A new quantitative approach in modelling regional tectonic processes and syn-depositional systems in coupled analogue-numerical models

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Rationale

Integrating Analogue & Numerical Models

Documented Workflow

Results

Summary & Future Work

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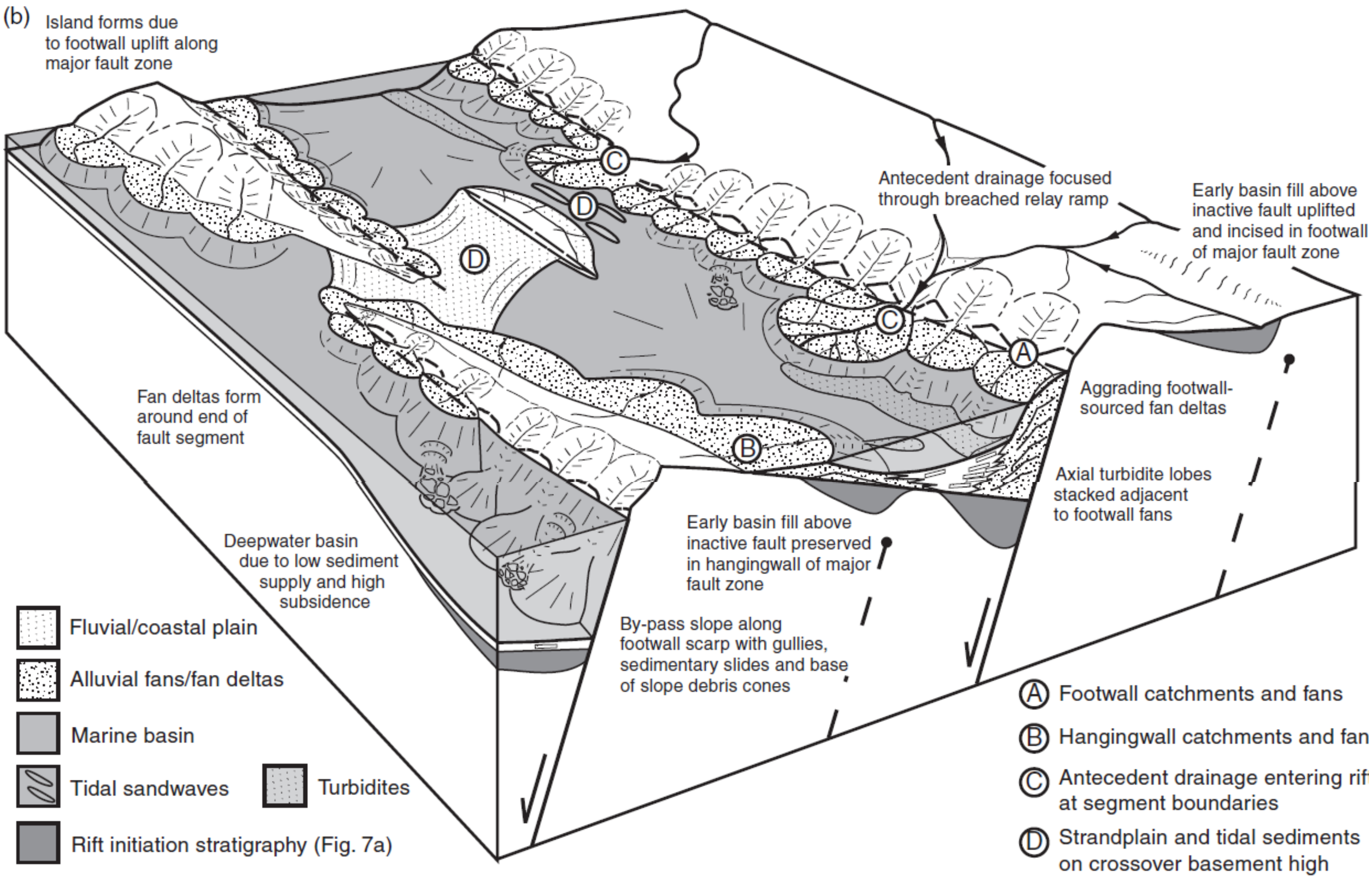
COMPASS Continental Margin Research

2 Minute Madness - Rationale PICO Spot 1.6

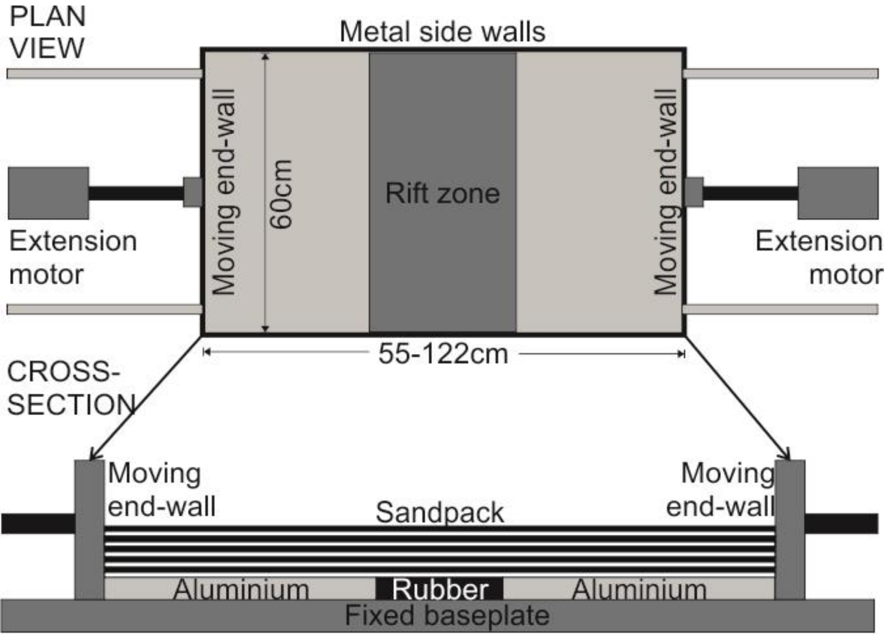


Gawthorpe and Leeder (2000)

2 Minute Madness - Integration

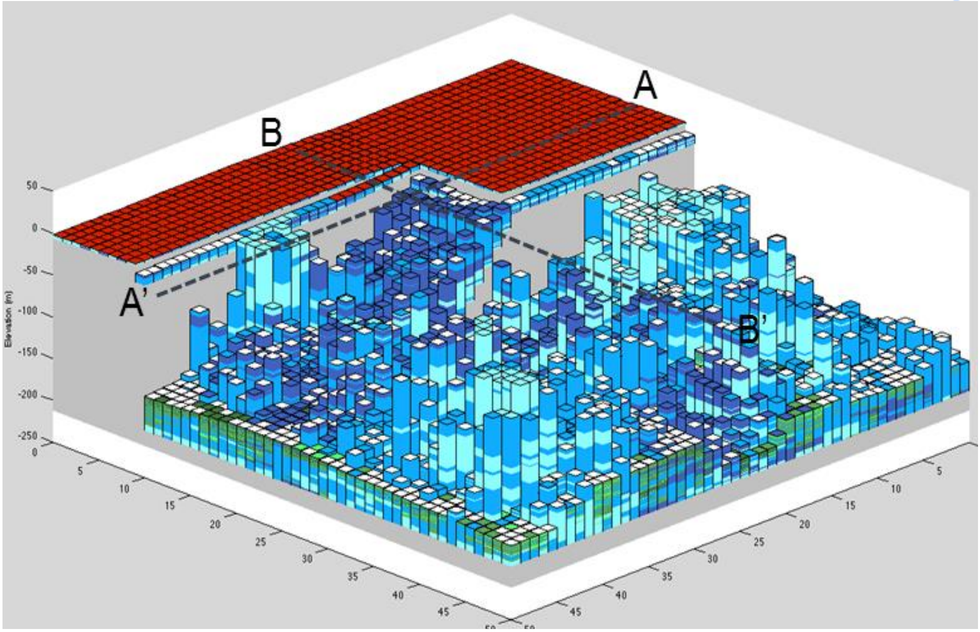
PICO Spot 1.6

Analogue models



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

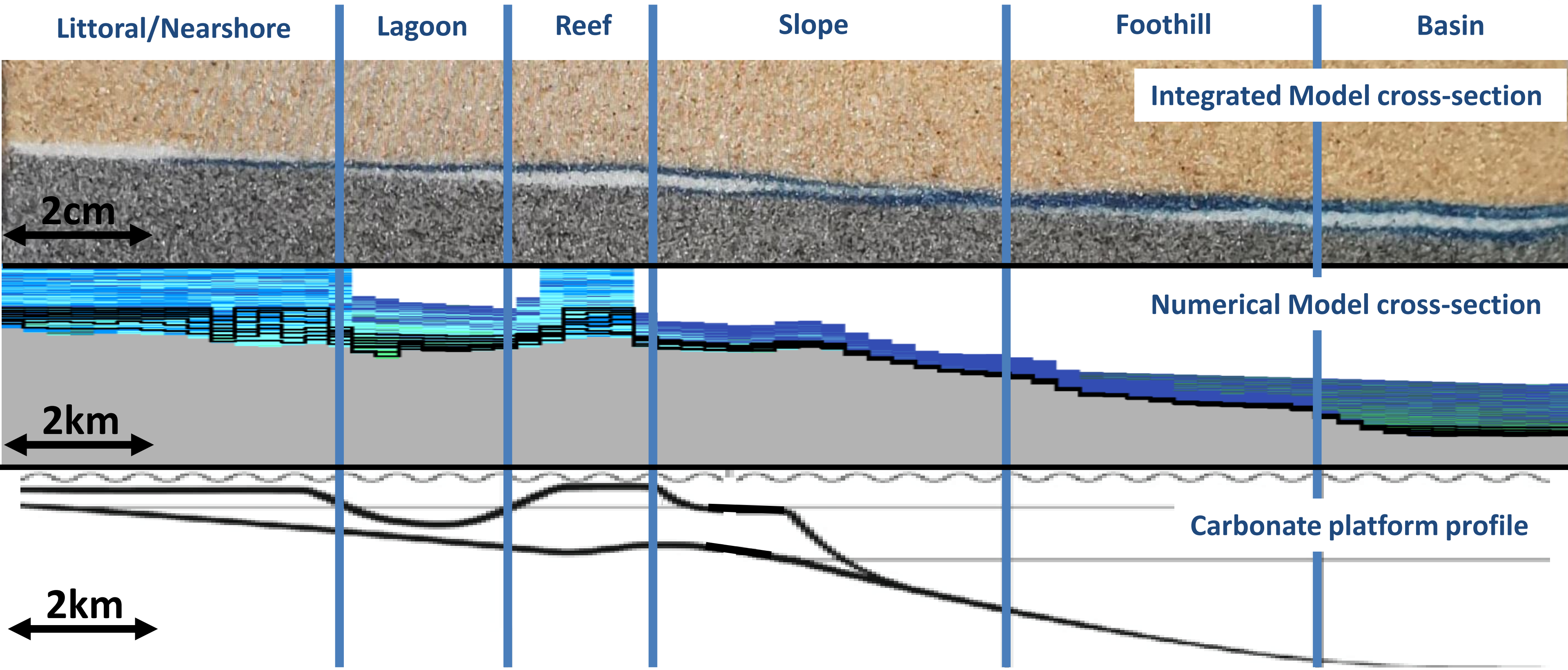
Numerical models



- Complex, realistic sedimentation patterns develop deterministically
- Includes impact of parameters such as sea-level, climate etc. (Non-tectonic)

