Characterizing Analogue Caldera Collapse with Computerized X-ray Tomography

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ABSTRACT

Analogue models of caldera collapse were imaged by computerized X-ray tomography (µCT). Interval µCT radiography sequences document ‘2.5D’ surface and internal model deformation in an unprecedented way, and carry the potential for a better understanding of the kinematics of various volcano-tectonic processes, of which caldera collapse is a mere illustration. A semi-automatic subsidence velocity analysis was carried out on radiographs. The developed method is a step towards the quantitative documentation of volcano-tectonic modelling that would render data interpretations immediately comparable to monitoring data available from recent deformation at natural volcanoes.

1. INTRODUCTION

Analogue experiments are used with the aim to provide insight into caldera collapse processes, in general set-ups or applied to specific field cases (*e.g.* Martí *et al.* 1994; Roche *et al.* 2000; Acocella 2007). Models mainly explored collapse caldera structures by documenting 2D model cross-sections. Kinematic aspects of caldera collapse are less well understood, though a necessity in the interpretation of recent monitoring data. µCT scanning was used for the first time in analogue volcano-tectonic modelling by Kervyn *et al.* (2010) to image analogue volcano deformation experiments. We apply µCT to image analogue models of caldera collapse by magma withdrawal at basaltic volcanoes. The models test and highlight the possibilities and limitations of µCT-scanning to qualitatively image and for the first time quantitatively analyse deformation of analogue volcano-tectonic experiments.

2. EXPERIMENTAL

2.1. Experiment set-up, material and scaling

Our analogue model set-up is similar to the ‘sandbox’ used in most fundamental analogue studies (*e.g*. Martí *et al.* 1994; Roche *et al.* 2000). A dry well-sorted (120µm) silica sand – plaster mixture (SP-mix) with a cohesion of ~2.10^2 Pa s simulated brittle rock. Golden syrup (GS) with a viscosity of ~10^2 Pa s (20°C) served as an analogue for basaltic magma. The models were contained within a plastic cylinder perforated at its base (Figure 1). A cylindrical GS body (the ‘reservoir’) was placed above the hole. The cylinder was filled above the reservoir with the SP-mix and intercalated with 2-3 grain sizes thick garnet sand layers. The difference in elemental composition and density between silica sand and garnet sand ensured high contrast for easy detection of deformation structures in the images. The model was placed on the scanning rotor and drainage was initiated. As the experimental scale was smaller than in nature, the physical properties of the analogue materials should be downscaled to ensure the simulation of processes similar to nature. Geometric, dynamic and kinematic scaling of the simulations is ensured by a set of dimensionless parameters, based upon the scaling scheme proposed by Roche *et al.* (2000).

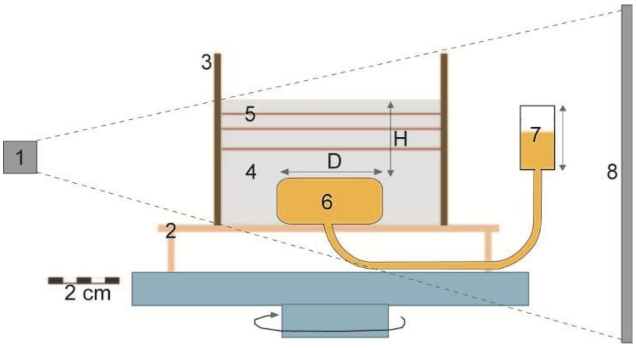

Figure 1: *X-ray tomography set-up: 1. X-ray beam source; 2. Plastic stand with central outlet; 3. Plastic tube; 4. SP-mix; 5. Thin garnet sand marker layers; 6. GS analogue fluid body; 7. Silo containing GS, adaptable in elevation; 8. PerkinElmer flat panel detector.*

2.2. µCT methodology and quantitative radiograph analysis

Radiograph sequences were taken at 2-minute intervals to document ongoing model deformation. Drainage typically lasted 200 - 500 minutes. A user-defined interface allowed semi-automatic detection of the vertical displacements of points along several garnet marker layers. Subsidence velocities were calculated for temporal intervals between two consequent images. After deformation, rotation was started and models were scanned with the µCT scanners of the UGCT (www.ugct.ugent.be; Masschaele *et al.* 2006). Scanning time for each model was below 1 hour. The spatial resolution was 84 µm, higher than in medical CT scanners. A high-resolution scan of a deforming model was thus infeasible. Data sets were reconstructed with the Octopus software. The Morpho+ and VGStudioMax software were used for 3D rendering of model volumes.

