[PS]Understanding the Controls on Clastic Sedimentation Using Forward Stratigraphic Modeling and Seismic Sequence Stratigraphy*

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Abstract

There are have been significant oil and gas discoveries in reservoirs associated with deltaic and deepwater sedimentation. However, despite the advances in data quality the industry has often struggled to quantitatively assess traditional qualitative geological assumptions, such as reservoir connectivity or facies variation; often resulting in a disconnect between the predicted sediment characteristics and the physical processes which influenced them initially. Thus, many approaches have often depended heavily on geostatistical methods. Our objective is to demonstrate the integration of numerical forward stratigraphic modeling to aid traditional methods of predicting facies distribution in a deltaic setting using data from the Dutch Sector, southern North Sea.

A robust geological model was created using the well and seismic data, interpreted in terms of system tracks and sequence boundaries, which lead to the understanding of the depositional environment, paleotopography, turbiditic events, and paleo-bathymetry. Combined with the regional geology, this information is integrated in a forward stratigraphic modeling simulator based on the well-established physical principles of sediment erosion, transport and deposition.

Stratigraphic sequences and lithologies were compared to the available data to calibrate the parameters and fine-tune the model. The final model which best honours the data is used to predict reservoir properties and geometries at both a basin and finer stratigraphic scale. The stratigraphic forward modeling results are consistent with the observed seismic and well data, including sequence boundaries and lithologies. We demonstrate that numerical simulation allows one to better characterize facies variations at a high resolution and matches qualitative predictions from previous studies. The resulting model can be used to generate quantitative predictions for reservoir connectivity, porosity, and broader play definitions. This study demonstrates that forward stratigraphic modeling can be used in both frontier exploration with limited data

and mature projects, allowing researchers to quantitatively assess their geological hypotheses; with insights into the dynamic interaction between sediment source, transport, deposition and diagenesis coupled to sea level variation and tectonics. Therefore, traditional qualitative methods can be enhanced using the quantitative results, thus increasing their predictive capabilities.

