[PS]Capturing Interwell Scale Heterogeneity from Process-Based Modelling for Reservoir Flow Simulations: A Study of the Middle Triassic Latemar Platform, Dolomites, North Italy*

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Abstract

Many carbonate reservoirs are characterized by complex depositional and/or diagenetic facies distributions at the inter-well scale which contribute significantly to uncertainty in prediction of flow behavior. Traditional approaches to populating reservoir models often lead to under-representation of geological continuity and loss of extreme (high/low) permeability features. This study demonstrates the potential of process-based models to provide valuable 3D datasets of key reservoir properties with 100% coverage that can bridge the gap between seismic and well data. The workflow uses the forward model CARB3D+ to simulate carbonate platform architecture and porosity and permeability distribution as a function of depositional and early diagenetic processes. Single phase tracer experiments using the streamline flow simulator 3DSL are then undertaken on CARB3D+ synthetic stratigraphies and flow behavior analyzed. Thus we can compare different synthetic platforms and evaluate approaches to layer aggregation.

CARB3D+ simulations of the Latemar platform successfully replicate the 3D distribution of facies and platform geometry described from outcrop. Third order sea-level variation generates alternating sequences of cyclic carbonates with a near-complete record of sedimentation, and condensed intervals where limited accommodation gives many “missed beats” due to non-deposition and/or subaerial dissolution and greater diagenetic overprinting. At reservoir depths, contrasts in depositional texture and early diagenesis result in condensed intervals with significantly lower porosity than cyclic intervals. However, cyclic intervals display much higher interior to margin differences, as well as greater systematic vertical variation within high frequency cycles. These patterns are reflected in the permeability distribution and, for simple injection/production scenarios with a fixed pressure gradient, give increased sweep efficiency of cyclic compared to condensed intervals. The effect of diagenesis is also more pronounced in the cyclic intervals, where it enhances sweep efficiency/production rate, whereas in the tighter condensed intervals diagenesis restricts fluid flow. Preliminary experiments in vertical amalgamation of high resolution synthetic stratigraphies

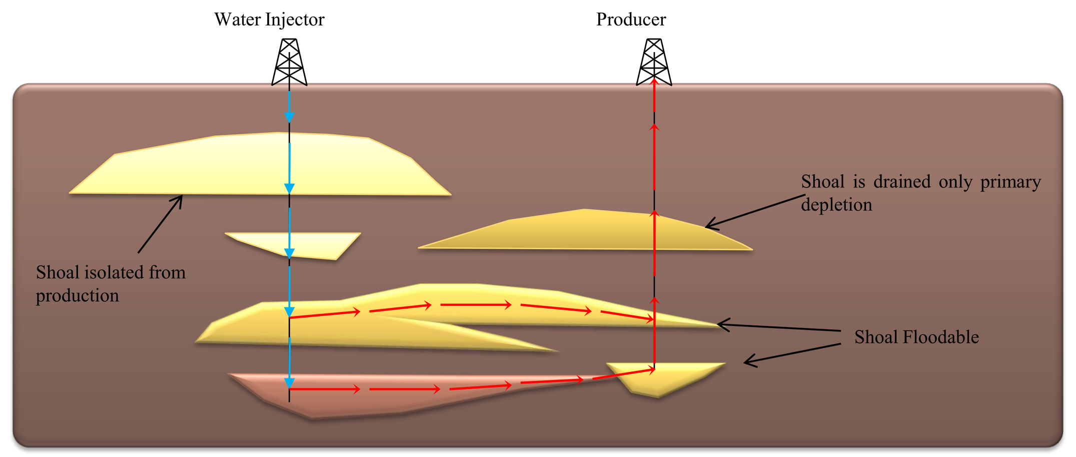
generated using CARB3D+ suggest that significant simulation efficiency gain is possible without loss of key heterogeneities controlling flow, enabling multi-phase fluid flow experiments to be undertaken.

INTRODUCTION:

Reservoir quality in shallow water carbonates is characteristically highly heterogeneous and challenging to predict. Temporal changes in depositional environments, and subsequent diagenetic alteration, generate sequences with marked vertical contrasts in porosity and permeability. In addition significant lateral variation often occurs at an inter-well scale and this is particularly challenging to predict.

This heterogeneity is a major contribution to uncertainty in prediction of in-place hydrocarbon volumes, design of well locations and production strategies, and production forecasts in carbonate reservoirs.

Whilst we routinely employ sophisticated multi-phase fluid flow models, high resolution quantitative data describing the distribution of rock characteristics in 3D is rarely available to populate these models. Traditional approaches to this problem often lead to under-representation of geological continuity and loss of extreme high and low permeability features.



Uncertainty of subsurface connectivity of geobodies is a critical critical control on flow response of a reservoir.

Forward sediment models [FSMs] can provide valuable 3D datasets of key reservoir properties with 100 % coverage that can bridge the gap between seismic and well data.

In this study we use the forward sediment model CARB3D+ to generate high resolution synthetic stratigraphies that capture spatial variations in the distribution of reservoir quality as a function of both depositional and early diagenetic processes.

Simulations are based on the cyclic carbonates of the Latemar platform, a small isolated Middle Triassic platform in northern Italy. Single-phase tracer experiments of water displacement are then used to compare flow behaviour in synthetic stratigraphies with and without diagenesis, and explore the effect of diagenesis under different climates. We also evaluate numerical approaches to amalgamation of sedimentary layers, which are predicted by the FSM at very high temporal [and thus vertical] resolution, by comparing their effect on flow behaviour.

OUTCROP ANALOGUE - LATEMAR:

Regional Setting:

The Middle Triassic Latemar carbonate platform is situated in Northern Italy and is part of the Southern Alpine region known as the Dolomites,. The isolated platform developed on the N-W rim of a wide continental shelf in the western-most Tethys Ocean, from the Late Anisian c.245 Ma to the Ladinian (Egenhoff *et al.*, 1999).

The outcrop provides excellent 3D exposure, in part due to erosion of much of the centre of the platform. It has been extensively studied and provides a useful analogue for many steep-sided isolated platforms, such as the Caspian reservoirs.

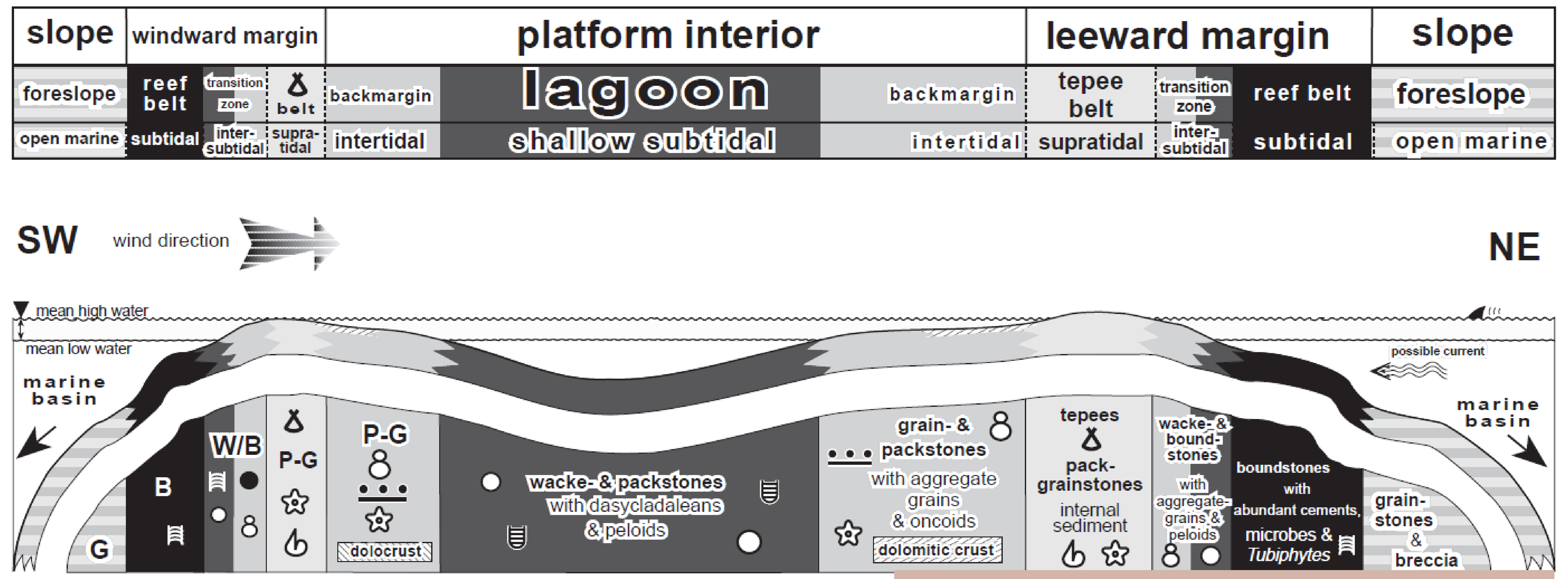
The c.3 km wide platform comprises a stacked sequences of highly-cyclic packages, totalling almost 720 m in thickness. The flat-lying subtidal lagoonal sediments are surrounded by a supratidal rim, with a deep-water reefal belt, and steeply sloping (35-25º) flank deposits of peloidal bioclastic turbidic grainstones (Egenhoff *et al.*, 1999), merging into basinal deposits at the toe-of-slope (Goldhammer & Harris, 1989). Whilst the exact nature of the slopes is disputed, this study is focused on the internal platform facies.

- Upper Tepee Facies (UTF): (100 m) — UTF
- Upper Cyclic Facies (UCF): (145 m) — UCF
- Tepee Facies (TF): (150 m) — TF
- Lower Cyclic Facies (LCF) (105 m) — LCF
- Lower Platform Facies (LPF) : (70 m) — LPF

LADINIAN / ANISIAN

Latemar interior stratigraphy, starting with the growth of partly-amalgamated bedding, building up to a strong cyclic section (LCF) which transitions into a condensed cyclic section (TF). These last two sequences are then repeated (after Egenhoff *et al.*, 1999).

