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Microfabrics and 3D grain shape of Gorleben rock salt: Constraints on deformation mechanisms and paleodifferential stress

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ABSTRACT

The Permian *Knäuel-* and *Streifensalz* formations (z2HS1 and z2HS2) are main constituents of the Gorleben salt dome (Northern Germany) and show different amounts and distributions of anhydrite. The reconstruction of 3D halite grain shape ellipsoids reveals small grain size (3.4 ± 0.6 mm) and heterogeneous grain shapes in both formations, the latter attributed to the polyphase deformation of the rock salt during diapirism. The halite microfabrics of both formations indicate that strain-induced grain boundary migration was active during deformation. Crystal plastic deformation of halite is further documented by lattice bending, subgrain formation and minor subgrain rotation. Evidence for pressure solution of halite has not been found, but cannot be excluded because of the small grain size, the lack of LPO and the low differential stress (1.1–1.3 MPa) as deduced from subgrain-size piezometry.

Anhydrite has been deformed in the brittle–ductile regime by solution precipitation creep, minor dislocation creep and brittle boudinage. No continuous anhydrite layers are preserved, and halite has acted as a sealing matrix embedding the disrupted anhydrite fragments prohibiting any potential migration pathways for fluids. Thus, anhydrite should not have a negative effect on the barrier properties of the Gorleben rock salts investigated in this study.

1. Introduction

The deformation behavior of rock salt is an important field of research for nuclear waste disposal (e.g. Bornemann et al., 2008; Hunsche and Hampel, 1999), for salt mining, for the localization of petroleum reservoirs in some salt structures (e.g. Schoenherr et al., 2007) and for understanding salt tectonics (e.g. Talbot and Jackson, 1987; Wagner and Jackson, 2011). For these reasons, microfabrics and related deformation mechanisms in halite have been intensely studied for naturally and experimentally deformed rock salt (e.g. Urai and Spiers, 2007, and references therein).

The rock salt deposits from the Gorleben salt dome (Northern Germany) attract major interest because the salt dome has been considered as a nuclear waste repository (e.g. Bornemann et al., 2008). Microstructural investigations of Gorleben rock salt are of major importance in the framework of a comprehensive characterization of these rocks. Regarding future evolution and safety aspects of the Gorleben salt dome, anhydrite in the form of layers, boudins and inclusions inside the rock salt is of major interest (e.g. Burchardt et al., 2011; Chemia et al., 2009). However, microstructural investigations of anhydrite are scarce for the Gorleben *Hauptsalz* group, which is targeted as potential medium for nuclear waste storage. Layers of anhydrite have been discussed to represent possible migration pathways for fluids (e.g. Zulauf et al., 2010), which is why the role of anhydrite is important to evaluate with respect to nuclear waste disposal.

Studying rock salt microstructures allows identifying the operating deformation mechanisms. For natural halokinetic conditions (20–200 °C) several deformation mechanisms should be considered. *Dislocation creep* results from glide and climb of dislocations within the crystal lattice causing a reduction of the internal strain energy of grains (e.g. Poirier, 1985). As a result, subgrains may develop, which reflect domains of homogeneous crystallographic orientation separated by boundaries with a low misorientation (<10°). The formation of subgrains as *recovery* mechanism is controlled by temperature, differential stress and strain rate, and furthermore by material properties, such as grain orientation, grain size and fluid content (e.g. Pennock et al., 2005). There are two processes that allow subgrains to be transformed into normal grains. One of these processes is related to the migration of a subgrain boundary through an area of cumulative lattice rotation defined as *sub-boundary migration* (Carter et al., 1993; Drury and Urai,

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1990). The second process is *subgrain rotation*, which is a common mechanism to accommodate crystal plastic strain in rock-forming minerals (Poirier, 1985, and references therein). Subgrain rotation (SGR) recrystallization gradually transforms subgrain boundaries with low misorientations into high-angle grain boundaries generating new grains out of former subgrains (Drury and Urai, 1990; Poirier, 1985; Urai et al., 1986b). Drury and Pennock (2007) summarized the process of SGR in minerals. The critical angle for the switch from a low to a high-angle boundary is not exactly defined in the literature. In some cases a high-angle grain boundary is referred to a misorientation angle >10° (Kleber, 1983; Trimby et al., 2000a, 2000b; White, 1977) or to an angle >15° (Bestmann and Prior, 2003; Bestmann et al., 2005; Pennock et al., 2002). Drury and Urai (1990) point to a more sophisticated nomenclature, because several minerals show different transitions deduced by changes in the mechanical behavior and the transition angle is dependent on the boundary conditions. Based on results presented in the present paper, we will assume 10° as critical angle.

Evidence for weak to moderate subgrain rotation in rock salt has been observed and discussed in several studies (Desbois et al., 2010; Leitner et al., 2011; Pennock et al., 2002, 2005; Pennock and Drury, 2005; Schléder and Urai, 2005; Talbot, 1981; Trimby et al., 2000a, 2000b). However, pervasive SGR *recrystallization* has never been described from naturally deformed halite, although evidence can be drawn from experimentally deformed rock salt (e.g. Franssen, 1994; Guillopé and Poirier, 1979). Moreover, deformation experiments on halite single crystals indicate that the pure formation of subgrains is able to accommodate significant amounts of strain (Linckens et al., under review).

