The Origins of Shallow-Water Carbonates Lithofacies Thickness Distributions: Modelling Accommodation and Supply Controls*

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Abstract

The observation that shallow-marine carbonate strata often have exponential lithofacies thickness distributions is of fundamental importance. This is because it is an observation that can be tested for its repeatability in outcrop and subsurface examples, and also because it raises the possibility that strata may be well represented with stochastic models with no intrinsic organization or hierarchy present in the strata. Most importantly however, it is significant because it poses the fundamental question of what sedimentary processes lead to the formation of particular lithofacies thickness distributions. This in turn links to the significant issue of how carbonate strata record climatic change through geological time.

This work builds on previous work using a simple 1D numerical stratigraphic forward model of carbonate platform strata (Dougal) to investigate how various controls such as amplitude and period of eustatic oscillation, variations in production rate, different lag depths and variations in erosion rate can control the type of lithofacies distribution produced. Dougal records platform-top carbonate accumulation influenced by water-depth dependent sediment production in euphotic, oligophotic and aphotic production profiles with a lag-depth controlling onset of production.

Results from single model runs highlight the issue of non-stationary behaviour where statistical properties of the strata change with elevation up the section, and show that exponential lithofacies thickness distributions can be generated from an entirely deterministic

model, in contrast to the stochastic models invoked previously. Simple model runs illustrate how different types of lithofacies distribution are constructed unit by unit as the depositional system responds to external forcing and internal autocyclic dynamics. These analyses are substantiated with hundreds of thousands of model runs that show in detail how different lithofacies distributions may arise under varying accommodation and production regimes likely to develop in different climate settings with different types of eustatic curves and different types of carbonate factory.

This 1D modeling lays important foundations for reproducing lithofacies thickness distributions using 3D models of fine-scale carbonate heterogeneity. An example of some initial results will be shown from CarboCAT, a 3D cellular automata model of carbonate facies migration and accumulation.

Selected References

Burgess, P.M., 2008, The nature of shallow-water carbonate lithofacies thickness distributions: Geology, v. 36/3, p. 235-238.

Drummond, C.N., and B.H. Wilkinson, 1993, Carbonate cycle stacking patterns and hierarchies of orbitally forced eustatic sealevel change: Journal of Sedimentary Petrology, v. 63/3, p. 369-377.

Grotzinger, J.P., 1986, Evolution of early Proterozoic passive-margin carbonate platform, Rocknest Formation, Wopmay Orogen, Northwest Territories, Canada: Journal of Sedimentary Petrology, v. 56/6/, p. 831-847.

Wilkinson, B.H., N.W. Diedrich, and C.N. Drummond, 1996, Facies successions in peritidal carbonate sequences: JSR, v. 66/6, p. 1065-1078.

Wilkinson, B.H., and C.N. Drummond, 2004, Facies mosaics across the Persian Gulf and around Antigua-Stochastic and deterministic products of shallow-water sediment accumulation: JSR, v. 74/4, p. 513-526.

The origins of shallow-water carbonates lithofacies thickness distributions: modelling accommodation and supply controls

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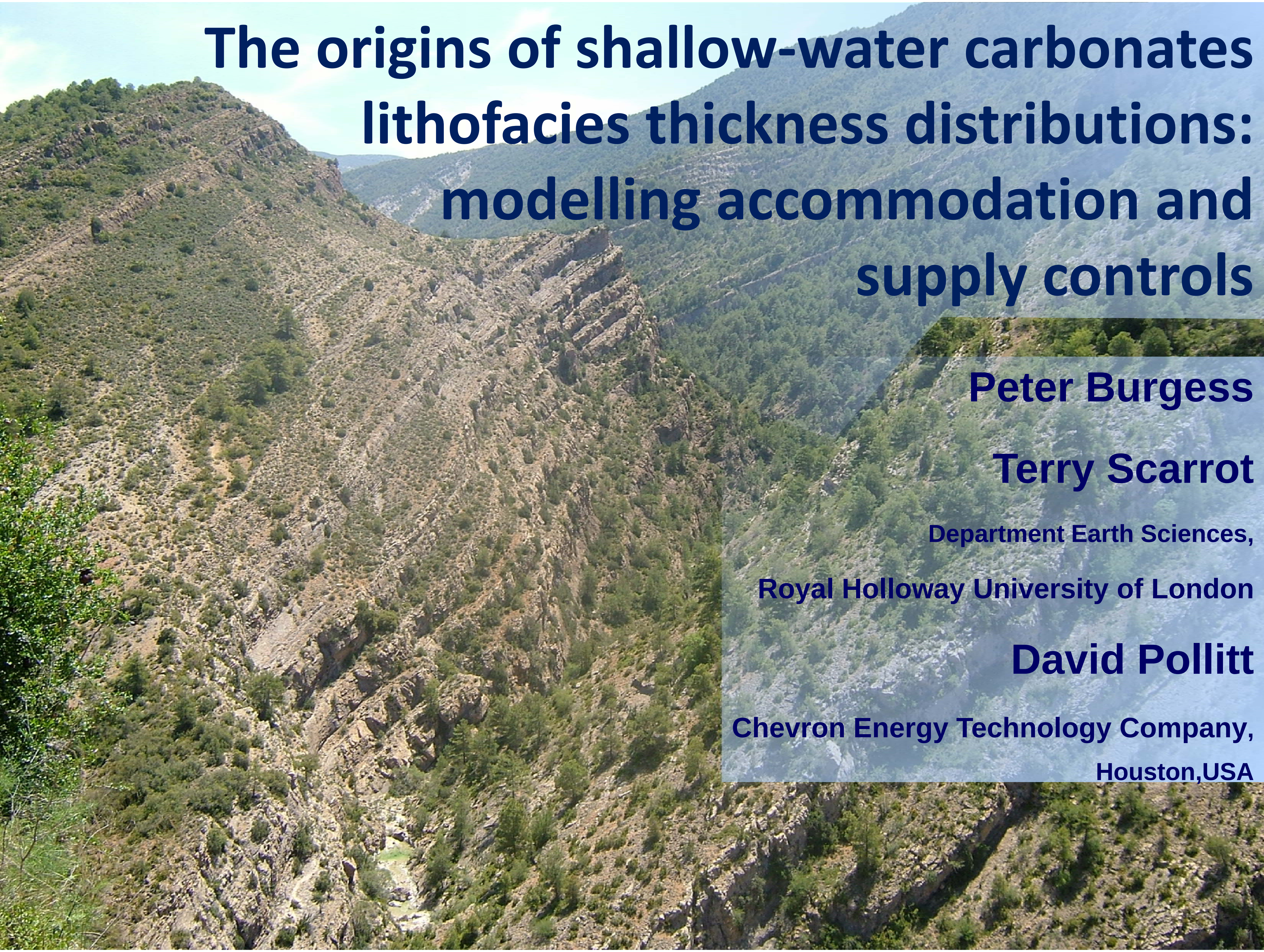

Presentation Outline

- Observations on lithofacies thickness distributions - What do these distributions mean?
- 1D forward modeling of controls
  - Single model runs
  - Multiple model runs
- Next steps

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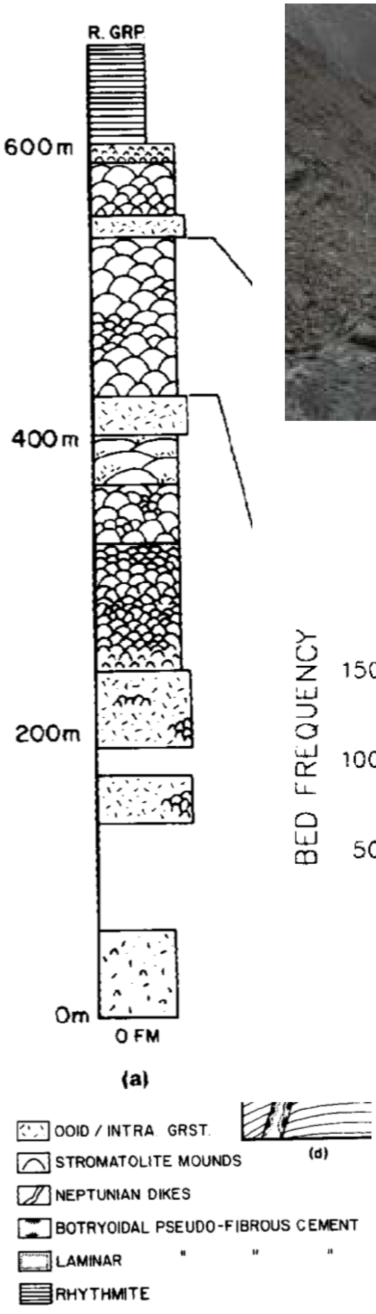
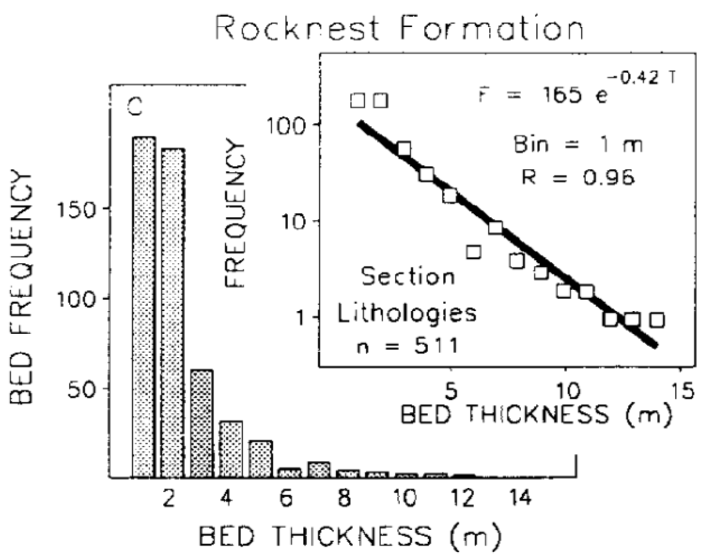
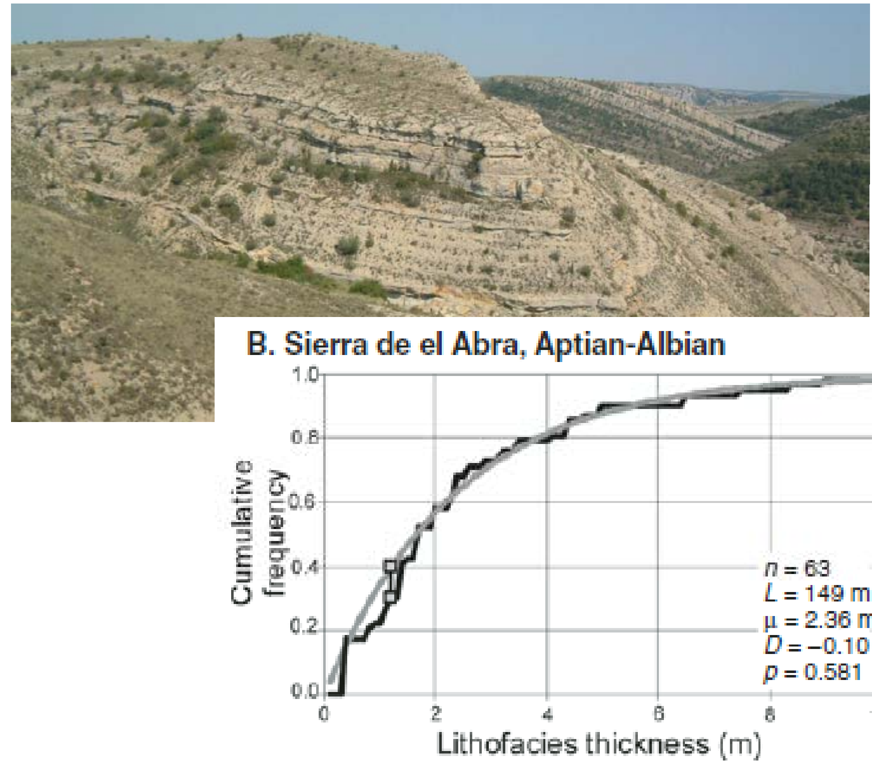
Lithofacies Thickness Distributions