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1. Introduction
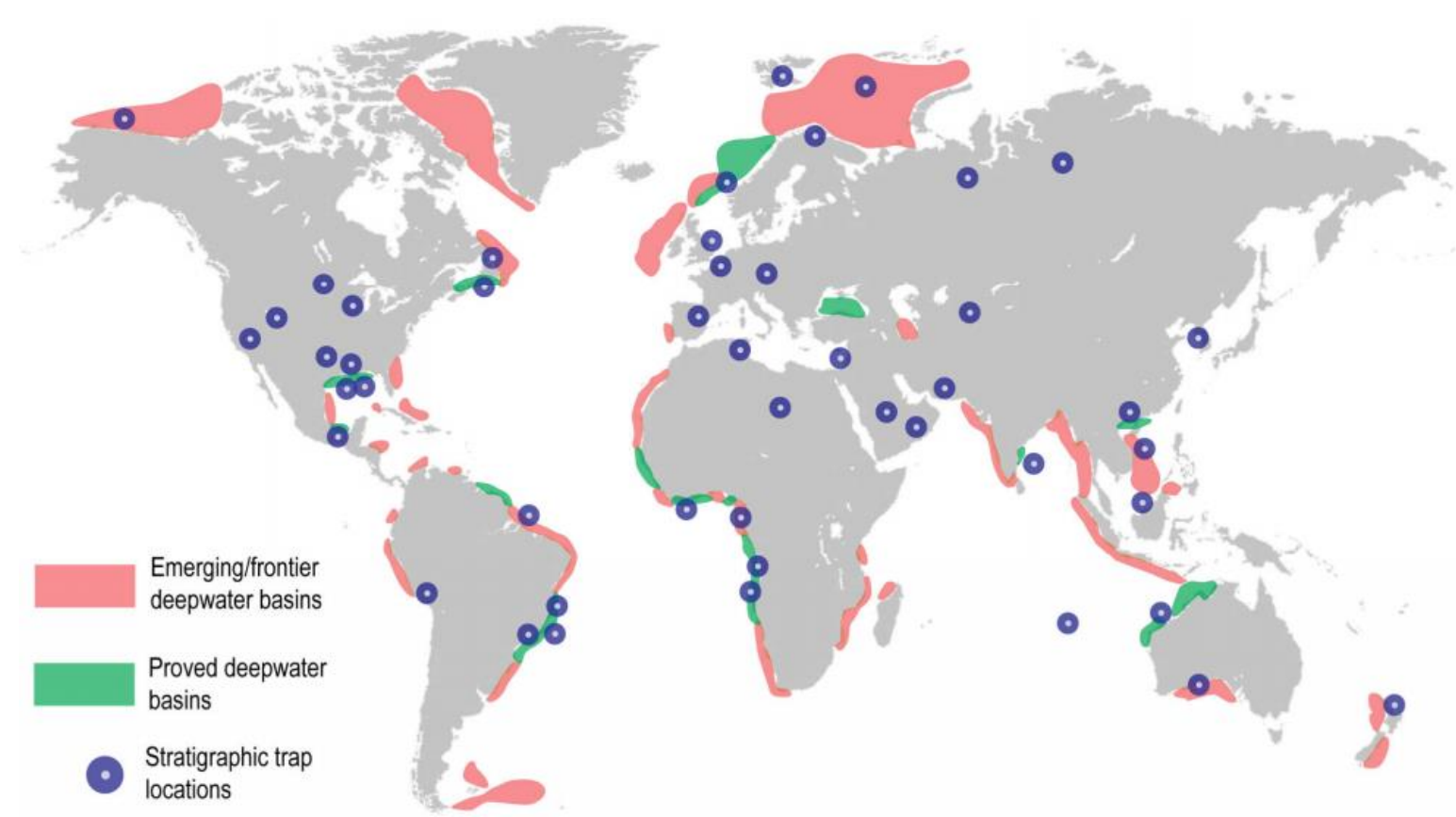
Map showing the generalized global distribution of deepwater plays
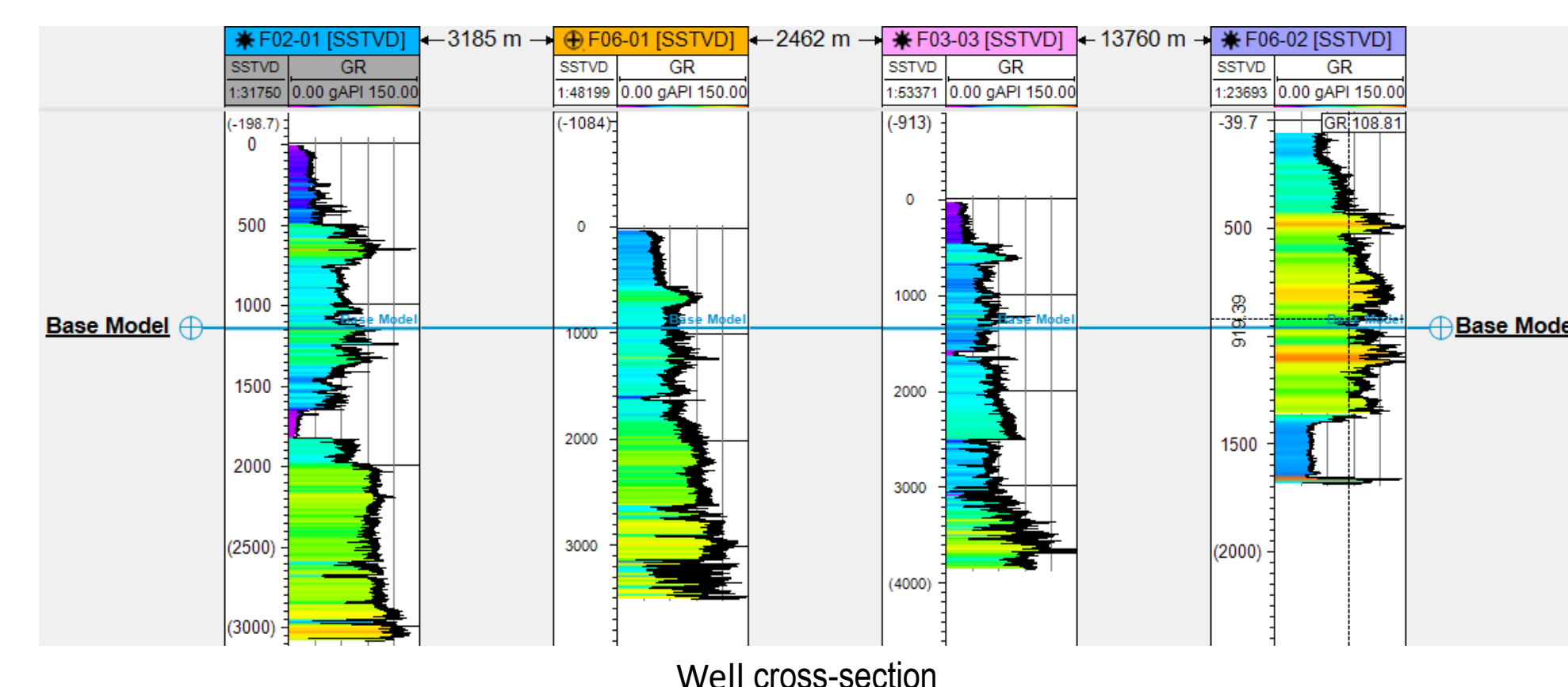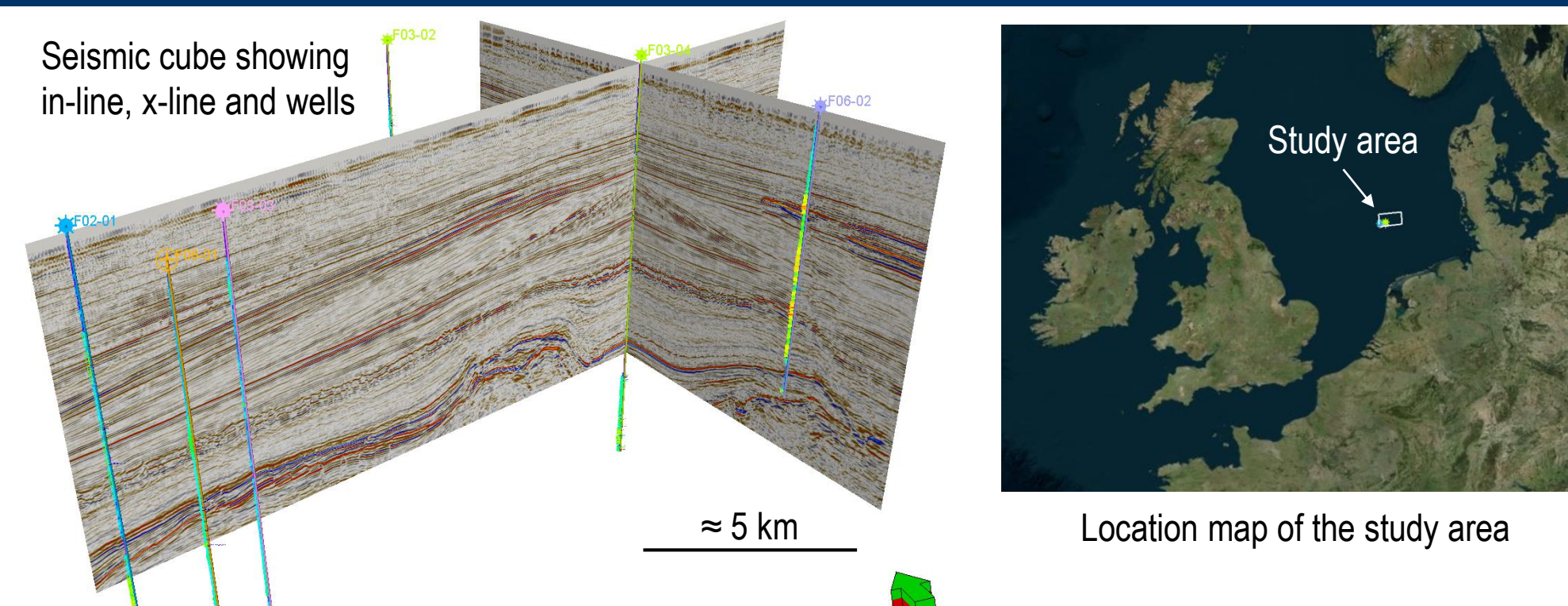
There have been significant oil and gas discoveries in reservoirs associated with deltaic and deepwater sedimentation. However, despite advances in data quality the industry has often struggled to quantitatively assess traditional qualitative geological predictions, such as reservoir connectivity or facies variation; often resulting in a disconnect between the predicted sediment characteristics and the physical processes which influenced them initially.

