A Big Fan of Signals? Exploring Autogenic and Allogenic Processes in Lobyte3D, a Numerical Stratigraphic Forward Model of Submarine Fan Development*

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Abstract

Distinguishing an allogenic signal from trends and patterns produced by autogenic processes is a critical element in interpreting, understanding and predicting strata. Lobyte3D is a new reduced-complexity model of dispersive flow over an evolving topography on fan systems that produces surprisingly complex strata despite a simple formulation. Two submarine fan model scenarios are run, one with constant sediment input, and one with a sinusoidal variation in sediment input. Both model scenarios show that flows cluster to produce lobes which migrate and can rapidly switch location. Runs tests and spectral analysis show strata can be ordered, even in the absence of any allogenic signal, with cycles and trends in bed thickness, but no single characteristic frequency. In the oscillating supply scenario, an allogenic signal is present in places, particularly in the axial mid fan, but may be difficult to distinguish from the autogenic signal without knowing a priori how the allogenic signal is likely to be preserved in complex and incomplete strata. Analysis of mid fan vertical sections, where stratigraphic completeness is relatively high and many flows are likely to be recorded, using simple power spectrum analysis and counting of the significant peaks present across a range of frequencies, may allow identification of a “signal bump” that could be evidence of the presence and nature of allocyclic forcing. However, this also requires a volume of stratigraphic data beyond what is typically collected from outcrop studies.

Even a reduced complexity numerical stratigraphic forward model like Lobyte3D produces stratigraphic behavior more complex than many stratigraphic conceptual models and interpretations account for. Almost certainly real depositional systems are even more complex. This deficit in the complexity of our stratigraphic interpretations and analysis methods needs to be addressed, by revision of existing conceptual models, and perhaps by more integration of outcrop and experimental modelling analysis

Selected References

Burgess, Peter, Isabella Masiero, Stephan Toby, and Robert Duller, 2019, A Big Fan of Signals? Exploring Autogenic and Allogenic Processes in Lobyte3D, a Numerical Stratigraphic Forward Model of Submarine Fan Development: Journal Sedimentary Research, v. 89/1, p. 1-12.

Burgess, Peter, 2016, Identifying Ordered Strata: Evidence, Methods, and Meaning: Journal Sedimentary Research, v. 86/3, p. 148-167.

A Big Fan of Signals?

Exploring Autogenic and Allogenic Processes in Lobyte3D, a Numerical Stratigraphic Forward Model of Submarine-Fan Development

SEPM/AAPG May 2019

Peter Burgess, Isabella Masiero,

Stephan Toby, Rob Duller

What's the Problem?

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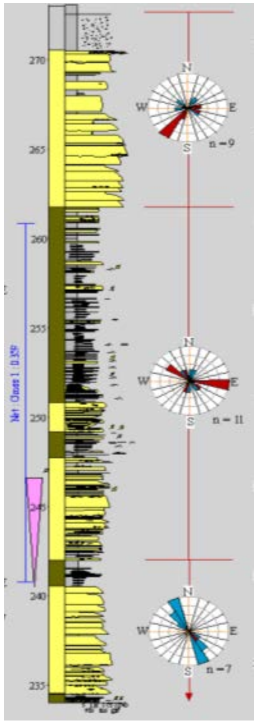
- **Distinguishing allogenic signal from autogenic "noise" is a critical element in interpreting, understanding, and predicting strata.**

- Example – lobes in mid Jurassic turbidite strata, Neuquén Basin, Argentina, typically interpreted as lowstand fan deposits that record a signal of relative sea-level oscillations

- But simple, qualitative interpretation problematic because:
  - Apparent patterns can occur "by chance"
  - Non-uniqueness , similar patterns produced by different processes e.g. autogenic
  - Often more modelling than observation?

- **So how can we reliably identify any order present that represents an external signal in submarine fan strata?**

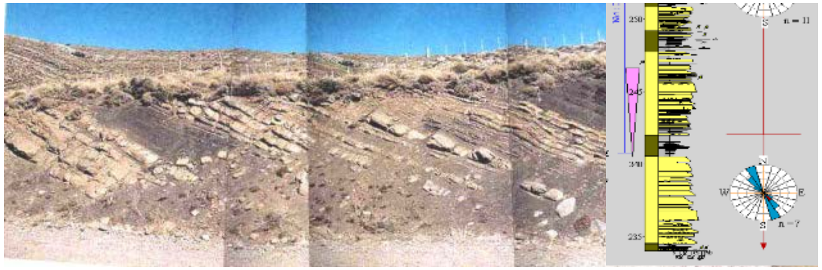


Log by Steve Johnson, from Burgess et al 2000, and Burgess and Flint, 1998

What's the Solution…?

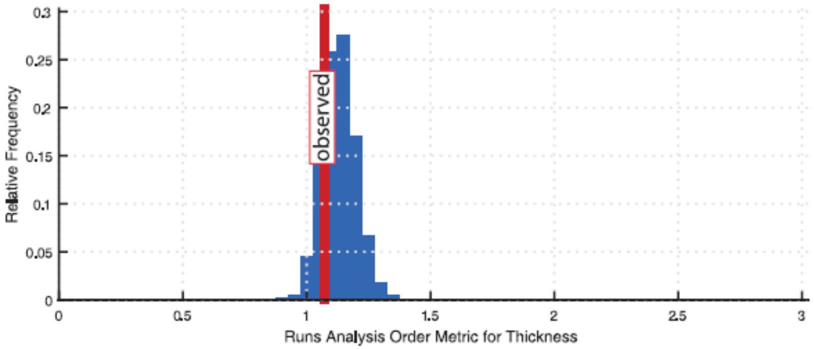
…an integrated, quantitative approach:

- Outcrop description, interpretation and analysis of submarine fan strata



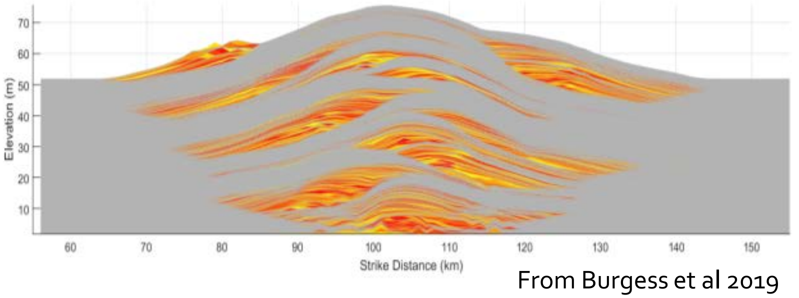
From Burgess et al 2000, and Burgess and Flint, 1998

- Quantitative methods to identify order & patterns of strata unlikely to occur by chance



From Burgess 2016

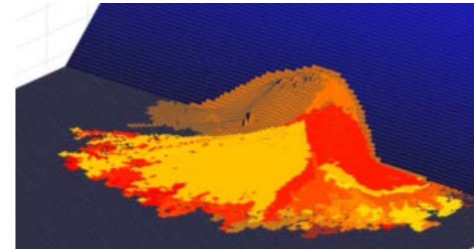
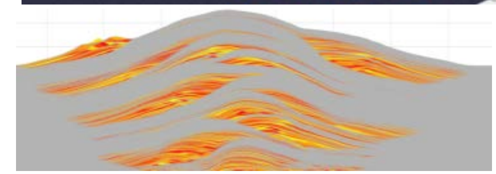
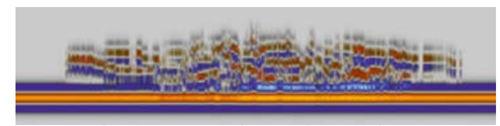
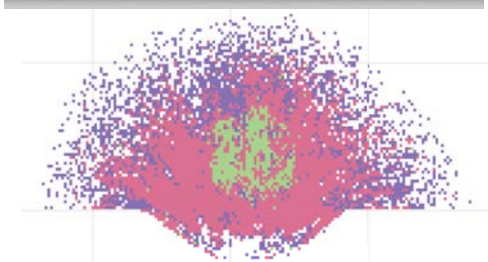
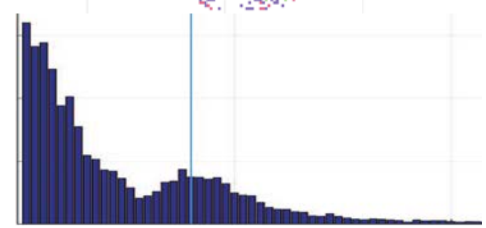
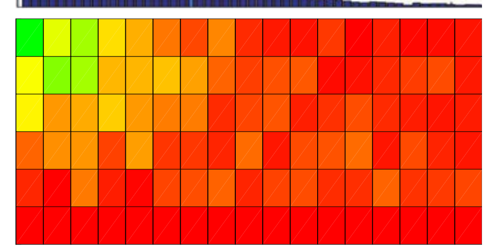
- Experimental analogue and numerical forward modelling to better understand how such order and patterns can form



From Burgess et al 2019

Presentation Outline

- Lobyte3D formulation and parameters
- Comparing two models: constant-supply "autogenic" and oscillating-supply "allogenic"
- Extracting a signal: bed thickness trends
- Extracting a signal: spectral analysis and signal bumps

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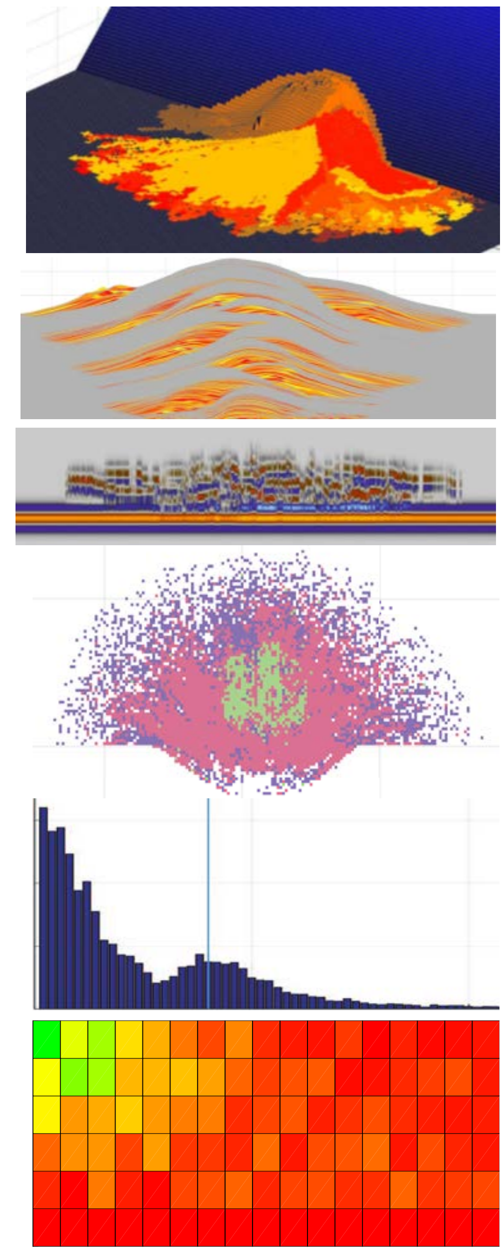
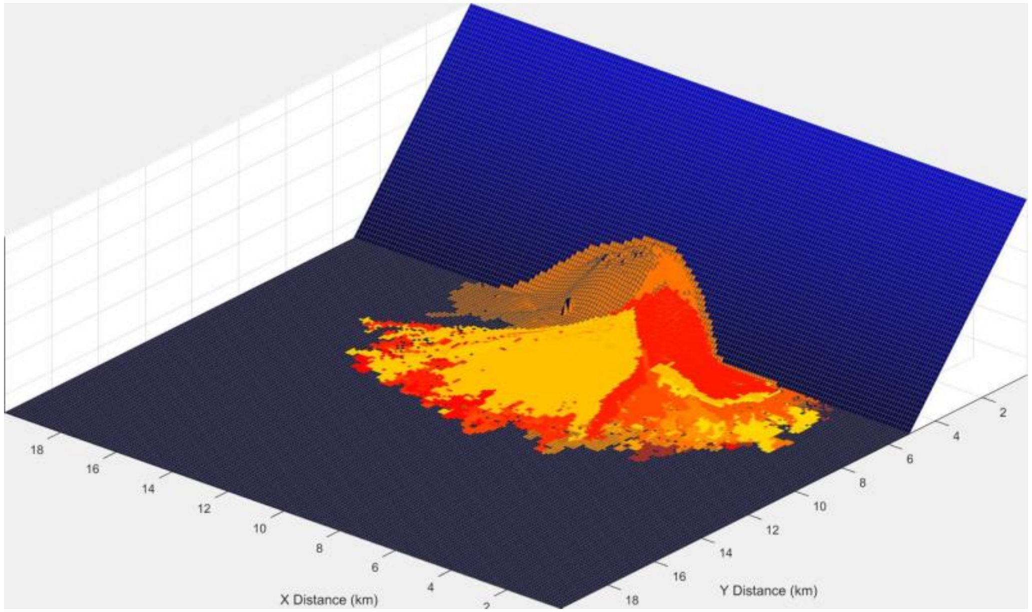


