PS The Origins of Shallow-Water Carbonate Lithofacies Thickness Distributions: 1D Forward Modelling of Factory Type and Relative Sea-Level Control*

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Abstract

The observation that shallow-marine carbonate strata often have exponential lithofacies thickness distributions is one of the most fundamental results in carbonate stratigraphy in recent years. This is both because it is an observation that can be tested for its repeatability in outcrop and subsurface examples, and also because it raises the 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 and oceanographic change through geological time.

This study applies a simple 1D numerical stratigraphic forward model of carbonate platform strata (Dougal) to investigate how relative sea-level oscillations could control lithofacies distribution. 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 behavior 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. Results of multiple model runs (more than 27,000 in total) spanning a range of production and accommodation creation rates, demonstrate that the accommodation and sediment supply do act as major, though non-linear, controls on carbonate lithofacies distribution, but significantly that lithofacies distributions also have an autocyclic control through oscillations in deposition during certain high-frequency rising limbs on the glacio-eustatic curve. In these multiple model runs only about 13% of the total runs created exponential distributions, compared to 28% in the documented outcrop examples, also suggesting that other processes, including three-dimensional process not included in this model, play an important role.

In addition to providing some understanding of the nature of lithofacies thickness distributions under varying oceanographic and climatic regimes, the findings presented here have broader implications. This is particularly true where lithofacies thickness has an impact on the performance and productivity of hydrocarbon reservoirs, such as economically-important platform and ramp interiors in both icehouse and greenhouse settings.

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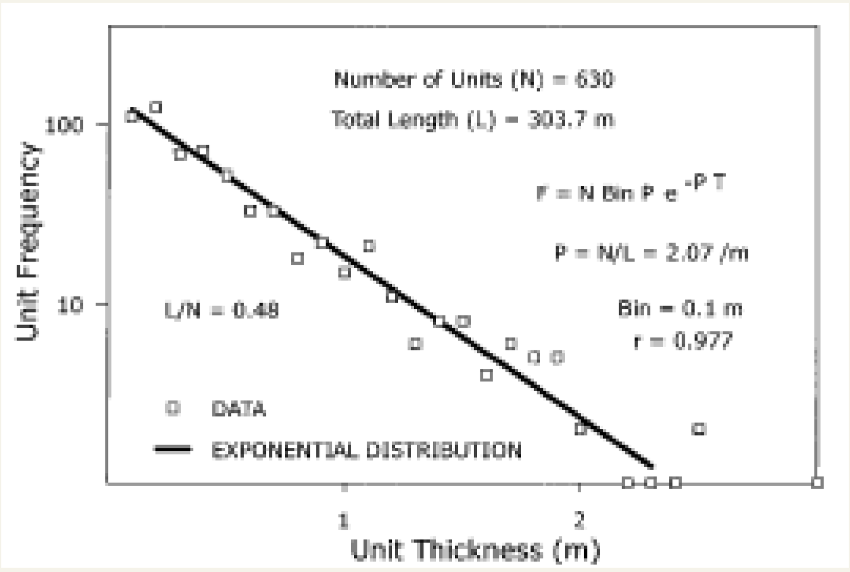
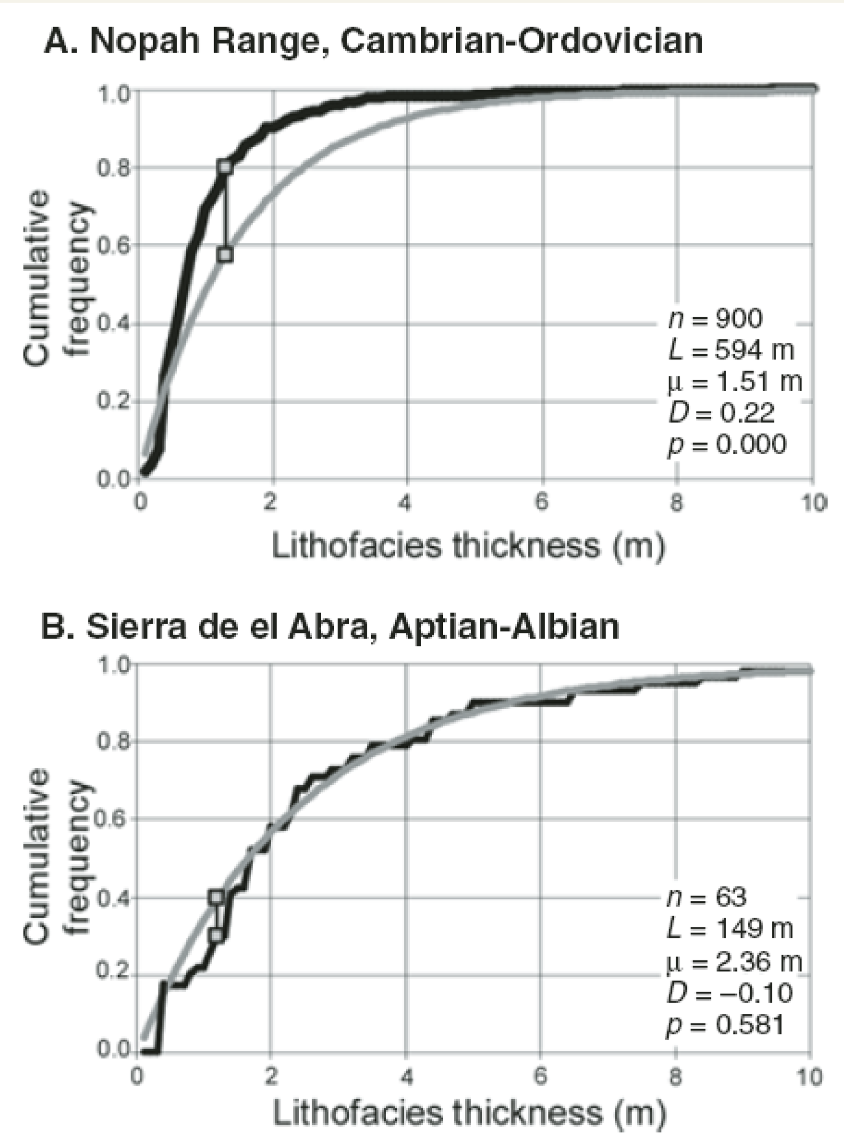
1 The Data

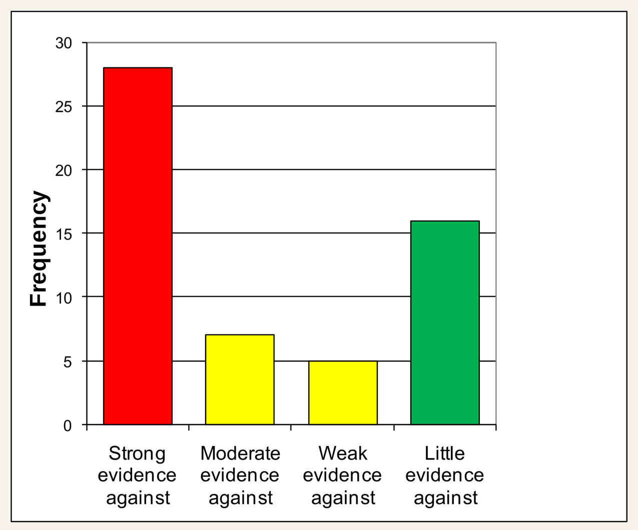


Data from Wilkinson et al. (1999) showing an exponential distribution of lithofacies thickness in Cambro-Ordovician carbonate strata outcropping in Wytheville, Virginia. The solid line is not a regression line but rather is theoretical exponential thickness-frequency calculated for Poisson populations of several different lithofacies types with the same number of units and the same mean thickness as the outcrop data

