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TIME-RESOLVED 3D X-RAY IMAGING OF GEODYNAMIC PROCESSES

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Summary: A deformation rig has been developed that allows reproducing conditions of pressure, temperature, and fluid flow relevant for studies of rocks in the ten first kilometres of the Earth's crust. This rig is installed on the beamline ID19 at the ESRF and can be used for time-resolved in situ experiments of rock deformation and chemical transformations processes. Processes such at precursors to failure or metamorphic reactions have been imaged in-situ in a series of experiments presented here.

1. INTRODUCTION

The rocks of the Earth's crust deform in environments as different as fault zones, volcanoes, geological reservoirs, sedimentary basins, mountain ranges, and oceanic crust, with a large variability of thermodynamic conditions (temperature, stress, fluid pressure and mineral composition). These deformations, either brittle (i.e. fracturing) or ductile (i.e. creep) play a major role in the release of the internal energy of the planet and control the transport of fluids between its deepest parts to the surface. As such, they control the formation of underground georesources mines (hydrocarbons, hydrogen, metals, rare earth elements, and raw materials) and the sustainability of long term waste storage in geological repositories (waste waters, carbon dioxide, nuclear fuels).
A major difficulty in understanding these geodynamic processes is that they occur at depths where data and samples cannot be accessed and observed directly. The domain of rock physics is evolving very fast as it becomes now possible to observe under laboratory conditions geodynamic processes occurring at large depths. This is the main goal of the present study where geodynamic processes are reproduced and imaged by X-ray microtomography at high spatial and time resolutions. Two examples are developed here: the search for precursors to rock rupture, and the coupling between a chemical reaction and fracturing during the hydration of a dry rock.

2. EXPERIMENTAL METHOD

We have developed a miniature triaxial rig to study rock deformations processes in well-controlled experiments (up to 100 MPa confining pressure, 200 MPa axial differential stress, pore fluid pressure up to 100 MPa, and 250°C temperature). Rock deformations are followed time-lapse image in 3D using high-resolution X-ray tomography at the European Synchrotron Radiation Facility (ESRF, beamline ID19). This triaxial rock deformation rig has been developed through a collaboration with the University of Oslo, the ESRF, and the company Sanchez Technology. All the technical details on the triaxial rig, called HADES (Fig. 1a), are given in Renard et al. [2016].

3. RESULTS

A first example is the search for precursors to large earthquakes, which represents a critical challenge in geophysics. Precursory signals to large earthquakes include foreshocks, increase or decrease of seismic velocities, or variations of the chemistry of spring waters. As stresses build-up at depth before rupture, these precursors may have different origins, from the formation of microfractures, to creep in the nucleation zone, or modifications of flow paths. However, these precursors are not observed for all earthquakes, making challenging their use to predict the occurrence of major ruptures. We have deformed several rocks at conditions relevant for earthquake nucleation and characterized the precursory damage and microfracturing before failure. Results show that in several samples, such as Carrara marble (Fig. 1d) or Anstrude limestone (Fig. 1b), damage forms prior to rupture and can be characterized.

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A second example is the existence of chemical transformations at depths, called metamorphism, where rock mineralogy, microstructure, and strength change with increase of temperature, stress, and presence of water. We have developed a series of experiments where a rock analogue, a magnesium oxide ceramics used as representative of dry rocks of the lower crust, was left in contact with water at conditions of pressure and temperature similar to that of several kilometres depth. In presence of water, the ceramics transforms into magnesium hydroxide, with an increase of solid volume of 40% and a strong coupling between a chemical reaction and fracturing (Fig. 1c).
In both example, high resolution in-situ X-ray microtomography allow reproducing and characterizing processes that occur at depth in the Earth's crust and that cannot be observed directly.

References

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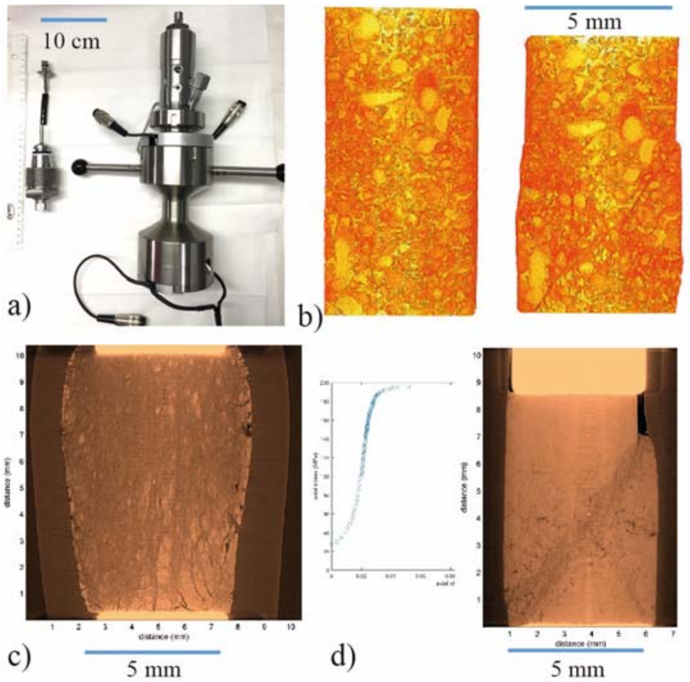

Figure 1: (a) Photograph of the triaxial rig HADES, with the sample assembly. (b) 3D view of a limestone core sample before (left) and after failure (right) at 20 MPa confining pressure. (c) Hydration of Mg-oxide into Mg-hydroxide and generation of microfracture and fragmentation of the initial mineral. Experiments performed at 10 MPa confining pressure, 5 MPa pore fluid pressure, and a temperature of 210°C. (d) Rupture of a Carrara marble sample by formation of a shear fault under a confining pressure of 25 MPa. Stress-strain curve is shown on the left, where each open circle indicates a 3D microtomography acquisition.