Lobyte3D Formulation

Lobyte3D

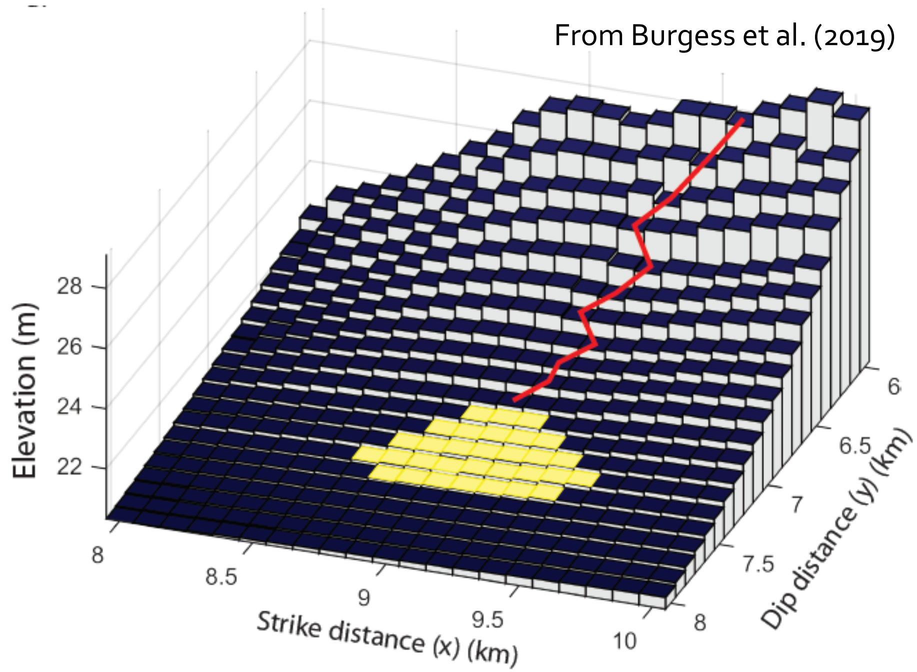
- **Reduced complexity model** written by me and Isabella Masiero, PhD student, University of Liverpool
- Entirely deterministic,simple, but physics-based
- Sediment transport modelled as events that evolve from transport and bypass to dispersive deposition forming lobes
- Can run models over geological time e.g. 1My of deposition
- Can explore constant sediment supply, periodic supply volume variation, or many types of random variation



Lobyte3D Formulation

- Model runs each have multiple flow events
- Flow velocity controls sediment transport and deposition as a function of topographic gradient and the flow thickness
- While flow velocity exceeds a specified threshold, sediment moves downslope in just one model grid cell at any time, following a steepest-descent algorithm: **analogous to channelised flow & bypass**
- When the flow reaches a lower threshold gradient and velocity, flow dispersion and deposition begins: **analogous to lobe deposition**

From Burgess et al. (2019)



Flow velocity

$$U = \sqrt{\frac{8gC_v}{f(1+\alpha)}}\, HS$$

$$U = 5\left({}^{h}/_{d_{50}}\right)^{1/6} (gHS)^{1/2}$$

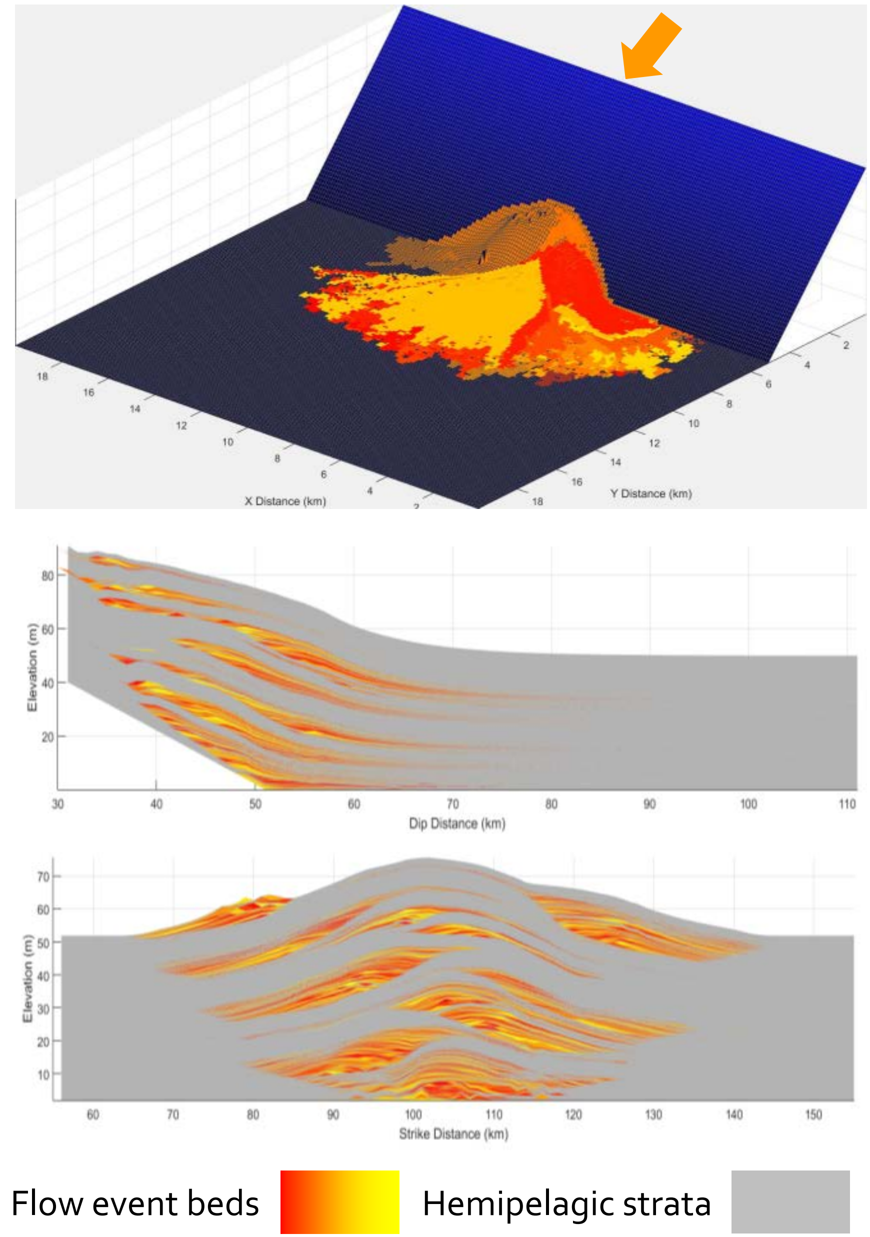
Flow volume dispersion and deposition

$$\Delta V_k = \left[G_k{}^{FRF} \cdot \left(\textstyle\sum_{k=1}^{8} G_k\right)^{-1}\right] \cdot V_{i,j} \qquad where \quad k = 1,2,3,\ldots,8;$$

From Burgess et al. (2019) JSR, v. 89, 1–12

Lobyte3D Parameters

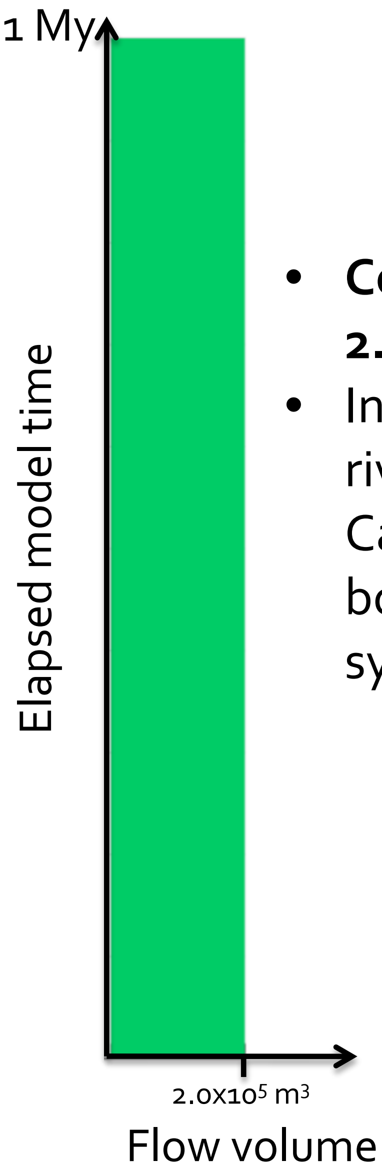
- **2 Lobyte3D model runs** presented and compared here
- 20km by 20km, 200x200 cell grid
- Duration 1My
- 1000 flows
- Each flow event has the same entry point on the slope
- Hemipelagic deposition rate 0.05 m ky^{-1}
- Model output as 3D views, cross-sections, chronostratigraphic diagrams and maps
- Each flow assigned random colour, in the range red to yellow



From Burgess et al. (2019) JSR, v. 89, 1–12

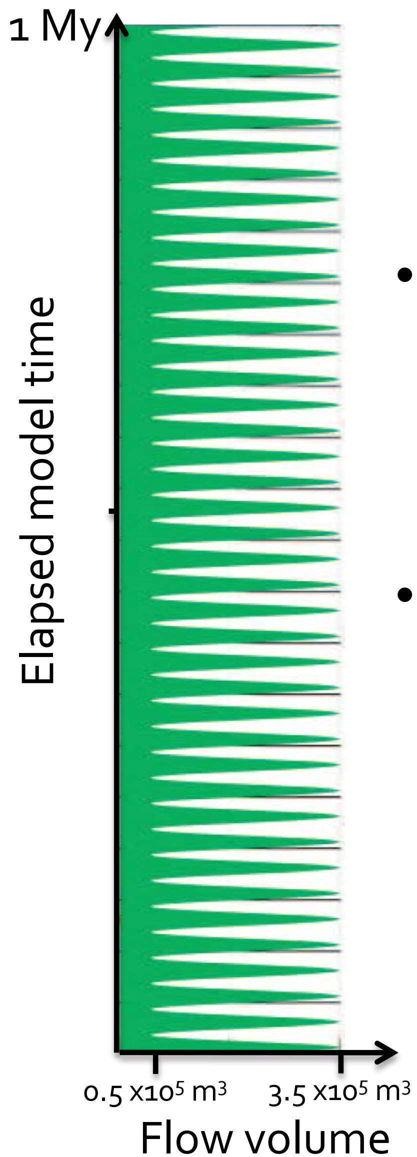
Lobyte3D Parameters

Constant sediment supply model run



- **Constant supply, 2.0 10^5 m^3 per flow**
- Input from a small river, similar to California borderland fan systems

Oscillating sediment supply model run



- **Variable supply, mean volume 2.0 10^5 m^3 per flow but 25ky period oscillations**
- Input from a similar river, but variable sediment discharge

