Steps towards successful prediction of the internal tectonics of salt structures

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Internal tectonics of salt structures are of importance to a wide group of geoscientists in society nowadays. Technical ways of determining the internal tectonics of salt are still poorly developed, hence other ways have to be sought to obtain the necessary insight. In this paper steps are outlined to successfully predict the internal tectonics of a salt dome. These steps consist of: 1. Establishing the nature and thickness of the inhomogeneities; 2. Knowing the reaction of the inhomogeneities to deformation; 3. Determining the structural position of the salt structure and the type of structure; 4. Reconstruction of the salt flow patterns in time.

1. INTRODUCTION

Detailed knowledge of the internal tectonics of salt structures nowadays is not only a matter for salt geologists anymore. In the oil and gas exploration, Pre-Stack Depth Migration is applied to enhance the definition of subsalt prospects. For this technique, a good velocity model of salt, including its internal structure, is essential. Besides, the internal structure of salt plays a role in the planning of well trajectories, to avoid drilling problems. High-pressure gas or brine pockets in anhydrite floaters and squeezing salts are two examples of Zechstein drilling problems encountered in the Southern North Sea area.

Ways of looking into subsurface salt formations are poor. Seismics reveal only the outside of salt bodies; even modern 3D seismic mapping tools do not produce sufficient insight in the internal tectonics. The main reasons for this are the lack of acoustic impedance contrasts between the various salt minerals in combination with steep bedding. Thick anhydrite floaters generally can be visualised, but form only part of the internal structure. Other ways have to be sought to obtain insight in the internal structure of salt bodies, and to successfully predict its internal tectonics.

Knowledge on the internal tectonics of salt structures has been obtained at the NITG-TNO through a number of studies. These included a literature review, seismic mapping of salt structures, core studies of Zechstein salts both from the Netherlands and NW Germany and detailed analysis of wireline log response of salt. Furthermore outcropping salt formations and salt mines have been visited in Germany, Spain, Poland and Iran. These field studies have provided us with a better insight in the complexity of 3D structures, and besides learnt us that these present analogons for the internal structures of salt domes in the subsurface of NW Europe.

This paper aims to present an overview of the various factors that control the internal structures, in the view of recent ideas on salt sedimentation and salt structures development. It concludes with a stepwise approach towards a successful assessment of the internal structures. This paper focuses upon Zechstein salt structures, the most widespread salt deposits in NW Europe.

2. SETTING OF THE ZECHSTEIN

During the Late Permian widespread sedimentation of evaporites took place over large parts of NW Europe, in the so-called Southern and Northern Permian Basin [1, 2]. In these basins, up to 1500 m of predominantly halites were deposited. These deposits were subject to strong Mesozoic and Cenozoic deformation, mainly in response to the opening of the Atlantic Ocean. The deformation was mainly of extensional character, but during the Late Cretaceous, compressional stresses affected the area and caused wide-spread basin inversion.

Under the combined influence of these stresses a large number of salt structures developed in NW Europe.

3. PREVIOUS WORK

Extensive literature exists regarding the internal structure of salt structures [3-9]. These publications provide us with well-documented examples of the internal tectonics of salt structures, including salt mines that are no longer accessible.

Exposed salt domes in the Iranian Dasht-i-Kavir [10] and the Zagros mountains [11] present a unique analogue for salt domes in the subsurface of NW Europe. They can be studied both from the air and in outcrop. The salt in the Dasht-i-Kavir area has been mobilised under a combination of extensional and compressional stresses. A great number of salt diapirs formed in the area. The stratigraphy, present-day depth and stress history are similar to that of the Zechstein in NW Europe [10,12].

In the Spanish Pyrenees, the effects of compressional stresses can be studied in detail. The outcropping salt dome at Cardona, 50 km NW of Barcelona, presents a perfect 3D picture of the internal structures in the salt dome [13]. Despite the intense deformation, the original sedimentary bedding of the salt was maintained; small-scale sedimentary structures like hopper crystals can still be identified [12].