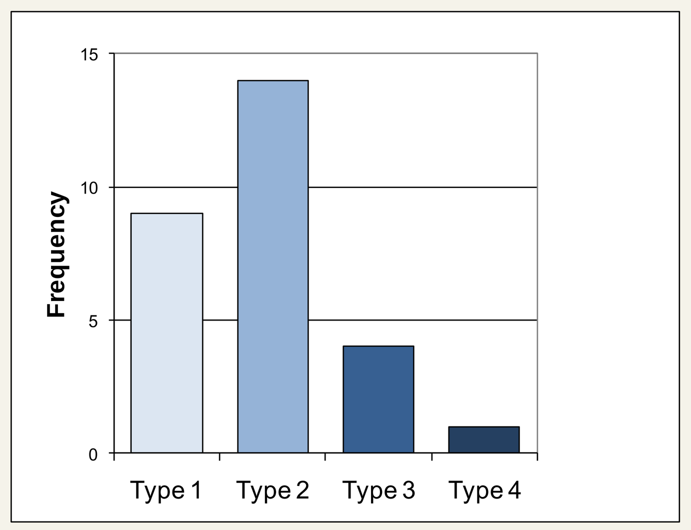
- Based on careful observations from many Neoproterozoic and Palaeozoic platformal carbonate outcrops Wilkinson et al. (1997 & 1999) asserted that a fundamental property of carbonate strata is an approximately exponential lithofacies thickness distribution
- An exponential distributions simply means many thin beds, and proportionately fewer thick beds, but with a particular rate of decrease in frequency from thin to thick
- Further testing in Burgess (2008) based on KS testing of outcrop data against theoretical exponentials showed that the situation is slightly more complex
- Results from this analysis show that 16 of 56 outcrop examples can be confidently shown to be exponential, while 28 are very probably not exponential, though still with a many-thin and few-thick lithofacies unit pattern
- All of which raises several questions that this poster will frame and make some tentative initial steps to answer…



From Burgess (2008) Examples of lithofacies thickness data plotted as cumulative frequency plots with accompanying theoretical exponential curves calculated based on the number of lithofacies units and the mean thickness of the outcrop data so $F(t)=1-e^{-(N/L)t}$ where t is unit thickness, N is number of lithofacies units and L is the total thickness. The degree of match of the outcrop thicknesses with the theoretical exponential is calculated using the Kolmogorov-Smirnov (KS) test (e.g. Press et al. 1992) based on D, the maximum offset or different between the two observed and the exponential distribution marked by the vertical lines with end circles. The KS test calculates a significance probability p that is the probability that values of D at least as extreme as that observed would occur just by chance sample variation if the distribution was an exponential. Low values of p ($p \leq 0.01$) indicate the distribution is probably not exponential (example A) while higher values of p ($p \geq 0.10$) indicate provide insufficient evidence to reasonably reject an exponential interpretation; in these cases an exponential distribution can be considered a good model to represent the observed thickness data.

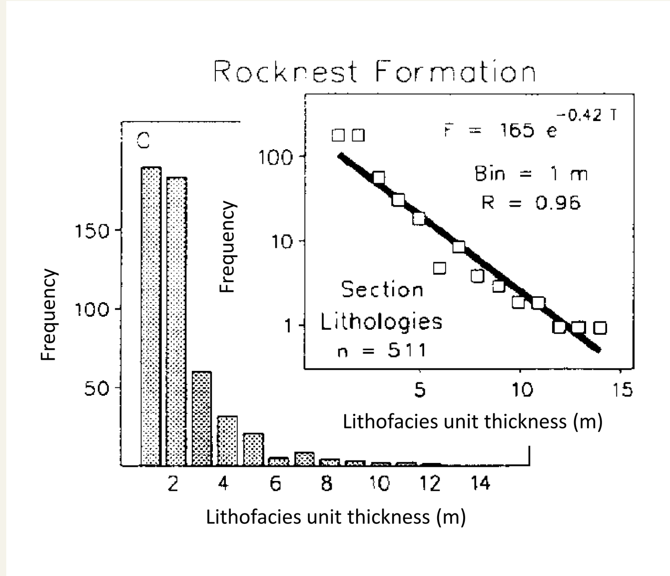


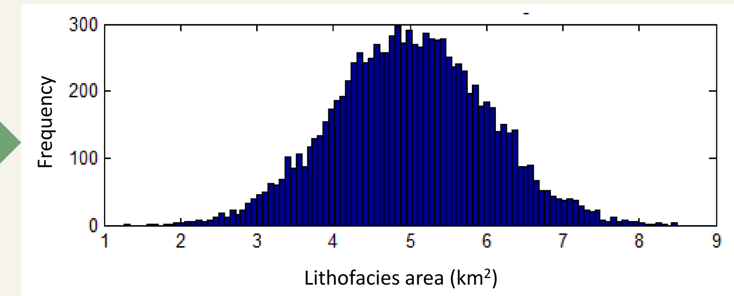
From Burgess (2008). Frequency of Kolmogorov–Smirnov test significance probability p values, categorized by degree to which they refute the null hypothesis that sample lithofacies thickness distribution is indistinguishable from an exponential distribution. The plot shows that just over half of the 56 outcrop sections deviate markedly from an exponential lithofacies thickness distribution, that 16 of the examples are well matched by an exponential model, and that the nature of the remaining 12 is more uncertain.



From Burgess (2008). Frequency plot of the non-exponential outcrop cases classified according to how observed curve differs from an exponential. Type 1 has relatively few thin and intermediate thickness lithofacies units, and too many thick units. Type 2 has too few thin units, and too many intermediate and thick units. Type 3 has too many thin units, and too few thick. Type 4, of which there is only one case, has too few thin and thick units, and too many intermediate thickness units.

2 Why are lithofacies thickness distributions important?





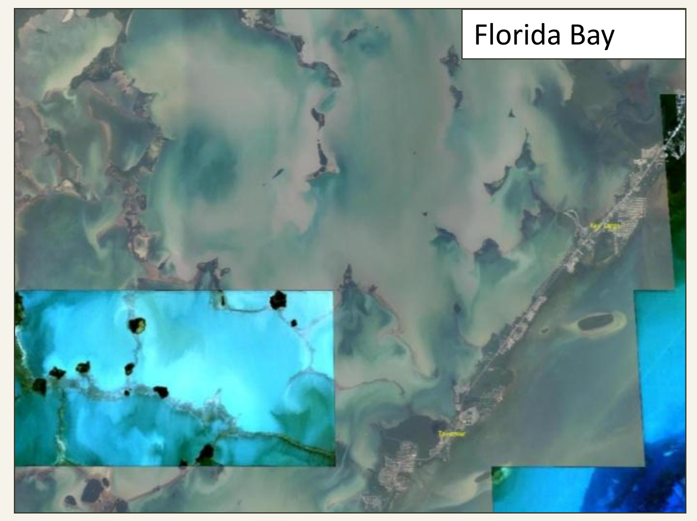
??

What kind of lithofacies areal extent distributions exist in ancient carbonate strata?

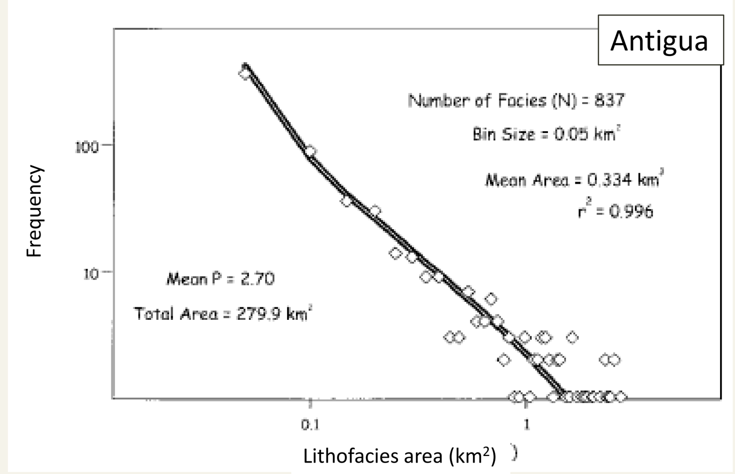
? ?

Do lithofacies thickness distributions contain any information on lithofacies areal extents?

Nb Lithofacies thickness distributions, exponential or otherwise, have nothing per se to do with order versus disorder unless specific processes of formation are invoked to explain their formation, and even then the link is complicated.



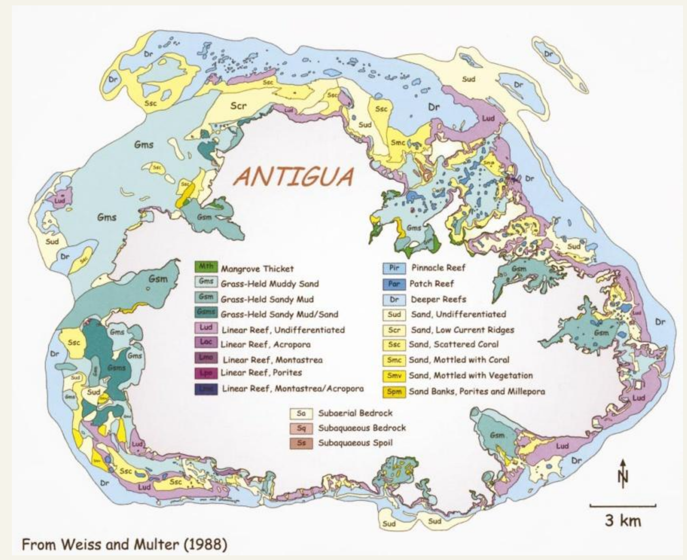
from Wilkinson & Drummond (2004)



Modern carbonate deposystems contain abundant information on lithofacies areal extents, BUT are these area distribution "snap shots" representative for the ancient record?

