Multiscalar Forward Modelling of Carbonate Heterogeneity*

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Abstract

Carbonates are challenging. Their very existence often depends on complex interactions between continuously evolving biological organisms and chemical and physical environmental conditions. Post-depositional processes such as subaerial exposure, tectonic stress, burial, and the passage of fluids, all act on the initial rock matrix to produce lithologic, porosity and permeability heterogeneity at all scales.

Several studies have emphasized that depositional facies, combined with diagenetic and stress histories exert a fundamental control on the evolution of flow properties in carbonates, with respect to both matrix and fracture characteristics.

In this document, we discuss the use of the stratigraphic forward modelling (SFM) program Sedsim (Griffiths et al, 2001a and b) to test our understanding of carbonate depositional facies distribution at a variety of scales and in different depositional environments.

Basic Principles of Sedsim Operation

Hydrodynamics make up the core of the Sedsim program through an approximation to the Navier-Stokes equations. Sedsim simplifies the flow model by using isolated fluid elements to represent continuous flow (Tetzlaff and Harbaugh, 1989, Chapter 2). This Lagrangian approach to the hydrodynamics increases computation speed and simplifies the fluid flow equations. Modelling of the fluid flow is performed by allowing fluid elements to travel over a regular orthogonal grid describing the topographical surface, reacting to the local topography and conditions such as the flow density and the density of the medium through which the element is passing (e.g. air, seawater, or fresh water). The fluid elements are treated as discrete points with a fixed volume within the grid, an approach known as "marker-in-cell".

In Sedsim, the sediment moves at the same rate as the fluid element, because there is no velocity gradient in the fluid. The boundary between erosion and transportation is determined by the critical shear stress, calculated as a function of particle diameter. Sedsim is typically run using four different siliciclastic grain sizes specified by the user, in addition to carbonate and organic growth.

Processes that can now be modelled within Sedsim include: catchment erosion; fluvial processes; wave, tide and storm effects; geostrophic currents; tectonic subsidence and uplift; limited faulting; eustatic and multiple-location lacustrine water level changes; syn-depositional and post-depositional compaction; isostasy; slope failure/slumping; density flows (debris flows to turbidites); carbonates (e.g. reef and pelagic) and organics (e.g. algae and vegetation); aeolian processes; carbonate diagenetic effects.

While clastic deposits can be modelled using hydraulic flow equations, carbonates and vegetation grow in-situ as a function of environmental conditions. Nordlund (1996) showed how a combination of fuzzy-logic and fuzzy-set theory could be used to predict facies distribution in both carbonate and siliciclastic environments. Sedsim incorporates a development of this approach to determine the location and characteristics of any material that grows rather than depends solely on hydraulics for deposition. Once grown, the carbonates and organics can be eroded and redeposited as for clastic material and are transported and deposited using the standard hydraulic routines.

Examples of Multiscale Forward Modelling of Carbonate Heterogeneity

We use Sedsim to explore our understanding of depositional systems by numerically testing hypotheses. Recent interest in microbialites in the Cretaceous sub-salt of the Atlantic margins prompted us to look at the growth conditions of stromatolites at individual colony scale, and then the process of upscaling to reservoir scale. The growth fluctuations associated with porosity distribution of the Hamelin Pool stromatolite in Figures 1a and 1b are produced by temperature and salinity variation, sea-level fluctuations, siliciclastic supply and directional wave action over the past 1,500 years. The model has a lateral resolution of 0.02 m over an area of 1 m by 1 m. The environmental conditions have been taken from the literature. Fieldwork at various present-day microbialite locations will enable lateral variation in character to be linked to environmental changes. The interaction between multiple colonies and the matrix, and resultant primary porosity and permeability heterogeneity mosaics can be seen in Figures 1c and 1d. A project is under way to forward model these deposits at scales of centimetres, metres and hundreds of metre resolution, combined with field studies and remote sensing, so that we can gain some understanding of how to upscale flow properties, calculate STOOIP, and recovery factors etc. in such systems.