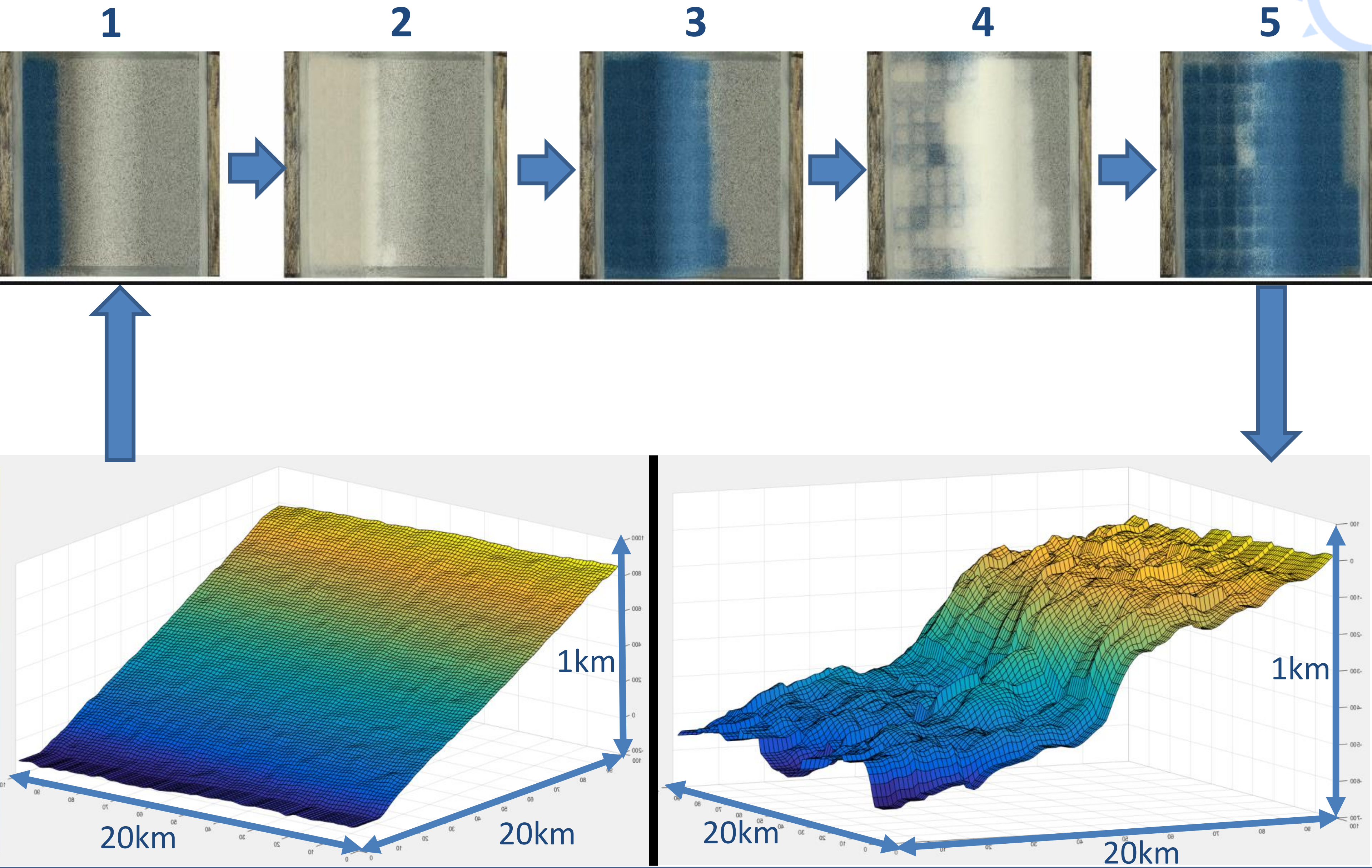
2 Minute Madness - Results

PICO Spot 1.6



2 Minute Madness - Results

PICO Spot 1.6

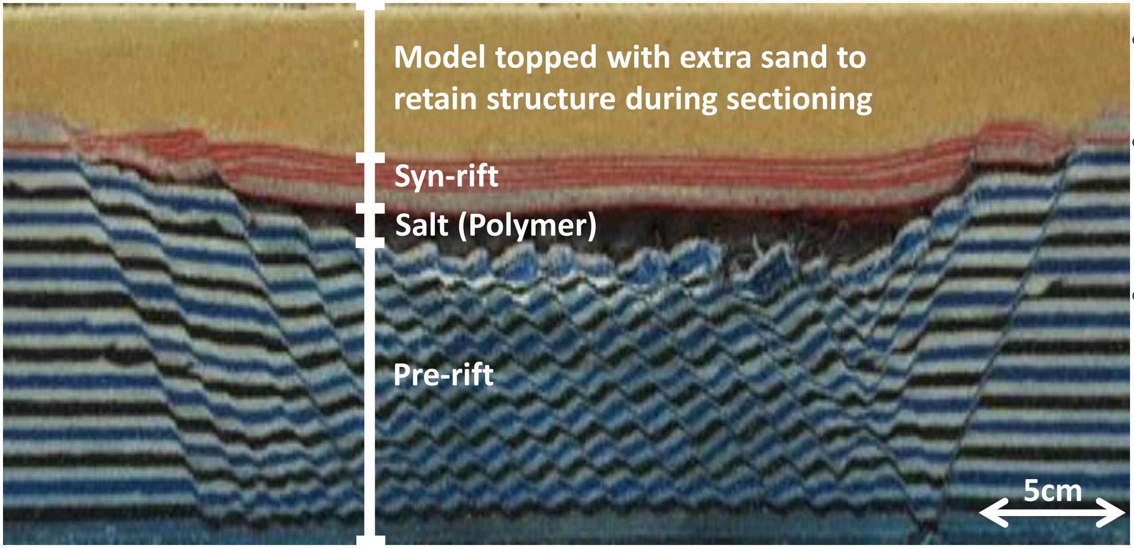


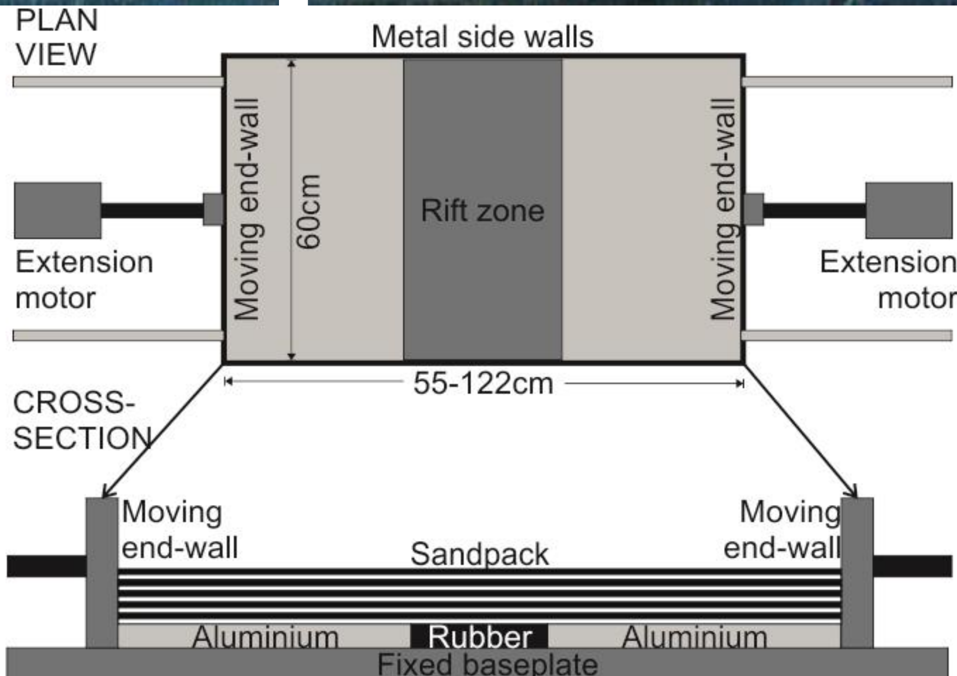
Rationale

Integrating analogue and numerical modelling successfully should produce 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.
- Feedback mechanisms between tectonic evolution and sedimentation can be investigated in a more in-depth manner due to their accurate replication occurring within a single integrated model.
- Non-tectonic controls such as sea level or climate can also be investigated in more detail, showing how they influence model evolution.
- Insights to aid in ongoing petroleum exploration efforts.

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
  - This work focuses on extension

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

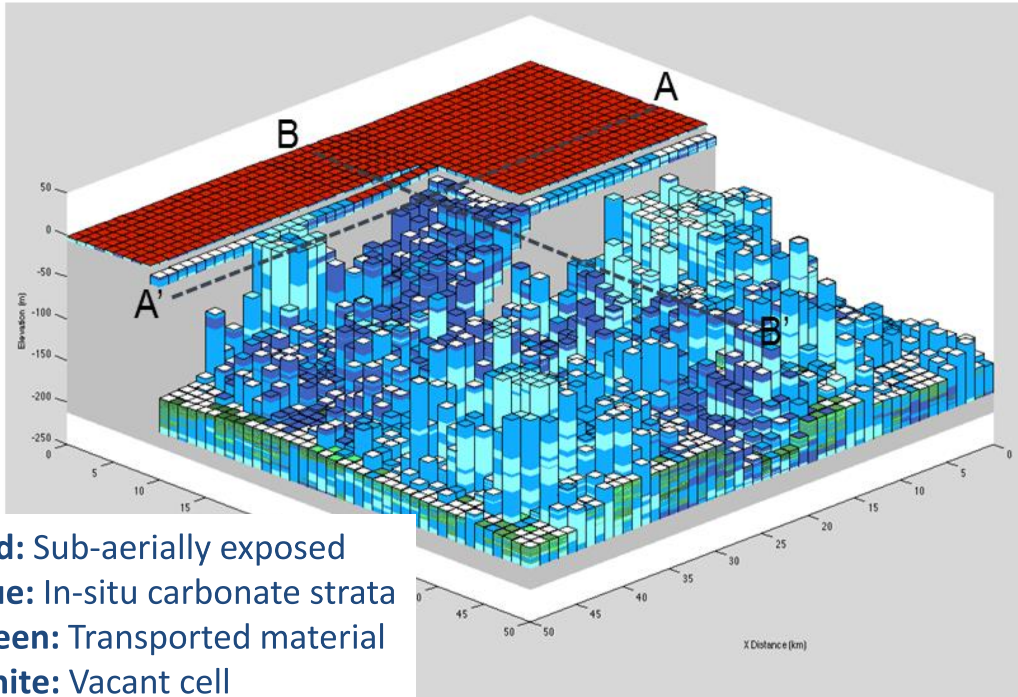
3D-rift extension model at syn-rift stage. Uniform sedimentation is currently being applied, blanketing the surface.

Dynamic scaling:

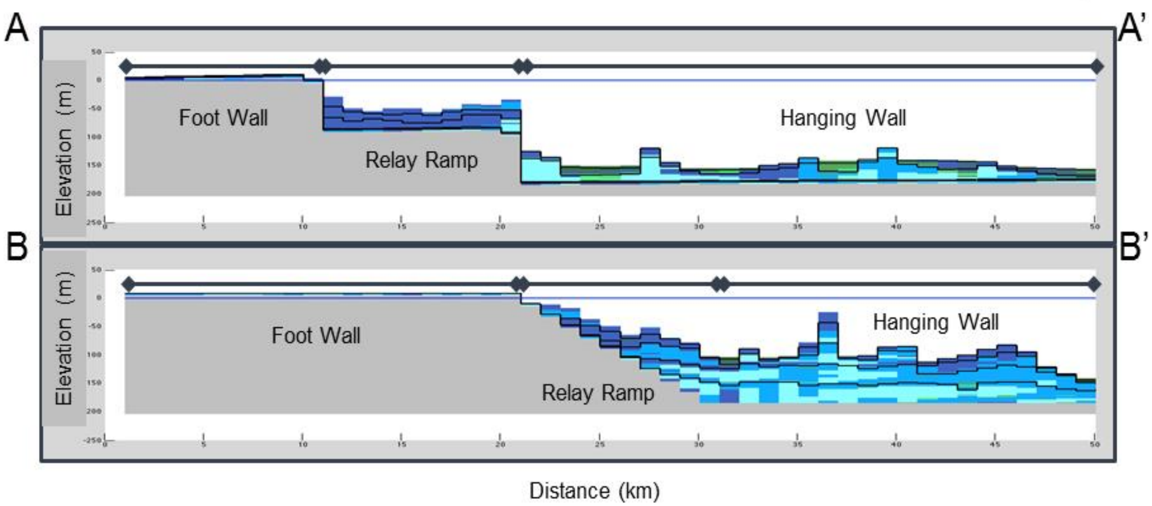
- Calibration with geological/geophysical data to model at regional scale
- Quantitative and qualitative comparison of model to nature, enabling meaningful reconstruction of basin architectures which can be applied to ongoing exploration efforts

Finished model which has been 'lithified' by addition of gelatin to enable sectioning and subsequent structural analysis.

Rationale: Numerical Modelling Overview (CarboCAT)



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



- Stratigraphic Forward Modelling software
- 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
- Sediment transport is modelled using simple steepest-descent and gradient cut-off rules
    - Includes sea-level changes etc. (Non-tectonic controls)
    - The modeller has been modified to incorporate complex subsidence distributions imported from analogue experiments.

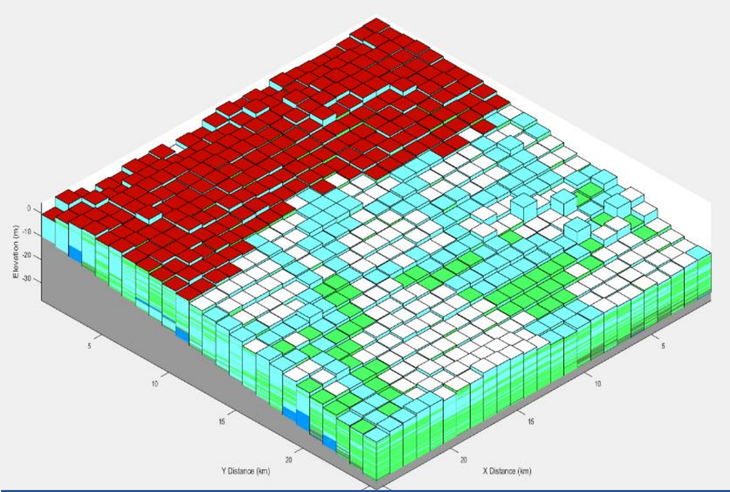
Rationale: Strengths of Numerical Modelling (CarboCAT)

Replicate complex, large scale stratal architectures:

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

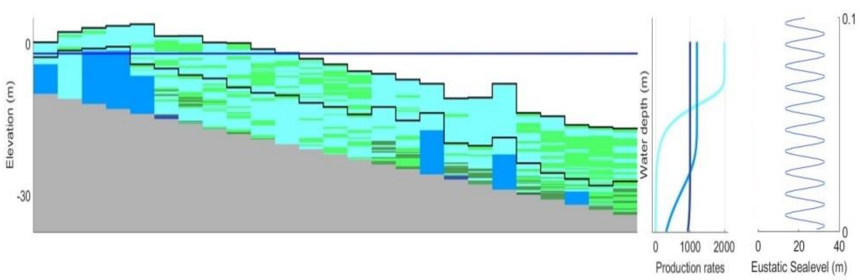
Inclusion of non-tectonic controls:

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



Output showing produced carbonate strata.

Blue= In-situ carbonate facies, Green= transported carbonate facies, Red= sub-aerially exposed surface.



Cross-section of final 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.

