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Rigid inclusions rotate in geologic materials as shown by torsion experiments

F.O. Marques*, L. Burlini

Swiss Federal Institute of Technology (ETH-Zürich), CH-8092 Zurich, Switzerland

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ABSTRACT

Jeffery showed 86 years ago that a sphere rotates synthetically with applied simple shear, at a rate equal to half the shear strain rate. However, it can be argued that rocks do not behave like viscous fluids hence Jeffery's model does not apply. In order to test this argument, we took a two-phase synthetic aggregate (rock) made of 70% halite and 30% muscovite (as anisotropic ductile matrix) with embedded rigid bodies with contrasting shapes: circular cylinder, sphere and cube. The sphere approximates the shape of a garnet and the cube the shape of pyrite crystals, both so common in nature. When subject to torsion at 250 MPa and 100 °C, the matrix deformed homogeneously and all rigid bodies rotated as theoretically predicted for a viscous fluid matrix. Therefore, we conclude that rocks deforming in a ductile fashion behave macroscopically like a continuum hence fluid mechanics can be used to study rigid inclusion rotation behaviour.

1. Introduction

Jeffery (1922) developed a full analytical solution for the rotation of rigid ellipsoidal inclusions immersed in a viscous fluid subject to simple shear. Two major conclusions of Jeffery's are that: (i) rigid inclusions with aspect ratio A_r (greatest over least axis) > 1 rotate continuously and synthetically with a sinusoidal rate, and (ii) rigid inclusions with $A_r = 1$ rotate synthetically at a constant rate equal to half the shear strain rate. Therefore, if Jeffery's model applies to the geological nature one expects to see features indicative of rotation of rigid inclusions in a creeping matrix, especially in ductile shear zones where rigid clasts are observed immersed in a finely recrystallized mylonitic matrix.

More recently, several workers have shown that Jeffery's conclusions do not apply under conditions that are very common in the geological nature. This is the case of: (1) addition of a component of shortening or stretching across the shear plane (e.g. Ghosh and Ramberg, 1976; Marques and Coelho, 2003); (2) slipping inclusion/matrix interface (e.g. Ildefonse and Mancktelow, 1993; Marques and Cobbold, 1995; Mancktelow et al., 2002; Ceriani et al., 2003; Marques and Bose, 2004; Bose and Marques, 2004; Mancktelow and Pennacchioni, 2004; Schmid and Podladchikov, 2004; Marques et al., 2005a, 2007; Mulchrone, 2007); (3) confined flow measured by the ratio between shear zone width (w) and inclusion's least principal axis (e_2) ($W_r = w/e_2$) (e.g. Marques and Cobbold, 1995; Marques and Coelho, 2001; Biermeier et al., 2001; Taborda et al., 2004; Marques et al., 2005a,b,c). However, none of these mechanisms has been shown capable of impeding the rotation of a sphere or a circular cylinder. Their rotation can only be reduced by confined flow.

One can accept these mechanical models (see also Williams and Jiang, 1999; Jiang and Williams, 2004) or argue that, although they apply to viscous fluids (continua), they do not apply to geologic materials, which are typically anisotropic and heterogeneous. Therefore, in the present study, instead of taking analogue viscous fluids as matrix (e.g. silicone putties), we took a two-phase synthetic aggregate (rock) made of 70% halite and 30% muscovite to serve as an anisotropic, heterogeneous, ductile matrix. We used halite for two main reasons: (1) it is one of the main minerals forming evaporitic rocks (together with gypsum and anhydrite), which, when mixed with phyllosilicates or interlayered within sedimentary sequences, can play an important role in localizing deformation. Evaporitic levels have often been found along the zones of movement of overthrust faults or at the lower boundaries of nappes (e.g. Laubscher, 1975; Malavielle and Ritz, 1989). The worldwide occurrence of deformation that involves evaporite sequences in compressive settings is reviewed by Warren (1999). (2) Halite is used in this study as analogue of silicate rocks, because it is plastically deformable under low temperature and relatively high shear strain rates. The deformability of evaporite rocks and minerals is the result of an intrinsically low resistance to deformation by intracrystalline plasticity compared to carbonates and silicate rocks. Both halite and quartz aggregates deform mainly by power-law creep at steady state flow; therefore, the use of halite as analogue of a quartz matrix

* Corresponding author. Tel.: +41 44 6328918; fax: +41 44 6321030.
E-mail address: fernando.ornelas@erdw.ethz.ch (F.O. Marques).