At a larger scale, we can look at the model proposed by Koeher et al (2010) for the Muschelkalk of the South German Basin, which has environmental features similar to the Triassic Khuff Formation and the Upper Jurassic Arab-C and -D Formation of the Arabian Platform. The 25 km x 15 km model at 250 m resolution presented in the above-mentioned paper was based on depositional facies interpolation between wells and pseudo-wells. Using Sedsim, we developed a test of the proposed depositional environments as illustrated in Figure 2a. The environmental conditions tested include initial bathymetry, sea level change, wind and wave direction, species growth rates, and controls on primary and post-depositional porosity. The forward model showed that, given the proposed bathymetric gradient, the proposed water depths, and the preserved depositional thickness of the units between 238 Ma and 235 Ma, the published eustatic sea level fall (Haq and Schutter, 2008) would have resulted in several hundred thousand years of exposure in the Anisian and consequent diagenetic changes to the porosity and permeability distribution.

At a regional scale, we are interested in petroleum systems and play fairways, lateral variation in total organic carbon content, primary and secondary migration routes and flow properties, and reservoir and seal distribution in complex mixed carbonate and siliciclastic environments. An example of such a regional study at 4,000 m resolution is shown in Figure 2c where an area of 1,000 x 1,000 km in the West Australian Canning Basin was modelled to examine Devonian reef development and interaction with fluvial sediments in the Fitzroy Trough and Kidson sub-Basin.

Summary

Modern stratigraphic forward modelling tools enable rapid testing of multiple working hypotheses concerning the relationship between environmental forcing processes and depositional facies over a broad range of scales. The aim of such modelling is to predict rock properties away from wells and below seismic resolution with a given degree of confidence.

Available well, seismic and remote sensing data are used to constrain the model predictions at appropriate resolution rather than develop the facies distribution patterns themselves. At present flow and mechanical properties are linked to each facies or facies combination either through appropriate empirical relationships or via geophysical forward modelling.

