Analogue Modeling of the Papua New Guinea Fold and Thrust Belt*

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Abstract

The island of New Guinea records a complex structural and tectonic evolution with large hydrocarbon reserves in the frontal section of the PNG Fold Belt. The jungle-covered mountains limit data acquisition so that the internal geometry and evolution of the large anticlines are poorly understood. It is postulated that the anticlines formed above normal faults in basement. This has been tested with 14 analogue sandbox experiments performed under an X-ray tomography device. These experiments provide new 3D images of structures similar to those in PNG testing different initial configurations. Each model was initially 0.4 m wide and 0.7 m long and ~5 cm thick, with sediments overlying a step in basement to represent an old normal fault. Layers of pyrex, sand, silicone and sand/silicone mixes were used to represent the PNG stratigraphy of 2 km of molasse, 1 km of carbonate, 1 km of mudstone, 500 m of sandstone and shale reservoirs, and 0.5–3 km of syn-rift clastics. The thicknesses, strengths, and velocities of deformation were all scaled appropriately and erosion/deposition was modelled by adding or removing 'molasse'. The wood basement could be moved up and down to simulate inversion. Materials allowed the development of overturned folds cut by faults, as observed in PNG. It was found that the carbonate deformation was often decoupled from the underlying reservoirs and that the structural style was critically dependent upon the strength of the intervening mudstone. Structural style was also strongly correlated to deformation rate, with a shortening of 6 cm/hour in the model giving optimum results, being similar in magnitude, when scaled, to tectonic convergence rates in PNG. Slower convergence rates yielded a single large fold, whereas optimum rates yielded detachment folds with development of forethrusts and backthrusts. A pre-existing normal fault in basement led to development of a detachment fold in the cover abutting the basement in the footwall of the fault. This required a weak layer providing a detachment above the basement, corresponding to syn-rift coals in PNG. The development of the overturned detachment fold was greatly enhanced when the basement fault was first partially inverted. These models have led to a significant improvement in the understanding of the geometry of PNG fold belt structures, in areas beneath the wells where seismic resolution is poor. Optimising this deep interpretation will hopefully yield new leads and better models of existing fields.

Introduction

The Papua New Guinea (PNG) fold and thrust belt records a complex structural and tectonic evolution and contains large hydrocarbon reserves. However, the jungle-covered mountains exhibit precipitous relief in the heavily karstified and strongly deformed Miocene limestone (Darai Formation). This severely limits data acquisition such that seismic data are often of poor quality or unusable. For these reasons, the internal geometry and kinematic evolution of the large anticlines recorded in this zone are poorly understood. It is postulated that the structural history has been marked by: Mesozoic-Paleogene rifting in basement, crustal scale Miocene inversion, detachment folds often above old normal faults in basement, thin-skinned thrusting along decollements in the Jurassic and Cretaceous and decapitation of inversion or detachment folds by out of sequence thrusts, (Hill et al., 2008; Hill et al., 2010). In order to validate some of the interpretations of the internal parts of fold-belt structures fourteen analogue sandbox experiments have been performed as geological forward models under a computerized X-ray tomography device. In this paper, we describe the experimental procedure and the results of these experiments, which have allowed us to test the following configurations:

(i) Pure compression (different rates of deformation have been tested);
(ii) Oblique compression (testing several angles of oblique compression);
(iii) Inversion of normal fault (reactivation of basement fault, variation of the remobilized throw).

Experimental Procedure

Analogue models were built in a 70 x 40 cm wooden deformation box (Figure 1A) with two free sides and two walls. A step constructed from wood constituted the basement and represented an old normal fault. Each piston (wall of deformation box) was connected to a step motor allowing movement. Sediments (~6 cm thick) overlay the wood basement and consisted of (i) sand and pyrex, which are dry granular materials simulating brittle sedimentary rocks and (ii) silicone (SGM 36) and sand/silicone mixes, which are viscous Newtonian materials simulating ductile rocks. Figure 1B shows the simplified sedimentary stack of the PNG fold belt and the analogue stratigraphy used for this set of experiments. The thicknesses of the different layers, strengths, and velocities of deformation were all scaled appropriately and erosion/deposition was modelled by adding or removing ‘molasse’.

