Salt occurrences in the Netherlands and Germany: new insights in the formation of salt basins

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Based on regional seismic mapping projects, a twofold subdivision can be applied between the tectonic setting of salts basins. This subdivision has practical applications in understanding and predicting lateral variations in thickness and lithology in a given salt succession. The first group comprises salt basins with a regional thermal subsidence. The internal configuration of the salt deposits was controlled to a great extent by the original palaeogeographical setting and the basin configuration. Knowing these factors is considered essential for understanding the salt succession. The second group of salts was deposited during periods of active tectonic movements. It shows a rapid, fault-controlled lateral variation, both in thickness and lithology. Rift zones tend to show more complete sedimentary record. Most salt deposits, however, show features of both groups. In this paper, two salt formations will be discussed in detail.

Salt basins show a behaviour which deviates strongly from clastic basins. This is caused by the far greater effects of sediment loading in an evaporite basin, owing to the high sedimentation rates of many of the evaporite minerals. Rifting is identified as a key process to create accommodation space for deposition of evaporites. After this space is filled with salt or anhydrite, loading of these minerals creates new accommodation space, which is filled with new evaporites.

1. INTRODUCTION

In the subsurface of the Netherlands and Germany a wide variety of salt deposits occurs. They are used for mining of rock salt or potassium-magnesium salts; besides, some of salt occurrences are used for storage of gas and liquid fluids and disposal of radioactive and toxic wastes. Furthermore, the salts form an excellent seal for hydrocarbon reservoirs.

Based on recent subsurface mapping projects in the Netherlands and NW Germany new insights have been obtained in the genesis of evaporite basins. Evaporite basins were previously mainly described in terms of the extreme arid climate and their polycyclic infill (i.e. [1-4]). Little attention was paid to the tectonic setting of the evaporite basins. Probably because evaporite layers can be correlated over large distances [2,3] it was assumed that these basins were tectonically quiet.

Subsurface mapping techniques have considerably improved over the last decades, with 3D seismics becoming applied as an exploration tool. This allowed the recognition of geological details previously not identified. With the support of the great well density in NW Europe, a clear separation in types of evaporite basins can be made between basins with a regional subsidence and rift basins. his paper starts with an overview of the basins. This paper starts with an overview of the salt deposits in the Netherlands and NW Germany.