What happens to the lithofacies areas when they go through the preservation filter?

And what kind of lithofacies thickness distributions would result from the above modern deposystems?

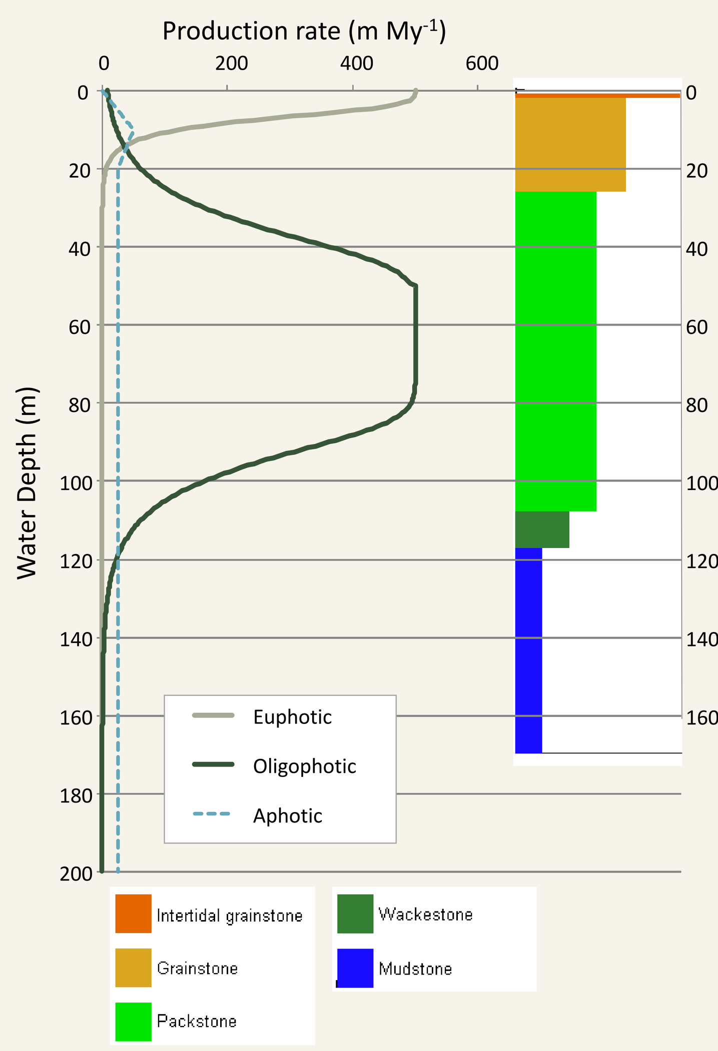


from Wilkinson & Drummond. (2004)

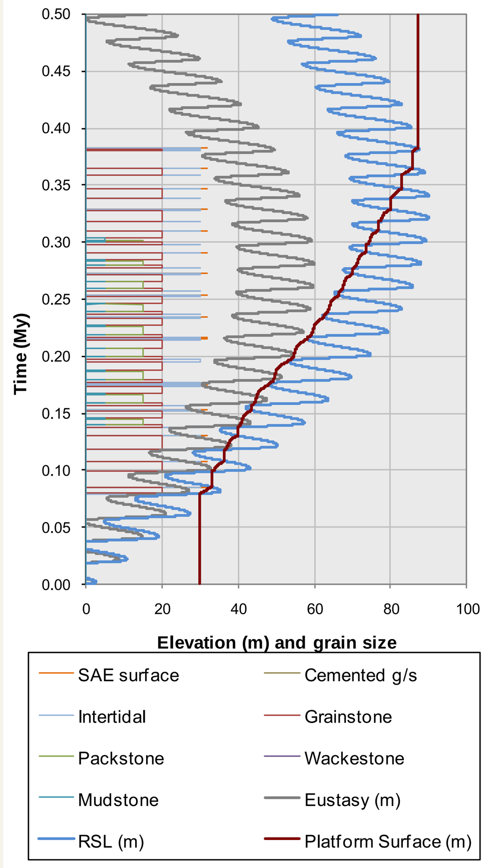
3 Questions arising…

- Why so many thin lithofacies units and relatively few thick units?
- What depositional processes are responsible for this pattern?
- What are the implications of this pattern for lateral extent of carbonate lithofacies and their areal size distributions??

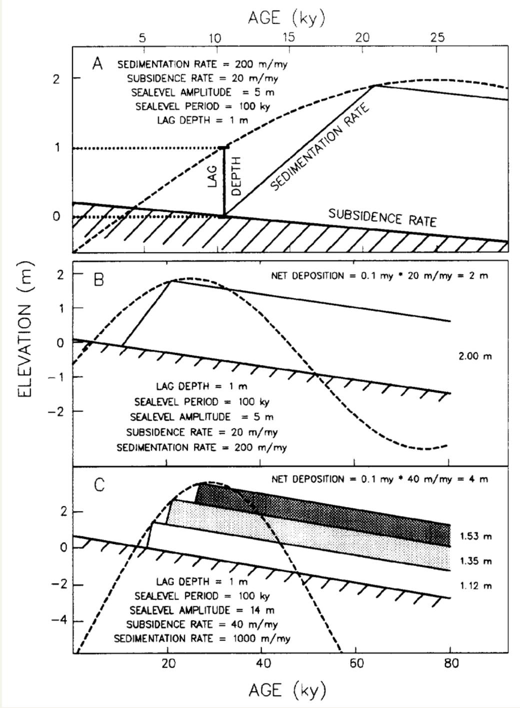
4 A model called Dougal



- A 1D SFM for platform-top deposition (Pollitt, 2008); Burgess and Pollitt (in review)
- Three production profiles accumulating five lithologies
- Variable production rate of each profile
- Also subsidence and erosion by disolution
  - But also an important control from lag-depth autocycles
  - Multiple cycles per eustatic rising limb



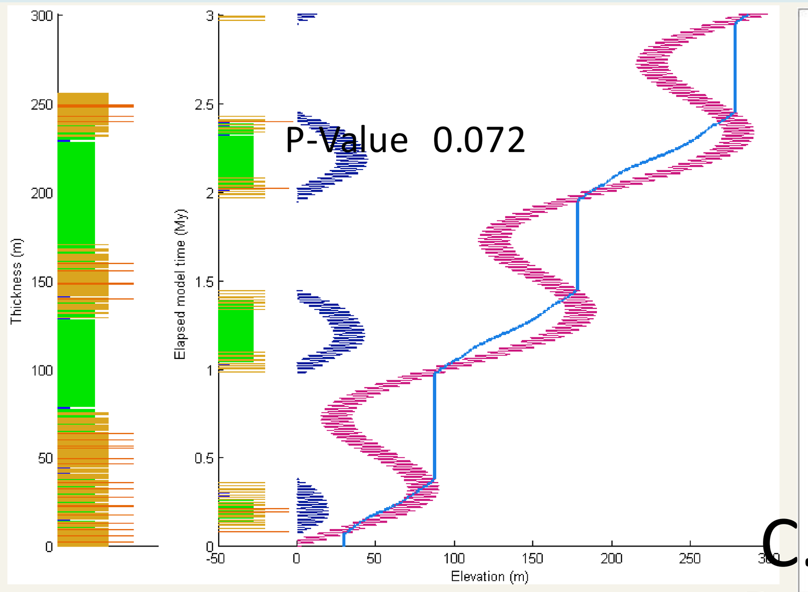
- Eustatic oscillations drive accommodation variations that control facies thicknesses

