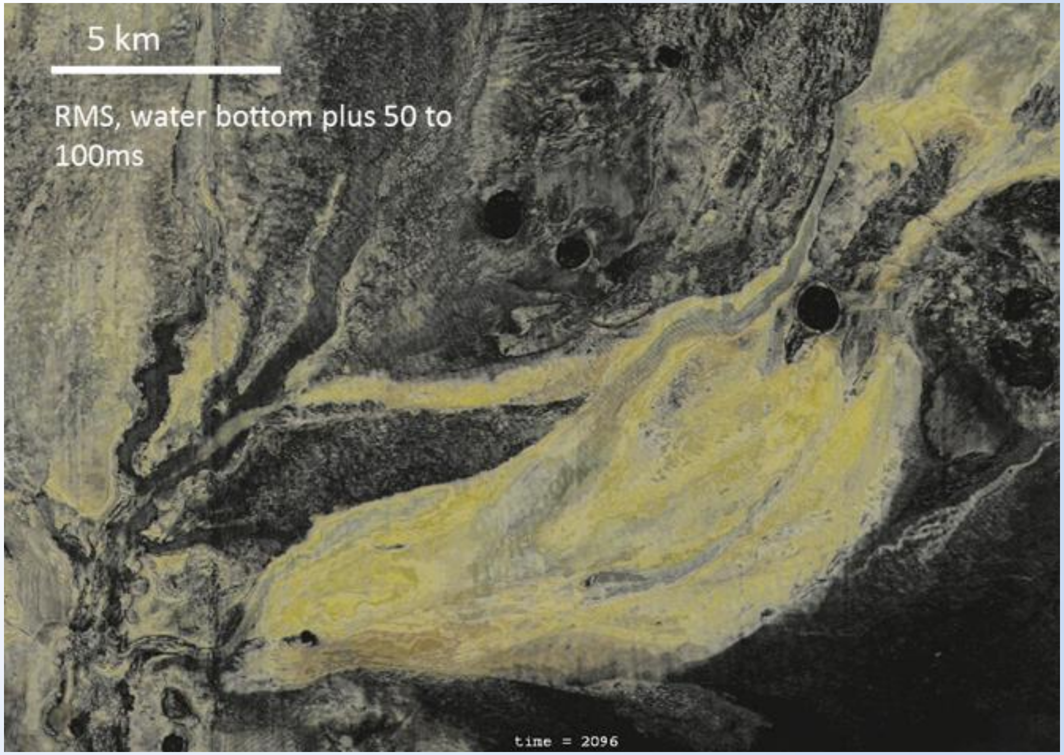
(5) Avulsions are recognizable only at the head of the fan, and channel forms are poorly developed within the fan



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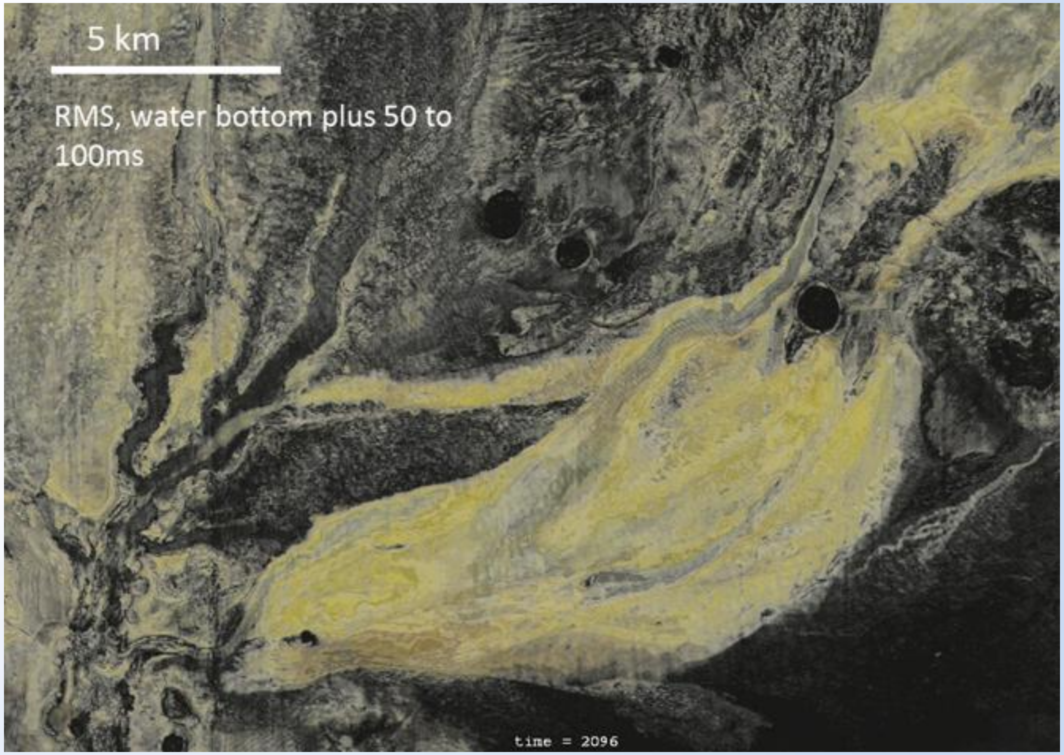
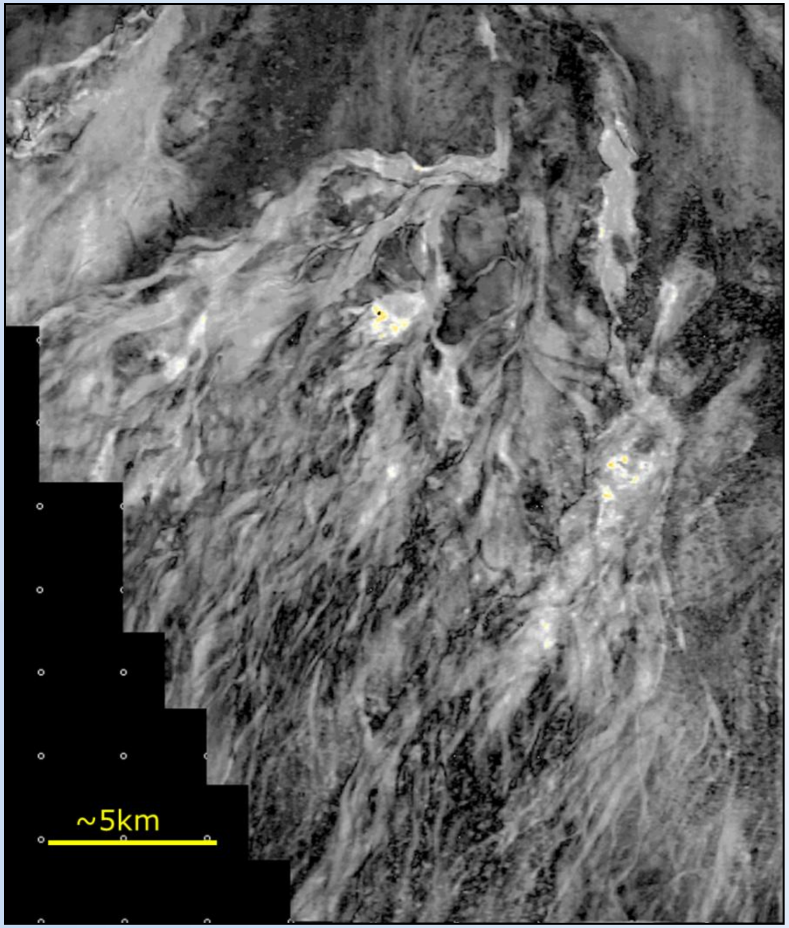
(5) Avulsions are recognizable only at the head of the fan, and channel forms are poorly developed within the fan
(6) Lack of levees suggest extremely sand-rich sediments with minimal accompanying mud

