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ORIGINAL PAPER

Yuriy Maystrenko · Ulf Bayer
Magdalena Scheck-Wenderoth

Structure and evolution of the Glueckstadt Graben due to salt movements

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Abstract The salt tectonics of the Glueckstadt Graben has been investigated in relation to major tectonic events within the basin. The lithologic features of salt sections from Rotliegend, Zechstein and Keuper show that almost pure salt is prominent in the Zechstein, dominating diapiric movements that have influenced the regional evolution of the Glueckstadt Graben. Three main phases of growth of the salt structures have been identified from the analysis of the seismic pattern. The strongest salt movements occurred at the beginning of the Keuper when the area was affected by extension. This activation of salt tectonics was followed by a Jurassic extensional event in the Pompeckj Block and Lower Saxony Basin and possibly in the Glueckstadt Graben. The Paleogene–Neogene tectonic event caused significant growth and amplification of the salt structures mainly at the margins of the basin. This event was extensional with a possible horizontal component of the tectonic movements. 3D modelling shows that the distribution of the initial thickness of the Permian salt controls the structural style of the basin, regionally. Where salt was thick, salt diapirs and walls formed and where salt was relatively thin, simple salt pillows and shallow anticlines developed.

Keywords Glueckstadt Graben · NW Germany · Extension · Salt tectonics and 3D modelling

Abbreviation GG: Glueckstadt Graben · CEBS: Central European Basin System

Y. Maystrenko (✉) · U. Bayer · M. Scheck-Wenderoth
Geoforschungszentrum Potsdam, Section 4.3,
Telegrafenberg, 14473 Potsdam, Germany
E-mail: yuram@gfz-potsdam.de
Tel.: +49-331-2881783
Fax: +49-331-2881349

Introduction

The study of halokinesis is a fundamental problem of structural analysis in sedimentary basins such as the Gulf of Mexico, North Sea basins, Precaspian basin, Dniepr-Donets basin, Dead Sea basin and many others. Postdepositional salt flow complicates the recognition of basin evolution both at the local and regional scale. The Glueckstadt Graben (GG) is one of the sedimentary basins where the sedimentary cover is strongly affected by salt tectonics. This means that salt movements had an important impact on sedimentation and the subsequent deformation of Mesozoic and Cenozoic strata in this basin.

The Southern and Northern Permian basins together with the superimposed Mesozoic Graben and basin structures (e.g. the GG, the Horn Graben, the Rheinsberg Trough and the Lower Saxony basin) form the Central European Basin System (CEBS). Two regional fault zones bound the CEBS basin at the deep crustal level: the Sorgenfrei-Tornquist Zone in the northeast and the Elbe Fault Zone in the southwest (Fig. 1). The GG is situated between the Ringkoebing-Fyn High to the northeast and the Lower Saxony basin to the southwest. The basin strikes in a north-eastward direction over a distance of approximately 180 km. The sedimentary cover of the GG is pierced by Permian salt, which has been mobilized during the Mesozoic and Cenozoic to form a variety of salt structures (walls, stocks and pillows; Figs. 1, 2). Although the large-scale tectonic evolution of the region has been highlighted by Sannemann (1968), Brink et al. (1990, 1992), Baldschuhn et al. (1996, 2001), Bachmann and Hoffmann (1997), Kockel (2002), Maystrenko et al. (2005), the salt tectonics in relation to tectonic events is still poorly understood.