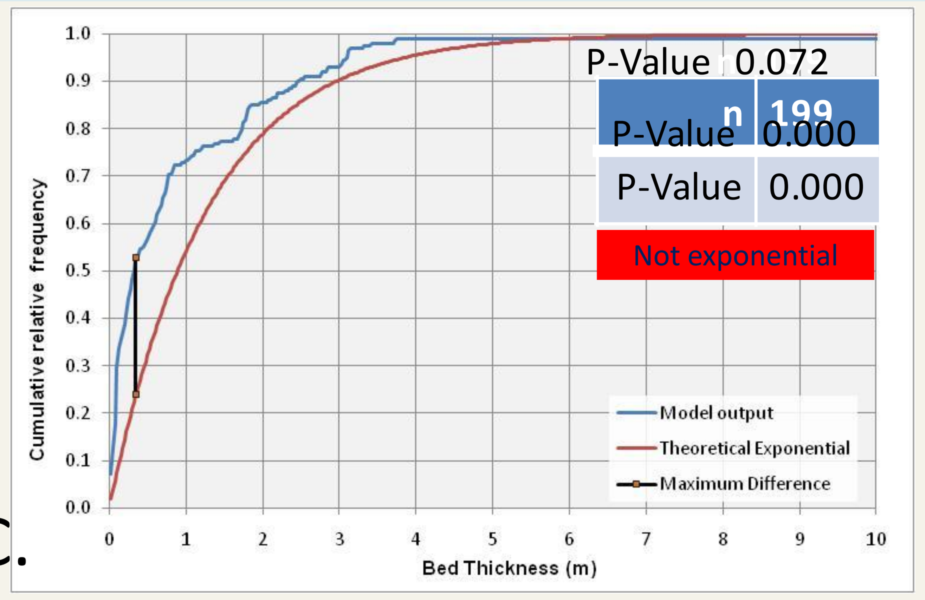


5 Single Dougal Runs: Production, RSL and autocycle control on lithofacies thickness distributions

A. B.

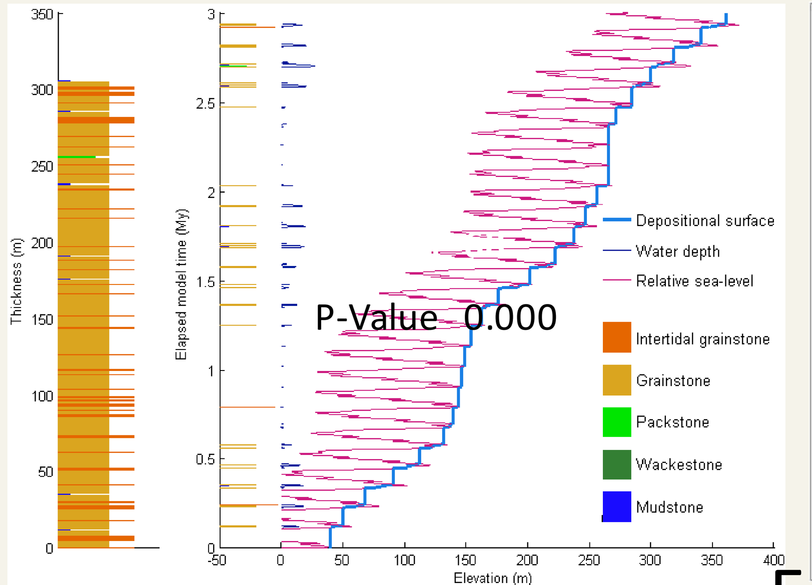
Model Case 1 20 ky, 10m & 1.2My 50m asymmetric eustasy, low production rate, no lag depth, 3My duration

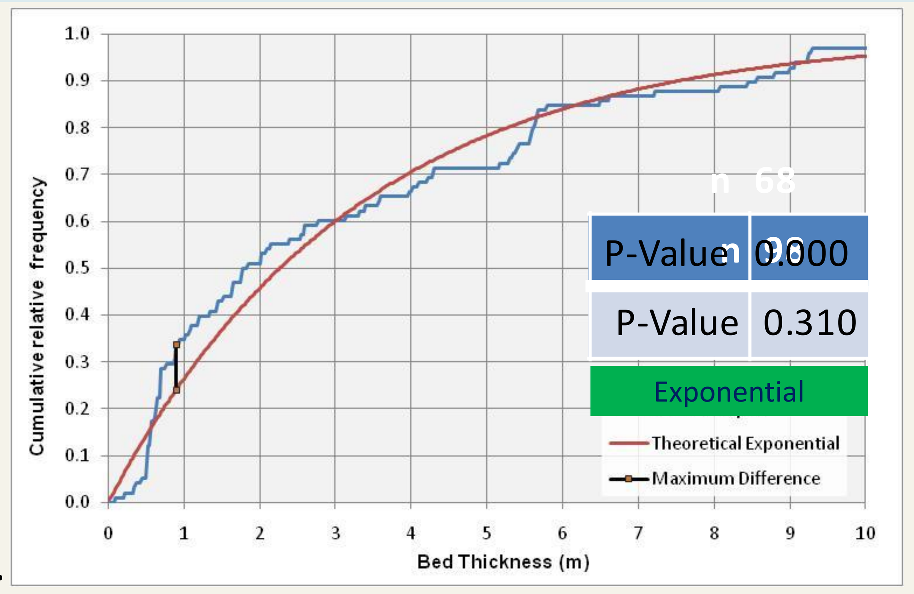




C. D.

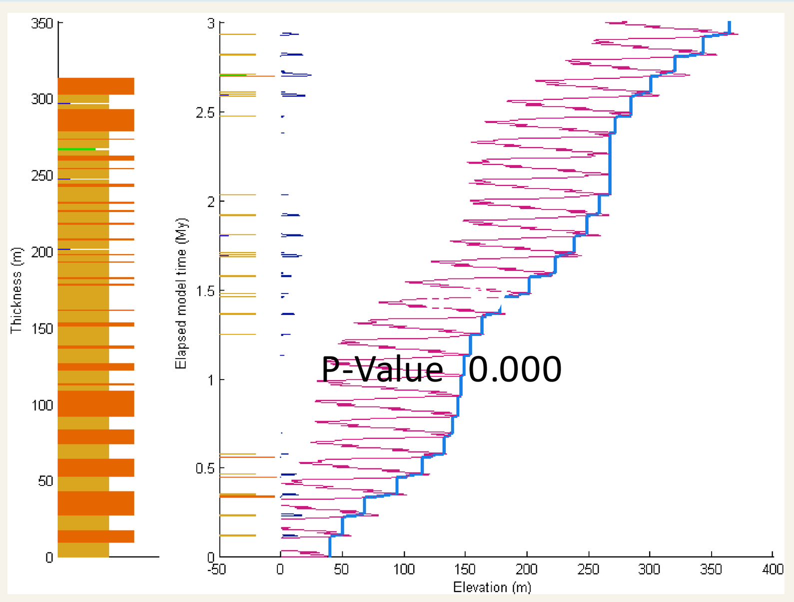
Model Case 2 23 ky10m & 112ky 50m & 1.2My 20m asymmetric eustasy, high prod rate, lag depth 2m, 3My duration

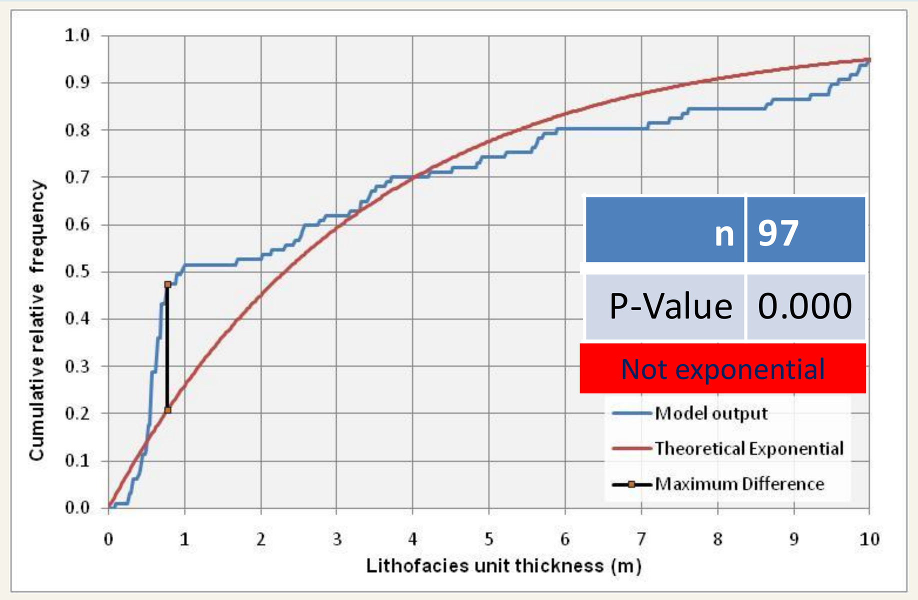




E.