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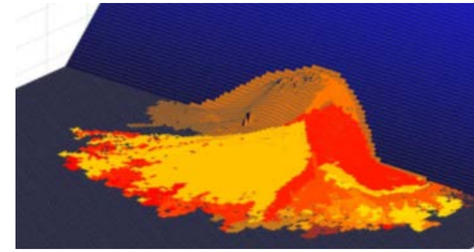

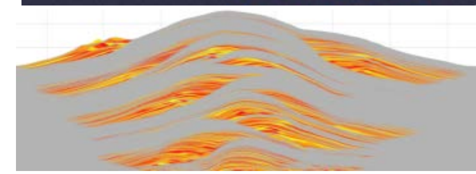

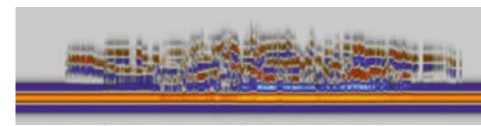

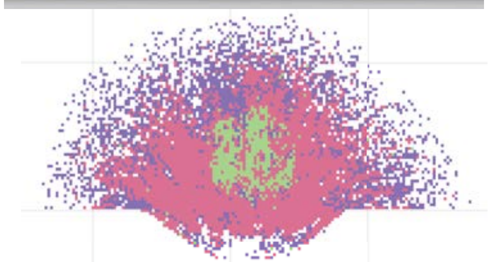

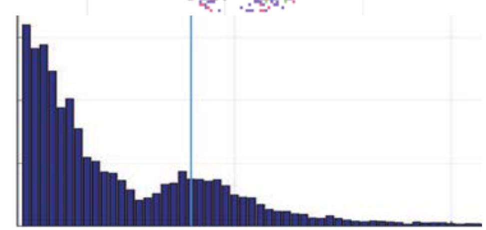

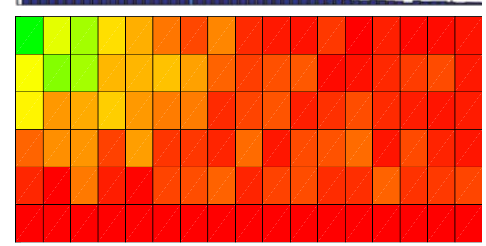

Allogenic versus Autogenic?

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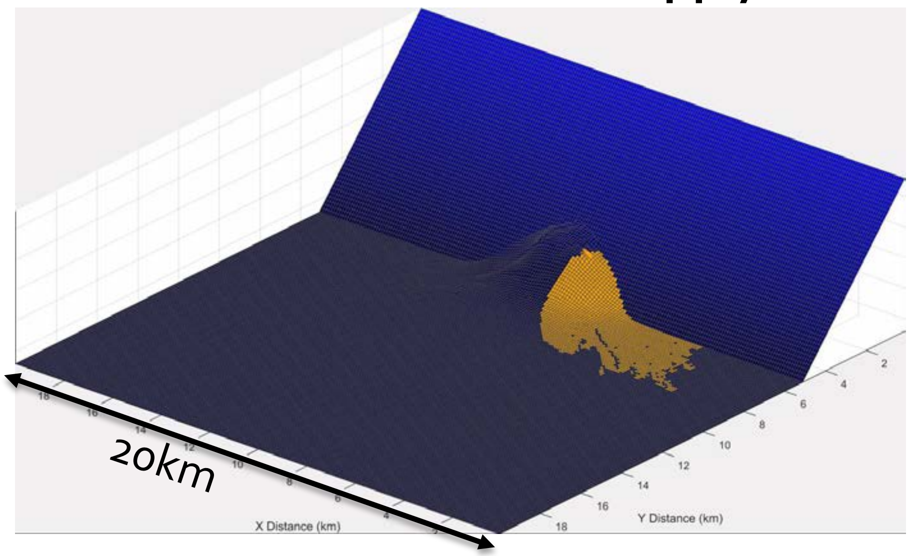
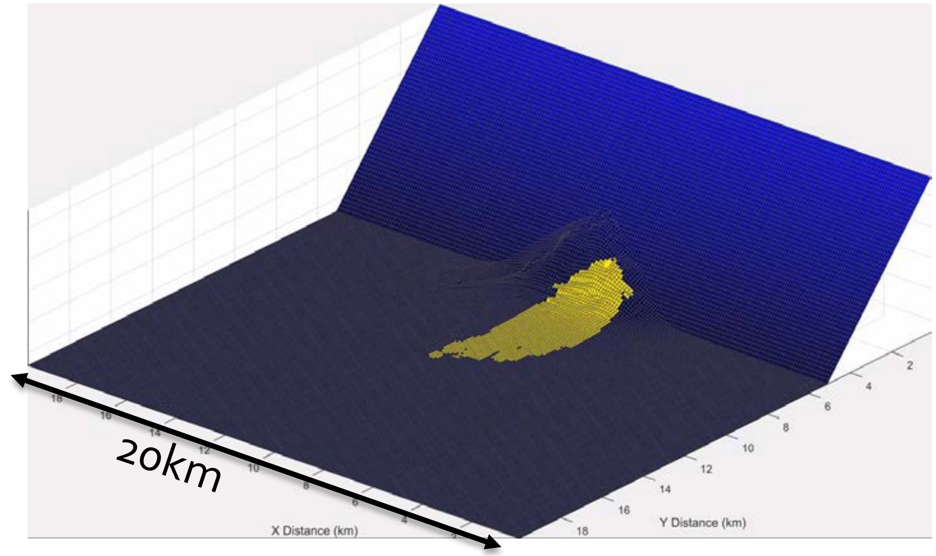
Constant sediment supply



Click to View Movie

Oscillating sediment supply



Click to View Movie

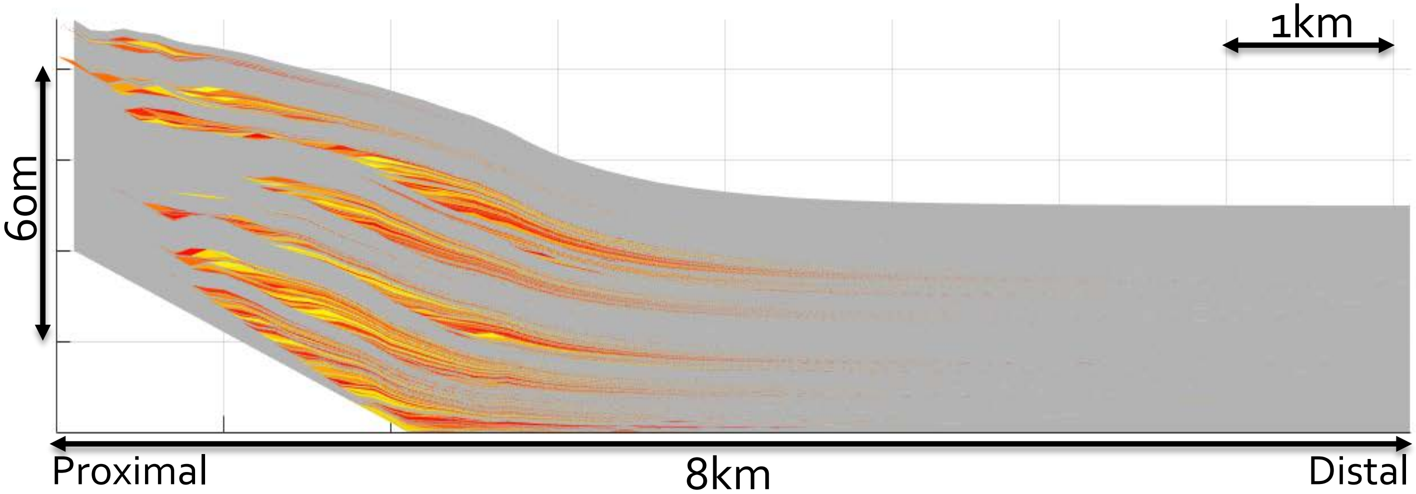
- Animation of section of model evolution, from 600ky to 700ky, 100 flow events shown in each movie

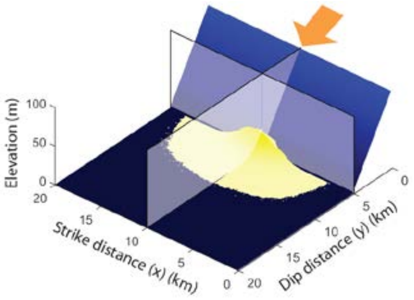
- Gradual migration and sudden large jumps in location of flow deposition due to complex routing of flows over developing depositional topography
- Stacking of flows in this way leads to clustering – lobes?

- Flow evolution in both models is similar overall, but different in detail
- Suggests that the stacking of strata is also likely to be similar?

Allogenic versus Autogenic?

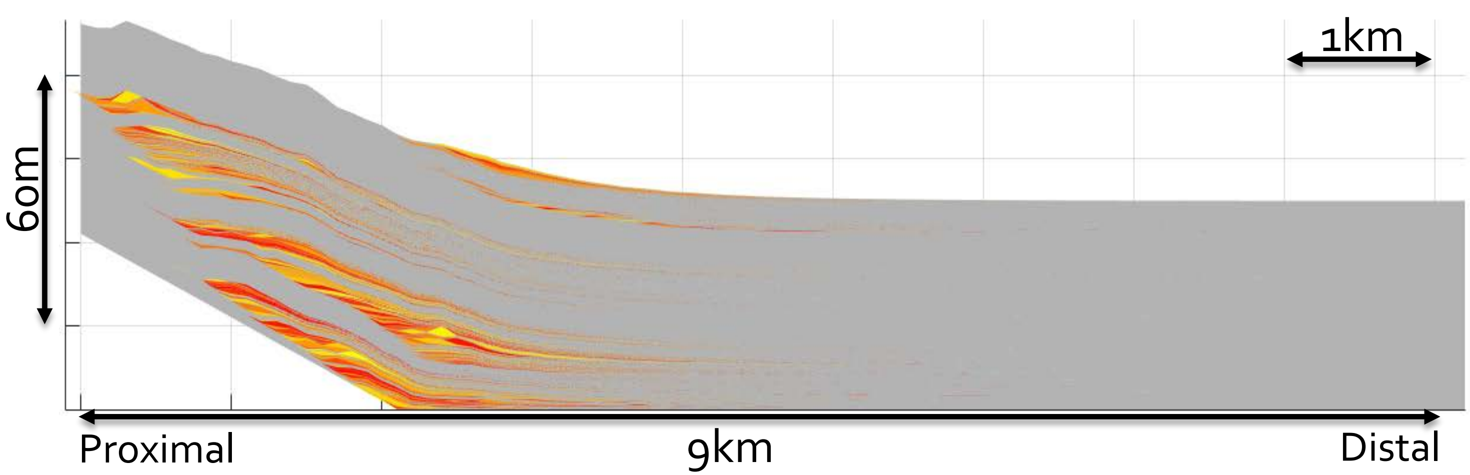
Dip cross section, **constant supply model**





- Strata show distinct clustering in both cases
- **Autogenic lobes**
- Emergent behaviour due to complex flow routing over developing sea-floor topography

Dip cross section, **oscillating supply model**



From Burgess et al. (2019) JSR, v. 89, 1–12

Allogenic versus Autogenic?