Photo by M. Mutti: looking north

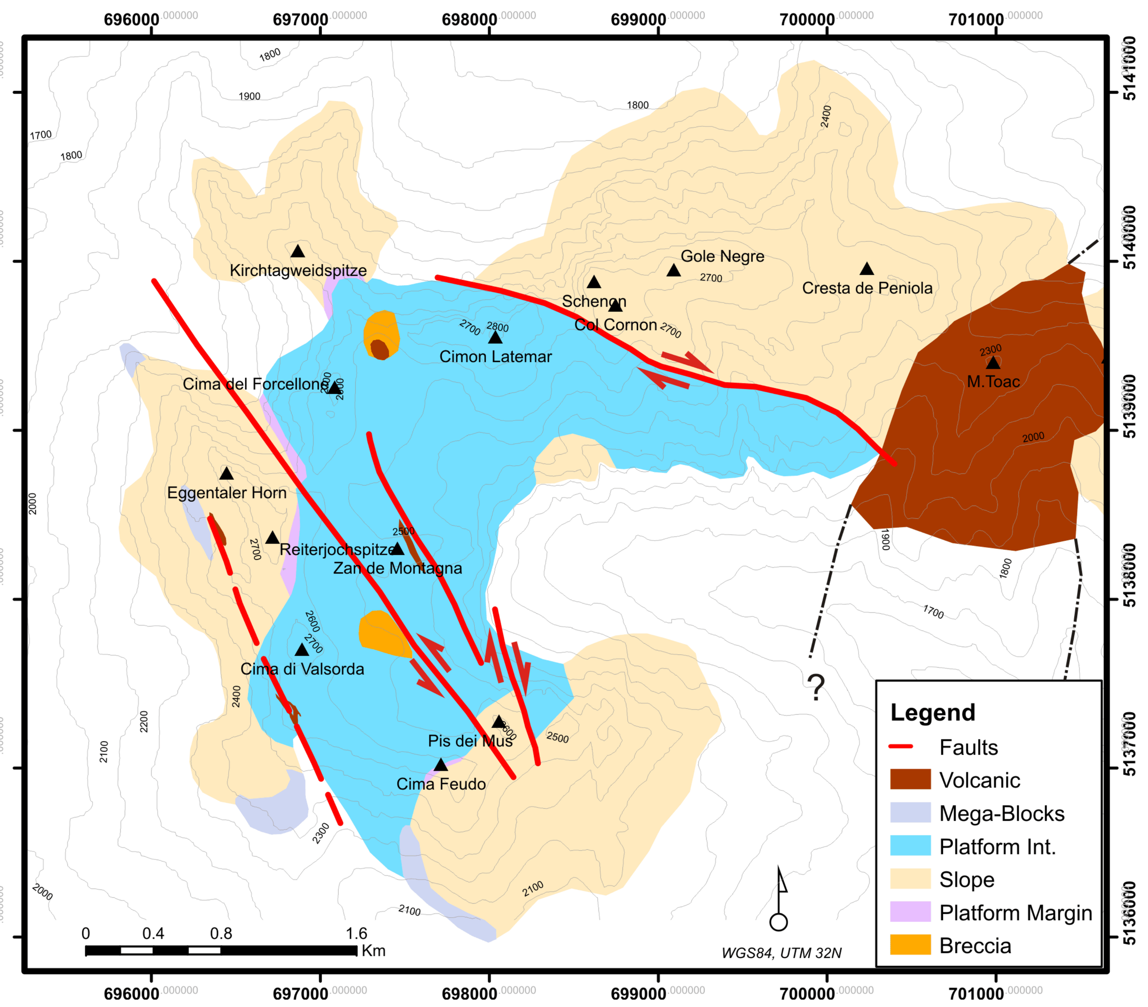


Schematic cross-section of the Latemar facies distribution (Egenhoff *et al.*, 1999)

Shallowing Upward Cyclic Sequences:

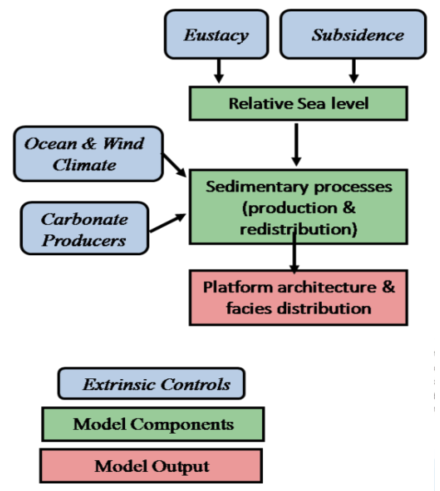
The platform interior is dominated by subtidal carbonate lagoonal deposits that form classic shallowing upwards metre-scale sequences that can be described by a series of successive repeating stratigraphic units (see above) with the LPF at the base and the UTF at the top. The Lower Platform Facies (LPF) are subtidal deposits with few exposure surfaces, but with reducing accommodation the cyclic units (LCF and UCF) record shallower conditions with more sub-aerial exposure events. These are overlain by the distinctive Tepee Facies (LTF and UTF) which form during extended exposure at the platform margin (Egenhoff *et al.*, 1999; Christ et al., 2011).

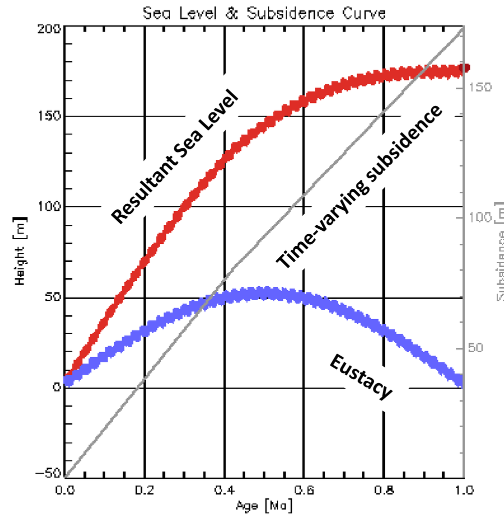
Diagenetically, the Latemar formed under arid climatic conditions and consequently there is limited evidence of early meteoric diagenesis. Many cycles are capped with supratidal dolomites, and exposure of the shallowest platform margin leads to dissolution and cementation providing important clues the evolution of platform palaeotopography (Egenhoff *et al.*, 1999).



Latemar platform region (Boro and Bertotti, 2011).

CARB3D+ FORWARD SEDIMENT MODEL:





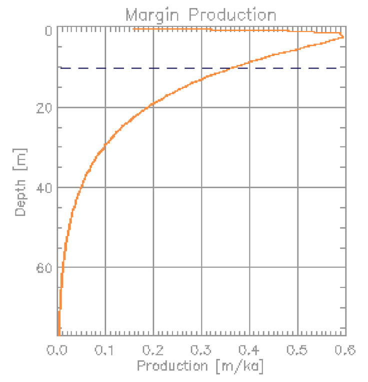
CARB3D+ is a three-dimensional process-based forward model for predicting carbonate sedimentology and early diagenesis. The model simulates sediment production by reef, shoal margin, interior and pelagic carbonate factories. Sediment is entrained by waves and currents, and transported by currents and by grain avalanching on slopes. Depositional facies, mineralogy, fabric selective porosity and matrix permeability are predicted for incremental sediment units through time in response to changing sea level. Importantly CARB3D+ includes dynamic feedback between platform morphology and sediment production and transport. For further details see Paterson et al, (2006, 2008).

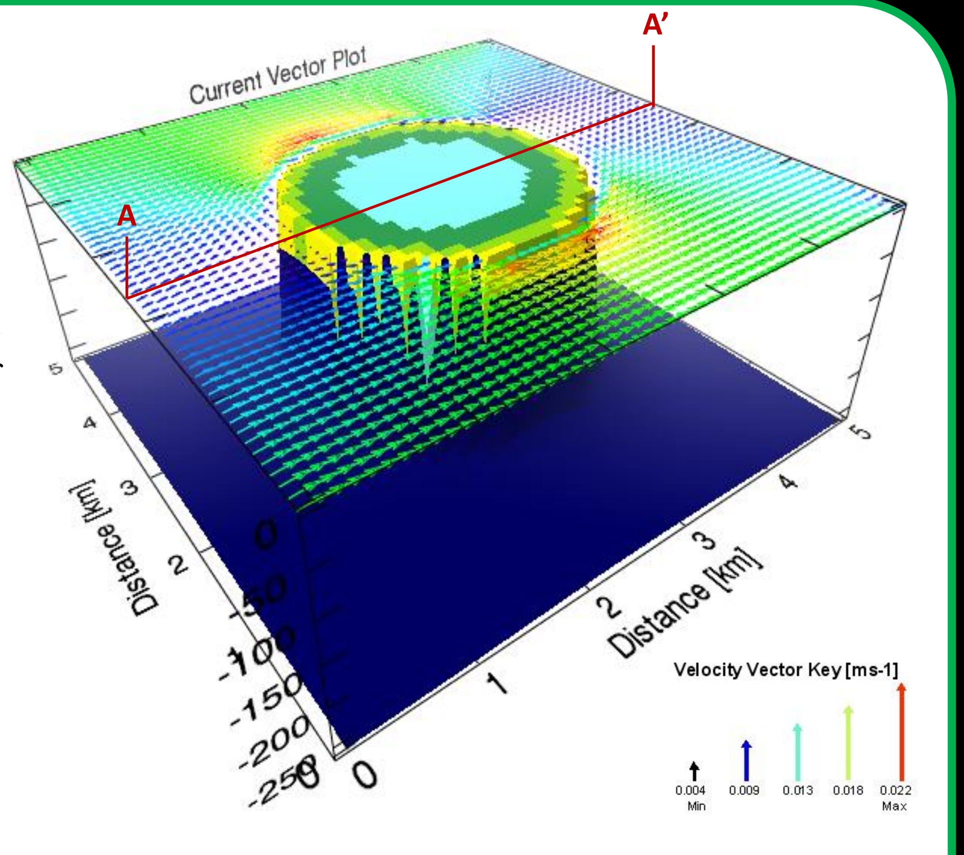
We simulate development of the Latemar platform within a 5 km^2 domain discretised into cells of 100 m^2. Vertical resolution is determined by accumulation rate, using a temporal resolution of 0.525 ky. Whilst accumulation rates are the subject of some debate, the simulations presented here represent evolution over the first 1 My of the platform development which we assume occurred over 2.95 Ma (Zuhlke et al., 2003). The model thus simulates platform development over 1905 time steps, generating >5 million cells.

The Middle Triassic was characterised by high-frequency, low amplitude eustatic sea-level oscillations characteristic of greenhouse periods (Zuhlke et al., 2003). At the larger scale, the progressive reduction in accommodation was modelled using a high amplitude third order curve and 0.16 mky^{-1} subsidence. Shoal margin production varied with depth with a maximum of 0.6 m/ky at a depth of 2 m, declining by 50% of the maximum at 15 m. Interior production was set at 0.5 m/ky, independent of depth. Reef growth is thought to occur in relatively deep water and boundstones were not a significant component of platform top sediments. Westerly wind driven waves and ocean currents, at 5.5 ms^{-1} and 0.01 ms^{-1} respectively, gave limited sediment re-working. After deposition porosity was reduced by texture-dependent compaction at every time step.

Below: Sea level parameterisation and right, margin shoal variable production curve with depth.