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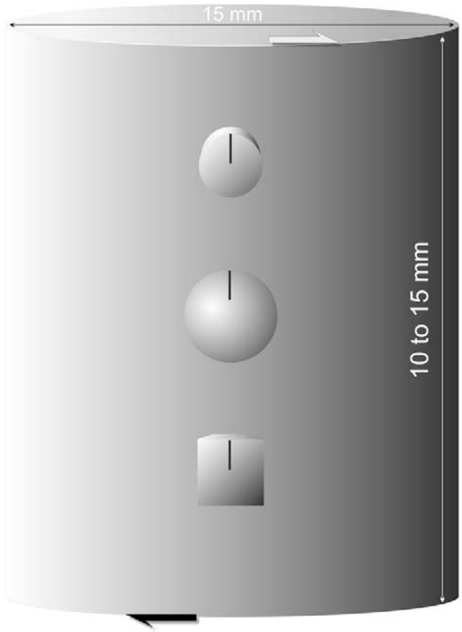

Fig. 1. Sketch to illustrate sample and shapes used as rigid inclusions embedded in a synthetic rock material.

seems valid. Although the used experimental shear strain rate may seem too high, it falls within the interval of natural shear strain rates in shear zones. Besides, it is known that at the applied shear strain rate the flow of halite is still power-law (plastic creeping), similarly to what has been deduced for natural quartz mylonites. Therefore, halite seems to be a very good low temperature, "high" shear strain rate analogue for a natural ductile quartz matrix, at least when a macroscopic plastic creeping behaviour is the aim.

In the halite matrix we embedded three contrasting rigid solids: sphere, cube and circular cylinder (Fig. 1). The sphere approximates the shape of garnets, the cube the shape of pyrite crystals (both very common in phyllites and schists), and the circular cylinder is a common shape in the modelling of 2D viscous flow (can also occur in the geological nature). The samples were subjected to torsion in an internally heated Paterson-type triaxial deformation apparatus equipped with torsion capabilities. Our main objective was to investigate whether rocks behave as a continuum, or not, when deforming in ductile fashion, and hence if continuum mechanics can be applied to study ductile flow in rocks. All inclusions rotated as theoretically predicted, which shows that a rock can behave macroscopically as a continuum.

2. Materials and methods

The specimens were synthesized by cold pressing a mixture of 70% halite and 30% of muscovite (grain size averaging 30 μm). The