Differences in tectonic setting will be

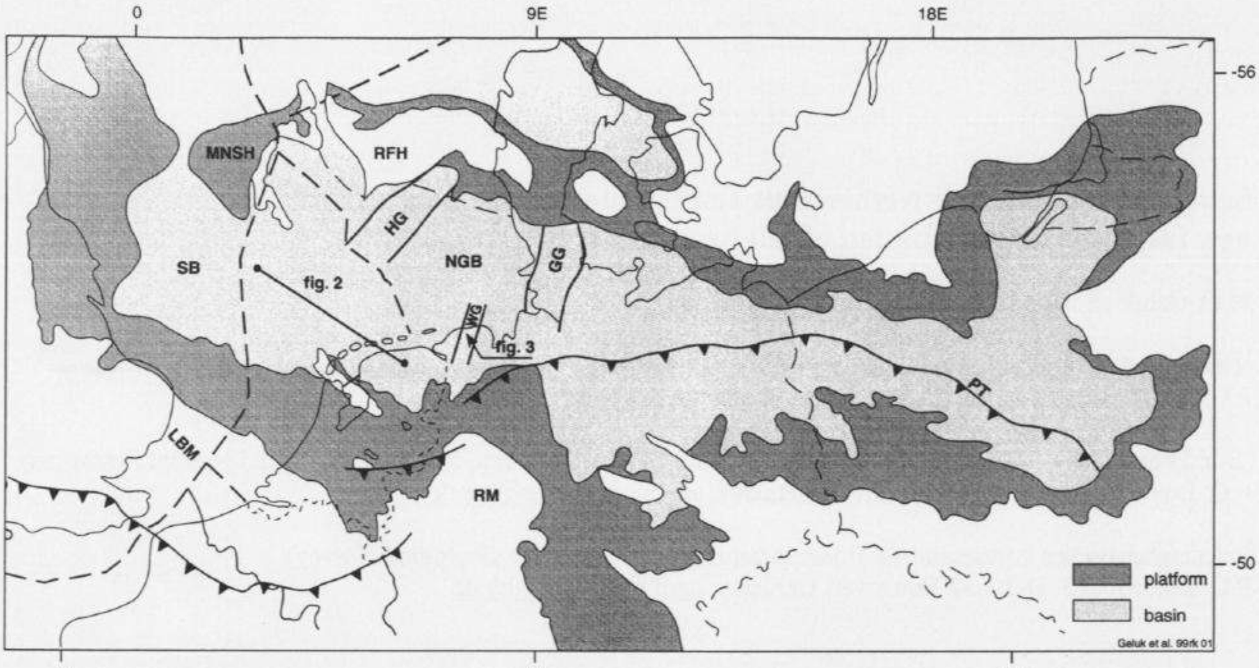

Figure 1 Outline of the Zechstein basin, showing the paleogeography at the beginning of the deposition of the Z2 (Stassfurt) Salt. SB: Silverpit Basin, LBM: London-Brabant Massif; RM: Rhenish Massif; NGB: North German Basin; PT: Polish Trough; MNSH: Mid North Sea High; RFH: Ringkøbing-Fyn High; WG: Westdorf Graben.

illustrated with an example of the Zechstein (Upper Permian) for a regionally subsiding basin and of the Muschelkalk (Middle Triassic) for an interaction of rifting and regional subsidence. The development of salt basins and their tectonic setting will be discussed at the end of this paper.

2. OVERVIEW OF THE SALT FORMATIONS IN THE NETHERLANDS AND NW GERMANY

The major part of the salt formations in the subsurface of the Netherlands and Germany is of Permian and Triassic age. Table 1 presents an overview of the major evaporite formations and the type of basin. Only the larger units have been presented; a further subdivision exist for many of the evaporites (i.e. Zechstein and Keuper) but it lies beyond the scope of this paper to treat all

beyond the scope of this paper to treat all formations in detail. Details of the various evaporite formations in the Netherlands and NW Germany can be found in literature [4-13].

Table 1. Overview of the evaporite formations in the Netherlands and NW Germany and their tectonic setting. The formations discussed in this paper are highlighted.

Evaporite unit/age	Basin type
Malm (Late Jurassic)	Rift
Keuper (Late Triassic)	Rift
Muschelkalk (Middle Triassic)	Rift + regional
Röt (Middle Triassic)	Regional
Zechstein (Late Permian)	Rift + regional
Rotliegend (Late Permian)	Rift + regional

In this paper, two salt formations will be discussed in detail. They have been selected because they present examples of different basin types, and because they have been subject of recent studies. First, the Z2 Salt of the Zechstein will be proposed as an example for a basin governed by regional subsidence. Second, the Middle Muschelkalk Salt will be proposed as an example of regional subsidence in combination with rifting.

3. EXAMPLES OF SALT BASINS

3.1 The Z2 Salt in the Zechstein Basin

The Zechstein basin is situated in the western part of the Southern Permian Basin, a large intracratonic basin stretching from the UK in the west to Poland and Lithuania in the east (Figure 1). This basin was bordered to the south by the London-Brabant Massif and the Rhenish Massif, and to the north by the Mid North Sea and Ringkøbing-Fyn High. This basin developed during Early Permian times in response to volcanism and E-W wrenching, and was inundated during Late Permian times from the Barents Sea to the north [3,4]. The repeated isolation from the ocean and the hot, arid climate resulted in the widespread sedimentation of evaporites in the Southern Permian Basin [14]. The basin morphology comprises an inherited topography from the underlying Rotliegend deposits, which was modified by extensional tectonics during deposition of the Z1 (Werra) Formation [15].

In this basin, a succession of predominantly salts was deposited. The thickest salt in the Southern Permian Basin is the Z2 or Stassfurt Salt. It filled in most of the relief in this basin, whereas the Northern Permian Basin was filled mainly by the Z3 or Leine Salt [14].