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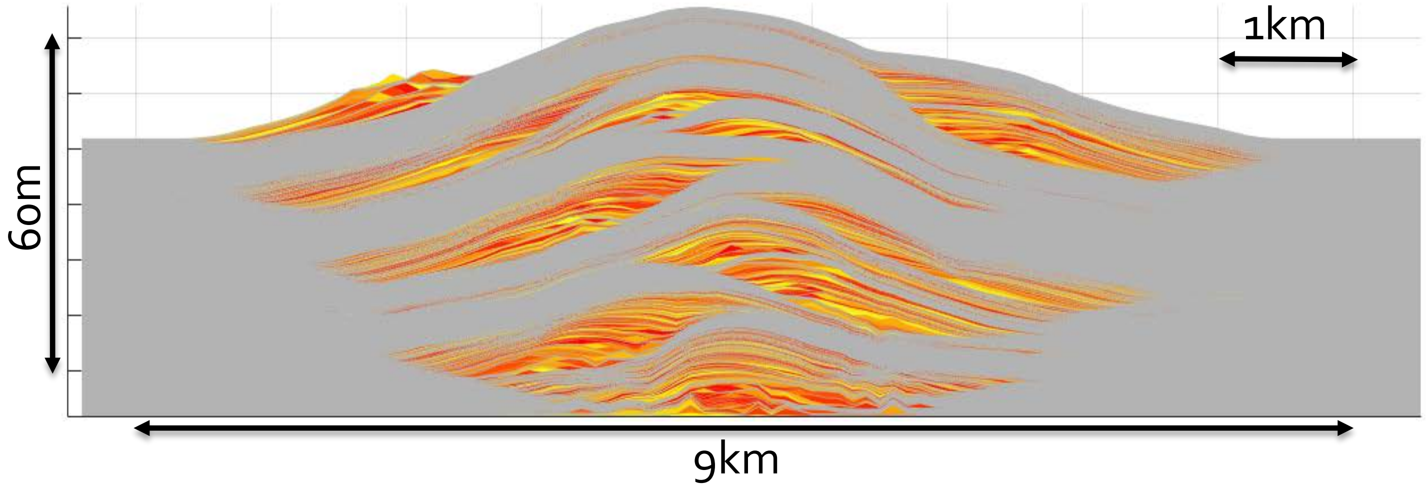
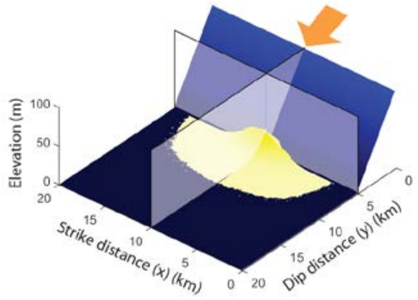
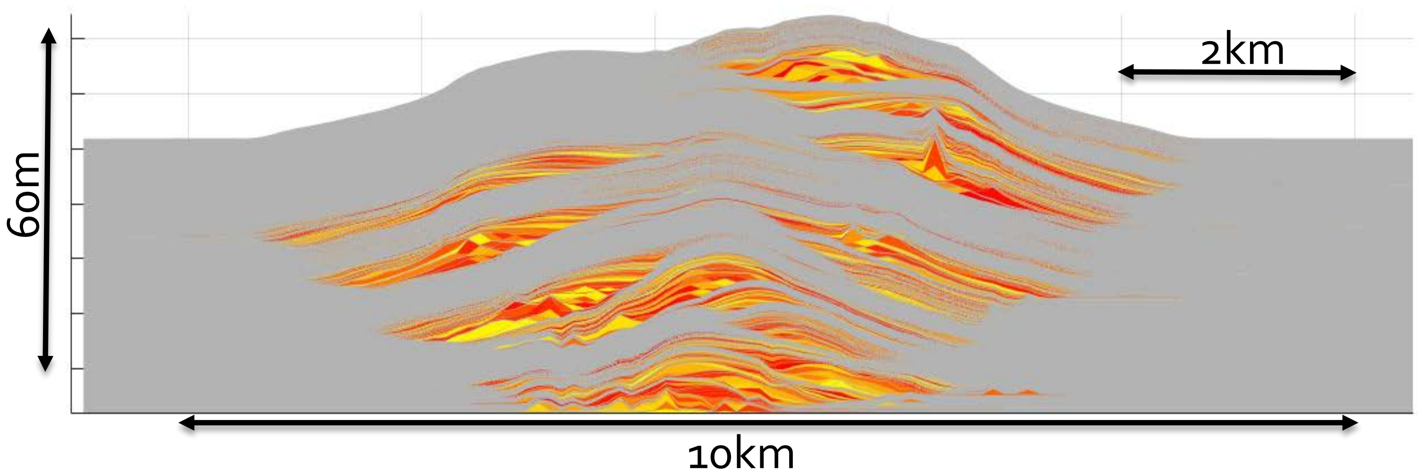
Strike cross section, **constant supply model**





Strike cross section, **oscillating supply model**



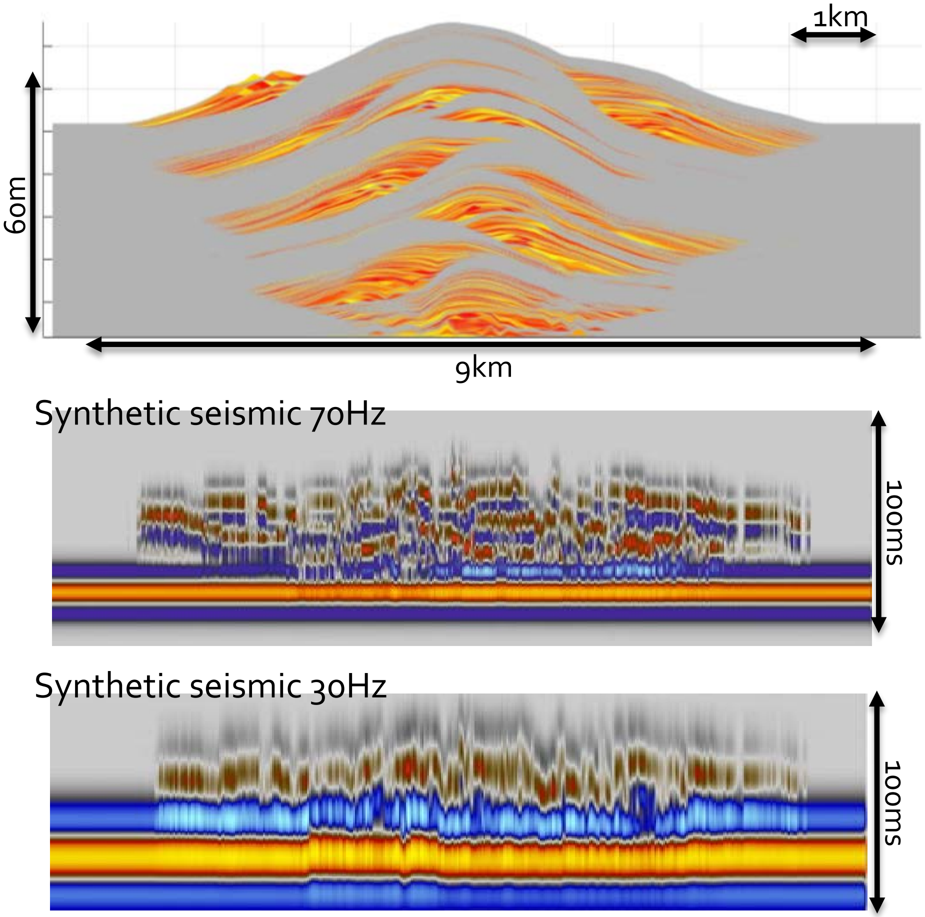
Flow event beds   Hemipelagic strata

- Strata show distinct clustering in both cases
- **Autogenic lobes**
- Emergent behaviour due to complex flow routing over developing sea-floor topography

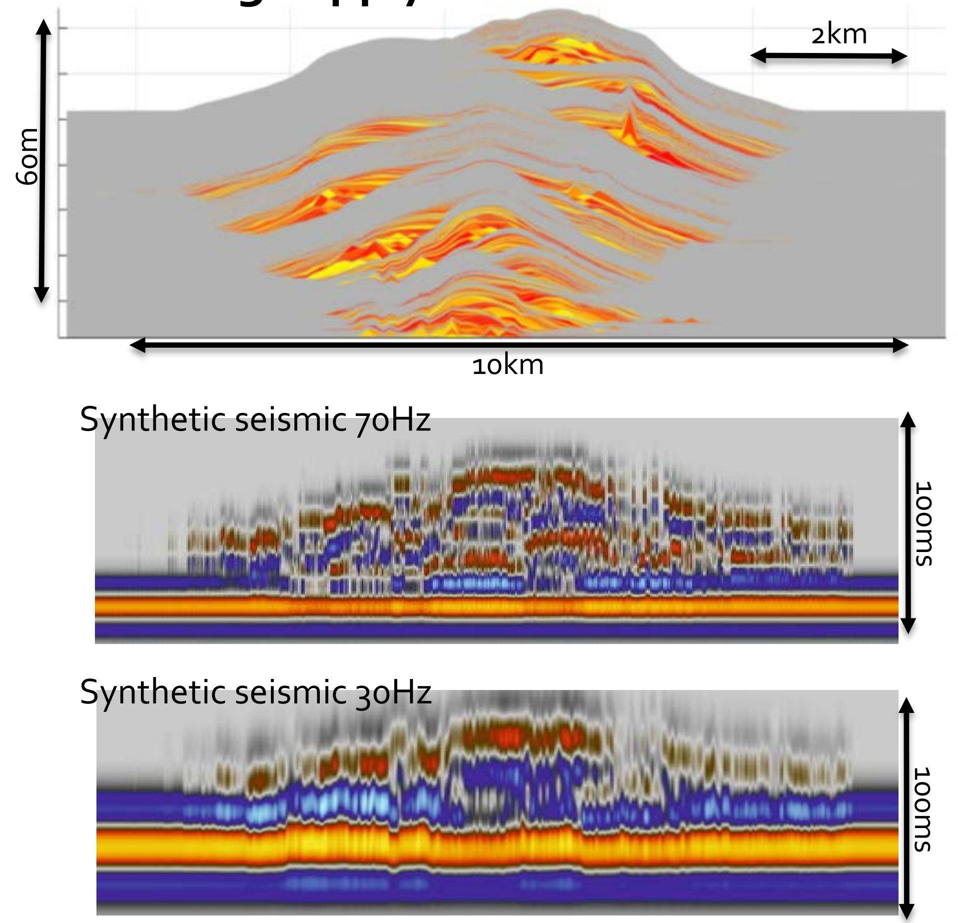
From Burgess et al. (2019) JSR, v. 89, 1–12

Allogenic versus Autogenic?

Constant supply model



Oscillating supply model

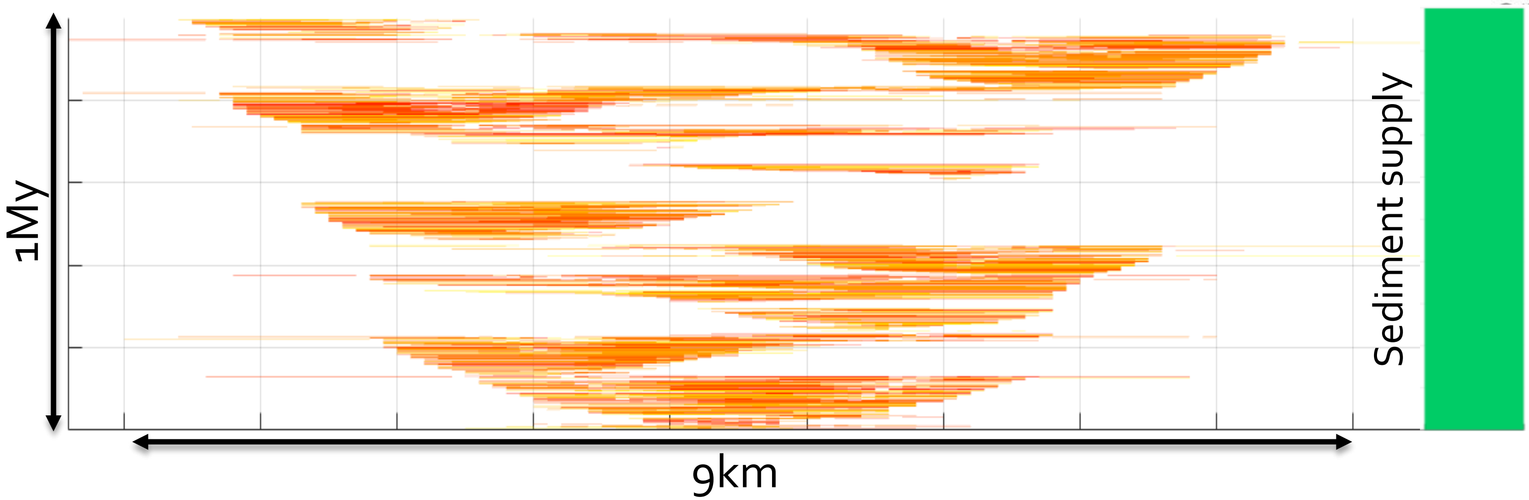


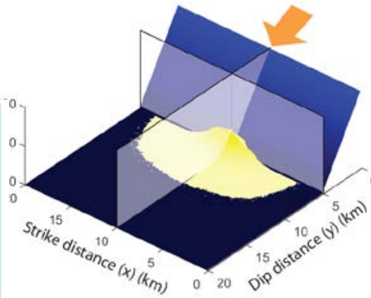
Norsar software used to run depth-domain convolution modelling with integrated illumination and resolution effects, thanks to Isabelle Lecomte, University of Bergen

- An interesting aside - how much of the lobe stacking is visible, or could be inferred, from seismic images?