Wilkinson et al, 1996, JSR, 66, p.1065-1068 & Grotzinger, 1986, JSP, 56, 813-847



- Many measured sections from outcrop show an exponential lithofacies thickness frequency distribution
- Which means lots more thin beds than thick beds

Lithofacies Thickness Distributions & Lateral Extent

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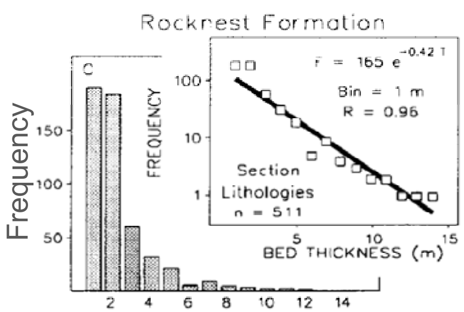
Vertical thickness



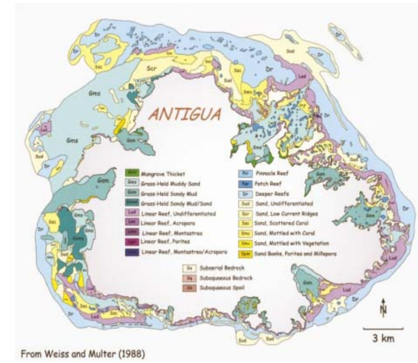
Lithofacies unit thickness (m)

Preserved lateral extent in 3D rock volumes

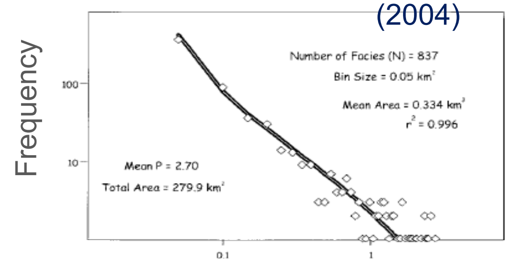
Lithofacies area (km^2)

??

Modern "planform" area



from Wilkinson & Drummond. (2004)

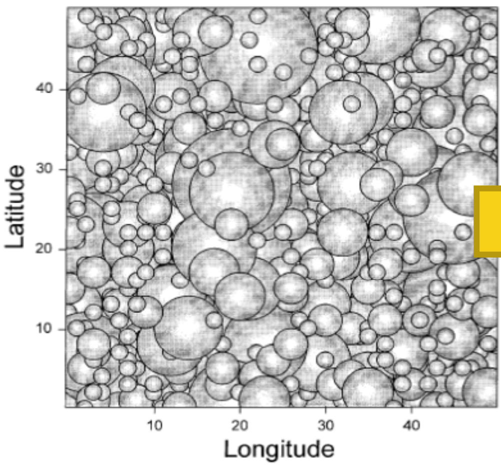


Lithofacies area (km^2)

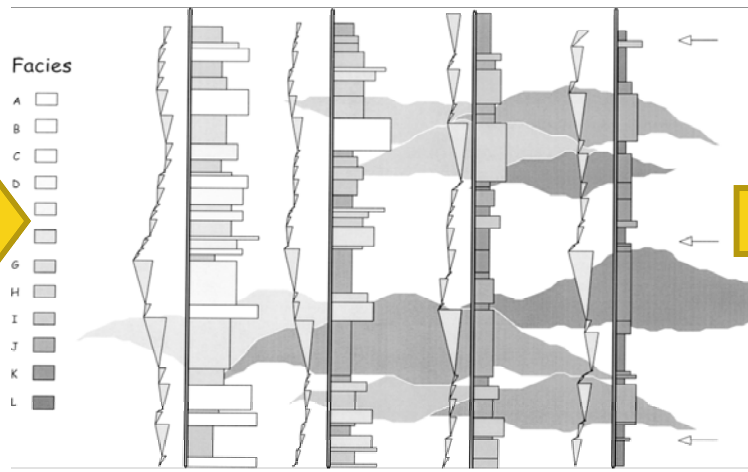
- What frequency distributions of lithofacies lateral extent exist in ancient carbonate strata?
- Do lithofacies vertical thickness distributions relate to lithofacies lateral extents?
- Are modern carbonate deposystems "snap shots" representative for the ancient record?
- And what kind of lithofacies thickness and area distributions would result from the above modern deposystems when they go through the preservation filter?

Lithofacies Thickness Distributions: Causal Mechanisms

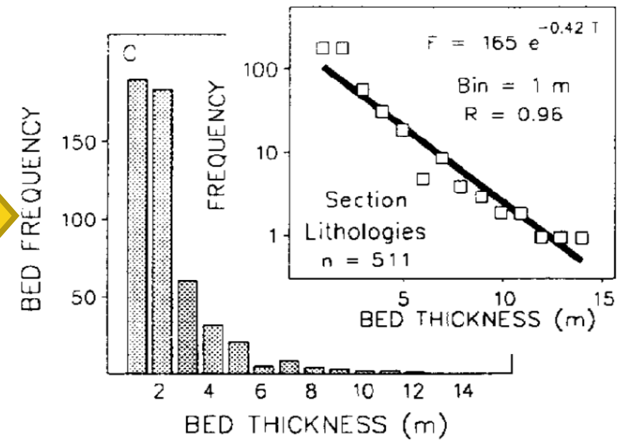
Model in map view
- Facies mosaic



Model in cross-section



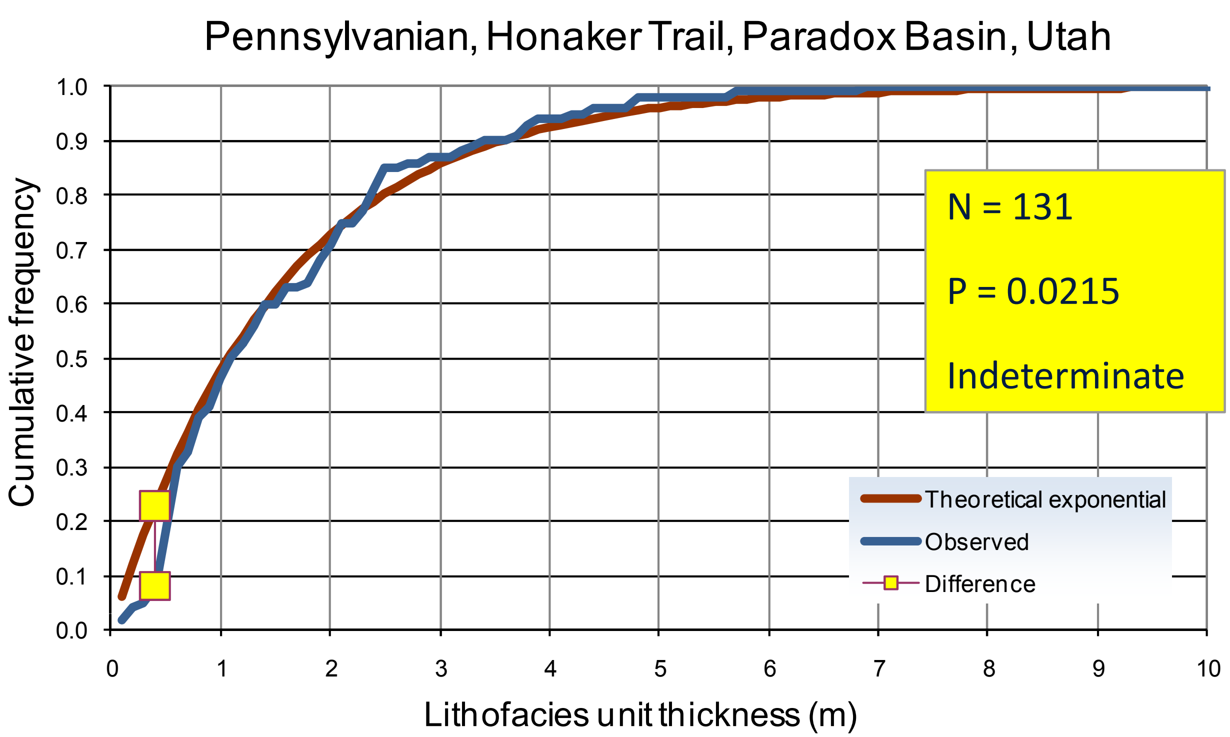
Modelled lithofacies thickness distribution



Wilkinson and Drummond, 2004, JSR

- Modelling carbonate deposystems as a stochastic Poisson process lithofacies mosaic
- **Very simple model but creates exponential lithofacies thickness distribution, as observed in some outcrops**
- **But,** no process explanation suggested by this model –you only get out exactly what was put in
- **And** do all carbonate examples show an exponential distribution??

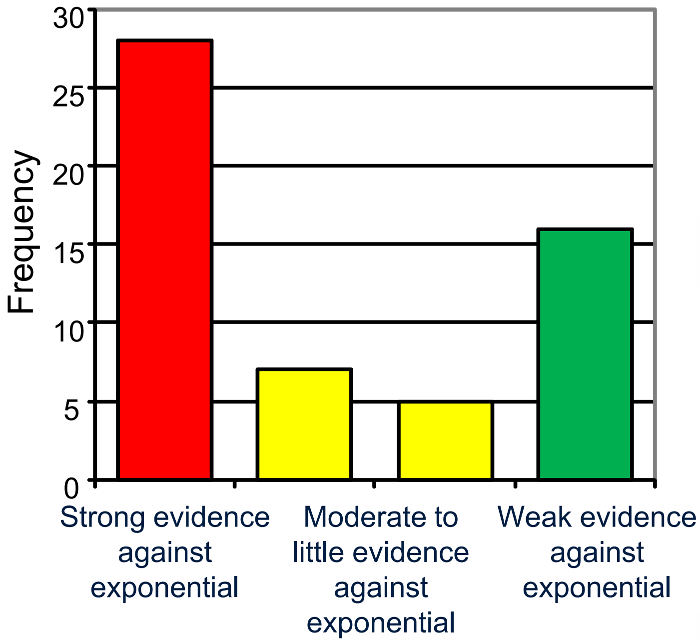
How to Determine The Type of Distribution

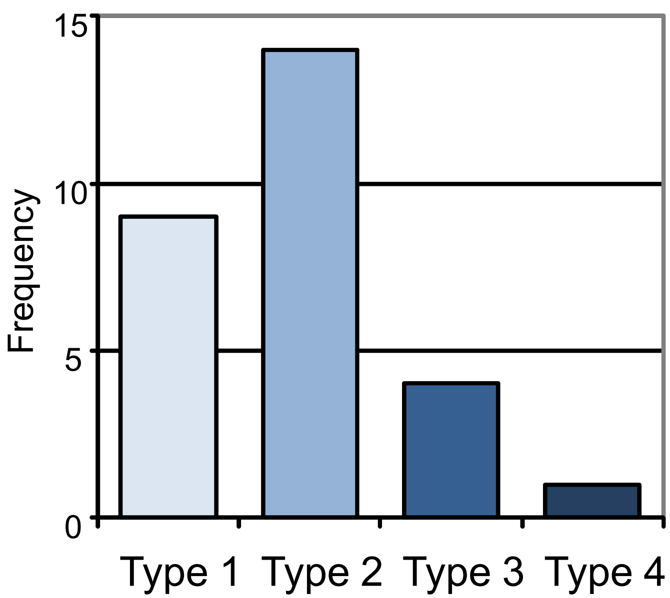


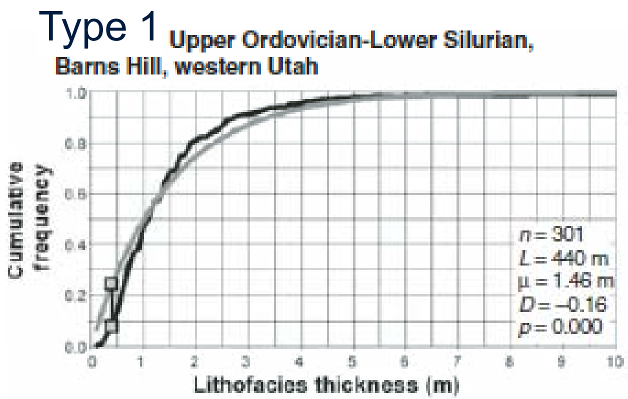
- A robust quantitative test is required to determine if an observed lithofacies thickness distribution is exponential or not
- Kolmogorov-Smirnov test is useful in this role
- Compares an observed distribution with a theoretical exponential for the same number of lithofacies units and same mean thickness
- P value indicates the degree of evidence against an fit with exponential