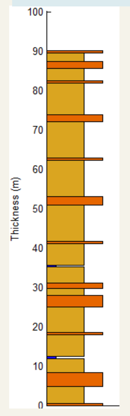
Model Case 3 23 ky10m & 112ky 50m & 1.2My 20m asymmetric eustasy, high production rate, no lag depth, 3My duration





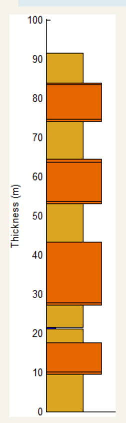
- Exponential lithofacies thickness distributions are possible with deterministic models.
- Production rate, relative sea-level history and operation of autocyclicity related to lag depth are all important controls on occurrence of exponential distributions.

Case 2: Allocyclic forcing & lag-depth autocycles

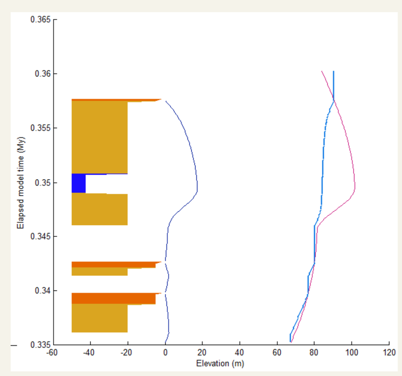


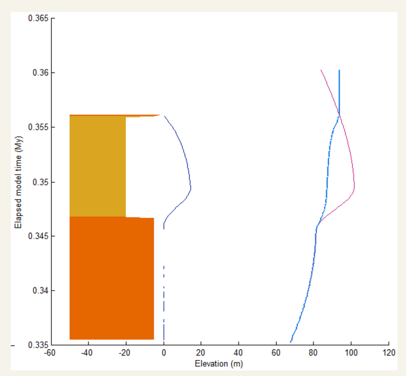
- Multiple shallowing upward parasequences per RSL rising limb
- Effectively random??

Case 3: Pure allocycles



- Single cycle per RSL rising limb
- Deterministic? Actually, in terms of cycle thicknesses, perhaps not either...





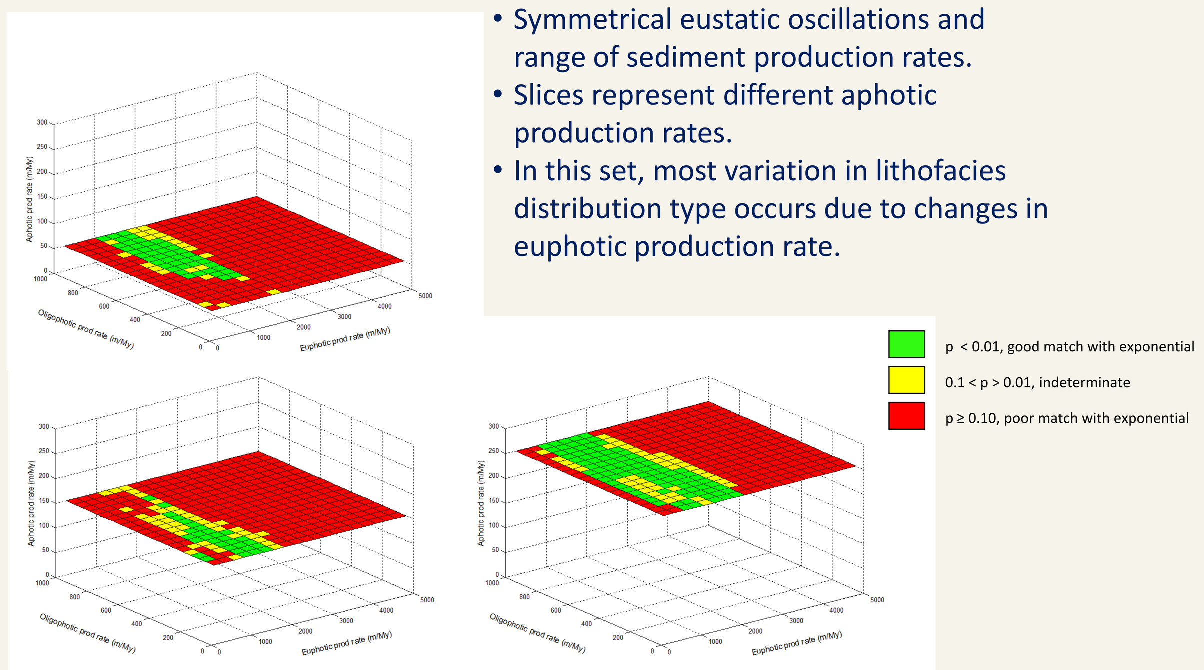
6 Multiple Dougal runs: Mapping the parameter space to understand the controls

To really begin to understand the controls on lithofacies thickness distributions it is necessary to run thousands of model cases to map the model parameter space

Model Set Number	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: $P \leq 0.01$ Not exponential	$0.1 > P > 0.01$ Indeterminate	$P \geq 0.10$ Exponential
1	Variable production symmetrical SL	4800	250–5000, 50-1000, 25-300	10, 50 & 20	1:1	2	0.756	0.098	0.146
2	Variable production asymmetrical SL	4800	250-5000, 50-1000, 25-300	10, 50 & 20	1:4	2	0.522	0.377	0.101
3	Low production rate lag 2m	4400	500	2.5-50, 5-100, 0-50	1:4	2	0.621	0.153	0.226
4	High production rate lag 2m	4400	2500	2.5-50, 5-100, 0-50	1:4	2	0.498	0.326	0.176
5	Low production rate lag 0m	4400	500	2.5-50, 5-100, 0-50	1:4	0	0.856	0.093	0.051
6	High production rate lag 0m	4400	2500	2.5-50, 5-100, 0-50	1:4	0	0.875	0.073	0.052

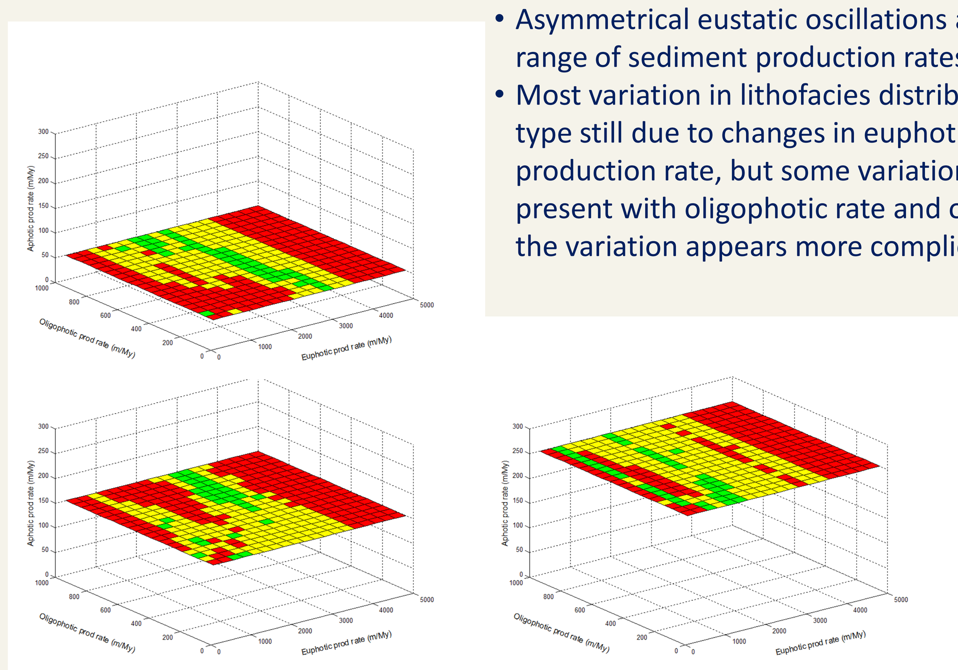
Model Set 1

- Symmetrical eustatic oscillations and range of sediment production rates.
- Slices represent different aphotic production rates.
- In this set, most variation in lithofacies distribution type occurs due to changes in euphotic production rate.