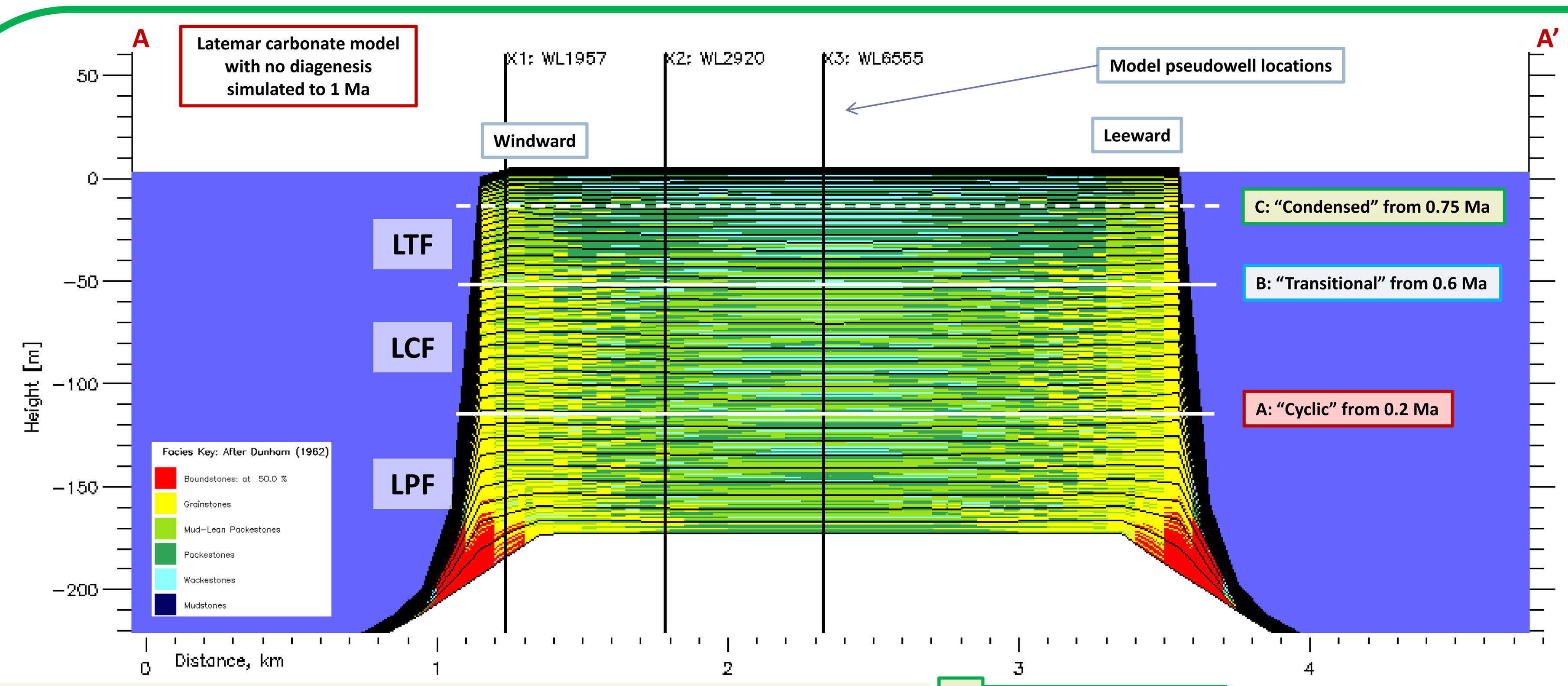
Frequency	Amplitude	Asymmetry
4.2 ka	3 m	50%
21 ka	1 m	80%
2 Ma	50 m	50%





Above: Simulated 3D platform depicting the facies distribution at the surface. Vector plot overlay gives the water velocity distribution for the westerly currents, as they interact with the island geometry, providing feedback on energy distribution, used to determine erosion and transport. Transect line highlights the position of the cross-sections below.

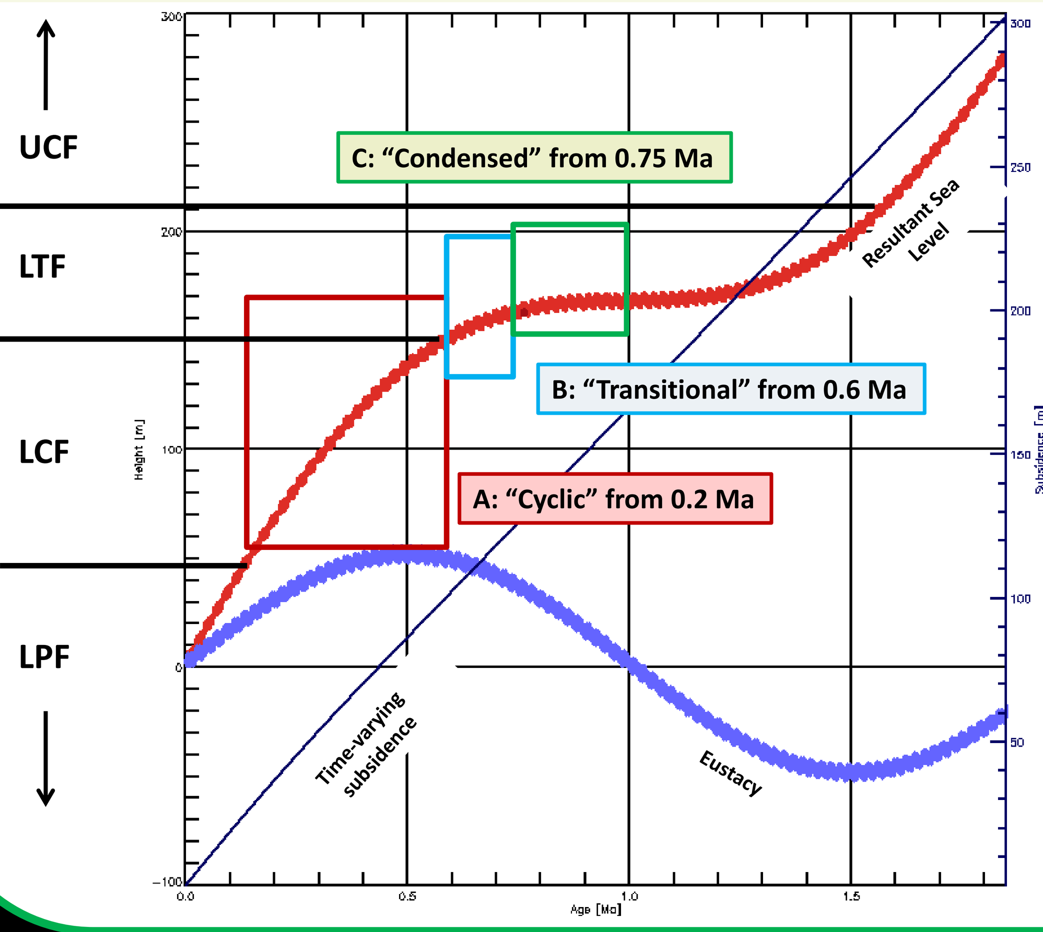
LATEMAR SIMULATION RESULTS:

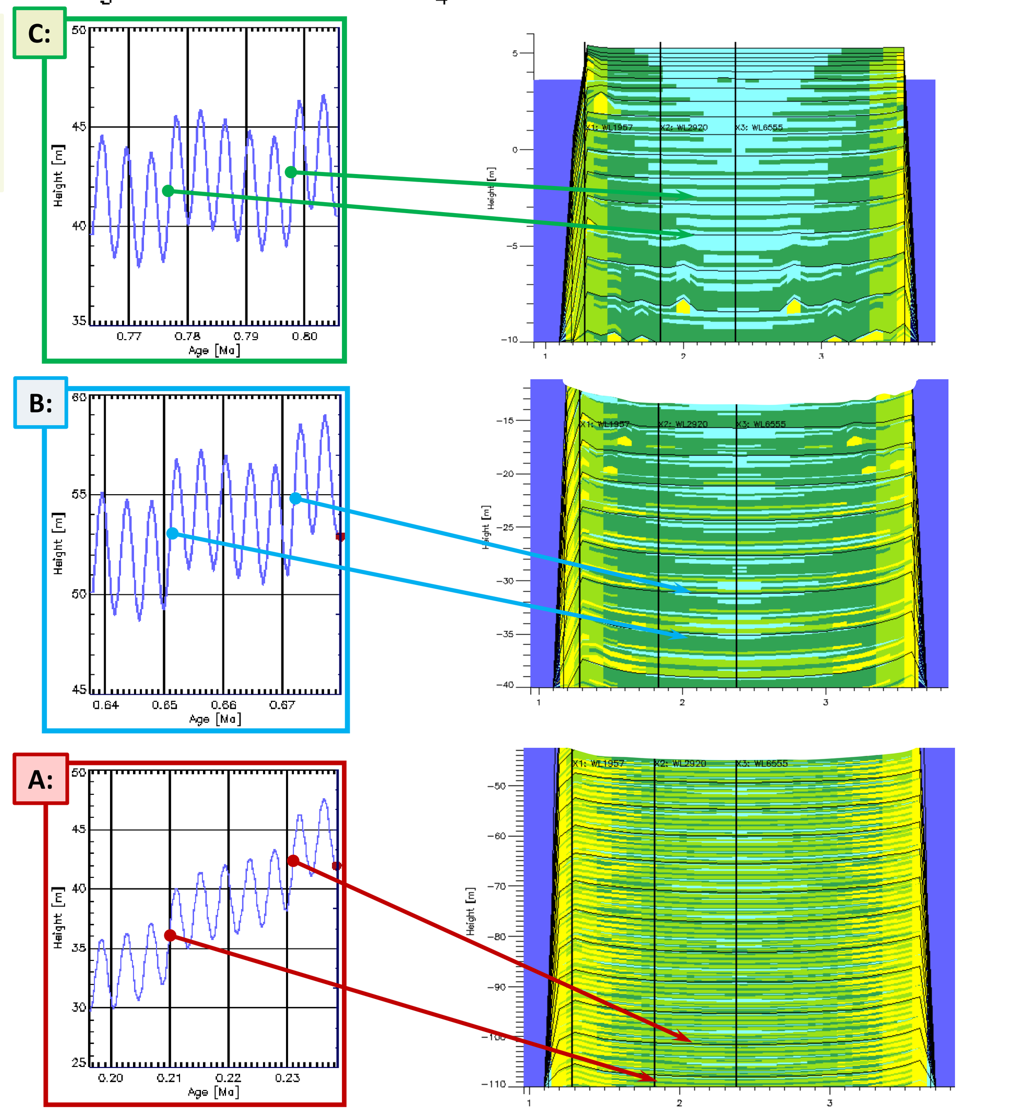


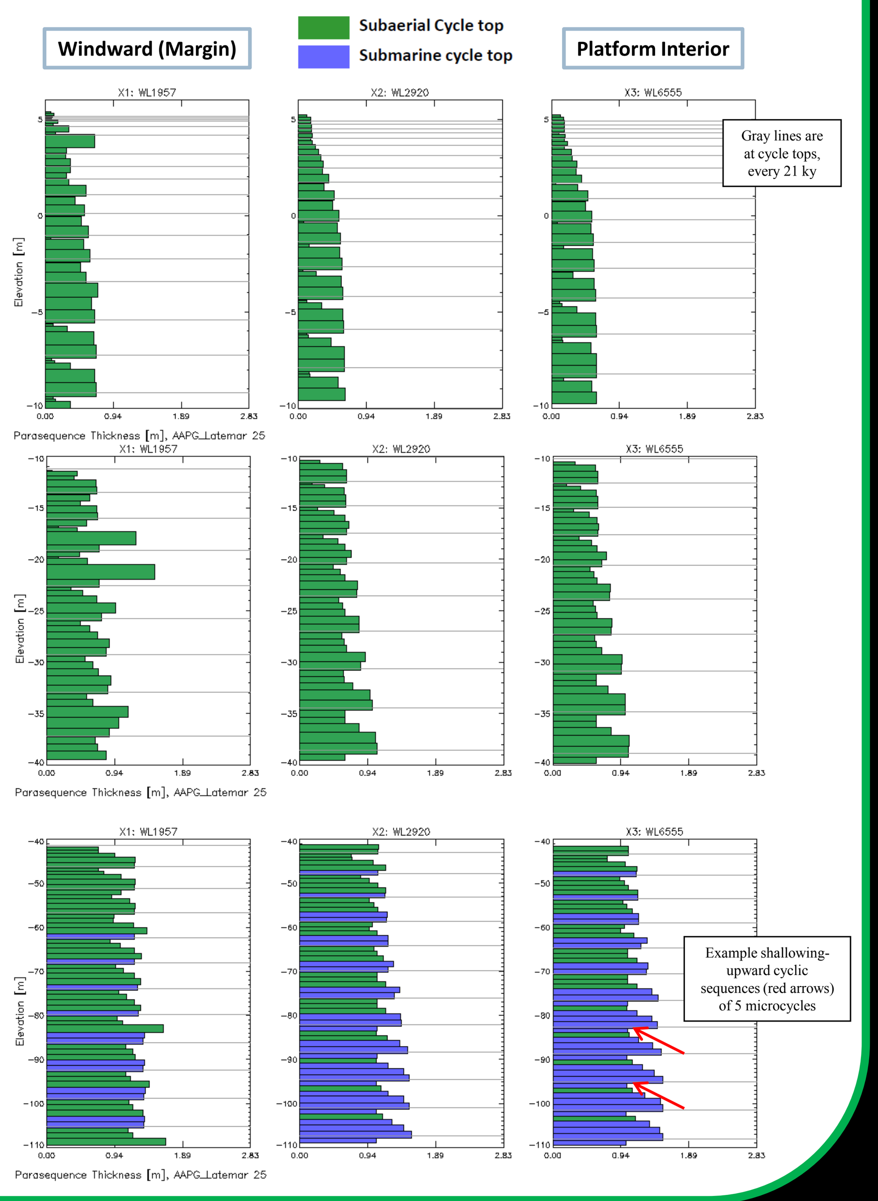
Using values for controlling parameters described above, the CARB3D+ forward sediment model captures key features of the shallowing-upward cyclic sequences at both large and small scales. Packages of 5 microcycles are preserved through the bulk of the platform, and most are capped by subaerial exposures horizons although within the LPF many cycles are never exposed. As the LCF transitions into the highly "condensed" LTF interval where accommodation is limiting, the model shows that many cycles are absent ("missed beats") due to lack of deposition and/or subaerial dissolution.