Selected References

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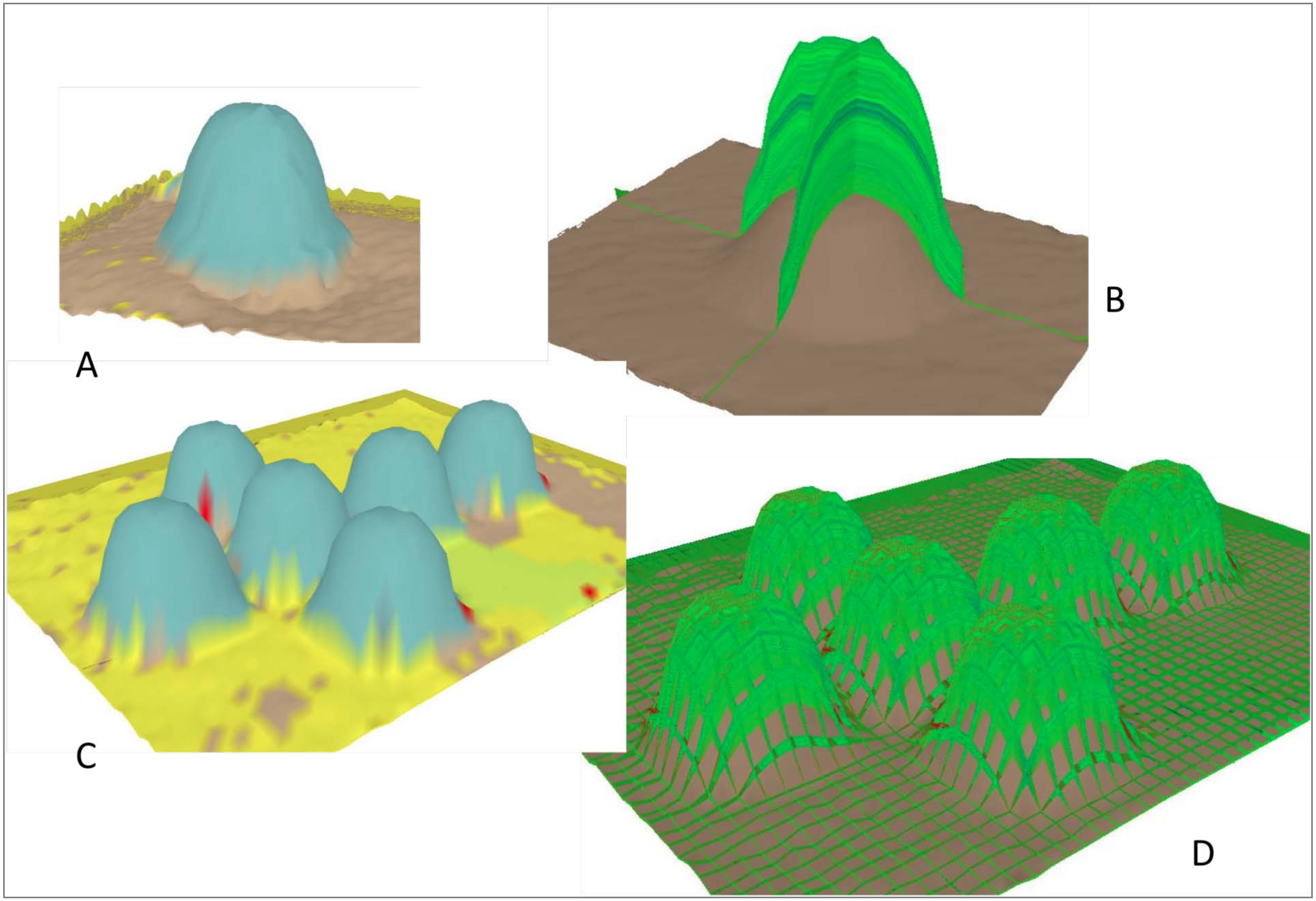

Figure 1. 3D stromatolite modelling using Sedsim. A) A model over a 1 m^2 area, at 2 cm lateral resolution, of stromatolite growth on an initial 20 cm seabed mound over a 1,500-year period at 5 years resolution given Shark Bay environmental conditions. The cyan colour represents carbonate growth. B) The same simulation as (A) but sectioned to show vertical and lateral porosity variation (lighter green colour is more porous). C) A model over a 4 m^2 area, at 4 cm lateral resolution, of stromatolite colony growth in Shark Bay. Cyan colour represents carbonate growth, yellow is carbonate clastic material moved around the individual colonies by wave action. D) The same simulation as (C) but sectioned at each grid node to show vertical and lateral porosity variation (lighter green colour is more porous, red colour is low to zero porosity).