The main objective of this work is to discuss the evolution of the GG, with emphasis on the influence of salt tectonics during the Mesozoic and Cenozoic periods. The origin and development of large salt walls and

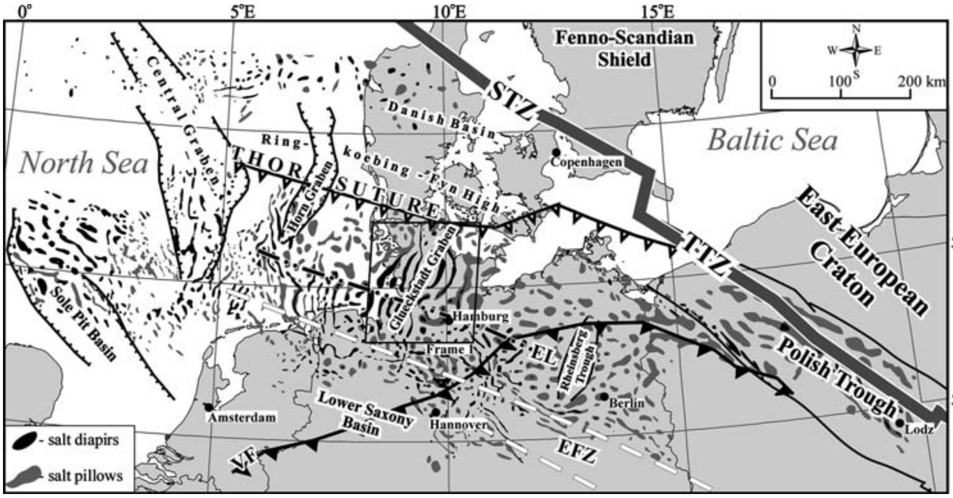

Fig. 1 Location of the study area (*frame 1*) in relation to major structural units within the Central European Basin System (compiled after Ziegler 1990b; Lockhorst et al. 1998; Pharaoh 1999; Bayer et al. 2002). *STZ* Sorgenfrei-Tornquist Zone, *TTZ* Teisseyre-Tornquist Zone, *EOL* Elbe-Odra Line, *EFZ* Elbe Fault Zone, *VF* Variscan Front

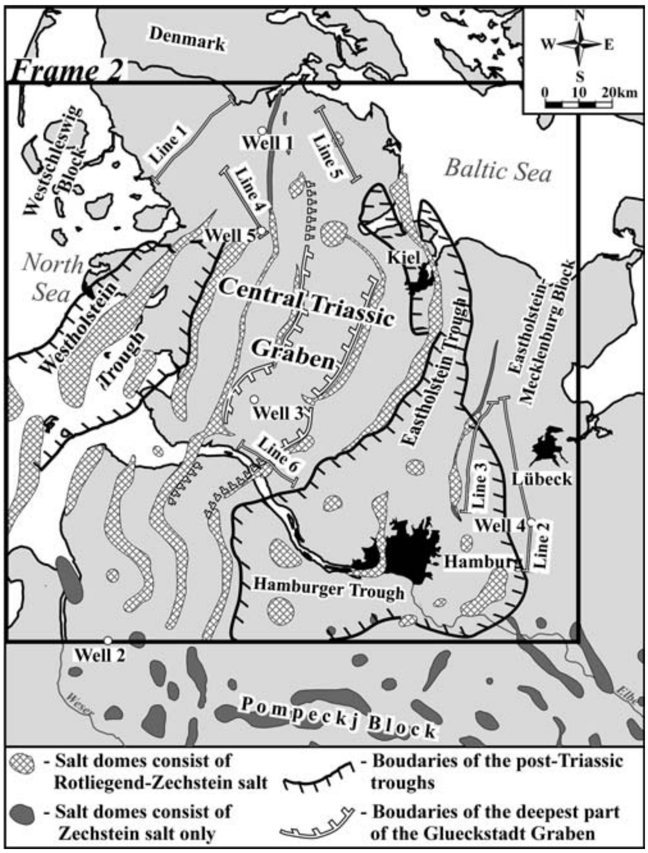

Fig. 2 Simplified tectonic map of the Glueckstadt Graben (*frame 1* in the Fig. 1) showing the location of the studied seismic lines and boreholes (position of salt domes after Baldschuhn et al. 1996)

intrabasinal structural features in the region are analysed by use of selected deep wells, reflection seismic lines and a 3D structural modelling approach. In particular, the ultimate aim of this study is to analyze the following aspects of the post-Carboniferous basin evolution: (1) the timing of salt movements, (2) the relationship between salt structures and styles of sedimentation, (3) the initial distribution of the thickness of Permian (Rotliegend and Zechstein) salt within the basin.