The well-logs of parasequence thickness also illustrate the contrasting cyclicity from deeper platform interior (pseudowell X3) to the more elevated windward platform margin (pseudowell X1) where exposure is more frequent. These differences in paleotopography would be expected to impact on development of meteoric hydrozones and the distribution of diagenesis during periods of platform top exposure.

The sea level is broken up into three sections representing distinct accommodation changes from a) "cyclic" to b) "transitional" section into c) a "condensed" section (see colour boxes). Sub-sample sea-levels (left) create the high-frequency cycles for each given section, and are shown with a corresponding sedimentary sequence.







AAPG Houston, 2011: Theme 7 – Insight into Carbonate and Evaporites

University of BRISTOL
School of Earth Sciences

Capturing interwell scale heterogeneity from process based modelling for reservoir flow simulations: a study of the Middle Triassic Latemar platform, Dolomites, N. Italy

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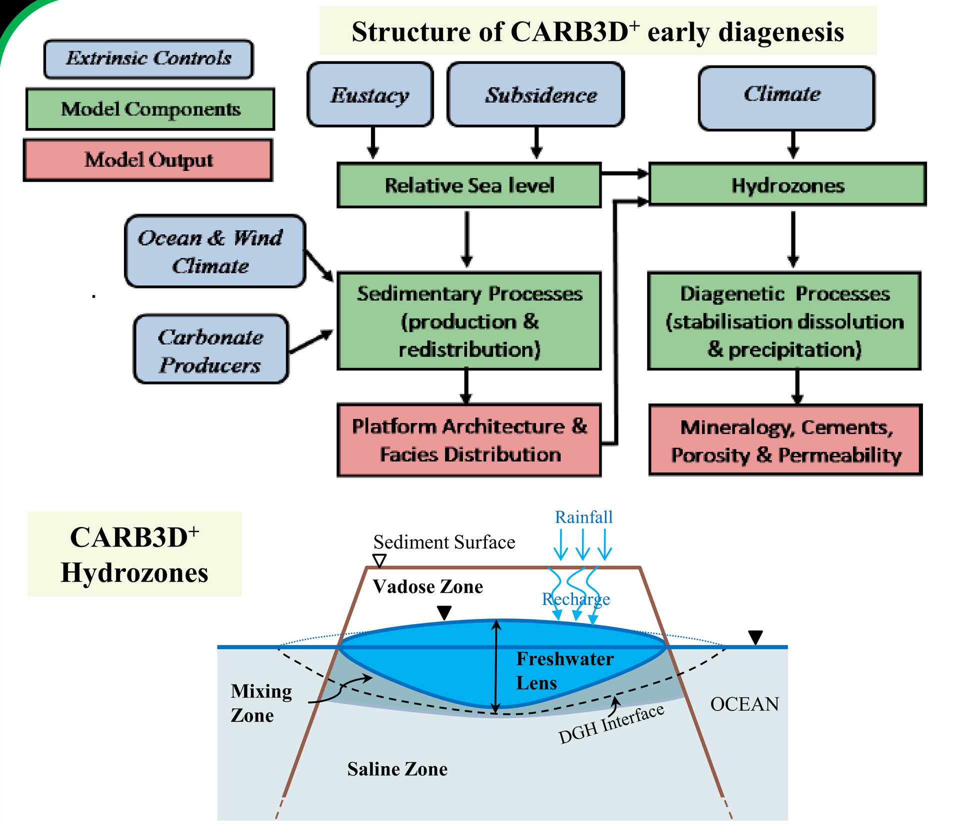
CARB3D+ DIAGENESIS:



After Whitaker et al., (1997)

Many fundamental controls on platform architecture and sedimentology, such as subsidence and sea level, also control diagenetic evolution via the position of hydrologically-defined diagenetic zones (hydro-zones).

CARB3D+ defines four hydro-zones in 3D for exposed carbonates using a spatially variable freshwater lens model. The vadose zone lies above the water table. The freshwater zone lies below the water-table and above the zone of mixing with underlying saline waters.

For each hydro-zone, the rates of mineral transformation are determined by the climate (recharge and soil development). Progressive changes in fabric-selective porosity, bulk mineralogy, cement volume and mineralogy are predicted, and non-fabric selective (secondary) porosity is up-scaled to derive island-scale permeability which controls the freshwater lens geometry. Grain-size dependent reactions and compaction are also incorporated. Critical feedbacks between the evolving poro-perm characteristics and distribution of the hydro-zones are included.

CARB3D+ gives us the ability to simulate syn-sedimentary diagenesis and investigate the impact of different paleoenvironmental conditions. By varying recharge rate we can generate scenarios ranging from arid to humid. At longer time scale, greenhouse and icehouse conditions can also be considered, for example by changing the amplitude of sea-level fluctuations and initial carbonate mineralogy

For the Latemar outcrop simulations, two climatic end member diagenetic scenarios representing ARID and HUMID climates were simulated to highlight key differences in the platform evolution. Climate differences are simulated by changing key input parameters

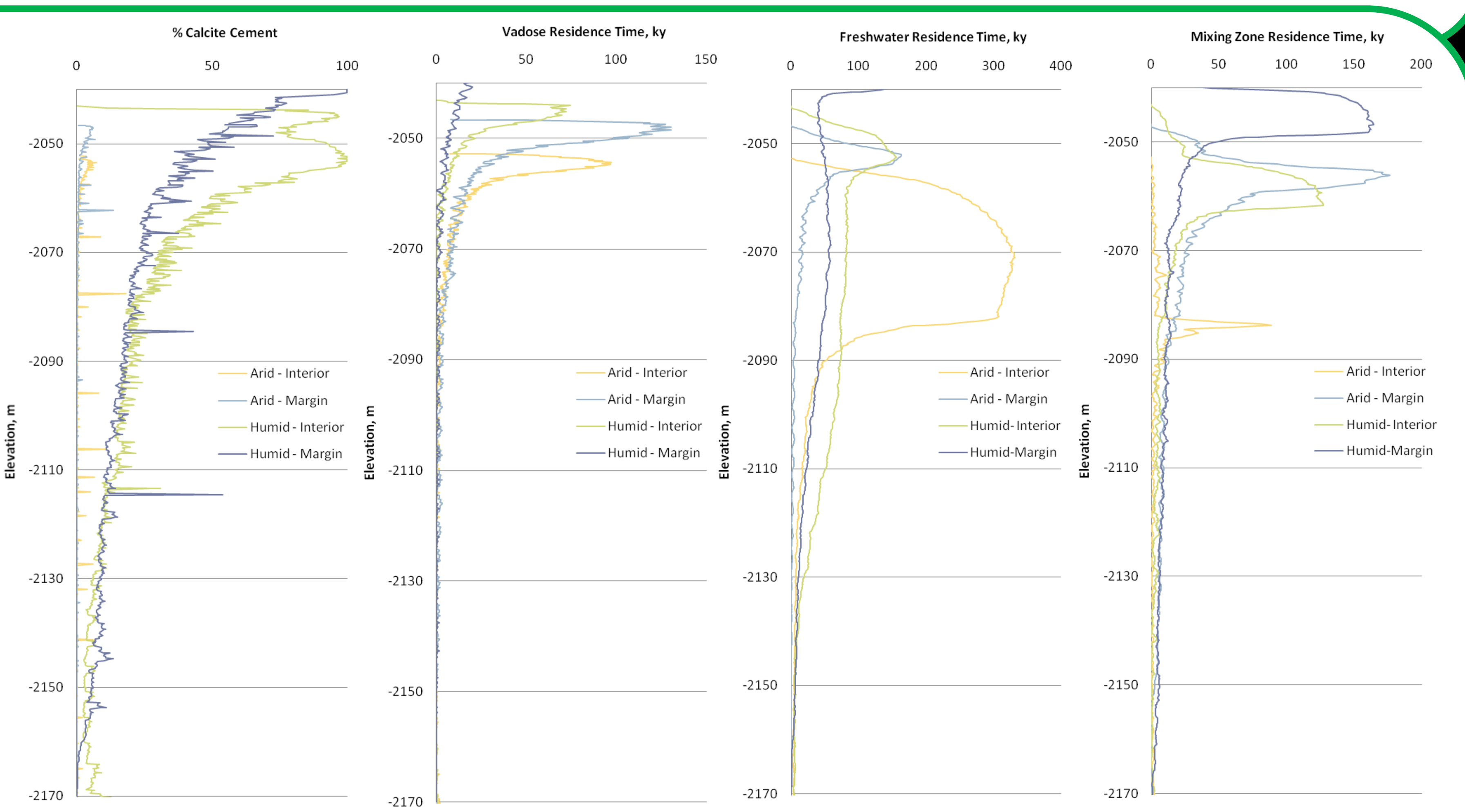
1. surface lowering rate; which liberates calcium carbonate to be re-precipitated as cements in the subsurface (vadose and/or freshwater lens);
2. meteoric flux, by changing rates of rainfall, potential evapotranspiration (PET) and actual evapotranspiration (AET) (but maintaining PET and AET as 90% and 70% of total rainfall respectively);
3. soil thickness, determining the soil CO_2 that controls subsurface dissolution potential in the vadose and freshwater lens (FWL);
4. Additional dissolution at the top of the freshwater lens driven by