Our objective is to demonstrate the integration of numerical forward stratigraphic modeling to aid traditional methods of predicting facies distribution in a deltaic setting using data from the Dutch Sector, southern North Sea.

The study is based on a new forward stratigraphic modelling simulator called Geological Process Modeling (GPM) which is fully integrated in the Petrel* E&P software platform. GPM is based on the well established numerical modeling principles of sediment erosion, transport and deposition[1, 2, 3].

Furthermore, the GPM results are directly usable in other workflows to improve on traditional geostatistical methods necessary for addressing uncertainty.
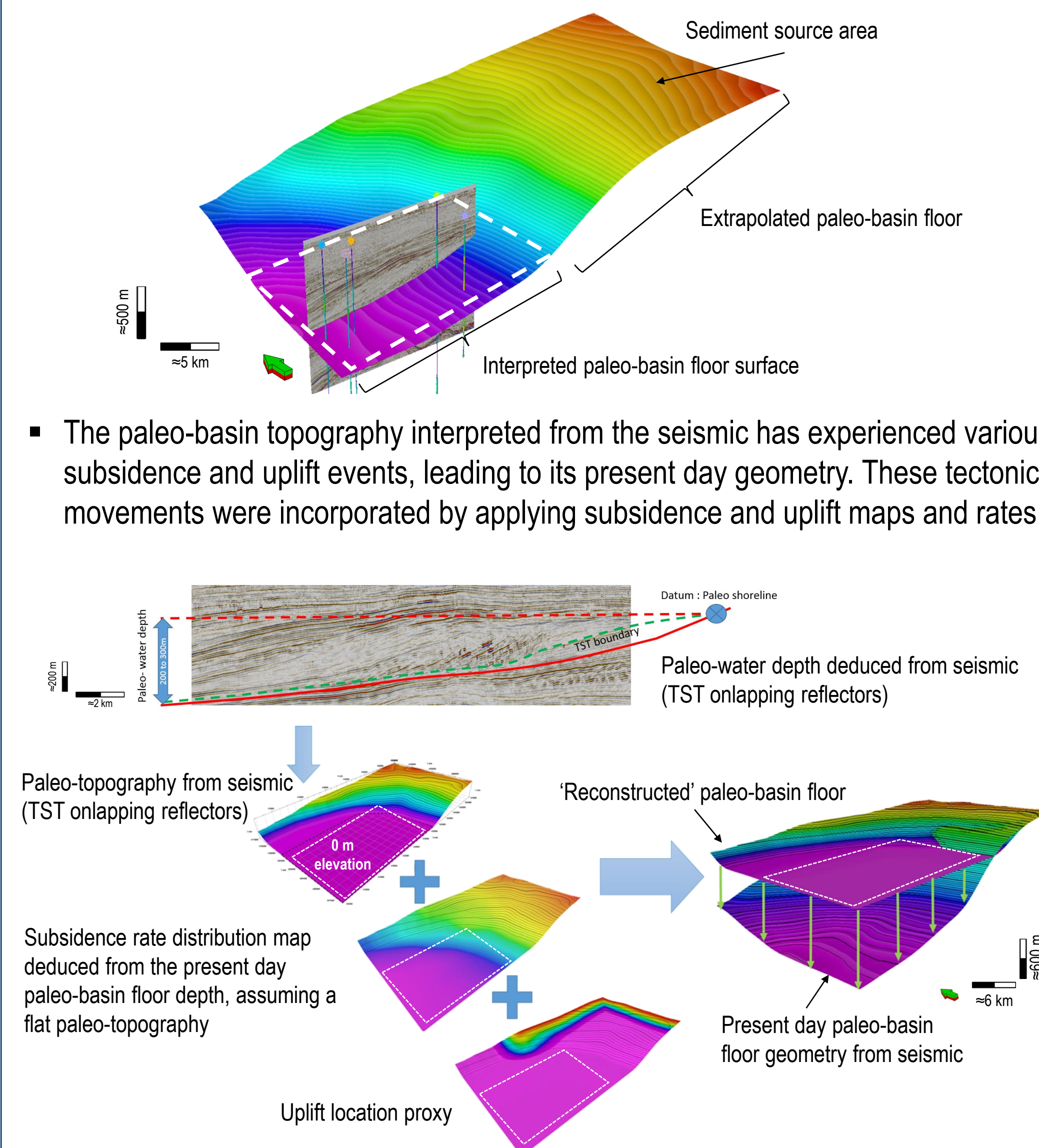
2. Study Area

