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Modification of natural H_2O–NaCl fluid inclusions under experimental deviatoric stress

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1. Introduction

Deformed fluid inclusions are extremely common in rocks displaying moderate plastic strain, but no theoretical basis has been available on which to interpret their significance. The questions are (1) whether deformed inclusions retain information on the chemical composition and density of the pre-deformation paleofluids, and (2) whether they record conditions of the ductile deformation itself.

Recent experimental studies (Tarantola et al. 2010; Diamond et al., 2010) have managed to reproduce the microstructures of naturally deformed inclusions by subjecting single quartz crystals, which were rich in CO_2–H_2O–NaCl inclusions, to high deviatoric stresses at 700 °C and ~600 MPa confining pressure in a Griggs piston-cylinder apparatus. The results show that intact inclusions (Fig. 1 explains the new nomenclature), though irregular in shape, do indeed preserve the pre-deformation fluid properties. However, most of the inclusions in the experiments had become dismembered into discoid clusters of tiny, new-formed "neonate" inclusions, surrounding irregularly shaped relicts of the precursor inclusions (Fig. 1).

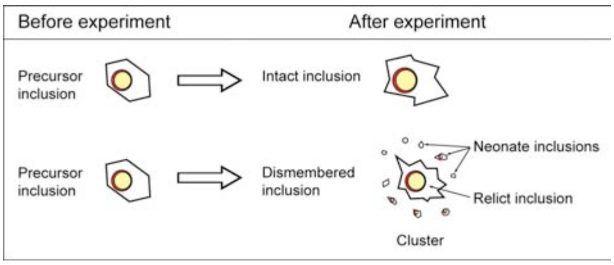

Fig. 1. Summary and nomenclature of shape changes accompanying ~1% plastic strain of the quartz host crystal. View looking down σ_1.

The thousands of discoid inclusions in each deformed sample define a planar fabric, which lies sub-perpendicular to σ_1. Tarantola et al. (2010) suggested that the direction of σ_1 can therefore be deduced from the corresponding fabric in natural samples. Whereas the relict inclusions preserve the original chemical composition, their densities bear no obvious relation to the *P*–*T* history of the sample. The neonates, in contrast, had lost H_2O and their densities had increased markedly, approaching the value consistent with the experimentally imposed principal stress, σ_1. Although there were some methodological ambiguities regarding the interpretation of the stress values, Diamond et al. (2010) suggested that this finding could be applied to natural samples. If the temperature of deformation is known, its intersection with the isochores of neonate inclusions defines the absolute magnitude of the principal stress, σ_1.

The latter result is of considerable interest to studies of rock deformation. However, owing to the uncertainty in the stress values in Diamond et al. (2010), the result needs confirmation. In the present study we report the results of 6 new experiments carried out using a similar approach of Tarantola et al. (2010) and Diamond et al. (2010), but on a different natural quartz crystal with compositionally simpler H_2O–NaCl inclusions. This permits an unambiguous interpretation of the stress conditions and of the resulting fluid inclusion isochores.

2. Experiments with H_2O–NaCl inclusions

Sample discs for the experiments were cut from a single quartz crystal from an Alpine cleft in the Aar Massif, Central Switzerland. Several generations of homogeneously trapped, liquid + vapour

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inclusions are abundant. Eutectic melting, Raman and LA-ICP-MS analyses confirmed that their bulk properties can be well modelled as binary H_2O–NaCl mixtures.

The samples were loaded isochorically (stepped path in Fig. 2) to a radially symmetric confining pressure (σ_3) of 700–1011 MPa at 700 or 900 °C. A control experiment was held at these hydrostatic conditions for 39 hr, then retrieved and its fluid inclusions reanalysed. Their ice melting temperatures (T_m(ice) = –8.7 to –7 °C) homogenisation temperatures (T_h(LV→L) = 168–208 °C), and isochores match those of the precursors (Fig. 2A). No microstructural evidence was found for quartz plasticity. This demonstrates that simple loading and heating to P_{conf},T_{exp} and retrieval of the sample produce no artifacts.