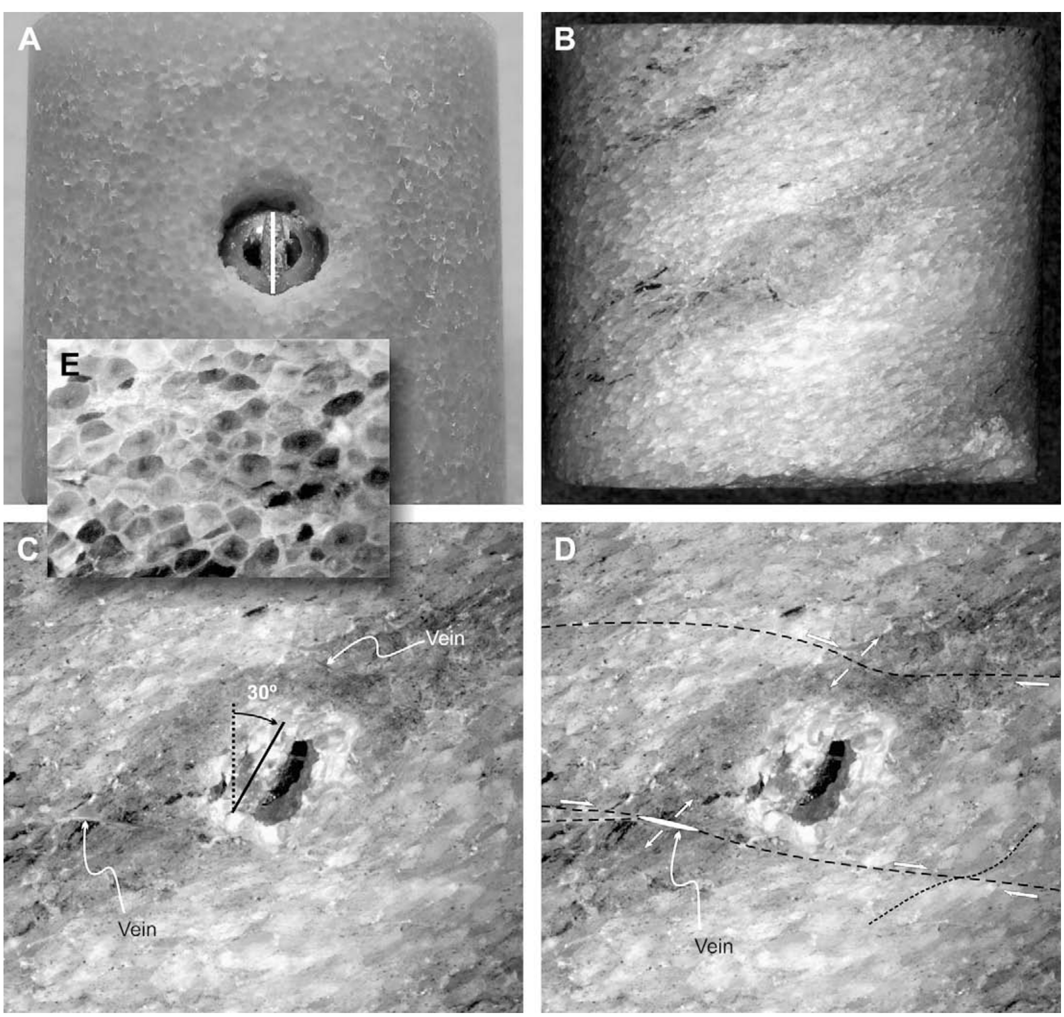

Fig. 2. Initial (A and E) and final (B, C and D) stages for the sphere. In B the final stage is shown with the rigid inclusion still covered with matrix. In C the inclusion is partially uncovered to reveal the rotated marker (initially vertical as shown in A). In D we show line drawings over image C to highlight shear bands formed around and close to inclusion. In E a zoom of the undeformed matrix is shown. The flattened halite crystals are coated by fine-grained muscovite, both defining a (weak) foliation parallel to the shear plane.

synthetic aggregate was then hot isostatically pressed at 200 °C for 1 week. After this procedure the sample showed an anisotropic texture made of a flattened honeycomb-like structure of halite crystals with ca. 200 μm surrounded by fine grain muscovite. Cylindrical samples of 10–15 mm in length and 15 mm in diameter were cored and oven-dried at 110 °C and atmospheric pressure for at least 24 h before the tests. The sample was inserted in a 0.5 mm thick and 15 mm inner diameter polymer jacket (very soft PTFE jacket to avoid interference with sample deformation behaviour). The experiments were conducted at 100 °C, at 250 MPa confining pressure and at constant angular displacement rate corresponding to a shear strain rate of $3E^{-4}\,s^{-1}$ up to various finite amounts of shear strain ($0.5 < \gamma < 5$).