Seismic cube showing in-line, x-line and wells

Study area

Location map of the study area

Well cross-section

- The dataset consists of a high-quality 3D seismic cube and six wells from the F3 block, located in the Dutch sector of the southern North Sea**.
- The key feature of the study area is a large Pliocene fluvio-deltaic system which contains large-scale characteristic sigmoidal bedding geometries.
- This fluvio-deltaic depositional setting provides an excellent opportunity to model/predict the physical distribution of sediments based on diffusion, steady and unsteady flow.

3. Modeling Inputs

- The paleo-basin floor, representing the initial surface on which the prograding delta was deposited during the Pliocene was interpreted from the 3D seismic.
- This paleo-basin floor was extrapolated to the hypothesized onshore sediment source areas ensuring spatial continuity between the source areas and the basin depocentre area of interest where seismic and well logs are available.

Sediment source area
Extrapolated paleo-basin floor
Interpreted paleo-basin floor surface

- The paleo-basin topography interpreted from the seismic has experienced various subsidence and uplift events, leading to its present day geometry. These tectonic movements were incorporated by applying subsidence and uplift maps and rates.

Paleo-water depth deduced from seismic (TST onlapping reflectors)
Paleo-topography from seismic (TST onlapping reflectors)
'Reconstructed' paleo-basin floor
Subsidence rate distribution map deduced from the present day paleo-basin floor depth, assuming a flat paleo-topography
Present day paleo-basin floor geometry from seismic
Uplift location proxy

- The system tracts were correlated to the accommodation, and thus, the sea level variations.
- Using the Haq sea level curve[4] and seismic sequence stratigraphy, three main prograding delta sequences were interpreted.
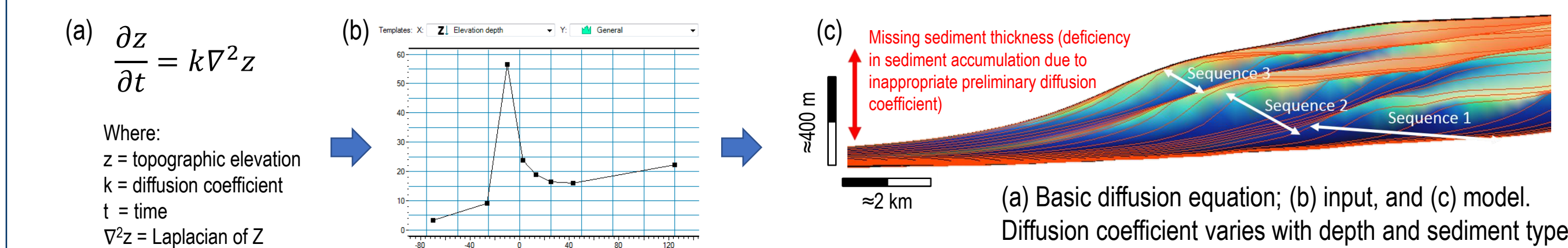