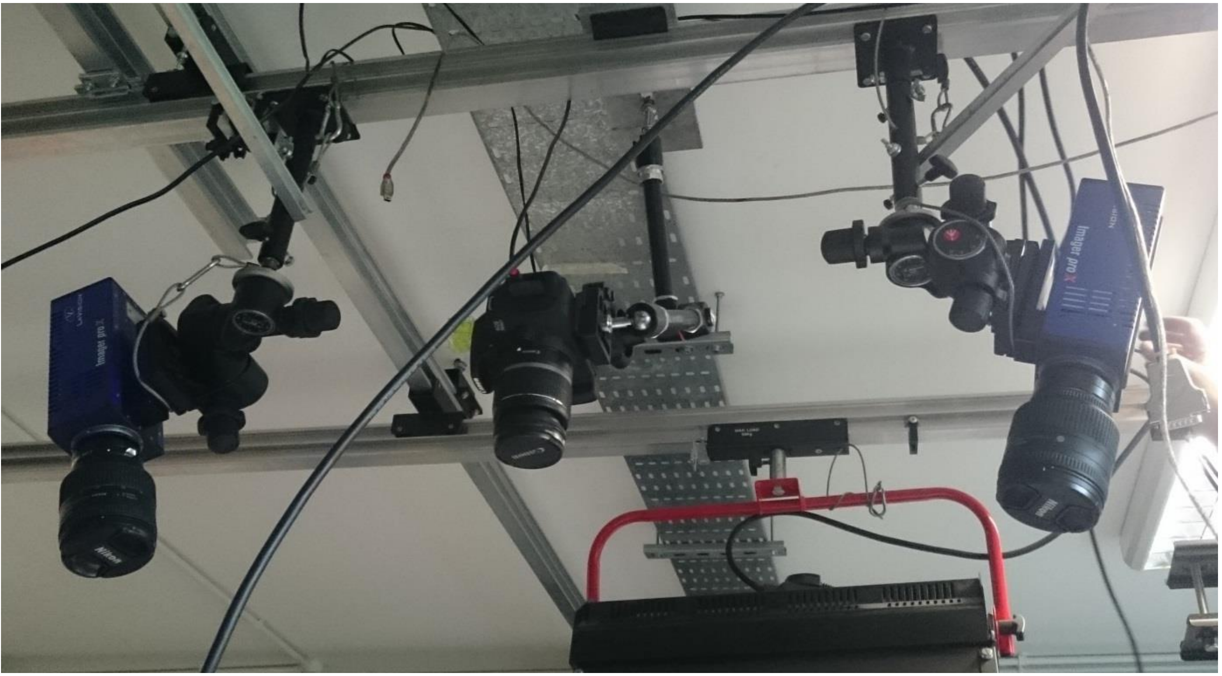
Integrating Analogue & Numerical Models

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

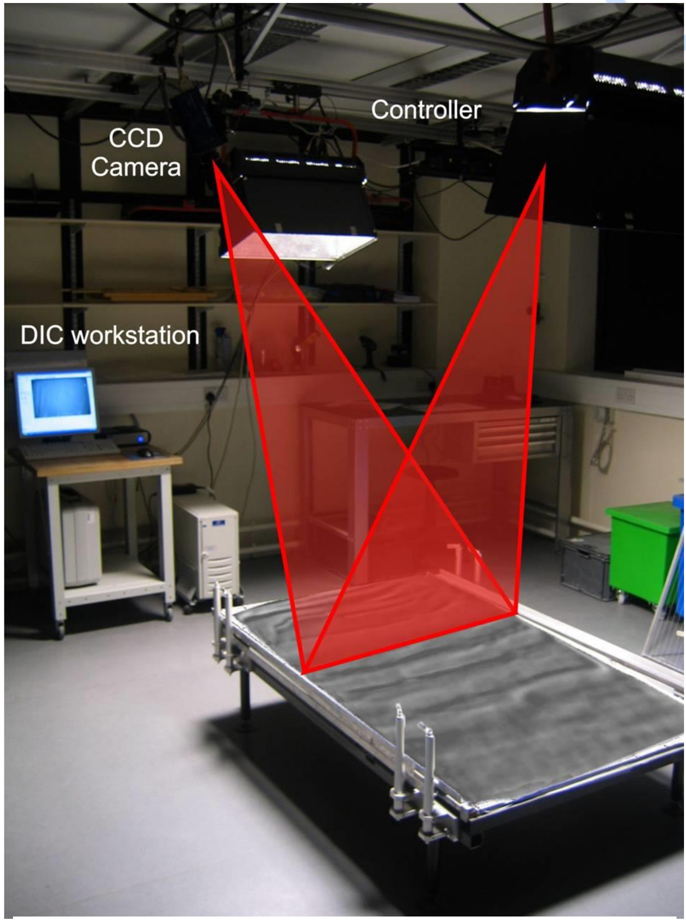
1. **Analogue data inputs for the numerical modeller:** Translate analogue model surface data recorded by cameras into the numerical modeller as inputs for topography and subsidence rate. Both of which are suitably scaled to natural dimensions.

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.

Integration: 1) Analogue data inputs for the numerical modeller



- 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

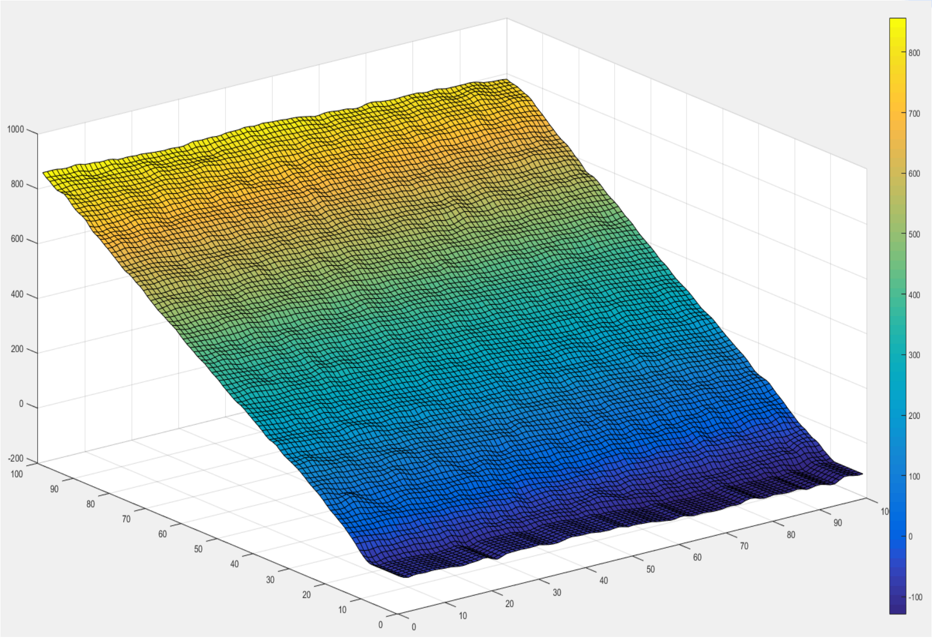


Angles recorded by the 3D stereo camera setup

Integration: 1) Analogue data inputs for the numerical modeller

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



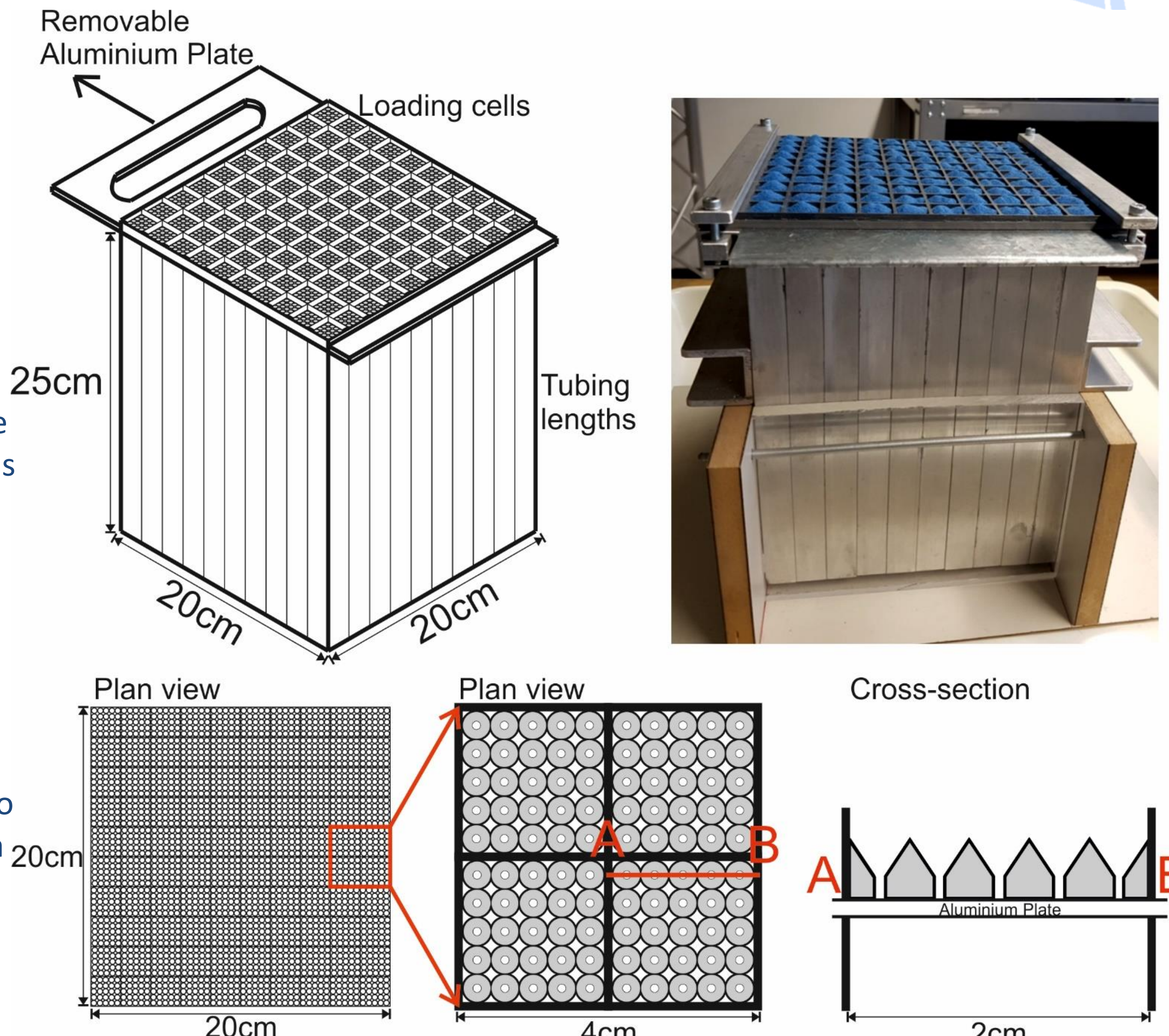
- The raw surface elevation format is a Tecplot (ASCII), with each recorded data point being represented by an x, y & z value in a list
- This data is transformed into a matrix (cellular grid) consisting of data points or cells representing bathymetries/elevations (depending at what point sea level is 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

Integration: 2) Numerical modeller 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



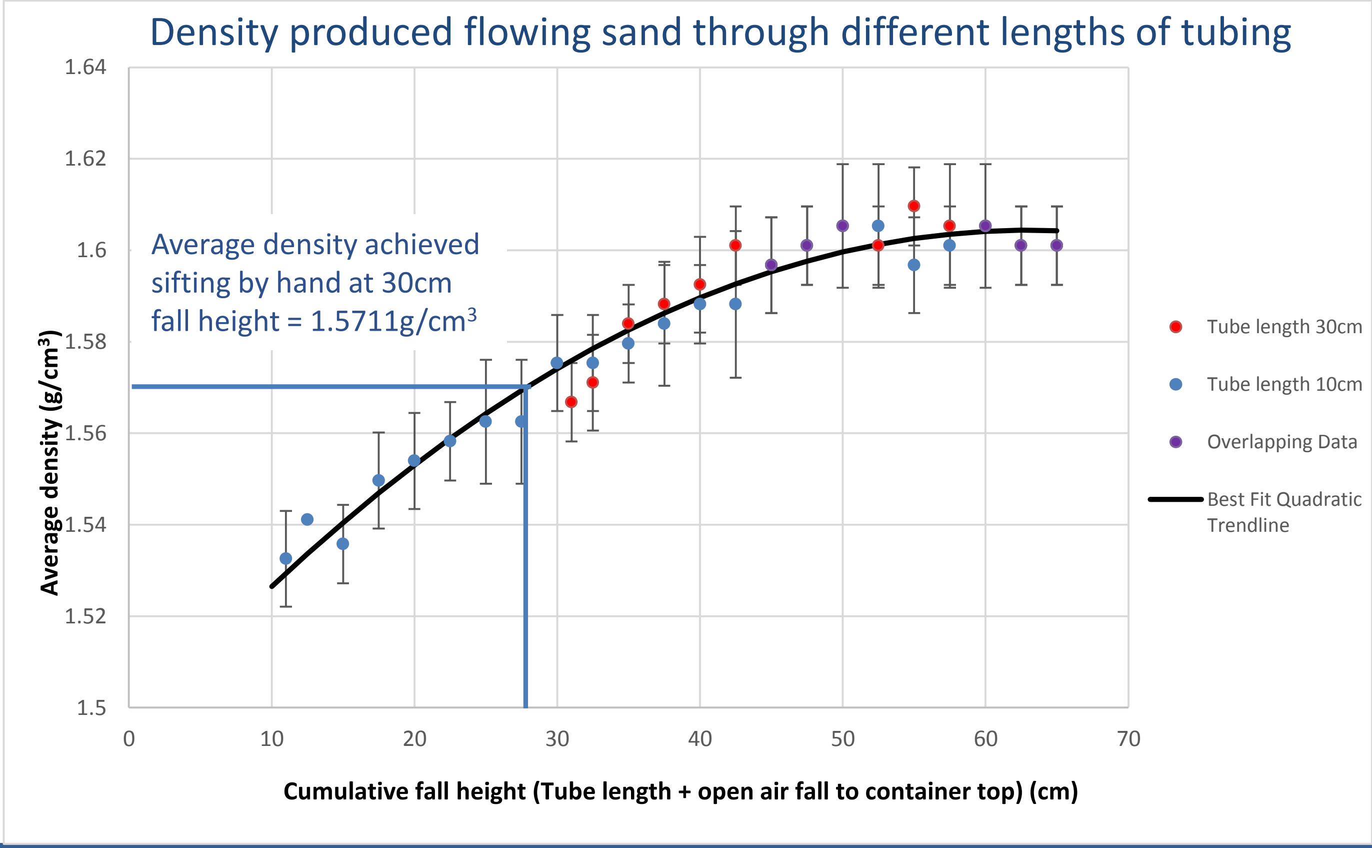
Integration: 2) Numerical modeller output delivered to the analogue model

- 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.