(i) All experiments have been analysed in an X-ray tomographer (Figure 1C; Colletta et al., 1991) that provides new 3D images of structures similar to those in PNG. The acquisition is made at regular time steps allowing us to record the 3D evolution of the model through time.

Results

(i) Pure Compression

It was found that deformation of the Darai layer was often decoupled from that of the underlying Toro reservoirs and that the structural style was critically dependent upon the strength of the intervening Ieru mudstone and of the basal décollement. Using the rheology and set-up described in Figure 2A, the deformation rate was varied to observe the response of the model in terms of faulting. It was found that increasing the deformation rate induced internal faulting of the brittle units consistent with that recorded in PNG (Experiment III and IV in Figure 2B).

To obtain a more brittle mechanical behaviour with the rheology, we also performed a fifth experiment with a high deformation rate (9 cm/h) and a different rheology (we decreased Ieru thickness and modified Barikewa beds; Figure 2C). This resulted in intense internal faulting which is probably beyond that recorded in the PNG fold belt.

Overall, the results obtained in a pure compression configuration suggest that a high deformation rate of more than 1.2 cm/year (equivalent to 6 cm/h in the models) with a mechanical stratigraphy close to that shown in Figure 2B would be a reasonable analogue for the geology of PNG.

(ii) Oblique Compression

An oblique convergence between the Australian (PNG) and Pacific Plates has been recorded during the Miocene and Pliocene (Hall, 2002). We performed two experiments with two different angles of net compression (30° and 45°) in order to determine if the angle of oblique convergence would have a strong impact on the deformation (Figure 3).

Results show that the upper part of the model is more faulted than the deeper levels due to a decollement in the Ieru layer which decouples deep Jurassic beds from shallow Miocene beds. The Neogene beds are naturally more brittle than the deeper ones and thus more faulted. However, in comparison with the previous experiments (Figure 2), the oblique compression led to more intense faulting near the main folded structure. Moreover, the structures obtained with a 45° net compression angle are more asymmetric (especially in the foreland part) than those obtained for a 30° net compression. This point is particularly contentious and another set of experiments should be performed to obtain more details on the cause and the reproducibility of this phenomenon.

(iii) Inversion of Normal Fault

It has been observed that anticlines are formed above old normal faults in basement, so we decided to test the impact of basement fault reactivation. We inverted 50% and 30% of the throw across the normal fault in two experiments (Figure 4A) and followed that with a component of pure compression as in Figure 2, thus combining inversion and compression. The results show that the reactivation of a basement fault is favourable for the development of a large folded structure. However, 50% for the inversion throw is excessive as the main fold generated is too large compared to the whole model. In terms of scale, an inversion throw of 30% is preferable although there is not enough internal faulting to be consistent with the natural data acquired.

Subsequently we increased the deformation rate in a third experiment (Figure 4B) with the aim of increasing internal faulting. The results show that the increase of the deformation rate has involved tectonic thickening of the folded structure, but has not sufficiently increased the general brittle behavior of the model.

The results obtained for normal fault inversion are consistent with the observation that anticlines are formed above normal faults in basement. A pre-existing large normal fault in basement led to development of a large detachment fold in the cover abutting the basement in the footwall of the fault (Figure 4). This required a weak layer providing a detachment above the basement, perhaps corresponding to syn-rift Magobu coals in PNG. The development of the overturned detachment fold was greatly enhanced when the basement fault was first partially inverted.

Conclusion

These models have led to a significant improvement in the understanding of the internal geometry of PNG fold belt structures, particularly in areas beneath the wells where seismic resolution is poor. Optimising this deep interpretation will hopefully yield new leads and better models of existing fields.