Three sequences correlated to sea level trends
Possible time intervals
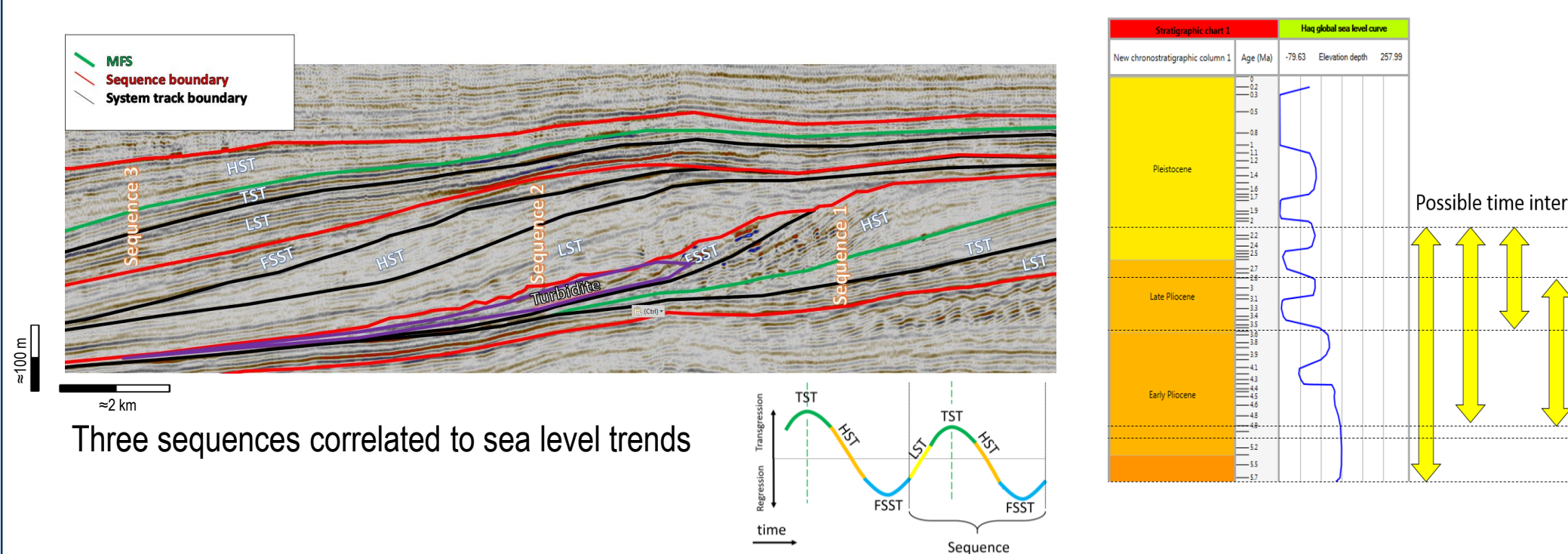
- Based on the paleo environments, accommodation, and published sequence ages[5, 6], subsidence and uplift rates were calculated.
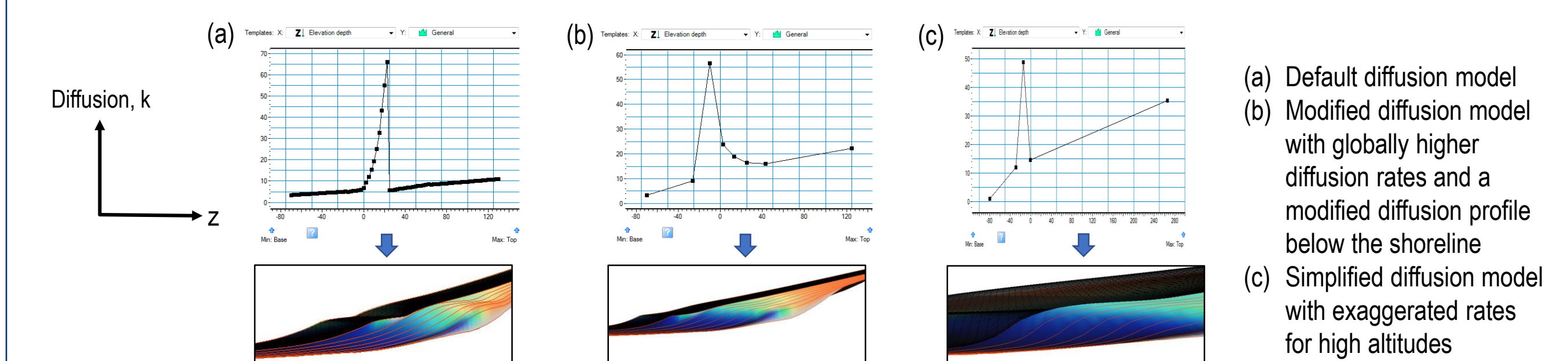

Input subsidence and uplift rates
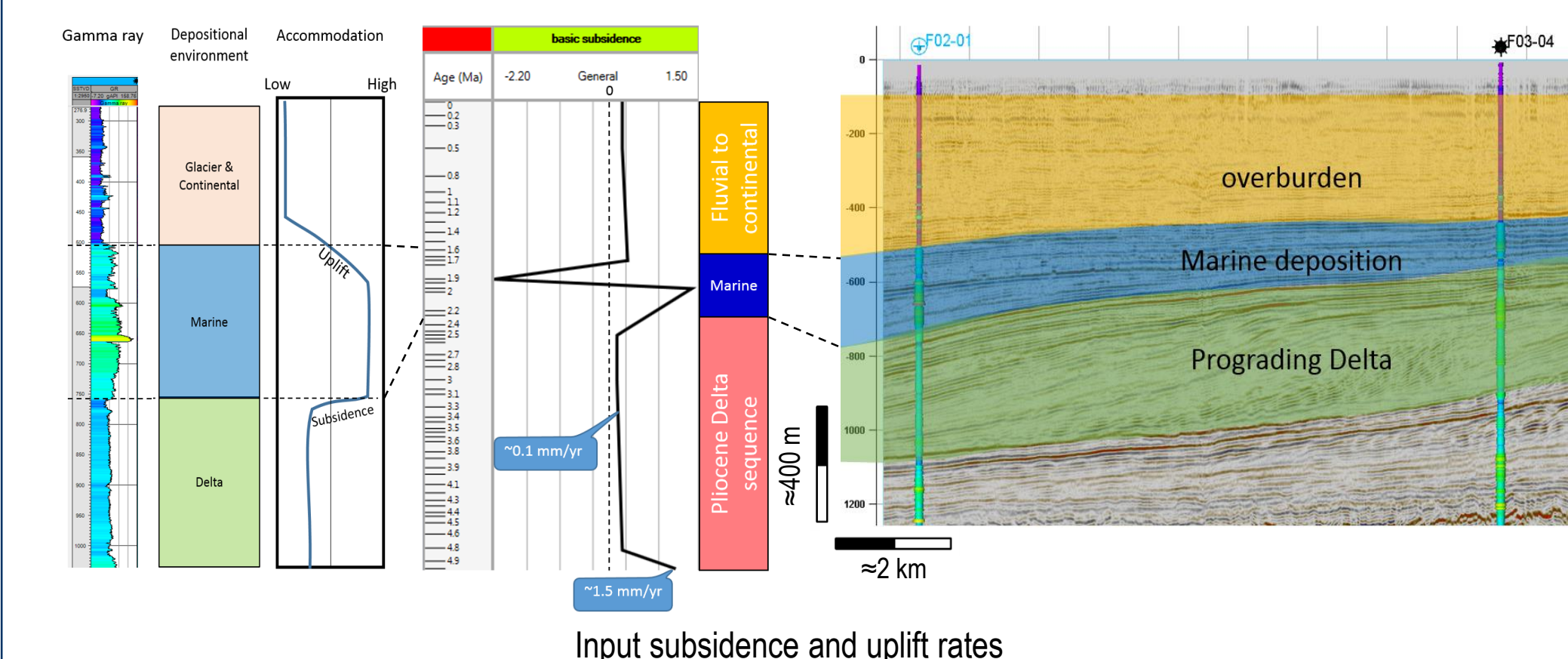
4. Methodology & Results

