Integrating analogue and numerical modelling techniques for improved simulation of coupled regional tectonic processes and syn-depositional systems

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Discussion material for TS10.3

Modelling of tectonic processes

04/05/2020
10:45-12:30

1 Rationale

2 Integrating Analogue & Numerical Models

3 Workflow Example

4 Static Models

5 Kinematic Models

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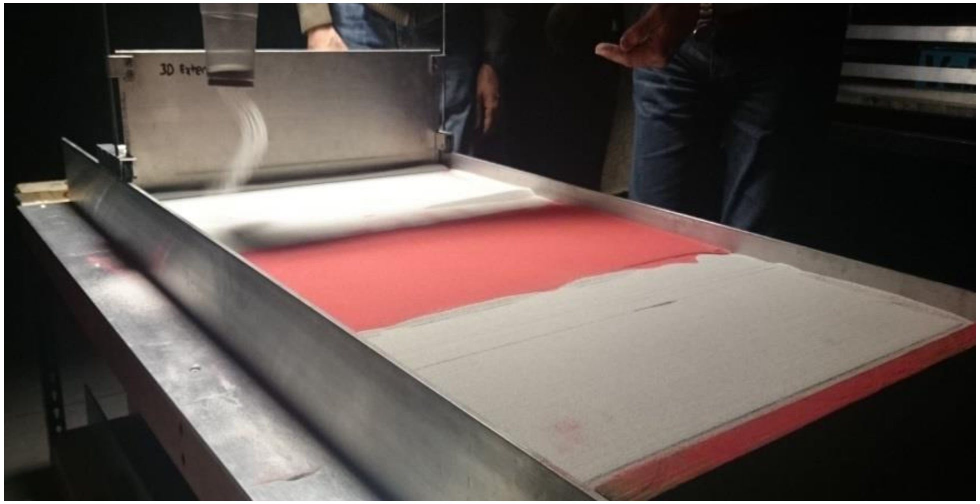
COMPASS Continental Margin Research

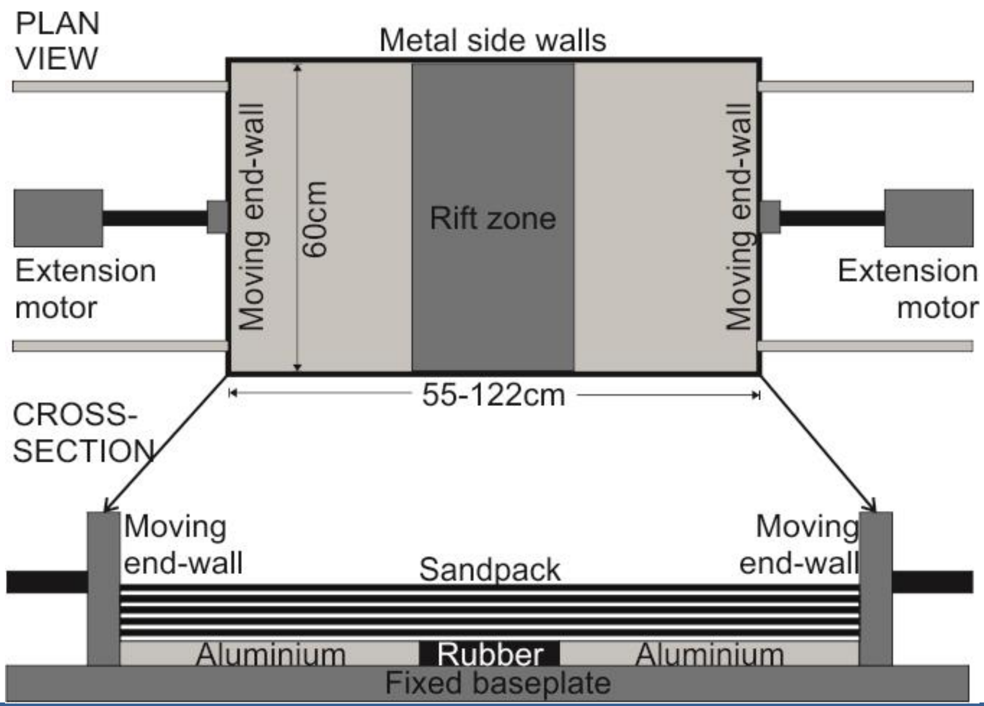
1 Rationale

Integration of analogue and numerical modelling techniques permits running of models which exhibit the following:

- **Contributed from Analogue modelling:** Realistic, quantitative structural architectures develop, including fault localisation, linkage and displacement. This provides meaningful tectonic-subsidence, captured in high resolution.
- **Contributed from Numerical modelling:** Sedimentation intervals are developed in a realistic manner, producing complex stratal geometries that will produce gravity-driven deformation.
- Non-tectonic controls such as sea level or climate can be investigated in more detail, showing how they influence model evolution.
- In future, feedback mechanisms between tectonic evolution and sedimentation can also be investigated in a more in-depth manner due to their accurate replication occurring within a single integrated model.
- Insights to aid in ongoing petroleum exploration efforts.

1 Rationale: Analogue Modelling Overview





- Physical sandbox models
- Use granular materials, primarily high purity, well-sorted quartz sand
- High resolution analysis permits observation and quantification of 3D structures produced during the geometric and kinematic development of experiments
- Models are scaled to their natural prototypes (1cm model = 1km nature). Dynamically-scaled models undergo similar evolutionary history to their ‘prototype’, just on a smaller scale and at a faster rate
- A variety of tectonic settings can be simulated; examples include extensional, strike-slip and thrust systems

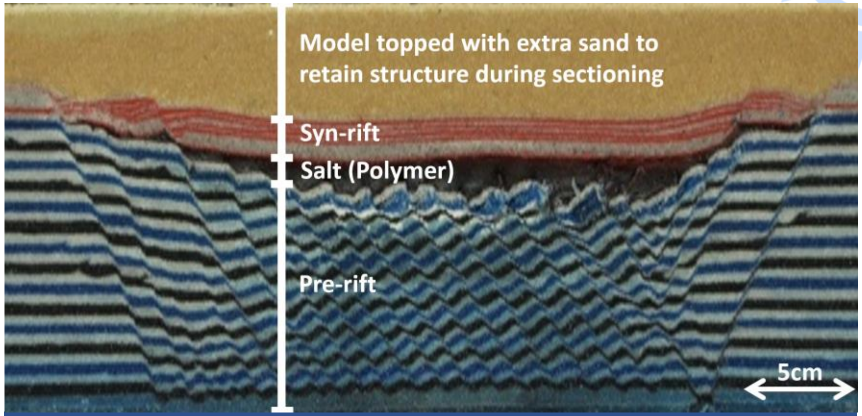
1 Rationale: Strengths of Analogue Modelling

Simulation of tectonic processes:

- Fault localisation, linkage, displacement and resulting tectonic basin subsidence
- Feedback mechanisms between sedimentary loading and tectonic response

Dynamic scaling:

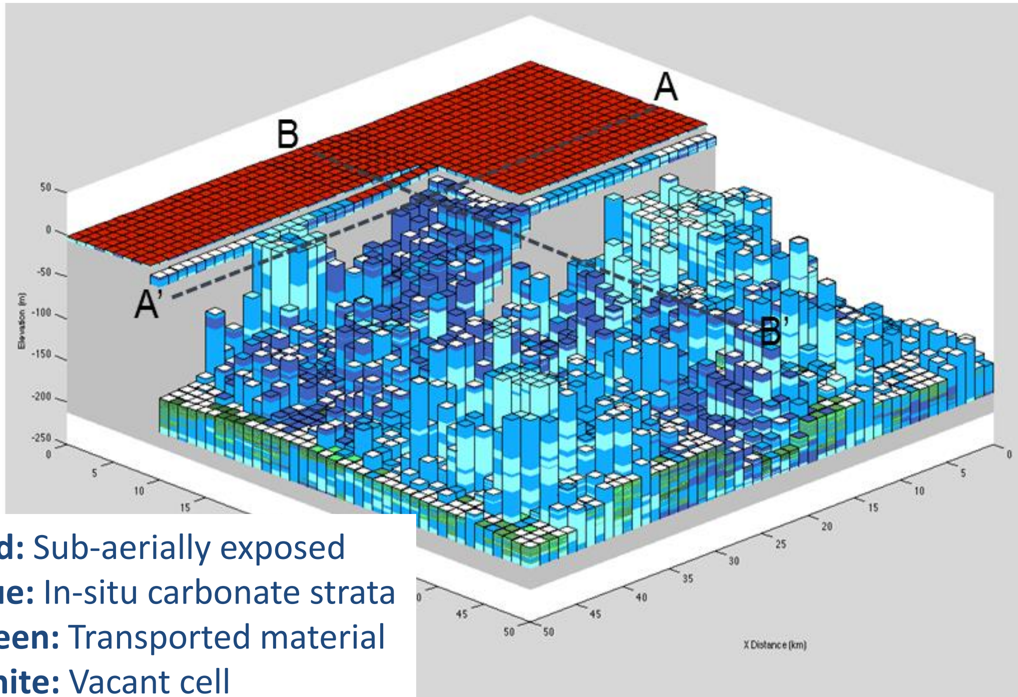
- Calibration with geological/geophysical data to model at regional scale
- Quantitative and qualitative comparison of model to nature, enabling meaningful reconstruction of basin architectures which can be applied to ongoing exploration efforts



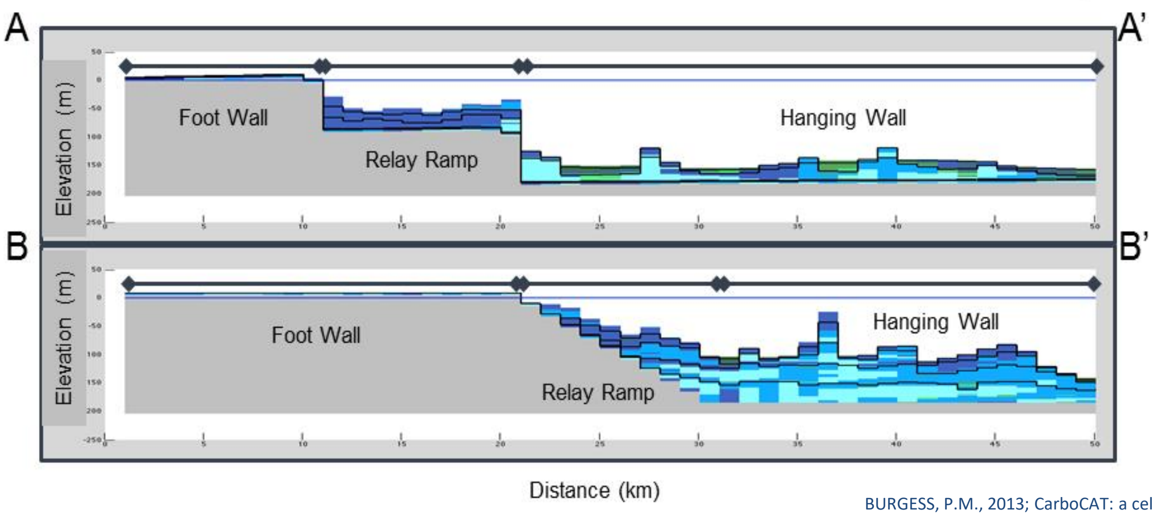
Section of a 3D-rift extension model, with relevant units highlighted

Finished model, prior to sectioning, which has been 'lithified' by addition of gelatin

1 Rationale: Numerical Modelling Overview (CarboCAT)



Red: Sub-aerially exposed
Blue: In-situ carbonate strata
Green: Transported material
White: Vacant cell



- Stratigraphic Forward Modelling software of carbonate systems, written in MATLAB (Burgess, 2013)
- Deterministic modelling of carbonate strata with heterogeneous facies distributions controlled by spatially and temporally variable production and accommodation
- In-situ accumulation is modelled using a cellular automata with multiple carbonate factories, each with a water-depth dependent production rate
- Includes sea-level changes etc. (Non-tectonic controls)
  - The modeller has been modified to incorporate complex subsidence distributions imported from analogue experiments
  - Work in this presentation is solely carbonate modelling, to show functional integration with analogue models. Clastic processes can easily be added in future.

BURGESS, P.M., 2013; CarboCAT: a cellular automata model of heterogeneous carbonate strata. *Computers and Geoscience*, 53: 129–140.

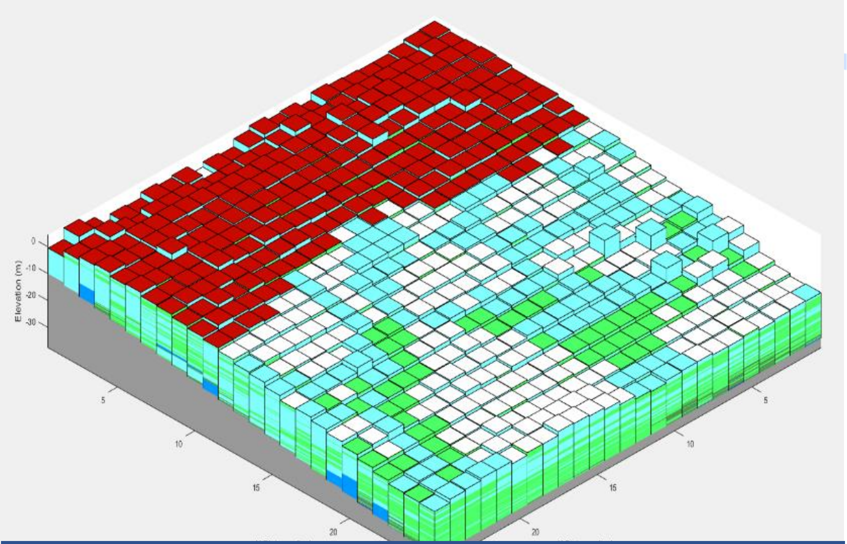
1 Rationale: Strengths of Numerical Modelling (CarboCAT)

Replicate complex, large scale stratal architectures:

- Heterogeneous platform interior strata
- Lateral migration
- Interfingering of lithologies
- Detailed, non-uniform sedimentation

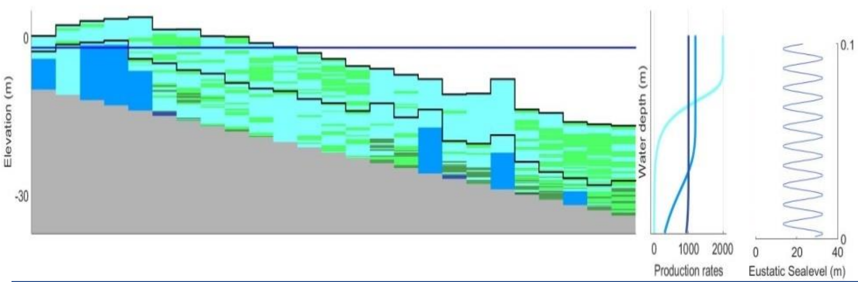
Inclusion of non-tectonic controls:

- Sea-level fluctuations, including sub-aerial exposures
- Facies distribution and resulting feedback mechanisms
- Climate variations



Example output showing carbonate accumulation for a single increment.

