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Direct shear experiments on Solnhofen limestone at high temperature – an experimental analogue of transpression

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Abstract: Specimens of Solnhofen limestone deformed dry in direct shear at 600 ºC, 200 MPa and bulk strain rates of $\sim 5\times 10^{-3}$ s^{-1}, show strain distributed heterogeneously with two high-strain bands close to the specimen edges accommodating most of the displacement. Strain analysis using calcite shape fabric and CPO (measured by EBSD) reveals that non-coaxial strain concentrating at the edges propagates towards the middle of the specimen, where flattening strain is predominant. Strain-hardening associated with flattening prevents initially non-coaxial strain from developing in the centre. Direct shear testing proves to be a good analogue for transpression when free boundaries are present to allow lateral extrusion.

Keywords: experimental direct shear testing, transpressional deformation, strain heterogeneity, plastic flow, shear localization, EBSD.

The direct shear experimental configuration, where two cylindrical forcing blocks cut at an angle sandwich a target specimen in the middle, has often been used in experimental rock deformation studies to simulate a natural shear zone. It is often assumed that strain is homogeneous and approaches simple shear.

Direct shear deformation tests on Solnhofen limestone at high temperature show that strain is not homogeneous across the specimen and that it tends to localise near the contacts with the sawcut forcing blocks.

Experimental methods

The starting material is Solnhofen limestone, a 97% wt calcite micrite with an average grain size of 4-5 µm and secondary impurities, mostly organic matter and clay minerals, along grain boundaries. It is a very well suited material for experimental studies and its fine grain size provides sufficient number of grains for the small specimen dimensions commonly used in experimental rock deformation. The starting microstructure in Solnhofen is homogeneous, allowing the direct identification of strain heterogeneities imposed experimentally.

Thin wafers of Solnhofen limestone, between 1-2 mm thick, were cut at 45º from cores perpendicular to the bedding and placed in the deformation apparatus in between two forcing blocks of Tennessee sandstone, also precut at 45º. Tests were run dry with pores vented to atmosphere.

Microstructural analysis was done using ultra-polished blocks in reflected light in optical microscopy and in electron microscopy. Optical microscopy was used for shape orientation analysis and electron backscattered diffraction (EBSD) in electron microscopy for crystallographic preferred orientation analysis.

Deformation tests were run at constant pressure (200 MPa), temperature (600 ºC) and bulk strain rates ($\sim 5 \times 10^{-3} s^{-1}$). These conditions ensured that deformation would be by dislocation creep.

Results

Deformed samples show that shear strain is heterogeneously distributed across specimens and that it localizes near the contacts with the sandstone forcing blocks (Fig. 1). The finite dimensions of the specimens also result in their substantial thinning, especially in the central part. We estimated the strain distribution across the specimen using the deflection of the shape fabric and the finite thinning recorded.

CPO patterns of c-axis, a-axis and <02-21> (common slip direction in calcite) are shown in figure 1 in a traverse of EBSD maps from high strain areas around the edge to low strain in the middle of the specimen. The CPO shows that patterns are asymmetric following the imposed sense of shear. Towards the high-strain domains, there is a tendency in the c-axis fabric to strengthen a pattern of double cleft girdles and to reduce the great circle girdle component parallel to the foliation to a single maximum following the stretching direction (which almost disappears in the highest strain domain).