Acknowledgements

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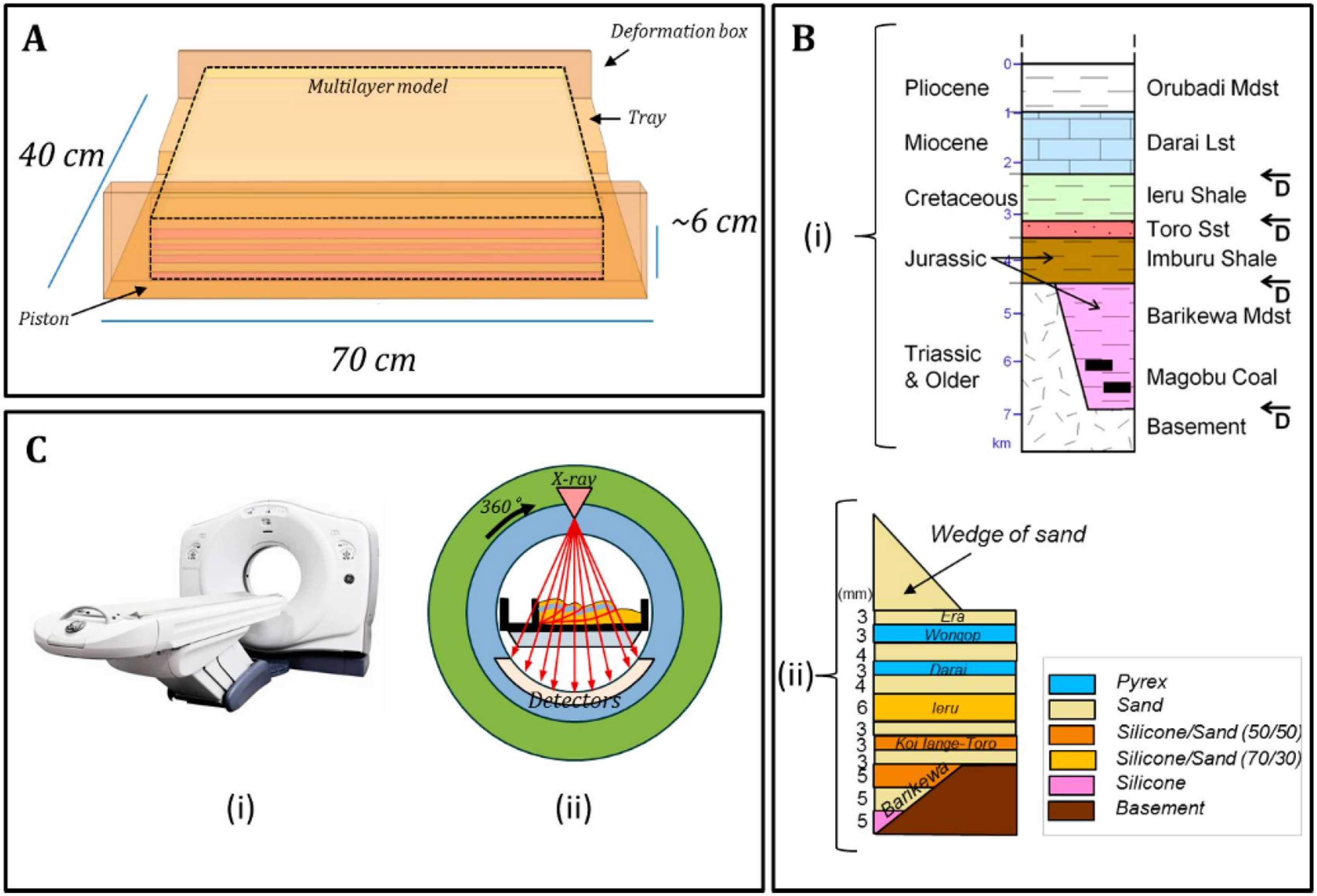


Figure 1. A. Sketch of the deformation box used. Piston and tray are mobile. The multilayer model is made by sand and pyrex for brittle layers and by silicone/sand mixes for ductile layers. B. (i) Simplified Stratigraphy for the Papuan Fold Belt. The source rock is Jurassic, the Toro is the reservoir and the Ieru is the regional seal. D = Decollement. (ii) Analogue stratigraphy used in models. Numbers on the left of the column are the thickness of each layer (in millimeters). Basement is made of wood. C. (i) Photograph of the X-ray tomography device used (medical scanner). (ii) Schematic diagram of the main components of the computerized scanner. Acquisition of a cross section is obtained by the complete rotation of X-ray source and coupled detectors. To reconstruct a 3D block, we acquire cross sections that are 1mm thick and spaced at 1 mm through the whole model.