Grey= Input surface, Blues= In-situ carbonate facies, Greens= transported carbonate facies, Red= sub-aerially exposed surface.



Cross-section of the above model displaying the heterogeneity observed in the carbonate build-up. Also shown are the independent production profiles (m/My) for each of the 3 facies and the eustatic sea-level which has affected model evolution.

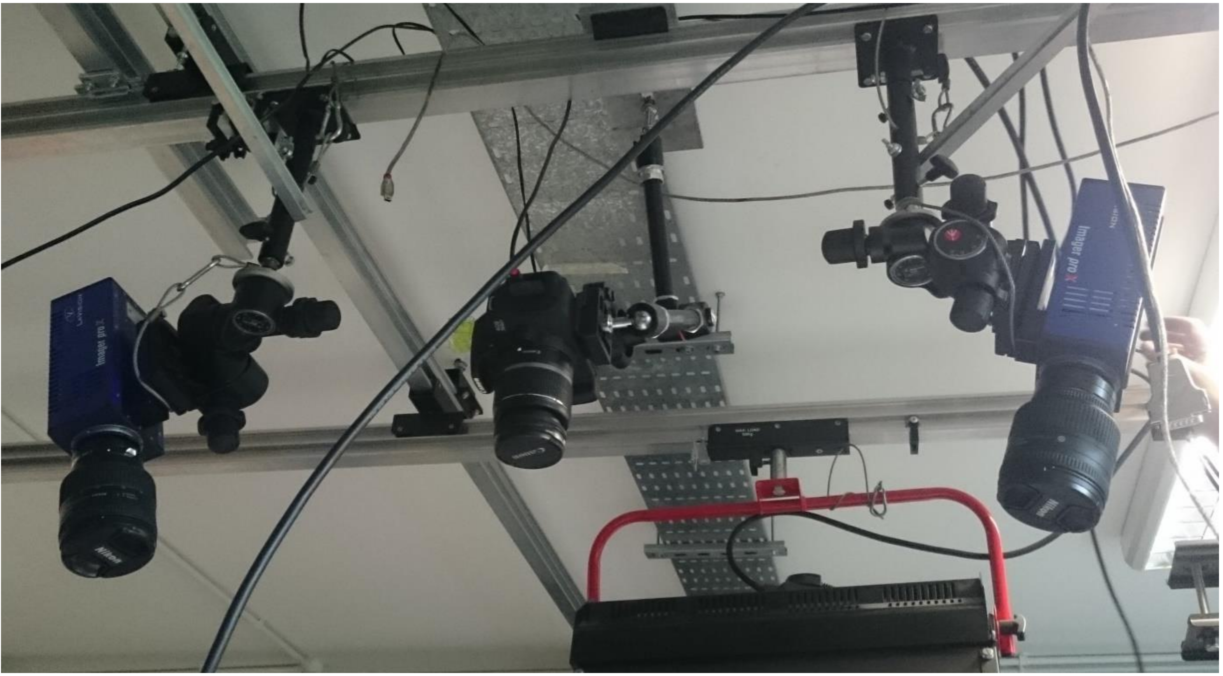
2 Integrating Analogue & Numerical Models

To permit a workflow integrating analogue and numerical modelling methodologies, two processes need to be developed:

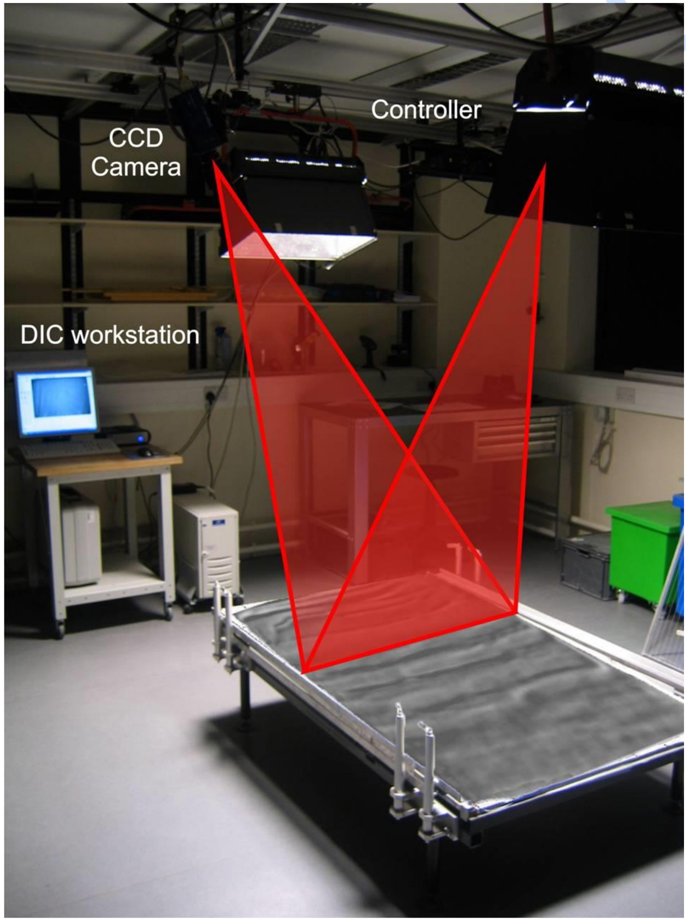
1. **Analogue data inputs for the numerical modeller:** Translate analogue model surface data recorded by cameras into the numerical modeller as inputs for topography and subsidence rate. Both of which are suitably scaled to natural dimensions.

2. **Numerical modeller output delivered back to the analogue model:** Once the numerical modeller has calculated sedimentation patterns; these need to be delivered back onto the analogue model. Correctly scaled volumes need to be delivered to their relevant locations, whilst maintaining homogeneous mechanical properties within the sandpack.

2 Integration: Analogue data inputs for the numerical model



- Two stereo cameras record detailed surface data, as well as a central DSLR for simple surface images.
- High resolution surface elevation and deformation is calculated by 3D stereo DIC (Digital Image Correlation)
- Subsidence rate is derived from vertical displacement over time in successive images

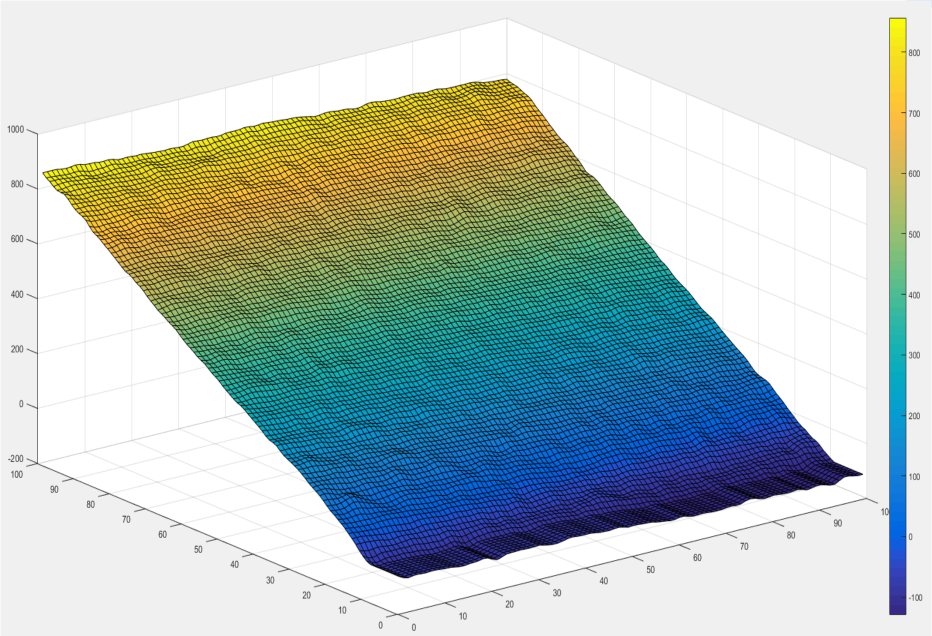


- Angles recorded by the 3D stereo camera setup

2 Integration: Analogue data inputs for the numerical model

ASCII data from DIC

	A	B	C
1	x	y	z
2	-107.864	85.9456	10.40603
3	-107.712	85.9456	10.41164
4	-107.56	85.9456	10.41721
5	-107.409	85.9456	10.42282
6	-107.257	85.9456	10.4285
7	-107.105	85.9456	10.43409
8	-106.953	85.9456	10.43958



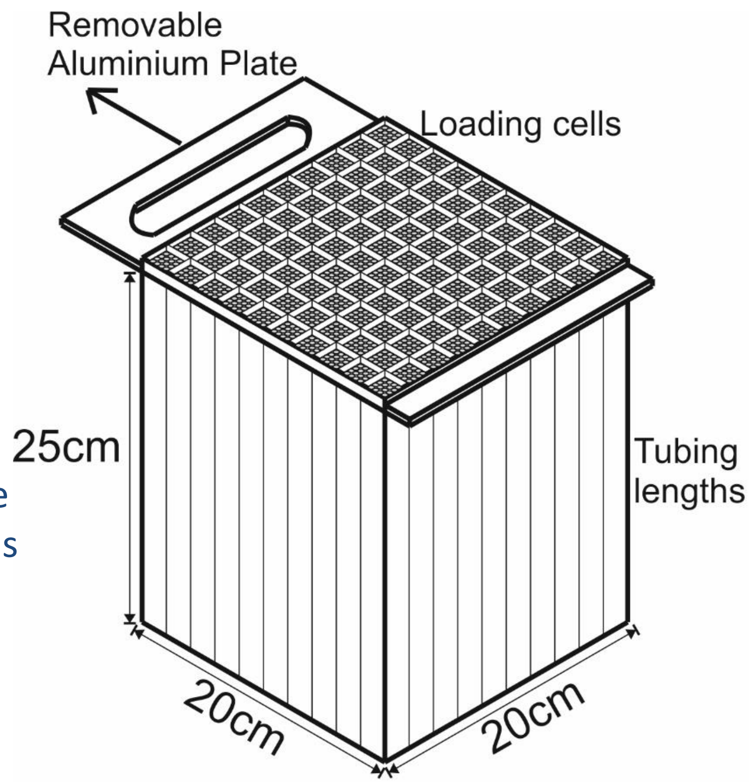
- The raw surface elevation format is a Tecplot (ASCII), with each recorded data point being represented by an x, y & z value in a list
- This data is transformed into a matrix (cellular grid) consisting of data points or cells representing bathymetries/elevations (depending at what point sea level is applied)
- Scaling is adjusted from millimetres (camera data) to metres (natural scaling). 1km nature = 1cm model
- Complexity is reduced from the approximate 40,000 input data points down to a 100x100 matrix
- Subsidence rate, where applicable, is calculated from vertical displacement of the surface over time

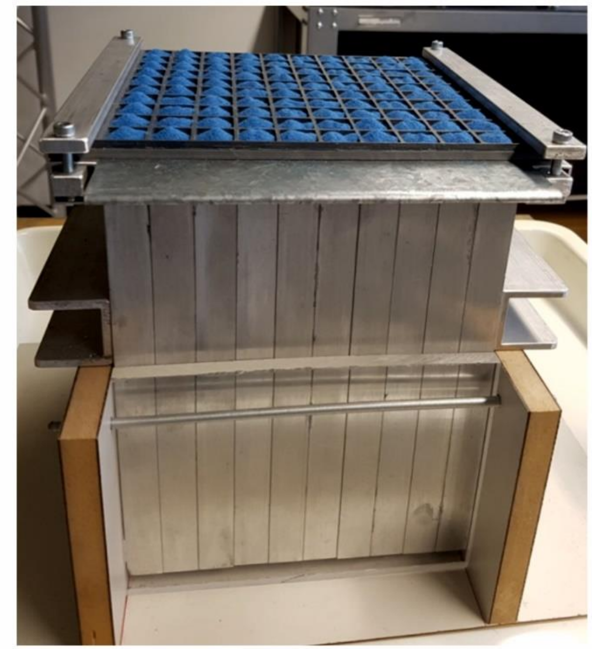
2 Integration: Numerical output delivered to the analogue model

