Investigation of deformation textures of salt rock from various Zechstein units and their relationship to the formation of the salt diapirs in NW Germany

O. Bornemann[a], R. Fischbeck[a] and G. Bäuerle[b]

[a]Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, D-30655 Hannover

[b]TU-Clausthal, Institute for Mineralogy, Adolph-Roemer-Str. 2A, D-38678 Clausthal-Zellerfeld

The primary bedded nature of the salt rock is very similar in both the Stassfurt Formation (z2) and the Leine Formation (z3) of the Zechstein. These formations consist of thin anhydrite beds alternating with layers of almost monocrystalline halite and layers of granular halite. These Fm were subjected to different degrees of deformation during the diapir uprise. In the Stassfurt Fm, deformation of a sequence of alternating layers of differing competence produced a salt breccia. In contrast, in the Leine Fm the primary bedding is mostly preserved; local differences in thickness are due partly to primary variations in sedimentation and partly to tectonic thinning and slight deformation of the layers. The resulting rock represents an early stage in the genesis of a salt breccia like that in the Stassfurt Fm.

1. INTRODUCTION

The salt diapirs in NW Germany are composed mainly of salt belonging to the Zechstein Fms z2 – z4. The Stassfurt Fm (z2) comprises the large core zone of these salt diapirs. The salt of the Leine Fm (z3) behaved relatively passively during diapir uprise.

Comparative studies show that the rock salt in these two formations underwent different degrees of deformation during diapir formation.

The studies were mainly conducted on the Gorleben salt dome, which is located in the northeastern corner of Lower Saxony. It has been studied since 1979 as a possible site for a permanent repository for radioactive waste. For comparison purposes, drill cores from various other salt structures in NW Germany were also analysed.

2. STUDIES OF THE ZECHSTEIN 2 - STASSFURT FORMATION

The objective of these geochemical studies was to demonstrate that the salt breccia of the Stassfurt Fm is a tectonic breccia produced at the time of the formation of the diapir (BORNEMANN 1991).

2.1 Methods

Samples of Kristallbrockensalz (z2HS3), Stassfurt Fm, were taken from the Go 1002 exploration borehole at depths of 530 – 603 m. Sampling was begun in the top layers of the Streifensalz (z2HS2) and continued through the Kristallbrockensalz into the Hangendsalz (z2HG, simplified Stratigraphy of the Zechstein, table 1). In each case, a sample from a monocrystalline halite fragment and a sample of granular halite were taken within a few centimeters of each other in the same horizon. Care was taken that the samples were not contaminated with the other type of halite.

The following ions were determined in all of the samples: Na^+, K^+, total Mg^{2+} – if >500 ppm total Mg^{2+} was present, then Mg^{2+} extracted with alcohol was also determined – SO_4^{2-}, Cl^- and Br^-. The cations were determined using an ICP-OES spectrometer and the anions by ion-exchange chromatography. The bromide content of the samples was recalculated with respect to the halite.

Bromine is a key element in marine chloride salt deposits. In these deposits bromine does not form any minerals itself, but substitutes for chlorine in chloride minerals. The distribution of bromide between evaporating seawater and the solid (e.g., halite) that crystallize from it follows a relatively constant law.

The distribution coefficient of bromide between a solution and the crystallizing halite is defined as follows:

$$b = \frac{\text{weight\% Br}_{\text{ in the halite crystal}}}{\text{weight\% Br}_{\text{ in the solution}}}$$

This coefficient is always less than 1. As sea water evaporates, the bromide concentration increases. Via the distribution coefficient, the bromide content of the halite provides a measure of the degree of evaporation. If evaporation is continual, the bromide content of the rock salt increases upwards in the succession.