Geological setting

Structural features

The studied area was part of the Southern Permian basin during the Late Carboniferous—Early Permian (Brink et al. 1990; Ziegler 1990b). The GG is mainly located in Schleswig-Holstein and in the northern part of Lower Saxony, north-western Germany. It can be subdivided into three structural domains (Fig. 2): (1) the Central Triassic Graben, (2) the marginal Jurassic and Cenozoic troughs—Westholstein, Eastholstein and Hamburger and (3) the flanks of the basin—Westschleswig and Eastholstein-Mecklenburg blocks. The isopach map of the Meso-Cenozoic sedimentary cover, provided in Fig. 3a, illustrates the thickness variations in these three tectonic zones. The Central Triassic Graben is by far the deepest part of the GG. In its central area, the base of Triassic sediments is located at more than 10,000 m depth (Fig. 3b). At its south-eastern margin, the Triassic depocentre is separated from the Eastholstein-Mecklenburg block by the Eastholstein and Hamburger troughs (Fig. 3b), which exhibit increased thicknesses of Jurassic and Cenozoic sediments (more than 1,900 m and 3,300 m, respectively). The Westholstein marginal trough is also characterized by thick Jurassic and Cenozoic deposits (more than 2,400 m and 5,000 m, respectively) and separates the Central Triassic Graben from the Westschleswig block (Fig. 3b). The Westschleswig and Eastholstein-Mecklenburg blocks bound the GG from the northwest and the southeast accordingly, and are covered by post-Permian sediments of up to 4,000 m thickness. These structural zones have small dip gradients (sometimes almost horizontal) at the base of Zechstein (Fig. 3b), and the salt overburden is characterized by relatively undeformed rocks. The generalized northwest–southeast cross-section of Fig. 3b runs

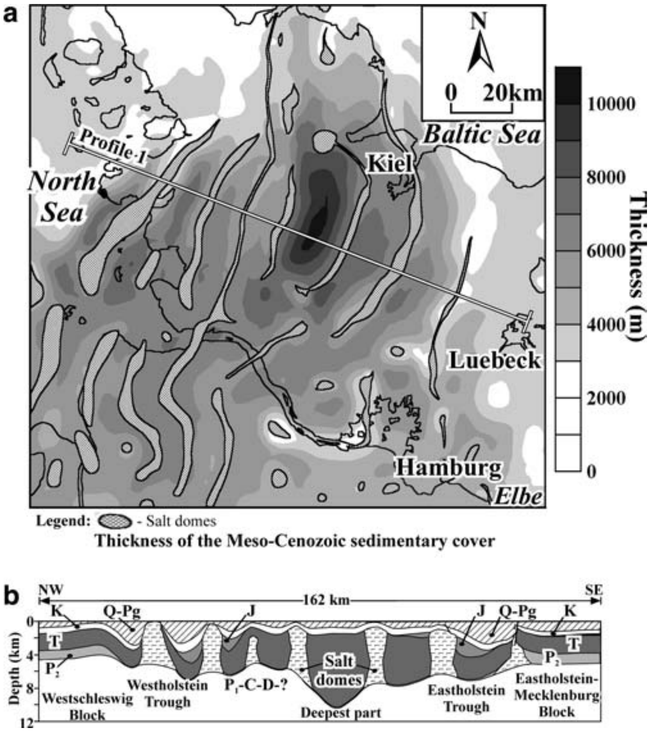

Fig. 3 (**a**) Present thickness of the sedimentary cover down to top Upper Permian (Zechstein) in the Glueckstadt Graben and its surrounding area (*FRAME 2* in Fig. 2; based on Baldschuhn et al. 1996). (**b**) Regional NW–SE cross-section across the Glueckstadt Graben, showing main structural features (vertical slice from 3D model of the Glueckstadt Graben). Stratigraphic key: P_1-C–D = Undivided Lower Permian (Rotliegend), Carboniferous and Devonian deposits; P_2 = Upper Permian (Zechstein); *T* Triassic; *J* Jurassic; *K* Cretaceous; *Q-Pg* Paleogene-Quaternary (including Neogene)