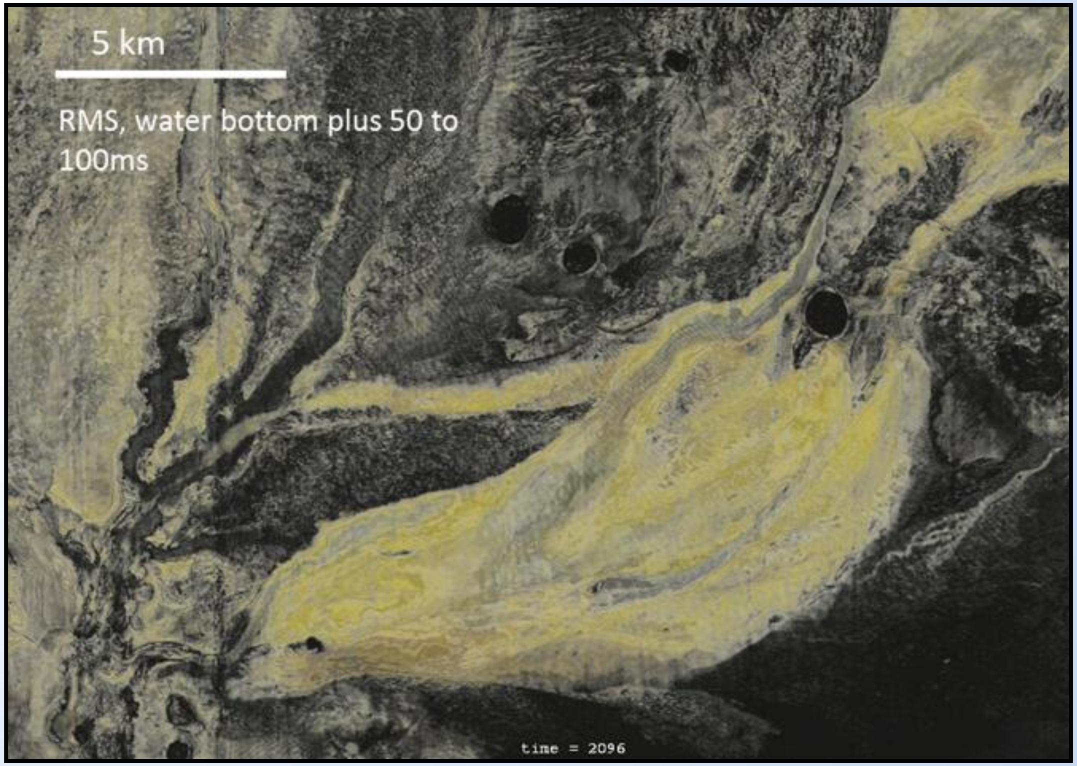


Seismic images courtesy of Chevron

Conclusion:

Multiple Fan Models Yield Very Diverse Predictions of Reservoir Architecture





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Thank You Chevron!

Michael Pyrcz, Julian Clark, Morgan Sullivan, Andrea Fildani, Marjorie Levy, Brian Romans, Jake Covault, Katie Maier

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Stanford Project On Deepwater Depositional Systems