Structural Geology and Genetic Analysis – Tools to decipher Internal Structures of Salt Bodies in a Pre-selecting Phase

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Information on internal structures of salt bodies are economically essential but difficult to obtain and at high costs. In all salt basins around the world sufficient modern 2D and 3D industrial hydrocarbon reflection seismics exists to decipher the outer morphology of salt structures and to draw conclusions on their genesis. Salt structures examples from northwest Germany and the North Sea clearly show that salt structures originated by dilatation of the pre-salt basement and the sedimentary overburden. Salt structures originated in a transtensional stress field show less complicated internal structures and seem to be more suited as hosts for caverns and radioactive waste disposal sites. Many salt structures in NW Germany suffered after their origin in a dilatational stress field a later overprinting by compressional forces. This overprinting caused large overhangs and stems very much reduced in diameter. Additionally salt wedges are pressed into the Mesozoic wall rock, especially into the Triassic salt layers. These features caused by compression during the inversion show extremely complicated interior structures in the salt layers and no large bodies of pure halite can be expected. These overprinted salt structures should not be taken into consideration when pre-selecting potential sites for caverns and other purposes.

When pre-selecting salt structures for cavern installations, disposal sites for toxic or nuclear waste, solution mining or whatever it is advisable to have sufficient information on the internal structure of the salt bodies in order to hit the most pure and uncontaminated portions of rock salt. Unfortunately this information as a rule is very scarce and the old miner's saying valid, that in front of the hoe it is dark. Data on the internal structure can only be obtained by expensive directed drilling into the salt body or sophisticated borehole measurements, but not from outside by any geophysical method.

Extensive research on more than 200 northwest German salt structures using interpretation of commercial 2D reflexions seismics executed for hydrocarbon prospection in the last 10 years have shown that there might be the possibility for at least a rough prediction of the interior qualities of salt bodies from the outer morphology and the deciphering of the genesis of salt structures. This will be demonstrated on examples from northwest Germany and the German North Sea sector. A pre-requisite for this method is that the seismic sections are optimally processed and migrated and seismic imaging is reliable.

The most ideal salt bodies to plan underground installation in, are salt pillows consisting only of either Zechstein or Keuper or Upper Jurassic salt. In the case of a Zechstein salt pillow it is a rule that the salt first mobilised is the pure halite of the Stassfurt cycle, which forms the core of the body, whereas the younger and more impure salt layers of the Zechstein 3 to 7 normally concordantly underlie the Buntsandstein of the pillow roof. Fig. 1 shows such a Zechstein salt pillow with a crest half graben at its top. The crest graben faults are covered by Late Tertiary sediments. This observation contradicts the hypothesis of TRUSHEIM (1960) and SANNEMANN (1968) of the pure halokinetic, that means autonomous and a-tectonic origin of salt diapirs, driven only by density differences. According to the halokinesis theory from a salt pillow with a crest graben a diapir should automatically originate and a salt pillow never should go to sleep again.

Unfortunately most of the salt pillow tops in NW Germany are deeply buried and therefore these structures are not suitable for opening up disposal mines in them.

As a rule diapirs in NW Germany and the German North Sea sector straddle pre-salt basement faults or lineaments and diapir distribution traces the basement fault pattern. The basement faults beneath the diapirs can either be observed directly in the seismic imaging or can be assumed from the asymmetry of the diapir and its rim synclines. Figs. 2 to 6 show a collection of asymmetric diapirs straddling basement faults. The ages of the secondary rim synclines are different across the fault. If salt is triggered by the movements along the basement fault and the overburden broken up sufficiently by the transtensional movements in a dilatation stress field, the salt will first move from the downthrown block into the diapir and only later from the high block. This will also cause asymmetric internal structures within the diapir and further complications which should be considered during exploration.

The dilatation pulses which triggered diapirism in the post-Permian overburden in NW Germany are rather short-lived and can be dated quite accurately: Buntsandstein prior to the "H"-unconformity, Middle Muschelkalk, Lower and Upper Gipskeuper prior to the Steinmergelkeuper unconformity, Lower Jurassic to Aptian (several pulses, the most intense during the Upper Jurassic "Münder Mergel Fm.) and Tertiary (several pulses, the most intense post-Middle Miocene). Nevertheless the age of diapirism has, as far as is known, no influence on the internal structures of the diapirs.