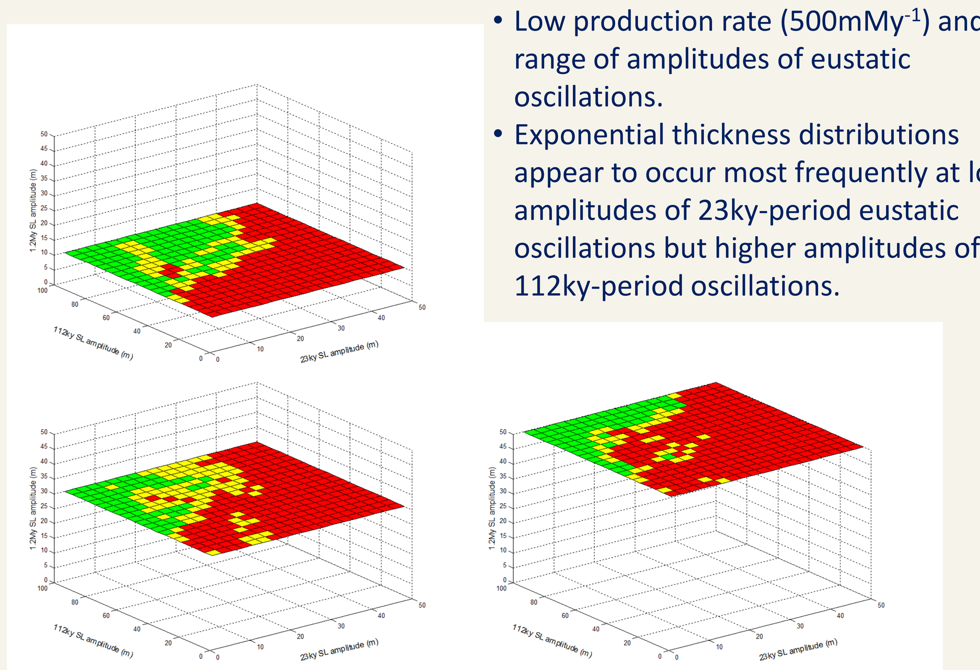
Model Set 2

- Asymmetrical eustatic oscillations and a range of sediment production rates.
- Most variation in lithofacies distribution type still due to changes in euphotic production rate, but some variation is present with oligophotic rate and overall the variation appears more complicated.



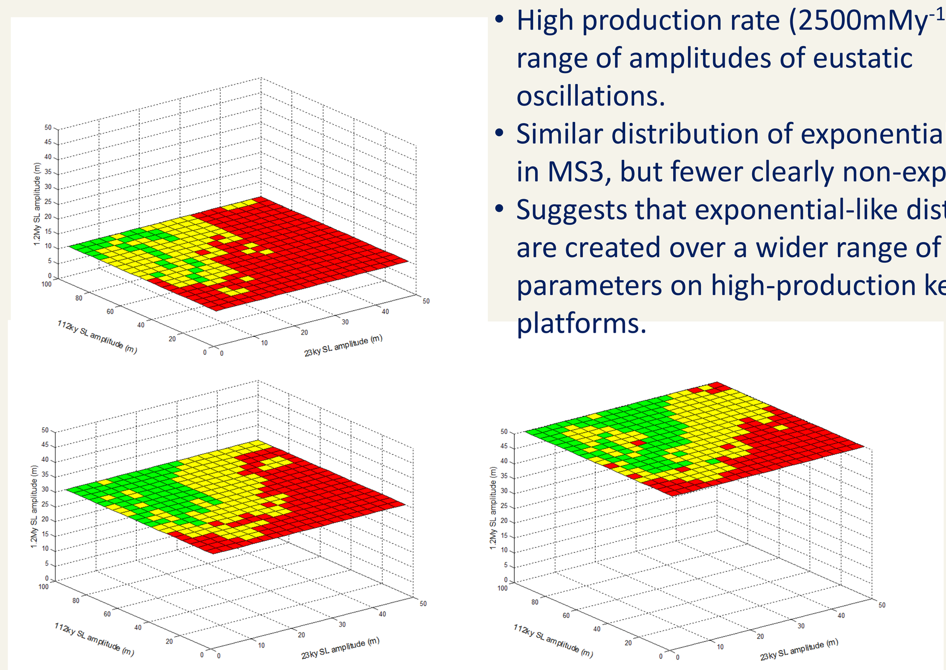
Model Set 3

- Low production rate (500mMy^{-1}) and a range of amplitudes of eustatic oscillations.
- Exponential thickness distributions appear to occur most frequently at lower amplitudes of 23ky-period eustatic oscillations but higher amplitudes of 112ky-period oscillations.



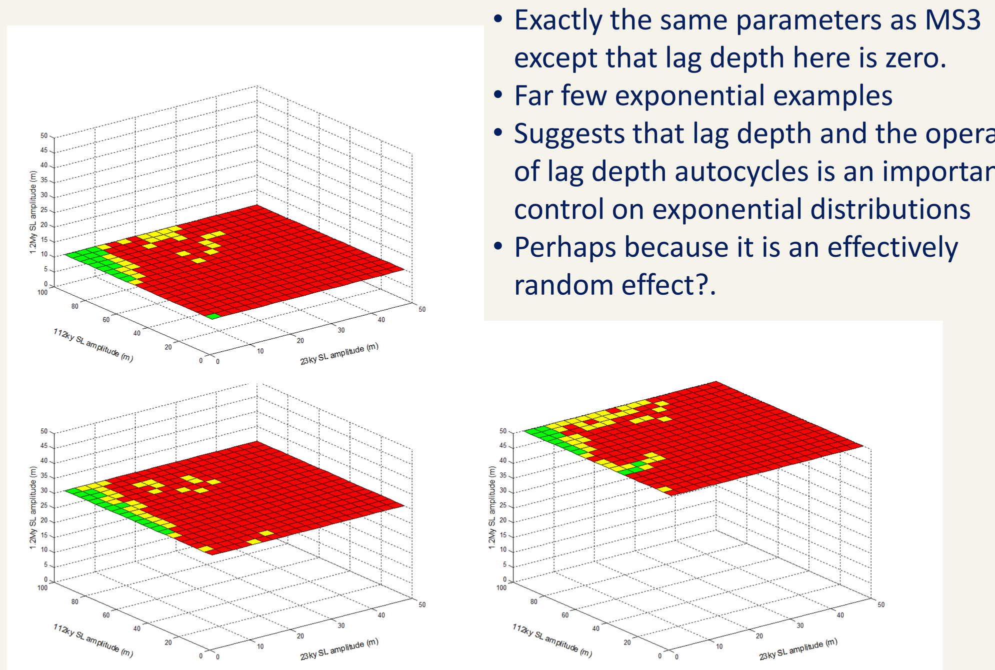
Model Set 4

- High production rate (2500mMy^{-1}) and a range of amplitudes of eustatic oscillations.
- Similar distribution of exponentials as seen in MS3, but fewer clearly non-exponential.
- Suggests that exponential-like distributions are created over a wider range of eustatic parameters on high-production keep-up platforms.



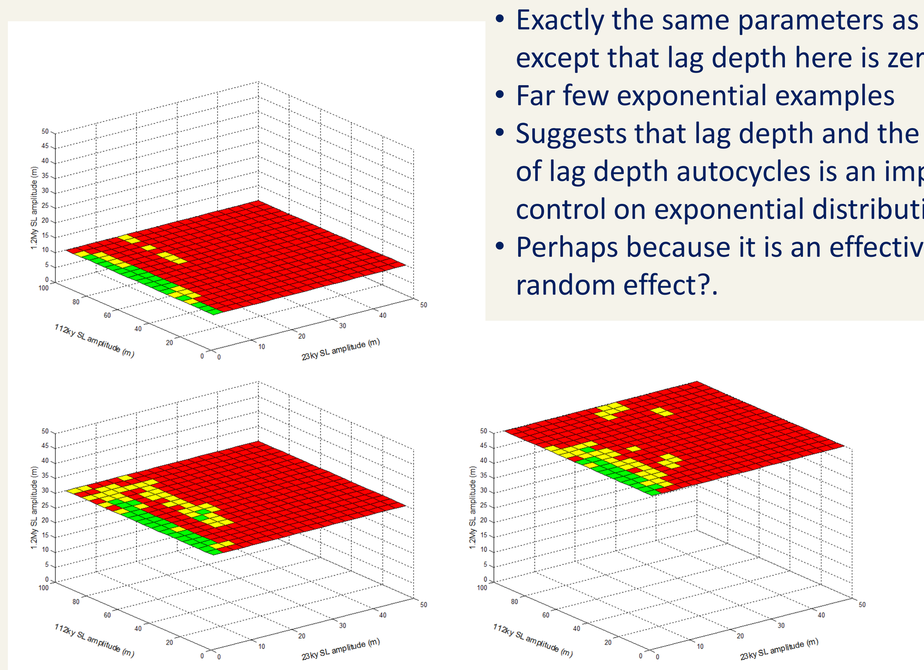
Model Set 5

- Exactly the same parameters as MS3 except that lag depth here is zero.
- Far few exponential examples
- Suggests that lag depth and the operation of lag depth autocycles is an important control on exponential distributions
- Perhaps because it is an effectively random effect?.