Five other samples were subjected to uniaxial compressive stresses (σ_1) of 940–1467 MPa (equivalent to differential stresses of 167–347 MPa) for 9–42 hr. All these samples showed undulatory extinction and bands of *c*-axis mismatch, demonstrating that the host quartz had deformed plastically. All the inclusions showed strong shape changes (as in Fig. 1), identical to those reported by Tarantola et al. (2010). All the neonate inclusions are markedly denser than their precursors, demonstrated by their lower T_h (116 to 166 °C) and T_m(ice) (–8 to –13 °C). Thus, the isochores that emanate from the T_h values at the base of the diagrams rise with steeper *P/T* slopes (shown in Fig. 2B–F by light shaded and stippled fans, truncated at T_{exp}). The most remarkable result is that, in each of the 5 deformation experiments, the densest of the neonate isochores (those with highest *P* at T_{exp}) intersects σ_1 at T_{exp}. These inclusions have thus equilibrated with $P = \sigma_1$ (not with $P = \sigma_{mean}$).

3. Conclusions

The deformation-induced changes in the fluid inclusions in the new experiments are consistent with the studies of Tarantola et al. (2010) and Diamond et al. (2010), but in part they represent more advanced steps along a progression in modifications of density, composition and shape. The plane of flattening of the intact and relict inclusions lies perpendicular to σ_1, and the isochores of the densest neonates pass through $P = \sigma_1$ at $T_{shearing}$. These results confirm the idea that deformed fluid inclusions can serve as monitors of both the orientation and magnitude of σ_1 during low-strain, plastic deformation of rocks.

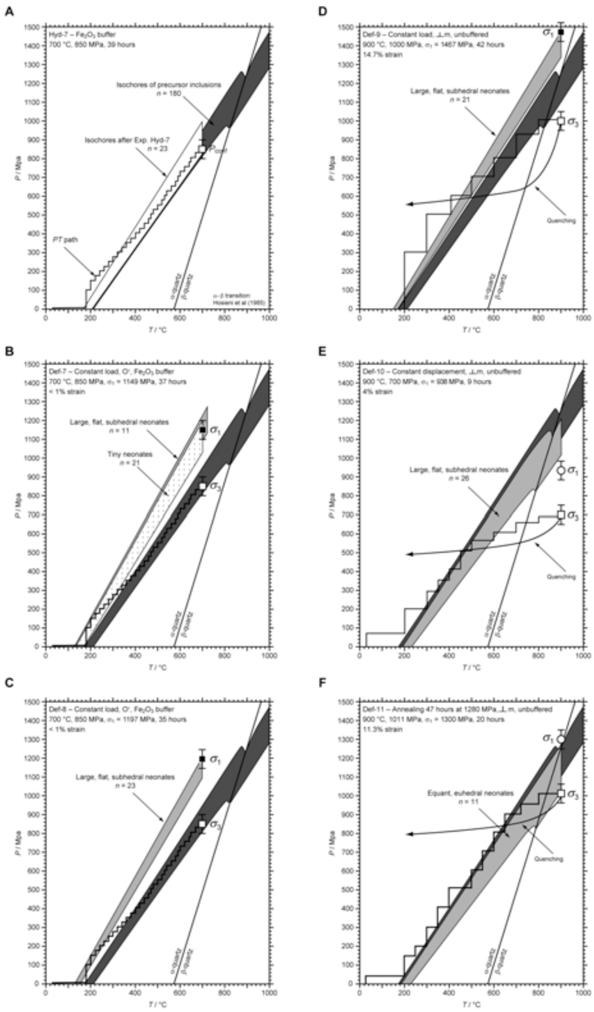

Fig. 2. Isochores of precursor inclusions used for the experiments (dark grey) and of resulting neonate inclusions following the experiments (white dotted and light grey). Isochores calculated from Bodnar and Vityk (1994). The stepped curves show the experimental PT paths.

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