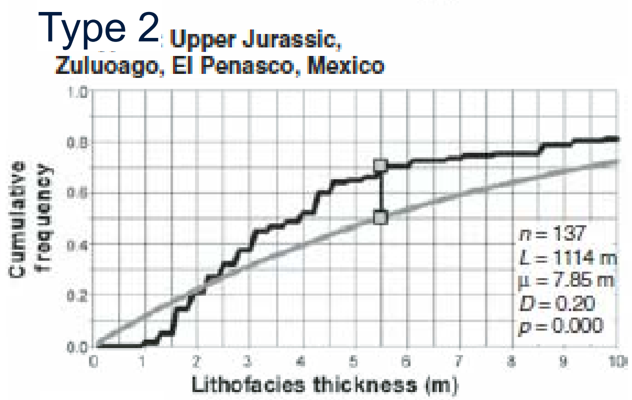
P	Interpretation
<0.01	Strong evidence against an exponential
0.01 – 0.1	Indeterminate
0.1 – 1.0	Good match with an exponential

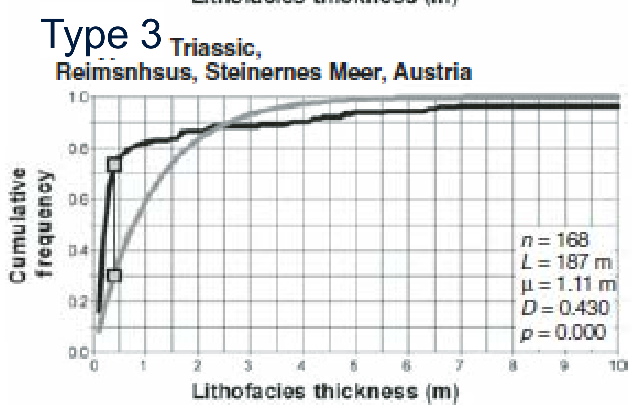
Exponential versus Non-Exponential











- More extensive analysis of outcrop data using KS test suggests that many <u>but not all</u> examples are exponential
- Examples that are not exponential can divided into three types based on how they differ from an exponential distribution with the same number of beds
- All of which raises the question – **what stratigraphic processes are responsible for the observed exponential and the non-exponential examples??**

From Burgess, 2008, Geology, 36, p.235-238

Presentation Outline

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- Observations on lithofacies thickness distributions - What do these distributions mean?
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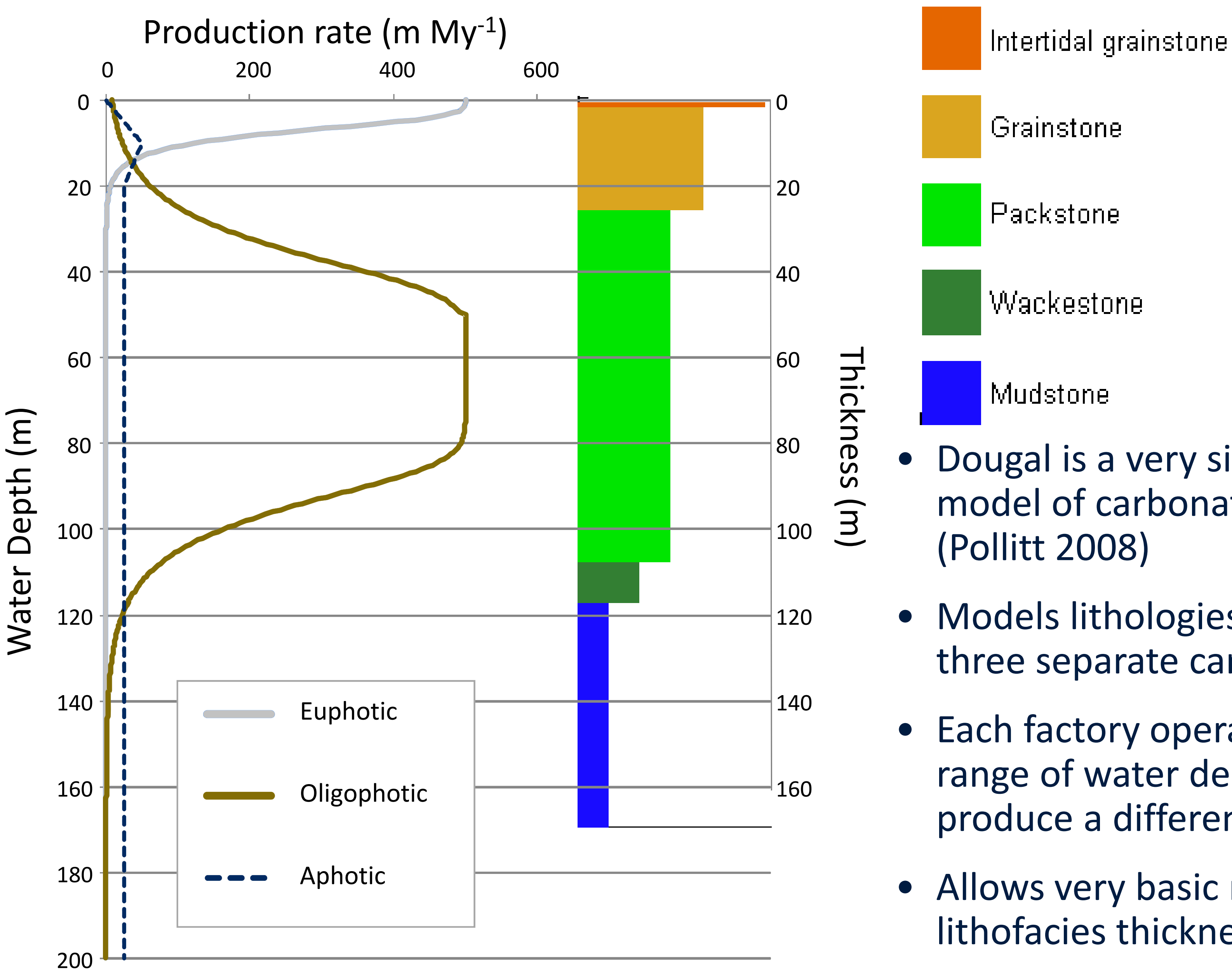
1D Modelling With Dougal: Input & Output



- Dougal is a very simple 1D forward model of carbonate accumulation (Pollitt 2008)
- Models lithologies as a product of three separate carbonate factories
- Each factory operates over a different range of water depths and tends to produce a different lithology
- Allows very basic modelling of lithofacies thickness distributions
- Short time step for numerical stability

1D Modelling With Dougal: Assumptions

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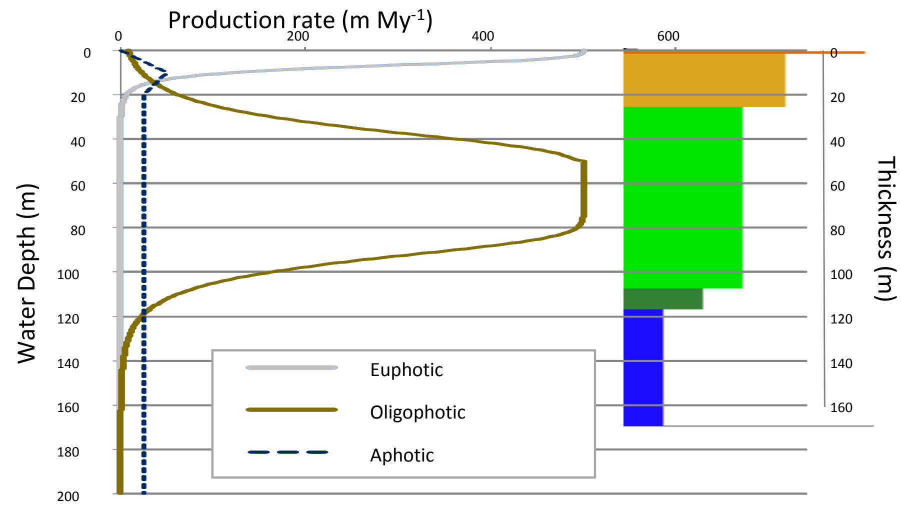
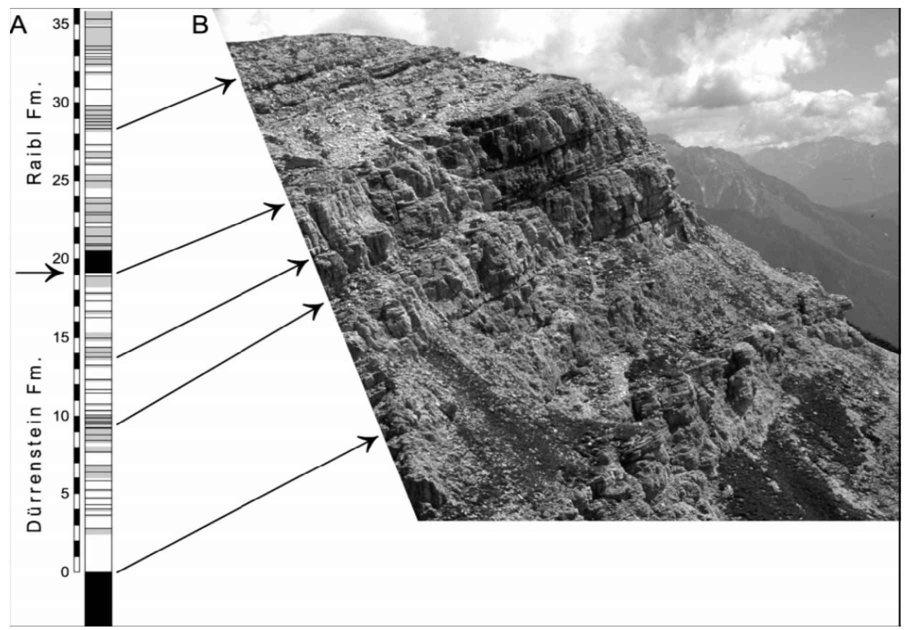
- Maximum production rate remains constant through time
- Carbonate production rate is a function of water depth, varying in a combination of euphotic, oligophotic or aphotic
- Different carbonate lithologies are produced by the three different factories at different water depths
- Accommodation varies in a simple manner according to two or three superimposed periods of eustatic oscillation with a background steady rate of subsidence
- Subaerial and submarine erosion rates are zero





