

Prediction of Multi-Scale Fluvio-Deltaic Stratigraphy by Forward and Inverse Modeling of Integrated Source-to-Sink Sediment Flux*

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Introduction

Numerical models are useful tools to simulate fluvio-deltaic sedimentary processes and can therefore be used to untangle the sea level and sediment supply histories from the sedimentary record by combining field data with new forward and inverse numerical modeling techniques. Applying models at various temporal and spatial scales provides the potential to predict reservoir properties, as well as quantifying their uncertainty.

We developed a new catchment model to predict the sediment flux from the hinterland, and a coupled floodplain-delta-shoreface forward stratigraphic model to quantify volumetric changes in sediment distribution in response to external or allogenic forcing. Combining the catchment and the computationally efficient stratigraphic model allows for quantification of the complex interactions between the sediment yield in the source and the stratigraphic response in the sink (shallow-marine domain) in relation to climate change and tectonics, sediment transfer rates and delays. At the same time, the low computational time of the forward stratigraphic model provides the opportunity to use inverse modeling to reconstruct sediment supply from stratigraphic data. At a more detailed temporal and spatial scale, a physics-based model (Delft3D) can be used to explore detailed aspects of stratigraphic heterogeneity.

PacMod and 2DStratSim

The 1D catchment module (PacMod) is a spatially lumped hydrological and sediment transport model which, based on climatic data, drainage basin characteristics, and a number of user-defined parameters, is able to calculate long time series (> 103 years) of fluvial water discharge and sediment load. It applies to the upstream, erosion-dominated area of a river system, and it combines PALAEOFLOW hydrological routine

(Bogaart et al., 2003) and HYDROTREND-BQART sediment routine (Syvitski and Milliman, 2007). The new developments in the model, with respect to previous ones, are: (1) the parameterized incorporation of the delayed response of vegetation and soil erodibility with respect to the climatic signal and the time for the coarse grain-size classes to be eroded and transported out of the catchment; (2) the modeling of individual floods; (3) the increased processing speed.

The forward stratigraphic model (2DStratSim) is a coupled behavior-based model consisting of three 2D modules representing a floodplain, a delta-shelf and shoreface depositional system ([Figure 1](#)). The efficiency of the model enables us to use 2DStratSim in an inverse modeling scheme and yet exploit 3D information. The delta-shelf and shoreface-shelf are based on DeltaSim (Hoogendoorn et al., 2008), and BarSim (Storms, 2003) respectively. The floodplain is a newly developed module where sediments can be stored or released in response to changes in sea level, discharge, and sediment supply.

Validation

PaCMod was successfully tested on two present-day fluvial systems, the Meuse and the Po River, and the results matched closely the measured data. In order to evaluate the importance of the user input on the final output, a sensitivity analysis for the different parameters, with distinct climatic settings, was undertaken.

Several synthetic and real world scenarios were simulated, using PaCMod output as an input for 2DStratSim. The different experiments showed the ability of the models to reproduce distinct stratigraphic patterns related to different forcing signals and, in detail, to model the effect of high-magnitude, low-frequency events (floods, storms) in the stratigraphic record. The results indicate that (1) environmental delays and sediment routing delays exert an important control on deltaic stratigraphy and (2) the initial climatic signal, although delayed and attenuated by wave reworking, is transmitted to the delta.

At reservoir scale BarSim was successfully applied in an inversion scheme designed to condition the model to field data and extract a time series for palaeo sea level, sediment flux and wave climate (Charvin et al., 2011 and references therein; see [Figure 2](#)). The inversion scheme is based on a combination of Bayesian statistics and Markov chain Monte Carlo techniques. The Bayesian framework is used in order to sample the full range of possible solutions and explicitly build in prior geological knowledge. The methodology combines Reversible Jump Markov chain Monte Carlo and Simulated Tempering algorithms which are able to deal with variable dimensional inverse problems and multi-modal posterior probability distributions, respectively (Charvin, 2011).

