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MJÖLNIR: A NOVEL X-RAY TRANSPARENT TRIAXIAL ROCK DEFORMATION APPARATUS.

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Summary: Mjölnir is a novel, low-cost x-ray transparent cell designed and built at the University of Edinburgh to enable the observation, in-situ, of damage localisation and shear failure during triaxial compression tests of rock cores. Here we present its design and construction as well as initial results of 4D in-situ observations of shear failure in micrograinte.

1. INTRODUCTION

Understanding the mechanisms that lead to catastrophic failure of rocks is of critical importance because shear failure occurs in the brittle Earth on a variety of scales, from landslides, to volcanic eruptions and earthquakes. In particular system-sized brittle shear failure is associated with the concentration of damage in localised zones leading eventually to a continuous fault plane. However the precise mechanisms and organisational patterns associated with strain localisation in shear fractures are not yet well understood. To date, most laboratory investigations of the mechanical properties and shear failure of rocks have utilised indirect techniques to visualise the deformation processes, primarily because the heavy-walled steel vessels required for traditional rock deformation experiments preclude direct observation. Synchrotron x-ray tomography enables the study of localisation and fracture propagation *in-situ* in real time with spatial resolutions of a few microns, provided suitable x-ray transparent experimental cells that enable triaxial loading of rock samples at sufficiently high confining pressures are available. At the School of Geosciences, University of Edinburgh we have developed and tested Mjölnir, a lightweight (<1.3 kg) x-ray transparent triaxial deformation cell which has been tested up to 35 MPa confining pressure and differential stresses of >200 MPa using 3 mm diameter cylindrical rock cores.

2. EXPERIMENTAL DESIGN

The design of Mjölnir is illustrated in figure 1 (a) & (b) and is an extension of the x-ray transparent high PT reaction cell of Fusseis et al., [1] which has been employed successfully for 4D investigations of fluid-rock reactions at 20MPa and 200°C [2]. Like its predecessor, Mjölnir is designed for flexibility and can be adapted to a wide range of imaging conditions, including those realised in standard laboratory scanners. The cell is 210 mm tall and 40 mm diameter and is constructed from commercially pure grade 2 titanium, with components situated within the X-ray beam path constructed from 6061-T6 aluminium alloy. The maximum sample diameter that can be accommodated is 3.2mm. The end load is delivered using a commercially available single-acting hydraulic actuator supplied by Enerpac™ which has a stroke of up to 7 mm and which can generate a maximum force of 4.4 kN. The pistons used to transfer the end load to the sample are 3.2 mm diameter high speed tool steel.

All seals between cell components are standard nitrile o-rings, and the design of the cell has been optimised so that only a single dynamic piston seal is required, and all other seals are in static configuration. Fluid connections to the cell are made via conventional 10/32 high performance liquid chromatography (HPLC) fittings to 1/16" 316 stainless steel tubing or to PEEK high pressure tubing where flexibility is required. The experimental sample is located between the two pistons and separated from the confining fluid via a thin, clear heatshrink jacket and a flexible elastomer (tygon™ or silicone) sleeve which is clamped to the pistons using wire to ensure a seal.

Mjölnir was deployed on the Psiché beamline of the Soleil Synchrotron Facility, France, in December 2016. Core samples of Ailsa Craig micrograinte (3 mm diameter, 9 mm long) were taken using a diamond drill. Some cores were heat treated (600°C for 15 minutes) to induce thermal damage at grain boundaries. The cores were triaxially deformed at 15 and 25MPa confining pressure. Delivery of fluid to the hydraulic actuator and confining fluid jacket was achieved using Centoni neMESYS™ high pressure syringe pumps operated using QmixElements™ software. Datasets were collected in ~10 minutes using a white beam with an energy maximum at 66 keV in a spiral configuration. Reconstructions yielded volumes of 1700 x 1700 x 4102 voxels with a voxel size of 2.7 µm.

3. RESULTS

Deformation of the heat treated sample illustrated in figure 1 (c) was imaged in 21 microtomographic volumes in intervals of 5-20 MPa (decreasing as failure approached) during loading up to failure and a further 3 volumes post-failure. Figure 1 (c) shows the tip damage zone of an experimentally induced shear fracture generated at a peak differential stress of 200 MPa. Our experimental results from Mjölnir document that fracture nucleation initiates at pre-existing cracks, grain boundaries and pores and the build-up of damage towards failure, including details suchas the coalescence of en-echelon tensile micro-fractures to form a fault plane. Such direct 4D observations of evolving damage, localisation of strain and ultimate shear failure complement the classic results of Lockner et al. [3], who provided the first images the process of fault growth captured *in-situ* using acoustic emission locations. Our results confirm that Mjölnir can be used to provide time-resolved direct visualisation of the features associated with strain localisation and failure, and local aseismic damage that cannot be recorded using conventional indirect methods.

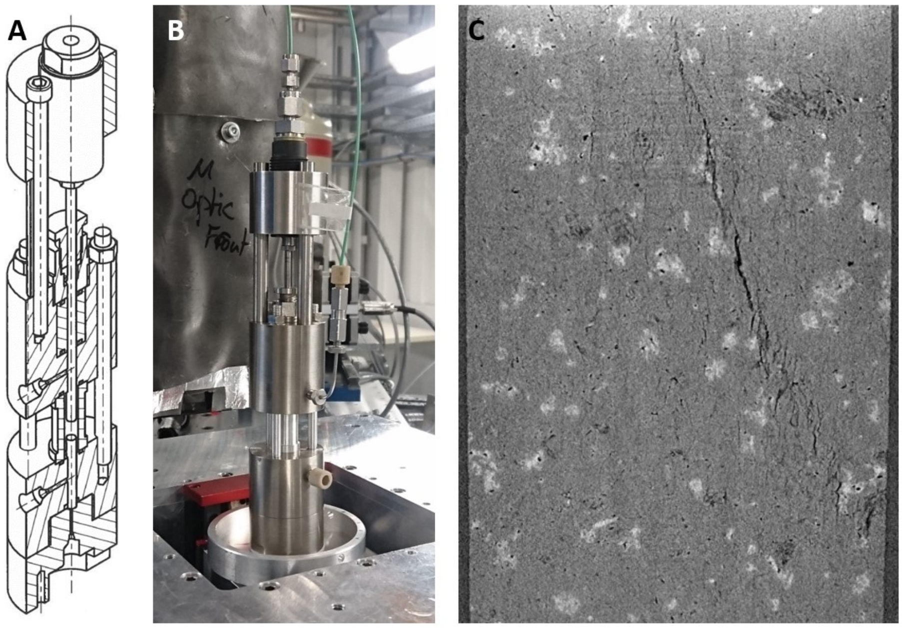

Figure 1: (a) Mjönir in section and (b) in operation at the Psiché beamline on Soleil. (c) Shear failure in heat treated Ailsa Craig microgranite (FOV width ~3mm).

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