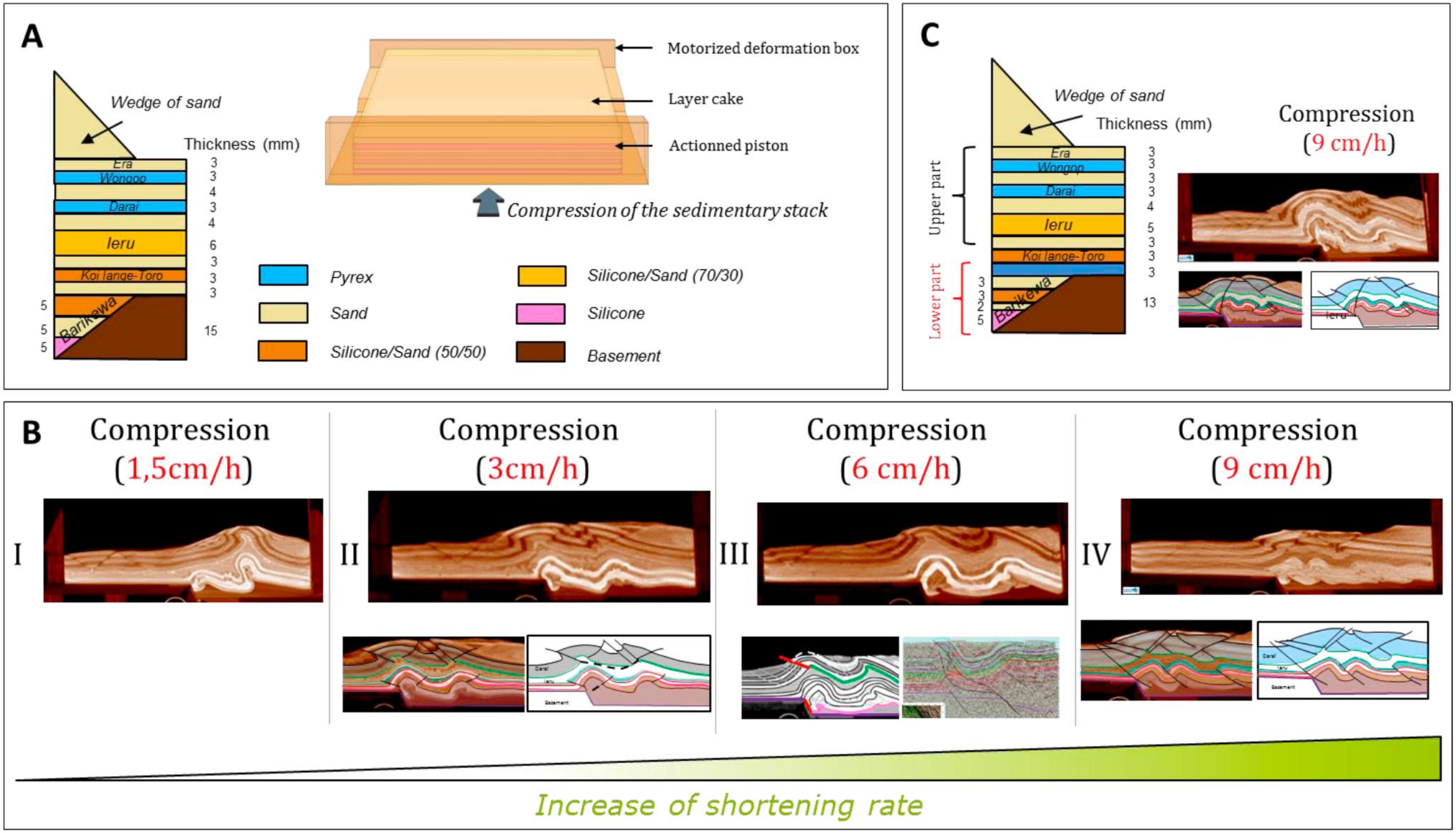