There are several diapirs in NW Germany which entirely lack all attributes of a "halokinetic" salt structure, especially the primary and secondary rim synclines. They are just salt-filled open faults in the Mesozoic overburden (fig. 7) and larger quantities of pure Stassfurt halite cannot be expected in them. Or the diapir has still so much salt preserved in its huge "pillow feet", that secondary rim synclines had not yet developed (fig. 8).

As already mentioned, diapirs in NW Germany originated in periods of rifting and dilatation. Space for the diapirs is created by stretching and breaking up the Mesozoic overburden during the rifting process. Diapirs on the other hand have a much more differentiated interior structure and for this reason exploration is much more expensive. Great parts of NW-Germany nevertheless after Triassic and Jurassic dilatation underwent compression and crustal shortening in combination with basin inversion in Late Cretaceous times, precisely during the Coniacian to Campanian. Compression and inversion strongly affected the Lower Saxony Basin, the southern Central Graben in the North Sea and the Braunschweig-Gifhorn fracture zone, but compressional features have also been observed along major lineaments in other parts of the North German basin. Existing salt structures which formed in a dilatational stress regime may become overprinted by Late Cretaceous compression. The external morphology and the internal structure then will alter: the stems become narrow and squeezed-out salt will form large overhangs, probably submarine salt glaciers. The former amount of dilatation of the overburden during the rifting phase may become overcompensated by compression (figs 9 - 11).

During compression and inversion "salt wedges" may originate (fig. 12 - 15). These are wedge-shaped intrusions of Zechstein salt into Mesozoic salt layers within the overburden, preferably into the Upper Buntsandstein Röt salt level, but also in the Middle Muschelkalk and Middle Keuper salt formations. Salt wedges proceed from diapir flanks or from major salt-filled faults. Transitions exist between overprinted salt structures and inversions structures. Salt-influenced inversion structures often show salt wedges.

Salt wedges can be very large - more than 20 km long - and may reach more than 8 km into the neighbouring rocks. They have been drilled several times and they can be recognised in the seismic images by the angle formed between the Buntsandstein and the Muschelkalk reflectors.

If a salt wedge by inversion is pushed up to the surface and the salt in the wedge is leached, the roof of the wedge will break down and form chaotic collapse structures, the so-called "Bruchfelder" in Lower Saxony the genesis of which could not be explained properly for more than a century.

Although at the turn of the century in NW Germany several potash mines had been sunk into salt wedges (Asse, Leinetal structure, figs. 12, 14) - the miners were always puzzled when they drilled from the galleries into the bottom of the mine and found Triassic Buntsandstein instead of the expected Zechstein salt. Compressed salt structures with salt wedges are not very suitable for hosting caverns or waste disposal sites. The highly mobile Stassfurt halite, normally forming the central part of the structure, is often squeezed out, wedge and over-hangs show highly complicated interior structures and the stems are narrow. The chance of finding larger quantities of pure rock salt is limited.

There are all kinds of transitions between salt wedges and salt-lubricated thrusts or thrust zones in the inverted parts of the basin, especially along the northern border of the Lower Saxony basin (fig. 16). Many of these salt accumulations in thrusts used to be regarded as diapirs but these salt bodies now have no connections with the original Zechstein salt layer. The salt on the thrust plains form a second structural decollement plain above the Zechstein salt layer in the Triassic. Salt-lubricated thrusts are totally unsuited for salt mining or underground storage installation and should be avoided.

A first step into estimating chances and risks of finding sufficient quantities of pure Stassfurt halite in a salt structure in order to construct underground installations like caverns or waste disposal mines safely, is the study of the outer morphology of the structures in commercial 2D reflection seismic lines produced by the hydrocarbon industry. Outer shape and genesis of the structures allow conclusions about the complexity of the internal structure to be made. Especially salt structures, which became re-shaped by the compressional stress field in Late Cretaceous times, salt wedges and salt-lubricated thrusts in general are less suitable for underground installations.