- In the first phase a model was simulated using the diffusion process only.
- The diffusion curve has a strong impact on erosion, sequence thickness & delta front slope; e.g. using an inappropriate diffusion curve can lead to a lack of sediments in the distal region of the model.

$$\frac{\partial z}{\partial t} = k\nabla^2 z$$

Where:
z = topographic elevation
k = diffusion coefficient
t = time
$\nabla^2 z$ = Laplacian of Z

(a) Basic diffusion equation; (b) input, and (c) model. Diffusion coefficient varies with depth and sediment type

- It was therefore necessary to test multiple diffusion curves in order to get an appropriate result. An efficient method was adopted by simulating a small interval of the model and comparing it to the seismic. To account for the lack of sediments, it is possible to increase the diffusion coefficient for the onshore regions.
- In this model it was found that diffusion was higher in elevated areas; this is consistent with glacial weather.

(a) Default diffusion model
(b) Modified diffusion model with globally higher diffusion rates and a modified diffusion profile below the shoreline
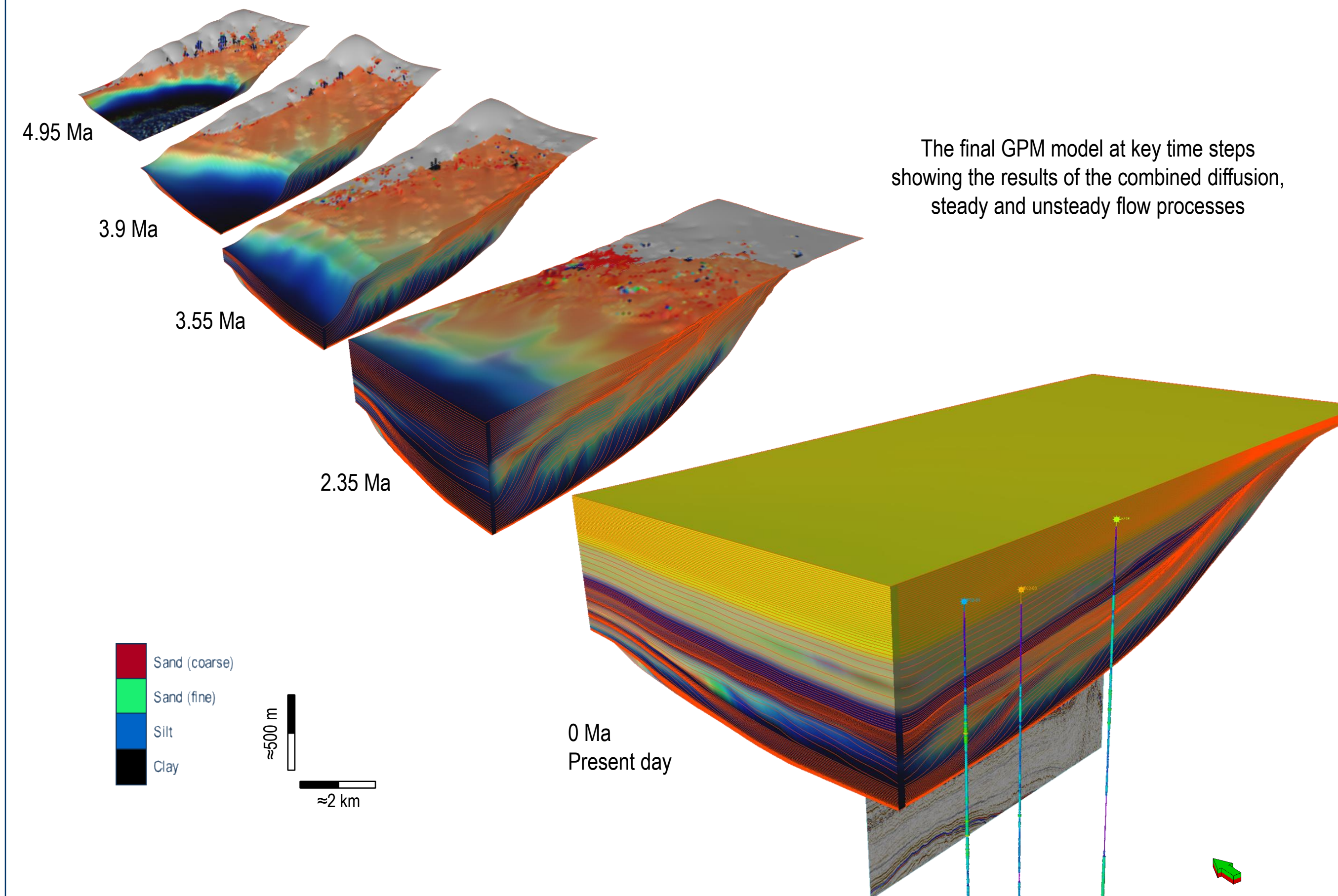(c) Simplified diffusion model with exaggerated rates for high altitudes