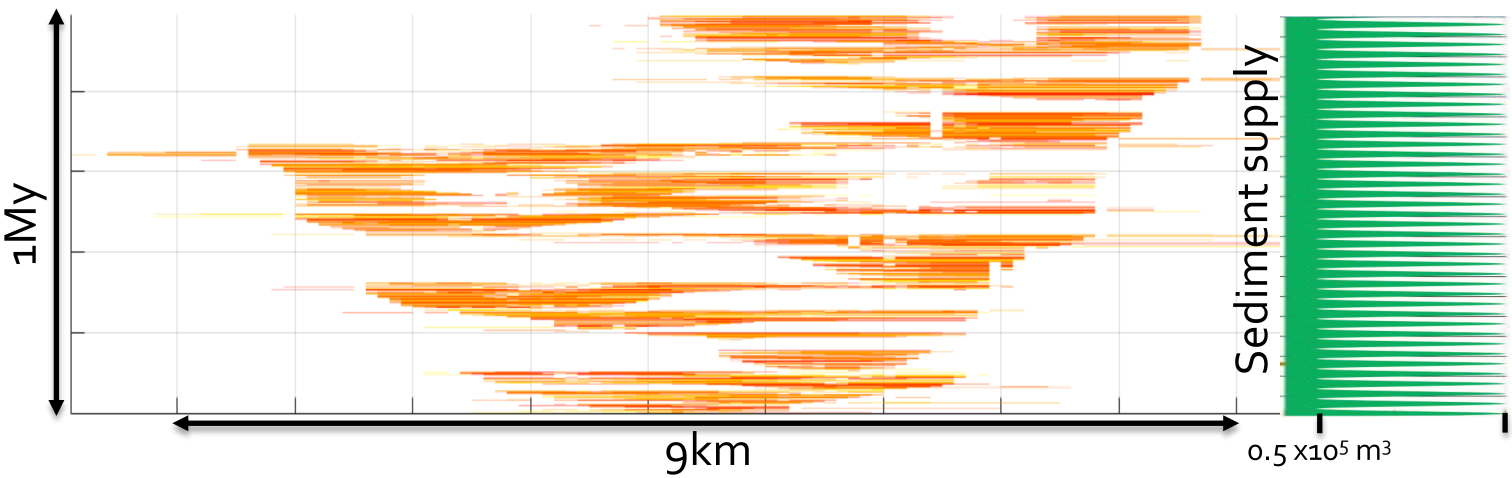
Allogenic versus Autogenic?

Chronostratigraphic diagram, **constant supply**





Chronostratigraphic diagram, **oscillating supply**



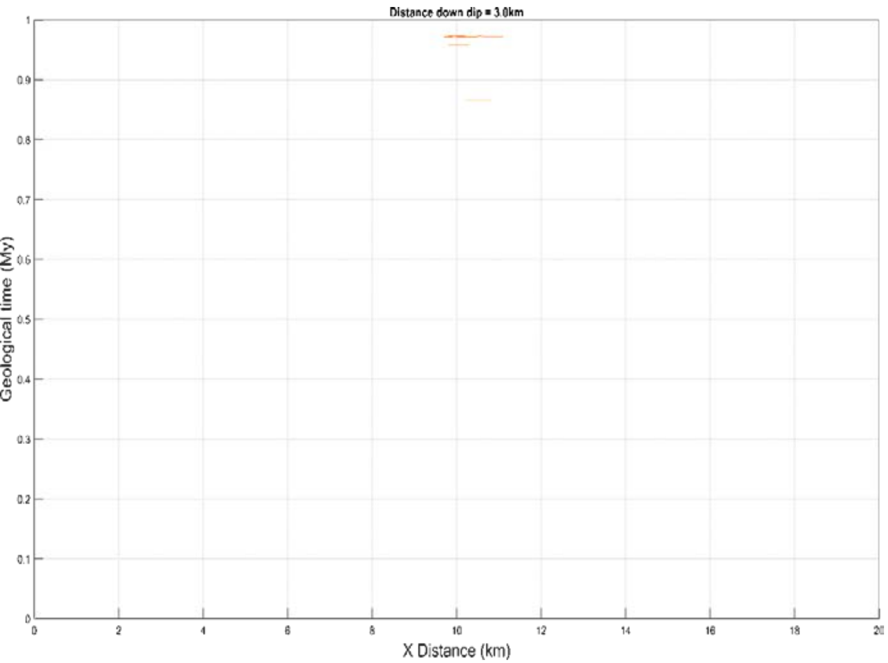
- Strata show distinct clustering in both cases
- **Autogenic lobes**
- Emergent behaviour due to complex flow routing

Flow event beds | Hemipelagic strata

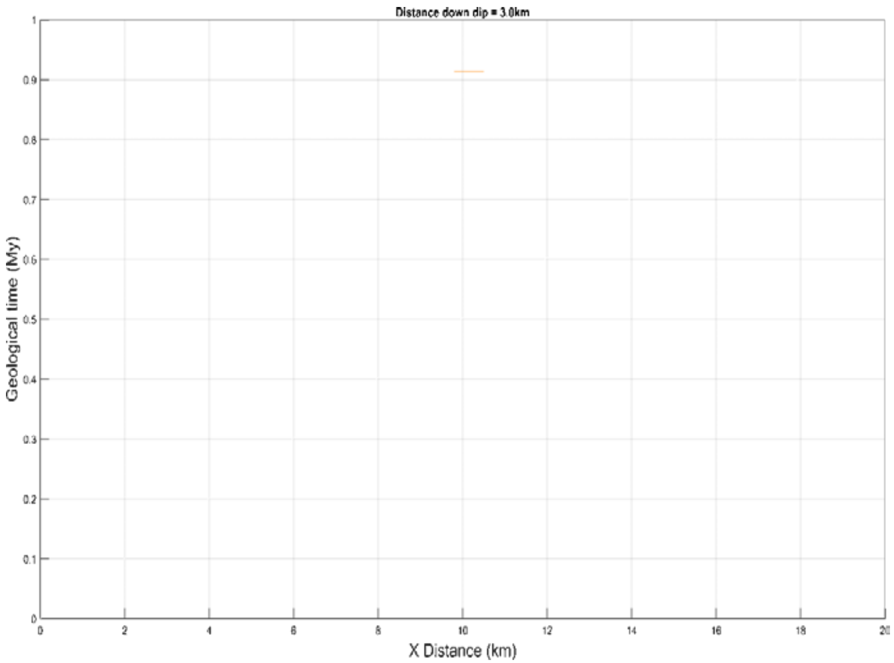
From Burgess et al. (2019) JSR, v. 89, 1–12

Allogenic versus Autogenic?

Constant sediment supply



Oscillating sediment supply



Scroll through of the strata, from proximal to distal chronostrat diagrams, shows that:

- Stacking is similar in both cases, dominated by autogenic jumps and creep in loci of deposition
- Allogenic variable flow size changes details of the spatial distribution of strata, but not the overall autogenic stacking pattern

Flow event beds Hemipelagic strata

Allogenic versus Autogenic?

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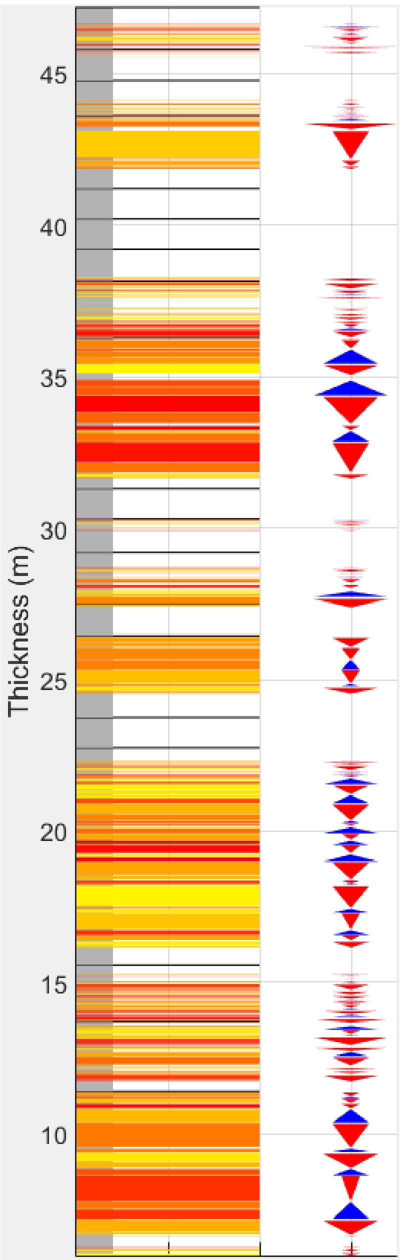


Constant sediment supply

Oscillating sediment supply

- Vertical section from each model x=10km, y=4.8km
- **Both sections seem to show similar stacking patterns**
- But can we say more about the presence or absence or order and signal?