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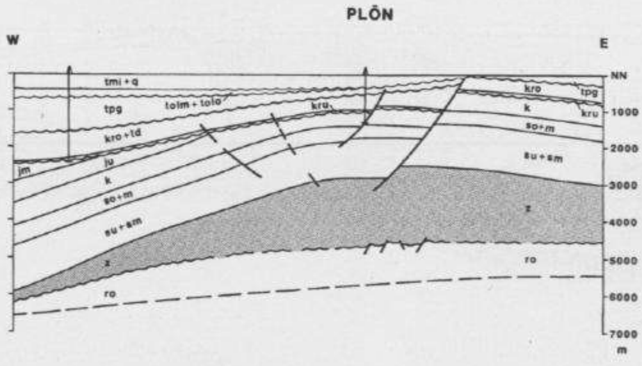

Fig. 1. Plön. Zechstein salt pillow with dilatation crest graben in the roof. Note the mobilised Rotliegend salt (Dethlingen and Hannover formations) beneath the basal Zechstein. The broken roof indicates stronger dilatation, but a diapir has not developed. Pillow activity decreased in Palaeogene and Neogene times. By DENEKE 1983 (BALDSCHUHN et al. 1996, 1999)

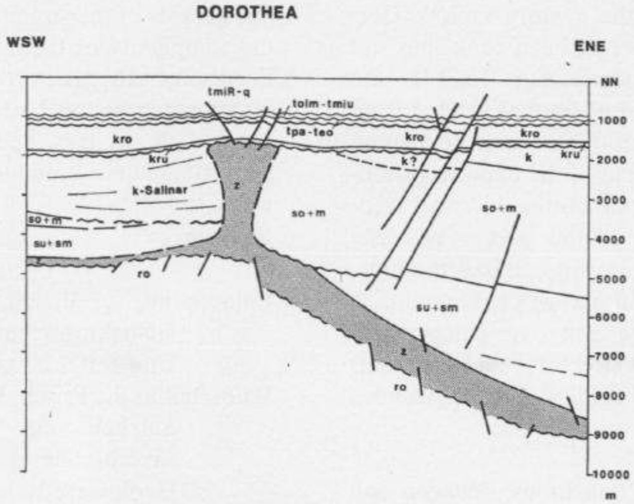

Fig. 2. Dorothea. Asymmetrical diapir straddling the western boundary fault of the Horn Graben, (German North Sea). By JÜRGENS 1989 (KOCKEL ed. 1995)

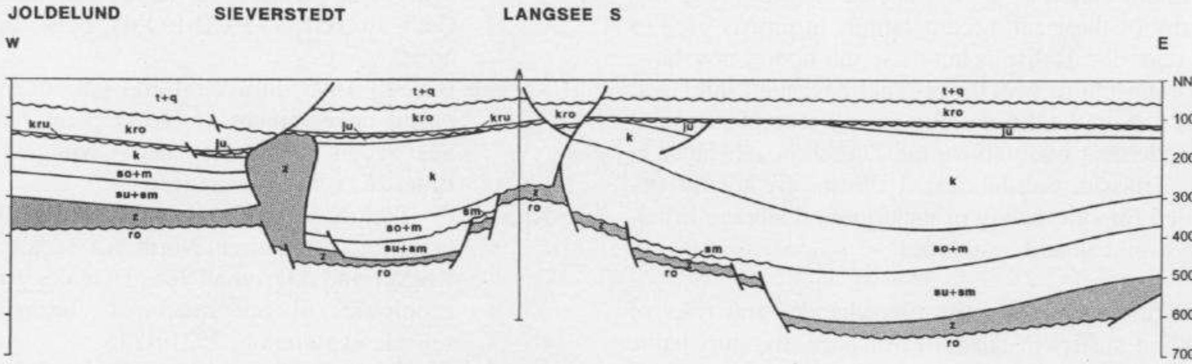

Fig. 3. Western boundary of the northern Glückstadt Graben. The salt structures straddle basement block boundaries. By BEST 1985 (BALDSCHUHN et al. 1996, 1999)