The Z2 Salt is treated as one unit in most of the area. Only in Germany it has been locally further subdivided. The Z2 Salt is composed of an alternation of 8-10 cm thick halite layers, and thin (1-2 mm) anhydrite layers. On a larger scale, three sequences have been identified in the Netherlands, based upon their wireline-log response. The subdivision can be applied to both the onshore and offshore area of the Netherlands, the UK Southern North Sea and parts of NW Germany [16]. The sequences, defined as the Z2 Lower Salt, Z2 Middle Salt and Z2 Upper Salt, each have their own

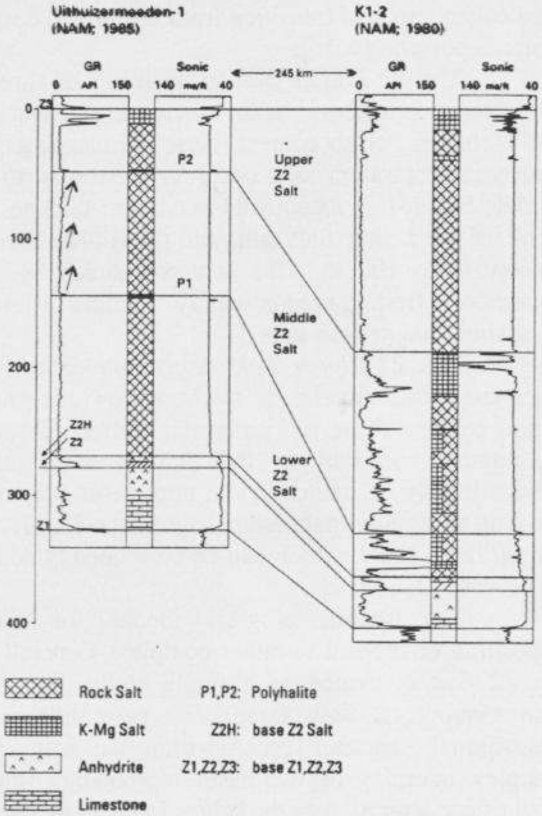

Figure 2. Well correlation of the Z2 Salt. The well Uithuizermeeden-1 reflects a position on the platform of the basin, while the K1-2 well is situated in the basin centre.

characteristics. The salt units are separated from each other by regionally extensive Polyhalite marker beds, which are assumed to mark a sudden influx of fresh sea water into the brine-filled basin [16]. Figure 2 shows a log correlation between the margin of the basin, represented by the Uithuizermeeden-1 well, and the centre of the basin, represented by the K2-1 well.

The *Z2 Lower Salt* is a sigmoidal-shaped salt body, which reaches its greatest thickness directly north of the former Z2 Carbonate platform areas. Within this body, a clear change in lithology occurs; in places where this salt unit reaches its maximum thickness it consists predominantly of halite. Towards the basin centre, the unit thins to 50 m, accompanied by a lithological transition from pure halite into a rapid alternation of polyhalite, carnallite and halite beds. It is assumed to represent a paleogeographical transition from shallow to deep water deposition [9, 16].

The *Z2 Middle Salt* is made up of three characteristic cycles, with increasing natural radiation, i.e. Potash content. Near the margins of the basin, Potassium salts occur in the top of the Middle Salt [5]. It reaches its maximum thickness north of the Lower Salt unit, and afterwards thins basinward to 100 m. This is accompanied by a transition from predominantly halites into potassium-magnesium salts.

The *Z2 Upper Salt* displays a different thickness development; it thickens towards the basin centre. There is no major difference in lithological composition, the unit is made up predominantly of halite. In the uppermost part of the unit, potassium-magnesium salts of the Stassfurt potash layer occur, which can be correlated almost basin-wide [4, 14, 17].

The sedimentological model for the deposition of the salt is rather complex. Generally the Z2 Salt is treated as a single entity, but as shown above, at least three units with different depositional character occur within the salt. A complex interplay of the basin morphology, the level of concentration of the brines in the basin and the amount of fresh sea-water flowing in the basin controlled the minerals deposited. In the Lower and the Middle Salt, the initial basin topography still controlled the thickness and lithology. A clear separation between a shallow-water setting, with halite precipitation, and a deep-water setting with a condensed succession of various salts can be made. These salts are separated by Polyhalite marker beds, which reflect isochronous changes in chemistry of the brines in the basin. At the end of the deposition of the Z2 Upper Salt, differences in relief decreased. The salt reflects an infilling of the remaining relief in the basin. During deposition of this salt, the basin did not dry out completely, in view of the good lateral correlability of the Stassfurt Potash Seam throughout the basin.

In its later history, there is a record of the drying-out of the Zechstein basin in the Z3 Leine Salt. Some remaining salt ponds showed a variety of potassium and magnesium salts, including the highly soluble Bischoffite ($MgCl_2.6H_2O$) [4, 9, 18].