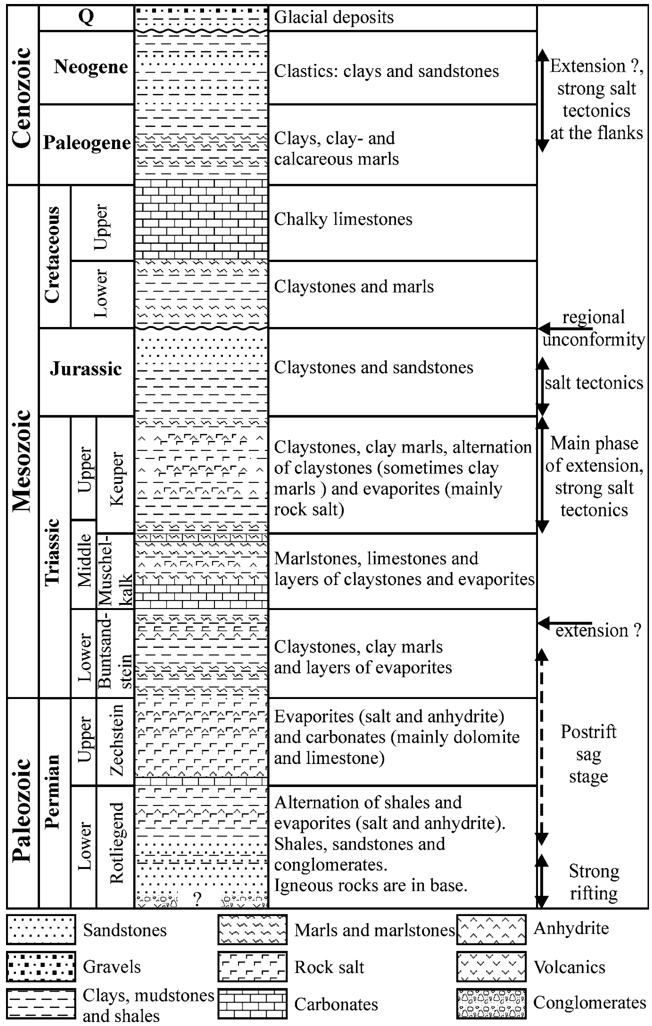

Fig. 4 Lithostratigraphic chart and main tectonic events of the Glueckstadt Graben. Lithologies are taken from well data

through the entire main structural zone described above. It is oriented approximately perpendicular to the central Triassic depocentre where the thickness of the Triassic reaches more than 8,500 m. It has been extracted from a 3D model of the GG to illustrate the key features of salt tectonics at a regional scale. The cross section shows that the development of three centres of maximum subsidence (during the Triassic, Jurassic and Cenozoic) has been strongly controlled by salt movements through time: the centre of sedimentation moves away from the central part of the original central Triassic trough towards its margins due to the gradual withdrawal of Permian salt (Sannemann 1968). In this sense, the GG was formed at least partially as a ‘‘basin-scale rim syncline’’ during post-Permian times (Maystrenko et al. 2005).