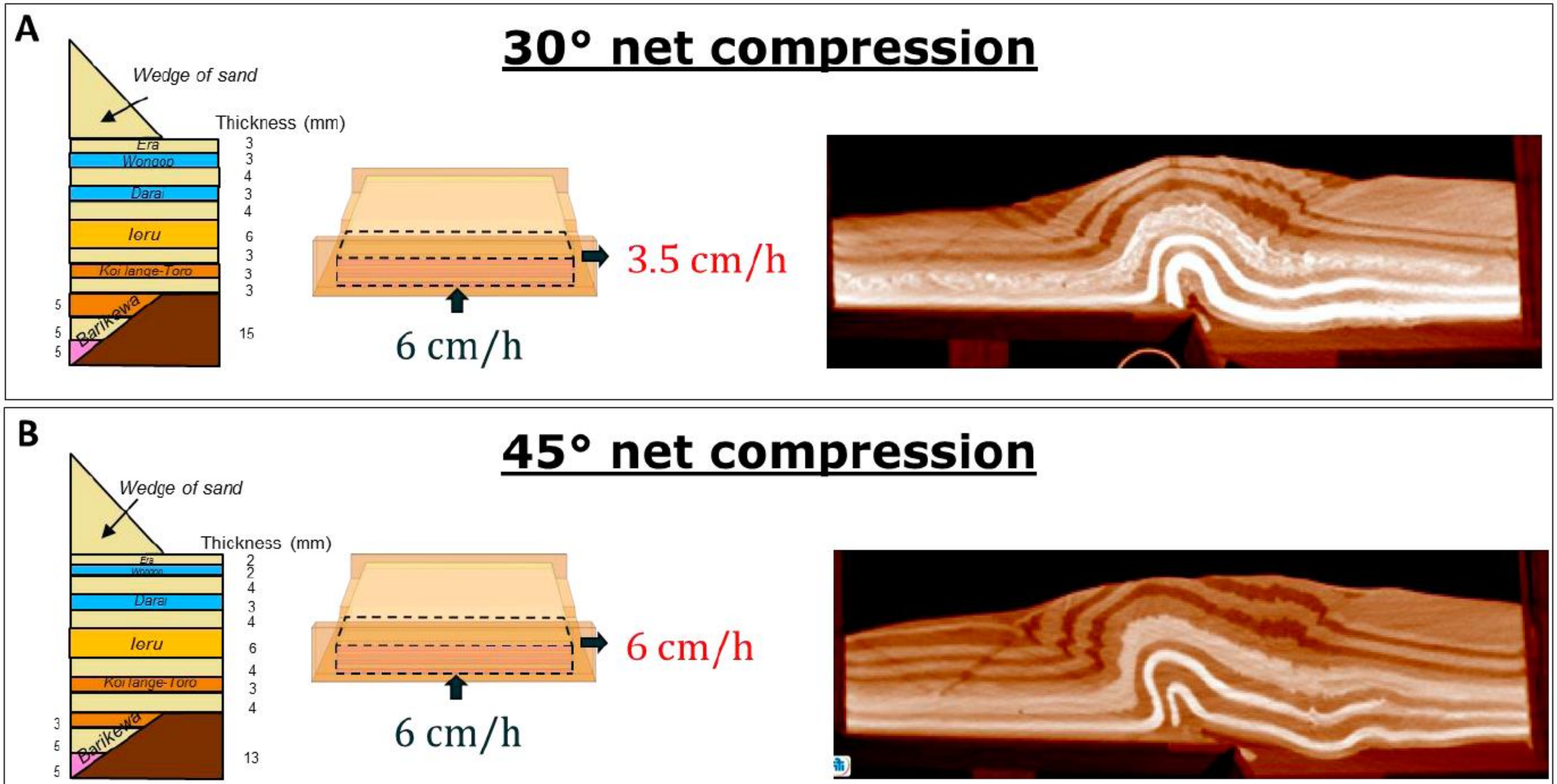