1D Modelling: A Catch-Up Non Exponential Case

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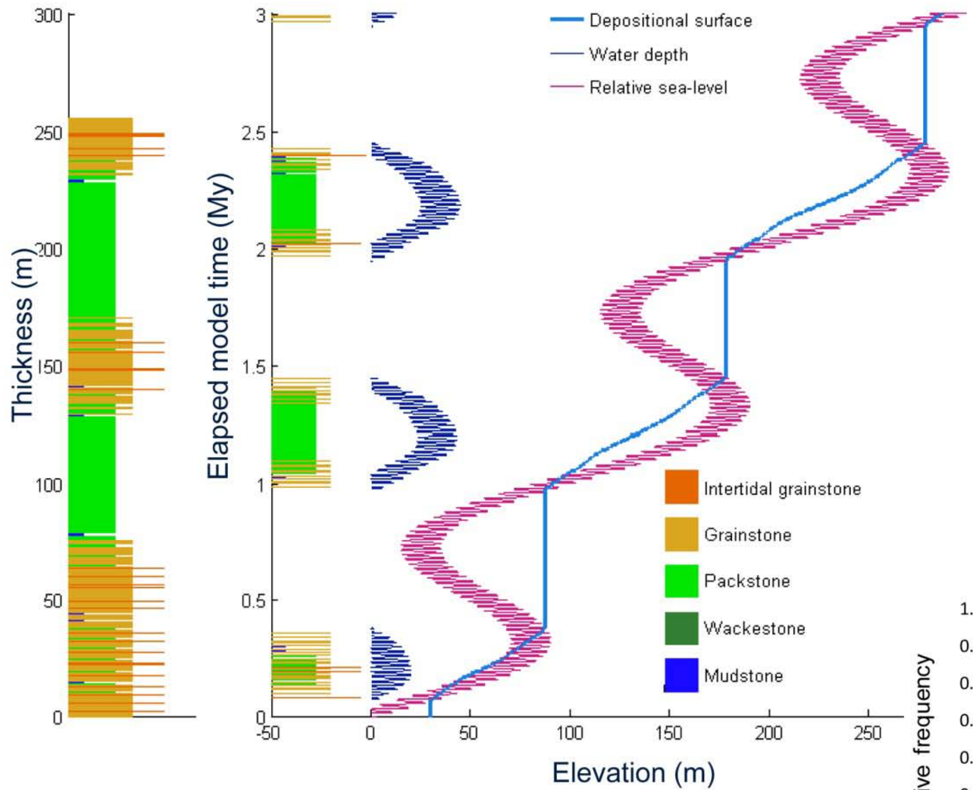
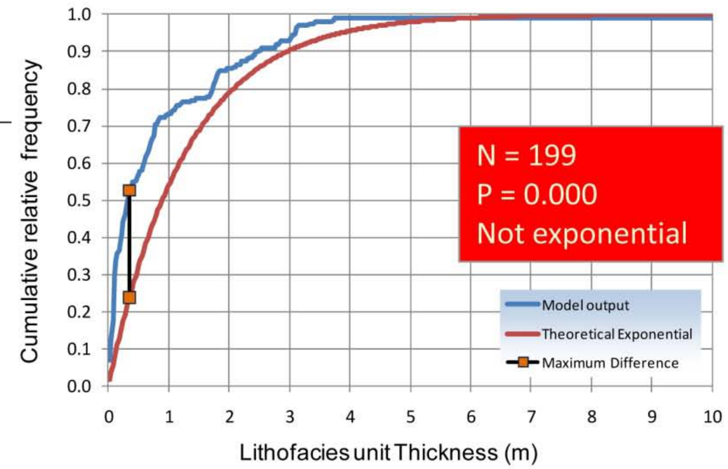
- Model with 20ky and 1My period eustasy
- Lag depth 0m – no autocycles
- Duration 3 My
- 20ky eustatic curve is asymmetric 1:3
- Euphotic and oligophotic production rates 500mMy^{-1}
- Produces a non-exponential lithofacies thickness





- Too many thin units 24 units < 0.1m thick
- Low deposition rates during rapid transgression & subsequent temporary platform drowning

Presenter's Notes: Complex variations in the rate of creation of accommodation, here due to high-frequency glacioeustatic oscillations, combined with sediment production and accumulation rates that favour catch-up style deposition. Under these conditions water depth changes drive changes in rate and type of carbonate accumulation and produce a mix of many thin beds and relatively few thick beds required for an exponential distribution. For example, thin beds are often deposited during rapid transgression.

1D Modelling: A Keep-Up Non Exponential Case

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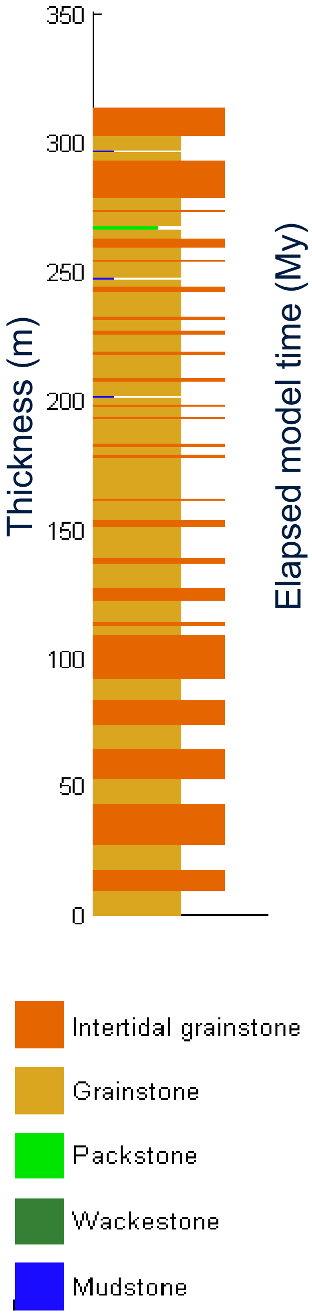
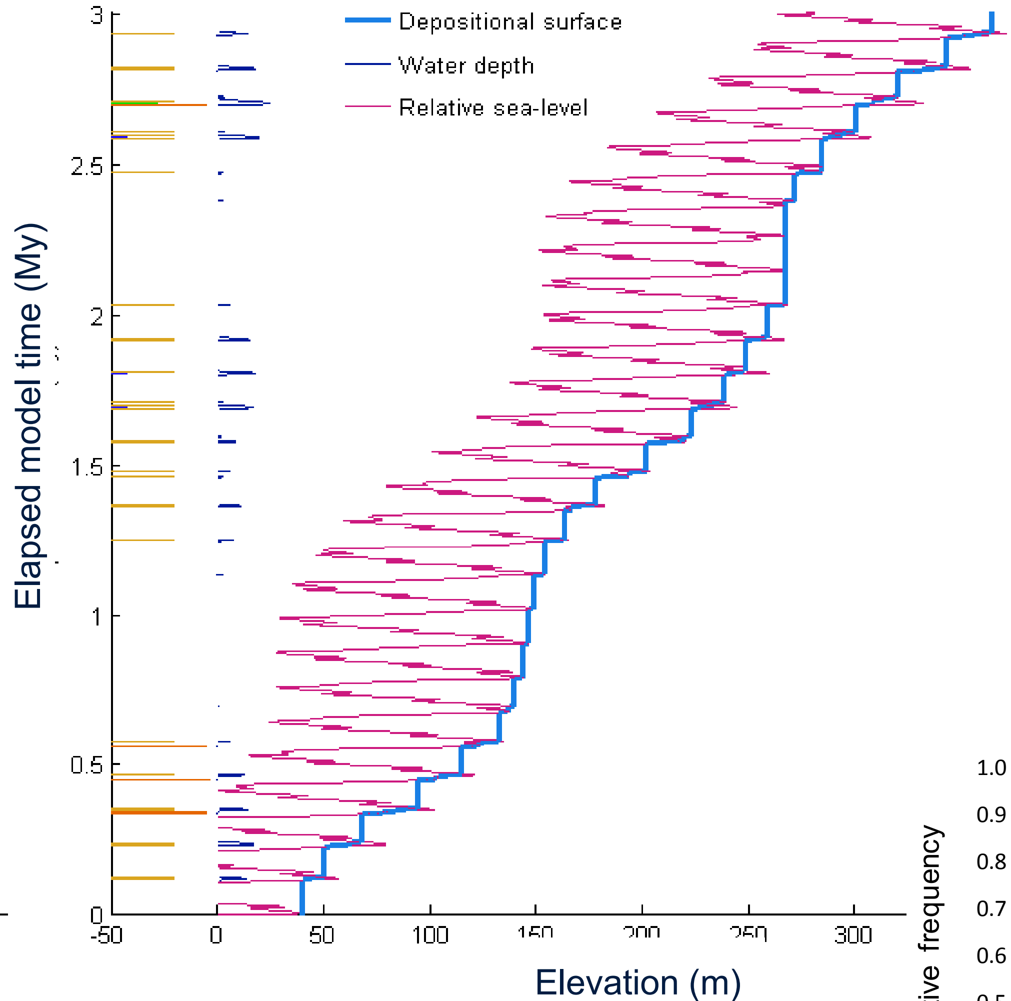
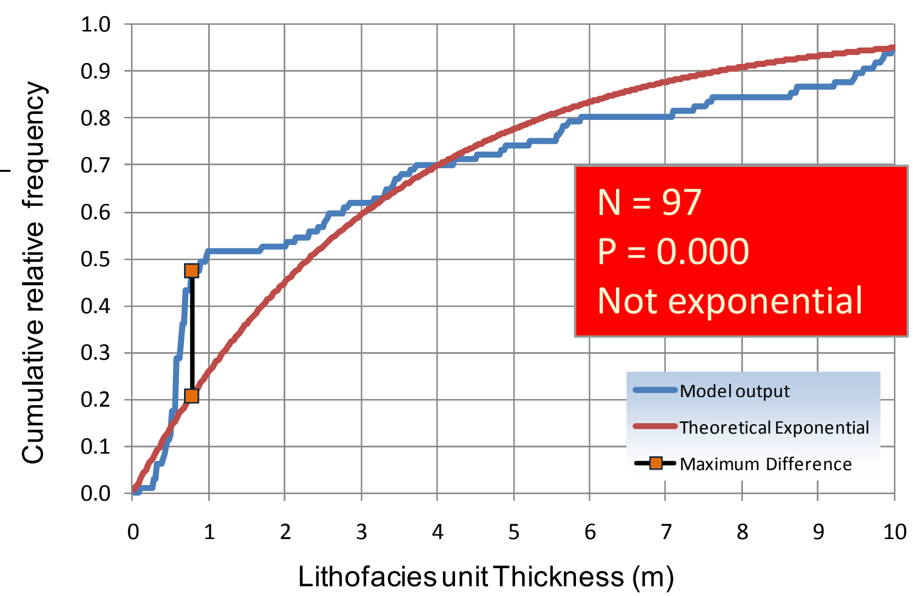




- Model with 20ky, 112ky and 1My period eustasy
- Lag depth 0m – no autocycles
- Duration 3 My
- All eustatic elements are symmetrical
- Euphotic and oligophotic production rates 2500mMy^{-1}
- Produces a non-exponential lithofacies thickness distribution



- Too many thin units < 2m thick
- Thin grainstone units form during rapid transgression