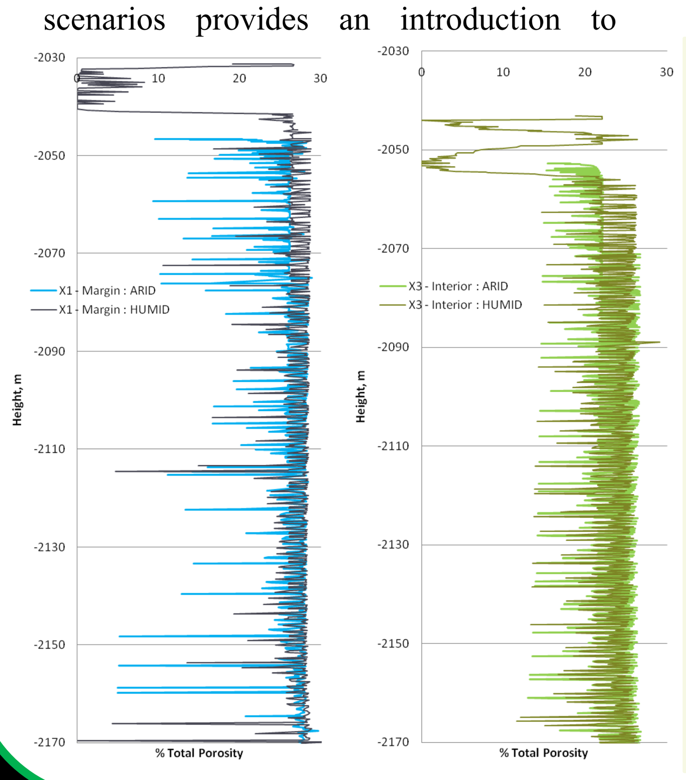
Climate-sensitive parameter	ARID CLIMATE	HUMID CLIMATE
Surface lowering (mm/ky)	12	200
Recharge (mm/yr)	100	2000
Soil thickness class	Thin	Thick
Meteoric cement redistribution	Surface to Vadose	Surface to Vadose & FWL
Dissolution by OM oxidation (mg/L $CaCO_3$)	nil	200

DIAGENESIS SIMULATION RESULTS:

The Latemar was likely subject to climatic conditions more similar to our arid simulation. Our model suggests that exposure to meteoric fluids was limited in the "cyclic" unit, but the slower rate of relative sea-level rise during deposition of the "condensed" low accommodation unit repeatedly exposed the entire platform and allowed for significant diagenetic overprinting. Whilst residence time in both the vadose and mixing zone was greater at the margins, the interior of the platform was more affected by diagenesis in the freshwater lens. Cementation in the interior reduced porosity by up to 15%, three times the rate at the margin, but this was largely balanced by higher rates of dissolution giving only minor net porosity occlusion.

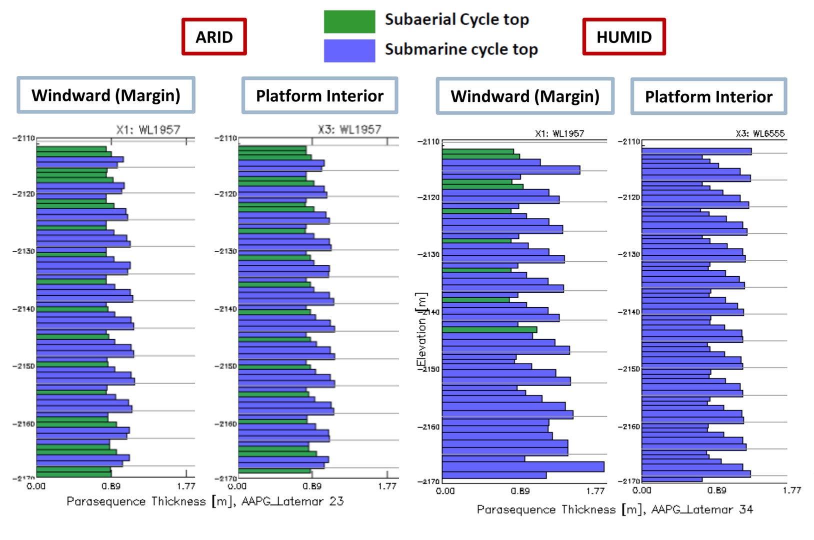
A comparison between our arid and humid scenarios provides an introduction to possible contrasts in the distribution and extent of diagenesis. With a more humid climate our simulation suggest an overall decrease in the number of cycles capped by subaerial exposure horizons (below), reflecting an increase in accommodation due to higher rates of surface lowering. The slightly elevated margins seen in arid and no diagenesis simulations are largely eliminated by surface lowering. This results in a reduction of vadose residence times in the humid climate scenario, particularly at the platform margins. The associated shorter duration of exposure is also seen in the reduction in freshwater lens and mixing zone residence times in the humid scenario, although during exposure events these zones do extend to affect much of the "cyclic" unit.





Pseudowell plot locations for X1 and X3 are given on the previous panel, where X1 intersects near the steep sided rim of the platform, and X3 is in the centre of the platform interior.

(left) – with burial, the arid and humid scenarios compact to different heights due to increased cementation in the humid model. Whilst porosity reduction in the "cyclic" is less distinct the impact of non-fabric selective porosity is very pronounced in the condensed section.



Although residence times in meteoric hydro-zones are shorter for the humid compared to the arid scenario, higher rates of surface lowering and both subsurface dissolution and cementation mean that diagenetic alteration is considerably more substantial. Within the "condensed" low-accommodation unit up to 100% replacement of allochems with cements is predicted, with complete elimination of depositional and diagenetic porosity in the platform interior. The margins are less affected (by ~50%), reflecting the thinner freshwater lens and/or greater rates of mixing zone dissolution with higher fluid flux. One notable effect of the cementation in the cyclic facies is that compaction of this unit is significantly reduced compared to the arid and no-diagenesis simulations. In the underlying "cyclic" unit lateral contrasts in porosity modification by diagenesis are less evident and also substantially less than in the "condensed" low-accommodation unit, with a gradual reduction in alteration with depth.

STREAMLINE FLOW SIMULATION:

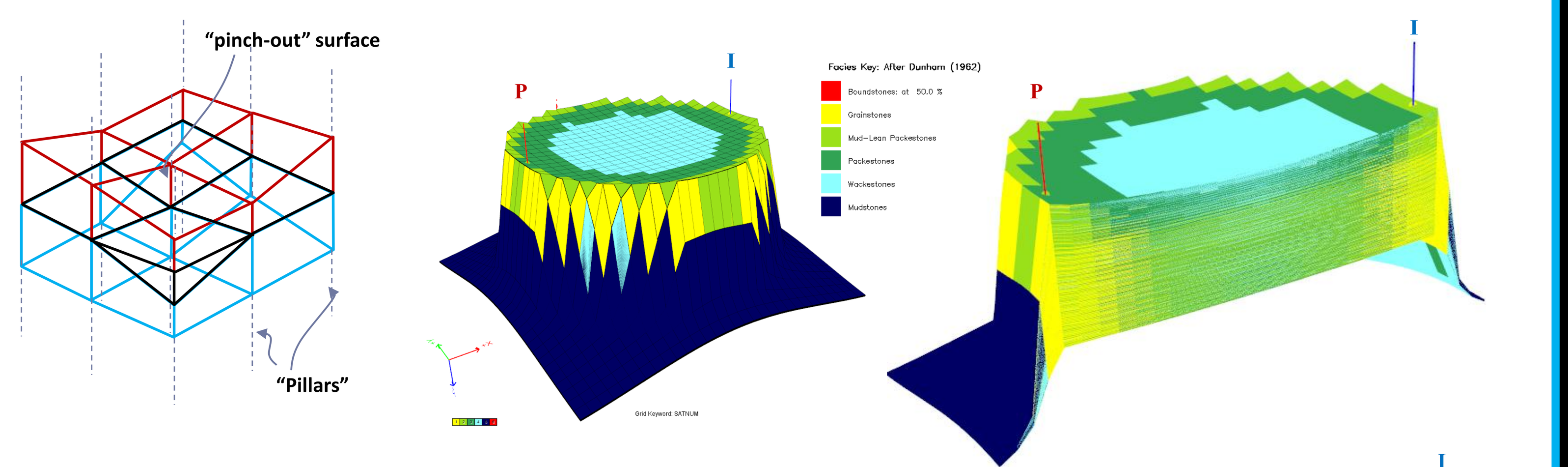
Streamline flow is an efficient numerical simulation method that can be used to determine the flow of fluid through a porous reservoir structure of known porosity and permeability.
Streamlines use the concept of particle tracking to define 1D pathlines of flow for transport in 3D space. Streamlines introduce the parameter of „Time of Flight"(ToF) which is the travel time of a tracer along a streamline. The ToF variable is used to decouple the underlying geologic grid from the transport (saturation) equations (reduce from 3D to 1D). This makes the model numerically efficient and is therefore well suited for quick ranking simulations, compared to traditional finite difference (FD) models (e.g. Eclipse) which require pressure solution calculations every time step. They are therefore more suited for heterogeneous property distributions and large scale models, as are often found with carbonate systems (Datta-Gupta & King, 2007).

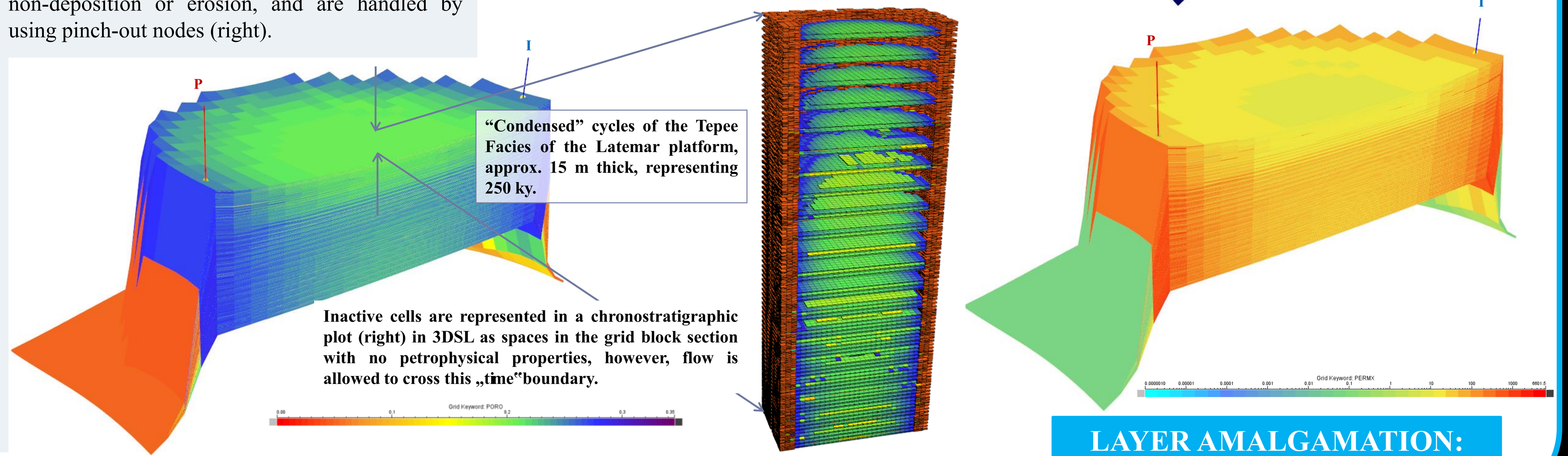
In this preliminary investigation we employ a streamline approach using the model **3DSL™** produced by **Stream*Sim* Technologies**.

For this research we have conducted simple tracer flow experiments for incompressible flow of water for a single injector/producer (I/P) scenario. The water injection is into a reservoir already saturated with a fluid of the same density, and so is just water displacement.