Tectono-stratigraphic sequence

The post-Carboniferous lithostratigraphy of the GG is shown together with some major tectonic events in Fig. 4. The post-Carboniferous basin fill may be divided into three major sedimentary sequences: pre-Permian deposits, Permian salt and Meso-Cenozoic overburden. Unfortunately, the oldest known sedimentary strata, Upper Devonian and Lower Carboniferous (Tournasian and Visean), have been penetrated in one deep well only within the limits of the GG. The Precambrian crystalline rocks have also been reached only within the Westschleswig block in the Nordsee Q-1 deep well (Best et al. 1983). Strong rifting took place during the Latest Carboniferous–Early Permian and was accompanied by extensive igneous activity and faulting within whole CEBS (Gast 1988; Plein 1990; Ziegler 1990b; Dadlez et al. 1995; Benek et al. 1996; Bachmann et al. 1997; Bayer et al. 1999; Stephenson et al. 2003; Abramovitz and Thybo 1999). This tectonic event is reflected in the lithology of the Lower Permian deposits by the presence of a conglomerate series and volcanics. The total thickness of the Lower Permian succession, which includes up to 450 m thick salt-rich layers, varies along the basin’s flanks from 1,500 m to more than 2,200 m. The Upper Permian (Zechtein) is characterized by carbonate-evaporite successions with a predominance of rock salt. The Lower Triassic (Buntsandstein) consists mainly of clastics and thin layers of evaporites, whereas the Middle Triassic (Muschelkalk) contains carbonates and evaporites. It was postulated that a minor extensional phase occurred during the late Buntsandstein (Brink et al. 1992; Kockel 2002). However, the main extension occurred during the latest Middle Triassic and Late Triassic (Keuper) when thick sediments were deposited up to 5,800 m in the basin depocentre (Brink et al. 1992; Baldschuhn et al. 1996; Baldschuhn et al. 2001; Maystrenko et al. 2005). The Keuper succession has a very complicated structure due to rapid subsidence and due to the presence of thick salt-rich layers (Bayer et al. 2003). The Jurassic sequence includes clastics, claystones and sandstones. Its thickness is significantly controlled by salt tectonics. The area around the GG was relatively uplifted, as indicated by a regional erosional unconformity in Late Jurassic–Early Cretaceous times. Sedimentation resumed in the Cretaceous, a time of tectonic quiescence and rising sea level. Lower Cretaceous strata unconformably overlie the Triassic and Jurassic sequences, and consist of marine and continental sediments. The Upper Cretaceous succession comprises mainly chalky limestones. Interestingly, a regional Late Cretaceous–Early Tertiary unconformity is not always obvious from the seismic data, although it is a prominent feature in other parts of the North German Basin. The Cenozoic succession consists mainly of clastics and occasional marls, reaching a maximum thickness of more than 5,000 m. During the Paleogene–Neogene, the basin was tectonically reactivated with rapid subsidence along the northwestern and southeastern margins of the Triassic trough (Sannemann 1968; Baldschuhn et al. 1996; Maystrenko et al. 2005). This event coincides with the rapid subsidence of the North Sea (Kockel 1988; Ziegler 1990b) and most likely is related to almost east-west directed extension (Maystrenko et al. 2005). Quaternary glacial deposits cover all older strata regionally.

Data and methods

The available data consist of reflection seismic profiles supplemented by deep well data. The seismic profiles and boreholes presented in this paper are examples taken from a larger seismic database. Preference was given to profiles showing dominant features of structural styles related to salt tectonics within the studied area. This database has been provided by the German oil and gas industry through the German Society for Petroleum and Coal Science and Technology (DGMK) in the frame of the research project "Dynamics of sedimentary systems under varying stress conditions by example of the Central European Basin system" (DFG-SPP 1135, DGMK Project 577). The quality of the seismic data varies within the study area, but in general, the data are of a high-to-medium quality. The medium quality data seems to be at least partly related to the complex structural style of the GG. Generally, the resolution of seismic images worsens beneath the salt structures because the salt dissipates much of the seismic energy. In some places, the deep reflections may represent Devonian or Carboniferous rocks but it is very difficult to correlate them due to a deficit or lack of well data in the GG. This study highlights mainly nine sequences which have been correlated using the seismic profiles and available well data, these being: (1) P_1(s) = upper part of the Lower Permian (salt-rich Rotliegend), (2) P_2 = Upper Permian (Zechstein), (3) T_1 = Lower Triassic (Buntsandstein), (4) T_2 = Middle Triassic without uppermost part (Muschelkalk), (5) $T_{2\text{-}3}$ = uppermost part of Middle Triassic and Upper Triassic (Keuper), (6) J = Jurassic, (7) K_1 = Lower Cretaceous, (8) K_2–Upper Cretaceous, (9) Q-Pg = Paleogene-Quaternary. The seismic lines have been interpreted in terms of seismic stratigraphy with some requiring migration in the frequency domain, using a software for digital processing of 2D and 3D seismic data (SPS-PC: the software package developed for Windows-based PCs and was provided by the Russian company Nord-Express). Migration in the frequency domain has been chosen because it allows the migration of seismic lines with steeply dipping reflections without the loss of the important dynamic characteristics of these reflections compared to the finite-difference scheme or Kirchhoff.

