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In Application

Simulation of Tectonic Deformation with Quantitative 3D Strain Analysis

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Introduction

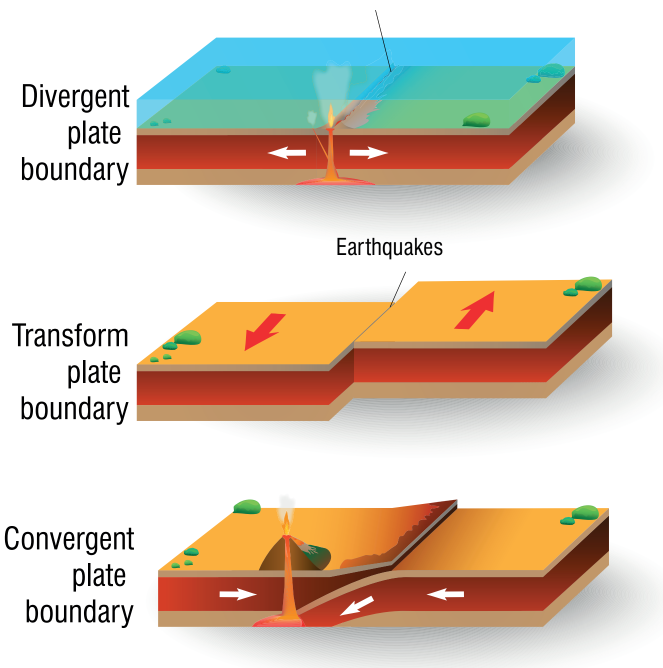

Figure 1: *Types of plate boundaries*

Analogue models have been used since the early 19th century to investigate the evolution of deformation structures in the Earth's crust and lithosphere. Traditionally, structural evolution was observed at the model's surface, through transparent sidewalls, or by cutting sections through the model at the end of the experiment. Major advances in the scaling theory during the 20th century have expanded analogue experiments from a qualitative technique and conceptual modelling tool to a quantitative technique relating the comparison of model geometry, kinematics and stresses to their natural prototypes.

Digital Image Correlation (DIC) is an important advance in quantitative physical modelling and helps to understand non-linear deformation processes. Optical non-intrusive (DIC) techniques enable the quantification of localized and distributed deformation in analogue experiments based either on images taken through transparent sidewalls (2D DIC) or on surface views (3D DIC). X-ray computed tomography (XRCT) analysis permits the non-destructive visualization of the internal structure and kinematic evolution of scaled analogue experiments simulating tectonic evolution of complex geological structures.

Unlike DIC which is traditionally observing the visible surfaces, XRCT volume data contains information about the entire volume revealing the sub surface details. Combining these volume images with Digital Volume Correlation (DVC) allows the calculation and quantification of full volume displacement and strain. This study represents the first experiment of this type done at such a large scale with 10-100 million of particles, with previous tests restricted to approximately 50.000 particles.

Experimental Setup

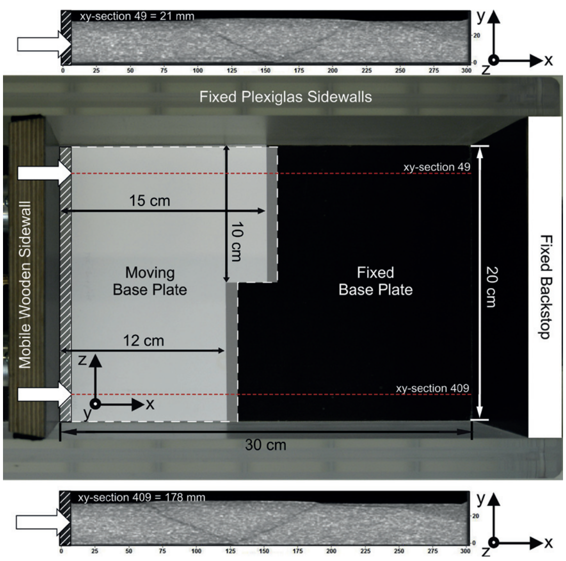

Figure 2: *Top view of analogue modelling apparatus used for both granular types. Top and bottom panels show section data of XRCT voxel space parallel to shortening direction. The basal position of the pop-up structure is controlled by the position of the basal discontinuity.*

The experimental setup is shown in Figure 2 and is designed to simulate the development of a contractional pop-up structure above a moving basal velocity discontinuity.