4. FACTORS CONTROLLING THE INTERNAL TECTONICS

Four factors are of great importance in the assessment of the internal tectonics of salt structures:

1. To predict the type and thickness of inhomogeneities in a salt structure
2. To understand the reaction of the inhomogeneities to deformation
3. To know the type of salt structure
4. The salt flow pattern in time

ad 1. The type of inhomogeneities in the salt is essentially controlled by the depositional setting. Marine salt deposits (Zechstein 1-3) are composed predominantly of halite, and typically display a stacking of evaporite sequences composed of clay--carbonate--anhydrite--salt--anhydrite. Continental evaporites on the other hand (Zechstein 5-7) are typically made up of claystone--salt cycles. Marine cycles reflect long-term sea-level fluctuations rather than short-term climatic controlled continental cycles. Marine cycles can thus reach greater thickness, in the order of 100's of m up to sometimes 1000 m. Continental evaporites cycles have a thickness in the order of several tens up to 100 m.

The thickness of the inhomogeneities is controlled both by the depositional environment and the tectonic setting. We can discern between evaporites deposited in a regionally subsiding basin and an actively subsiding rift basin [14]. In the former, a thorough understanding of the dynamics of the sedimentary system, and in the latter the tectonic setting is the key to the understanding of the thickness. The assumption that evaporite units have been deposited with a constant thickness in a basin no longer holds; an example for this is the Main Anhydrite, which varies in thickness from 5—125 m in the southern North Sea area [12].

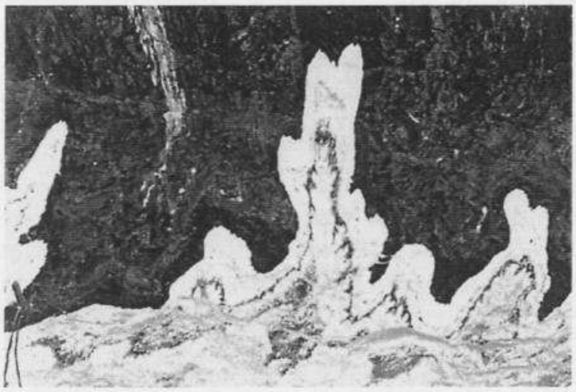

Figure 1. Folding in potassium-magnesium salts, Potash seam Hessen, Neuhof-Ellers mine, 535 m floor, Fulda, Germany. Fold size approx. 2 m.

ad 2. A thorough understanding of the mechanical behaviour of the various lithologies in the Zechstein during deformation forms a prerequisite to the understanding of their deformation. Some lithologies deform in a brittle way, other lithologies deform in a ductile way. The boundaries between the response of a particular rock is, however, not very well defined, but depends upon many variables. Interbedded claystones and thick (>1m) anhydrite intercalations, react the most brittle to deformation [7]. Especially claystones (e.g. the Grey Salt Clay) can become entirely crumbled. Potassium-magnesium salts are most ductile in deformation (Figure 1). Pure lithologies are, however, an exception rather than the common practice. Mixed lithologies can show anomalous behaviour to what one expects. For instance, a thin-bedded alternation of anhydrite and salt can be deformed in a ductile manner [7], when one would expect a brittle behaviour as of massif anhydrite.

ad 3. The type of salt structure controls the internal tectonics. In rate of increasing deformation we separate between salt layers, pillows and domes (diapirs). Previously salt movement or halokinesis (Greek: ʽαλσ, salt; κινειν, movement) was considered a buoyancy driven process [15]. Salt movement, however, now is considered the resultant of the complex interplay of various intraplate stresses and buoyancy [16-18]. Extensional stresses caused the rupture of the stiff overburden, and the salt structures moved upwards. Compressional stresses squeezed these salt structures [18].

ad 4. We have to bear in mind that the orientation of the stress-field displayed a significant variation through geological history. In response, the flow directions of salt must have displayed variations, as these are triggered by the orientation of the stress-field [12].

A comprehensive overview of the internal structure with increasing deformation will be given below.

In *salt layers* the bedding of the top and bottom of the salt layer are parallel, like those of inhomogeneities like anhydrite beds. Faults may occur if their throw exceeds the thickness of the salt. This will normally be the case only in the marginal areas of the Zechstein basin or on intra-basinal highs. The internal structures are mainly flow folds with a horizontal orientation of the fold plain. They occur in the dm to 10's of m scale. Potassium-magnesium salts are the first affected by this folding (Figure 1). In some areas, basalt dikes cut the salt without much influence (Figure 2). Only a zone of between 5-10 cm from the basalt has been affected by the volcanic melts.