Table 1
Simplified Stratigraphy of the Zechstein

Zechstein Formation			lamina counts
Zechstein 4 (Aller-Folge)	Orangesalz z3OS	Oberes Orangesalz z3OSO	1
		Mittleres Orangesalz z3OSM Gorleben-Bank	267 - 276
		Unteres Orangesalz z3OSU	230 - 240
Zechstein 3 (Leine-Folge)	Liniensalz z3LS	Liniensalz — 110-Linie — z3LS	110
	Basissalz z3BS		1
Zechstein 2 (Staßfurt-Folge)	Hangendsalz z2HS	Kristallbrockensalz z2HS3	
	Hauptsalz z2HS	Streifensalz z2HS2	
		Knäuelsalz z2HS1	

2.2 Previous results

The geological investigation of the Gorleben salt dome has shown that the Stassfurt Fm was the driving force of the diapir uprise primarily on account of the large thickness of rock salt (c. 800 m). This uprise forms the core zone of the diapir (BORNEMANN 1991) and has been extensively dissolved at the top of the salt dome (ZIRNGAST 1991). The Hauptsalz of the Stassfurt Fm moved laterally into the salt dome from the site of the present-day rim synclines over distances of several kilometers; the Leine and Aller Fms were only "dragged" along with the Stassfurt salt. The Hauptsalz of the Staßfurt Fm is present today mostly as a tectonic breccia (BORNEMANN 1991). In contrast, neglecting folding and slight deformation, the Leine Fm has retained its sedimentary bedded nature.

PAPE (1993) observed chevron patterns of fine inclusions in the fragments of halite single crystals from the Kristallbrockensalz in drill cores from the Stassfurt Fm. Chevron patterns are characteristic of hopper crystals formed during sedimentation. Therefore, the presence of chevron patterns indicates that the fragments of single halite crystals are relicts of the primary sediment and are not the result of secondary recrystallization.

2.3 Kristallbrockensalz: Petrographic results

The primary sedimentation of the Stassfurt Fm consists of a rhythmic alternation of gray anhydrite beds several millimeters to centimeters thick and halite beds several decimeters thick. The halite beds consist partly of layers of almost monocrystalline halite several centimeters thick and partly of medium and coarse granular halite several centimeters thick. Beds like this are found in the less deformed parts of the Liniensalz in the Leine Fm as well as in the Stassfurt Fm outside the area where salt diapirs have developed, e.g. in the area of Halle (Fig. 1).

The Kristallbrockensalz in the diapirs is a mixture (Fig. 2) of three components that were originally deposited in separate layers: fragments of monocrystalline halite and anhydrite rock set in granular halite.

Figure 1: Sedimentary texture of z2HS inclined bedding, area of Halle (upper part) and z3LS (Go 1003). Width of picture 50 cm.

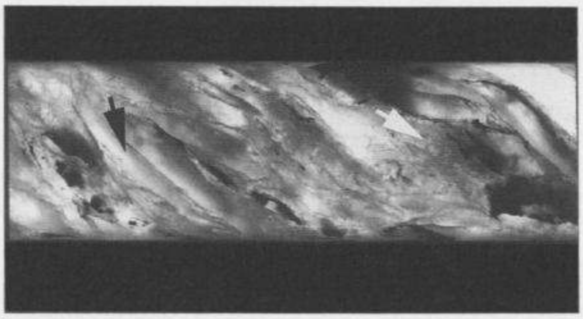

Figure 2: Tectonic breccia (z2HS3), black arrow: fragment of monokristalline halite, white arrow: granular halite. Width of picture 35 cm.

Figure 3: Chevron structure (z2HS3). Width of picture 3,5 cm.

Halite type 1: The granular halite forms the matrix of the Kristallbrockensalz. It consists of a mosaic of mostly clear halite crystals 0.5 – 1 cm across showing curved grain boundaries.

Halite type 2: The fragments of monocrystalline halite are 1 – 18 cm across. They have irregular shapes with sharp edges. They are often preferentially oriented parallel to their long axes. Some of them are transparent, mostly with interned bedding and others are milky due to fluid inclusions. Chevron patterns are observed in the fragments of monocrystalline halite (Fig. 3).

The original fine-grained, gray, 1 – 10 mm thick anhydrite layers are fragmented. The larger slab-like fragments may be attached to the edge of the Kristallbrocken and the small flakes are set in granular halite.

2.4 Geochemical results

The bromide content of the halite at the top of the Streifensalz, in the Kristallbrockensalz, and in the Hangendsalz is shown in Figure 4.