1D Modelling: Adding Complexity With AutoCycles

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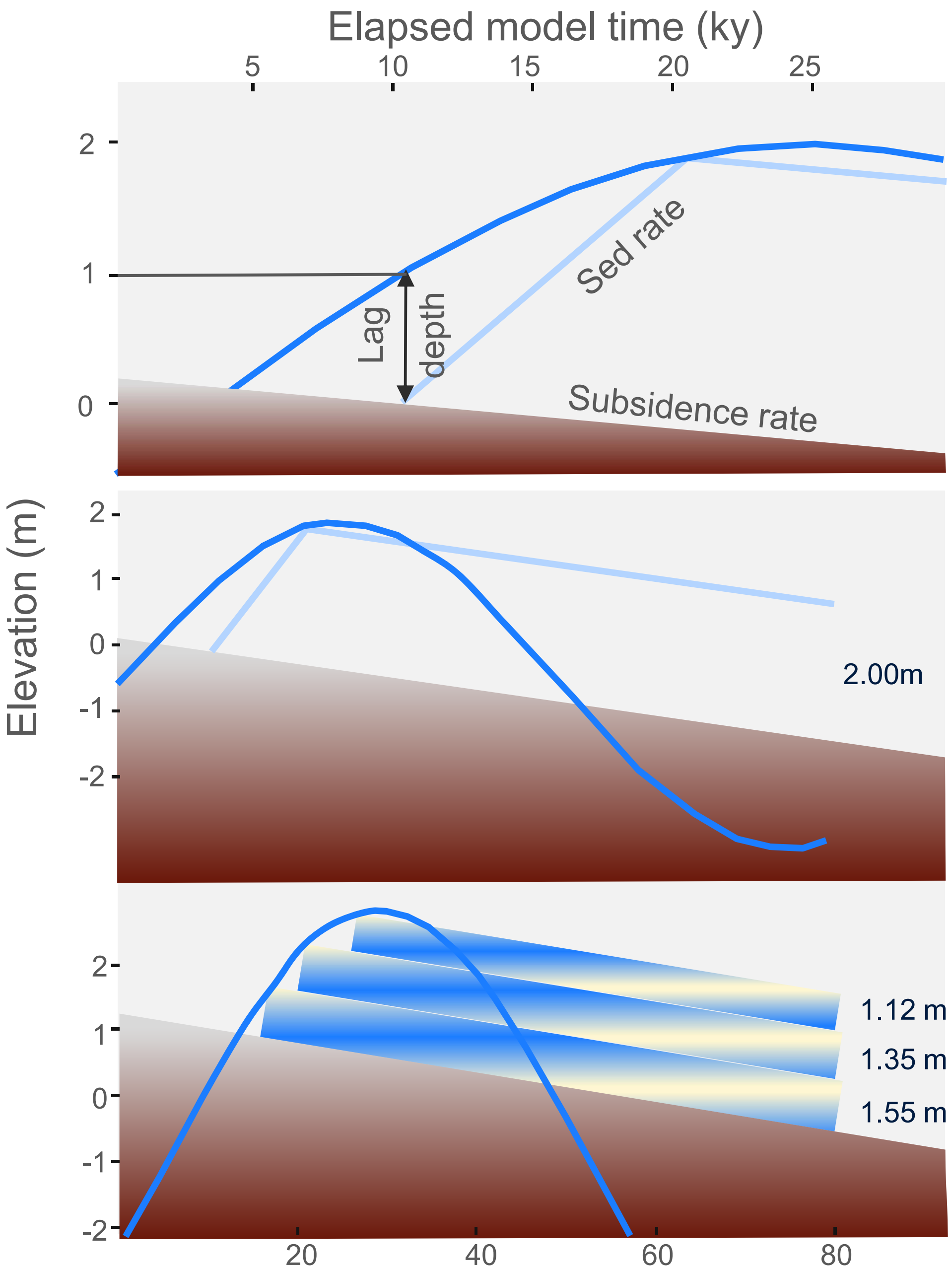

Lag depth = 1
Eustatic period = 100 ky
Eustatic amplitude = 5m
Subsidence rate = 20 mMy^{-1}
Production rate = 200mMy^{-1}

Lag depth = 1
Eustatic period = 100 ky
Eustatic amplitude = 5m
Subsidence rate = 20 mMy^{-1}
Production rate = 200mMy^{-1}

Lag depth = 1
Eustatic period = 100 ky
Eustatic amplitude = 14m
Subsidence rate = 40 mMy^{-1}
Production rate = 1000mMy^{-1}

Redrawn from Drummond and Wilkinson 1993, JSP, v.63, p.369-377

1D Modelling: AutoCycles & Exponentials

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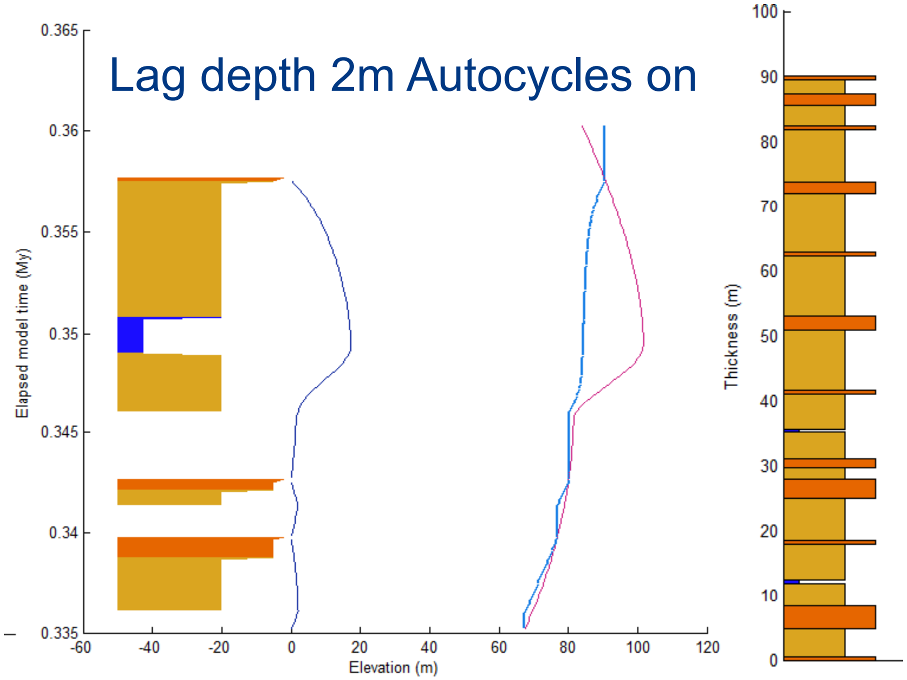
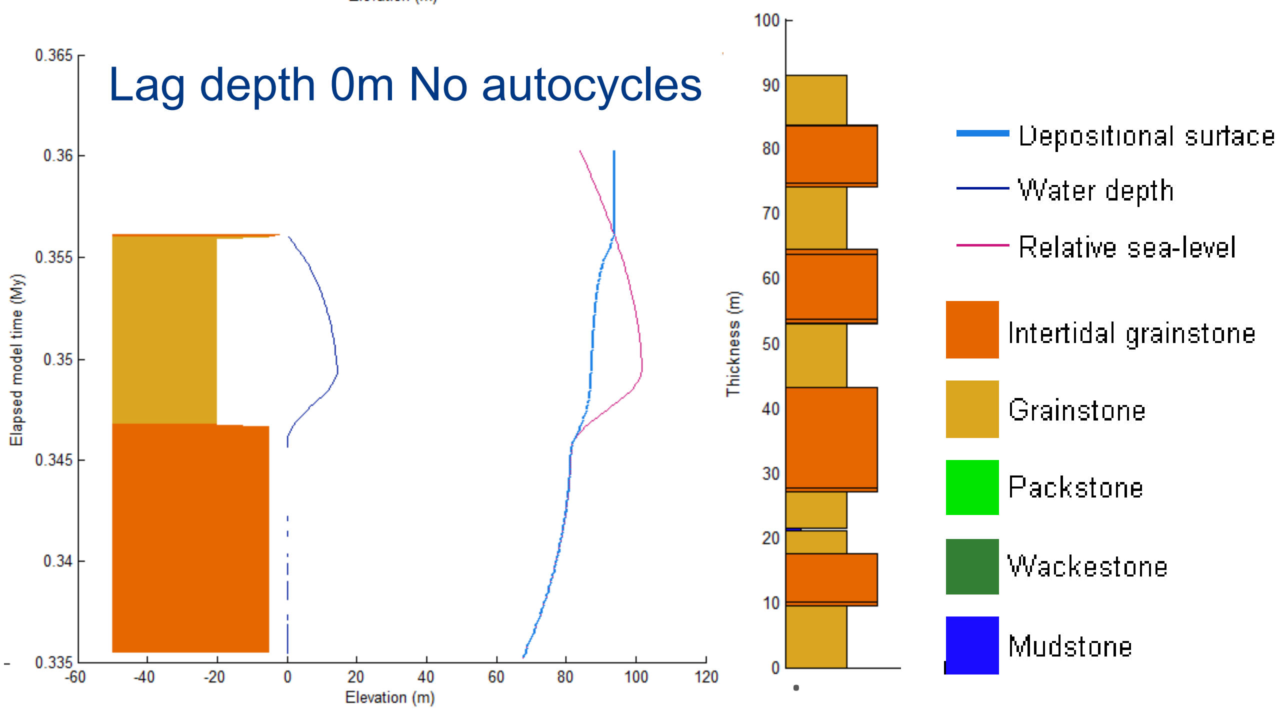


- Operation of lag depth combined with keep-up rates of carbonate production lead to generation of autocycles
- Autyocycles represent a somewhat complex interplay of accommodation and supply, with influence from both auto and allocyclic processes
- Autocycles influence the lithofacies thickness distribution produced…



1D Modelling: A Keep-Up Exponential Case

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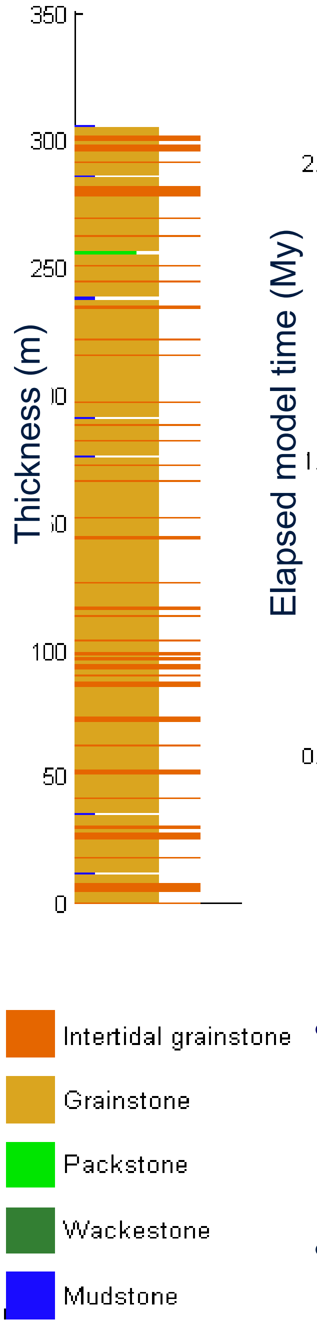
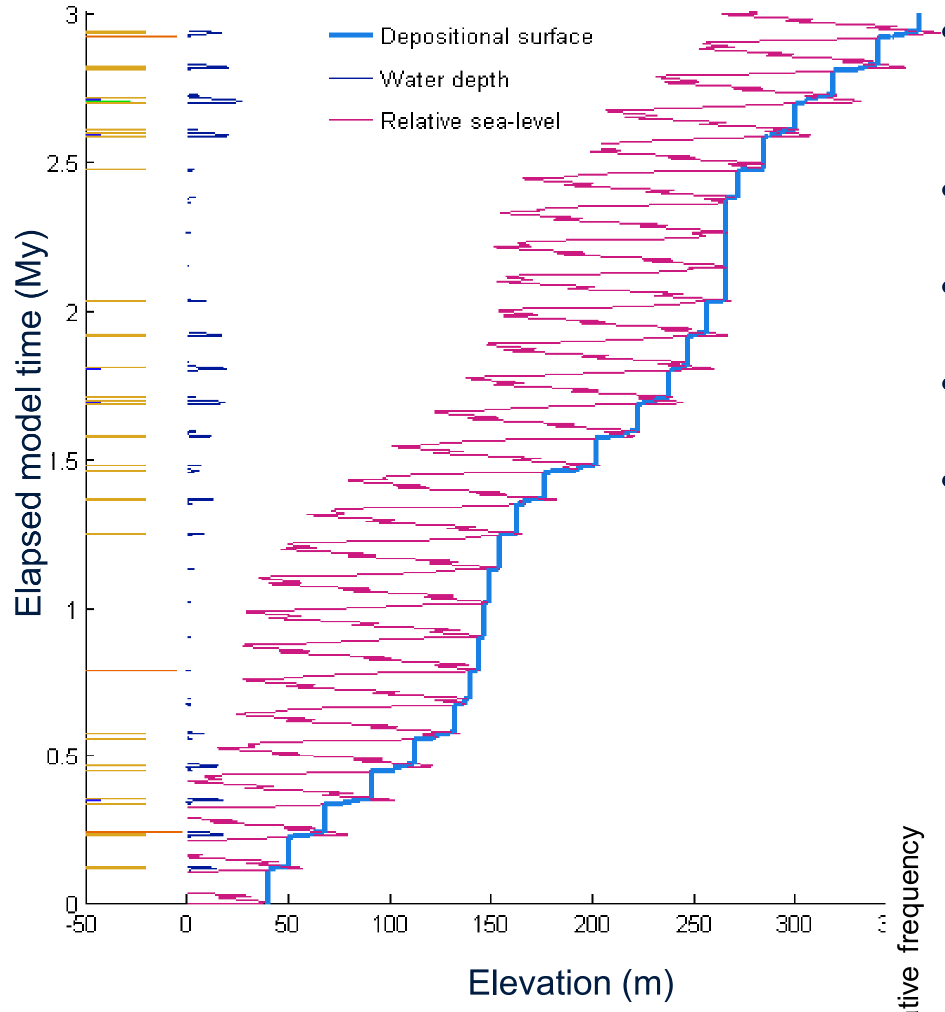
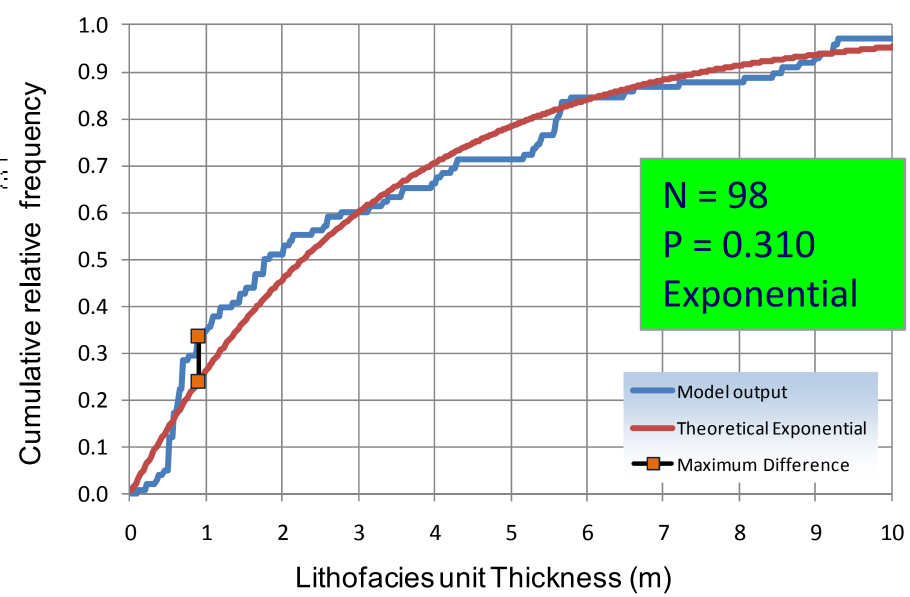