Figure 2. Basalt dike cutting the Werra (Z1) rock salt. The zone influenced by this process extends only up to 10 cm from the dike; no melting of the salt occurred. Mine Neuhof-Ellers, 535 m floor, Fulda, Germany. Chisel for scale.

Salt pillows formed by a more or less horizontal flow of the salt. This resulted in a pillow-like thickening of the salt. Normal faulting commonly affects the cover beds over the crest of the pillow. This thickening essentially is caused by a series of stacked large-scale flow-folds in the salt, with horizontal fold plains. This was reconstructed for the Anloo salt pillow [19] based upon a detailed analysis of the Anloo-1 well (Figure 3). Superimposed upon these large-scale folding we inferred smaller folds. In the late pillow stage, the direction of salt flow changes from horizontal to vertical. The mobilised salt (Z1 Salt or Z2 Salt) will start to intrude in the stratigraphically higher levels of the Zechstein in the salt pillow without yet the roof of the salt pillow being affected. The structure of the brittle rocks (carbonates, anhydrites) within a salt pillow is parallel to the top of the pillow. These beds will have been broken up in large slabs.

In *salt domes* or *diapirs* the sense of movement of the salt changed to vertical, and the salt broke through the cover beds. In many instances, the salt will have reached the surface at some point in the geological history. The main result on the internal structure is the superimposement of structures with vertical fold axes (curtain folds) upon the older generation of folds with horizontal fold axes. Along the margins of the diapir, friction between the cover beds and the uprising salt mass resulted in vortices within the

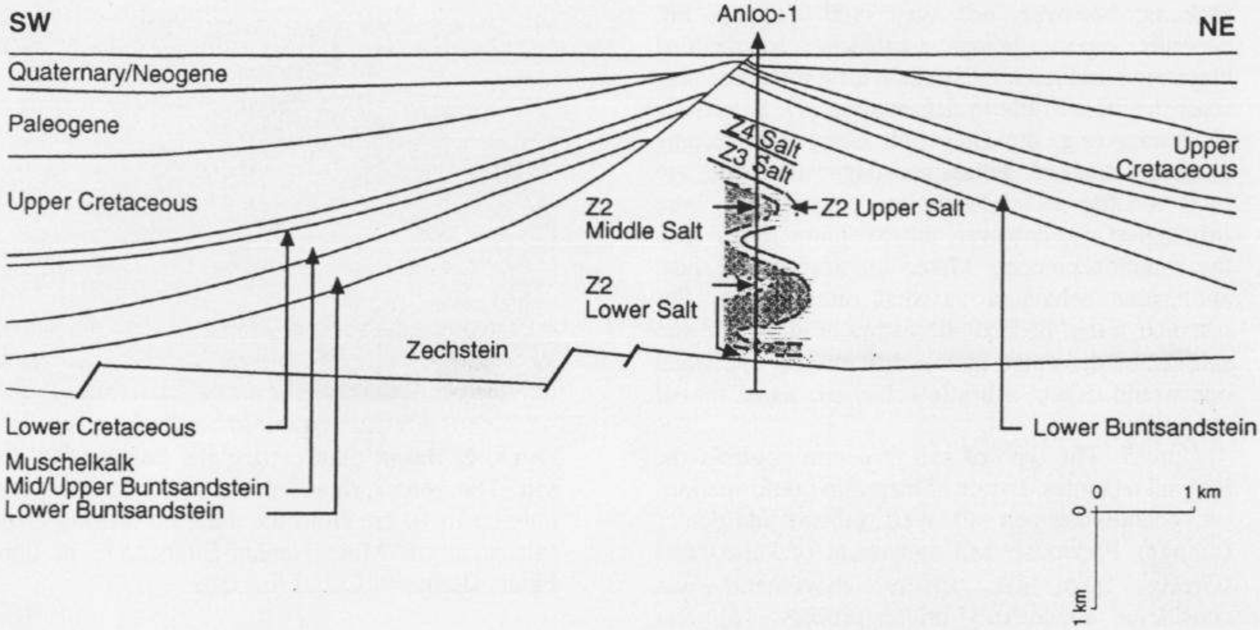

Figure 3. Internal structure of the Anloo salt pillow, based upon seismic mapping and the interpretation of the salt succession in the Anloo-1 well [12]

flowing mass, with an additional complex fault-pattern [11]. The whole of the upward movements resulted in an extremely complicated picture of the internal structure of salt domes, with folds in all different scales and orientations (Figure 4).