306 beds
Mean thickness 0.021m
Max thickness 0.88m

Runs up:
Total count 110
Longest 5

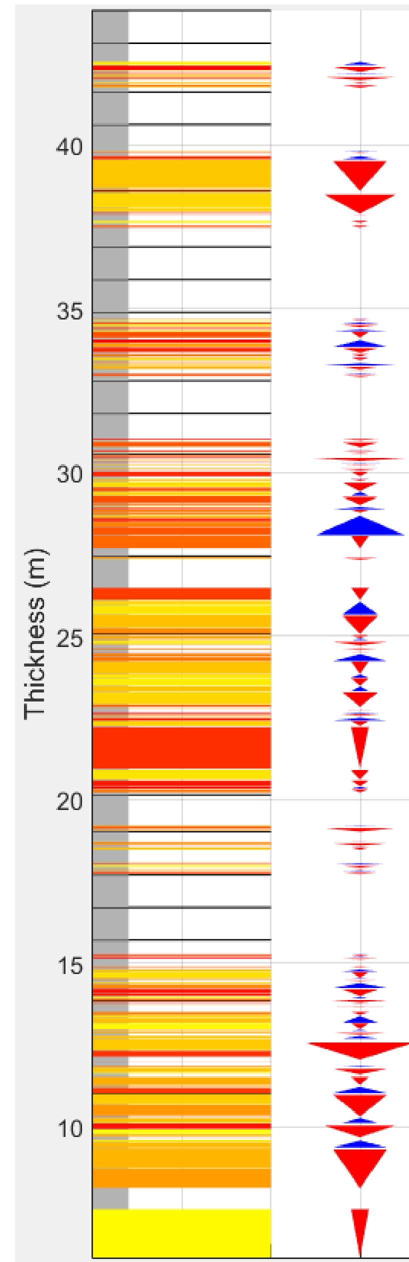
Runs down:
Total count 110
Longest 4

260 beds
Mean thickness 0.018m
Max thickness 1.47m

Runs up:
Total count 91
Longest 6

Runs down:
Total count 91
Longest 5

Flow event beds   Hemipelagic strata



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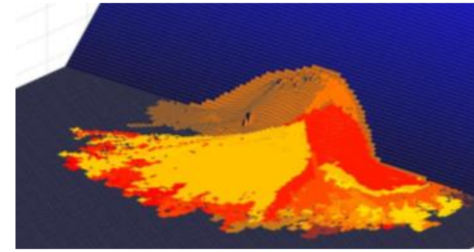
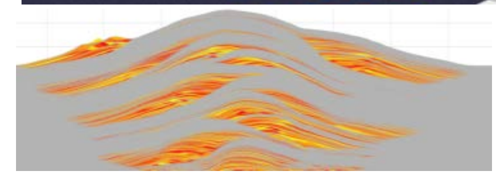
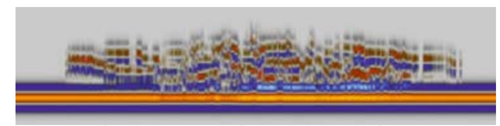
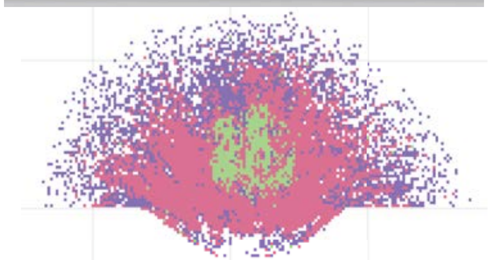
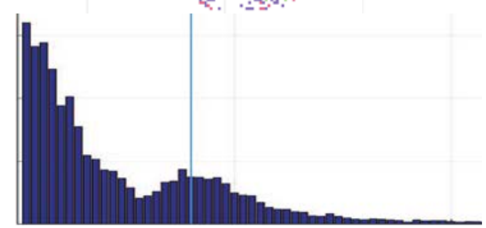
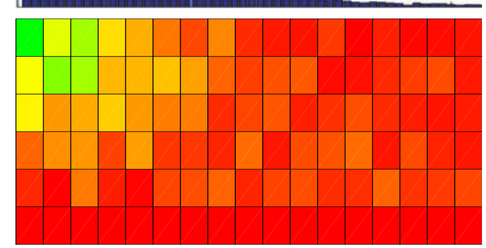






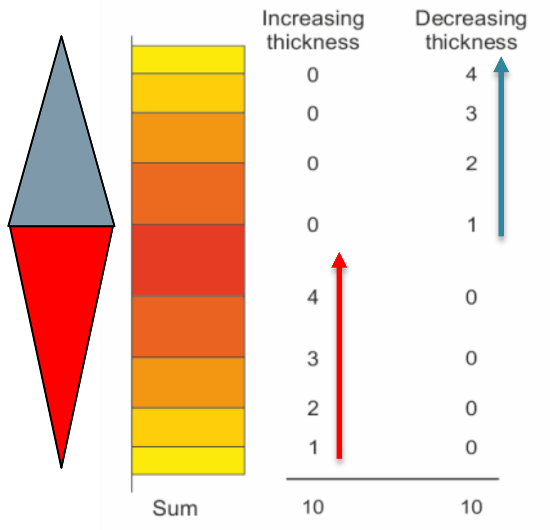






Extracting a signal: bed thickness trends

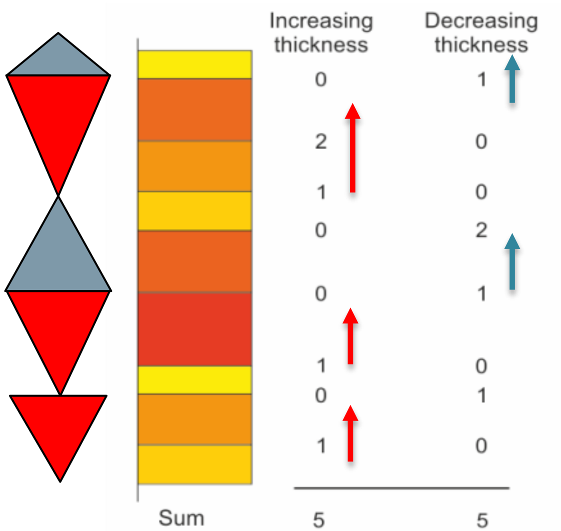
Ordered strata example



- Ordered strata with clear thickening and thinning upwards trends has fewer, longer runs of increasing and decreasing thickness
- ***r* = 2.50**

$$r = \frac{\sum \text{increasing thickness layers} + \sum \text{decreasing thickness layers}}{\text{number of layers}}$$

Disordered strata example



- "Random" strata lacks thickening and thinning trends, has more, shorter runs of increasing and decreasing thickness
- ***r* = 1.25**

Method from Burgess (2016), v. 86, 148–167

Extracting a signal: bed thickness trends

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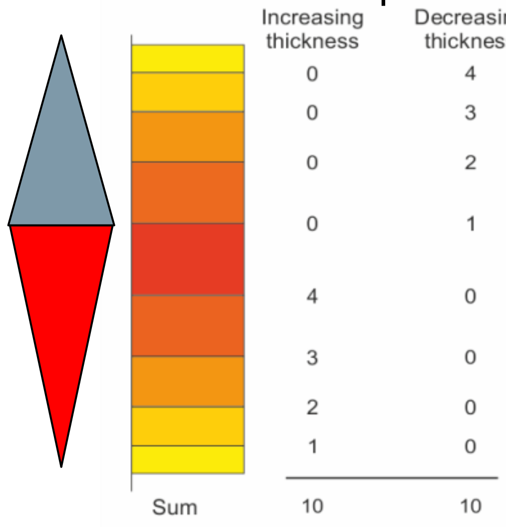
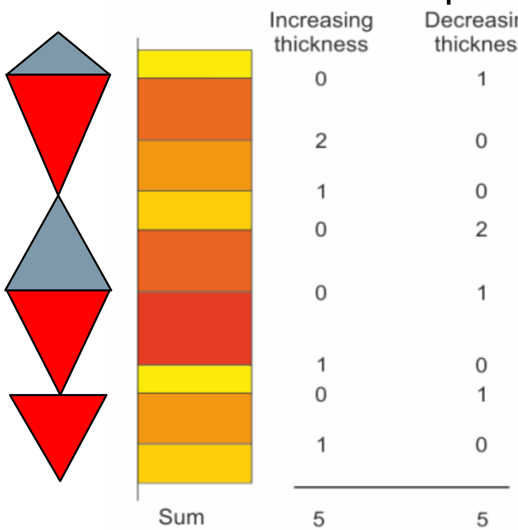
Ordered strata example



Disordered strata example



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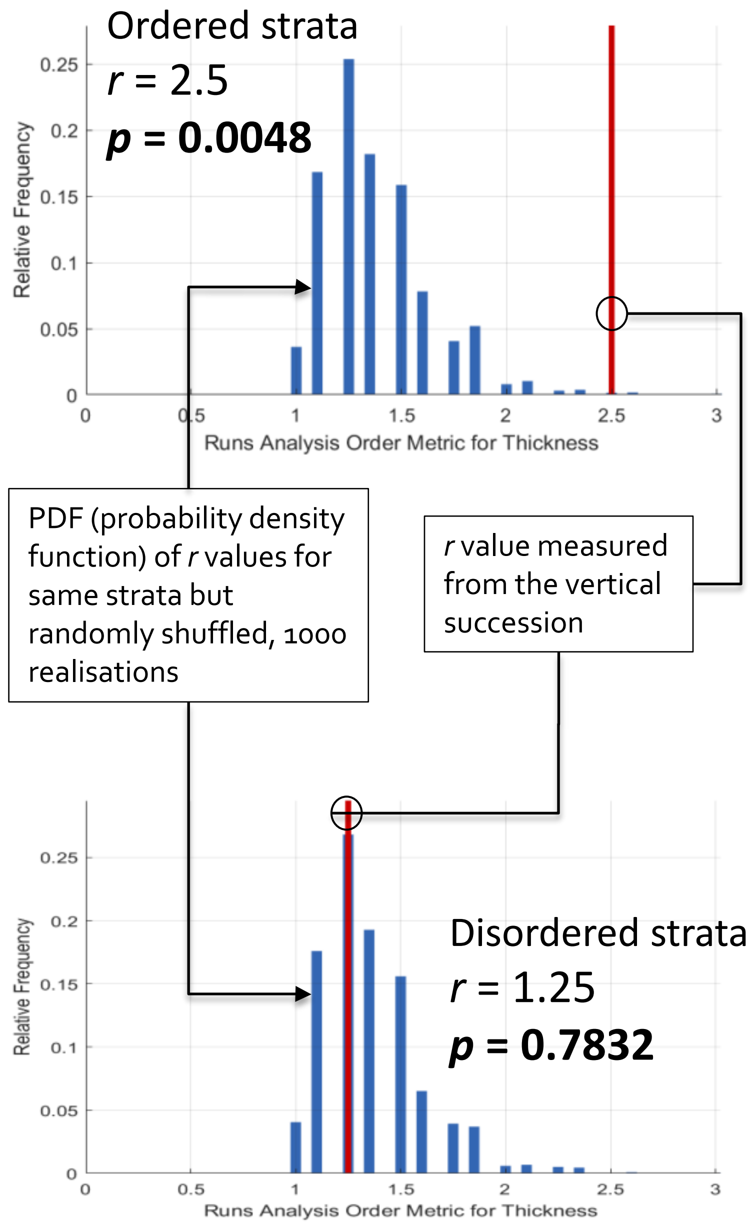
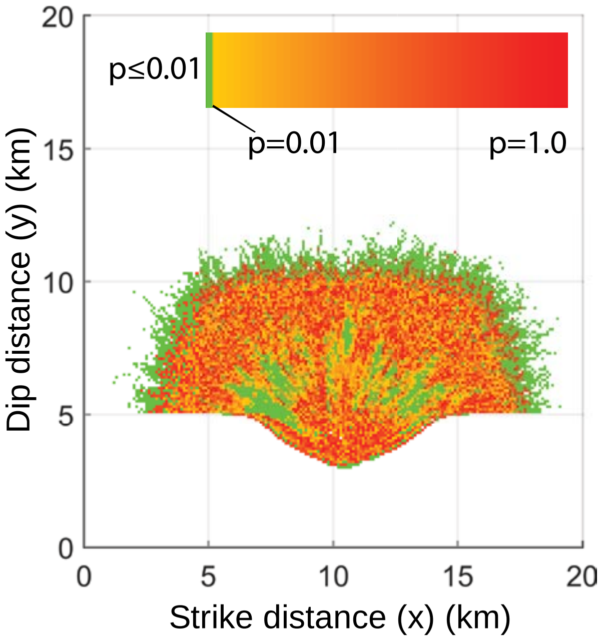


- If the r value falls outside the limit of the probability density function (PDF) defined by 1000 randomly shuffled sections, *p* value is low
- If the r value is within the PDF, *p* value is higher
- So a **low *p* value is strong evidence for ordered strata** that are unlikely to occur by chance