Delft 3D

While the above models can be used to constrain large-scale sediment supply and sea-level boundary conditions, they do not provide detailed stratigraphic information at the lithofacies scale due to their 2D nature. Process modeling of depositional systems is able to simulate detailed stratigraphy, but it has a long history of being very interesting yet unsuitable to be incorporated in the reservoir geology workflow. This is predominantly due to the complexity to condition forward process models to well data. Although some progress has been made (e.g., Michael et al., 2010, Bertoncello, 2011), our approach to the application of process models to reservoir building is to treat their output (synthetic

stratigraphy) as numerical outcrop data. The synthetic stratigraphy of the simulated sedimentary systems (c.f., grain-size distributions, lithofacies) provides relevant and unbiased information that can be used in addition to existing statistic and geometric data collected in the field at outcrops or from modern sedimentary systems. The reservoir geologist can choose from a suite of 2D and 3D forward models and apply wide range of possible input boundary conditions. The resulting synthetic stratigraphy provides training sets that can be used to characterize fluvio-deltaic deposits using a geometric (e.g., channel dimensions) or statistic (e.g., channel density) approach, similar to field data and can therefore be directly used in Petrel or RMS modeling software.

The physics-based model aims to increase our understanding of clastic river delta formation and stratigraphy. A coupled model (Delft3D), comprising formulations for water flow, transport of sands and silts, bed level dynamics, and internal sedimentary composition has been used to simulate progradation and aggradation of alluvial deltas under steady forcing. Model output comprises an emerging self-organizing distributary channel network, of which we calculated metrics, including channel aspect ratio, drainage density and shoreline roughness. Simulated internal delta architecture reveals typical sorting patterns, such as infill of abandoned distributaries and large-scale horizontal fining associated with the progradation of the sandy channel network and deposition of fines off the moving delta front (Geleynse et al., 2010, 2011). Recent work focuses on property modeling, such as predicting sedimentary structures and lithofacies. Accordingly, this study points to the complexity of autogenic river delta functioning and offers the opportunity for field/laboratory case-comparison.

Ongoing research

Integrating models at different spatial and temporal scales is important to fully understand the fluvio-deltaic system and the allogenic and autogenic characteristics. At a larger spatial (exploration) scale, a similar inversion scheme will be applied to 2DStratSim to infer sediment-flux histories from real-world data for the three coupled modules. Further study will focus on the role of the floodplain in signal propagation, on the link between the delta-shoreface system in terms of reservoir distribution and on the preservation potential of shallow marine deposits, i.e., how much of the forcing signal is recorded in the sink, and how much is recoverable in practice.

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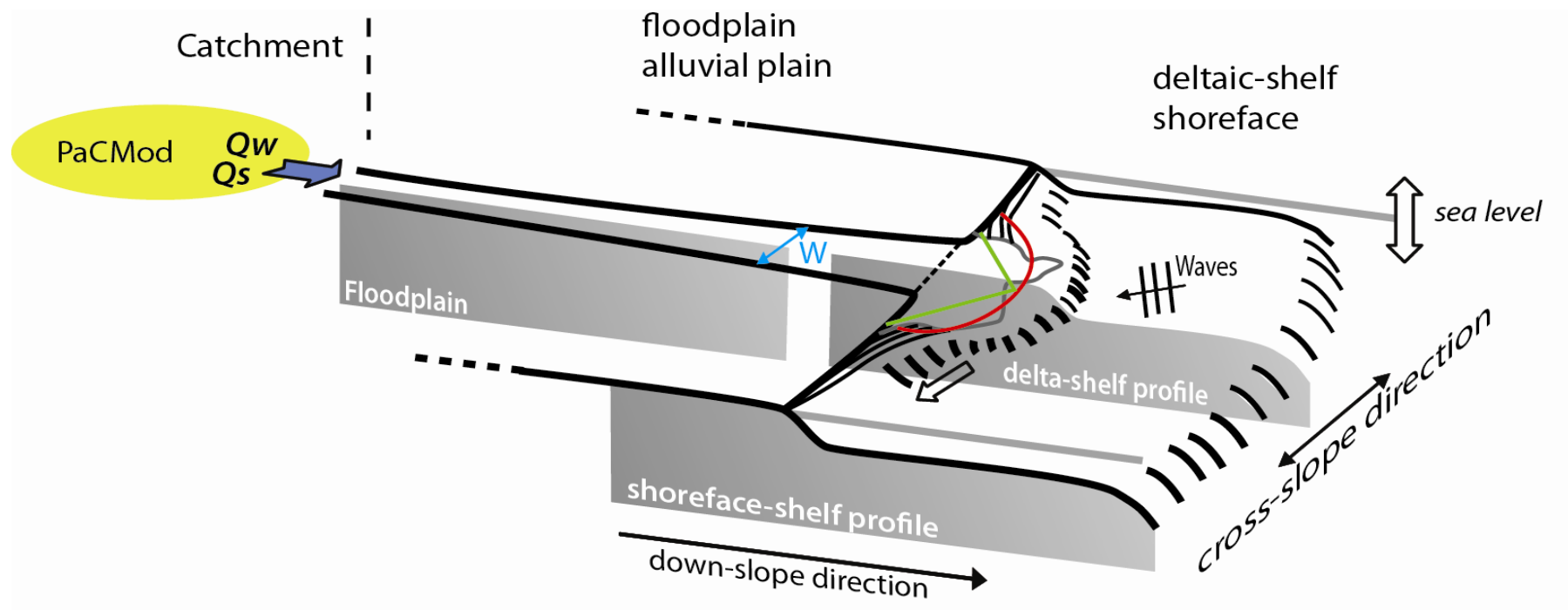