3. RESULTS AND DISCUSSION

3.1. Model results

Figure 2 presents interval radiographs and 3D scanning results for a model with magma reservoir roof aspect ratio H/D at 1.2 (H = overlying column height; D = reservoir diameter). A caldera ring fault nucleated at the reservoir and propagated upwards through the incremental collapse of metastable cavities, similar to the process described by Ruch *et al.* (2012). Immediately after drainage initiated, the gray value of the subsiding volume decreased. Dilatation of the SP-mix volume within the caldera bounding ring fault thus seems to accommodate roof support loss (Panien *et al.* 2006). During the whole drainage process, all subsidence was confined within the SP-mix volume inside the caldera bounding faults, and caldera structures resemble those found by Roche *et al.* (2000).

3.2. Vertical displacement and subsidence rate

The temporal subsidence rate pattern within the subsiding volume of model CCT1 can be divided into 3 phases (Figure 3): 1) Upward ring fault propagation; 2) Rapid subsidence with the highest subsidence rates within the uppermost subsiding volume; 3) Relatively slower velocity over the whole column and intermittent subsidence rate acceleration. Such acceleration does almost never affect the whole column. The vertical displacement curves gradually evolve towards a constant slow subsidence rate until the end of the documented deformation.

3.3. Model advantages and limitations

µCT is non-destructive, 3D reconstructions can be sliced in any direction and revisited any time, compared to wetted models which can only be sectioned once, physically destroying at least half of the model. The µCT technique avoids edge effects in the boundary layer against an experimental glass pane. The scans provide an unprecedented 3D view on fault geometries. However, due to restrictions in the image resolution, model diameters and heights should not exceed ~10 cm, posing significant challenges to experiment set-up and scaling adaptations.

Temporal and spatial radiography resolutions were still too low in order to provide data with satisfactory detail, thus we suggest radiography sequences should be acquired in the future at a temporal interval of 0.5-1 s. By using radiography sequences it is possible in a non-destructive manner to obtain a continuous observation of fault propagation, down sag mechanisms and the subsequent development of collapse structures. At last, the scans and radiographs make it possible to *e.g.* calculate the actual deformation velocity at discrete intervals and positions within models.