Extracting a signal: bed thickness trends

Constant sediment supply

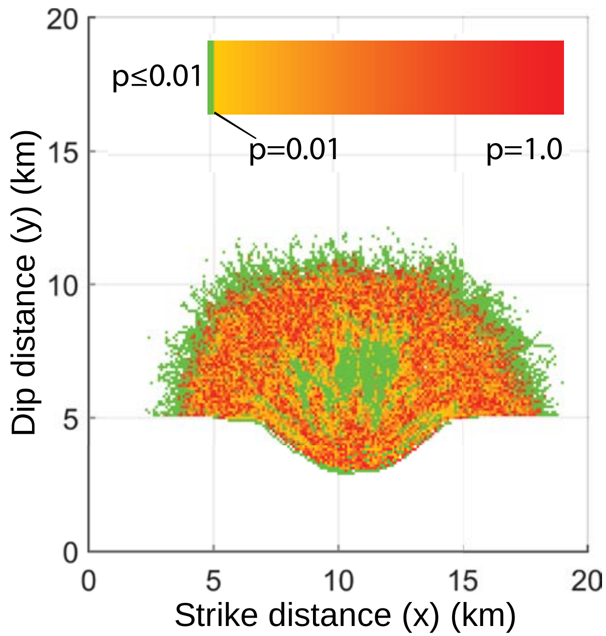


Runs analysis R values:
- Mean 1.5338
- Maximum 3.8409

Runs analysis **P values:**
- Minimum: 0.0000
- **Mean 0.1077**
- Maximum 0.5000

Sections with unlikely-to-occur-by-chance bed thickness trends are **23% of fan area**

Oscillating sediment supply



Runs analysis R values:
- Mean 1.5215
- Maximum 5.2500

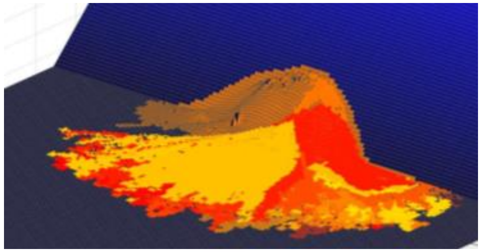
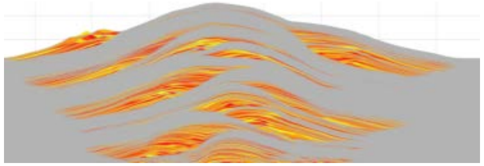
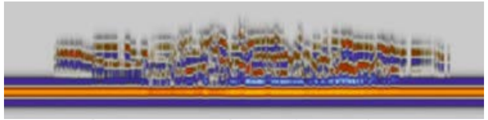
Runs analysis **P values:**
- Minimum: 0.0000
- **Mean 0.1300**
- Maximum 0.5000
- Sections with unlikely-to-occur-by-chance bed thickness trends are **26% of fan area**

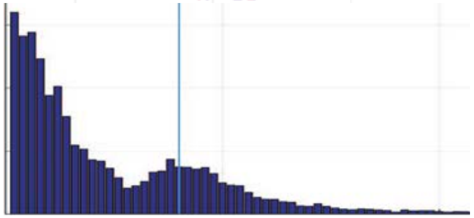
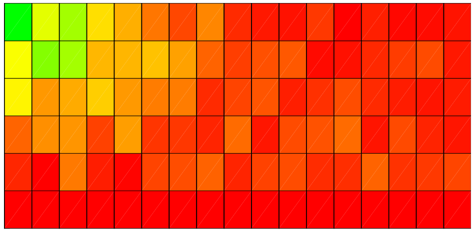
- Green on the map indicates vertical sections that contain thinning- and thickening-upward trends unlikely to occur by chance
- Occurrence and distribution of ordered strata in both modelled fans is similar
- Similar occurrence of ordered strata in both the constant supply and oscillating supply model demonstrates this is due to **autogenic** not **allogenic** processes

From Burgess et al. (2019) JSR, v. 89, 1–12

Presentation Outline

- Lobyte3D formulation and parameters
- Comparing two models: constant-supply "autogenic" and oscillating-supply "allogenic"
- Extracting a signal: bed thickness trends
- Extracting a signal: spectral analysis and signal bumps

Extracting a signal: spectral analysis

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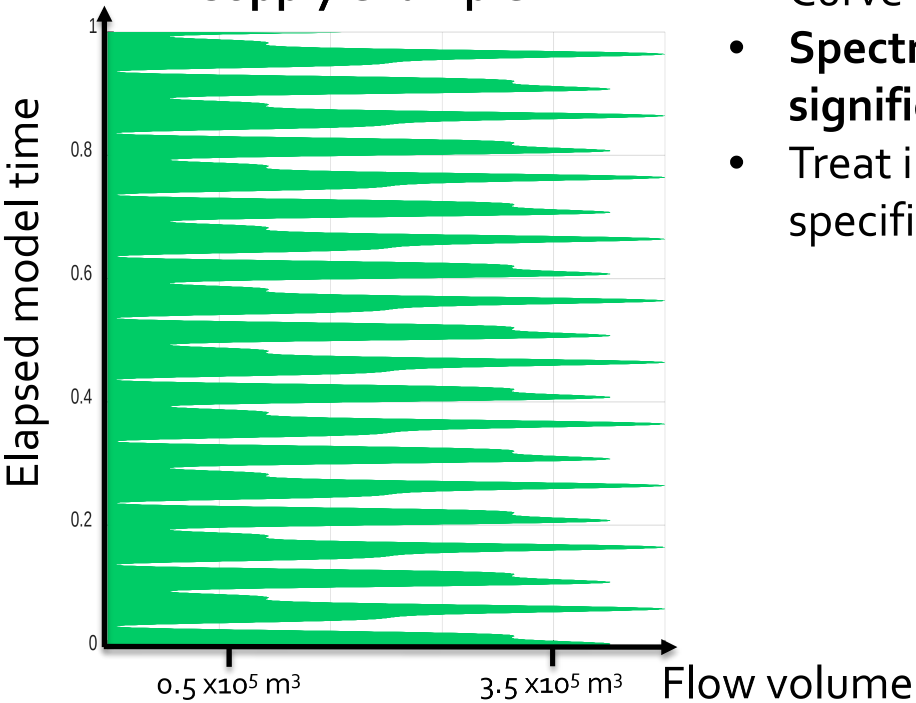
Oscillating sediment supply example

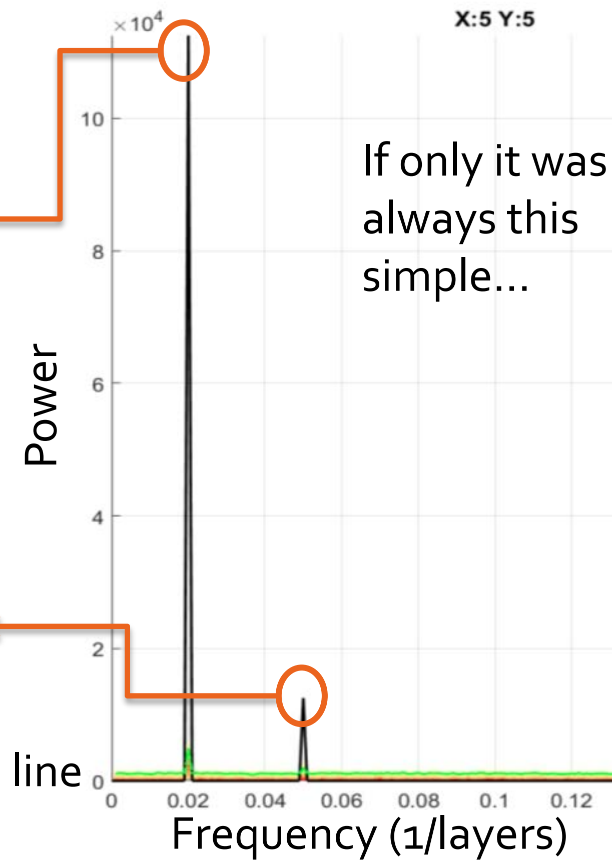


Sediment supply history constructed from two sin curves superimposed

- Curve 1 period 50ky amplitude $30 \times 10^5 m^3$
- Curve 2 period 20Ky amplitude $5 \times 10^5 m^3$
- **Spectral analysis shows strong statistically significant peak at input signal frequencies…**
- Treat input signal as number of layers, no time specified, to avoid requirement for age control

1/layers
So 1/0.02
= 50

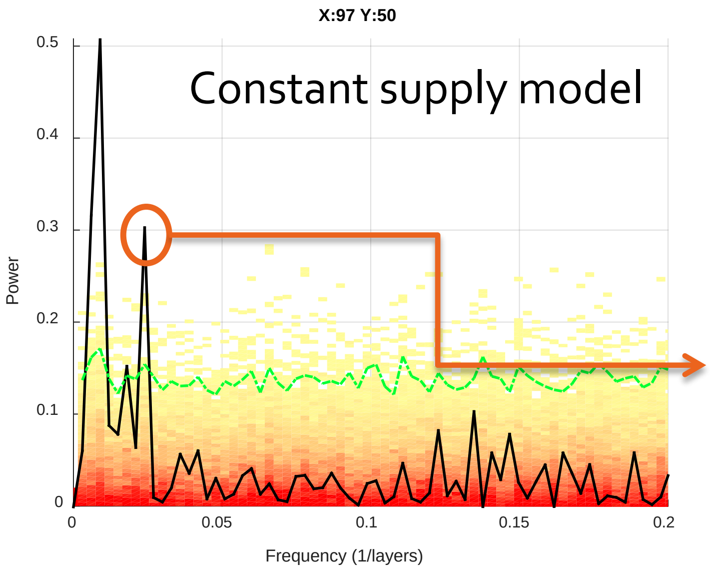
1/layers
So 1/0.05
= 20



If only it was always this simple…

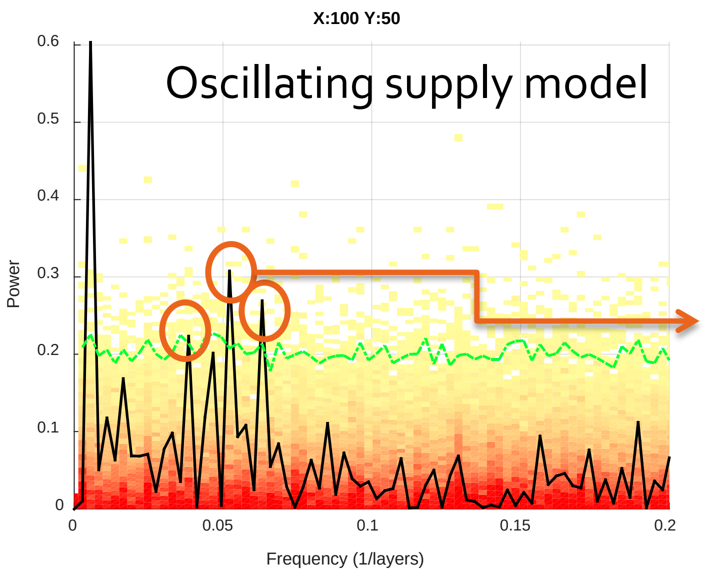
Green line is 99% significance line

Extracting a signal: spectral analysis



Significant peak at 42 ky

- (1/layers)=0.023
- So 1/0.023=42 layers, and each layer 1ky
- so peak at 42ky



Significant peaks at 25 ky, 19Ky and 16Ky

From Burgess et al. (2019) JSR, v. 89, 1–12

- Spectral analysis examples from Lobyte3D output are more complex
- Some apparently significant frequencies present in the constant supply model – autogenic processes
- Significant peak at or near the input signal of 25ky in oscillating supply model, but also other significant peaks present!
- And of course from 1/layer frequency you would not necessarily know the highest peak was 25ky without independent high-resolution age data