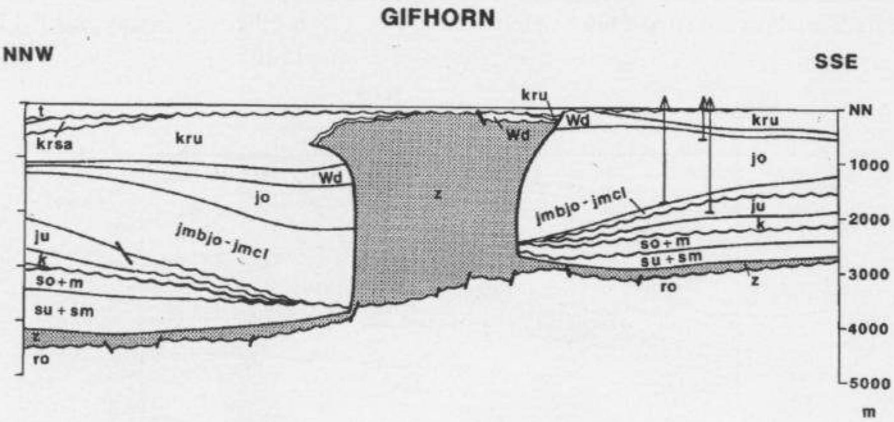

Fig. 4. Gifhorn. Asymmetrical salt diapir straddling basement fracture zone. Note the different ages of the secondary rim synclines to the left (= downthrown block, Bajocian-Callovian) and right (Upper Jurassic). By BALDSCHUHN 1983 (BALDSCHUHN et al. 1996, 1999)

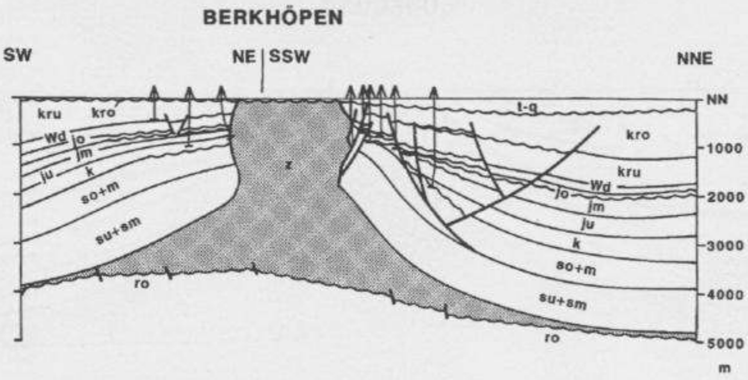

Fig. 5. Berkhöpen. Asymmetrical salt diapir straddling basement fracture zone. By BALDSCHUHN 1983 (BALDSCHUHN et al. 1996, 1999)

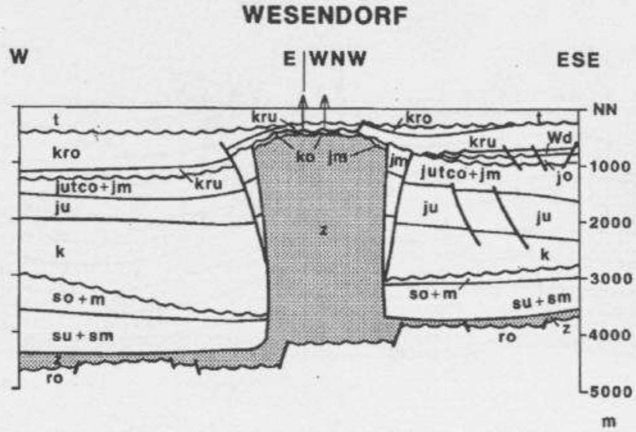

Fig. 6. Wesendorf. Asymmetrical salt diapir straddling basement fracture zone. By BALDSCHUHN 1983 (BALDSCHUHN et al. 1996, 1999)

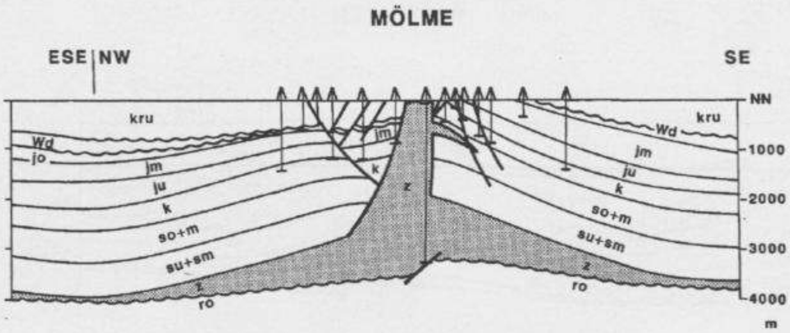

Fig. 7. Mölme. Salt-filled fault, repeatedly active during the Mesozoic. Note, that this „diapir" has no secondary rim synclines. By KOCKEL 1984 (BALDSCHUHN et al. 1996, 1999)