- Model with 20ky, 112ky and 1My period eustasy
- Lag depth 2m –lots of autocycles
- Duration 3 My
- All eustatic elements are symmetrical
- Euphotic and oligophotic production rates 2500mMy^{-1}

- Lag depth prevents deposition of too many thin grainstone units during rapid transgression
- Produces a clear exponential lithofacies thickness distribution



1D Modelling: Adding Complexity Leads to Exponentials?

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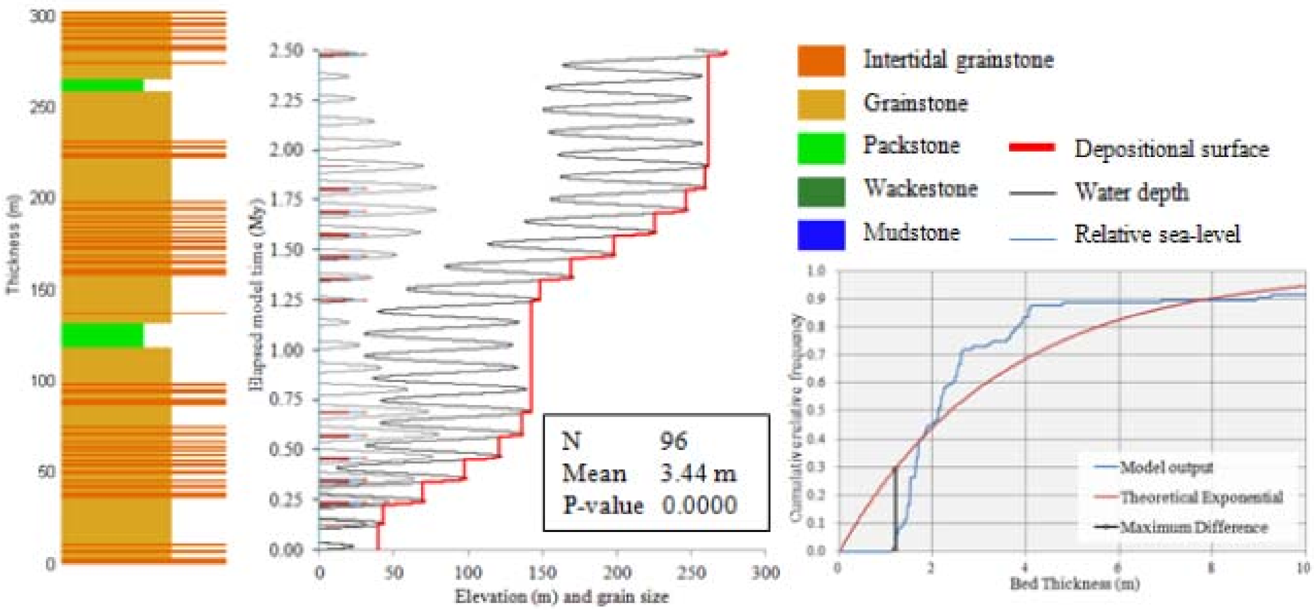
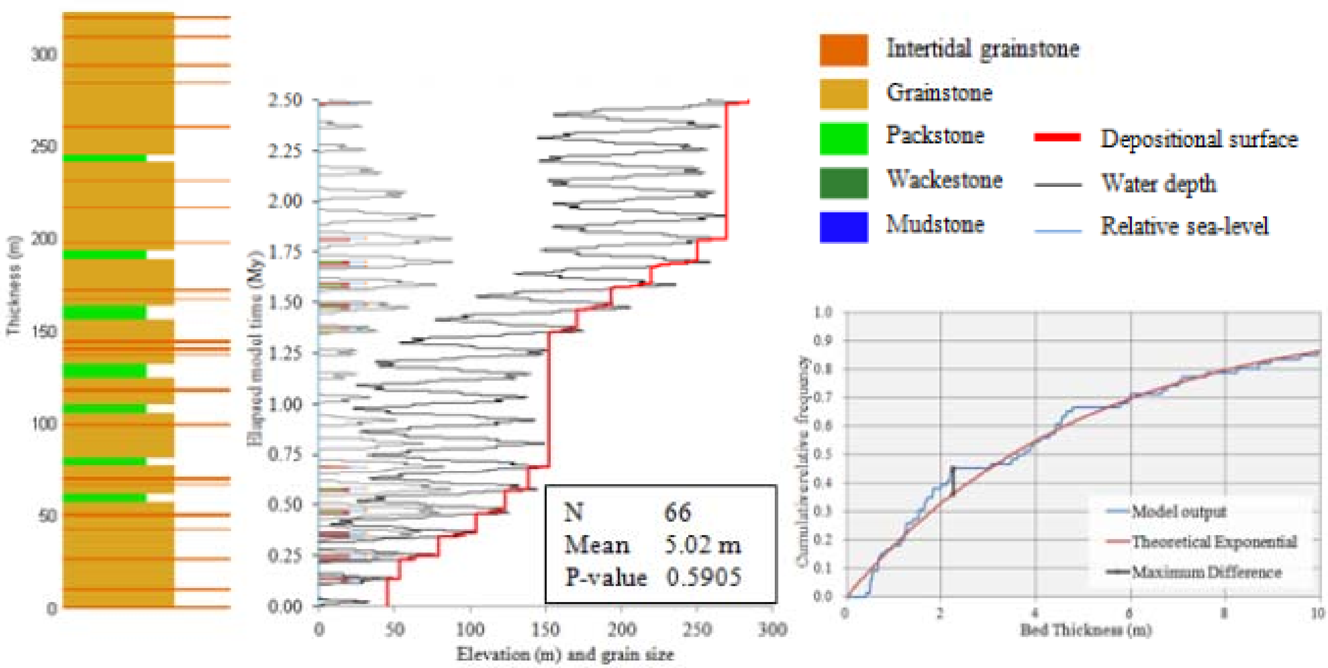


- Model with 112ky and 1My period symmetrical eustasy
- Lag depth 2m –lots of autocycles
- P=0.00 Not exponential



- Model with 23ky, 112ky and 1My period symmetrical eustasy
- Lag depth 2m –lots of autocycles
- P=0.59 Exponential

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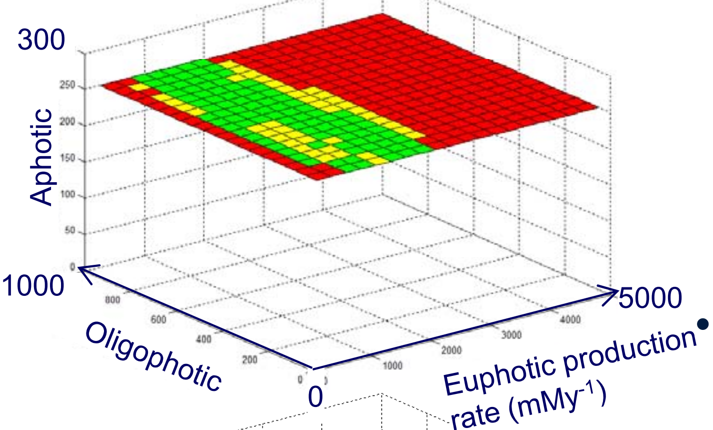
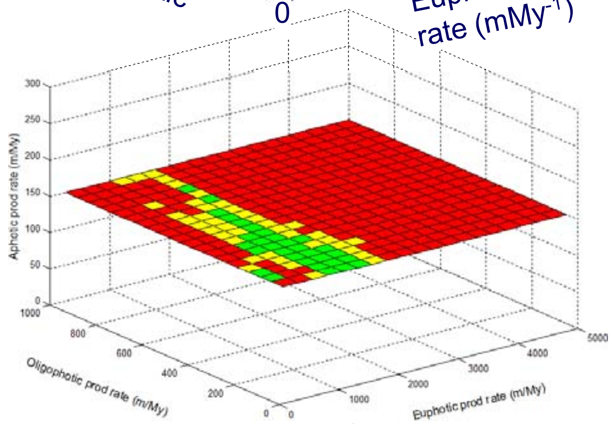
1D Modelling: Exploring the Whole Parameter Space

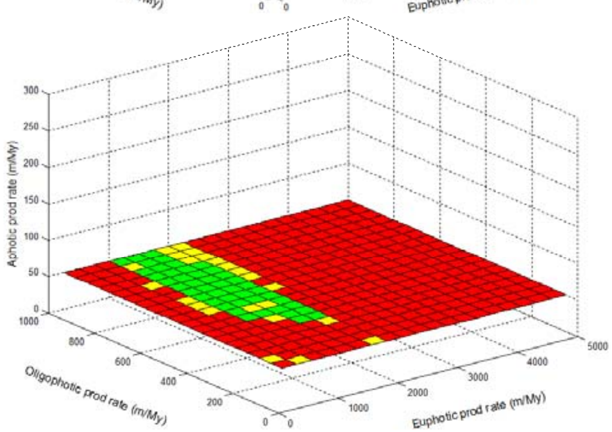
Model Set	Model set name	# of model runs	Range of production rates (mMy^{-1})	Range of amplitudes of eustatic sea-level oscillations (m)	Asymmetry of eustatic oscillations	Lag depth (m)	Proportion of model runs		
							P ≤0.01 Not exponential	0.1>*P*>0.01 Indeterminate	*P*≥0.10 Exponential
1	Variable production symmetrical SL	4800	250–5000, 50-1000, 25-300	10, 50 & 20	1:1	2	75.6%	9.8%	14.6%
2	Variable production asymmetrical SL	4800	250-5000, 50-1000, 25-300	10, 50 & 20	1:4	2	52.2%	37.7%	10.1%
3	Variable SL Low production rate lag 2m	4400	500	2.5-50, 5-100, 0-50	1:4	2	62.1%	15.3%	22.6%
4	Variable SL High production rate lag 2m	4400	2500	2.5-50, 5-100, 0-50	1:4	2	49.8%	32.6%	17.6%
5	Variable SL Low production rate lag 0m	4400	500	2.5-50, 5-100, 0-50	1:4	0	85.6%	9.3%	5.1%
6	Variable SL High production rate lag 0m	4400	2500	2.5-50, 5-100, 0-50	1:4	0	87.5%	7.3%	5.2%