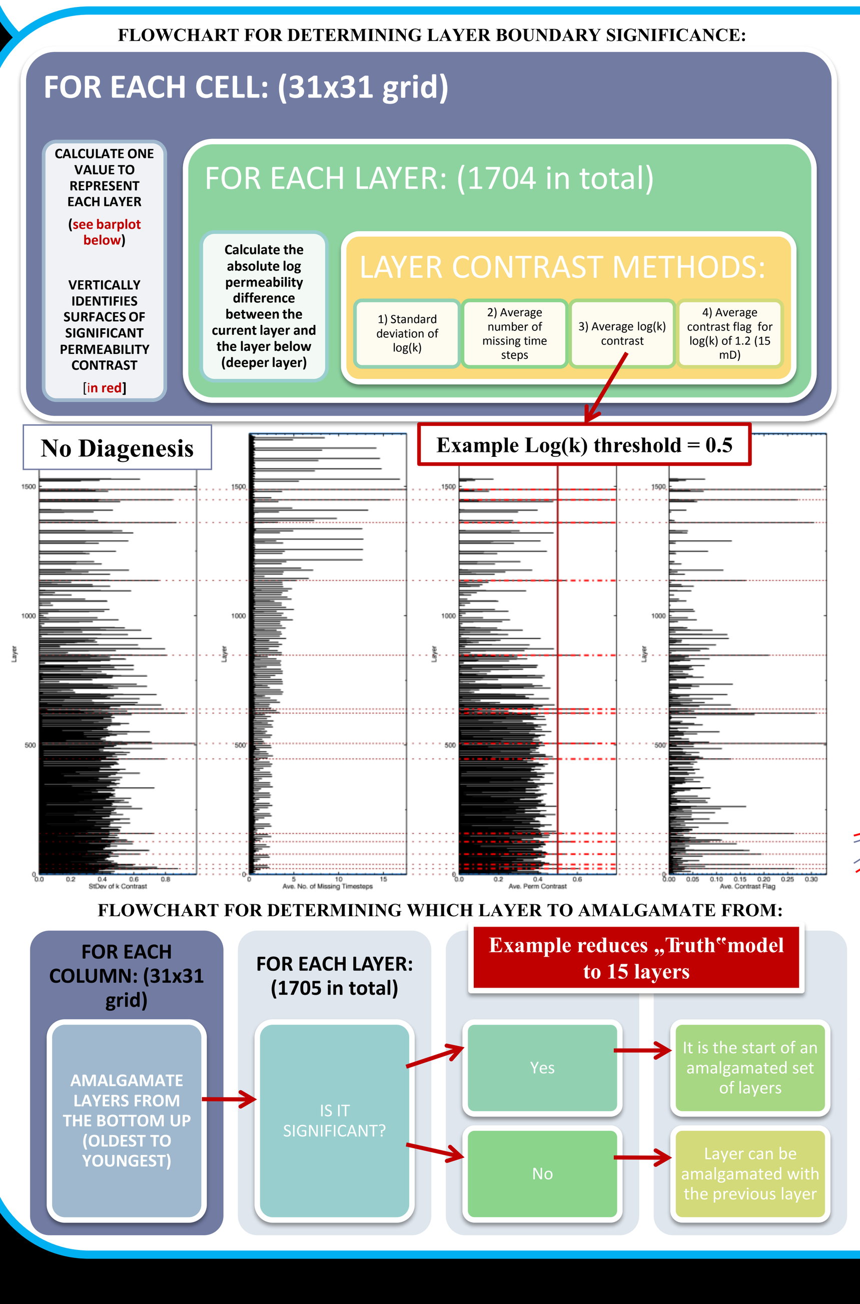
All flow simulations have a producer BHP of 14,000 kPa and a water injector rate of 1.594E+07 m^3 per 250 days. All simulations are run for 3000 days of production, which equates to a cumulative total of 1.46 PV injected.
The full resolution „truth" flow model of the Latemar sediment model is a subset of the domain simulated by CARB3D+ and spans a timeframe of 0.2 ky to 1 Ma (see previous poster) covering the "cyclic", "transitional" and "condensed" low-accommodation sedimentary sequences. The domain subset consists of 31x31x1704 gridblocks (1637544) of which 763759 are active. The inactive gridblocks represent periods of non-deposition or erosion, and are handled by using pinch-out nodes (right).

The Latemar domain is exported using the CPG (corner-point grid) geometry format with porosity and isotropic permeability values as simulated by CARB3D+. Petrophysical properties reflect burial compaction to2 km.

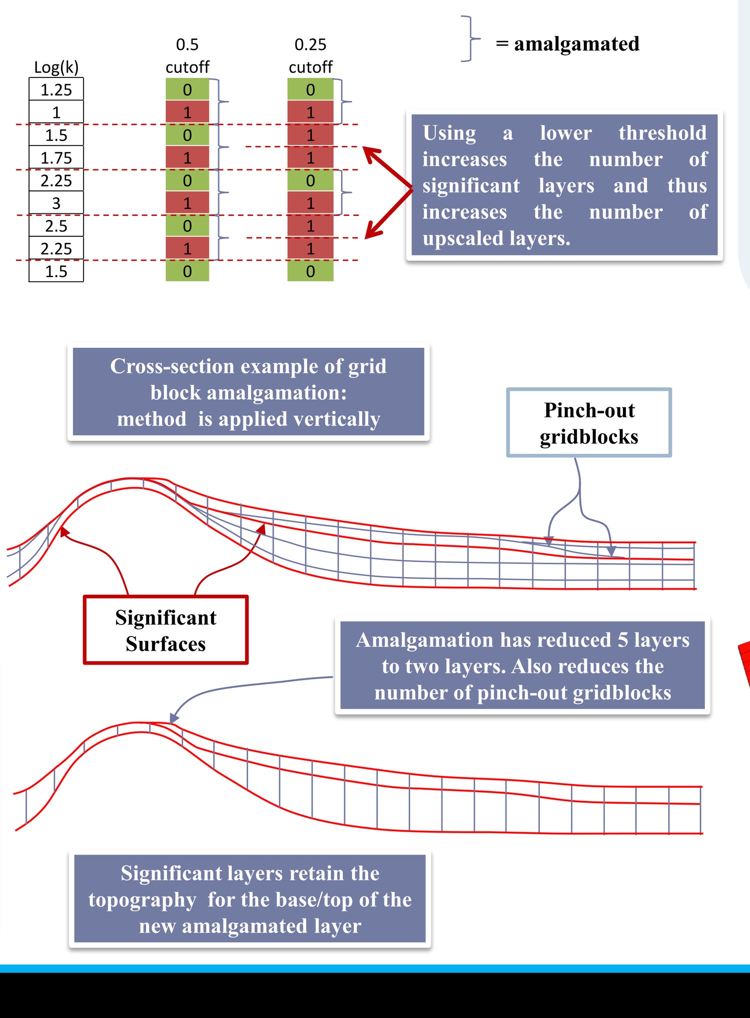




LAYER AMALGAMATION:

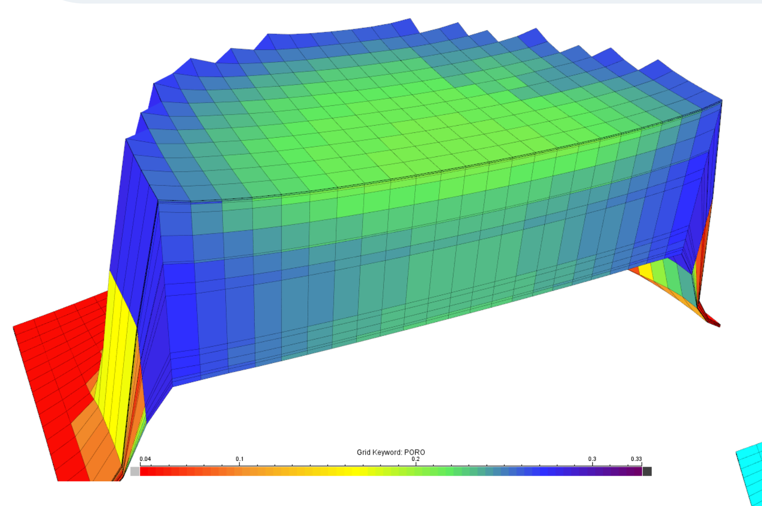


Each method of evaluating the permeability contrast can be displayed as a barplot (below-left). A threshold value is chosen to identify which layers are significant when the underlying layer **exceeds** the user-defined threshold:



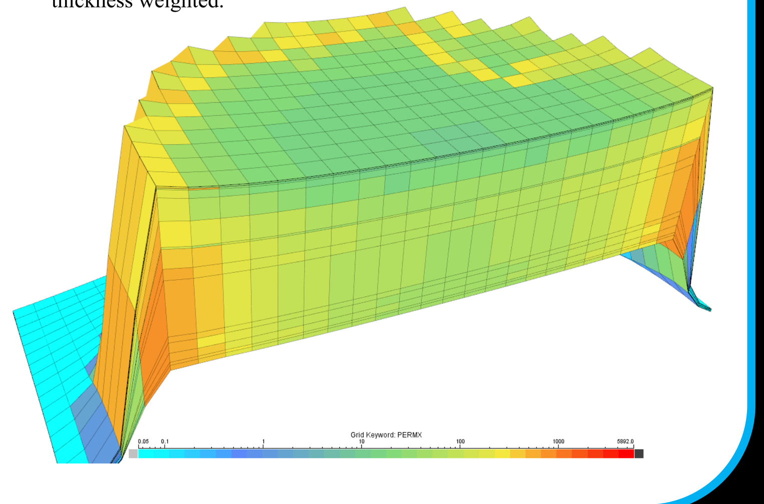
Layer amalgamation is a widely discussed and researched topic where the primary objective is to reduce the number of simulated gridblocks of a geologic model by upscaling (or upgridding) effective reservoir properties to a coarser resolution to that of the high-resolution „truth' model. Whilst there are different upscaling techniques for different flow methods (Christie and Blunt, 2001) including flow based scale averaging (FBSA) (Stern, 2005), including time-of-flight averaging (Ates, *et al.*, 2005) or simple geometric averaging (Kelkar and Perez, 2002), the guiding principle of scaleup is to ensure that the bulk volume is maintained but that heterogeneities in the original geologic model that matter to flow are captured. For carbonate rocks, which are naturally heterogeneous, preservation of more details is usually required, although it is not intuitively obvious which layers should be preserved.

We adopt here our own version of the geometric averaging method-type for static properties of porosity and permeability, in the vertical direction only. Here, a threshold in vertical permeability contrast, derived from different methods (see left), is used as a cutoff for layers chosen to be significant.