In addition to well and seismic data, structural maps were provided by the Federal Department of Geosciences and Mineral Resources (BGR; Baldschuhn et al. 1996). These cover the area under consideration. The digital versions of depth maps from the Geotectonic Atlas of northwest Germany (Baldschuhn et al. 2001) were integrated into a 3D structural model after calculation of thickness maps. This 3D model was finally adjusted by using the results from seismic interpretation. It includes seven layers from the Rotliegend to the Pliocene: salt-rich Rotliegend plus Zechstein, Triassic, Jurassic, Lower Cretaceous, Upper Cretaceous, Paleogene and Quaternary-Neogene. The model covers area 170 km long by 166 km wide (see frame 2 in the Fig. 2a) and has a 2×2 km grid spacing. The 3D structural model has been used to calculate the initial salt thickness within the limits of the GG by using software developed at the GeoForschungsZentrum Potsdam by Ulf Bayer, Magdalena Scheck-Wenderoth and Björn Lewerenz. The detailed theory of the 3D modelling has been described in Scheck and Bayer (1999) and in Scheck et al. (2003). Here we only elucidate the basic concept of modelling. The salt flow has been determined by using a finite-element method, depending mainly on the sedimentary load and the shape of the isostatically balanced base of the salt. A basic assumption in this approach is that the behaviour of salt is similar to a viscous fluid that is usually in hydrostatic equilibrium with the overburden and that its volume is conserved. This modelling was already successfully applied within the northeastern German Basin by Scheck et al. (2003) in order to investigate Zechstein salt movements.

Three thick salt sequences

The basin infill of the GG contains three major salt sequences: salt-rich Rotliegend, Zechstein salt and salt-rich Keuper. These salt successions have been distinguished because they played an important role during basin evolution due to their great thicknesses. In addition, solitary salt beds are present in the Buntsandstein, Muschelkalk and Jurassic strata but they are rather thin with known thickness less than 100 m. Hence, they were not able to form significant salt structures during the post-depositional period. In contrast, the Rotliegend and Zechstein evaporites have been the source of the majority of huge salt structures within the GG (Fig. 2). The salt-rich Rotliegend mainly consists of an alternation of salt and shales which are concordantly overlain by the Zechstein evaporites. The latter reach a thickness of 1700 m at the flanks of the basin. The salt-rich Keuper is widespread within the area under consideration and has a maximum thickness of up to 2000 m within the Central Triassic Graben.

Rotliegend sequence

The salt-rich Rotliegend is present in all the boreholes that penetrated the deposits of Lower Permian age. The typical sequence of the salt-rich Rotliegend is shown in Fig. 5 and the interpreted gamma-ray log of Well 1 (for location see Fig. 2). The true composition of the Rotliegend is unknown within the deep part of the basin where these sediments have only been drilled in the crest of salt diapirs and where they consist of displaced carbonates, clastics and mainly salt. The salt-rich strata overlie a sequence of shales which have been deposited in semi-desert areas or continental deserts (Ziegler 1990b). The salt-rich Rotliegend represents sabkha and desert-lake evaporites (Plein 1990; George and Berry 1997). The beginning of the salt-rich sequence is marked by a distinct fall in gamma-ray values (Fig. 5), lithologically corresponding to the presence of evaporites. The detailed structure of this argillaceous-evaporite sequence is shown in Fig. 5 by the enlarged interpreted interval of the gamma log. The rock salt is placed where the gamma log shows the lowest response. It is seen that the salt-rich succession consists of shales with remnant radioactivity (up to 88 g API), intercalated salt layers and not much anhydrite. The thickest salt beds are up to 80–85 m thick and, together with other salt layers, form more than fifty percentage of this argillaceous-evaporite sequence.