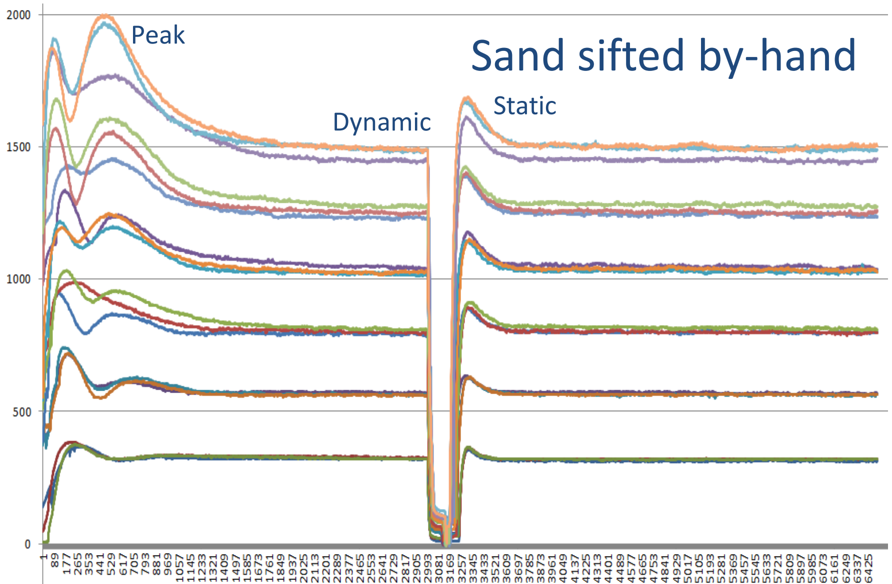
- This is achieved by letting the sand fall for a specified distance to achieve the correct density / internal friction, whilst the tubing lengths maintain the desired sedimentation pattern

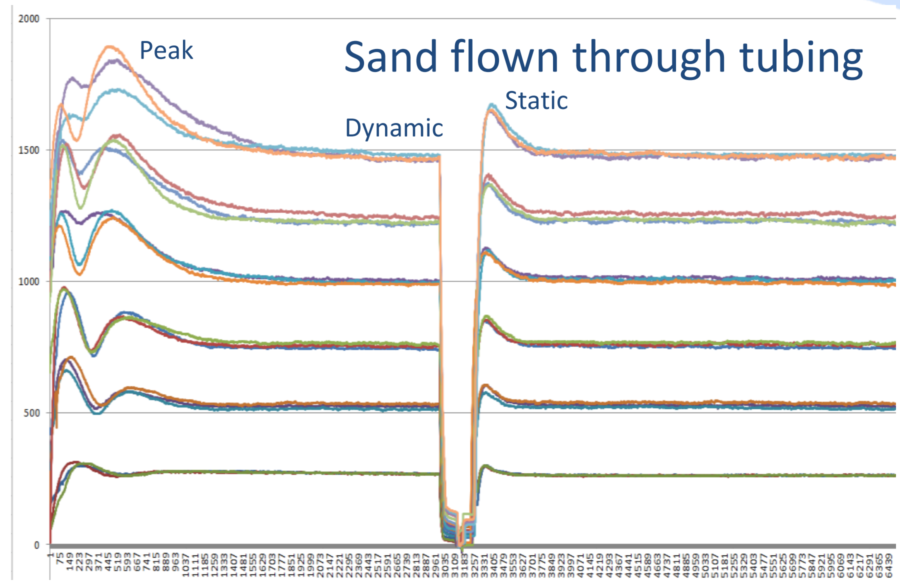
- When depositing a pre-kinematic layered sandpack, sand is sifted from a height of 30cm by hand. This yields a density of 1.57g/cm^3.

- 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)

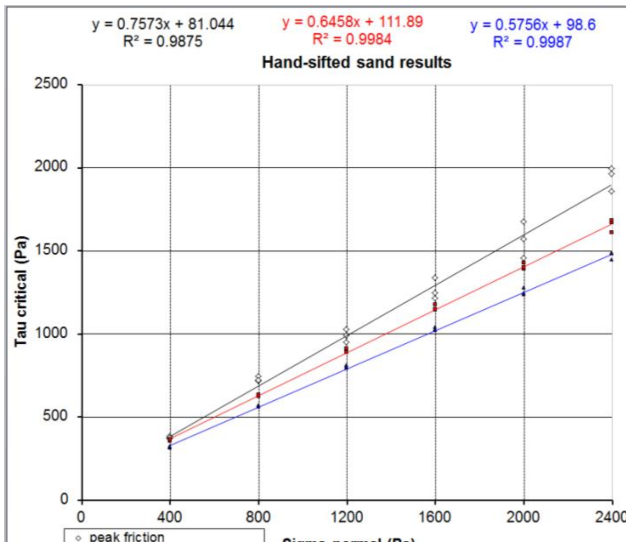


Integration: 2) Numerical modeller output delivered to the analogue model

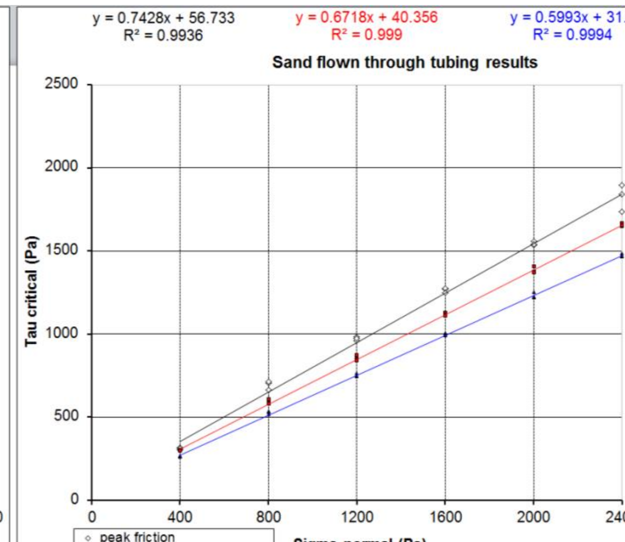




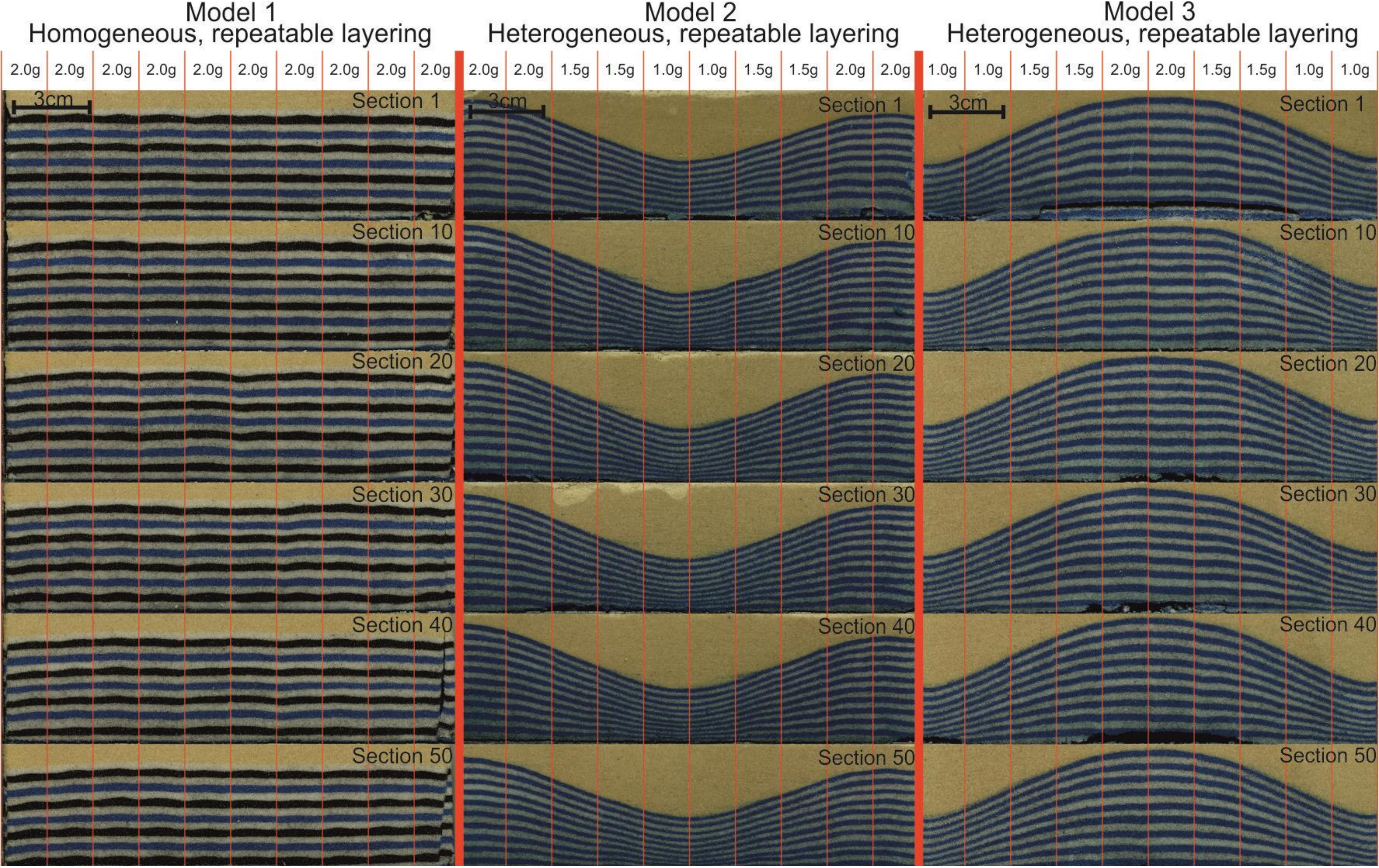
- Material testing profiles shown above demonstrate sufficiently similar, repeatable behaviour between the two different methods of deposition
- Frictional parameters produced using the tubing apparatus and by-hand are consistent
- Therefore sandpacks produced using the tubing apparatus will be valid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



	Coefficient Internal Friction	Angle Internal Friction	Cohesion
Peak	0.76 ± 0.02	37.1 ± 1.2	81.04 ± 33.14
Static	0.65 ± 0.01	32.9 ± 0.4	111.89 ± 9.98
Dynamic	0.58 ± 0.01	29.9 ± 0.3	98.6 ± 8.07



	Coefficient Internal Friction	Angle Internal Friction	Cohesion
Peak	0.74 ± 0.01	36.6 ± 0.9	56.73 ± 23.3
Static	0.67 ± 0.01	33.9 ± 0.3	40.36 ± 8.18
Dynamic	0.6 ± 0	30.9 ± 0.2	31.6 ± 5.94



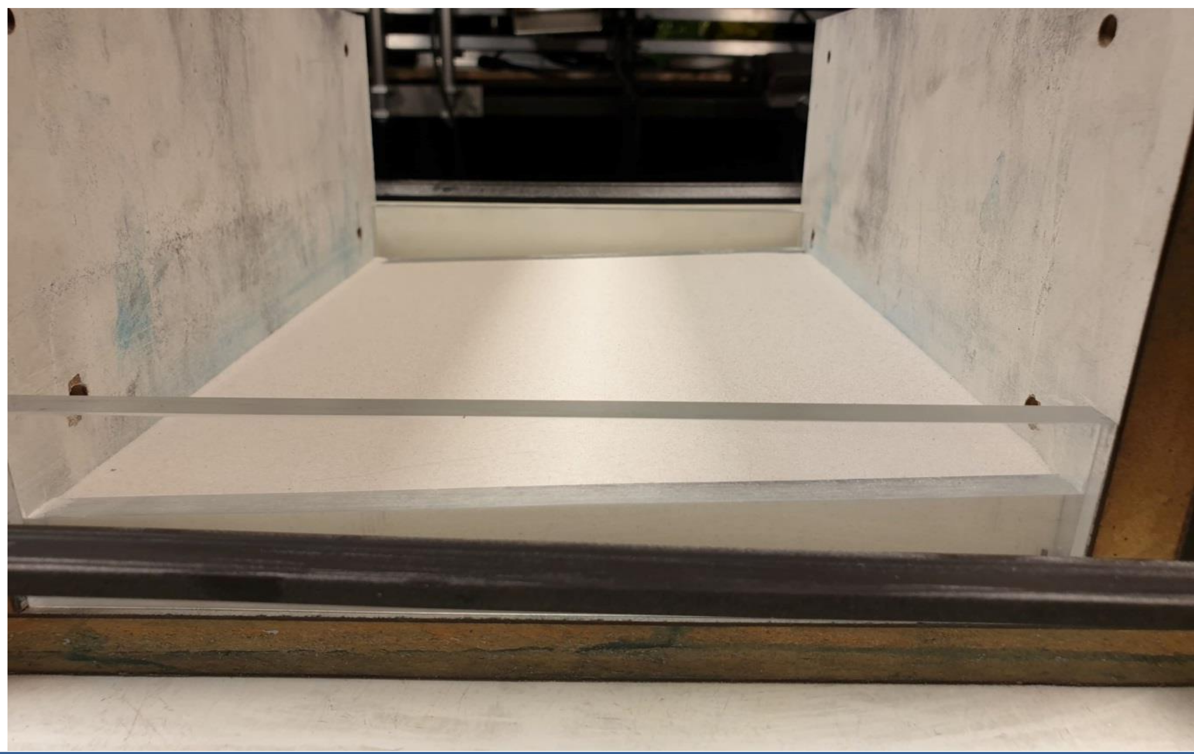
- Composite image showing cross-sections from three experiment sandpacks produced using the apparatus
- Each model has an overlay indicating the relative position of each of the 10-wide tubing arrangement
- Each cell had a constant sand weight deposited in it for all layers within a given experiment (weights shown at the top)
- Model 1 demonstrates repeatable, homogeneous layering, with minimal variation observed
- Models 2 & 3 demonstrate the capability of heterogeneous sedimentation layers to evolve into 3D structures over time