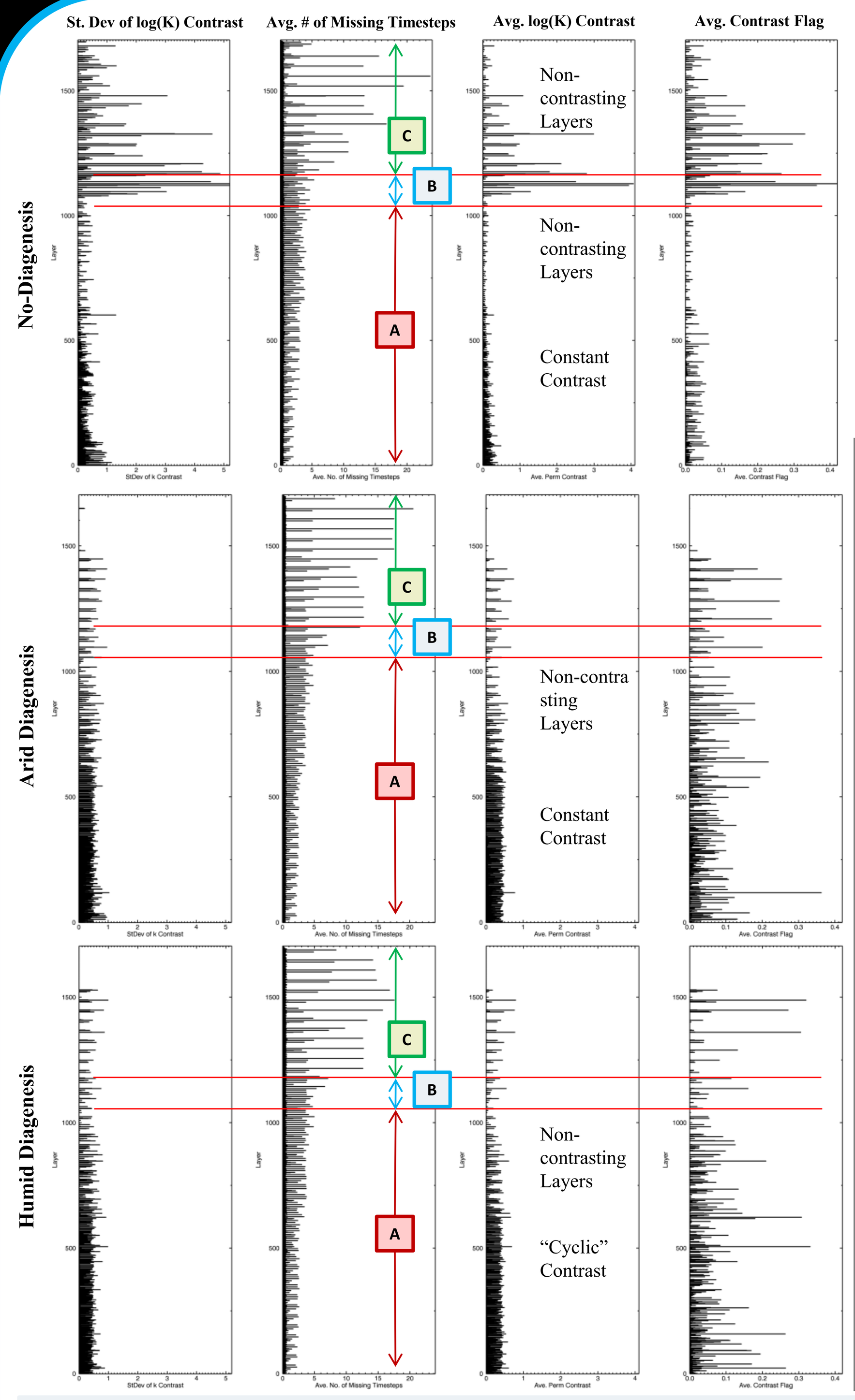


Upscaled porosity (PORO) is calculated by computing the pore volume (porosity * grid block dimension) for all the gridblocks to be averaged and then divided by the cell volume. This preserves STOOIP correctly.

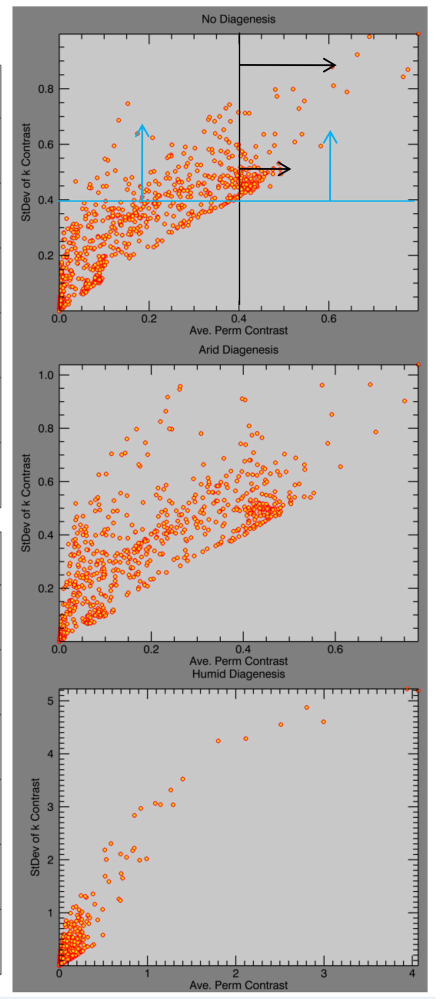
Upscaled horizontal permeability (PERMX and PERMY) is calculated by the Arithmetic Average, weighted by the thickness of each gridblock in that layer to the total thickness of all layers to be amalgamated. Vertical permeability (PERMZ) is taken as the Harmonic Average, but is also thickness weighted.



PERMEABILITY CONTRAST AND AMALGAMATION RESULTS:

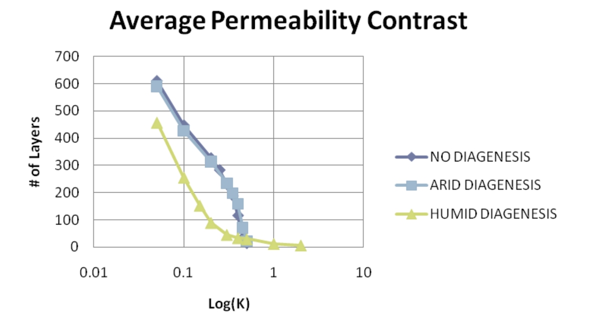


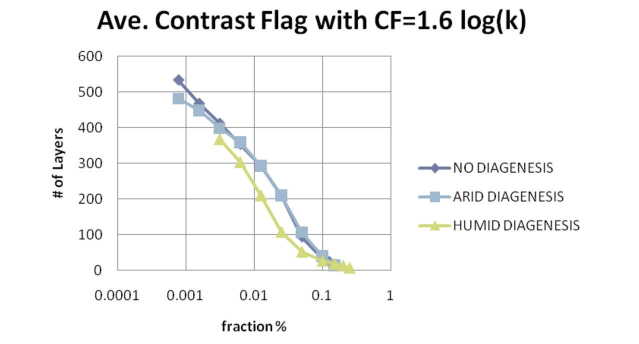
The work with CARB3D+ has produced three full resolution „truth" models, two of which have been overprinted with early diagenesis representing arid and humid climates. Our simple method of amalgamation allows the contrasts in permeability to be compared between two climate scenarios and a non-climate scenario.

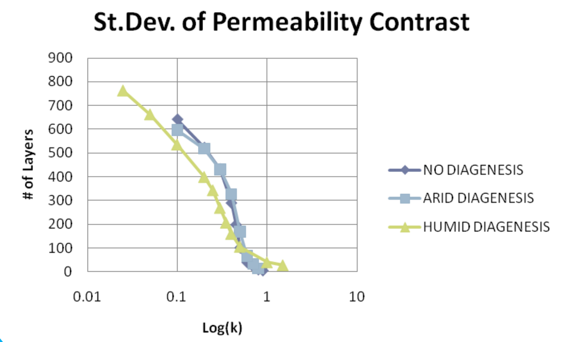


For the arid climate, the average log(k) contrast in the "cyclic" sequence (A) is comparable to the non-diagenesis distribution, with both showing minor variations in contrast upwards, towards the "transitional" sequence (B), indicating that most layers contrast each other. Whereas the humid "cyclic" sequence has a more noticeable repeating high-low cyclicity in which average log(k) contrast decreases to c.0.1, but increases again higher up towards to the "transitional" sequence (B), to layers which are zero, indicating a change to an almost homogeneous permeability contrast for some of the layers. This latter pattern is also observed for the arid climate and non-diagenesis simulation, where these non-contrasting layers, interspersed with contrasting layers continue up through the "transitional" (B)) into the "condensed" low-accommodation (C) sequence. For the humid climate, the contrast increases to almost 4 orders of magnitude greater, coinciding with more porous layers that contain non-fabric selective porosity. These trends are also somewhat correlative with standard deviation of contrast per layer, and are also observed in the above cross-plots for average perm contrast.

When considering the threshold method for selecting significant layers, the above cross-plot for non-diagenesis, for example, highlights a key difference in layers that would be tagged as significant using different threshold methods. Here, the standard deviation covers a range of high and low permeability contrasts, whereas the average covers just the absolute contrasts, missing out the low range values.

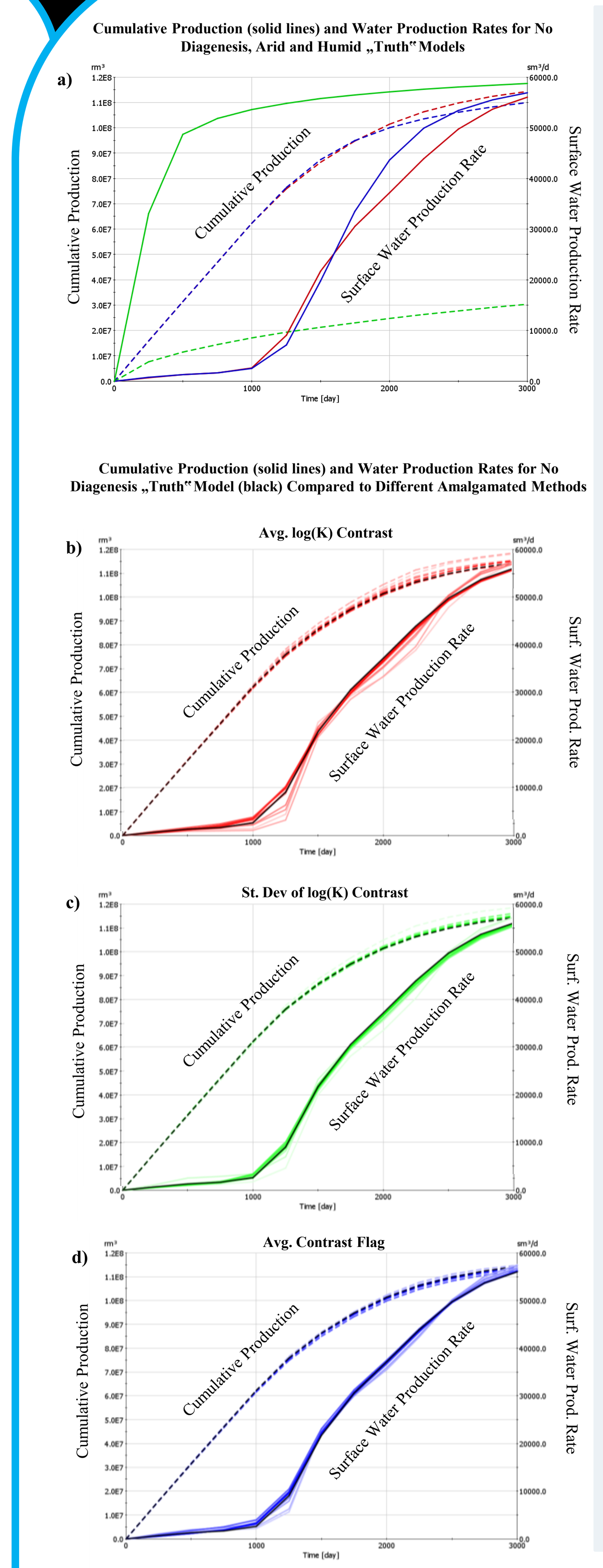






For three of the above contrast methods, amalgamation was implemented for upscaling the 3 full-resolution „truth" models, each of which consisted of 1704 layers each. From the three graphs above and left, the no diagenesis and arid diagenesis models are virtually identical. However the humid climate model reduces to fewer layers on average for all three methods, due the methods ability to capture small perm contrasts.

FLOW SIMULATION RESULTS:



Fluid flow simulations of the Latemar sediment and diagenesis models were done using a simple tracer experiment of water displacement, simulating production for 3000 days, from which upscaled domains were created using various methods as described previously.