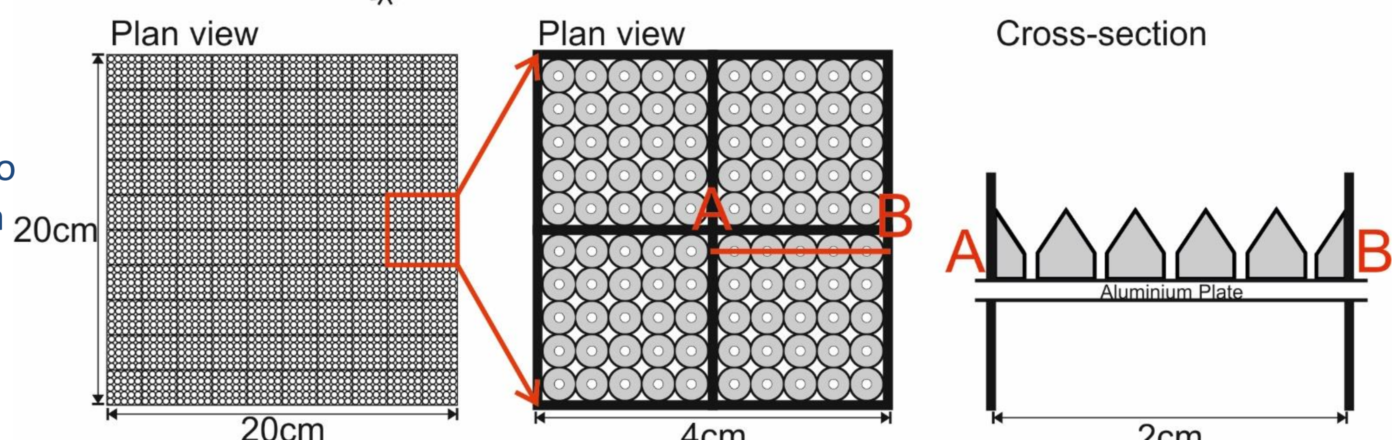
- Generated thicknesses from the numerical modeller will be heterogeneous and in a cellular format, so an apparatus was developed that permits single layers to be deposited with variable thicknesses

- Correctly scaled volumes are pre-loaded into a grid of cells which overly their relevant location on the analogue surface

- Once all the required cells are loaded, an aluminium plate is withdrawn from beneath and the sand falls to the model surface through a network of tubes, maintaining the desired sedimentary distribution from the numerical model







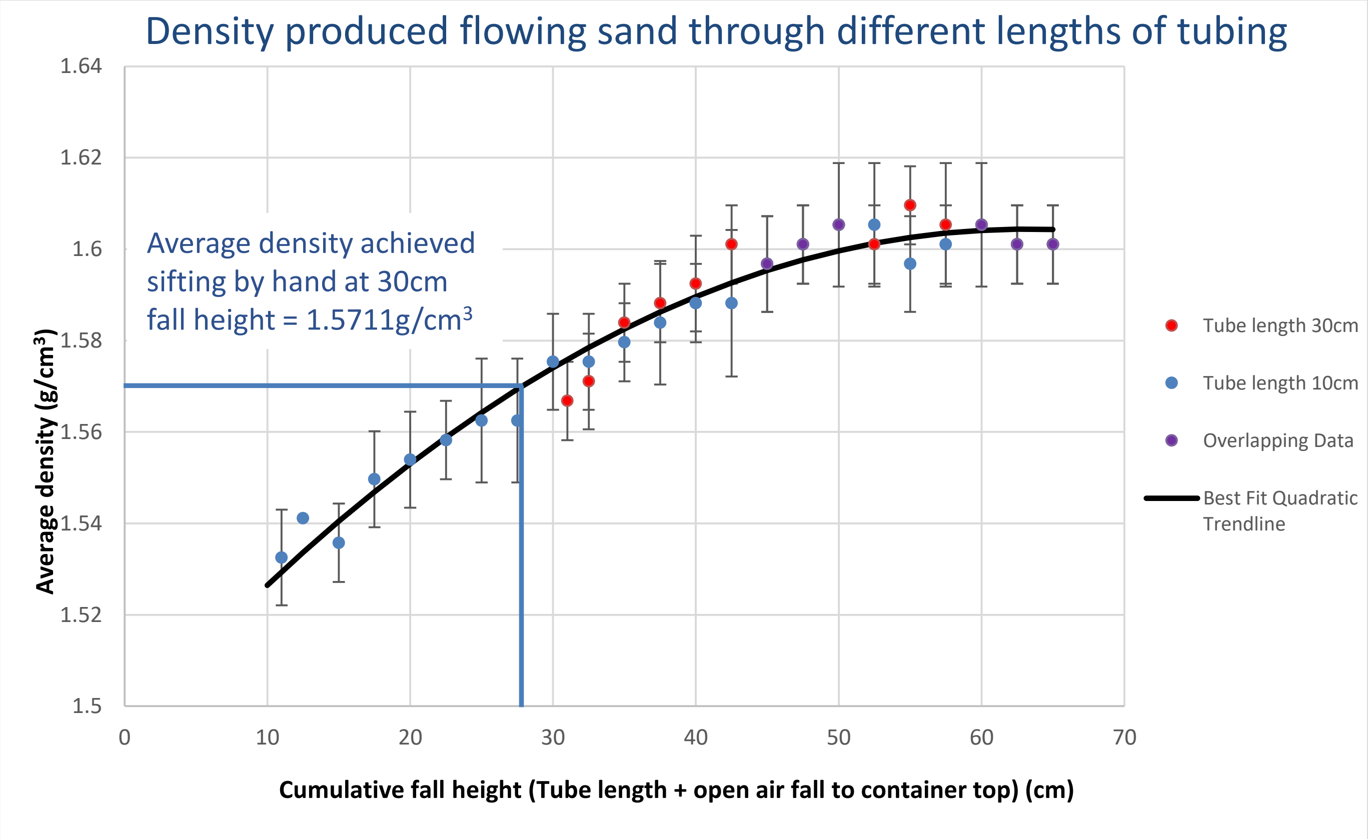
2 Integration: Numerical output delivered to the analogue model

- The purpose of the tubing lengths is to provide the capability to deposit a sandpack with homogeneous mechanical properties, identical to that of an underlying basal/pre-kinematic sandpack which is deposited by hand, with a non-linear strain dependent deformation behaviour

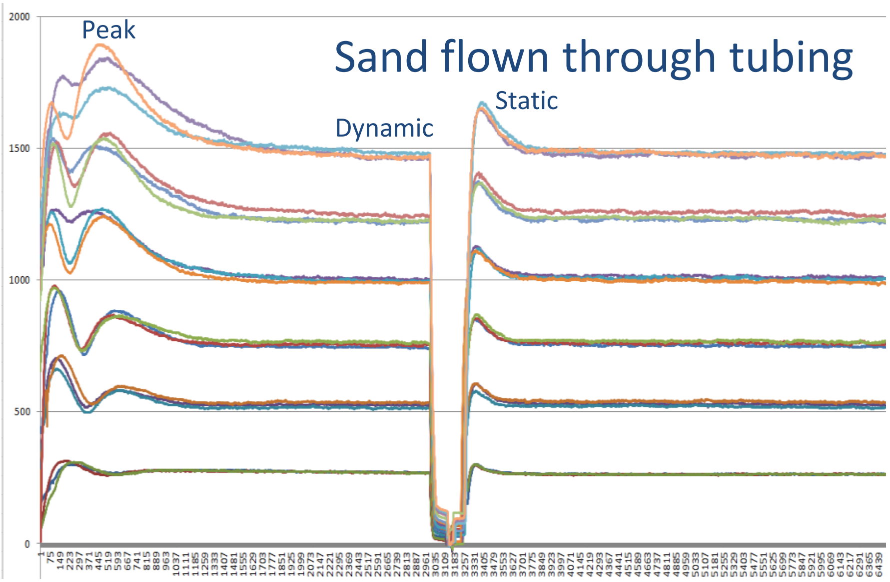
- This is achieved by letting the sand fall for a specified distance to achieve the correct density and internal friction, whilst the tubing lengths maintain the desired sedimentation pattern

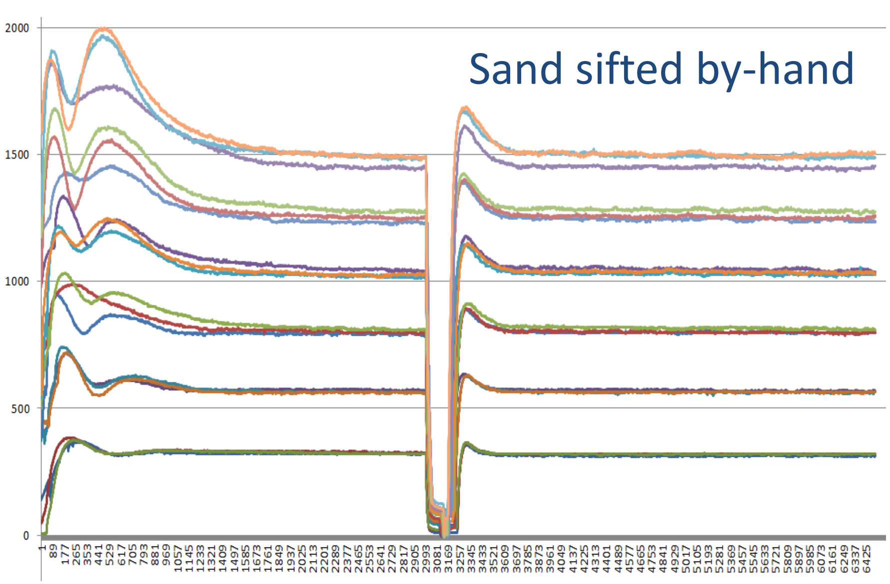
- When depositing a pre-kinematic layered sandpack, sand is sifted from a height of 30cm by hand. This yields a density of 1.57g/cm³

- Wall friction within the tubing has a negligible impact on the produced density, with the mechanical approach only slightly increasing density. Thus a total drop of 28cm is ideal. (Apparatus is 25cm tubes + 3cm gap to model)

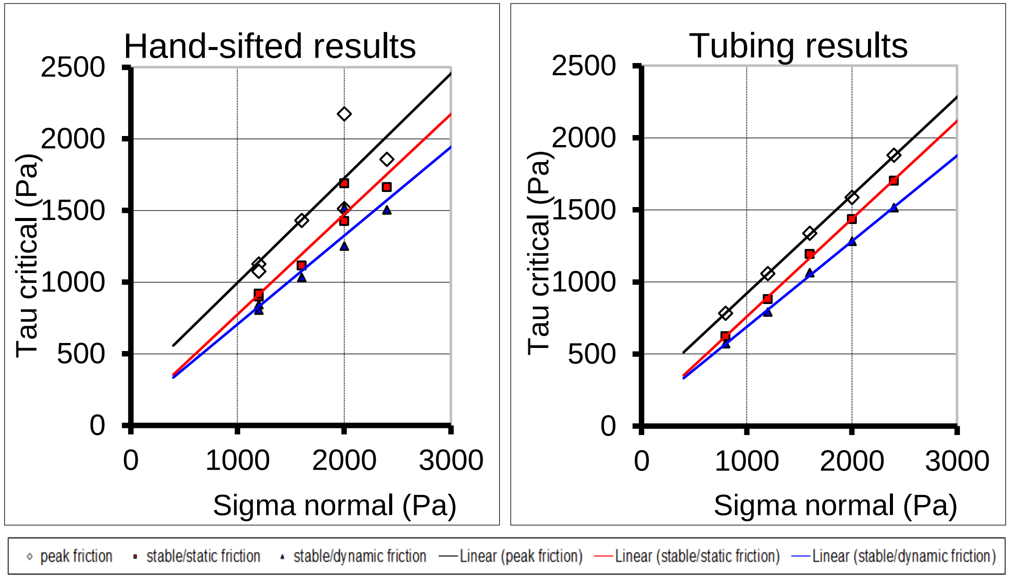


2 Integration: Numerical output delivered to the analogue model





- Material testing profiles shown on the left demonstrate sufficiently similar, repeatable behaviour between the two different methods of deposition
- Frictional parameters produced using the tubing apparatus and by-hand are consistent
- Therefore sandpacks produced using the tubing apparatus will be valid if integrated with pre-kinematic sandpacks laid by hand



	Coefficient Internal Friction	Angle Internal Friction	Cohesion
Peak	0.73	36.1	264.19
Static	0.70	35.0	73.09
Dynamic	0.62	31.7	87.07

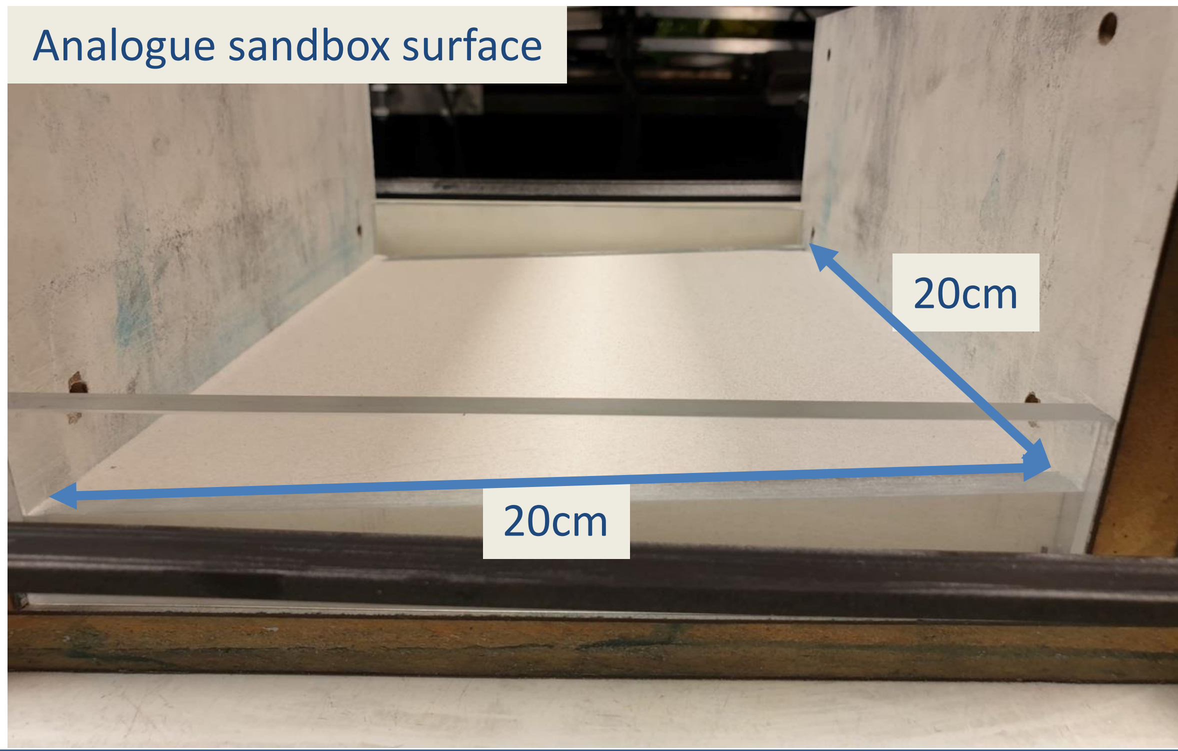
	Coefficient Internal Friction	Angle Internal Friction	Cohesion
Peak	0.68	34.2	240.27
Static	0.68	34.2	81.72
Dynamic	0.59	30.7	95.54