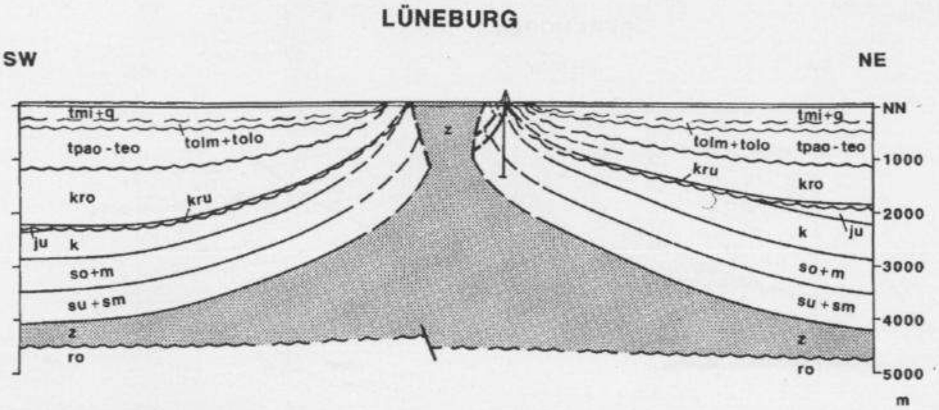

Fig. 8. Lüneburg. This diapir which reaches the surface, has not yet developed secondary rim synclines. By JÜRGENS 1982 (BALDSCHUHN et al. 1996, 1999)

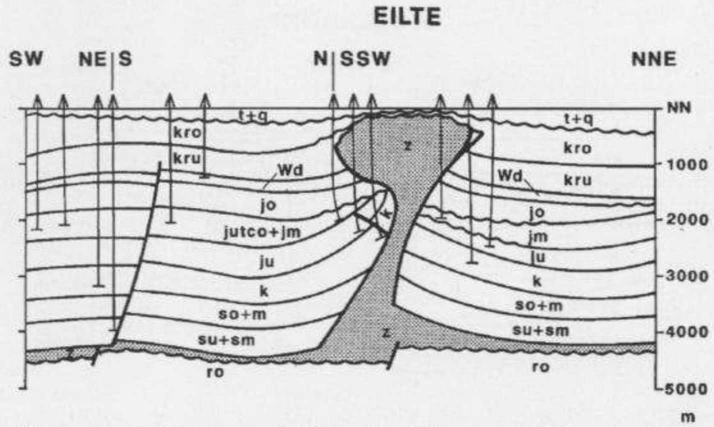

Fig. 9. Eilte. Salt diapir straddling basement fault as part of the Allertal lineament. Active diapirism took place in Upper Jurassic-Lower Cretaceous times, compressional overprinting by inversion in Late Cretaceous times. By BALDSCHUHN 1985 (BALDSCHUHN et al. 1996, 1999)

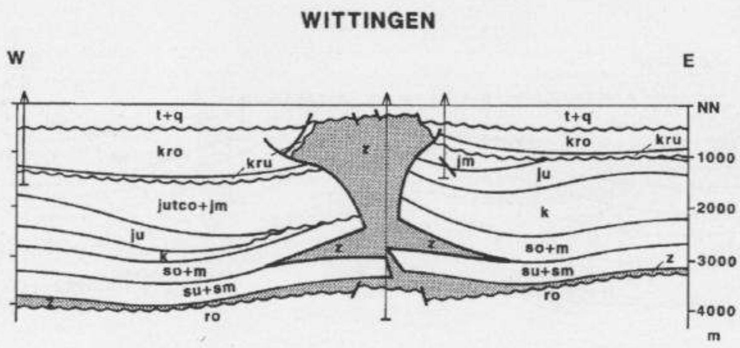

Fig. 10. Wittingen. Salt diapir straddling the NNE-SSW-trending Braunschweig-Gifhorn fracture zone. The diapiric phase took place in the Middle Jurassic times, compressional deformation and formation of salt wedges in the Upper Buntsandstein salt level in Late Cretaceous times. By FRISCH 1994 (BALDSCHUHN et al. 1996, 1999)

