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

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Sedimentary basins in tectonically active settings, such as rift basins, are characterised by complex, dynamic depositional environments, with the interplay between sedimentation and tectonic processes controlling basin architecture and resource distribution. Scaled 3D analogue sandbox experiments with high-resolution digital 3D deformation monitoring, constrained by geological and geophysical data, can realistically simulate upper-crustal brittle deformation on crustal to basin-scale and allow kinematic and mechanical analysis of complex 3D fault systems. First-order syn-kinematic sedimentation can be conceptually applied to the surface of evolving experiments, permitting investigation of its effect on fault localisation, linkage and displacement and resulting tectonic basin subsidence. However, to date, first-order syn-kinematic sedimentation onto analogue models has been done manually; depositing incremental, homogeneous sand layers on top of the evolving experiment surface to simulate tectonic loading. Consequently, current syn-kinematic sedimentation methods are not capable of simulating complex stratal architectures or incorporating depositional controls like eustasy and climate variations. Conversely, numerical stratigraphic-forward modellers are able to produce these more complex stratal geometries, including their controlling parameters, however they currently lack the ability to simulate the complex tectonic subsidence of basins realistically, or in sufficient spatial resolution.

This work presents a new integrated experimental method; applying cellular numerical stratigraphic forward modelling to dynamically scaled analogue sandbox experiments, permitting realistic, incremental deposition of syn-tectonic sediments. Surface topography and displacement components (e.g. subsidence) of the analogue experiment are derived by 3D-Stereo Digital Image Correlation (DIC) and yield scaled inputs for the cellular carbonate stratigraphic forward modelling software (SFM - CarboCAT). These are then run in combination with suitable production parameters (production rate, surface light intensity, extinction coefficient etc.) as a numerical model, to generate a realistic spatial distribution of sediment facies to be incrementally deposited back onto the surface of the evolving sandbox experiment. Deposition of volumes onto the analogue sandbox is achieved using a cellular sieving device which utilises an array of tubes to maintain the spatially heterogeneous material volumes within their corresponding analogue surface locations. This apparatus has been shown to be capable of repeatedly depositing
heterogeneous sandpacks with locally controlled volumes and homogeneous mechanical properties.

The novel integrated analogue and numerical workflow is systematically tested in a series of static (depositional ramp) and dynamic (asymmetric half-graben) analogue experiments with varying initial parameters for both the analogue and numerical models. Results demonstrate that model evolution is purely deterministic, producing diverse final architectures solely as a result of initial parameters and ongoing feedback between the analogue tectonic subsidence history and the SFM-derived sediment loading.

Deposition of SFM-calculated sediment volumes onto the analogue model produces more realistic syn-tectonic depositional patterns and facies distributions than current methods can achieve. If applied to larger-scale experiments, this workflow would be capable of simulating more complex, tectonically-controlled settings like segmented rift basins or passive margin sedimentary basins affected by gravity-driven deformation, as well as investigating the role of climatic impacts on basin evolution. Findings have potential to improve understanding of basin evolution and subsequent facies distribution, with implications for resource exploration.