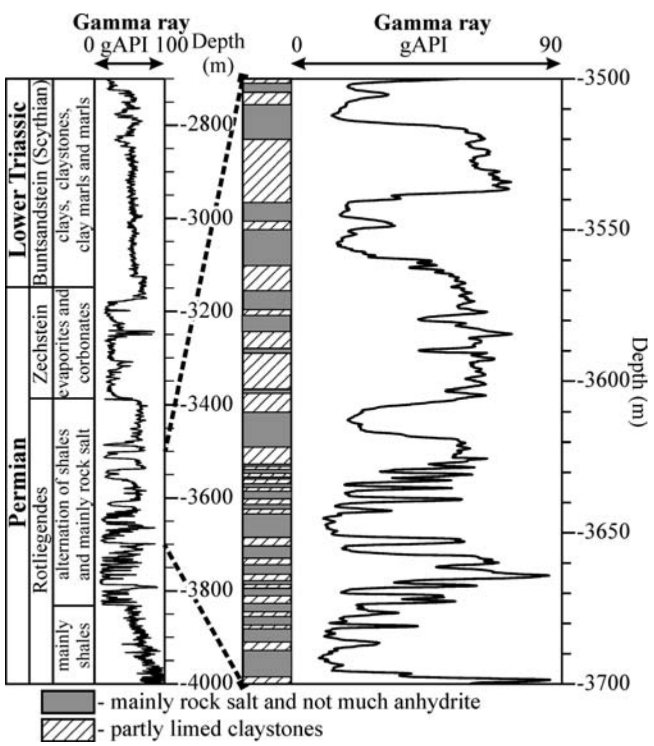

Fig. 5 Gamma-ray log (*Well 1*) of the salt-rich Rotliegend (see text for discussion)

Zechstein sequence

The Zechstein sequence is shown by the example of the gamma logging curve from the Well 2 (Fig. 6; for location see Fig. 2). At the beginning of the Zechstein, a marine environment developed during the initial transgression of the Zechstein sea (Ziegler 1990b). During the Zechstein, carbonates and thick evaporite rocks accumulated under arid climatic conditions. In the GG, the Zechstein is characterized by five cycles of evaporite deposition reflecting increasing evaporation and salinity through time. One of these cycles is shown in Fig. 6 at the depth interval of 5,235–5,198 m. It indicates the gradual precipitation from dolomitic limestone, anhydrite, halite to potassium salt. The enlarged interval of the data in Fig. 6 shows sharp spikes within the gamma-ray curve, related to the alternation of carbonates, anhydrites, halite and potassium. Radioactive potassium salt coincides with high gamma-ray peaks up to 68 gAPI. Carbonate beds are characterized by lower (up to 40 gAPI) gamma-ray values. The relative low gamma-ray values correspond to almost pure rock salt intervals. It is observable from the well-log data that rock salt predominates in the Zechstein section occupying more than seventy percent of it.