Figure 1. Cartoon of 2DStratSim and model domains. Indicated in grey are the three down-slope profiles that are simulated and exchange sediment by longshore currents and floodplain-alluvial plain deposition. The imposed width of the floodplain (W) is denoted by the blue arrow. Two possible delta plan-view shapes, indicated in red and green, can vary in shape or radius. The boundary condition at the upstream part of 2DStratSim is the Catchment module (PaCMod).

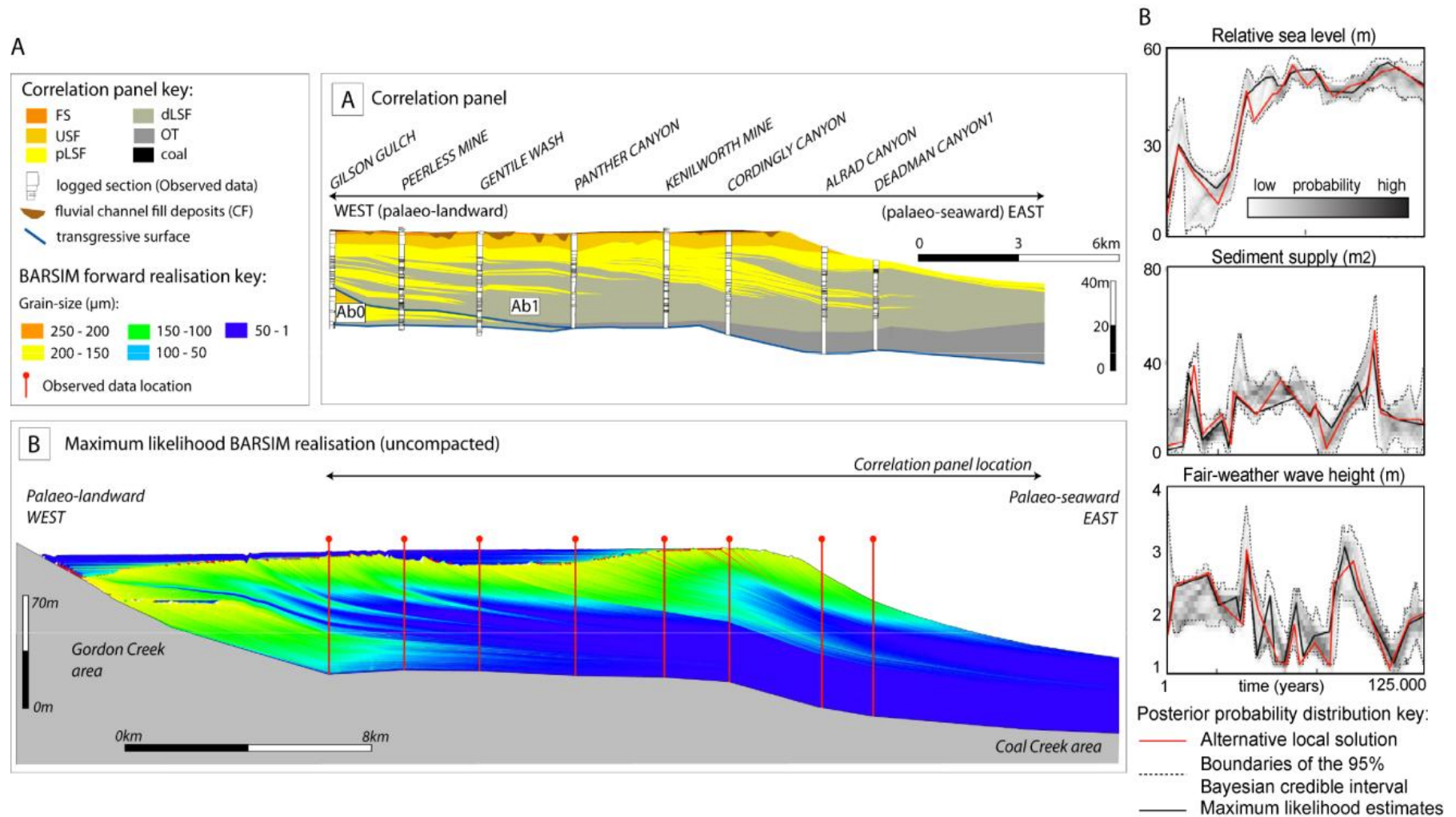