Dynamic recrystallization in terms of (strain-induced) *grain boundary migration* (GBM) (Urai et al., 1986a, 1986b) plays a significant role for the deformation of rock salt (e.g. Schenk and Urai, 2004; Schléder, 2006; Ter Heege et al., 2005a, 2005b). GBM is driven by differences in dislocation density across grain boundaries and is significantly supported by grain boundary fluids, which should have a significant impact for rock salt deformation, because already small amounts of brine may result in mechanical weakening of rock salt (Peach et al., 2001; Pennock et al., 2006; Urai et al., 1986a; Urai and Spiers, 2007; Zhang et al., 2007). Since sedimentary and diagenetic fluid phases are common constituents of most salt deposits (e.g. Davison, 2009; Roedder, 1984; Talbot and Rogers, 1980; Závada et al., 2012), the ductile (long-term) behavior or rock salt is ensured (Carter and Hansen, 1983; Carter et al., 1993).

Pressure solution is active along grain boundaries involving grain boundary sliding (GBS) and dissolution/precipitation of halite (Schutjens and Spiers, 1999; Spiers et al., 2004; Urai and Spiers, 2007). By the presence of grain boundary fluids, highly-stressed parts of grains are dissolved (for instance at grain contacts) and material is transported and finally deposited at sites of low stress (e.g. Passchier and Trouw, 2005; Schutjens and Spiers, 1999; Urai and Spiers, 2007). The process of solution precipitation creep has been reported for salt glaciers of

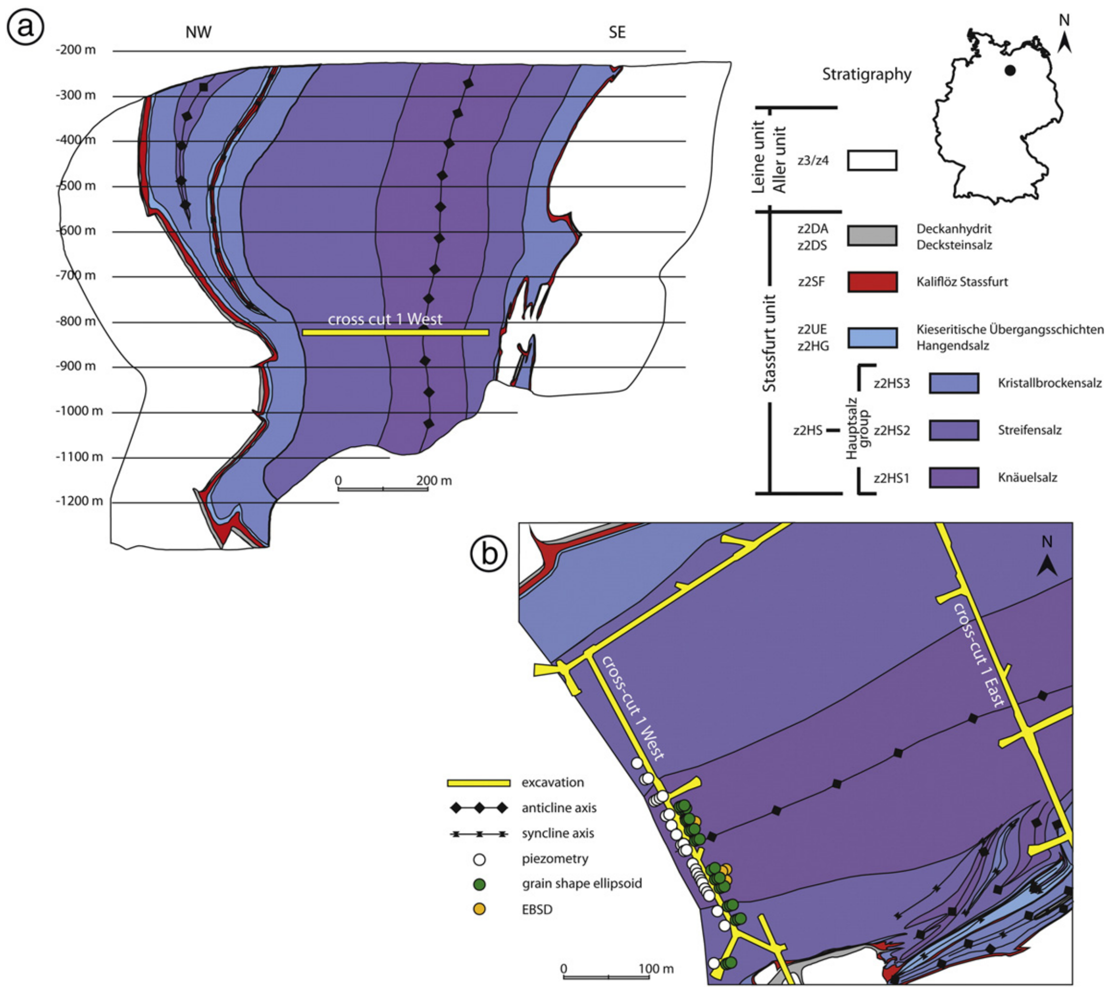

Fig. 1. Geology of the Gorleben salt dome (Northern Germany) in the area of the exploration mine after Bornemann et al. (2008). a) Cross-section showing the main salt anticline and composing salt formations. b) Top view of the 840 m exploration level with approximate sample positions along cross cut 1 West. The detailed stratigraphy of Gorleben salt rocks is illustrated in Bornemann et al. (2008).