3.2 The Middle Muschelkalk salt

The Middle Muschelkalk was deposited in the southern Mid-European Basin, which is known as the Germanic Basin during Triassic times. The outline of this basin was in broad terms similar to the Zechstein Basin (figure 1).

From the Middle Anisian onwards, a marine environment dominated the North German Basin. The Muschelkalk was deposited in an intracratonic epeiric sea. Hypersaline conditions prevailed during sedimentation of the Middle Muschelkalk (Late Anisian). Contemporaneously with a sea level rise at the Anisian/Ladinian boundary, fully marine conditions were restored.

In the North German Basin the Middle Muschelkalk contains a succession of approximately 150 m thick evaporites. Salt precipitation led to the development of 6 salt-bearing layers of different lateral extent. They have been studied recently [10-11] using cores and wireline logs. The Remlingen borehole, in which the halite beds of the Middle Muschelkalk were completely cored, has been used as a standard profile. Microfacies and geochemical studies allow a subdivision of the sequence into 9 cycles and which are interpreted as chemocycles.

Chemocycle 1 consists only of dolomite without massive anhydrite and halite. It was deposited in the centre of the basin as well as at the margins. The saliniferous cycles of the Heilbronn Formation, the chemocycles 2 to 8 consist of dolomite, anhydrite and halite. The complete second chemocycle comprising, dolomite to halite, is preserved only in the basin centre. Towards the basin margins the halite of the second chemocycle is missing. In this paleogeographic position the carbonates, sulphates and the halite of the third chemocycle directly overlap the lower part of the second cycle. Over the whole North German Basin the third chemocycle contains halite. This chemocycle is the most widespread and the thickest of all cycles. A sequence of dolomite, marl, anhydrite and halite is typically for the third chemocycle. Over the hole north German Basin the fourth chemocycle shows a characteristical development formed by anhydrite or anhydritic marly clay intercalated by a salt layer at the base and halite at the top of this cycle. In the chemocycle 5 halite has only been deposited in the basin centre. In contrast to the underlying cycles the halite beds developed here are more contaminated with claystone/anhydrite.

During the Middle Muschelkalk, tectonic

activity gave rise to horsts and grabens, which influenced sedimentation in the North German Basin. Extremely thick Middle Muschelkalk was encountered in the Glückstadt, Horn and Westdorf grabens. In the Westdorf Graben approximately 525 m of Middle Muschelkalk was drilled and all cycles displayed unusual thickness. As a local phenomenon, chemocycles 6 and 7 here contain halite (figure 3).

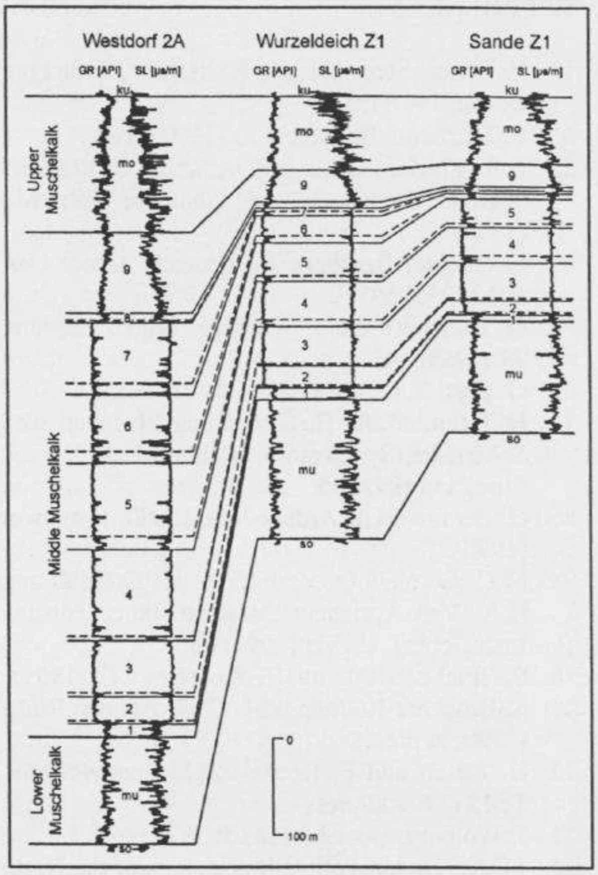

Figure 3. Correlation and subdivision in chemocycles of the Middle Muschelkalk in the center of the Westdorf Graben (Westdorf 2A) with the SW margin (Wurzeldeich Z1) and outside the graben (Sande Z1); ku: Lower Keuper.