Figure 2. Inversion realization using BarSim (lower panel) based on data of the Standardville parasequence (top panel), near Helper, Utah, USA. To the right (B) are the inferred parameters for sea level, sediment flux and wave regime. For details, see Charvin, 2011, and references therein.

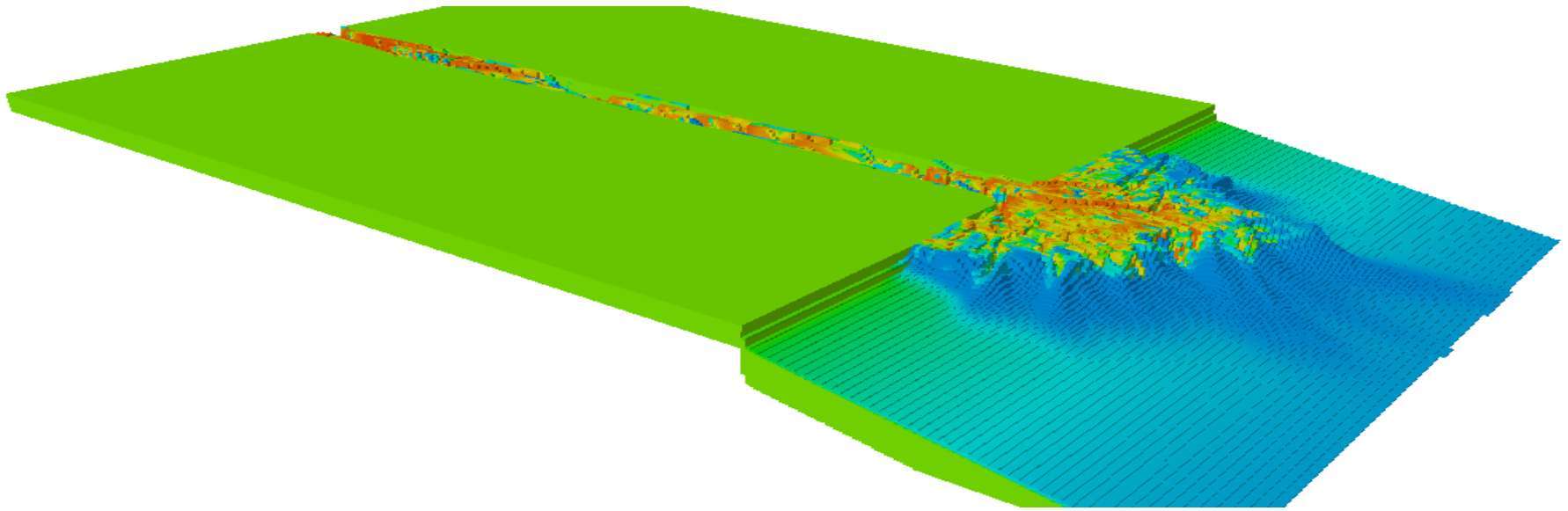


Figure 3. Example of a simulated fluvial-dominated delta building in a shallow (<10 m water depth) basin using Delft3D. The model domain is 10 by 16 km. Warm colors represent sand while cold colors represent fine silt.