Integrated Workflow

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

- 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)

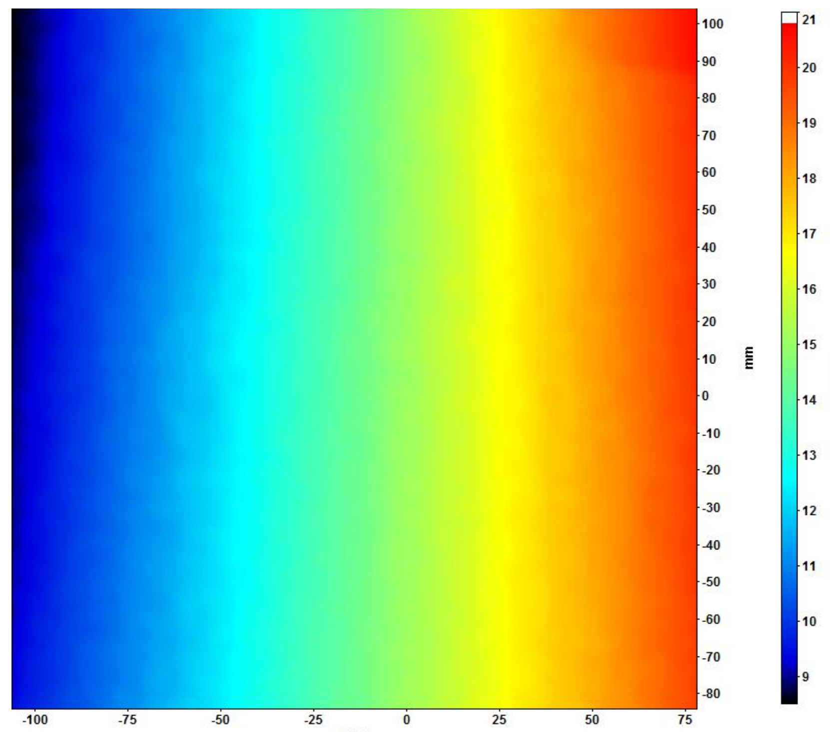


Integrated Workflow

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**

- 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

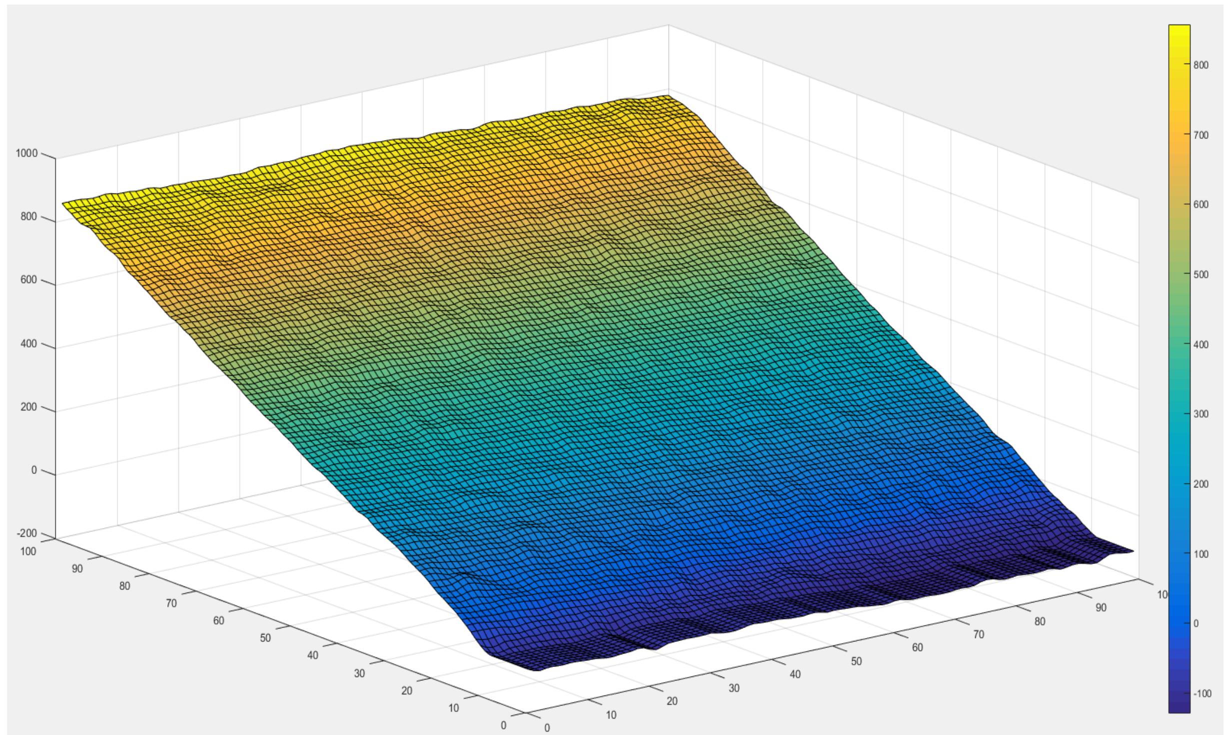


Integrated Workflow

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.



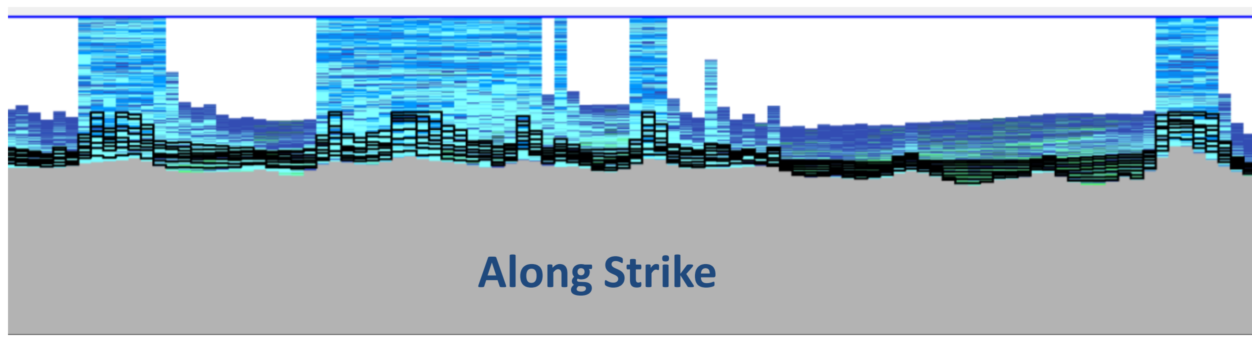
Integrated Workflow

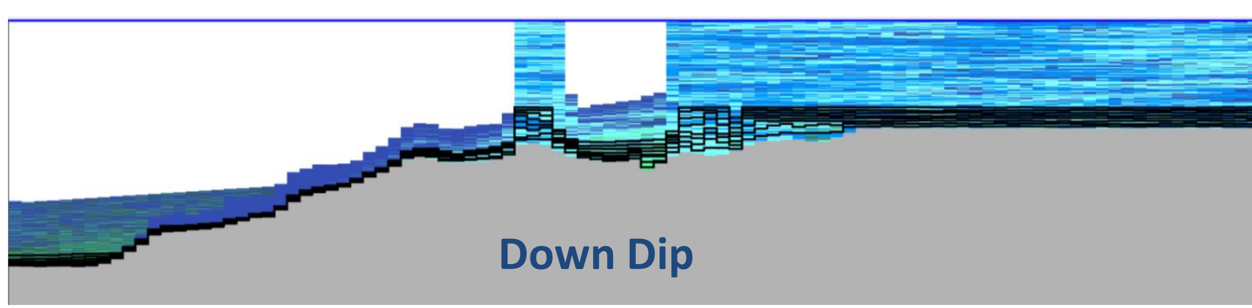
Analogue model initiates / continues with extension

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

- 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.

- In this later stage example, on the down-dip section, there is a reef crest and lagoon forming, with deeper facies and transport occurring further into the basin.



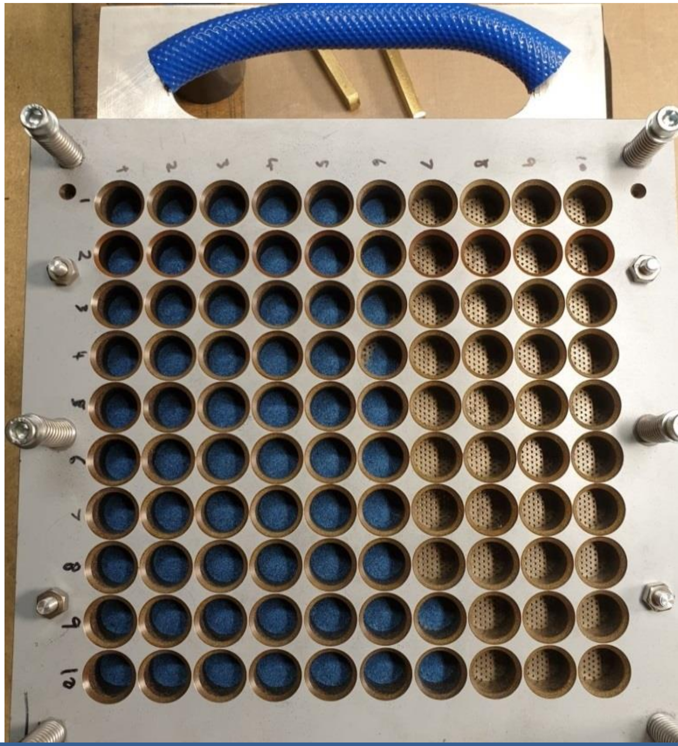


Integrated Workflow

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



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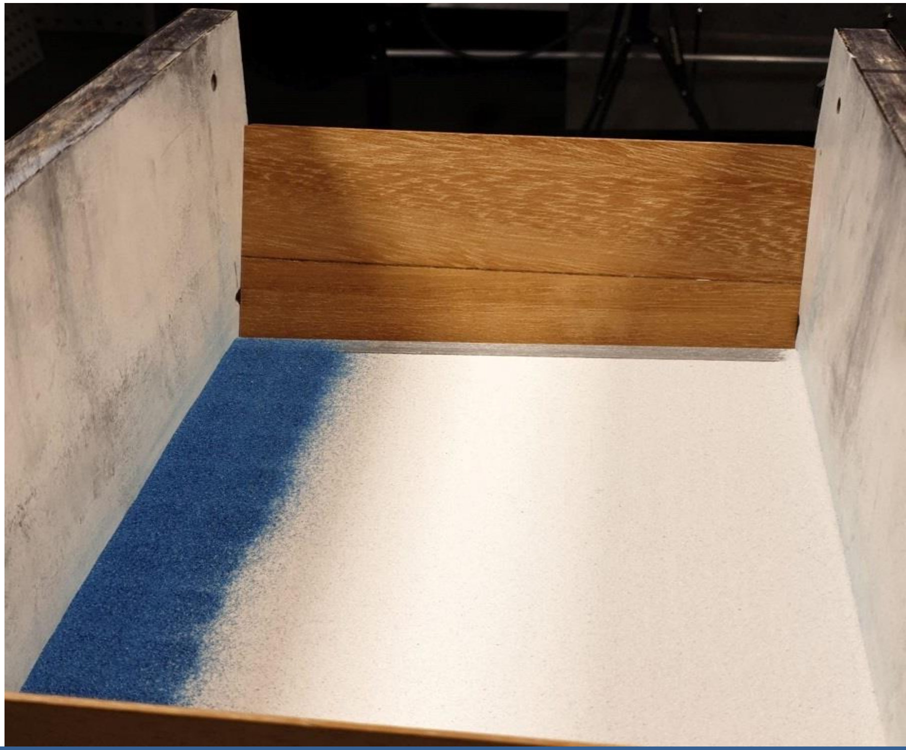
Analogue model initiates / continues with extension