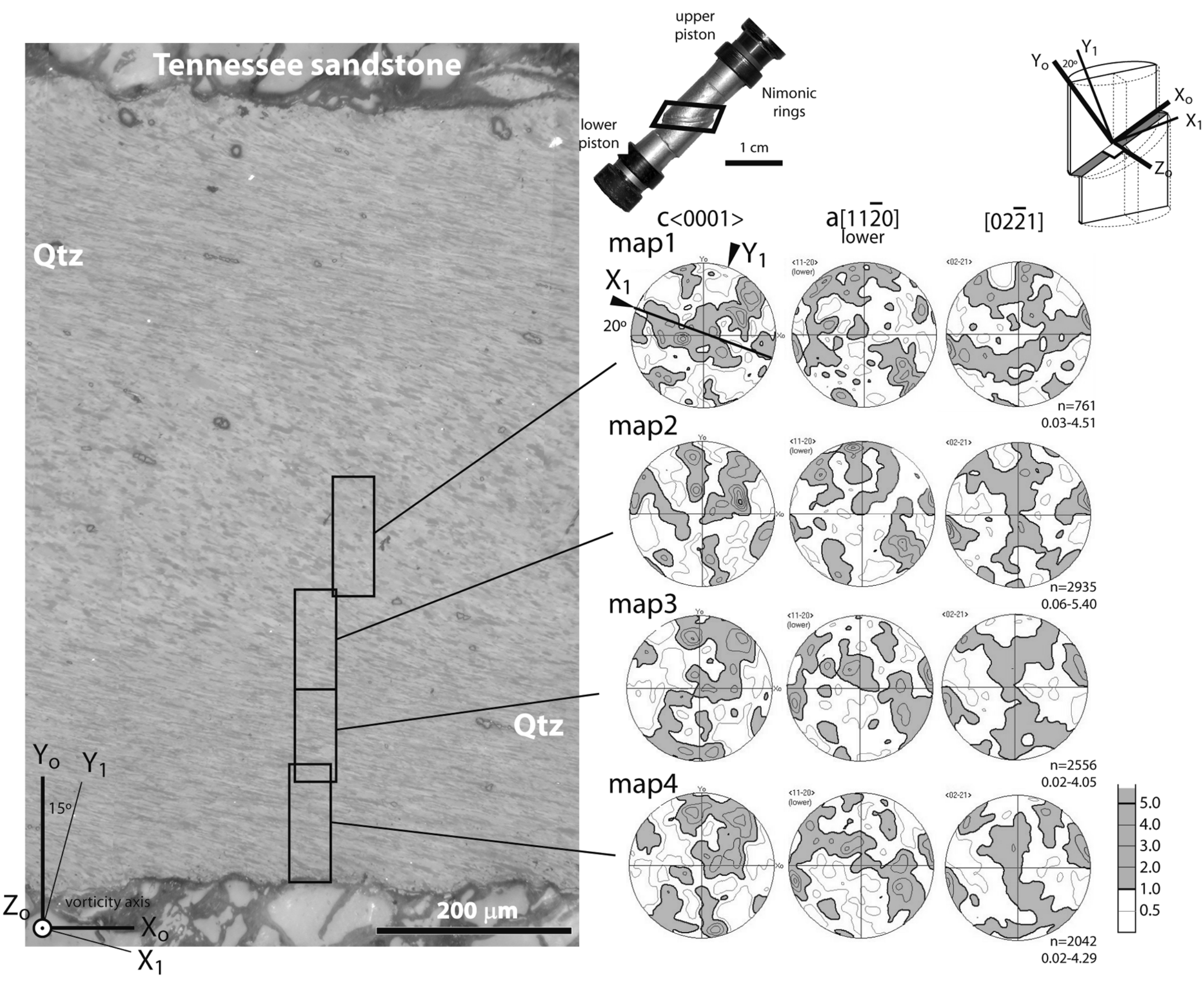

Figure 1. Micrograph of a Solnhofen limestone sample deformed in direct shear to a bulk shear strain of γ~2.7, taken in optical microscopy under reflected light. CPO patterns of c-, a- and <02-21> are shown to the right. All stereoplots are equal area upper hemisphere.

Discussion and conclusions

On the basis of the analysis of the shape fabric, the bulk change in specimen dimensions and the CPO, we inferred that a large non-coaxial (shear) strain component accumulated in the high strain bands and that a dominantly flattening deformation with radial extension accumulates in the central, low strain zone. The strain distribution was interpreted in terms of a heterogeneous strain due to superimposition of a flattening normal to the plane of the sample with a shearing deformation parallel to the planar boundaries of the sample (details in Llana-Fúnez and Rutter, 2008). Flattening deformation with associated lateral extrusion was possible owing to the limited lateral extent of the sample, despite its thinness. The flattening strain was zero adjacent to the forcing blocks, rising to a maximum in the centre of the specimen, analogous to the extrusion profiles of short cylinders of Solnhofen limestone deformed by axisymmetric shortening under similar P/T conditions (Llana-Fúnez and Rutter, 2005).

The inhibition of the development of a high shear strain in the central part of the sample is attributed to the strain hardening that accompanies the enhanced flattening strain developed in the central region. Where the flattening strain is low, close to the edges of the limestone slice, there is insufficient strain hardening to prevent the non-coaxial deformation from dominating.

In a natural shear zone of sufficiently great lateral extent away from free boundary surfaces so that deformation by simple shear is predominant, or in a material displaying no dependence of flow stress on strain, and/or in a material of more linearly viscous rheology, this type of strain partitioning would not be expected.

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References

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