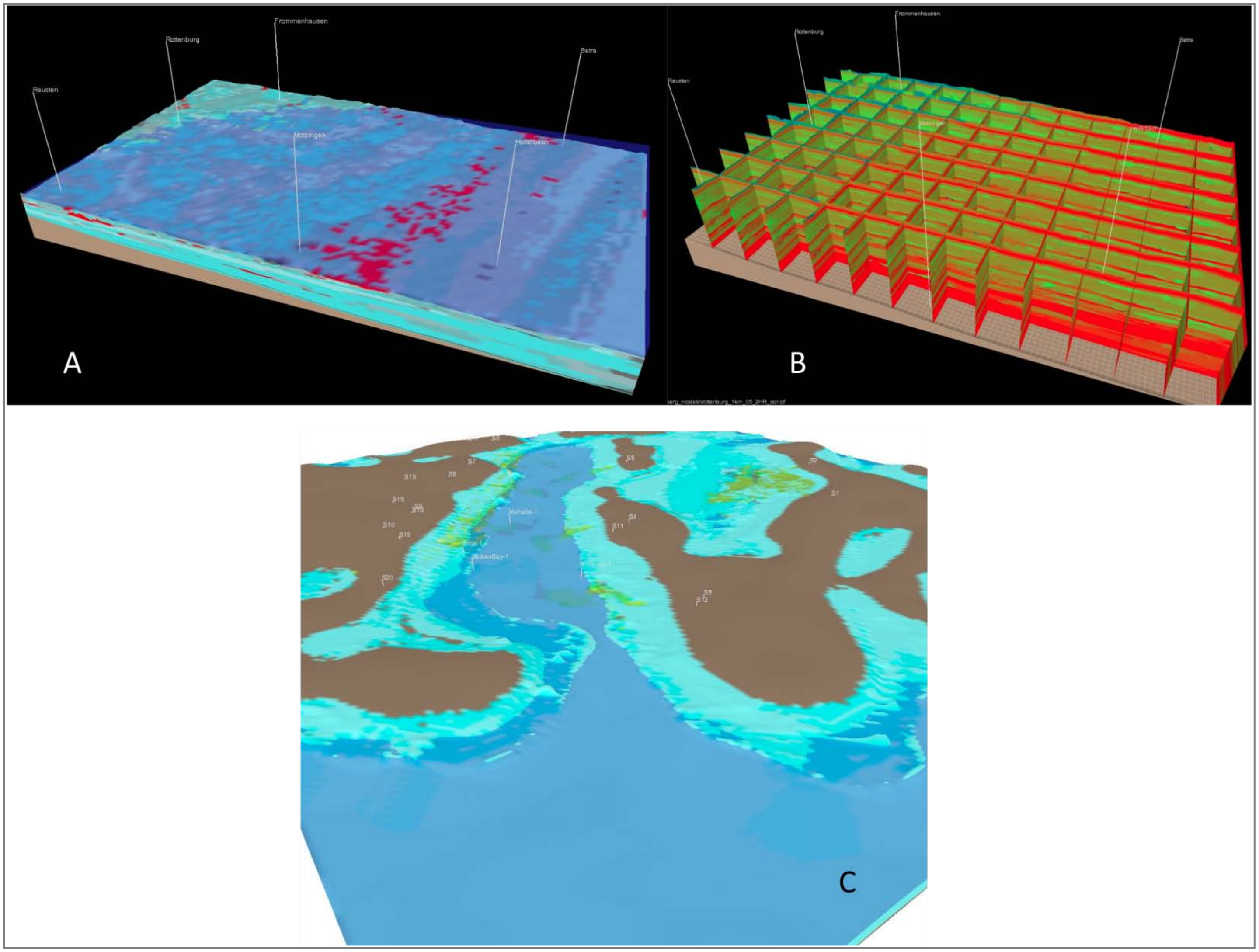

Figure 2. Larger scale carbonate heterogeneity modelling using Sedsim. A) A model over a 25 km by 15 km area, at 250 m lateral resolution, of Muschelkalk carbonate facies development on an initial 0.1° seabed bathymetry from 238 Ma to 235 Ma at 20 ka resolution. The cyan colour represents Koeher et al (2010) LFT9 facies (peloidal dolo-wackestone to packstone), dark grey/black represents Koeher et al (2010) LFT2 facies (mudstone), darker blue represents Koeher et al (2010) LFT4 facies (skeltal wackestone to packstone sheets) and red represents et al (2010) LFT7 facies (cross-bedded oolitic grainstone). B) The same simulation as (A) but sectioned at every 4th grid node to show vertical and lateral porosity variation (blue and lighter green colour is more porous, red has low to zero effective porosity). C) A model over a 1,000,000 km^2 area, at 4 km lateral resolution, of Devonian reef development in the West Australian Canning Basin. Cyan colour represents carbonate growth; yellow is silici-clastic material from identified river sources.