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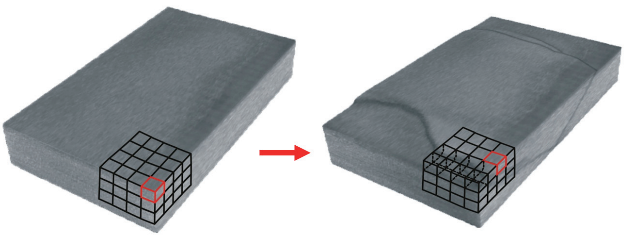

***Figure 3:** Tomographic strain analysis of 3D XCT analogue experiment using Digital Volume Correlation (DVC). Voxel data of time-series experiment scans are subdivided into subvolumes.*

The volume scanning was performed at the University of Bern with a final imaging resolution 0.4 mm per voxel, examples of which are shown in Figure 3. The granular material composed of a mixture of quartz sand and ceramic beads at a ratio 50:1.
The DVC calculations were performed at Royal Holloway University of London using 3 iterations of 24 x 24 x 24 voxel sub volume size and 75% overlap resulting in 145,376 displacement vectors in each result field. Averaging of successive volume scans (of the same material state) provided significant noise reduction and improved material patterns.

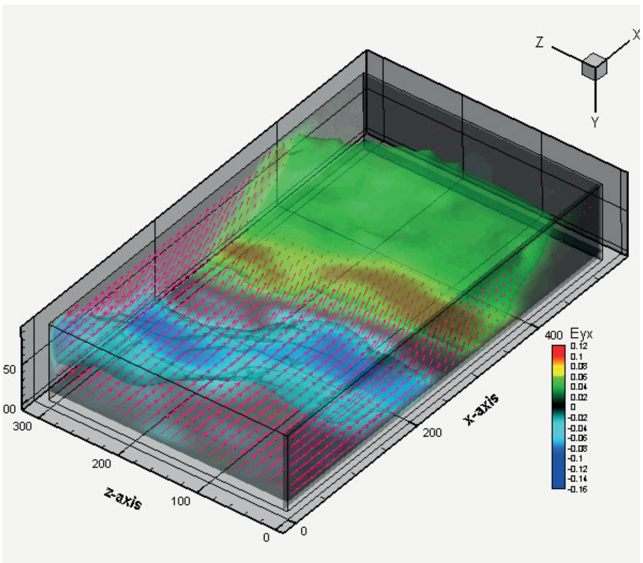

***Figure 4:** Shear bands having developed at the edge of the pop up structure can be quantified*

Results

The strain data quantified changes in shear strain along the bivergent shear zones, with the magnitude of shear strain increasing along the parallel segments of the pop-upstructure away from the transfer zone. A result is shown in Figure 4 illustrating how DVC is able to quantify the development of the internal shear bands. The results highlighted an incremental shortening of the sand layer and formation of a non-cylindrical pop-up structure bounded by synthetic and antithetic shear zones.

The results indicate that the application of DVC techniques on XRCT volume data can successfully be used to quantify the 3D spatial and temporal strain patterns inside analogue experiments. The DVC analysis of the XCT volumetric data highlights structural features that are either not observable in the XCT image data or that are difficult to discern or quantify. DVC is able to monitor the distributed deformation in the granular material before and during shear zone localization and demonstrates the power of DVC to calculate strain and deformation phenomena to sub-voxel precision. Prior to this work no results had been obtained to quantify the internal displacements of this type of experiment.

For further information the reader is referred to Adam et al. (2013) Journal of Structural Geology 55, 127-149.

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