Figure 2. A. Sketch of the configuration used for the pure compression experiments. The rheology was defined from seismic and associated well data and by four preliminary analogue experiments similar to these ones, performed to validate the scaling. Only one piston was activated, allowing pure compression of the model made by sand and Pyrex for brittle material and silicone and sand/silicone mixes for ductile material. B. Results of four pure compression experiments carried out with the same rheology. The shortening rate increases from Ist to IVth experiments. The increased compression rate induced an increase in internal faulting for the whole model. C. Change in rheology for the Vth experiment: No changes for the upper part; reorganization of the lower part to obtain a better brittle behavior between Barikewa and Koi Iange Toro analogue formations (in comparison to rheology A, there is a decrease in the thickness of the ductile layer and an addition of a thin layer of sand).



- Decrease of Barikewa thickness (less ductile) and increase of sand Toro layers thickness (more brittle by the decreasing of the top 50% silicone layer)
- Decrease of the basal throw (2 mm)

Figure 3. Oblique compression has been simulated by the combination of pure compression and strike slip movements. A. Setup and results of the 30° net compression experiment. B. Setup and results of the 45° net compression.

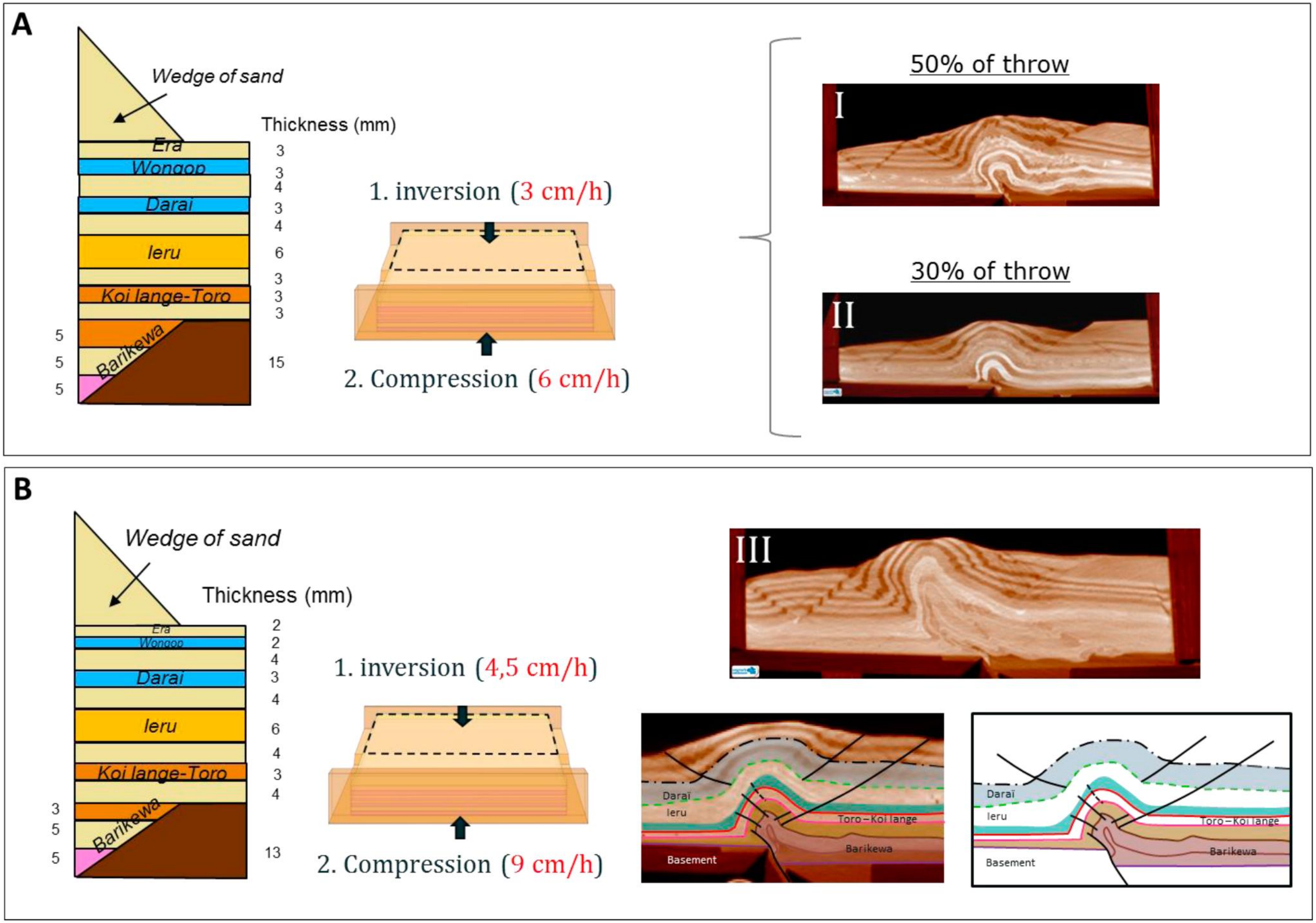


Figure 4. Inversion of a normal fault in basement, followed by a compression phase. A. Set-up and results of the two experiments with a medium deformation rate: 50% inversion of the normal fault and 30% inversion of the normal fault, respectively. B. Setup and results of an experiment with a high deformation rate simulating the 30% inversion of the normal fault.