Thickness development and stratigraphic completeness of the evaporitic Muschelkalk were guided by tectonic movements belonging to the Early Cimmerian rifting processes, which began in the Buntsandstein (Hardegsen phase [19-21] and continued with some slowdowns in the Middle Muschelkalk [10-11] and the Middle Keuper [8, 12, 13]. Whereas the distribution and thickness of the salt layers of the Röt are controlled by the basin configuration e.g. the regional thermal subsidence, the salts of the Middle Muschelkalk tend to be constrained partly to the rifts and grabens e.g. to zones of high subsidence, whereas outside these lows a sedimentary hiatus or condensed sections occur. The salts in these lows display a great variation in thickness, lithology and sequential development; these reflect the local variations in depositional setting and the tectonic behaviour of the grabens. These salts are not only an expression of climatic changes; they marked a distinct phase of structural development and are therefore syn-rift sediments. Extensional tectonic stresses, related to the disintegration of the supercontinent Pangea, were responsible for these rifting movements.

4. DISCUSSION

The examples presented in this paper show that in a basin dominated by regional subsidence, gradual lateral changes in depositional thickness and mineralogy can be expected. In the Z2 Salt a change from platform-type halite sedimentation to deep-water salts can be observed in the Lower and Middle Salt units, whereas the Upper Salt unit filled the remaining relief in the basin. In the late stages of deposition of the Upper Salt, a large shallow basin remained; here the Stassfurt Potash Salts were deposited. Hence, the infill of the basin clearly was a multiphase event, not a simple single evaporation process of the brine. It records the effects of several sea-level fluctuations, which are recognised throughout the basin. Prediction of the lithological composition of the salt requires a proper understanding of the original basin morphology and sedimentary conditions.

The Middle Muschelkalk Evaporite on the other hand is an example of combined rift-related and thermal sedimentation. The basal and uppermost chemocycles of the Middle Muschelkalk are restricted to rifts, whereas the other salts have a regional distribution. Predicting the lithological variations in the salt requires a proper understanding of the basin tectonics.

In geological basin reconstructions, no clear distinction is made between evaporite and clastic basins, except for the arid climatic conditions during evaporite sedimentation [3]. This is, however, only one of the differences, and not the most important. The sedimetation of evaporite minerals, rock salt in particular, distinguishes itself in two ways from clastic sediments:

- Rock salt precipitates up 1000 times faster than clastic sediments (10 cm/a compared to 10 cm/ka) [22];
- Rock salt does not show compaction effects during burial, but has a depth-independent density of 2.14 g/cm^3; it is controlled by the crystalinity of the salt, not the intergranular porosity as with clastic sediments.
- Anhydrite has lower sedimentation rates than rock salt (4 cm/a), but a much higher density (2.9 g/cm^3)

These differences have a great impact on the behaviour and development of evaporite basins in comparison to clastic basins, which are generally not considered. Any initial topography in an evaporite environment is filled in almost instantaneously (on a geological scale) with salt or anhydrite. Furthermore, the weight of this evaporitic infill is much higher than that of clastic rocks, causing a substantially greater basement loading and renewed subsidence. The evaporite infill in this way triggers renewed subsidence, which is filled again by evaporites. It is clear that subsidence models applied to clastic sedimentary basins can not be applied in a similar way to evaporite basins, and a clear distinction between these types is proposed with respect in basin modelling.

Rifting is identified as a major process in the creation of initial accommodation space. Most evaporite basins originated after a rifting pulse, also the basins which are considered examples of regional, thermal subsidence.

5. CONCLUSIONS

Evaporites have been deposited under quite different basin conditions. Basins where the subsidence is of regional, thermal origin, show an evaporite succession where the lateral variations are governed by the dynamics of the sedimentary system. Understanding the sedimentary system is the key to the prediction of the evaporite successions.

In rift basins on the other hand, tectonics control the distribution and facies of the individual salt layers. Understanding the tectonics is the key to understand the evaporite characteristics.

Evaporite basins form a unique type of basins, in view of the high sedimentation rates and the loading effects of their basin infill. Rifting has been identified as a major process to create the initial accommodation space, in other words to create an evaporite basin.

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