3 Workflow Example

Analogue model initiates / continues with extension

1. Analogue surface scanned by DIC cameras, producing topography and subsidence data →
2. Topography and subsidence data is correctly scaled, formatted and input to the numerical modeller →
3. Numerical modeller is run, calculating realistic sedimentation patterns →
4. Heterogeneous sedimentation patterns are deposited onto the analogue model

- The integrated process begins with setup of the analogue model
- This example has a ramp topography with 1cm difference in height between the bottom and top of the ramp
- Areal coverage measures 20x20cm (the dimensions of the tubing apparatus used to deliver sand), which represents a natural area of 20x20km



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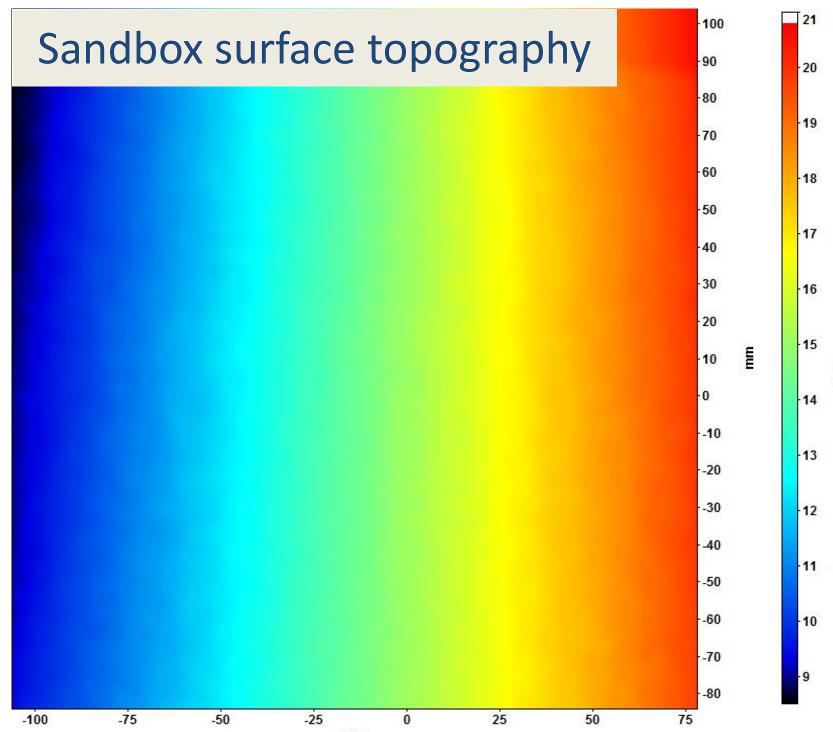
- The surface of the ramp is recorded using a pair of stereo cameras
- High resolution surface elevation and deformation is calculated by 3D stereo DIC (Digital Image Correlation)
- The image format is exported as a TECPLOT (ASCII), with each recorded data point being represented by an x, y & z value
- ***NB** this model is static, so there is no subsidence to be recorded by measuring topography change over successive images. Subsidence is manually input to the numerical modeller in this case

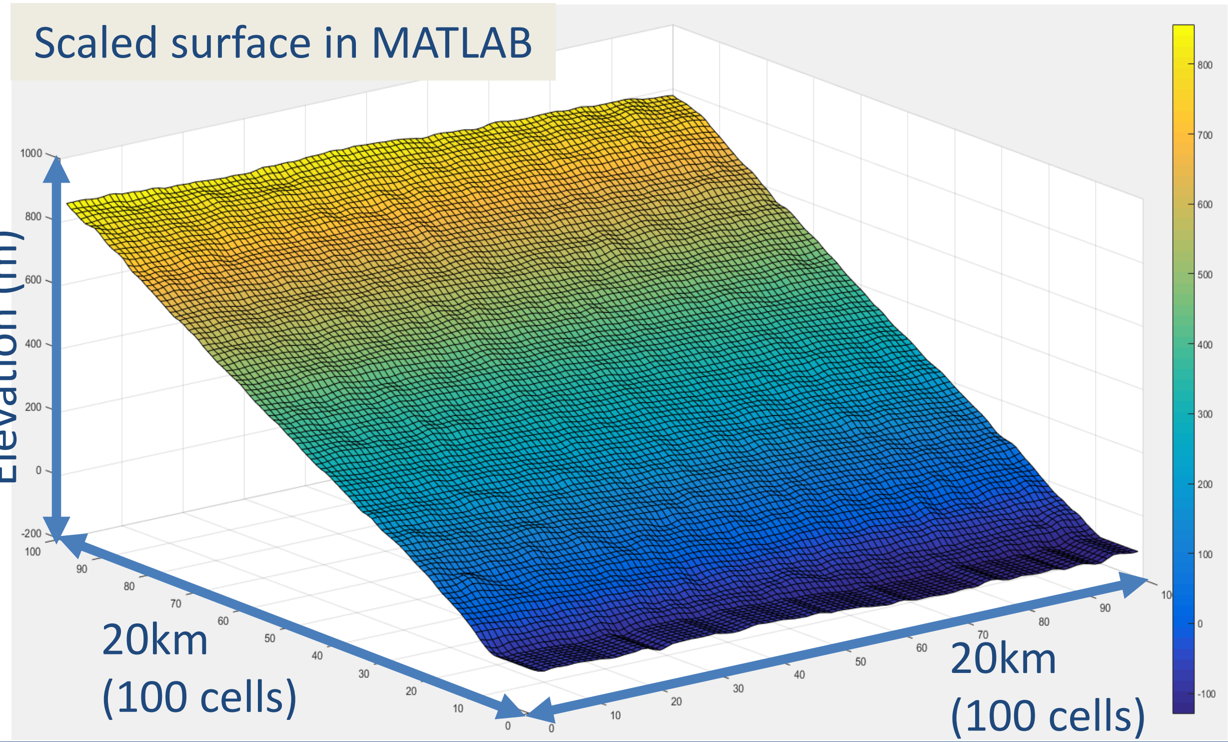


3 Workflow Example

Analogue model initiates / continues with extension

Analogue surface scanned by DIC cameras, producing topography and subsidence data → **Topography and subsidence data is correctly scaled, formatted and input to the numerical modeller** → **Numerical modeller is run, calculating realistic sedimentation patterns** → **Heterogeneous sedimentation patterns are deposited onto the analogue model**

- Raw surface data from the cameras now needs to be correctly formatted to be input to the numerical modeller.
- This is achieved by changing the changing the TECPLOT format (x,y,z list) into a matrix (grid) of surface heights.
- Scaling is shifted from mm to metres and complexity is reduced to 100x100 cells.



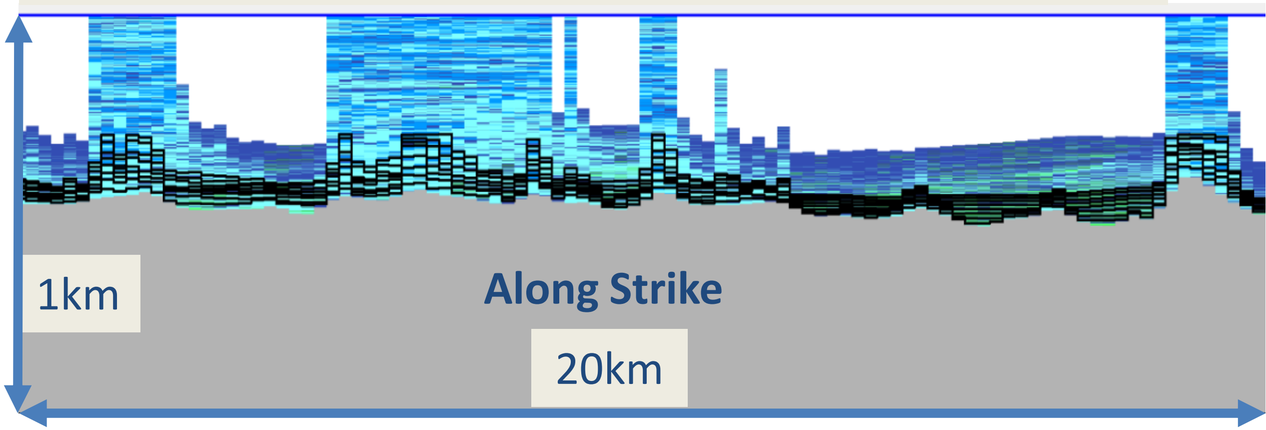
3 Workflow Example

Analogue model initiates / continues with extension

1. Analogue surface scanned by DIC cameras, producing topography and subsidence data
2. Topography and subsidence data is correctly scaled, formatted and input to the numerical modeller
3. Numerical modeller is run, calculating realistic sedimentation patterns
4. Heterogeneous sedimentation patterns are deposited onto the analogue model

- The topographic surface, now suitably formatted for use with the numerical modeller, is run with a series of parameter files. These include subsidence rate, carbonate production rates, total time and number of increments.

Cross-section of calculated accumulation from CarboCAT



- In this example there is an observable variation in accumulation along strike. Some areas have kept-up with subsidence, developing isolated platforms, whereas others have not and consist of deeper production of different facies / transported material

Grey: Input surface (i.e. scanned sandbox topography
Blue: In-situ carbonate strata
Green: Transported material

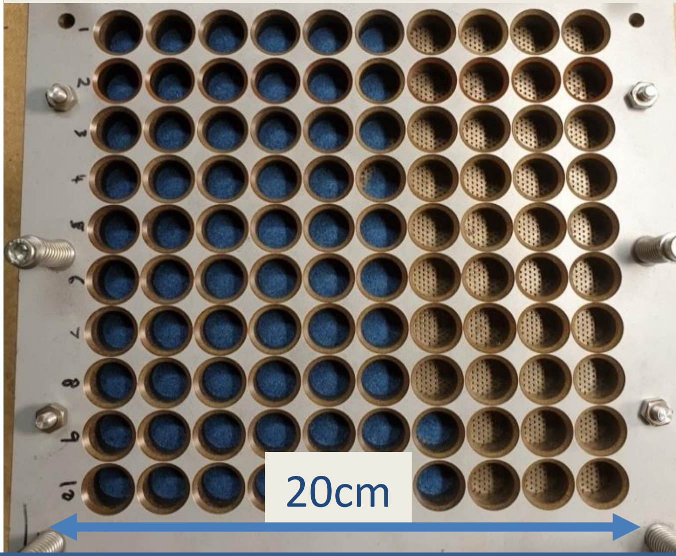
3 Workflow Example

Analogue model initiates / continues with extension

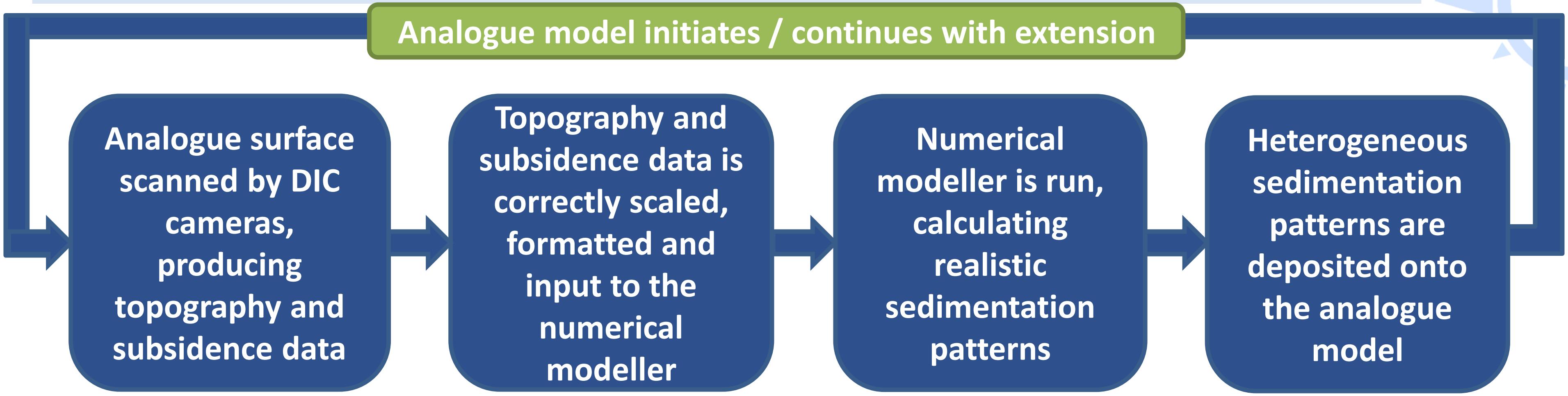
Analogue surface scanned by DIC cameras, producing topography and subsidence data → **Topography and subsidence data is correctly scaled, formatted and input to the numerical modeller** → **Numerical modeller is run, calculating realistic sedimentation patterns** → **Heterogeneous sedimentation patterns are deposited onto the analogue model**

- Since the numerical modeller is run at a 100x100 complexity, and the tubing apparatus is made up of a 10x10 cell layout, thicknesses are averaged down to the tubing resolution
- Thicknesses are re-scaled from natural dimensions back to sandbox sizes (metres to mm)
- Volumes are loaded into specific cells on the apparatus and delivered to their relevant location on the analogue surface
- The apparatus is able to deliver 0.5mm thickness increments. If there is a surplus thickness (e.g. 0.7mm would leave 0.2mm unaccounted for), then a matrix is produced containing these ‘missing’ thicknesses which is combined with the next input surface

