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Aspects of the internal kinematics and dynamics of salt diapirs: Results from thermomechanical experiments

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The internal parts of salt diapirs are characterized by constrictional deformation supporting steeply plunging prolate fabrics and related linear (L>S) fabrics (Talbot and Jackson 1987). The youngest folds recognized in stems of salt diapirs are known from German Zechstein salt as curtain folds (Kulissen- or Vorhangfalten, Hartwig 1925) because the steeply inclined bedding planes define steeply plunging cylindrical folds. The grain-shape lineation tends to parallel the hinge lines of curtain folds. In cases of rheological stratification (e.g. stiff anhydrite or shale layers embedded in a weaker halite matrix), the curtain folds should be associated with boudins, the latter resulting from vertical extension parallel to the steep axes of the curtain folds.

A new deformation apparatus has been used to model the internal kinematics of rheologically stratified salt diapirs. Composite natural samples consisting of a single layer of Gorleben anhydrite, embedded in matrix of Asse halite (both from Zechstein formation of northern Germany), were constrictionally deformed at temperature, T = 345°C, strain rate, $\dot{e}$ = 10^{-7} s^{-1}, maximum viscosity, η = 2 x 10^{13} Pa s, and maximum finite strain, e_X = 122%.

Viscous flow of Asse halite under the conditions listed above was accommodated by dislocation creep, which can be approximated by the equation obtained experimentally by Carter et al. (1993) for low stresses. Dislocation creep was related to formation of subgrains which are forming a striking chessboard pattern in sections cut parallel to the major stretching axis, X. The subgrain size, D, has been used to estimate the differential stress, σ, using the equation obtained by Schléder and Urai (2005) after combining the calibrations published by Carter et al. (1993) and Franssen (1993). The piezometrically derived stress values are between 2 and 6 MPa. Although the prerequisites for piezometry are not fully met in the present case of Asse halite (e.g. steady-state deformation is not given in each run), the derived stresses are quite similar to the actual stresses recorded by the load cells of the machine.

At advanced state of constriction (e_X $>$ 90%) a strong increase in strain hardening of halite led to a transient tension fracture that healed up and was shortened by folding during the final phase of viscous deformation. Tiny prismatic anhydrite inclusions disseminated inside the halite matrix were reoriented during constriction resulting in a linear grain-shape fabric.

3D-images of the anhydrite layer, based on computer tomography, revealed rare kink folds with axes subparallel to X, and boudins which result from brittle tension fracture. With increasing layer thickness, H_i, the width of boudins, W_a, increases linearly and can be described by

W_a = -0.3 + 1.3 * H_i (1).

The normalized width of boudins ($W_d = W_a/H_i$) is almost constant at 1.5 ±1.0. These geometrical parameters can be used to reveal fracture boudinage under bulk constriction. The oblique orientation of most of the boudins, with respect to the principal strain axes, results from folding o the boudins by a second generation of folds, the latter with axes subperpendicular to the layer. Similar structures have been produced using plasticine as rock analogue (Zulauf and Zulauf, 2005).

The necks between the anhydrite boudins are different in shape and composition. Some necks are entirely filled with viscous halite. Others show open space that is coated with black organic matter (as shown by fluorescence microscopy) and/or with halite, both resulting from precipitation from a fluid. Fluorescence microscopy has also revealed organic matter inside fluid inclusions which are resting on grain boundaries of initial (only naturally deformed) Asse halite. The shape of these fluid inclusions varies significantly from isolated bubbles to finger like tubes (see also Urai et al., 1987), all of which show a central part that is dark under the fluorescence microscope (probably NaCl brine) and an outer bright rim consisting of organic matter. In some cases the tubes are fusing into dark fluid films which are decorating the grain boundary.

Grain boundary fluid inclusions are still present in experimentally deformed samples. However, these fluid inclusions are stretched and are more irregularly distributed along the grain boundaries compared to those of the initial samples. Organic matter is still present in the outer rims of the inclusions as is shown by fluorescence microscopy. Of particular interest are the interfaces of viscous halite and rigid anhydrite which were acting as rheological boundaries, along which halite was strongly sheared. In these high-strain domains the grain boundary fluid inclusions were also strongly stretched resulting in accumulation and trapping of fluid phases at these sites. This observation explains why the open space in the neck domains is coated with organic matter. After the latter was expelled from deformed and fused grain boundary fluid inclusions it migrated into the open neck space where it was precipitated. First investigations using RAMAN spectroscopy have confirmed that the composition of the organic matter of fluid inclusions and black coatings of open necks is the same. We argue that the release of fluids from grain boundaries has significantly controlled the strain hardening which is a characteristic feature at advanced states of finite strain.

The new data presented above might have implications for selecting rock salt of the Asse type as host rock for a radioactive waste repository. Further investigations will focus on the texture (crystallographic preferred orientation) of deformed halite and on the composition of the fluid inclusions inside both undeformed and deformed samples.

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