1D Modelling: Exploring the Whole Parameter Space

Variable production, symmetrical SL oscillations







Symmetrical oscillations

- Exponential examples occur for narrow range of euphotic production rates and are relatively insensitive to oligophotic and aphotic production rates.
- High euphotic rates produce too many thick units

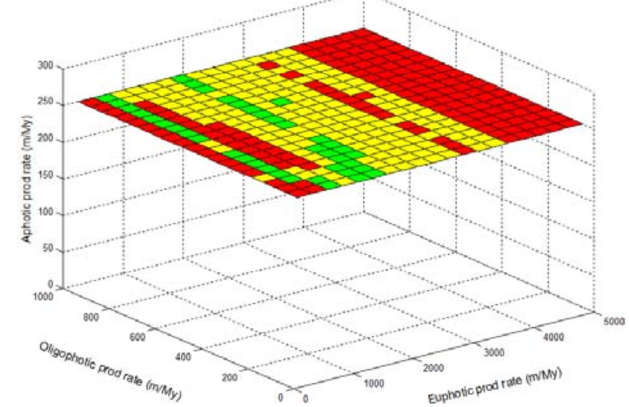
Asymmetrical oscillations

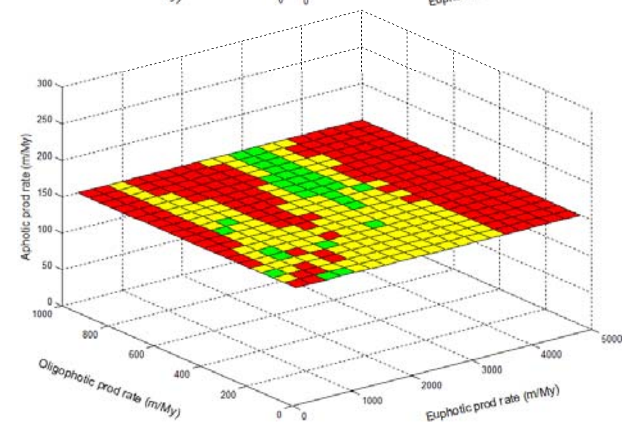
- Distribution of exponentials is more complicated due to asymmetric curve
- Overall number of occurrences of exponentials are similar in asymmetrical versus symmetrical cases

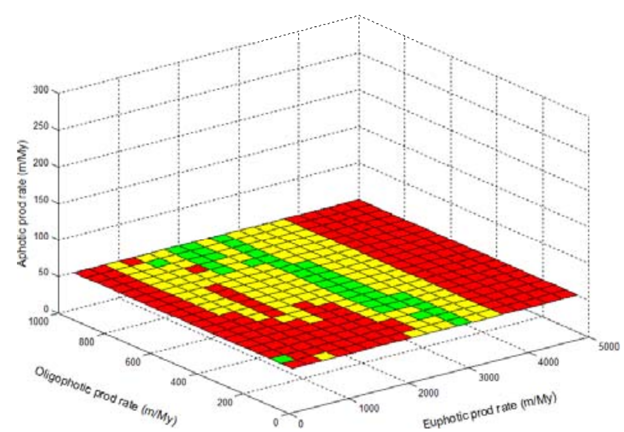
n=4400 for each plot

- Green: $p < 0.01$, good match with exponential
- Yellow: $0.1 < p > 0.01$, indeterminate
- Red: $p \geq 0.10$, poor match with exponential

Variable production, asymmetrical SL oscillations







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Next Steps: More 1D Modelling & Outcrop Analysis

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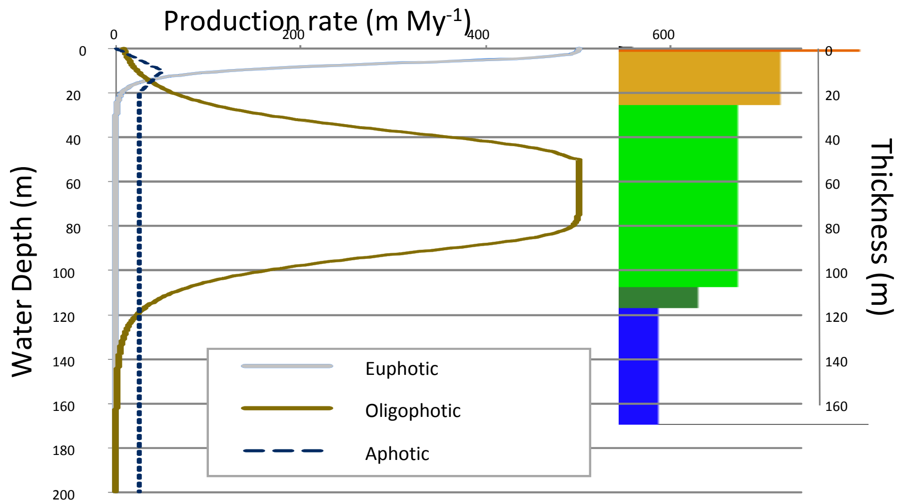
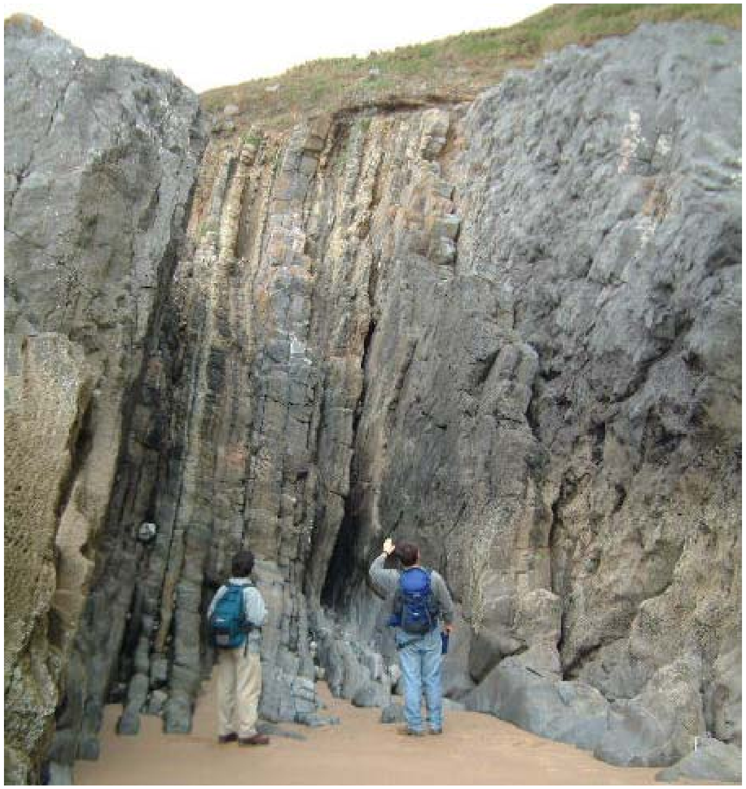
- Need to consider very carefully how the model results are influence by the model assumptions and run more models with different assumptions e.g. different production profiles
- A key objective is to compare model output directly with outcrop examples via inversion methods to see if additional insight can be gained this way
- Also need to consider the objectivity and repeatability of section logging…





Next Steps: 3D Modelling

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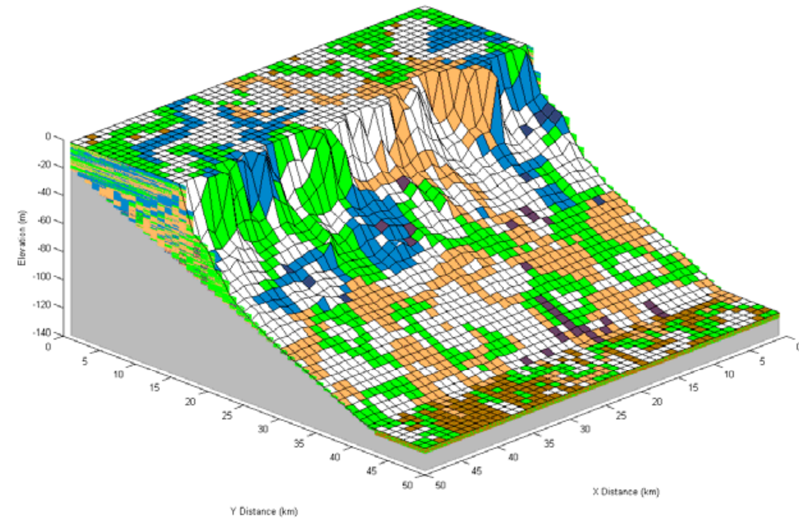
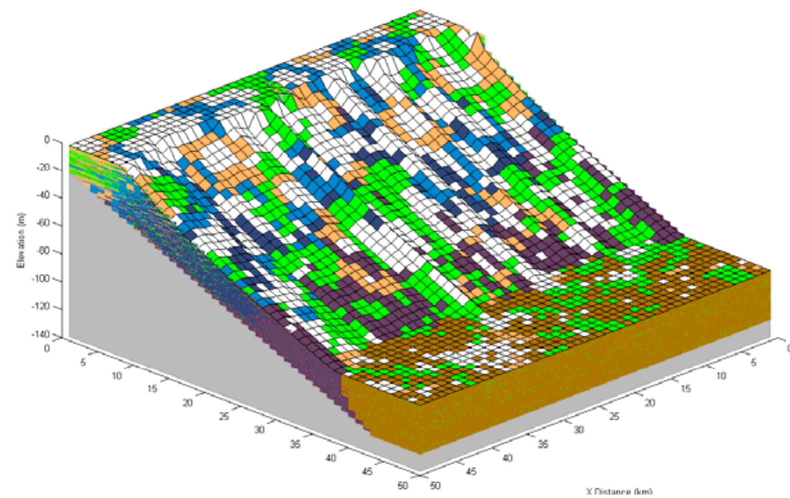
- How do the results from the 1D modelling translate into 3D systems? Do the processes identified that create exponentials in 1D modelling also create exponentials in 3D modelling?



- In 3D, how do vertical thickness distributions relate to facies stacking and facies lateral extents in deterministic models?