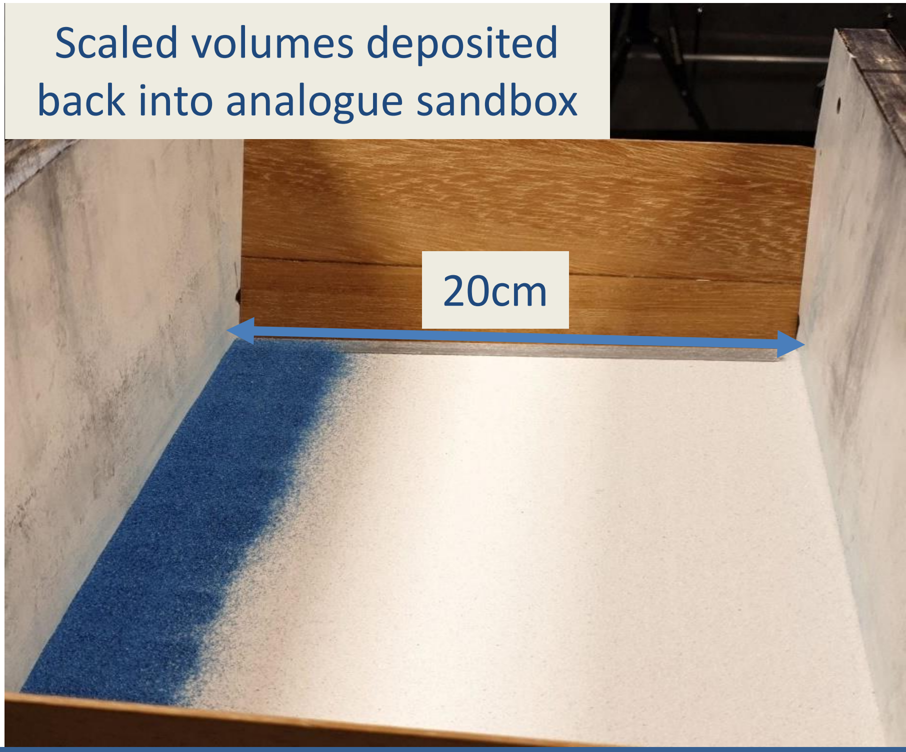
Calculated volumes re-scaled to analogue model and loaded into apparatus



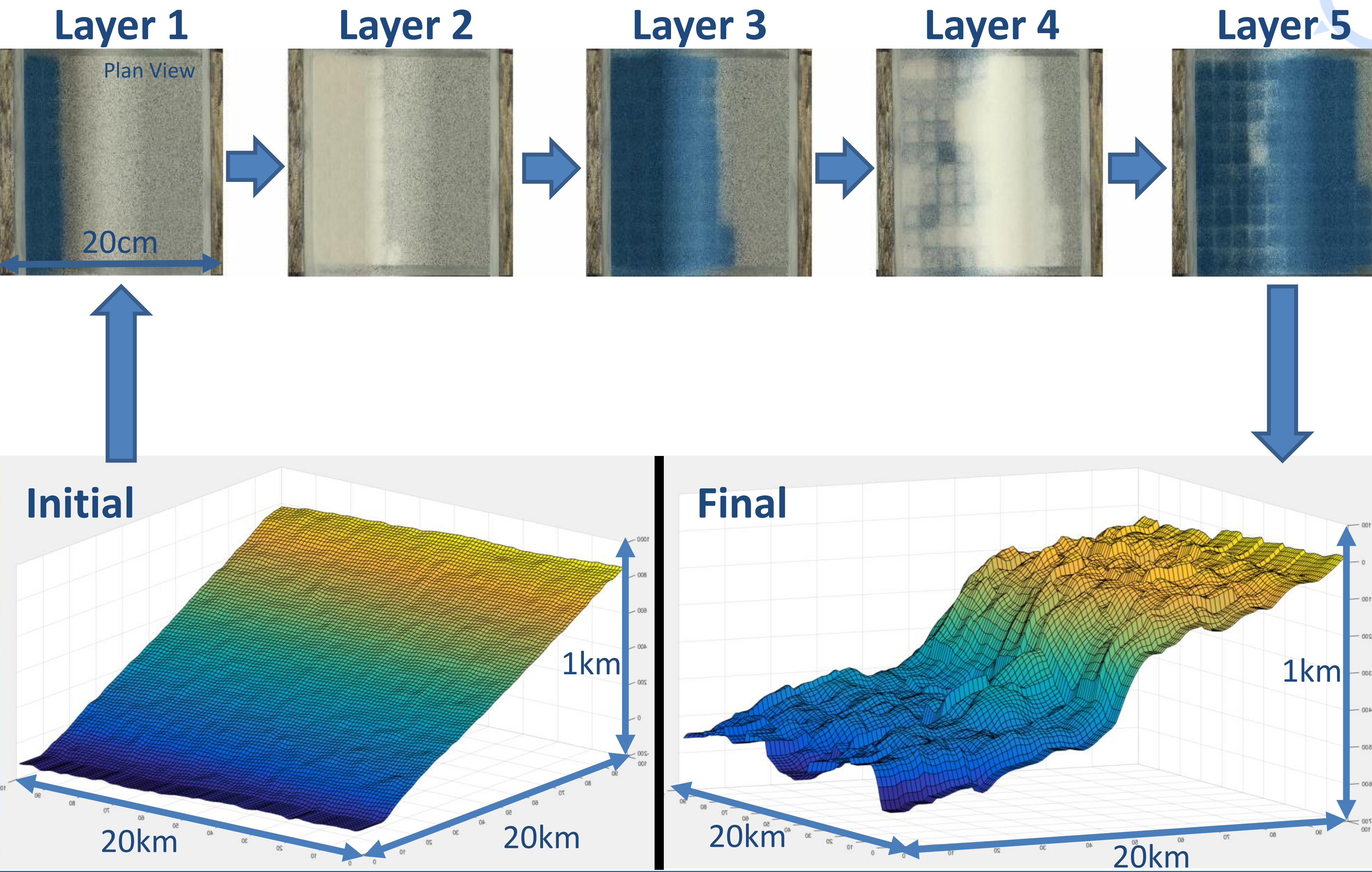
3 Workflow Example



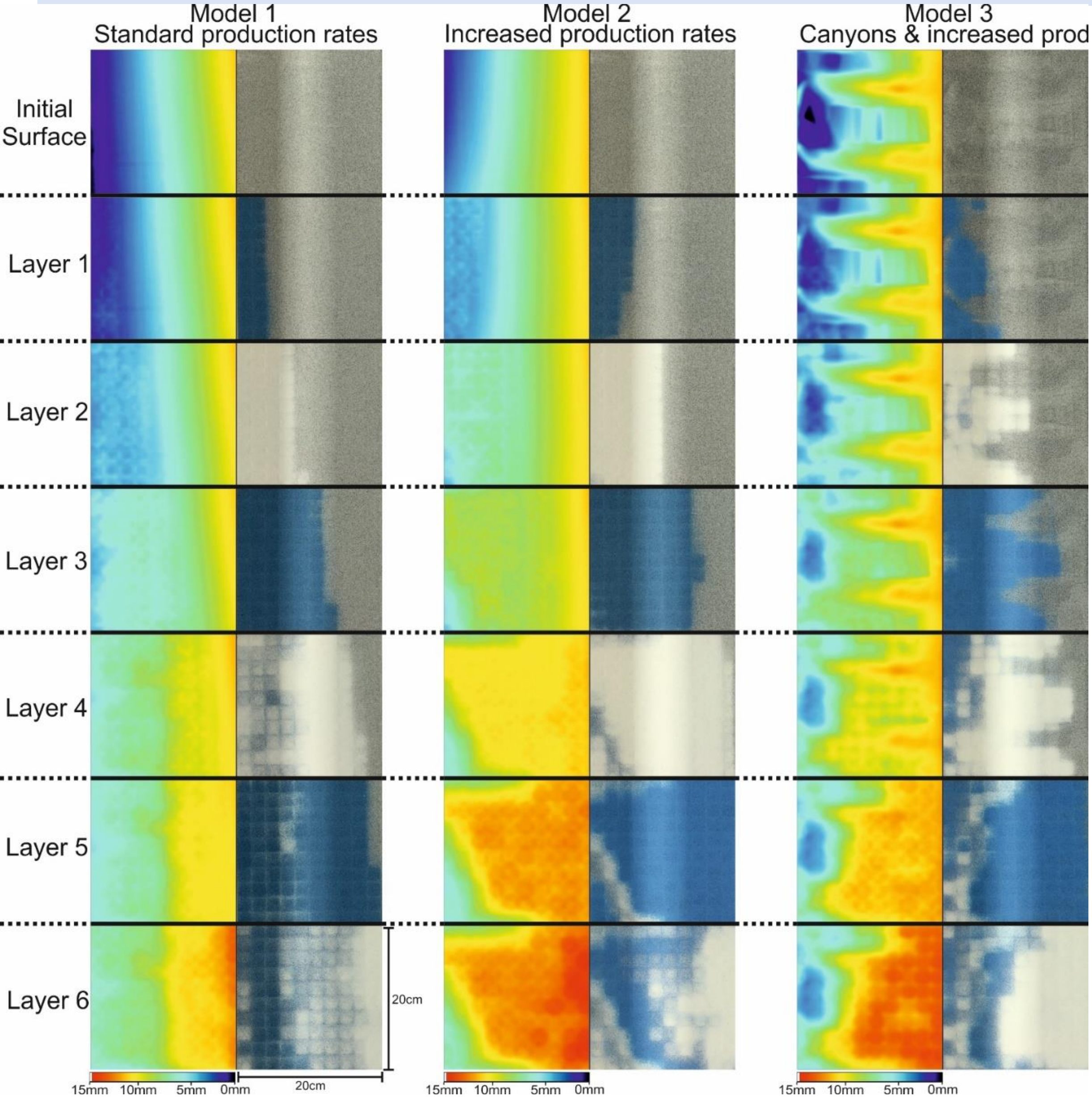
- Correctly scaled sand volumes have been translated from the numerical modeller onto the analogue surface in a single depositional event
- The deposited sand layer has coherent mechanical properties with the underlying basal / pre-kinematic sandpack
- At this point the model is ready to be scanned again for further sedimentation patterns to be generated onto it
- ***NB** If the model was kinematic then it would be left to extend for a set distance