- Increasing the diffusion at high altitude increases the sediment input and gives the expected results for a HST. Increasing the diffusion curve at sea level flattens the top of the delta which is consistent with the erosional process associated with HSTs.
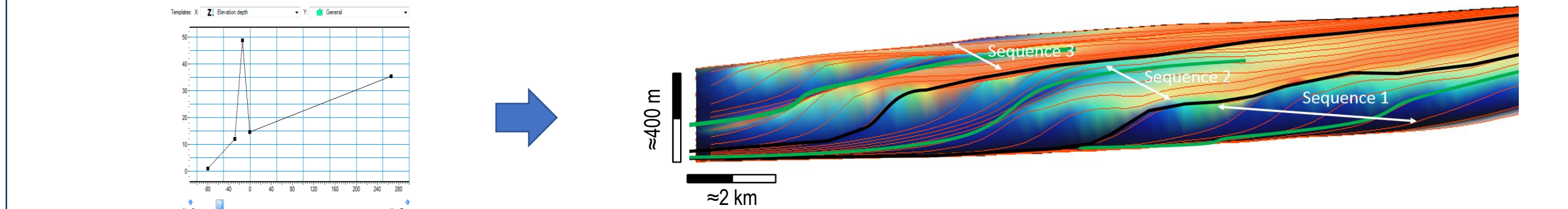
- Once the diffusion-only model results became acceptable, channels (steady flow) and turbidites (unsteady flow) were included by adjusting the flow parameters over a short time interval (e.g. 500,000 years).


Diffusion only
Diffusion + steady & unsteady flow
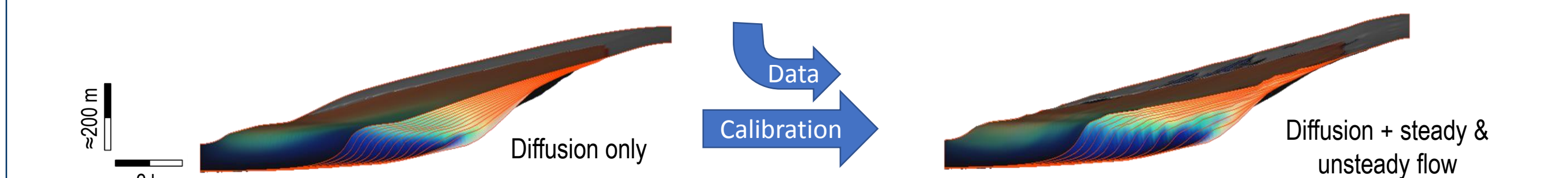
- The final result is consistent with the initial diffusion model and the seismic and well data with some minor variations

4.95 Ma
3.9 Ma
3.55 Ma
2.35 Ma
0 Ma Present day
The final GPM model at key time steps showing the results of the combined diffusion, steady and unsteady flow processes
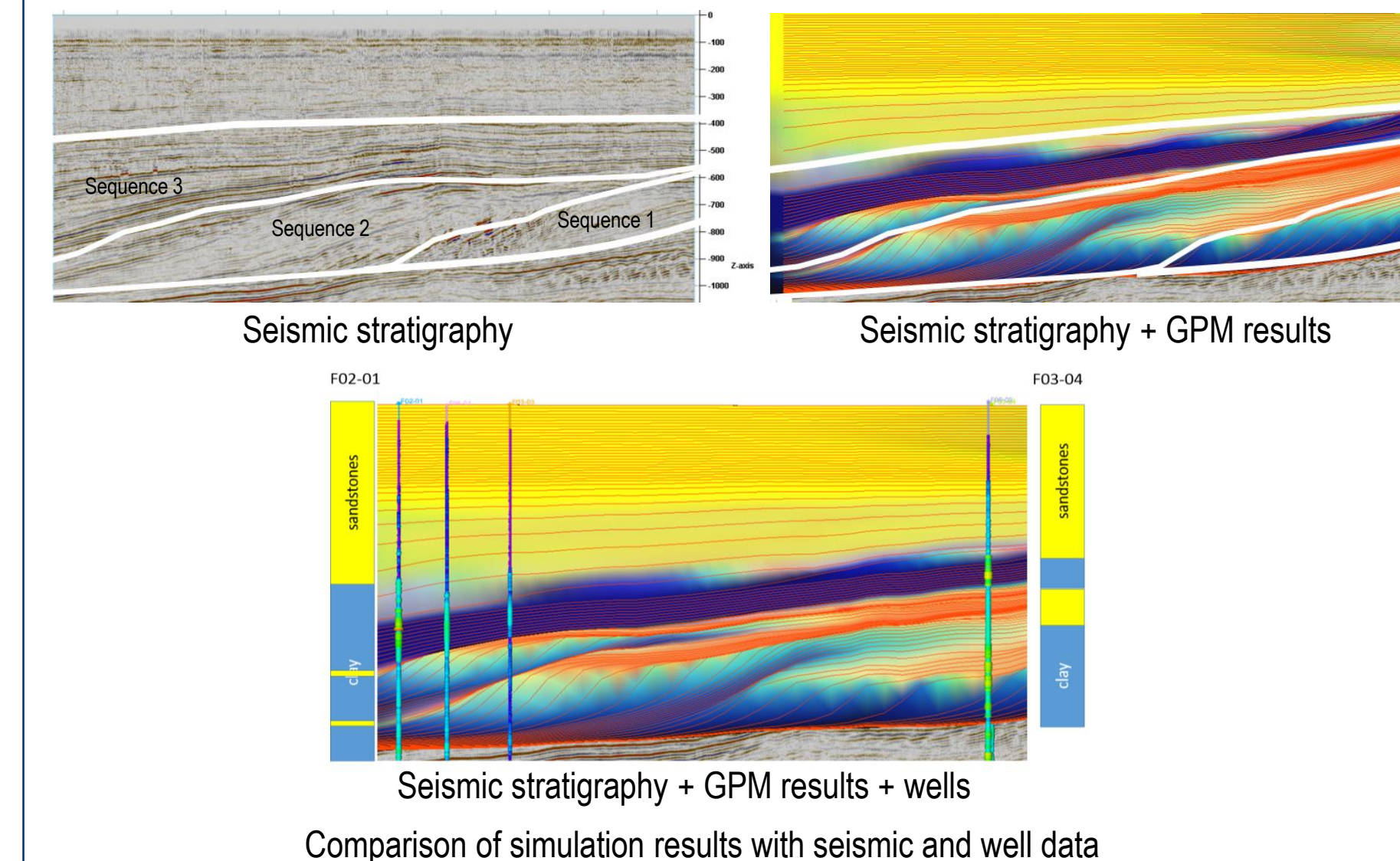
Sand (coarse)
Sand (fine)
Silt
Clay

