Journal of Structural Geology 31 (2009) 460–474

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Experimental deformation of a single-layer anhydrite in halite matrix under bulk constriction. Part 1: Geometric and kinematic aspects

G. Zulauf[a,*], J. Zulauf[a], O. Bornemann[b], N. Kihm[c], M. Peinl[a], F. Zanella[c]

[a] Institut für Geowissenschaften, Universität Frankfurt a.M., Altenhöferallee 1, D-60438 Frankfurt a.M., Germany
[b] Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, D-30655 Hannover, Germany
[c] Institut für Neuroradiologie, Universität Frankfurt a.M., Theodor-Stern-Kai 7, 60596 Frankfurt a.M., Germany

A R T I C L E I N F O

Article history:
Received 9 July 2008
Received in revised form
14 January 2009
Accepted 25 January 2009
Available online 5 February 2009

Keywords:
Salt diapir
Constriction
Halite
Anhydrite
Folds
Boudins
Computer tomography

A B S T R A C T

A new deformation apparatus has been used to model the internal kinematics of salt diapirs. Composite natural samples consisting of a single layer of anhydrite, embedded in halite matrix, were constrictionally deformed at temperature, $T = 345\,°C$, strain rate, $\dot{e} = 10^{-7}\,s^{-1}$, maximum viscosity, $\eta = 2 \times 10^{13}$ Pa s, and maximum finite strain, $e_x = 122\%$. The anhydrite layer, oriented parallel to the major stretching axis, *X*, was deformed by fracturing, whereas halite behaved viscously. 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 tension fracture. With increasing layer thickness, H_i, the width of boudins, W_a, increases linearly ($W_a = -0.3 + 1.3 \times H_i$). 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 of the boudins by a second generation of folds, the latter with axes subperpendicular to the layer.

1. Introduction

Salt diapirs are important for the storage of hazardous waste, the exploitation and mining of rock salt, and petroleum exploration and storage. Seismic exploration, deep drilling, and gravity surveys have provided accurate details on the shape and deformation of many salt diapirs. However, although deformation structures in the internal parts of salt diapirs are known for a long time (e.g. Posepny, 1871; Stille, 1925), their origin is only poorly understood because these structures are notoriously complex and require investigation in three dimensions (Jackson, 1995). Mushroom diapirs are characterized by crescentic folds in horizontal section and by downward facing folds in vertical section (Jackson and Talbot, 1987). The internal parts of salt stocks are characterized by steeply plunging linear (L > S) fabrics, examples of which are present in the salt domes of northern Germany (Lotze, 1957, and references therein), the Grand Saline Dome of Texas (Balk, 1949) and the Jefferson Island, Avery Island, Weeks and Winnfield Dome in Louisiana (Rogers, 1918; Balk, 1953; Hoy et al., 1962). Near the core of the Upheaval Dome in Utah, radial shortening produced constrictional bulk strain, forming an inward verging thrust duplex and tight to isoclinal, circumferentially trending folds (Jackson et al., 1998).

The youngest folds recognized in stems of salt diapirs are known from German Zechstein salt as curtain folds (Stier, 1915; Hartwig, 1925; Lotze, 1957, Fig. 176b; Trusheim, 1960; Zirngast, 1996) because the steeply inclined bedding planes define steeply plunging cylindrical folds with steeply dipping curved axial surfaces. In a horizontal section of a salt stock the axial planes of curtain folds are generally radial and the envelope is more or less concentric. Based on experiments by Torrey and Fralich (1926), curtain folds were experimentally produced by pressure forcing a ductile stratified sequence through a circular vent in a brittle overburden (Escher and Kuenen, 1929).

The modeling results of Ramberg (1981) suggest constrictional flow in the basal parts of axisymmetric diapirs. Thus, only curtain folds with steep hinges, aligned parallel to the subvertical *X*-axis of the finite strain ellipsoid, are likely to be generated in the basal parts of diapiric stems. 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

* Corresponding author.
E-mail address: g.zulauf@em.uni-frankfurt.de (G. Zulauf).

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doi:10.1016/j.jsg.2009.01.013

from vertical extension parallel to the steep axes of the curtain folds. Examples of folded and boudinaged anhydrite layers, embedded in a steep prolate halite matrix, have been described from Miocene salt diapirs of Yemen (Davison et al., 1996a, b). Modeling of salt diapirs using rock analogues has further shown that competent layers like anhydrite could be subjected to boudinage before being entrained and constrictionally deformed in the stem of the salt diapir (Koyi, 2001).

The 3D-geometry, flow lines and distribution of finite strain within an idealized axisymmetrical salt stock have been illustrated by Talbot and Jackson (1987). All the stream tubes in the lower half of the stem converge upward. The strain near the central axis is characterized by pure constriction supporting linear fabrics and related L-tectonites. Apart from these idealized axisymmetric salt stocks, there are other types in nature showing different shape and internal structure. The shape of a diapir and the amount of entrainment and distribution of initially interbedded dense layers are strongly controlled by salt supply which depends on sedimentation rate, viscosity of salt, perturbation width, and initial stratigraphic position of the embedded anhydrite layer (Chemia et al., 2008; Chemia and Koyi, 2008).