3 Workflow Example

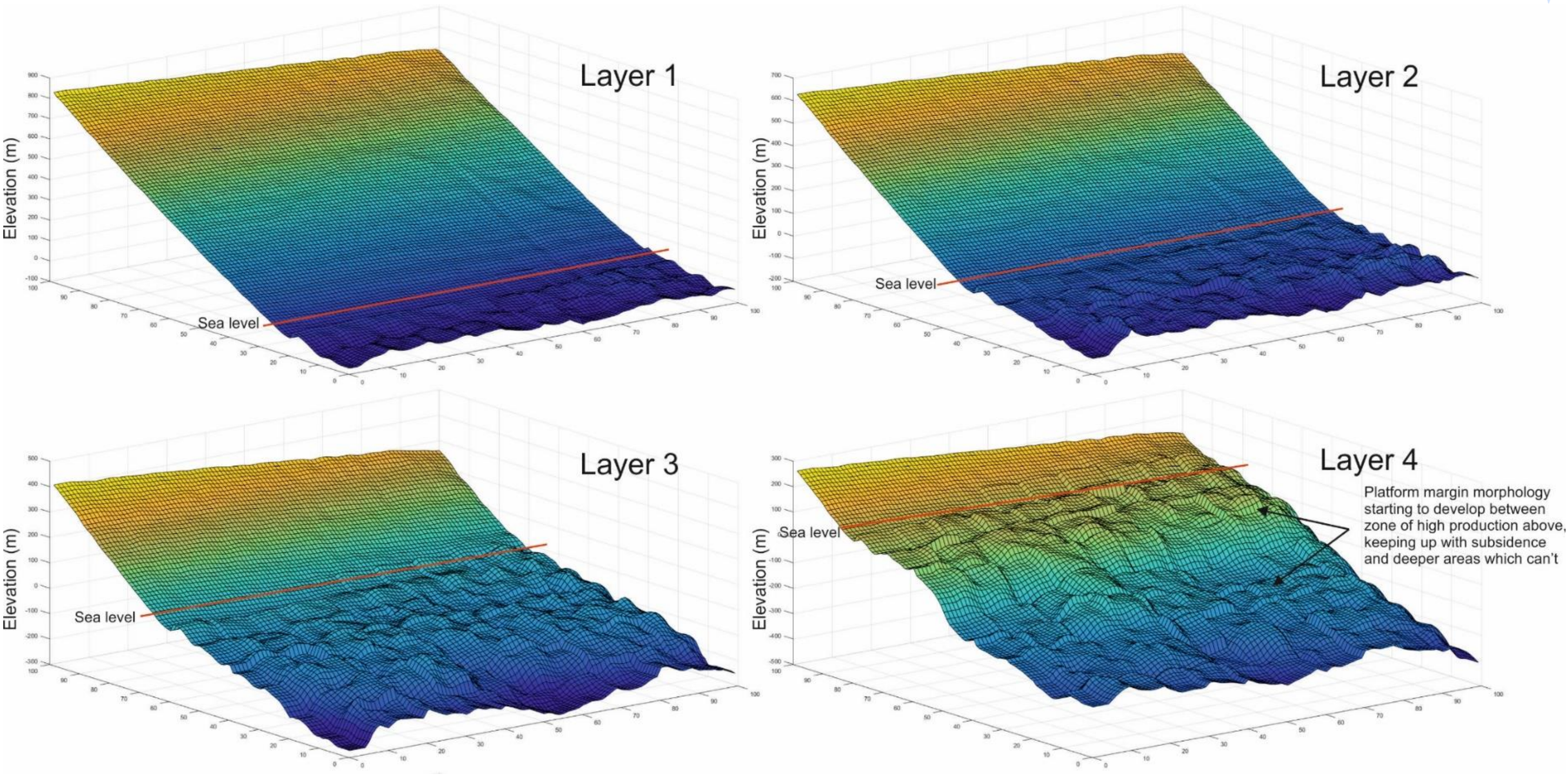


4 Static Models: Overview

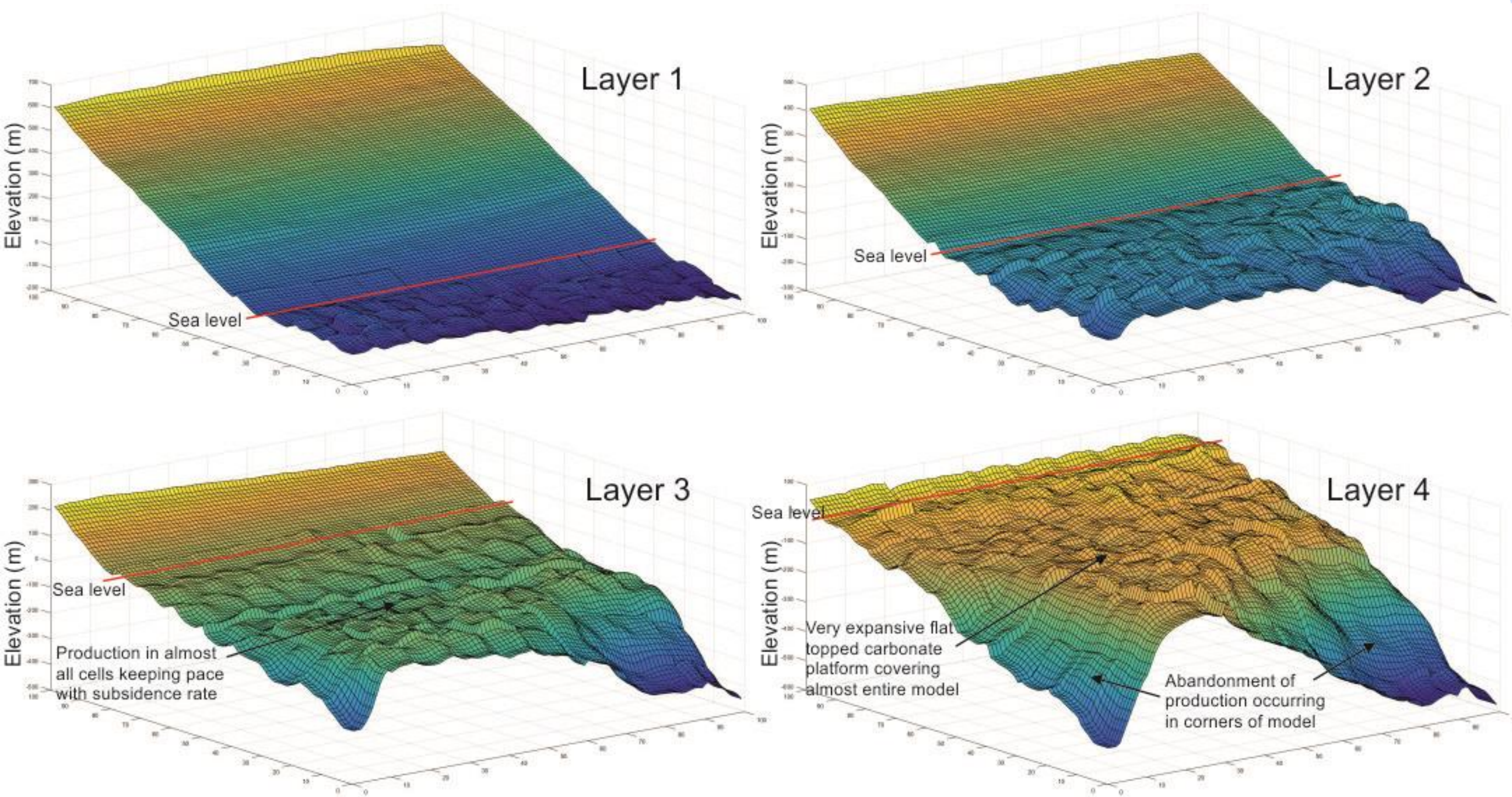


- Static analogue models
- Subsidence (to generate accommodation) is applied within the numerical model
- Left-hand images: surface topography captured by DIC
  Right-hand images: Regular SLR showing deposited sand distribution
- Model 1 = Baseline experiment
- Model 2 = Increased production parameters in numerical model
- Model 3 = Increased production parameters in numerical model and variable initial topography

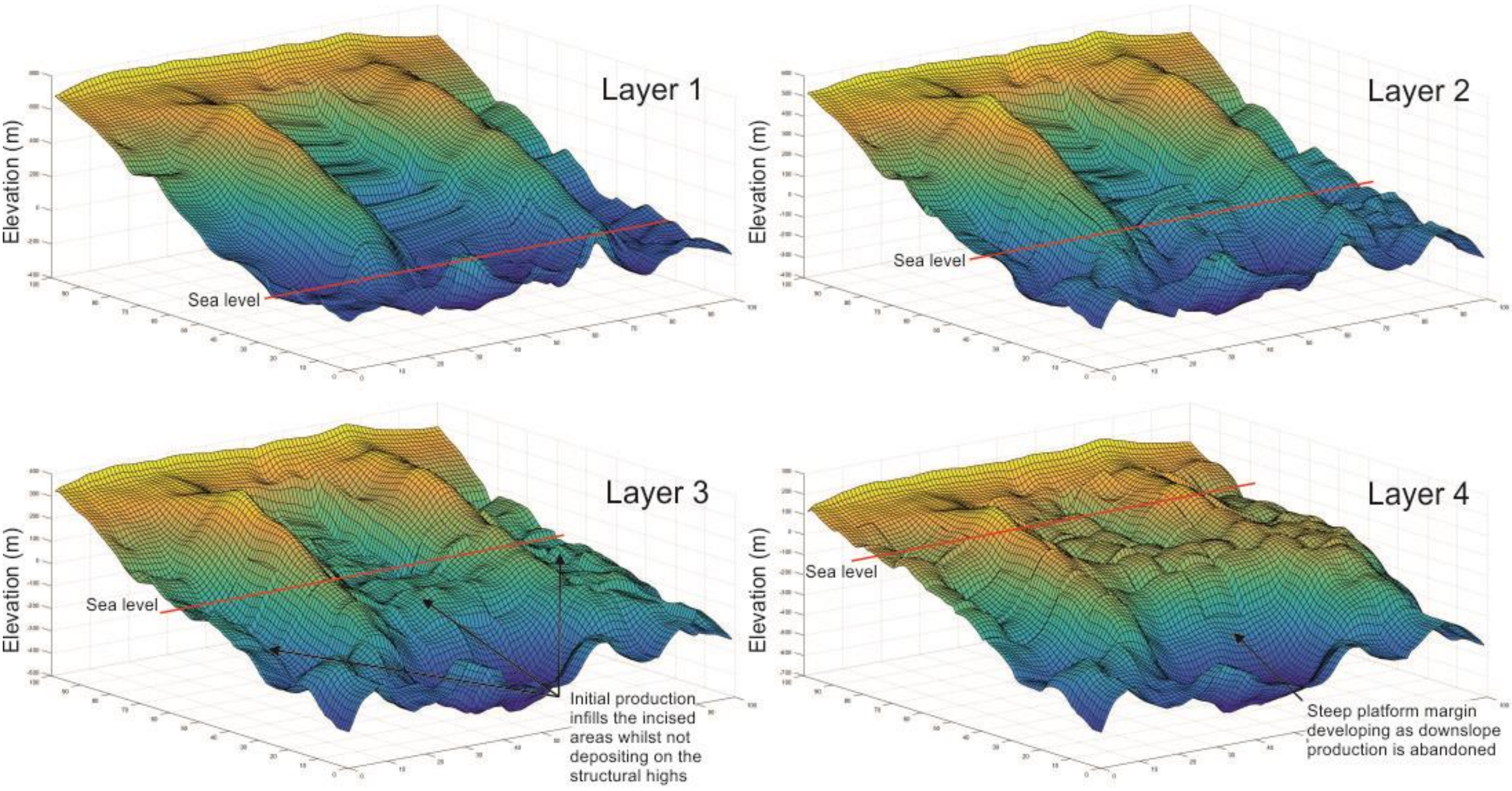
4 Static Models: Model 1 (Baseline)



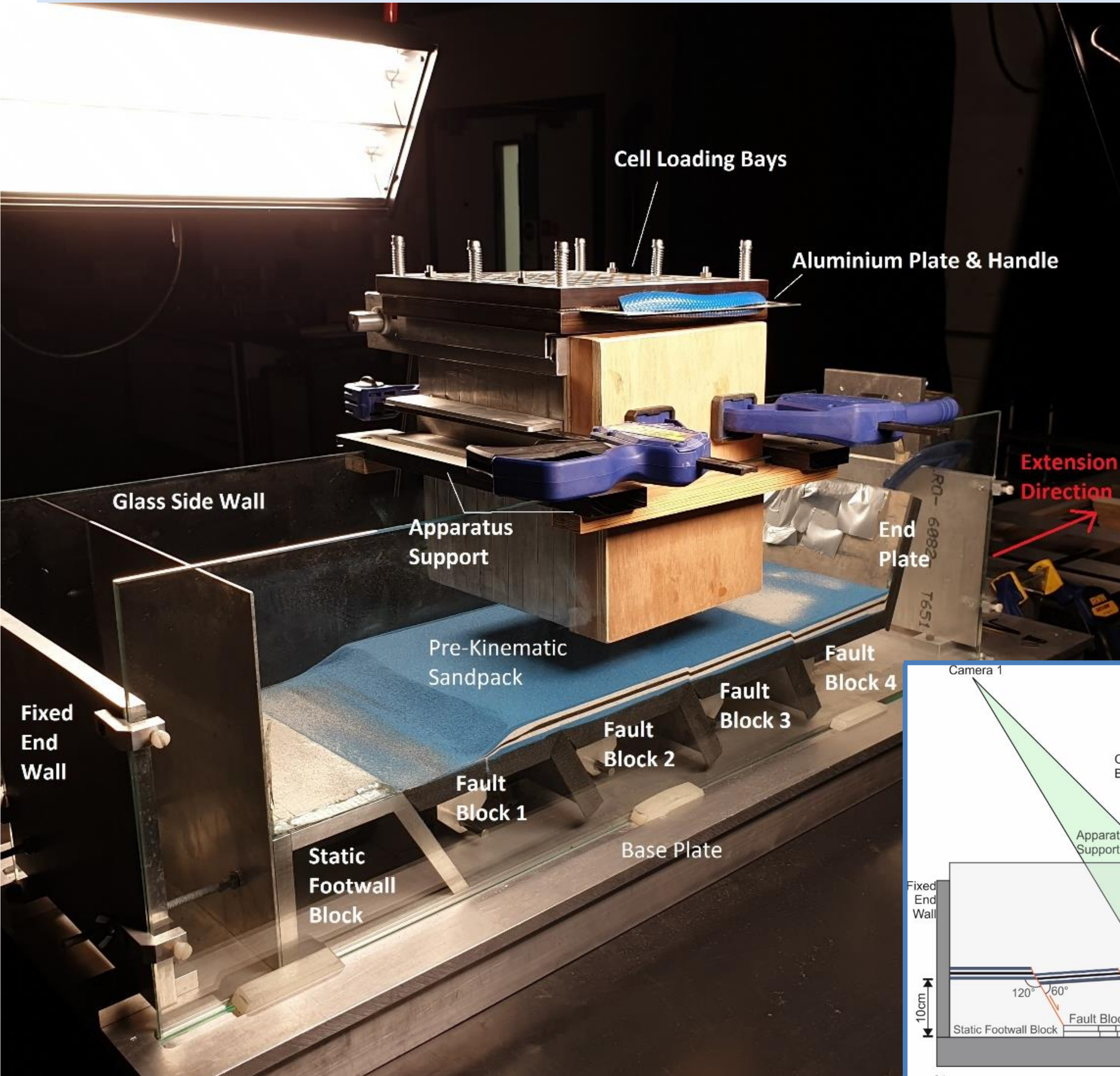
4 Static Models: Model 2 (Increased carbonate production)



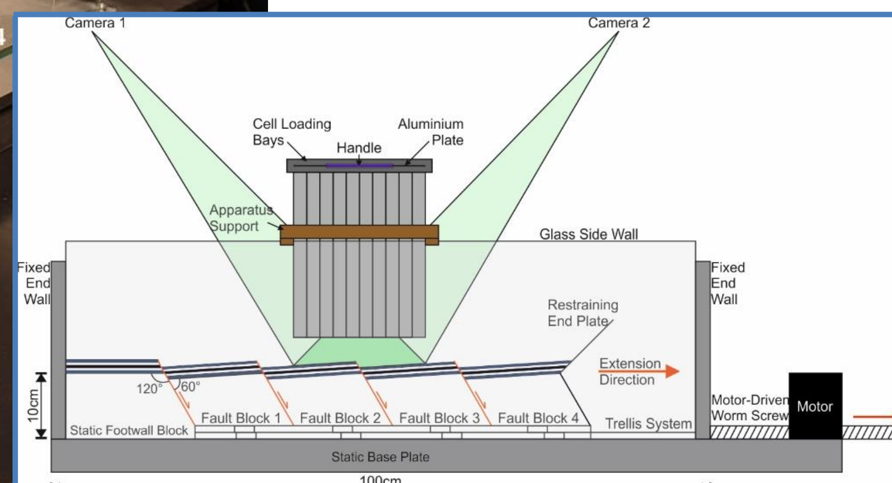
4 Static Models: Model 3 (Variable initial analogue surface)



5 Kinematic Models: Setup



- Workflow has also been applied to a kinematic setup with motor-driven extension
- Area of investigation is on the relative footwall and hanging wall blocks either side of a fault plane (Blocks 2&3)
- Both topography and subsidence are derived from the ongoing analogue surface evolution and used as inputs for the numerical model