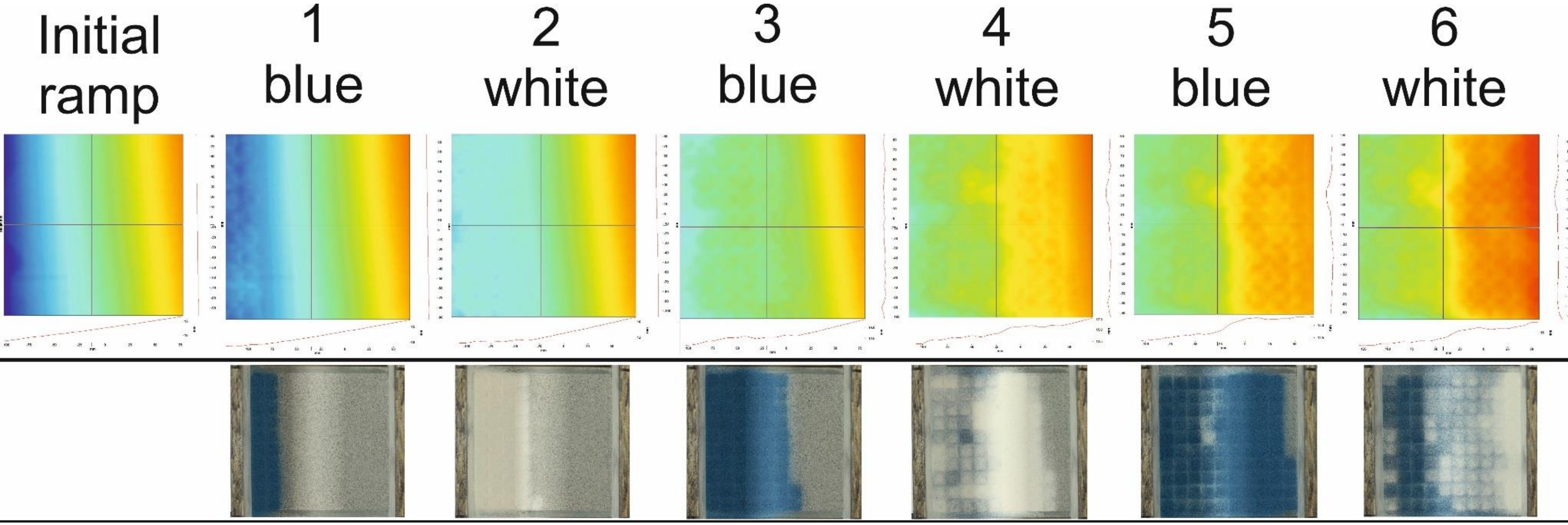
Analogue surface scanned by DIC cameras, producing topography and subsidence data → Topography and subsidence data is correctly scaled, formatted and input to the numerical modeller → Numerical modeller is run, calculating realistic sedimentation patterns → Heterogeneous sedimentation patterns are deposited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

- 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



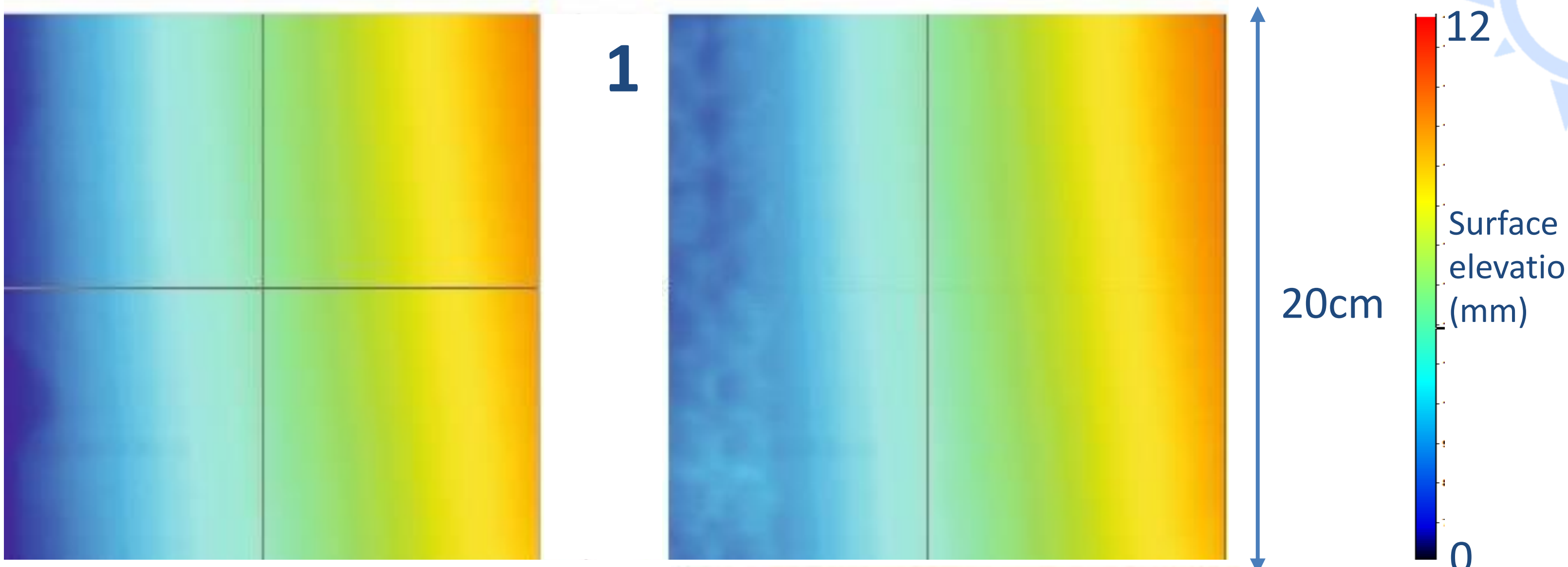
Results

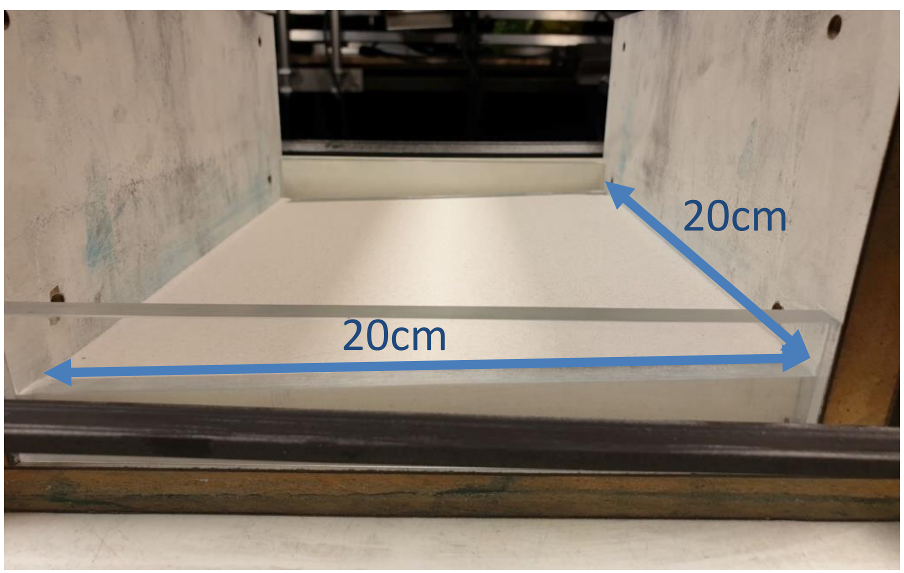
- The workflow outlined in the previous section was continued on through to completion
- 6 sedimentation intervals were calculated and added to the analogue model
- Each interval applied 0.2mm (200m natural scale) of subsidence over 2Ma, beginning close to the bottom of the ramp and eventually covering the top