Extracting a signal: Spectral Analysis

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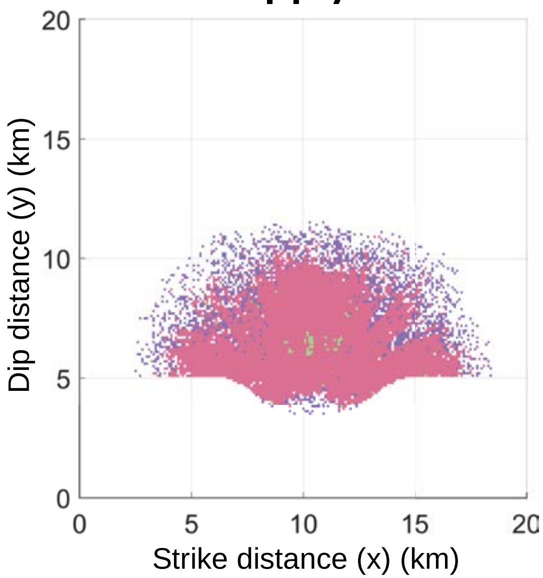
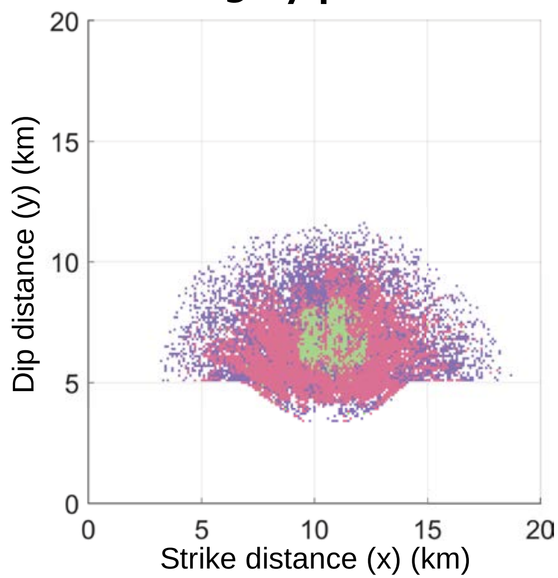
Constant sediment supply



54 locations, 0.5% of the fan area, record a 25 ky signal

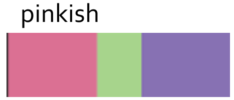
Oscillating sediment supply 25 ky period



455 locations, 4.3% of the fan area, record a 25 ky signal

Peaks at lower frequency than signal

pinkish



Peaks at higher frequency than signal

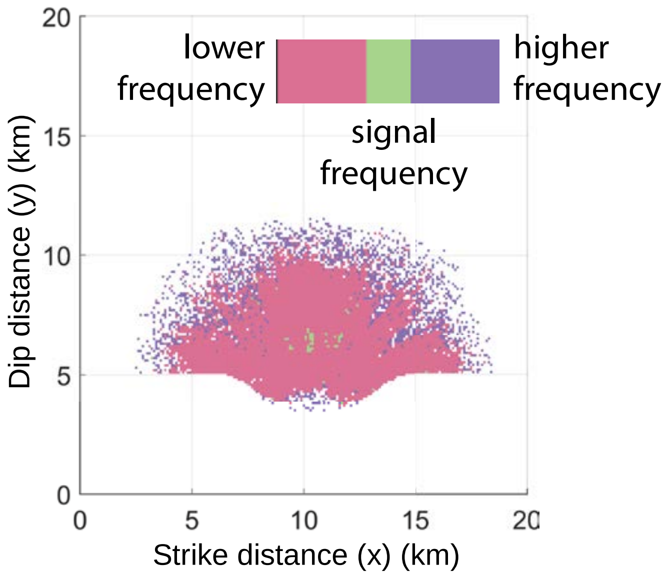
Peaks at signal frequency

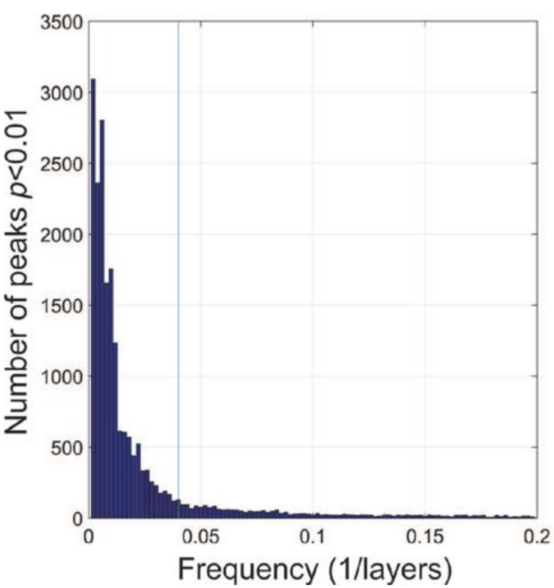
- Green on the map indicates vertical sections that have a significant spectral peak at the signal frequency
- Signal concentrated in mid fan – highest stratigraphic completeness?
- Occurrence of signal in the variable supply scenario much more common
- But in the constant supply scenario, there are some sections with bed thickness trends at the signal frequency, but due to **autogenic** not **allogenic** processes

From Burgess et al. (2019) JSR, v. 89, 1–12

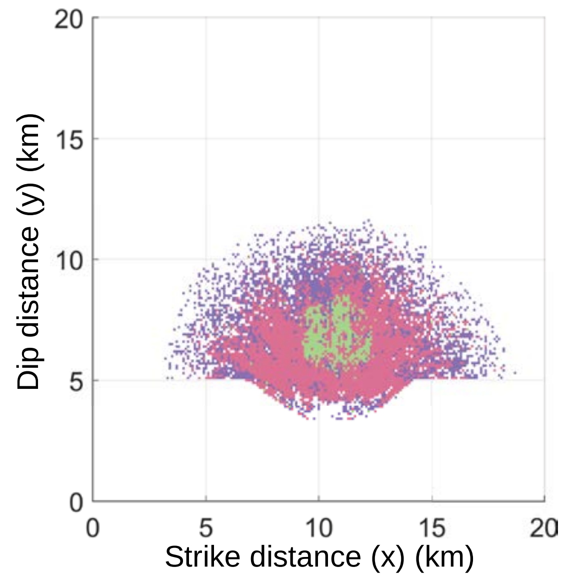
Extracting a signal: signal bump

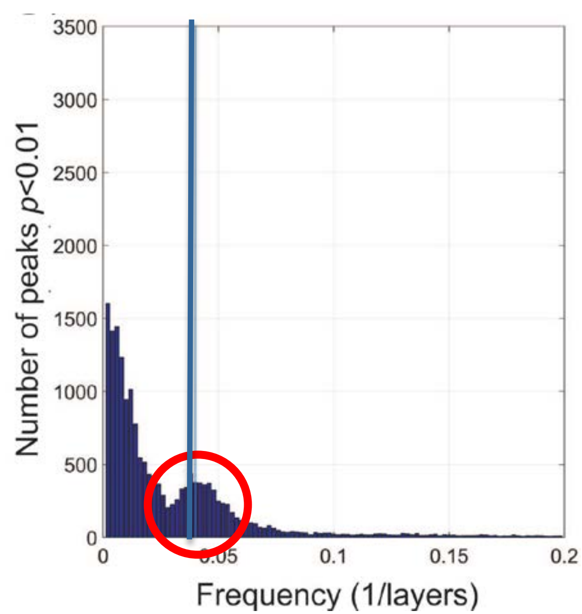
Constant sediment supply





Oscillating sediment supply





- Compile all the significant spectral peaks from the power spectra for all vertical sections on each map…
- Plot the number of significant peaks against their frequency
- If there is a signal present in the strata, even if is partly shredded by autogenic processes, partial preservation etc, we still get …
- A signal bump, around the input signal frequency!

From Burgess et al. (2019) JSR, v. 89, 1–12

Extracting a signal: signal bump

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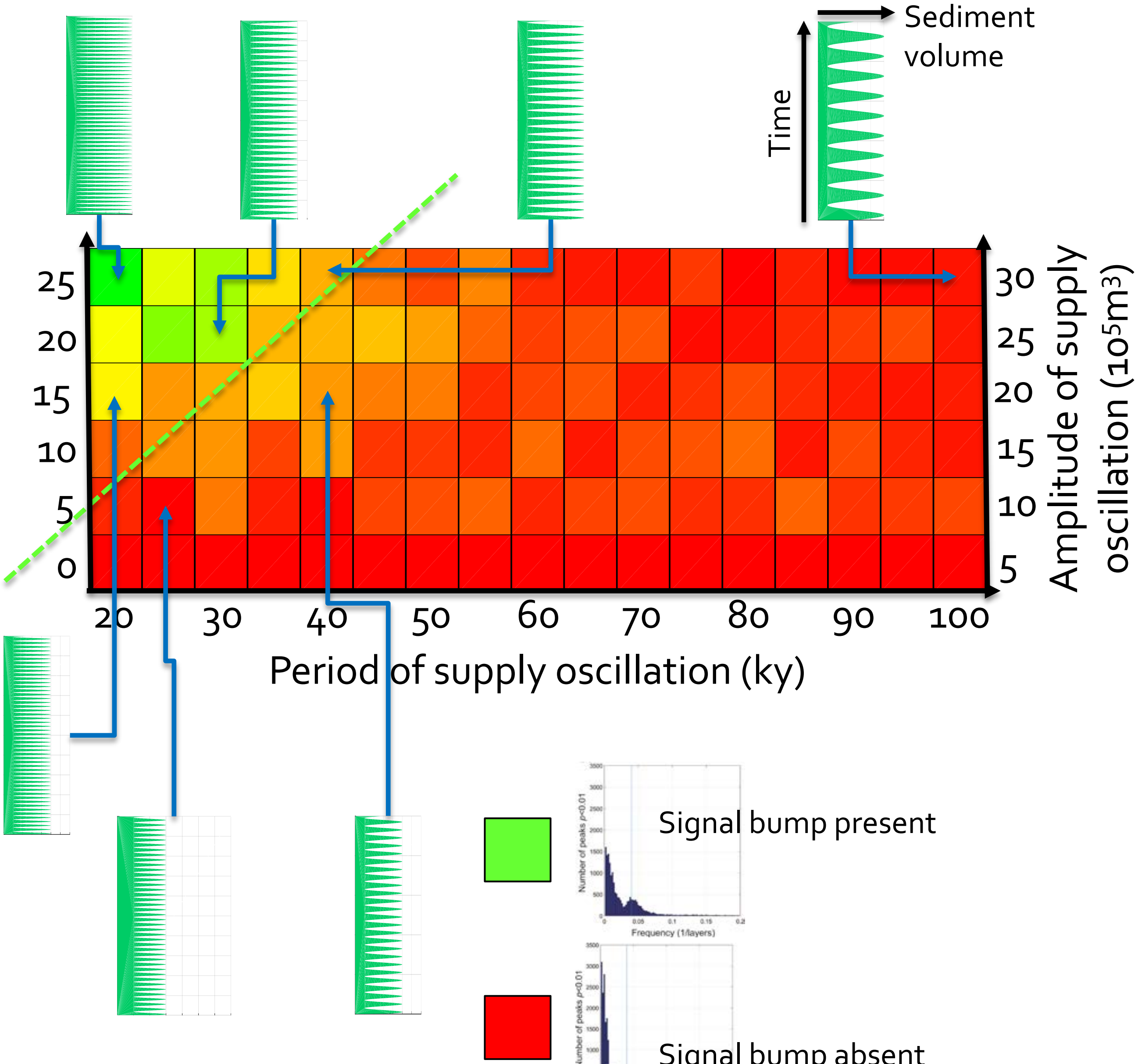

From Burgess and Duller. (in prep)

- Running Lobyte3D with a range of different input signals - **sediment supply oscillations with various amplitudes and periods**
- Analyse the results to determine presence/absence of signal bump
- **Results suggest that high-amplitude high-frequency signals are preserved best**
- Why?
- Perhaps because in incomplete autocyclic strata, fragments of the higher-frequency external signals are most easily preserved

Conclusions

- Lobyte 3D models show emergent behaviour:
  - Clustering of deposition to form lobes
  - Lobe switching and compensational stacking
  - Due to flow over evolving seafloor topography

- Ordered strata form due to deposition repeatedly shifting on the fan surface and revisiting previous locations of deposition, producing thickening and thinning trends, even without any allogenic forcing signal.
- Difficult in one vertical section to distinguish allocyclic from autocyclic order without knowing *a priori* how the allogenic signal frequency is likely to be recorded
- **So measure and analyse many mid-fan axial 1D vertical sections, to count significant spectral peaks and identify a "signal bump"**

- But how is the "signal bump" preserved with input signals across a range of frequencies and amplitudes – need to better understand interaction of autogenic and allogenic processes…