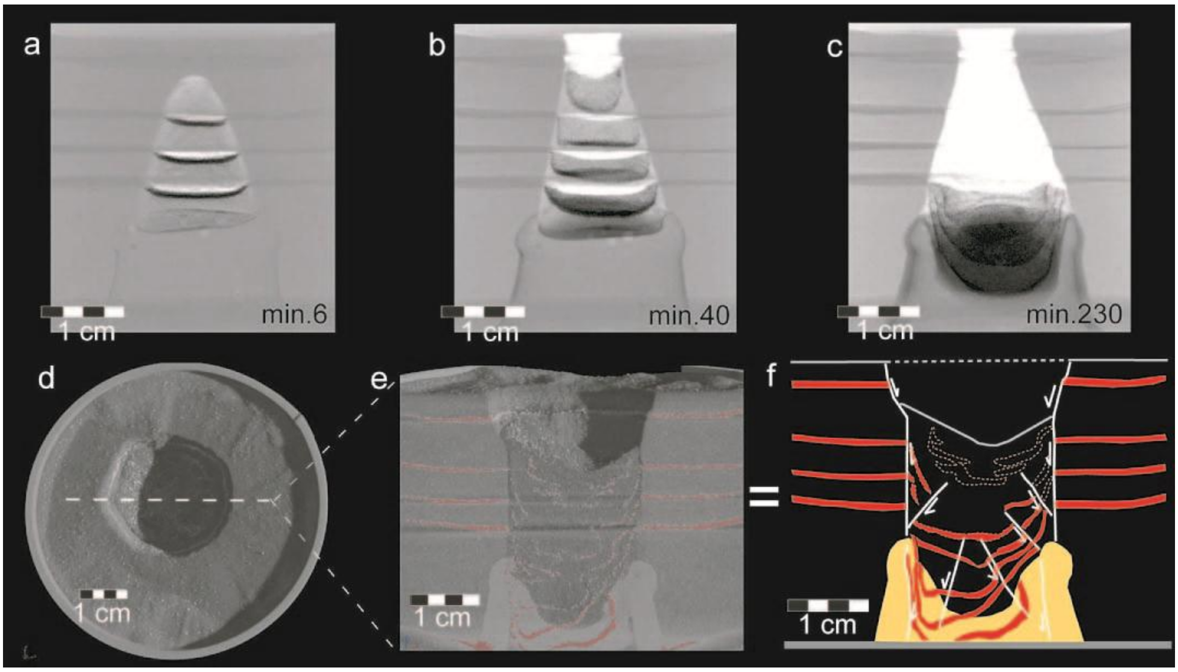

Figure 2: *a., b. & c.: radiographs of model CCT1 with H/D = 1.2, the time of drainage initiation is marked; d. model top shaded 3D scan view; e. 3D model scan cross-section with position marked in d.; f. sketch of faults (white), garnet markers (red) and GS/SP-mix interaction layer in e.*

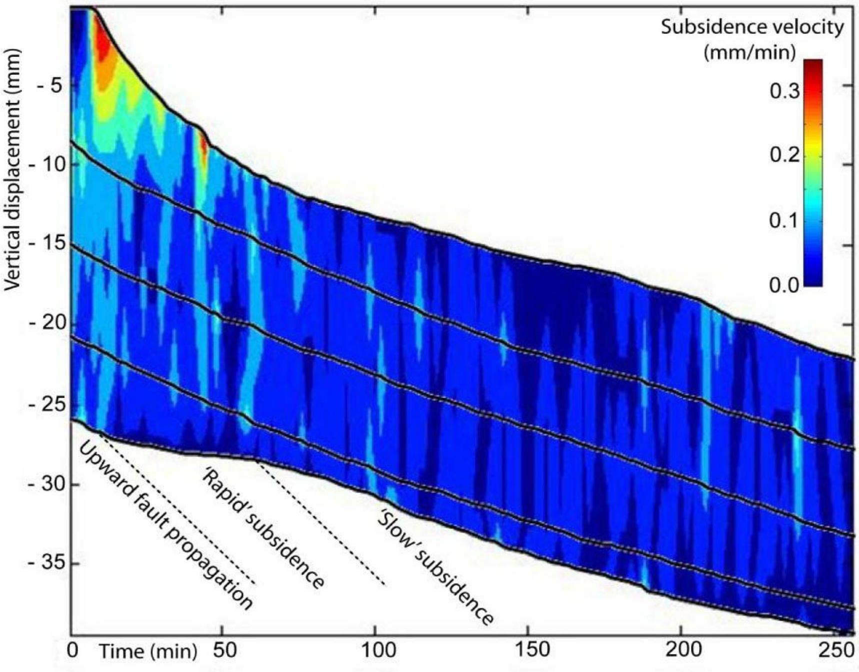

Figure 3: *Vertical displacement (black curves) of 4 garnet sand marker layers and the reservoir roof and subsidence velocities interpolated from these levels within model CCT1.*

4. CONCLUSION

Computerized X-ray scanning (µCT) was successfully applied to image the deformation evolution during analogue fluid withdrawal of small-scale caldera collapse models. Interval radiography images allowed to image and analyze the geometry and kinematics of subsidence of a collapsing caldera block into an emptying fluid body. The models illustrate the value of µCT-techniques towards the quantitative study of deformation processes in analogue volcano-tectonic models. The results of such study could be compared directly with the scarce monitoring data available from recent collapse events at natural volcanoes (*e.g.* Miyakejima 2000, Geshi *et al.* 2002; Piton de la Fournaise 2007, Longpré *et al.* 2007). Adaptations to the model set-up and the imaging methodology will lead to analogue µCT-models that will carry high value in enhancing the quantitative assessment of the geometry, kinematics and dynamics of volcano-tectonic processes, with immediate comparison of modelling results to monitoring data in the field.

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