Model Set 6

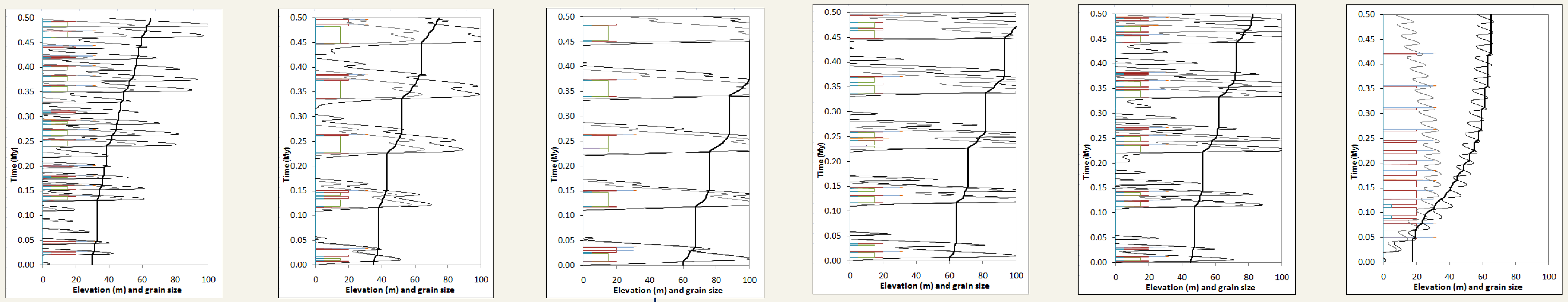
- Exactly the same parameters as MS4 except that lag depth here is zero.
- Far few exponential examples
- Suggests that lag depth and the operation of lag depth autocycles is an important control on exponential distributions
- Perhaps because it is an effectively random effect?.



7 Current Investigation - Control by production profile in Dougal

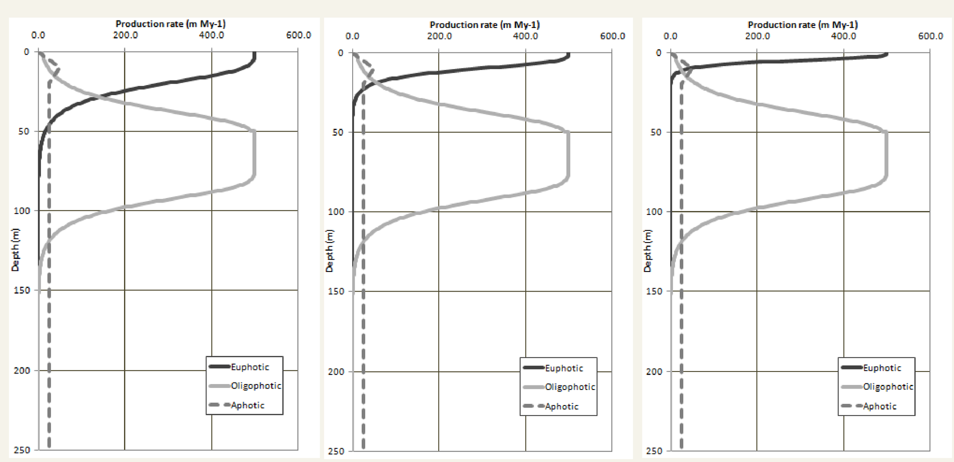
Multiple eustatic curves spanning the range of likely variation, from greenhouse to icehouse

23Ky cycle: 30m 112Ky cycle: 20m 1.2My cycle: 10-50m	23Ky cycle: 10m 112Ky cycle: 50m 1.2My cycle: 10-50m	23Ky cycle: 10m 112Ky cycle: 100m 1.2My cycle: 10-50m	23Ky cycle: 30m 112Ky cycle: 80m 1.2My cycle: 10-50m	23Ky cycle: 30m 112Ky cycle: 50m 1.2My cycle: 10-50m?	23Ky cycle: 5-10m? 1.2My cycle: 10-50m



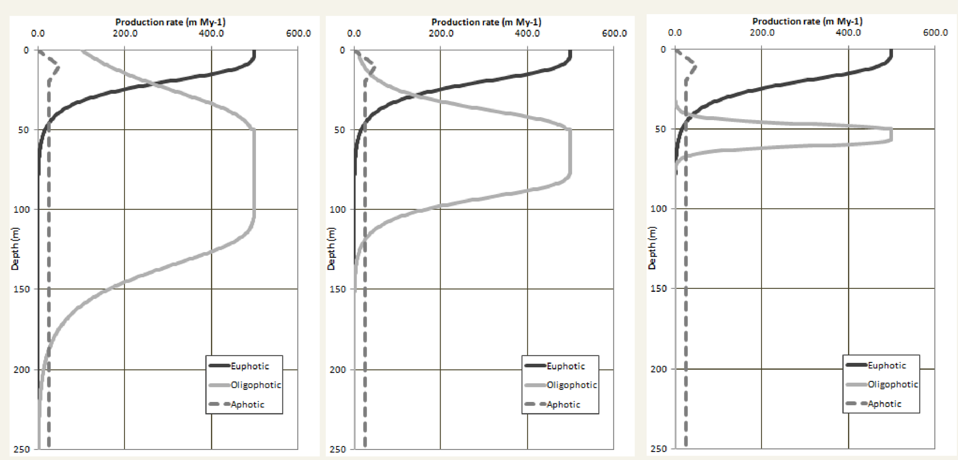
Each eustatic curve is then run with multiple production curves and production rates

Euphotic decay rate



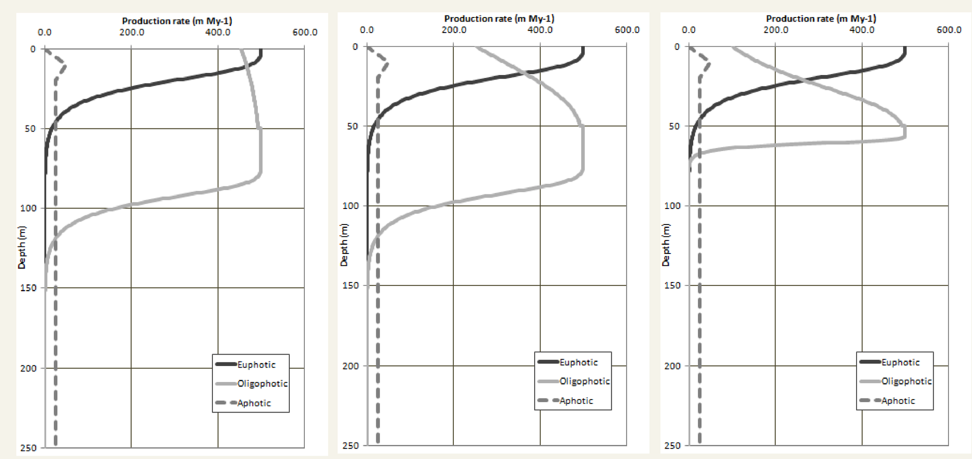
Euphotic decay -0.1 | Euphotic decay -0.2 | Euphotic decay -0.4

Oligophotic decay rate (symmetrical profile)



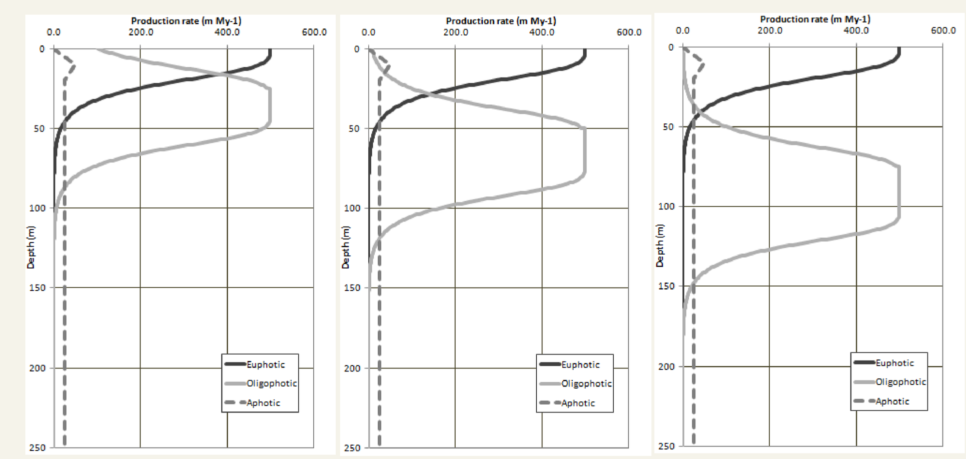
Oligophotic decay -0.05 (both upper and lower profile) | Oligophotic decay -0.1 (both upper and lower profile) | Oligophotic decay -0.4 (both upper and lower profile)

Oligophotic decay rate (asymmetrical profile)



Oligophotic decay: Upper profile -0.01 Lower profile -0.1 | Oligophotic decay: Upper profile -0.03 Lower profile -0.1 | Oligophotic decay: Upper profile -0.05 Lower profile -0.4

Oligophotic decay rate (Variable turnaround depths)



Turnaround depth 25m | Turnaround depth 50m | Turnaround depth 75m

- Multiple production profiles representing various interactions of: euphotic, oligophotic and aphotic production at various rates (50-5000mMyr^{-1} range),
- Requires in the order of 70000 model runs but should be a robust mapping of the parameter space and should shed light on control by factory type
- Work currently in progress…

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Wilkinson, B.H., Drummond, C.N., Rothman, E.D. and Diedrich, N.W. (1997) Stratal order in peritidal carbonate sequences. Journal of Sedimentary Research, 67, 1068-1082.