- Currently under investigation using new 3D model CarboCAT

Conclusions

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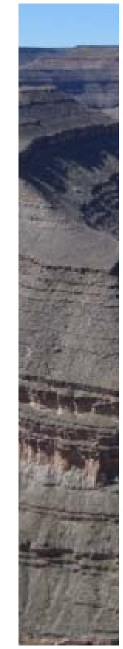
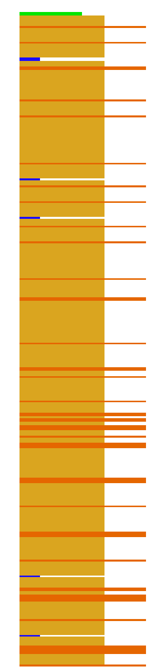


- Exponential lithofacies thickness distributions can be generated from a purely deterministic model.
- Increasing the complexity in the model tends to lead to formation of exponential thickness distributions. Examples of increased complexity are additional frequency components of a eustatic sea-level curve, and adding autocycle processes.
- Rate of sediment production is a key control. Euphotic factory production rate appears to be a dominant control in these model runs, but probably only because it has the highest production rates and is most responsible for a “keep-up” stacking pattern
- Only 13% of the 27200 model runs created exponential distributions, compared to 28% in the documented outcrop examples, suggesting that other processes not included in this model play an important role e.g. erosion during subaerial exposure, various sedimentary processes that occur in three dimensions on platform tops and slopes…
- Need to test these conclusions further with newly developed 3D models



Backup slides

1D Modelling: Exploring the Whole Parameter Space

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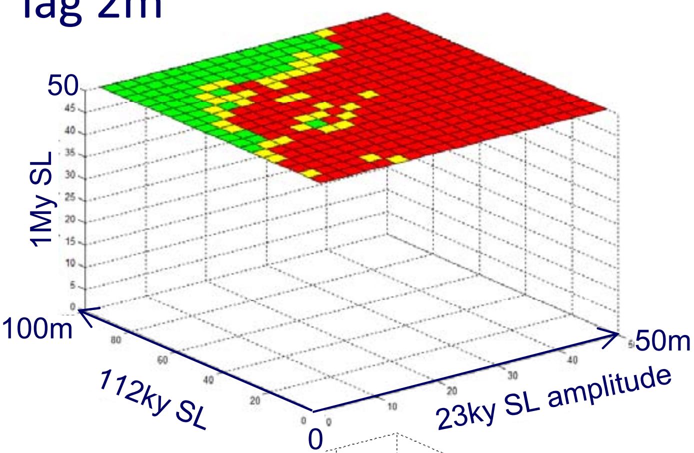
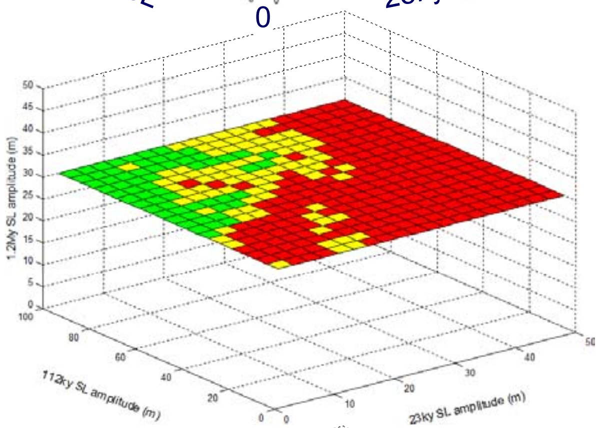
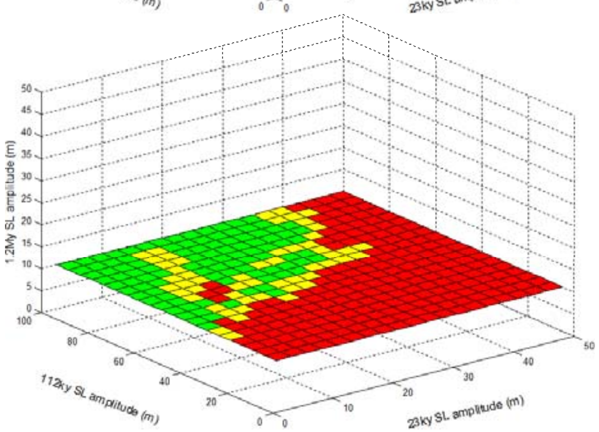
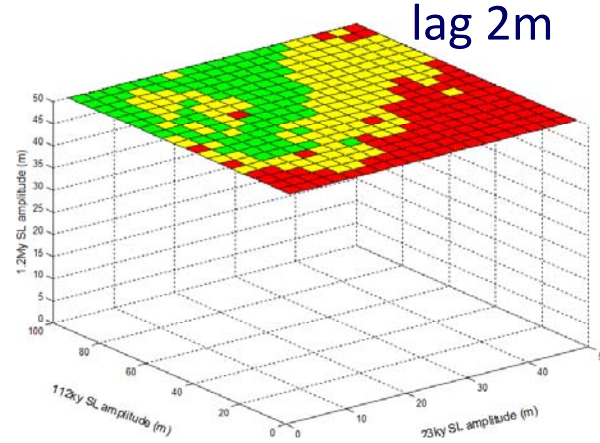
Variable SL, production 500mMy^{-1}, lag 2m

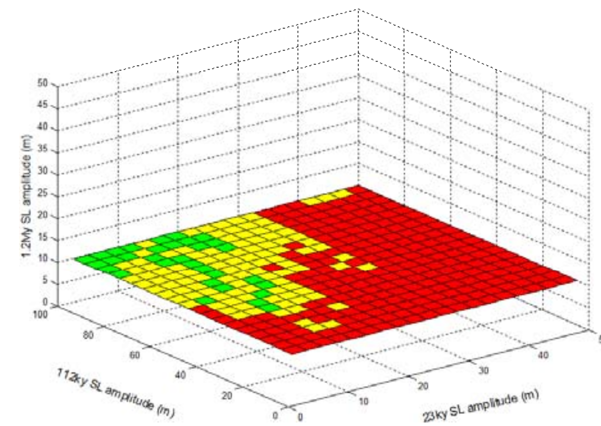


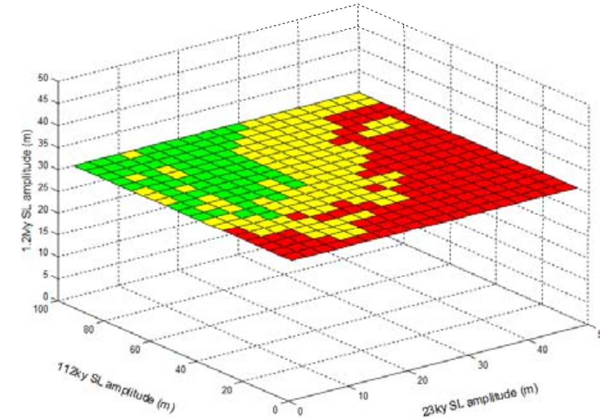




Variable SL, production 2500mMy^{-1}, lag 2m







Production 500mMy^{-1}, lag 2m

- Exponential distributions occur most frequently at lower amplitudes of 23ky-period eustatic oscillations but higher amplitudes of 112ky-period oscillations
- Higher amplitudes of 112ky SL oscillations create complex accommodation variations and autocyles, favouring exponentials

Production 2500mMy^{-1}, lag 2m

- The pattern at higher production rate is similar but with an extended range of Sl amplitudes

n=4800 for each plot

- $p < 0.01$, good match with exponential
- $0.1 < p > 0.01$, indeterminate
- $p \geq 0.10$, poor match with exponential

1D Modelling: Exploring the Whole Parameter Space

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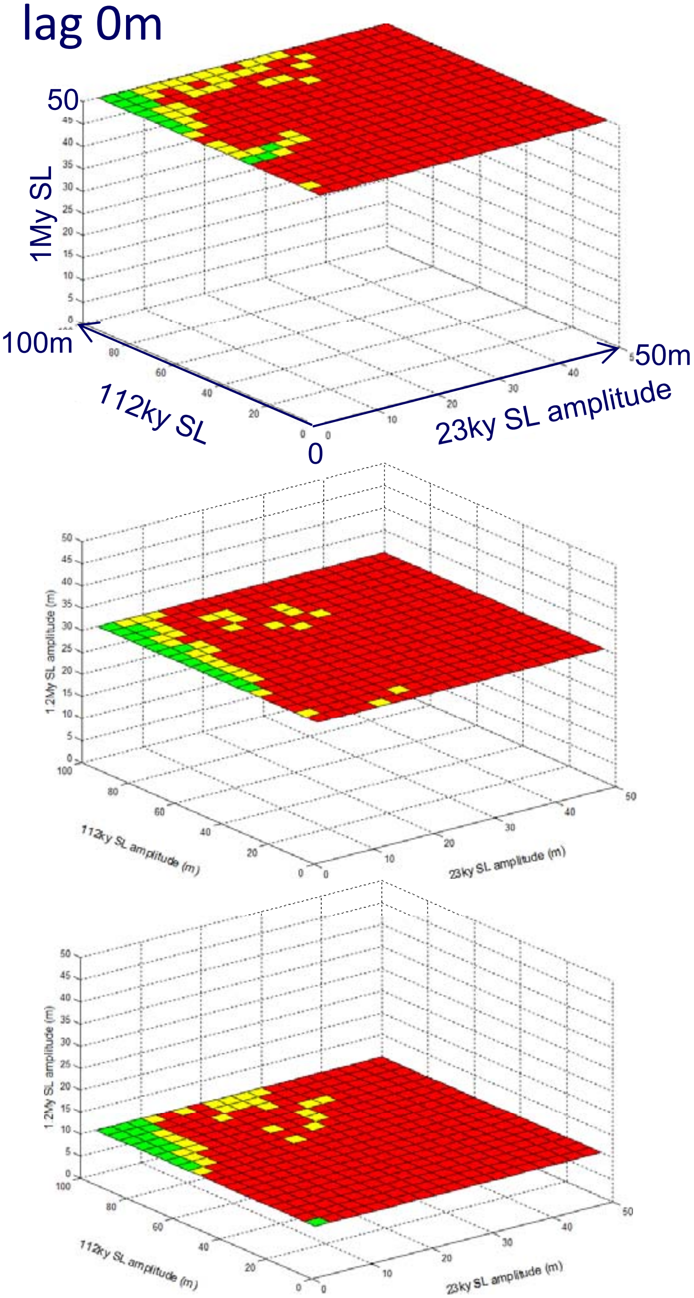
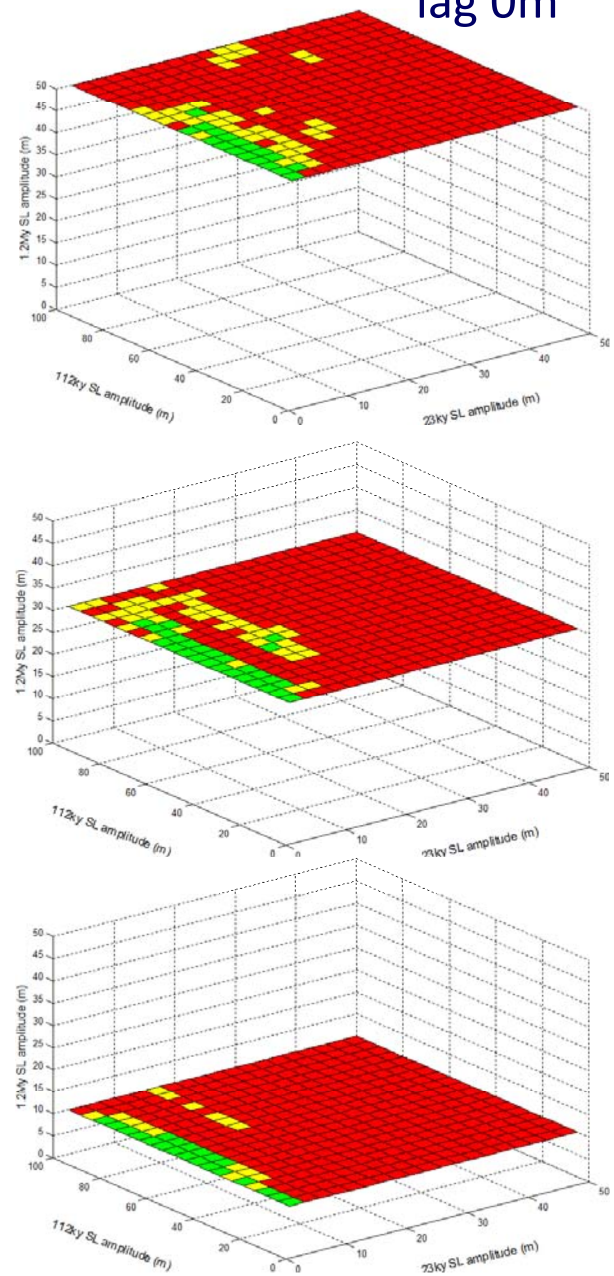
Variable SL, production 500mMy^{-1}, lag 0m



Variable SL, production 2500mMy^{-1}, lag 0m



- Both low and high production cases show very few exponential examples across the range of modelled SL amplitudes
- In high production cases the lack of lag and hence the lack of autocycles causes too many thick beds for an exponential distribution

n=4800 for each plot

- p < 0.01, good match with exponential
- 0.1 < p > 0.01, indeterminate
- p ≥ 0.10, poor match with exponential