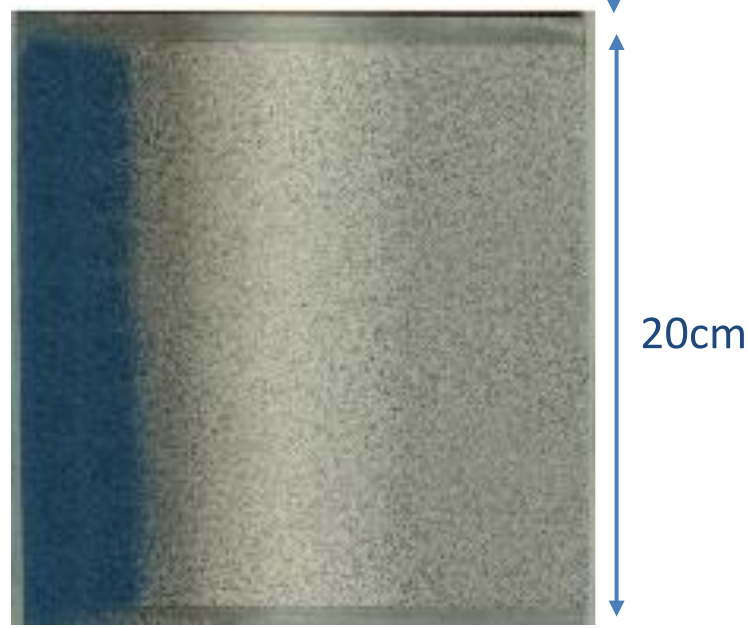


Results

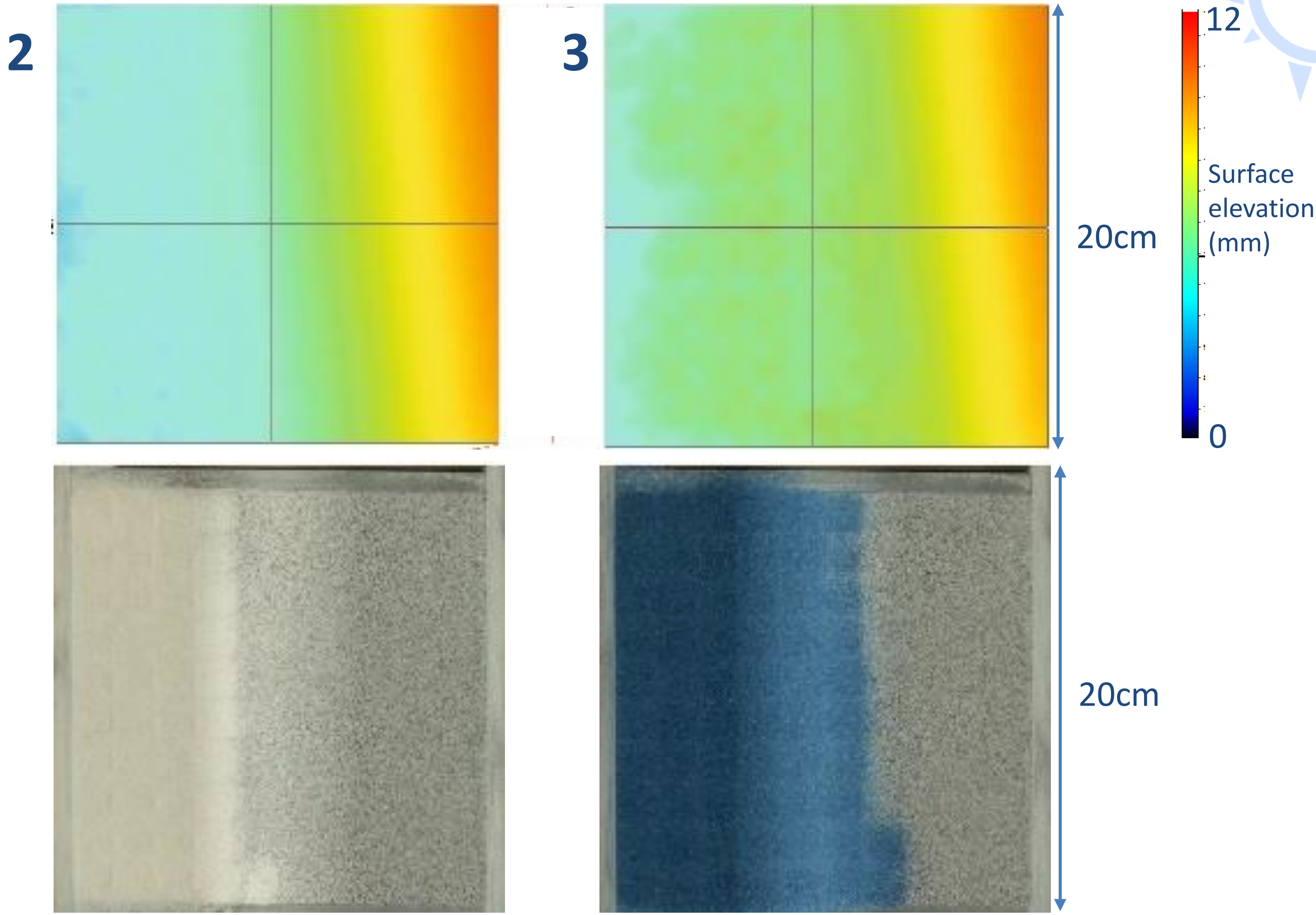
Initial Surface



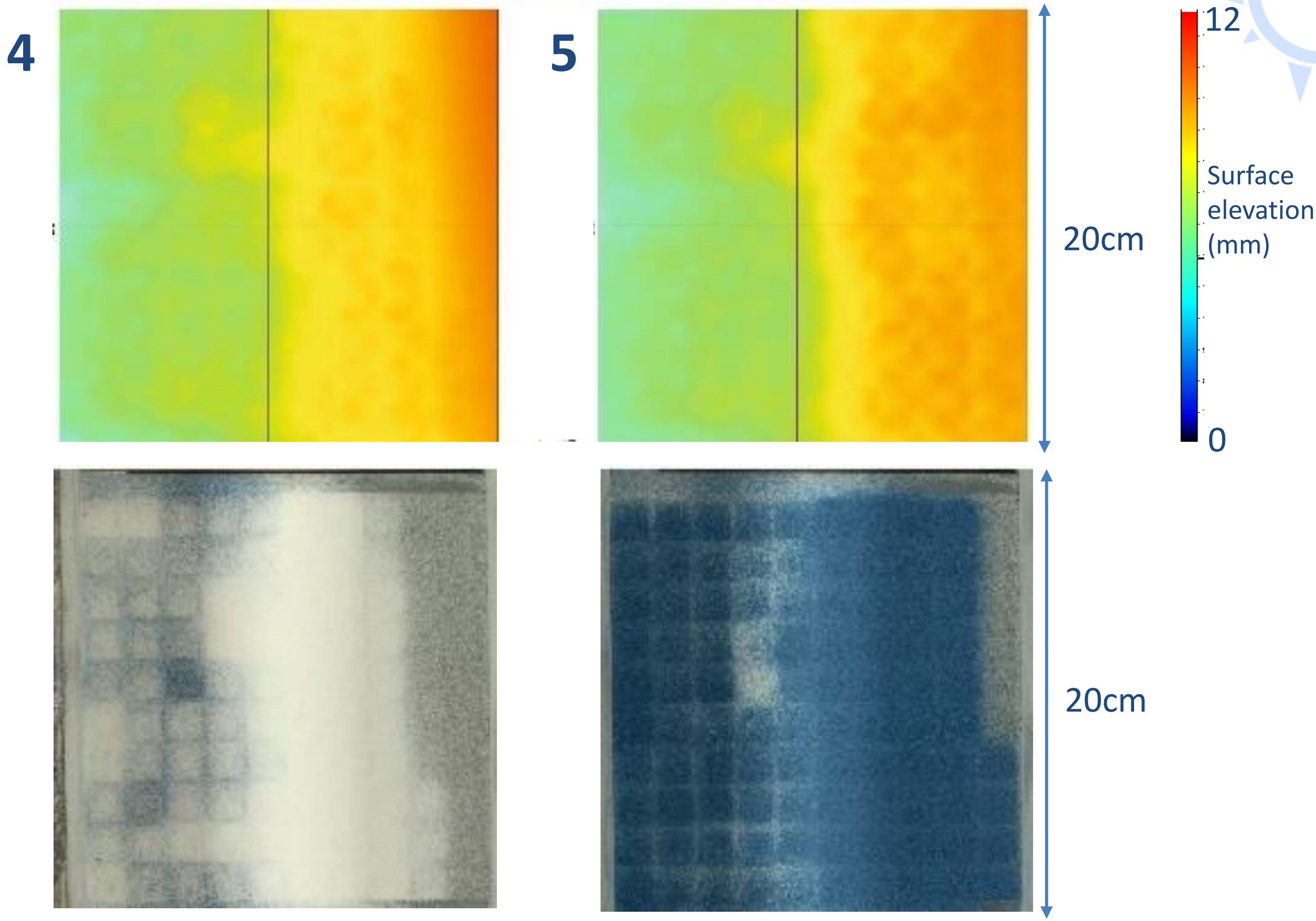




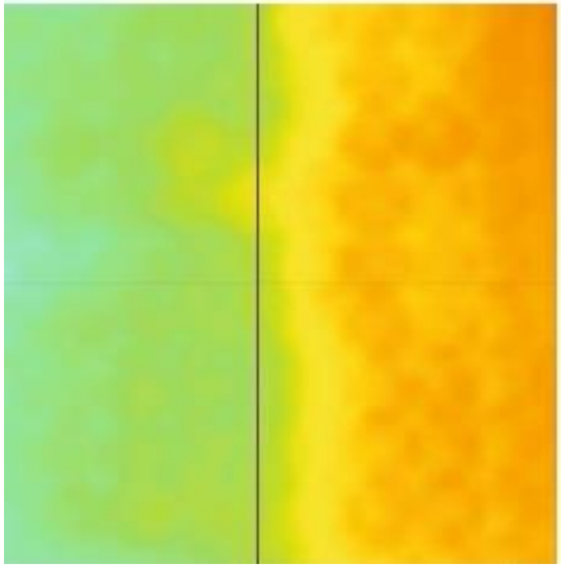
Results



Results

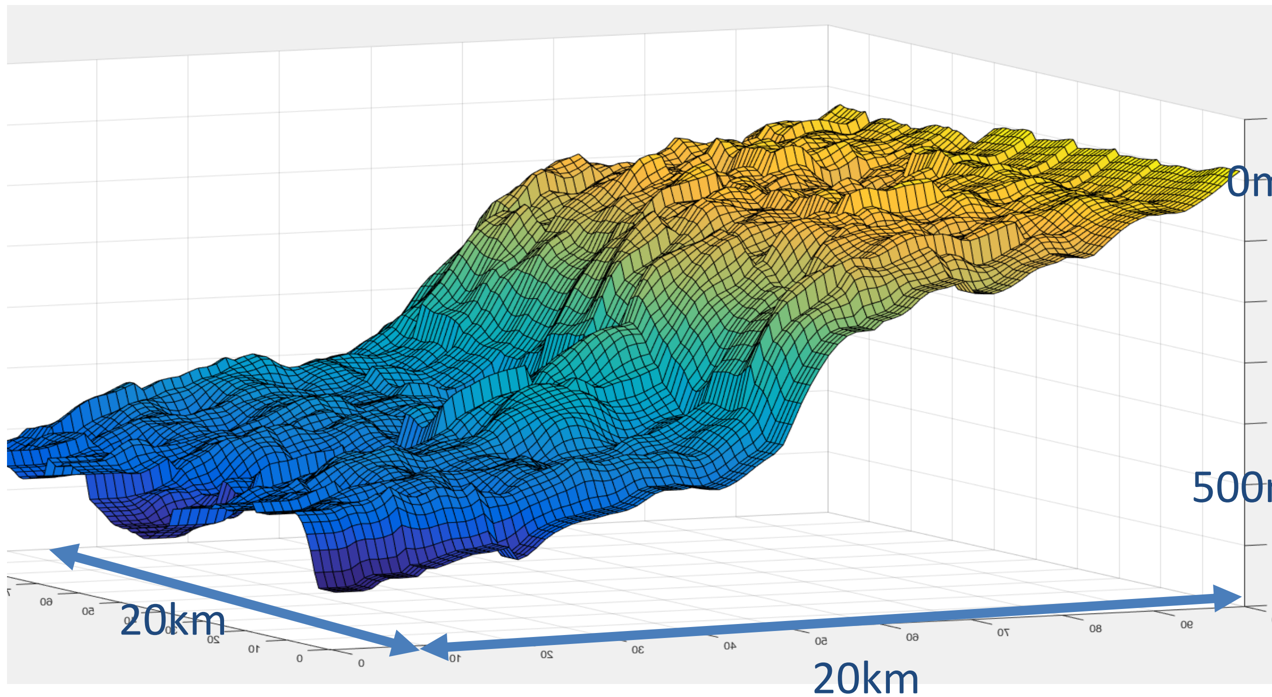


Results



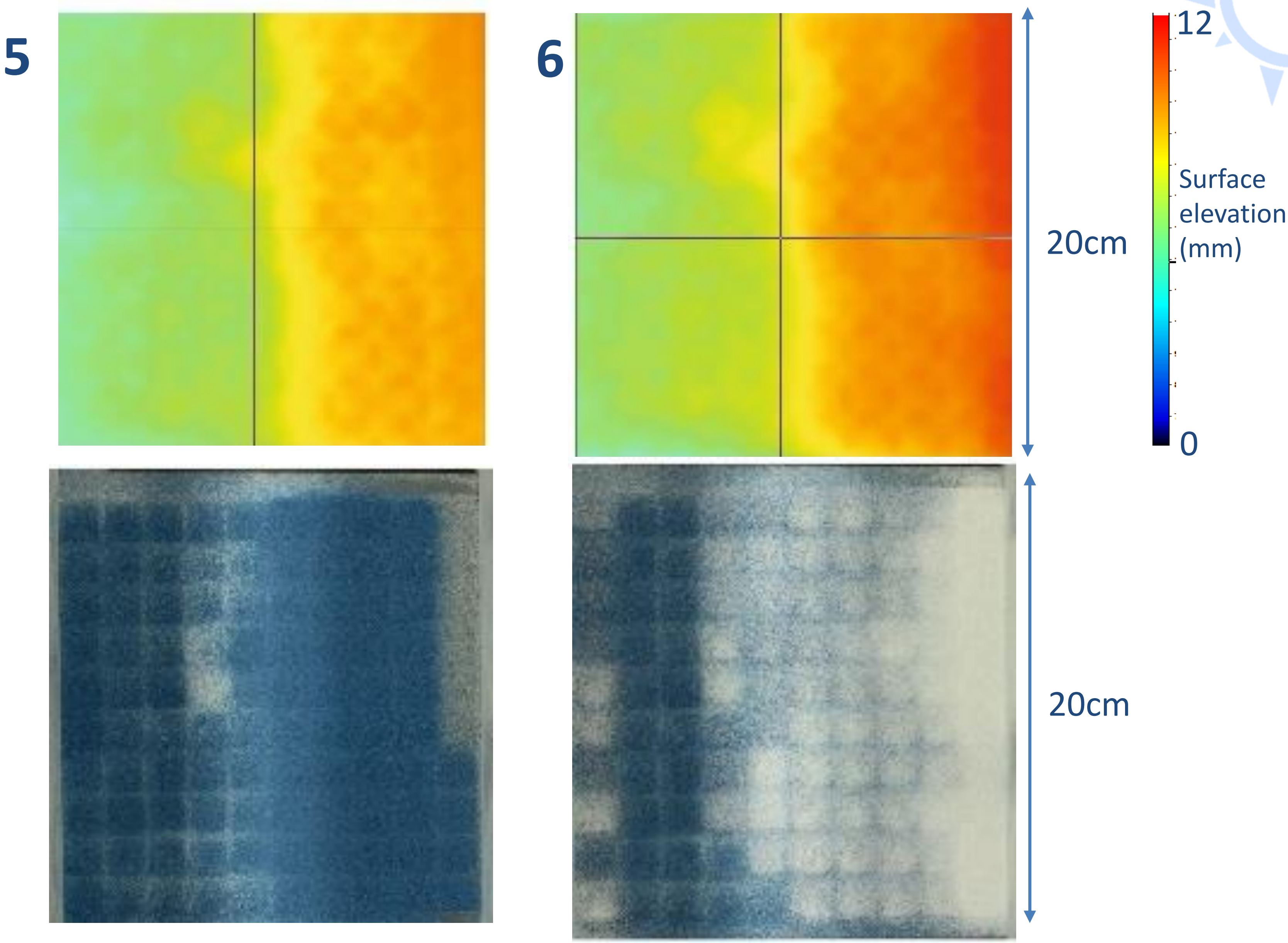
5

20cm

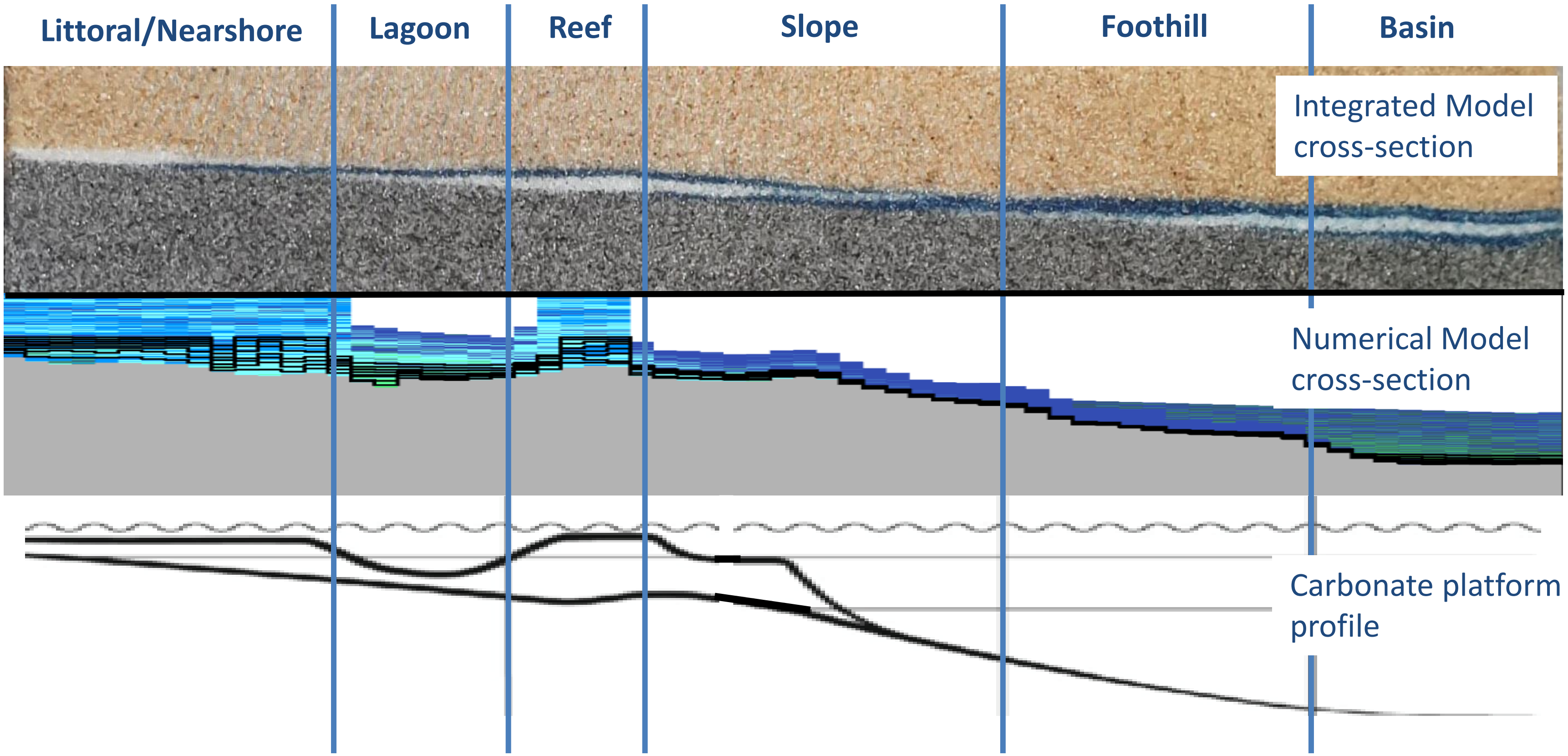


20cm

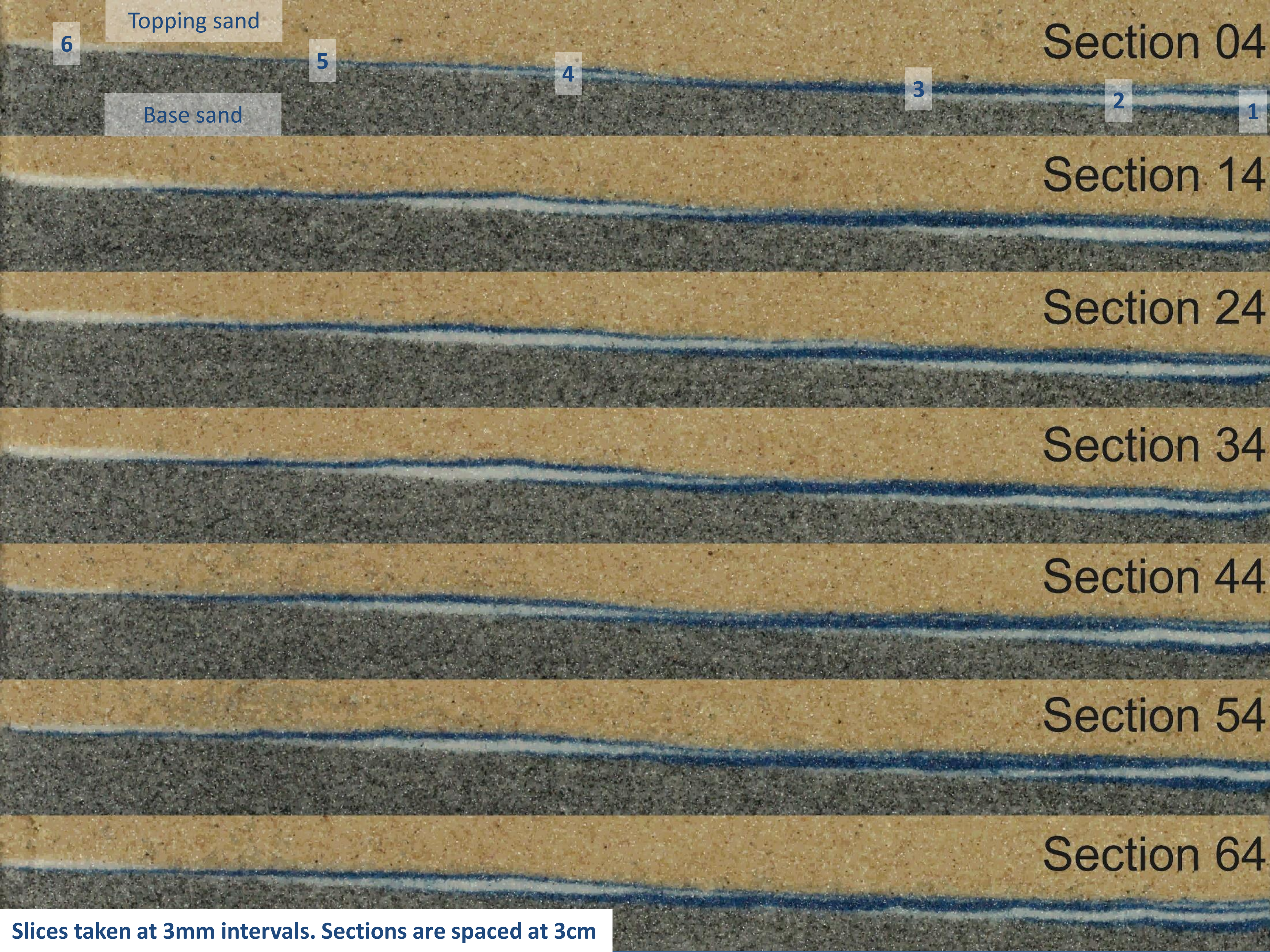
Results



Results



- The integrated model cross-section demonstrates successful translation of generated thicknesses from the numerical modeller onto the analogue surface
- This has produced a realistic carbonate platform architecture over the several depositional events
- ***NB** lower two images are both vertically exaggerated & orientation relative to previous slides is flipped horizontally. Numerical cross-section represents uppermost blue layer in the integrated mode.



Slices taken at 3mm intervals. Sections are spaced at 3cm

Summary

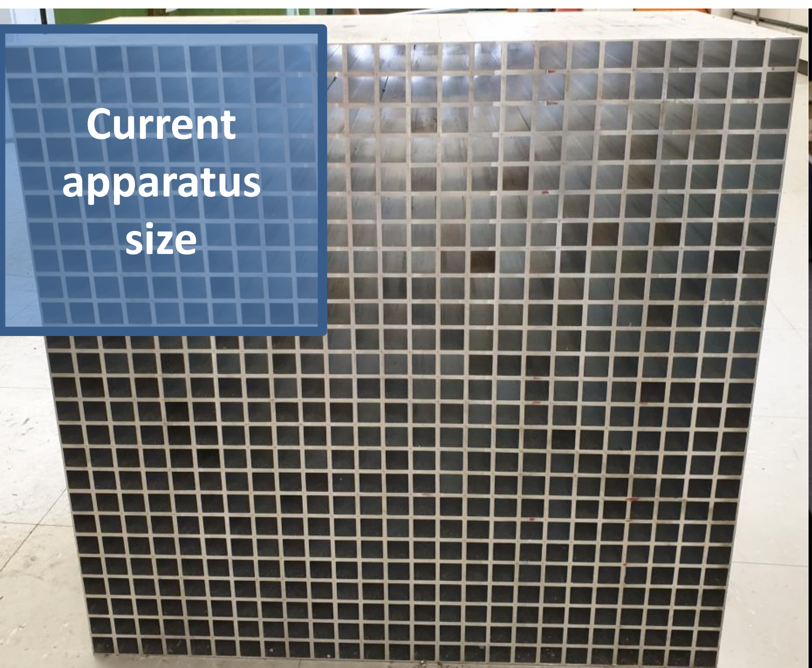
- **The project has successfully developed a workflow which integrates numerical stratigraphic forward modelling software with analogue sandbox models. This has been achieved by:**
  - Adapting data derived digitally from analogue exeriments to represent topography and subsidence rates, which is then 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.

- **Next steps…**

Future work: Integration with kinematic models

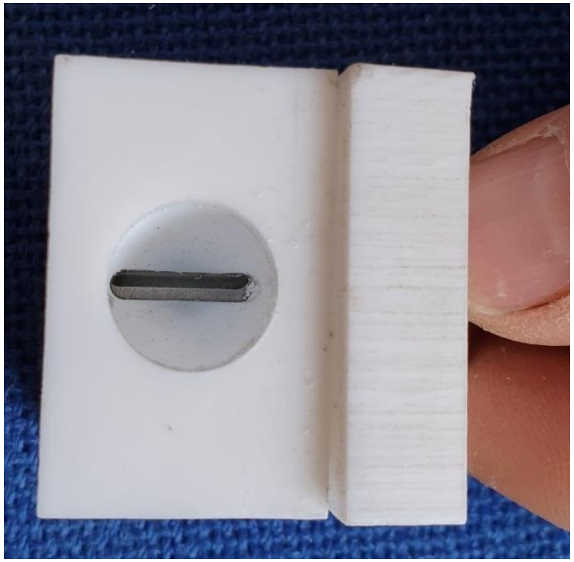
- A larger-scale version of the sieving apparatus is currently under construction. This is to be integrated with a 3D-rift apparatus, shown below.

- Once complete, the established workflow will be used to begin testing feedback mechanisms between gravity-driven and tectonic-driven deformation processes, including impacts of climate and sea-level.