Curve 1 shows the bromide content of the fragments of monocrystalline halite; curve 2 shows the bromide content of the granular halite. Both curves show an increase from 90 ppm bromide at the bottom of the bed to 200 ppm at the top. The original bromide content during sedimentation of this part of the Stassfurt Fm can be roughly seen in the trends of both curves. If both types of halite that were taken from the same horizon were deposited at the same time, they should have the same bromide values. But there are significant differences between the bromide contents of the two halite types taken from the same horizon. Both bromide curves show large, abrupt fluctuations in a continually rising trend. The fragments of monocrystalline halite show larger deviations from the general trend of the curve than shown by the granular salt.

Examination of the curves shows that in 21 of the 52 sample pairs the bromide content is lower in the fragments of monocrystalline halite than in the granular salt, in 26 sample pairs the bromide content is higher in the

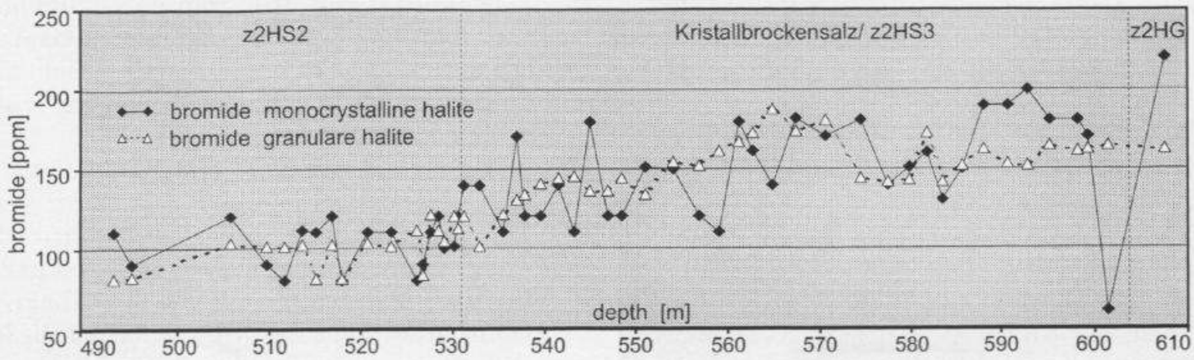

Figure 4: Bromide content of Kristallbrockensalz halite of the Stassfurt Fm. The salt layers are overturned.

former than in the latter, and in five pairs the bromide content is practically the same. Since the differences are not in the same direction, the possibility that the present salt breccia was formed by a synsedimentary submarine slide is excluded. The bromide values confirm that the two types of halite have undergone tectonic mixing. During the development of the diapir the original interbedded sediments were fragmented and mixed, forming a tectonic breccia.

3. STUDIES OF THE ZECHSTEIN 3

The sequence of halite layers from the Liniensalz up to the Oberes Orangesalz was studied on the NW side of the Gorleben salt dome (borehole Go 1003) and on the SE side (borehole Go 1005) from the following points of view: Counts of sulfate laminae, bromide content of the halite, and structures formed by tectonic deformation. This showed that these beds have retained their primary sedimentary character despite tectonic thinning and deformation.

3.1 Methods

During sampling, care was taken to collect each sample from only one stratigraphic halite layer.

The main ions were analyzed in the same way as for the samples from the Stassfurt Fm. The bromide contents were determinded by XRF analysis.

3.2 Petrography of the Liniensalz and Orangesalz

Two different types of halite can be distinguished in the Liniensalz of the Leine Fm: Halite type 1: The granular halite consists of a mosaic of fine-grained (> 0.5 cm) and medium-grained (0.5 – 2 cm), irregularly shaped halite crystals showing curved grain boundaries.

Halite type 2: A bed of mostly clear, nearly monocrystalline halite several centimeters thick.

The Liniensalz is fine- to medium-grained and is grayish yellow coloured. It contains intercalated anhydrite layers several decimeters apart and up to a centimeter thick, often finely laminated. The rock salt between the anhydrite layers contain both granular halite layers and layers of monocrystalline halite (Fig. 1). The Untere Orangesalz is fine- to medium-grained and is brownish orange to light orange. The salt consists mainly of granular halite layers. Beds of monocrystalline halite are relatively rare.