A generalised simplification of the structures is that the central parts of the salt dome will contain mostly Z2 (Stassfurt) Salt and the parts along the margin will be made up of younger salt units. This is shown to be true for many salt structures, as Benthe salt dome in Germany, Winschoten and Zuidwending in the Netherlands, and some of salt domes in the Dasht-i-Kavir in Iran [9,12,20]. For other structures, the opposite of this simplification is true; the central parts are made up also of younger salts and the Z2 (Stassfurt) Salt occurs at the margin. This occurs in the Gorleben and the Hänigsen salt domes in Germany and the Pieterburen salt dome in the Netherlands [3,20,21]. These are considered typical examples of squeezed salt domes.

Friction between the rising salt and the cover rock will cause strong folding near the margins, and

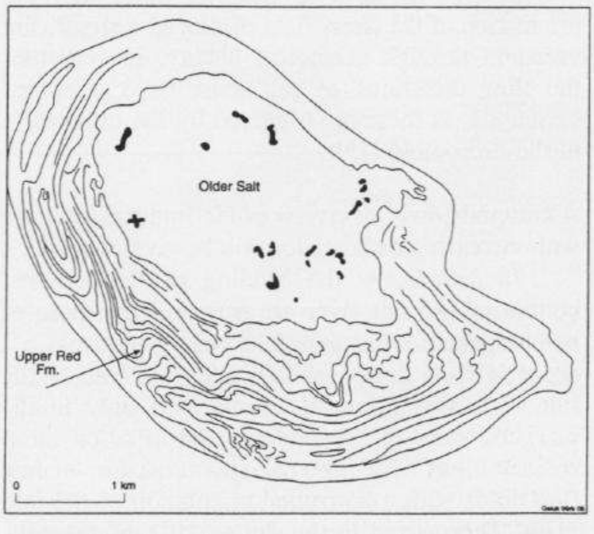

Figure 4. Line drawing of salt dome 20 in the Dasht-i-Kavir (Iran). This dome presents an analogon for Zechstein domes in NW Europe, where the Older Salt would represent the Z2 Salt, and the Upper Red Formation the Z3-Z5 salts. The black spots are volcanic rocks. After [11,12].

sometimes the salt contains blocks of the overlying succession. The salt in a diapir does not always move with the same speed; some parts display higher velocities that other parts [6]. The so-called spines are separated by shear zones occur from other parts of the salt structure, moving at different speed. They can be studied in outcrop at Cardona, Spain [13] and in Iran. In these zones blue halite crystals may occur in the vicinity of potassium-rich beds (Figure 5). Their blue colour is caused by free Sodium, set free by radiation from Potassium-bearing minerals [22].

Figure 5. Blue halite crystals (dark spots on the picture) in a shear-zone near Gamsar (Iran). Pen for scale.

5. CONCLUSION

The main conclusion of this paper is, that the internal tectonics of salt structures always is more complex than we think. We have to address each structure as an individual. It is hard to predict the internal structure, but unravelling the structural development of individual salt diapirs might provide a clue. Hereby we have to take into account the stress history since the Zechstein, and to include this in models. Detailed knowledge of the stratigraphy of the salt is hereby of great importance [19,23,24].

The following steps should be followed in predicting the internal tectonics of a given salt structure:

1. to assess the inhomogeneities within the salt. Ideally, this should be carried out with all available well information in the vicinity, supported by seismic data. Lateral facies variations within the salt and the anhydrites should be taken into account.
2. to understand how these inhomogeneities will react to deformation.
3. to determine the structural position of the structure (bedded salt, pillow, salt dome, salt wedge) and its shape (elongated, circular, overhangs etc.). This is carried out by detailed seismic mapping.
4. to unravel the structural development in geological history; was the salt flow symmetrical or asymmetrical? Did the shape of the structure stay the same during geological history? What were the consequences of the salt flow pattern for the internal structure?

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