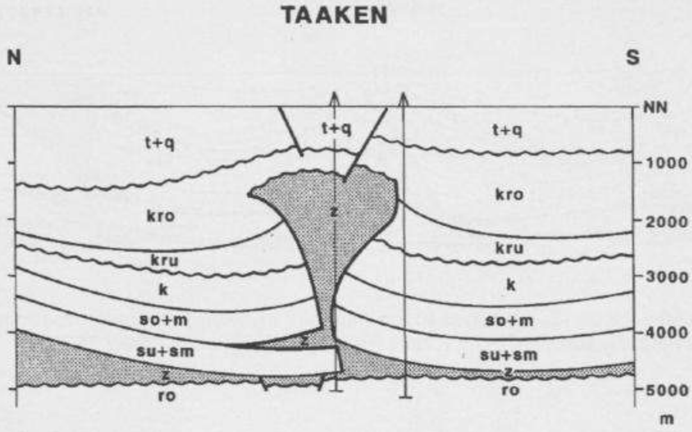

Fig. 11. Taaken. Salt diapir. The diapiric phase took place in Early Cretaceous times, overprinting by compression in Late Cretaceous times. Note, that in the Buntsandstein level the former dilatation is overcompensated by compression, as Lower and Middle Buntsandstein are doubled. By FRISCH 1994 (BALDSCHUHN et al. 1996, 1999)

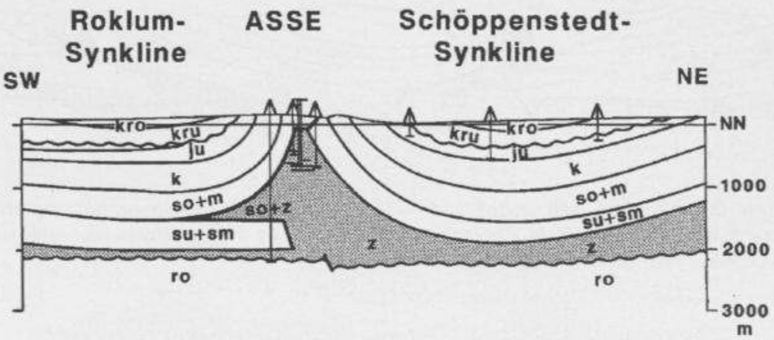

Fig. 12. Asse. Salt structure and salt wedge in front of a thrust, a result of Late Cretaceous compression. By KOCKEL 1987 (BALDSCHUHN et al. 1996, 1999)

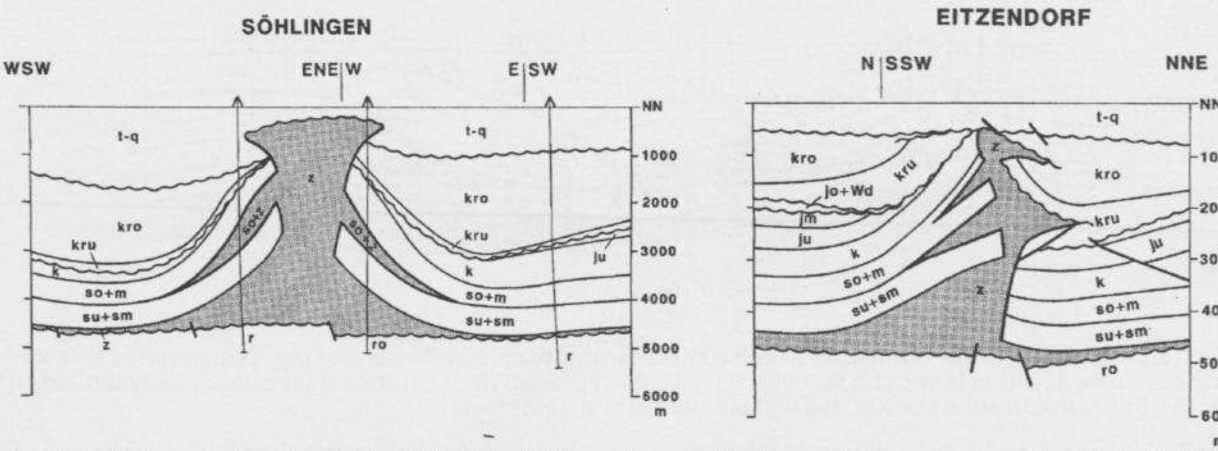

Fig. 13a. Söhlingen. Salt wedges in the Röt salt level. The wedges are tilted by post-Cretaceous rise of the diapir. By BALD-SCHUHN 1987 (BALDSCHUHN et. al. 1996, 1999)

Fig. 13b. Eitzendorf. Salt wedges in the Röt and Middle Muschelkalk salt levels. The structure straddles the inverted Aller lineament. By FRISCH 1994 (BALDSCHUHN et. al. 1996, 1999)