5. Conclusions

- This flowchart summarizes the complete GPM workflow and can be adapted/extended to address carbonate growth & diagenesis.
- The calibration phase allows one to convert diffusion into fluid flow controlled sedimentation where appropriate.
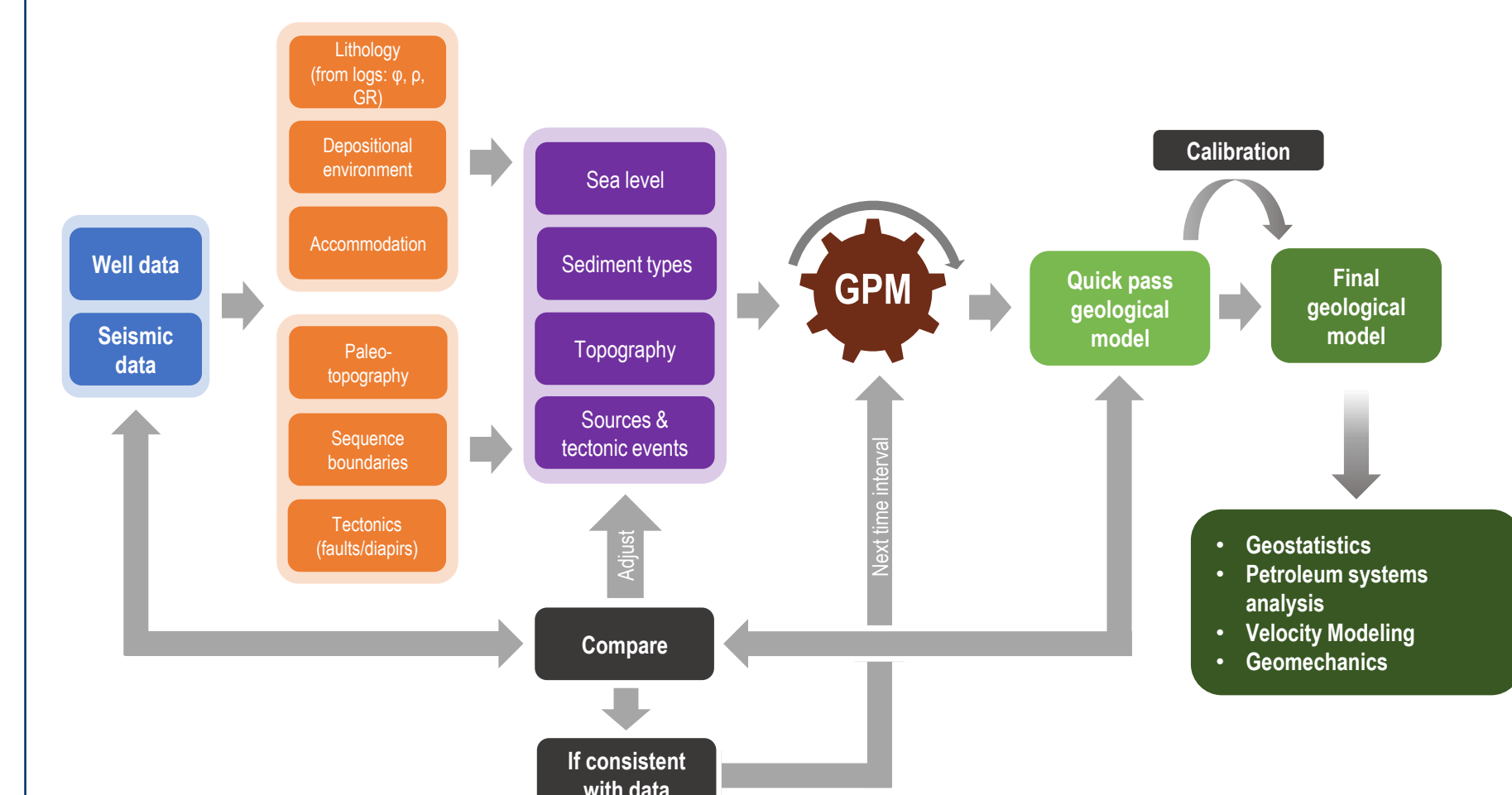
- Comparing the GPM simulation results to the seismic and well data shows that the model is generally consistent with the main delta sequences.

Seismic stratigraphy
Seismic stratigraphy + GPM results
Seismic stratigraphy + GPM results + wells
Comparison of simulation results with seismic and well data

This study demonstrates that forward stratigraphical modeling can be used in both frontier exploration with limited data and mature projects, allowing researchers to quantitatively test their geological hypotheses; with insights into the dynamic interaction between sediment source, transport, deposition and diagenesis coupled to sea level variation and tectonics. Therefore, traditional qualitative methods can be enhanced using the quantitative results, thus increasing their predictive capabilities.

Based on these results, it is evident that GPM results can be used for:
- Deriving lithology fractions as 3D probability volumes and trends for geostatistics.
- Predicting facies and lithology distributions during exploration; and as an input to petroleum systems modeling.
- Predicting lithologies & porosities below seismic resolution which can potentially aid in building more rigorous velocity models.

6. References

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* Mark of Schlumberger
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