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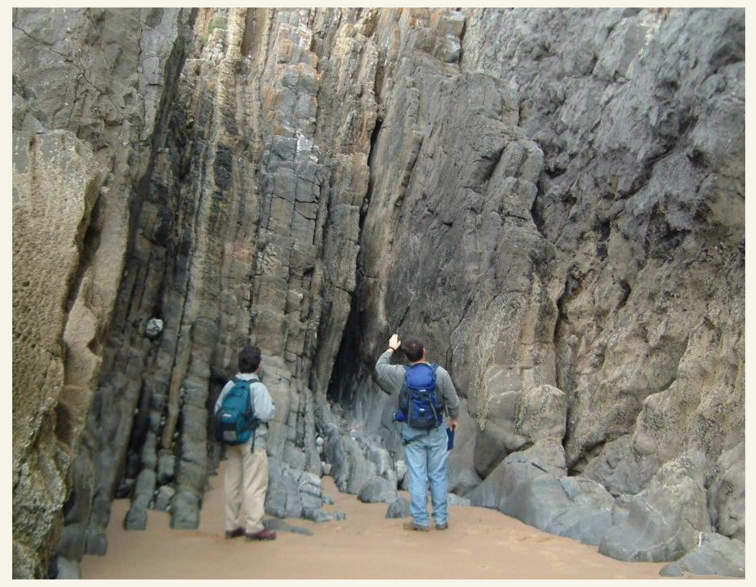
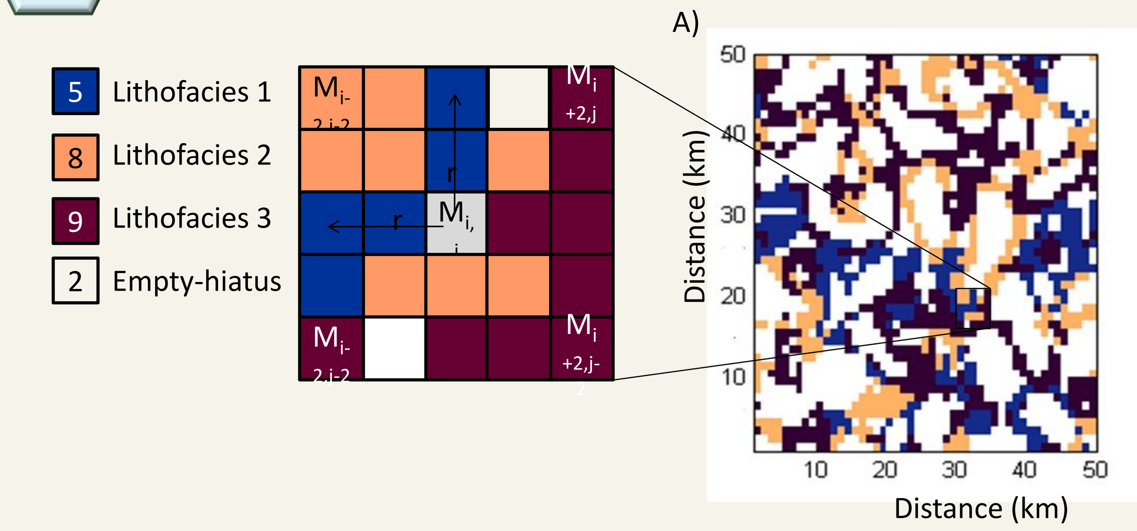
9 Comparison with outcrop examples

- Is it possible to invert Dougal against lithofacies thickness distributions measured from outcrop?

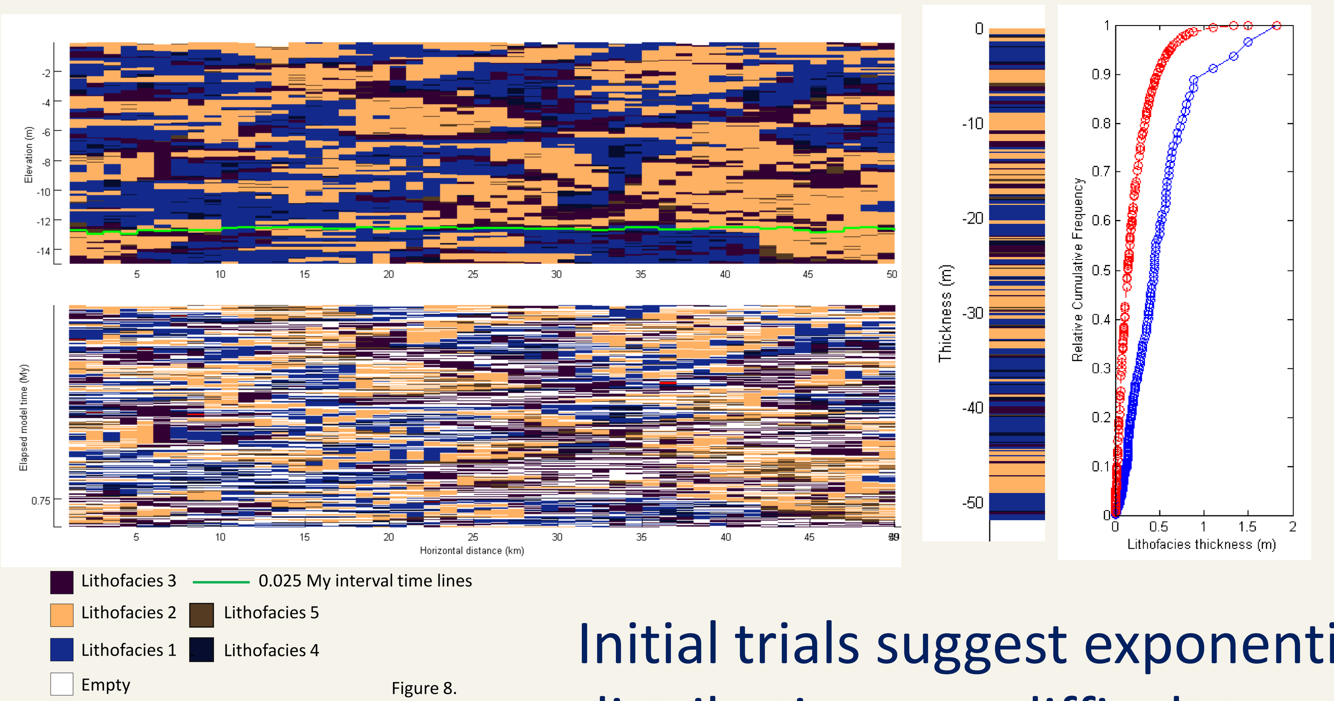


- If best-fit inversions are possible, what would this tell us about the responsible depositional processes?

8 3D facies body modelling with CarboCAT



CarboCAT is a cellular automata model that calculates spatial evolution of lithofacies according to simple rules



Initial trials suggest exponential distributions are difficult to produce…

10 Conclusions

- Information contained in lithofacies thickness distributions could prove useful for subsurface prediction – use SFMs to begin to understand the processes
- Three main factors appear to favour formation of exponential lithofacies thickness distributions in the 27,205 model runs performed for this study.
  - Complex variations in the rate of creation of accommodation
  - Rate of sediment production
  - Lag-depth oscillations
- Exponential lithofacies thickness distributions can be generated from a purely deterministic model.
- Other processes not included in Dougal probably play an important role…