5 Kinematic Models: Results

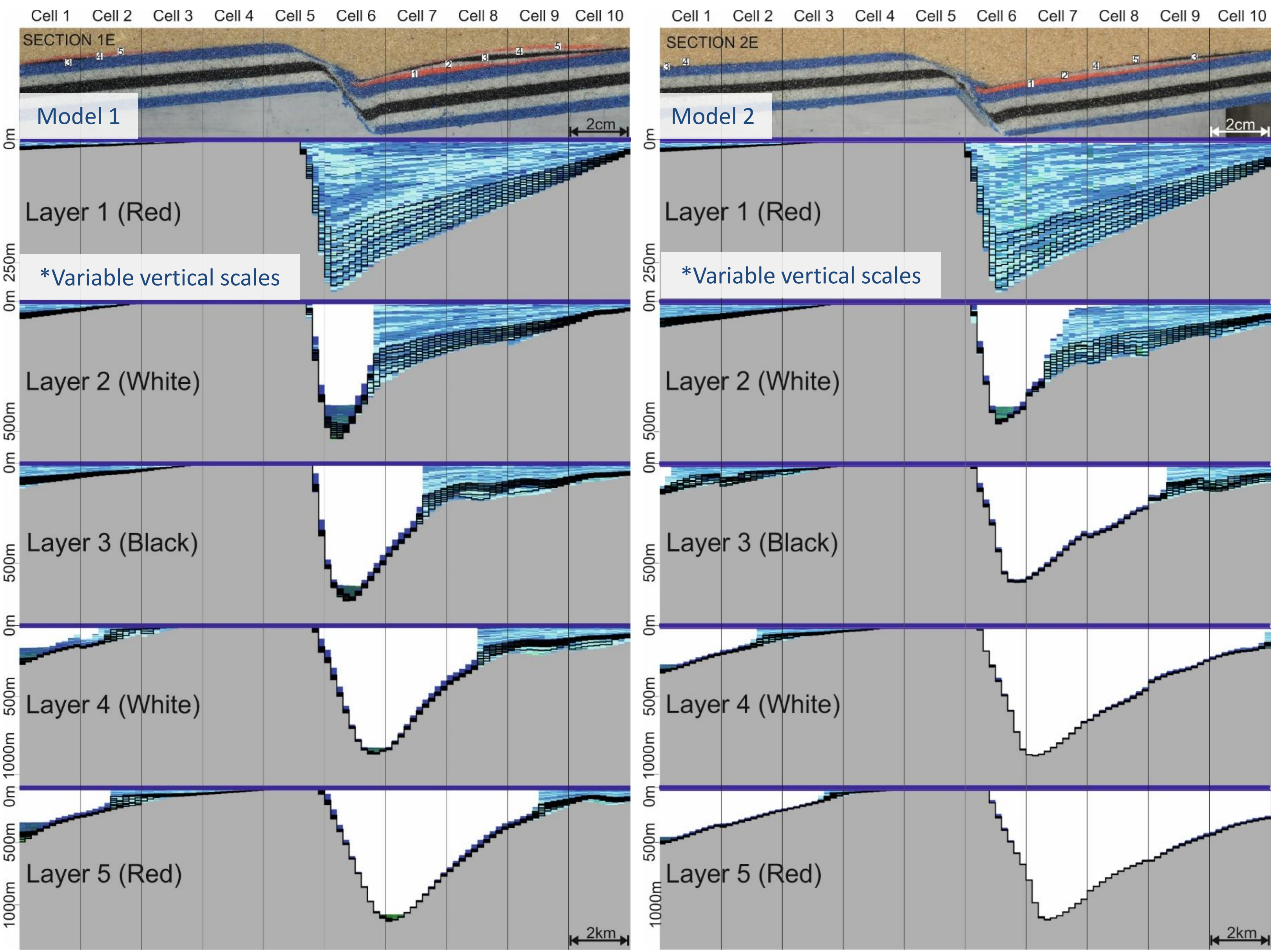
- Results are shown for 3 models, with the only difference being the extension rate (total extension remains constant)
- Calculated syn-kinematic fill (incremental layers) is the red-white-black-white-red layering

Model 1: 4My per increment **Model 2:** 2My per increment **Model 3:** 1My per increment

Slowest ⟷ **Fastest**

Extension Rate

5 Kinematic Models: Results comparison (Models 1v2)



The analogue model (top) extends for a predetermined distance for each increment. Surface evolution is captured and then used as a scaled input for the numerical model (below) to replicate evolution. This is run for a set time, representing extension rate, calculating a scaled sedimentary accumulation which is transferred back onto the analogue model (red, white & black layers) and the process repeated.

The higher extension rate (I.e. higher subsidence rate) in model 2 results in an earlier backstepping of the carbonate platform. Which in turn means future intervals have smaller accumulations, as carbonate only produces in a comparatively narrow window close to the water's surface.

The workflow is deterministically producing notably different models based only on initial parameters

Summary

- **The project has successfully developed and demonstrated a novel workflow which integrates numerical stratigraphic forward modelling software with analogue sandbox models. This has been achieved by:**
    - Adapting data derived digitally from analogue exeriments to represent topography and subsidence rates, which are then scaled and used as inputs for the numerical modelling software.
    - Producing a sieving apparatus, capable of translating volumes calculated from the numerical modeller onto the analogue sandbox – i.e. depositing heterogeneous volumes within a single sand layer, whilst maintaining coherent mechanical properties within the sandpack.
- **Models evolve deterministically, with only the analogue setup and numerical parameters governing development.**
- **The produced workflow could be employed in future to simulate a suite of geological processes, such as rifting, potentially more faithfully than either existing analogue or numerical techniques are capable of.**

Thank you for your interest!

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Department of Earth Sciences

COMPASS Continental Margin Research

Discussion material for TS10.3

(Modelling of tectonic processes)

04/05/2020
10:45-12:30

Overview

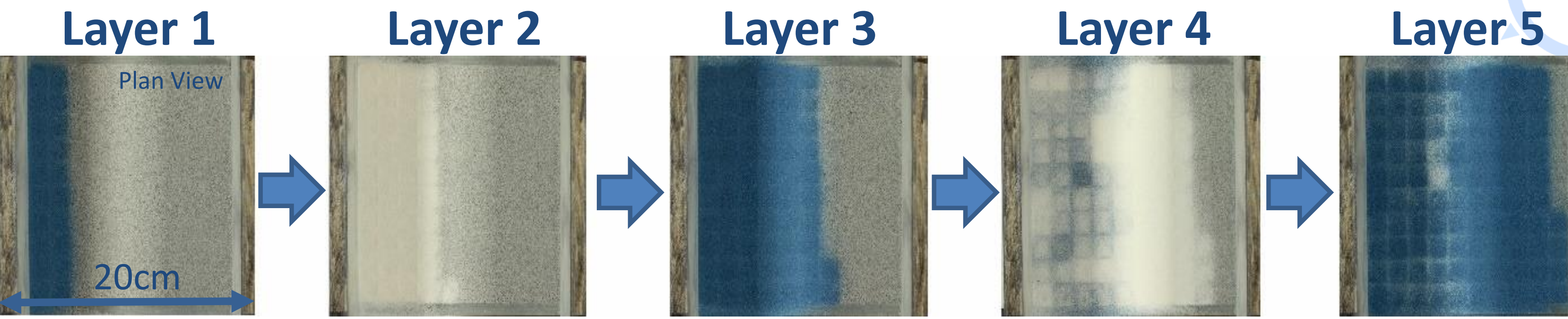
- **Integration of analogue sandbox models and numerical stratigraphic forward modelling permits combined models which exhibit the following:**
  - **Contributed from Analogue modelling:** Realistic, quantitative structural architectures develop, including fault localisation, linkage and displacement. This provides meaningful tectonic-subsidence, captured in high resolution.
  - **Contributed from Numerical modelling:** Sedimentation intervals are developed in a realistic manner, producing complex stratal geometries that can produce gravity-driven deformation (*Models consist of only carbonate sedimentation at this stage).

- **The integration process (documented in-depth in the main presentation) functions by:**
  - Adapting data derived digitally from analogue experiments to represent topography and subsidence rates, which are then scaled and used as inputs for the numerical modelling software.
  - Producing a sieving apparatus, capable of translating volumes calculated from the numerical modeller, back onto the analogue sandbox – i.e. depositing heterogeneous volumes within a single sand layer, whilst maintaining coherent mechanical properties within the sandpack.

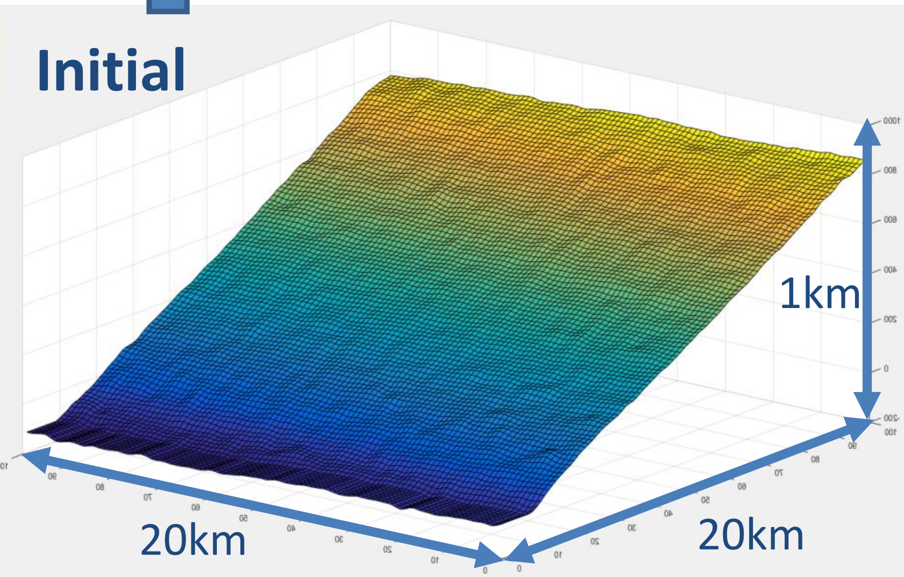
- **The following results show models which evolve deterministically, with only the analogue setup and numerical parameters governing development.**

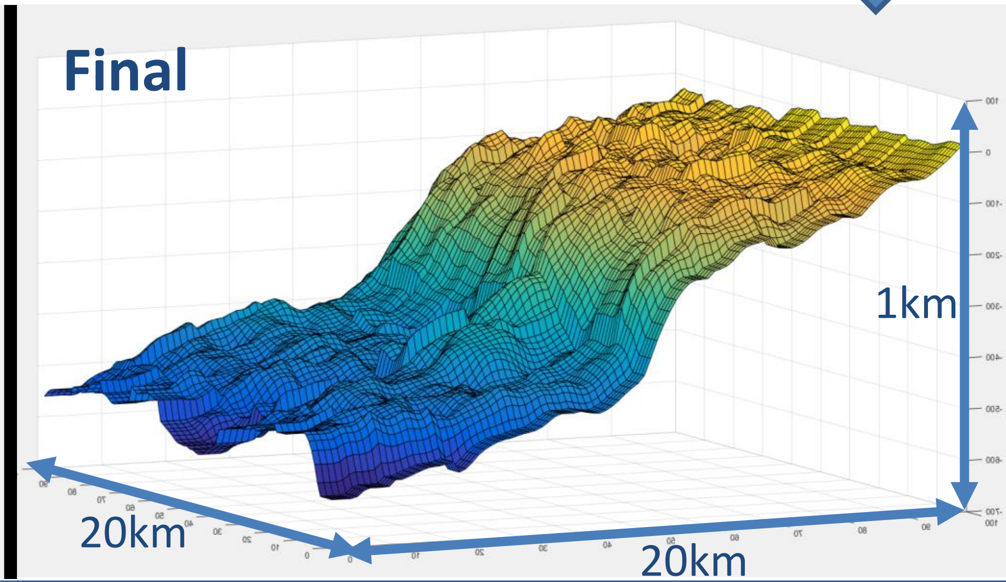
- **The produced workflow could be employed in future to simulate a suite of geological processes, such as rifting, potentially more faithfully than either existing analogue or numerical techniques are capable of.**

Workflow Example

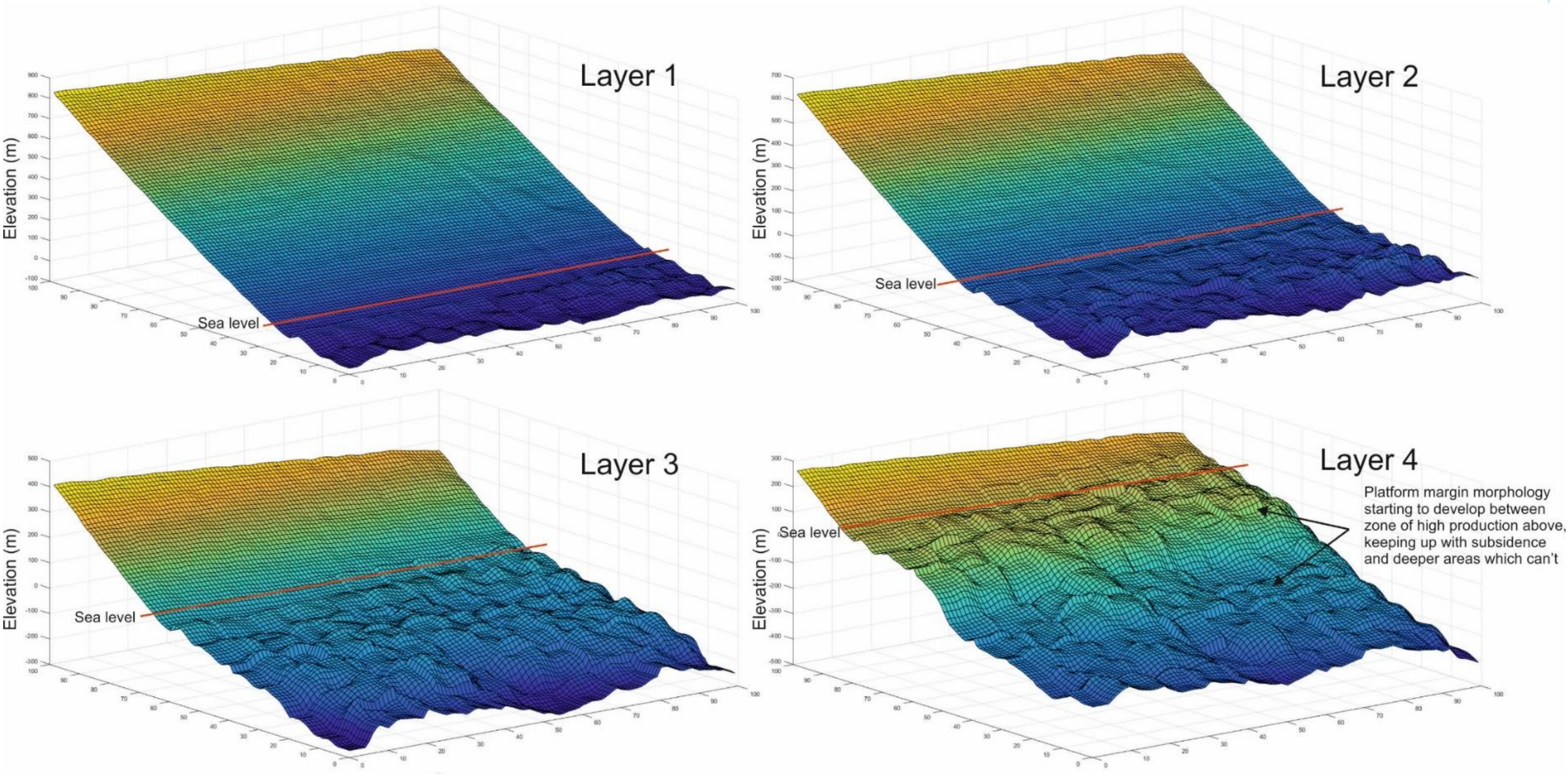


- Analogue sandbox surface topography is captured (Stereo-DIC camera setup) and formatted to produce a naturally-scaled, digital representation (Bottom images).
- This surface is then run in combination with a series of parameter files. These include subsidence rate, carbonate production rates, total time and number of increments. This simulates carbonate accumulation for a pre-defined period of time.
- The calculated accumulation is then then re-scaled to the analogue model and volumes are deposited to their correct locations with suitable mechanical properties necessary for producing dynamically scaled models. The process is then repeated (Top images).
- Carbonate accumulation over time deterministically produces a distinct platform margin.