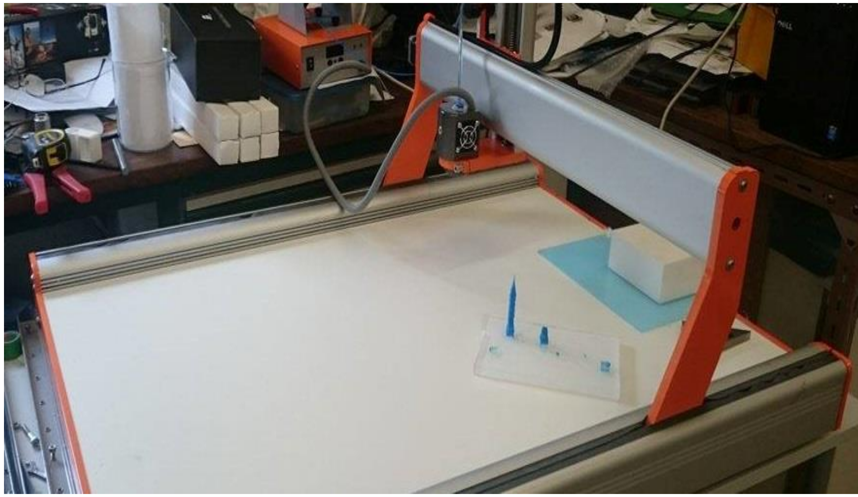


Future work: Automated sediment loading

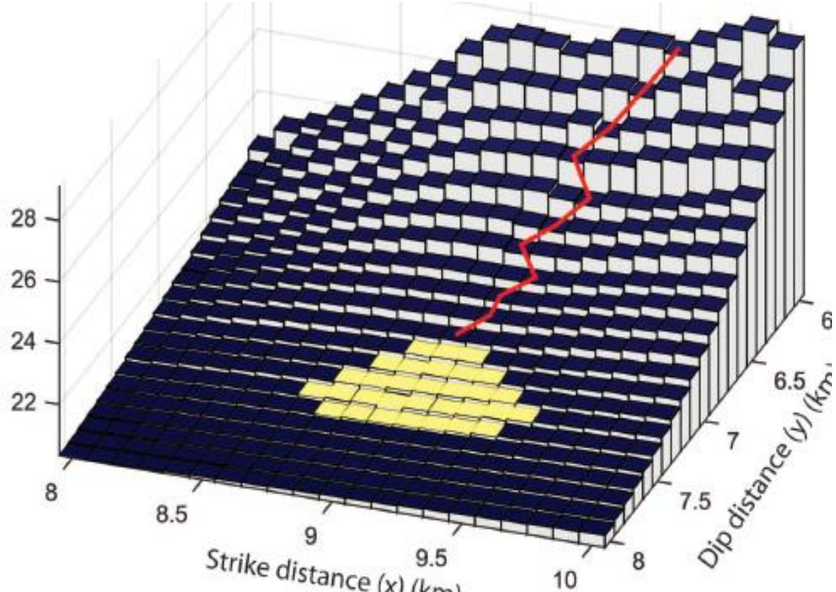
- Sand loading into the apparatus is currently a manual process. This is not feasible when the model is increased in size and integrated with a kinematic apparatus (25x25 cells, 625 total possible per layer).

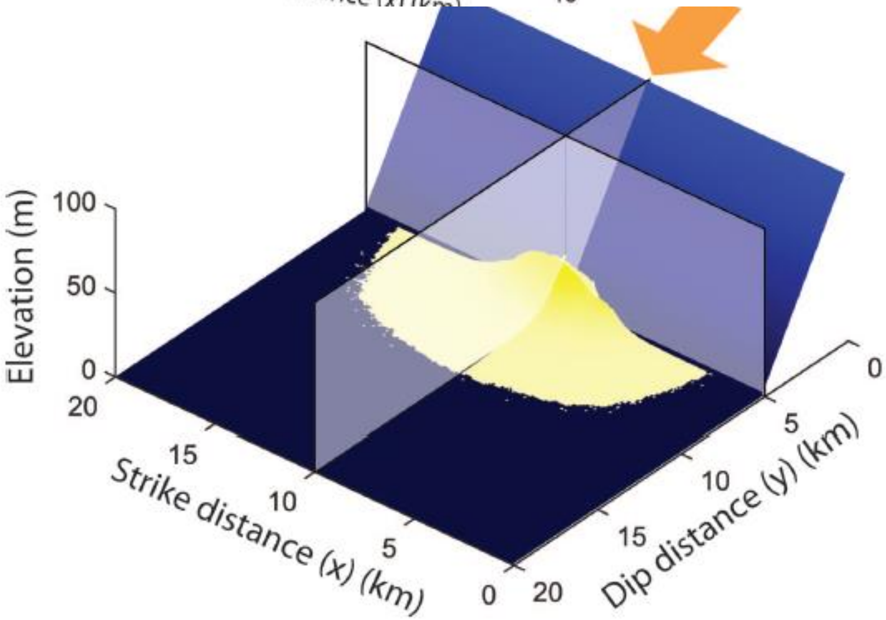


- Currently in construction is an automated system which will derive the scaled thicknesses from the numerical modeller and deposit the relevant volumes to the sieving apparatus, ready to be deposited onto the model. Compared to by-hand, this should achieve:
  - **Better accuracy of volumes**
  - **More precise coordinates filled (i.e. centre of the cell)**
  - **Quicker – particularly relevant for potential studies involving salt and gravity-driven deformation**



Future work: Addition of clastic modelling





- Workflow is also to be integrated with a new clastic modeller - Lobyte 3D (Burgess et al., 2019).
- A reduced-complexity model of deposition in dispersive-flow fan systems that shows emergent behaviour such as lobe switching and compensational stacking of a potentially hierarchical nature due to flow over a complex, evolving seafloor topography.
- Written in MATLAB and can function with CarboCAT, the existing numerical modeller, providing both clastic and carbonate sedimentation patterns.

References

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

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GAWTHORPE, R.L. and LEEDER, M. R. (2000), Tectono-sedimentary evolution of active extensional basins. *Basin Research;* 12: 195-218.

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