During torsion experiments, approximate simple shear deformation occurs locally at any given position in the sample. The shear strain and shear strain rate increase linearly from zero along the central axis of the sample to a maximum value at the outer circumference. Shear strain rates at any radius are calculated from the angular displacement rates using Eq. (3) in Paterson and Olgaard (2000). The experimental shear strains and shear strain rates mentioned are the maximum values, which occur at the outer rim of the cylindrical specimen. The temperature distributions were regularly calibrated so that the temperature variation across the sample was never more than 2 °C.

We used small rigid inclusions to avoid confinement effects and 3D rotation due to the strain gradient inherent in torsion deformation. The inclusions were inserted in the sample by making a cavity, which was filled with the inclusion and sealed with the cuttings (same material). Then the sample was baked at 200 °C for 24 h to make the inclusion adherent to the matrix. The inclusions had a marker line to record the rotation.

3. Experimental results

The experimental results are shown in Figs. 2 and 3. There we show initial and final stages, with the angles measured for comparison with the applied shear strain. The final stage of all experiments was quite similar, despite the contrasting shape of the rigid inclusions.

The sphere rotated by an amount similar to that predicted theoretically for a body embedded in a homogeneously deformed matrix as shown in Fig. 2. In some experiments, although the deformation in the matrix was mostly homogeneous, discrete shear bands formed around and only close to the rigid inclusion, at a small angle to the shear plane. Where the shear bands curved around the rigid inclusion, tension gashes formed that were filled with halite (Fig. 2).

A circular cylinder and a cube inserted diametrically opposed in the same sample cylinder showed a similar finite rotation (Fig. 3). This finite rotation is very close to the theoretically predicted for the applied shear strain. The far field matrix deformed homogeneously, without visible localization into internal smaller scale high