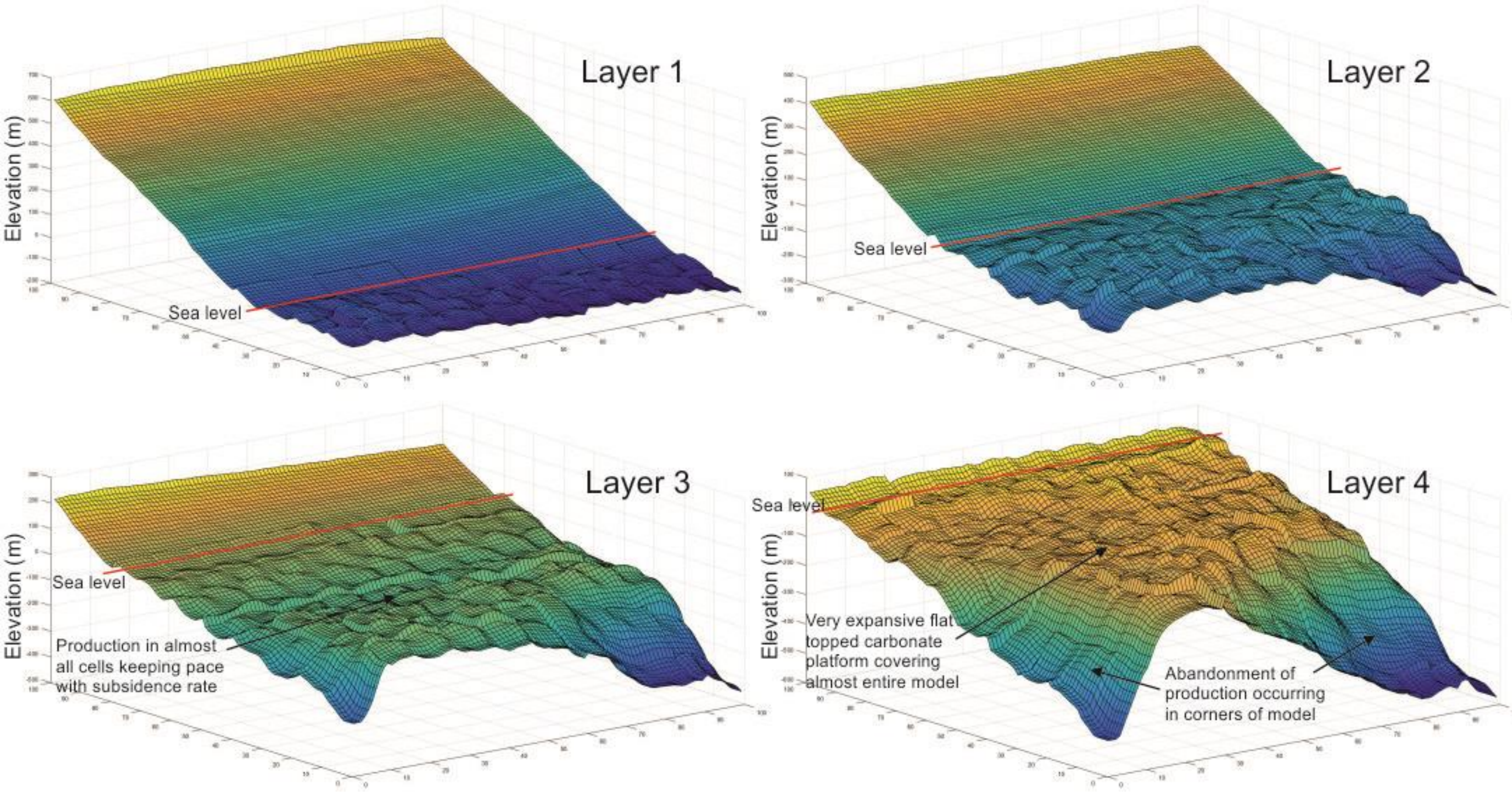




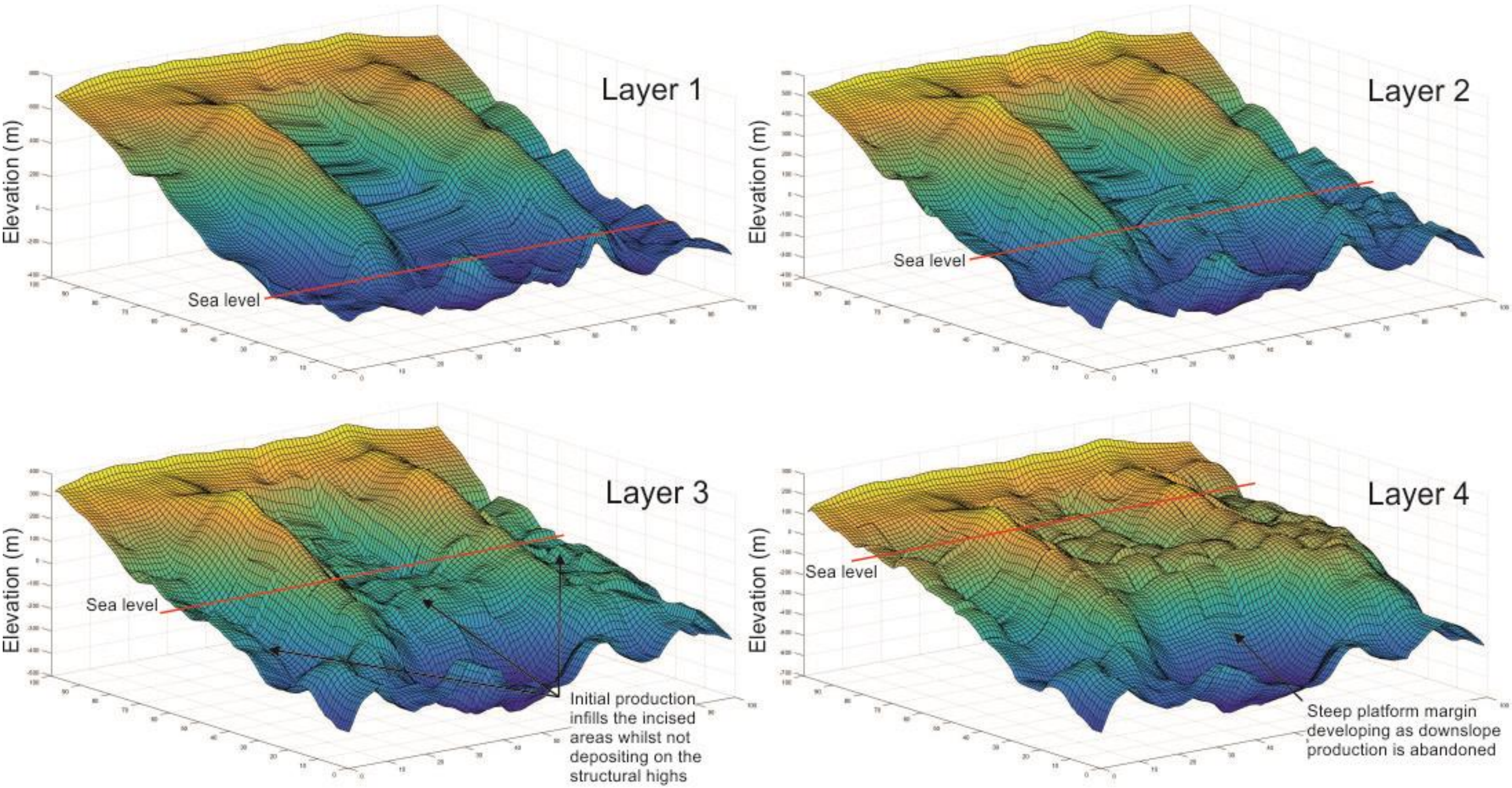
Static Models: Model 1 (Baseline)



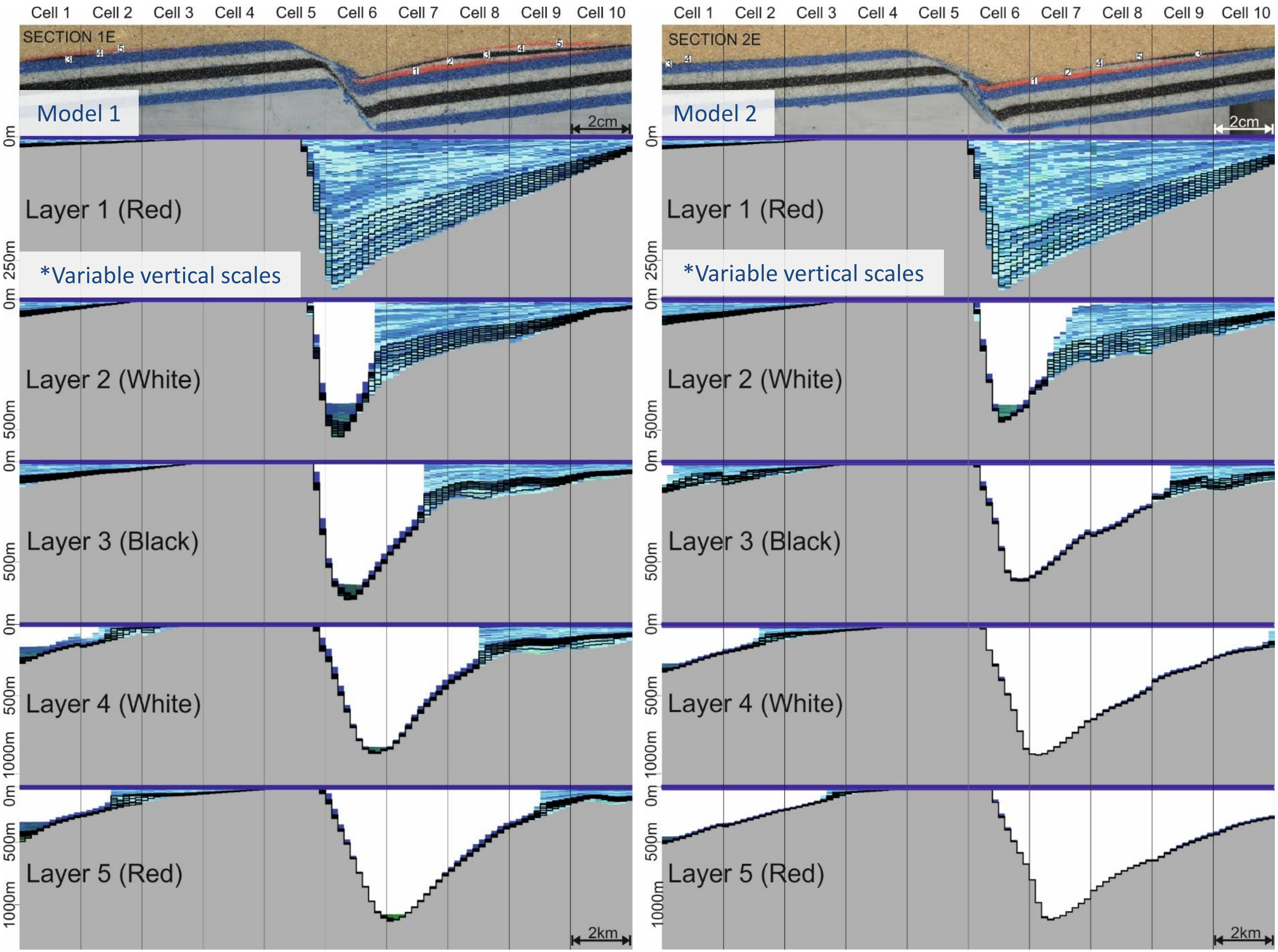
Static Models: Model 2 (Numerical change – Increased production)



Static Models: Model 3 (Analogue change - Variable initial surface)



Kinematic Models



The analogue model (top) extends for a predetermined distance for each increment. Surface deformation is captured and then used as a scaled input for the numerical model (below) to replicate evolution. This is run for a set time, representing extension rate, calculating a scaled sedimentary accumulation which is transferred back onto the analogue model (red, white & black layers) and the process repeated.

The higher extension rate (I.e. higher subsidence rate) in model 2 results in an earlier backstepping of the carbonate platform. Which in turn means future intervals have smaller accumulations, as carbonate only produces in a comparatively narrow window close to the water's surface.

The workflow is deterministically producing notably different models based only on initial parameters