The rhythmic sulfate layers several decimeters apart are seen in sections across the bedding as lines of grey to reddish brown "flakes" (Flockenlinien), consisting of irregular lenses of sulfate minerals. Between these sulfate layers, the halite has yellow orange bands. The differences in the color of the halite layers and the Flockenlinien at the

Liniensalz/Orangesalz boundary is caused by differences in the content of polyhalite.

The Oberes Orangesalz is fine- to medium-grained and is mostly bright orange. The intercalated mm-thick sulfate layers several decimeters apart consist of anhydrite. Beginning in the middle of the Oberes Orangesalz, the color changes and polyhalite Flockenlinien are present.

The sulfate laminae were counted to set a fine stratigraphy for the Leine rock salt (Fig. 5). Counting was begun at the Basissalz/Liniensalz boundary. A bed consisting of an alternating halite-anhydrite sequence 2 – 15 cm thick was used as a marker horizon in the Liniensalz. It was found in numerous counts to be horizon 110. The Liniensalz/Unters Orangesalz boundary is marked by the appearance of sulfate Flockenlinien. This boundary normally lies between sulfate horizons 230 and 240 (BORNEMANN 1991). The Unteres Orangesalz is overlain by the Gorleben-Bank, up to which a maximum of 276 sulfate horizons were counted. The Gorleben-Bank, another marker horizon, is 3.5 – 70 cm thick and also consists of a alternating sequence of halite and anhydrite. In the Oberes Orangesalz, the counting was started again with horizon 1.

3.3 Sedimentary and petrographic findings

It was found that the sequence of halite layers from the Liniensalz up to the Oberes Orangesalz on the NW side of the salt dome (Go 1003: c. 54.5 m) are about twice as thick as on the SE side (Go 1005, c. 27.5 m; Fig. 5). Two possibilities may be considered as the reason for this difference:

1) Primary thickness differences: This is supported by differences in the thickness of horizon 110 and of the Gorleben-Bank, as well as by differences, by as much as 10 laminae, in the first appearance of the polyhalite-bearing Flockenlinien (BORNEMANN 1991).

2) Reduction of thickness by tectonic processes: On the NW side of the salt dome (Go 1003) the original bedded nature of the halite layers is largely preserved. However, the beds of monocrystalline halite are locally fragmented, and stepped fractures and offsets are often observed. The original sequence is still present, or can be reconstructed. In contrast, the halite layers on the SE side of the salt dome (Go 1005) show strong shearing and brecciation. The sulfate horizons are present mostly as lines of fragments. The beds of monocrystalline halite have been broken up into small fragments. The attitude of the relict bedding represented by fine lines of inclusions within the individual crystal fragments shows that most of them have been rotated. Counts of the sulfate laminae in the sequence of halite layers from the Liniensalz up to the Oberes Orangesalz showed that there are eight laminae fewer on the SE side (268 horizons in Go 1005) than on the NW (276 in Go 1003), which also supports tectonic thinning.

These results support both primary and tectonic reasons for the thickness differences. The more fragmented nature of the halite in Go 1005 than in Go 1003 indicates a predominantly salt tectonic cause.

3.4 Geochemical results

The two curves for bromide content of the Liniensalz to Orangesalz show the same trend (Fig. 5). At the Basissalz/Liniensalz boundary, the bromide concentration is c. 85 ppm. The bromide concentrations increase steadily from this boundary up to horizon 110. Above this marker horizon, the concentrations fall abruptly by 30 – 40 ppm and then steadily increase again up to the Gorleben-Bank. In the Gorleben-Bank, the bromide values fall abruptly again by 50 – 80 ppm.

This pattern of bromide concentrations reflects the progressive evaporation of the Zechstein sea. The spacing of the sulfate laminae also support this: The spacing increases up to the marker horizons; above the marker horizons narrow spacing begins again (Fig. 5). The abrupt decrease in the bromide concentration at the marker horizons can be interpreted as resulting from the introduction of slightly concentrated sea water.