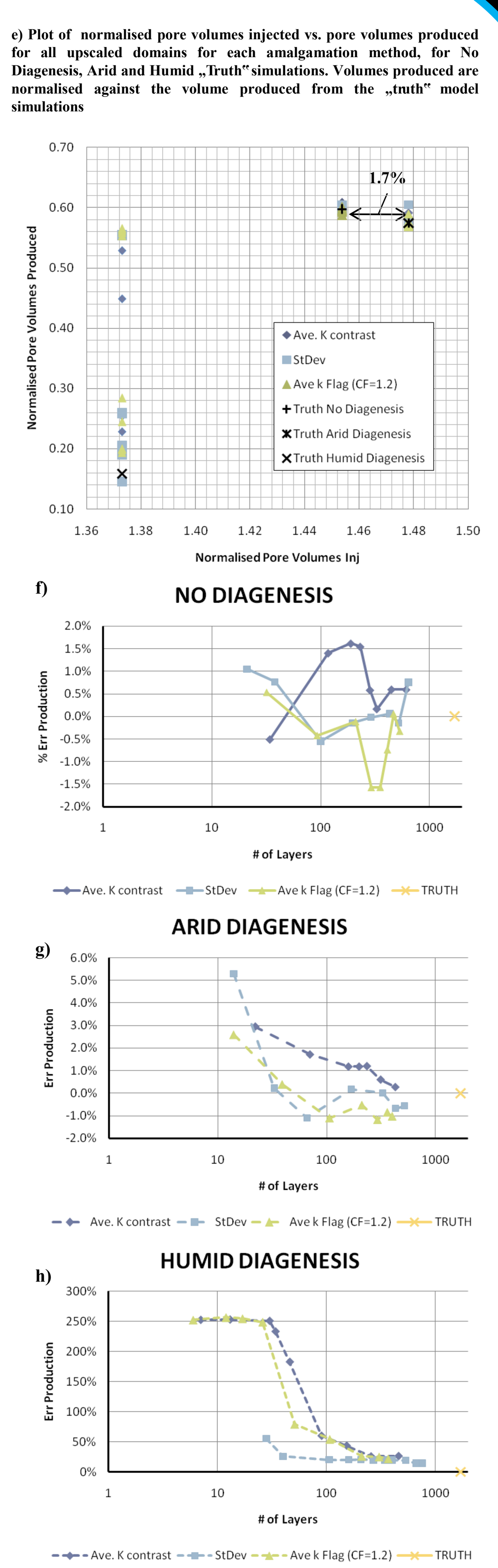
Graph a), left, gives the cumulative production (dashed) with time for the non-diagenesis (red), arid (blue) and humid (green) sediment models. The former two show the closest similarity due to limited rock fabric alteration from diagenesis associated with an arid environment (blue), with only a minor drop in production by comparison. The differences (see graphs b-d) arise due to a higher water production rate (solid lines) which are similar for the first 1500 days, but then diverge as more water is produced which is caused by a decrease in reservoir pore volume in the arid model of 1.7% (see graph e). Within the "cyclic" section of the 3D water saturation plots below, after 1000 days of production the flood front in the non-diagenesis model is more uniform/even moving up towards the "transitional"/"condensed" low-accommodation units, whereas the arid model has clearly more vertical flow variation in sweep.

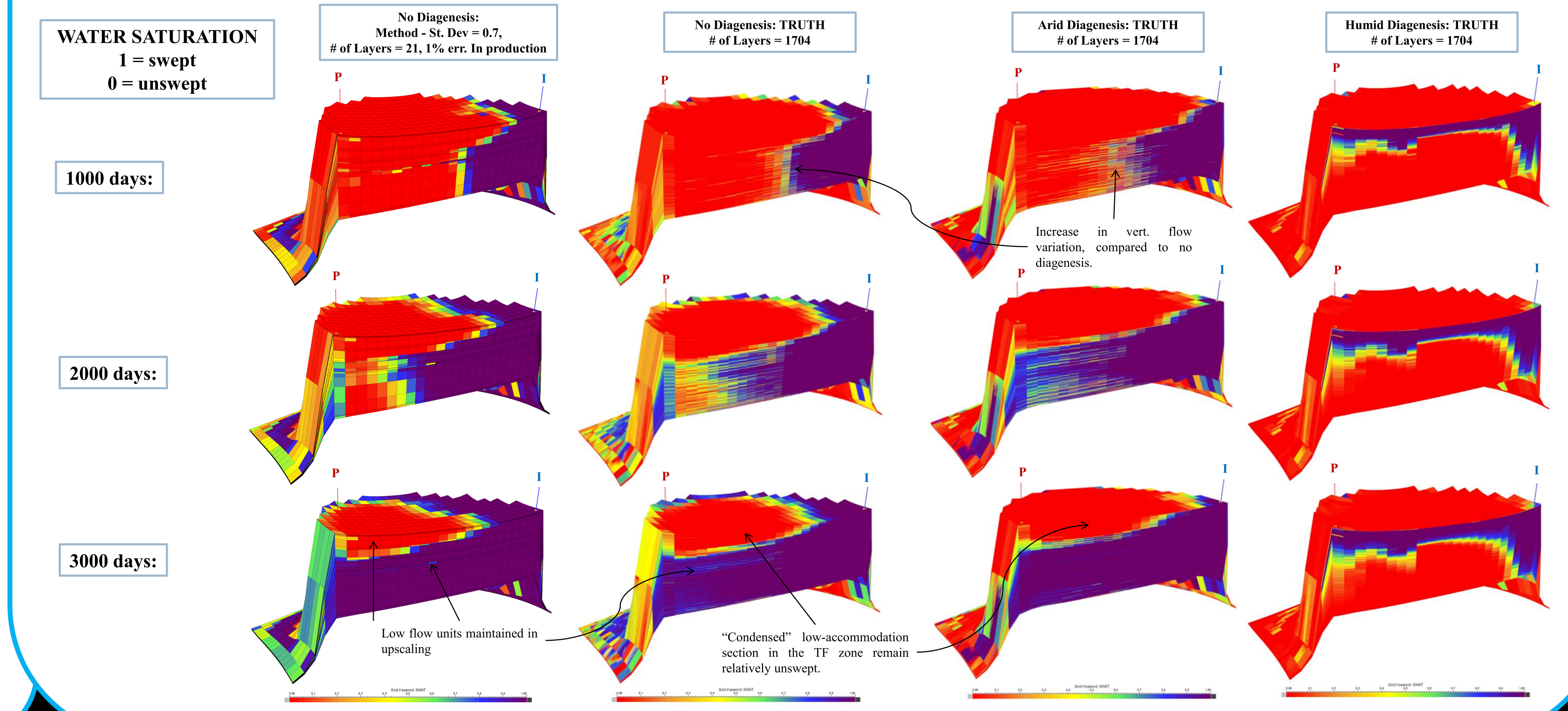
The humid model simulation is very different with a high, early water production rate breakthrough which leads to a relatively low cumulative production. This early water breakthrough is very prominent in the 3D plot of water saturation (below) where the non-fabric selective porosity in the "condensed" low-accommodation units has created a highly permeable pathway allowing water to flow more quickly to the producer, than through the "cyclic" section as seen with the arid model.

For flow simulation of the non-diagenesis model, using the three amalgamation thresholding methods, the ability of each upscaled domain to match the cumulative production is given right, along with their associated water production rates. Whilst the results are somewhat obscured by over-plotting, the greatest deviation is observed with the average k contrast where domains with fewer layers (lighter colours) which over-produces in nearly all cases after 3000 days. The graphs left also show the number of layers vs. percentage error production for the non-diagenesis and the arid/humid simulations.

For the non-diagenesis model (graph f), the variation between the thresholding method give an error in cumulative production to the truth model by < +/- 2% in all cases, but with no single threshold method giving a smaller error in production with more layers used to define the domain. This suggests that the heterogeneity cannot be adequately captured by any one single thresholding method, but can be closely approximated. In the 3D plot of water saturation the upscaled non-diagenesis model constrained by the standard deviation method is compared to the truth model with quite clear similarities, where low flow are maintained (as indicated) in both the "cyclic" and "condensed" low-accommodation units.

Comparing the arid (graph g) and humid (graph h) upscaled domains, the error in production, for both cases, decreases with increasing number of layers. For the arid climate, whilst fewer layers capture the production of the truth model poorly, it becomes more comparable with a larger number of layers. For the humid environment, the production is grossly over predicted. This suggests that for the higher thresholding values (equivalent to fewer layers), where the high-permeability layers caused by non-fabric selective dissolution, whilst they greatly influence flow, they do not capture the whole behaviour of the reservoir, and the response of the matrix permeability is also needed.





SUMMARY AND CONCLUSIONS:

Using a combination of forward sediment and diagenetic modelling, geostatistical upscaling techniques, and streamline simulation, a numerical reconstruction and characterisation of the Middle Jurassic Latemar isolated carbonate platform has been successfully captured.

The key structures captured in the sedimentology model CARB3D+ are the distinct stratigraphic sequences of the Lower Cyclic Facies that transition into "condensed" low-accommodation cyclic unit of the Lower Tepee Facies, where sediment accommodation was driven by the cyclic sea level parameterisation of Zuhlke et al., (2003). The model also captures the platform facies distribution with respect to the interior part of the platform, compared to the work of Egenhoff *et al.,* (1999), with grainy packstone-grainstone margins transitioning into finer subtidal packstone-wackestone units. Additionally, the observation of exposure horizons on the margin of the platform, which are not present in the interior was also captured, and is important when considering diagenesis.

For the simulation of diagenesis, two scenarios of an arid and humid climate were modelled using CARB3D+, allowing the interplay of hydrozone residence times and cyclicity to be compared. The diagenesis simulations illustrate how residence time a) difficult to predict due to complicating effects of surface elimination of exposure duration and b) residence time, by itself, can be a poor predictor of diagenesis because rate changes for a given hydrological zone are associated with the effect of changes in both fluid flux and geochemical potential. This highlights the importance of simulating both sedimentology and diagenesis simultaneously, as the interplay has highly contrasting outcomes.

For streamline fluid flow, simple tracer experiments on upscaled domains (using geometrical upscaling) were compared to the full resolution „truth" models of the modelled Latemar with no diagenesis, arid and humid petrophysical alterations. Whilst differences in cumulative production are apparent between the arid and humid flow simulations, the structures can be confidently captured with a 98% reduction of gridblocks, and < 1% error in production for the arid, they must be comprised of flow units from both the matrix and secondary porosity/permeability rock fabrics for the humid scenario, even if the secondary permeability is controlling the fluid flow.

FUTURE WORK:

The research presented here provides the groundwork for further study to be done in a number of key areas to aid in our understanding of how the heterogeneity of carbonate rocks effect the flow of fluids in the subsurface, and can be categorised as follows:-

Sedimentology & Diagenesis Model:

1. The Latemar sediment model is currently built on a circular platform that only approximates the areal extent of the Dolomites outcrop; a more realistic surface could improve sediment distribution later used for flow simulations.
2. Simulations could involve the Upper Cyclic and Upper Tepee Facies of the Latemar platform.
3. Diagenesis model could be improved with the introduction of tepee cements, which may have important consequences for fluid flow simulations.

Fluid Flow:

1. The amalgamation routines could be used to better characterise the heterogeneity distribution
2. Amalgamation of the domains allow for more accurate flow simulations to be undertaken to simulate the effects of relative permeability in an outcrop analogue reservoir.

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