Constrictional experiments on pure natural rock salt have been carried out by Skrotzki and Welch (1983) focusing on the crystallographic preferred orientation of halite. Experimental studies on composite salt rocks (e.g. layer(s) of clay or anhydrite in halite matrix), however, are lacking. Such types of experiments are restricted to rheologically stratified rock analogues (plasticine). They have shown that both folds and boudins may grow simultaneously under pure constriction (Kobberger and Zulauf, 1995; Zulauf et al., 2003; Zulauf and Zulauf, 2005).

In the present paper we present details about a new deformation rig that was used for constrictional thermomechanical experiments of natural rocks. It will be shown how boudins and folds develop in a single anhydrite layer that is embedded in a viscous halite matrix. We are focusing particularly on the geometry of growing instabilities and on rheological aspects. With exception of the starting samples, the microfabrics of deformed halite and anhydrite are not considered in the present article because of limited printing space. The results of microfabric studies will be published separately in a companion paper.

2. Experimental setup

2.1. Selection, production and preparation of samples

A major problem of the present project was to find appropriate samples consisting of an anhydrite layer which is embedded in halite matrix. There are three possibilities to obtain such samples: (1) natural samples in which anhydrite is already sandwiched in halite matrix; (2) synthetic composite samples made of natural anhydrite and natural halite; (3) preparation of composite samples using synthetic material.

Natural samples of halite with a layer of anhydrite are available and thus could be used in principle. Examples from the borehole Teutschenthal (Germany) have been used when carrying out first experiments to calibrate and test the new machine. However, the anhydrite layer of such samples is in most cases already deformed by folding or boudinage. This holds particularly for cases where the anhydrite layer is thin (which is also the case in our experiments). Another problem of natural anhydrite–halite samples is the fact that the upper and lower interface of both phases can be different (e.g. sharp contact at one interface and gradual contact at the other interface). In this case the interpretation of experimental data will be more difficult. Entirely synthetic samples have the disadvantage that they may differ significantly from natural samples (e.g. in grain size, grain shape, amount of impurities, fluid inclusions, etc.). Because of these reasons we decided to build composite samples using natural halite as matrix and natural anhydrite as layer (Fig. 1a). All samples were delivered by BGR Hannover.

Halite samples of the Asse borehole of northern Germany (800 m level, Speisesalz Na2SP) which are – with one exception – largely free from a grain-shape fabric (SPO) show the lowest degree of mechanical anisotropy under constriction and thus have been used for the experiments. The grain size varies from 2 to 12 mm. According to microscopic and XRD analyses the Speisesalz (Na2SP) used in the present study consists of almost pure halite, with anhydrite and polyhalite ($K_2MgCa_2(SO_4)_4 \times 2H_2O$) as the most important impurity phases. The total water content of other Asse Na2SP samples is 0.05 wt% (Urai et al., 1987). Inclusions of partly twinned anhydrite with grain sizes up to 4 mm are present within the halite grains and along halite grain boundaries. These inclusions do not show a preferred orientation. The microfabrics of Asse halite have been described by Urai et al. (1987). Evidence for dislocation creep is indicated by the presence of crystallographic preferred orientation (Brokmeier, 1983), subgrains and lobate grain boundaries, the latter resulting from strain-induced grain boundary migration (Urai et al., 1987). The fact that most of the high-angle grain boundaries are enriched by opaque phases and inclusions suggests that dissolution–reprecipitation creep operated as a further deformation mechanism. The inclusions are the terminations of a complicated network of grain boundary fluid inclusions which are present on at least 80% of the grain boundaries (Urai et al., 1987; see also Schenk and Urai, 2004).

For the present studies we selected samples of Asse halite, most of which do not show a grain-shape fabric. The anhydrite samples used for our experiments have been collected from the Gorleben deep borehole 1004. XRD analyses revealed impurities of halite, polyhalite and magnesite. The grain size of the samples used varies considerably from <100 μm to 10 mm. Most of these grains have a dirty habitus, the latter resulting from numerous fluid inclusions and opaque phases. Rosette shaped aggregates of anhydrite are frequently present on almost all scales. The anhydrite rosettes are partly truncated by highly lobate seams which are rich in opaque phases. These seams reflect localized dissolution–precipitation creep (see also Bauerle et al., 2000).

Our decision to use composite samples of natural halite and anhydrite for the experiments, led to a serious problem concerning the preparation of such samples. We had to build a halite cube which includes a single layer of anhydrite with interfaces showing strong cohesion similar to that of natural examples. To fit anhydrite slices in-between halite blocks, we carried out more than 15 long-term experiments at different but always wet conditions. The parameters changed were (i) temperature, (ii) degree in saturation of NaCl brine, (iii) pressure, and (iv) nature of the contact surfaces. The right procedure for producing composite halite–anhydrite samples which show interfaces with sufficient cohesion includes the following steps:

- Dry cutting of halite cube ($60 \times 60 \times 60$ mm) into 2 halves and cutting of a reference sample out of the cube (ca. 1/3 of the cube).
- Heating of halite up to 40 °C and dry grinding of surfaces which will be in contact with anhydrite (SIC grain 180).
- Wet cutting and grinding of anhydrite layer (SIC grain 120). If the thickness of the anhydrite layer was <1.5 mm, the layer is prone for buckling. In this case the grinding had to be carried out using SIC grain 240 and a plane plate made of glass.
- Cutting of a reference sample of anhydrite (ca. 1/3 of the layer).
- Immersing of anhydrite and halite into slightly undersaturated NaCl brine for 45 s at room temperature.