The bromide concentrations just below the

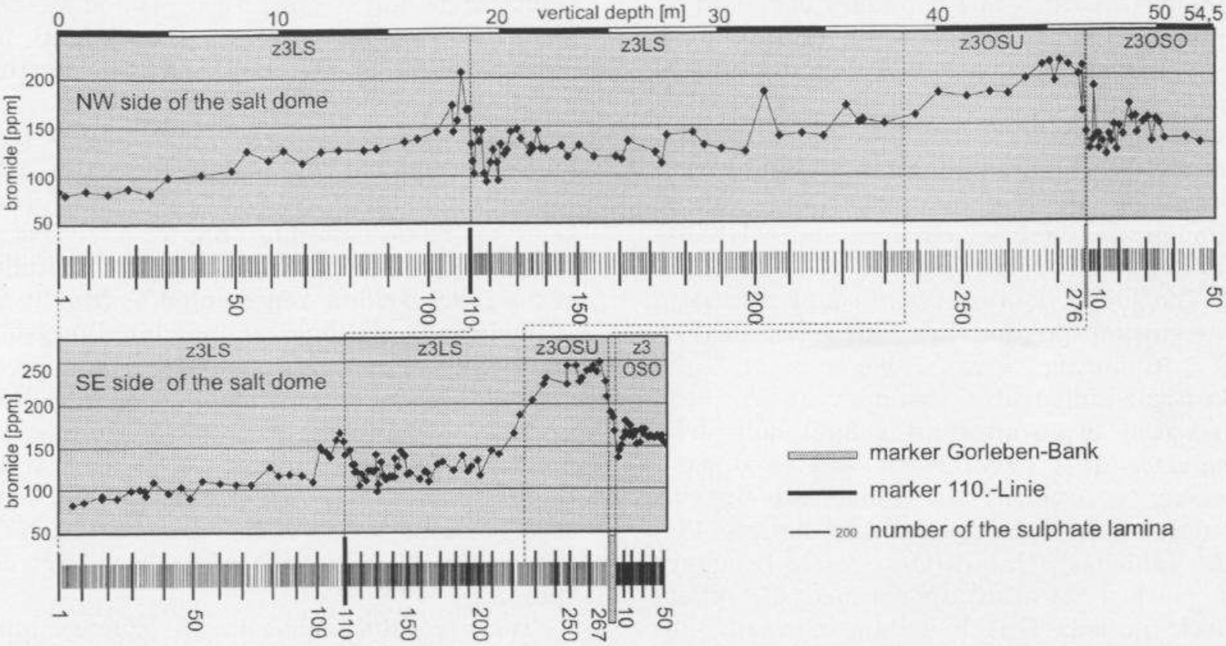

Figure 5: Bromide content of Liniensalz and Orangesalz halite of the Leine Fm.

Gorleben-Bank and below horizon 110 vary considerably between the two boreholes. This observation, the differences in the position of the first appearance of the Flockenlinien, and the variations in thickness of the marker horizons suggest that there were differences in seafloor relief during evaporation.

The bromide curves indicate practically uninterrupted sedimentation. They exclude reduction of thickness by dissolution. If saline solutions from within or outside the salt dome caused a reduction in the thickness of the halite layers from the Liniensalz up to the Oberes Orangesalz, the bromide concentrations would show much larger deviations from the primary concentrations.

4. CONCLUSIONS

The degree of deformation of a given salt sequence in a diapir depends on the length of the path along which it moved during formation of the diapir. This explains why, in the core zones of diapirs, the halite beds of the Stassfurt Fm are present as a tectonic breccia. The halite beds of the Leine Fm, which moved a much shorter distance, are considerably less deformed.

Despite the salt tectonic deformation, the primary bromide distribution in the halite beds of the Leine Fm is preserved. Even in the case of the Stassfurt Fm, in which the halite beds have been brecciated, relicts of the primary bromide distribution are found.

There is no indication that saline solutions from within or outside the salt dome were involved in the deformation of the Zechstein 2 and 3 Fm.

REFERENCES

1. O. Bornemann, BfS-Schriften 4/91, Salzgitter, 1991.
2. M. Zirngast, Geol. Jb. A 131, Hannover, 1991.
3. T. Pape, Diplomarbeit, unveröff., Hannover, 1993.