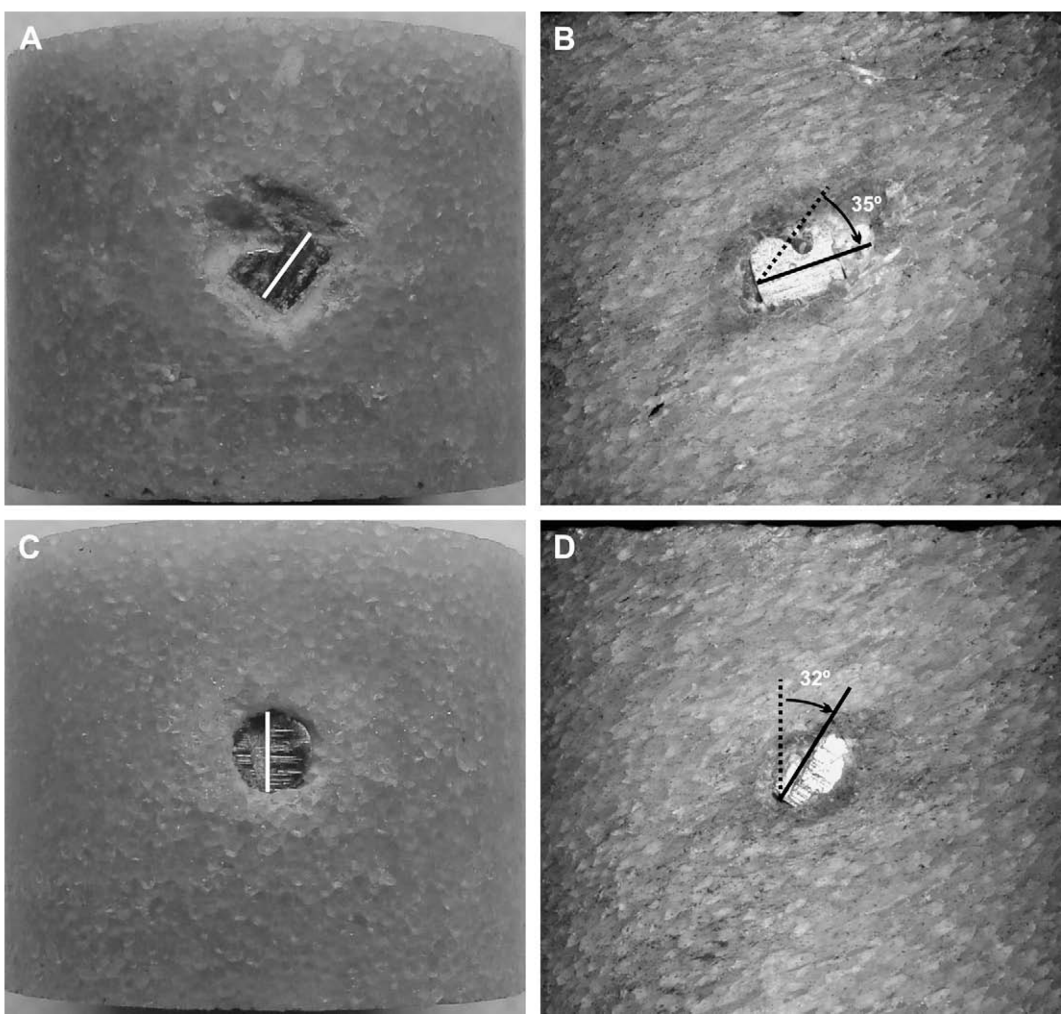

Fig. 3. Images of initial and final stages for a cube (A and B) and a circular cylinder (C and D). The measured angles of inclusion rotation are very close to the theoretically predicted. Note that the matrix deformed homogeneously except very close to the inclusion.

strain zones or shear bands. The whole sample behaved like a unique shear zone, with a penetrative foliation made up of stretched halite grains separated from one another by thin films of fine-grained mica. Around the rigid inclusion, deformation was more heterogeneous, but still not localized into smaller scale high strain zones or shear bands. Deformation of the matrix was greater close to the inclusion faces exposed to greatest contraction (highly stretched halite crystals), and much smaller in strain shadows.

4. Discussion and conclusions

Although the rigid inclusions were relatively big ($W_r = 5$ in some experiments), the rotation was not appreciably affected. Marques et al. (2005b) showed numerically that $W_r = 5$ is the limit for unperturbed rotation of a rigid circular cylinder. Small differences in rotation of inclusions embedded oppositely in the same cylinder can be well justified by the length of the inclusion and/or depth of insertion of inclusion relative to cylinder surface, because of the strain gradient inherent in torsion. This argument is also valid to justify small differences between measured inclusion rotation and theoretical prediction. Moreover, the present experiments show that mica does not seem to affect rotation, by forming shear zones that could partition flow around the rigid inclusion with shear concentrated in mica (e.g. shear bands in Fig. 2). Even if shear would concentrate in mica around the rigid inclusion, as in the present experiments, it could not impede inclusion rotation, as it did not in the present experiments (cf. Fig. 2), because inertia of inclusion rotation is negligible. Therefore, the inclusion rotates, however, small the friction may be.

It has been shown theoretically and experimentally that spheres, cubes and circular cylinders (with long axis parallel to the vorticity axis) embedded in a viscous matrix do not rotate in pure shear, but do rotate in simple shear or combinations of pure and simple shears. However, one can argue that rocks are anisotropic, unlike the linear viscous fluids used in mathematical analysis or physical modelling. Besides, to our knowledge, theoretical or experimental analogue (viscous) models have never been validated with rock-like materials. We show with the present rock deformation study that rigid inclusions with $A_r = 1$ rotate in rock as they do in analogue or numerical experiments, and as predicted by fluid mechanics. Therefore, regarding rigid inclusion rotation, rocks behave as continua and hence fluid mechanics can be applied. A very fine-grained matrix best approximates a fluid; however, the present experiments show that even a quite coarse-grained matrix (though one order of magnitude smaller than the rigid inclusion dimension) can behave as a continuum.

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