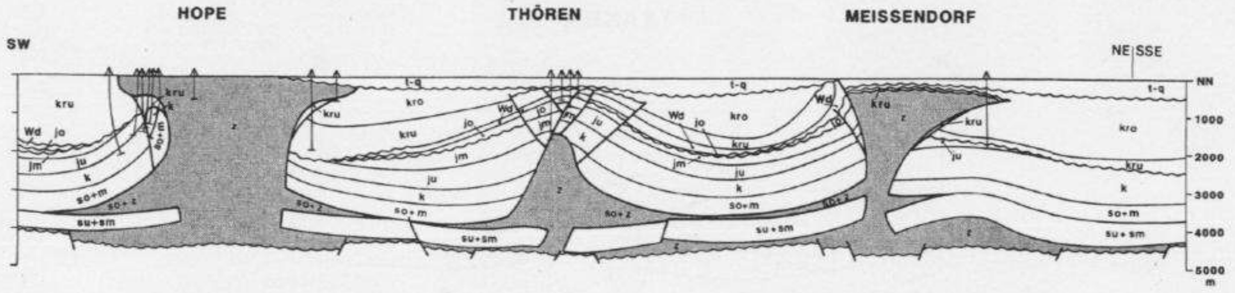

Fig. 14. Meissendorf – Thören – Hope. Salt wedges at the flanks of inverted and compressed salt structures straddling basement faults of the Aller lineament. By BALDSCHUHN 1987 (BALDSCHUHN et. al. 1996, 1999)

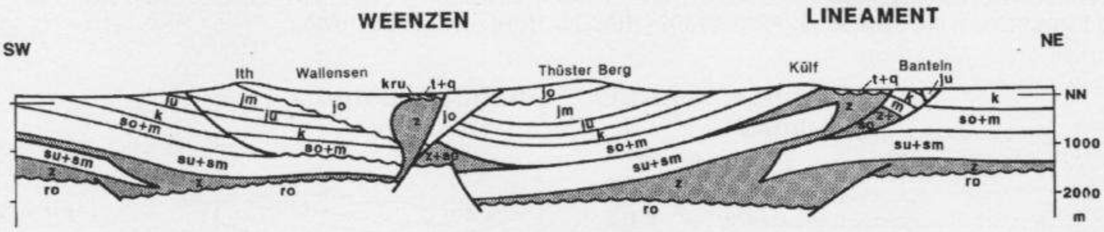

Fig. 15. Leinetal structure. Salt structure, salt wedge and salt-lubricated thrust. In Upper Jurassic times the Leinetal structure was a normal fault, dipping towards the SW. In Coniacian-Santonian times this fault was reversely activated and transformed into an overthrust. By KOCKEL 1987 (BALDSCHUHN et al. 1996, 1999)

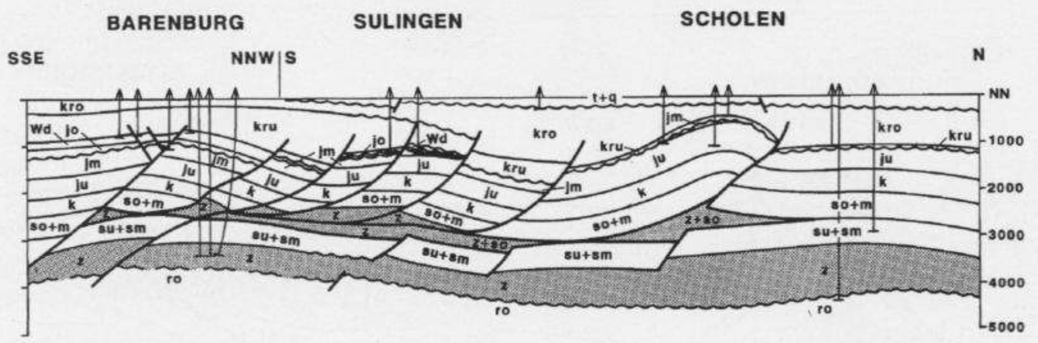

Fig. 16. Barenburg, Sulingen, Scholen. Inversion structures at the northern boundary of the Lower Saxony Basin. Note the decollement in the Zechstein layer and in the Upper Buntsandstein salt level. The thrust plane is lubricated by Zechstein and Triassic salt. By BALDSCHUHN & KOCKEL 1997 (BALDSCHUHN et al. 1996, 1999)