Keuper sequence

The gamma-ray curve of Well 3 shows a typical section of the salt-rich Keuper (Fig. 7). Well 3 is located within the central part of the GG (Fig. 2) where the Keuper contains the thickest salt-rich beds. The salt-rich Keuper is very thin within the flanks of the basin and is sometimes represented by anhydrite or complete pinching-out of evaporite beds. In terms of depositional environments, the Keuper is characterized by arid or

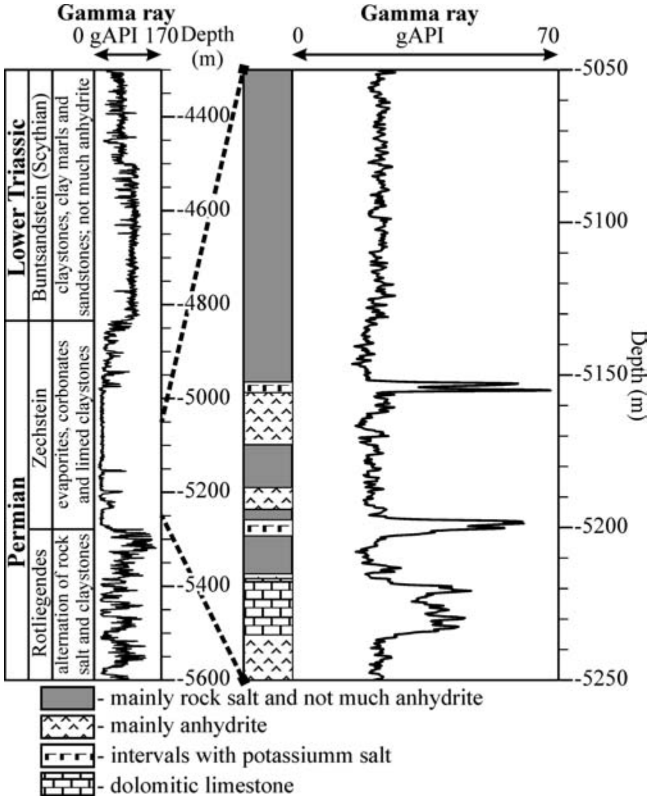

Fig. 6 Gamma-ray log (*Well 2*) of the Zechstein (see text for discussion)

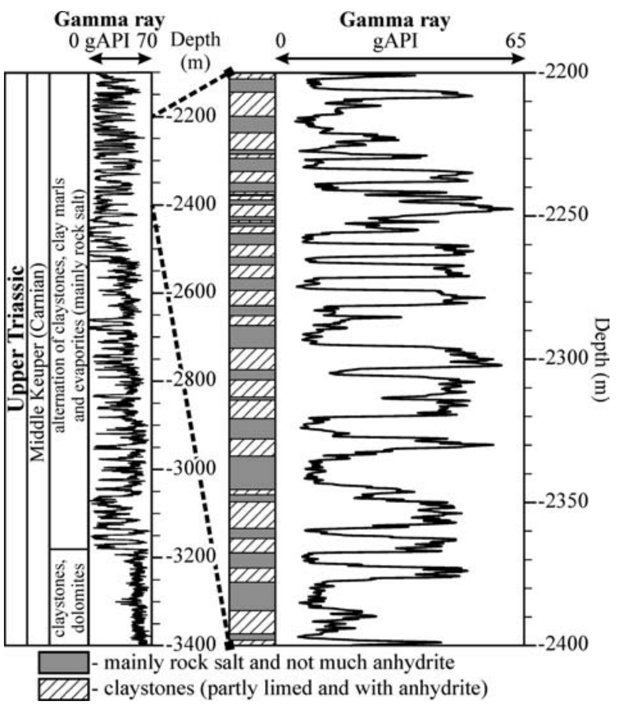

Fig. 7 Gamma-ray log (*Well 3*) of the Keuper (see text for discussion)

semi-arid intracontinental conditions (Ziegler 1990b). The Keuper succession consists of alternations of claystone, carbonate and evaporite series. The evaporite sequences are mainly represented by successions of interbedded halite, claystone, anhydrite and carbonates. During the time of their deposition, strong salt tectonics occurred within the studied area, where the majority of the Permian salt diapirs reached the paleosurface providing a source for salt redeposition. It is important to note, that Permian spores have been detected side by side with Triassic ones within the Triassic salt layers (Trusheim 1960) somewhat south of the area under consideration. In addition, salt-rich layers are everywhere connected directly to the Permian salt diapirs within the Keuper succession (Maystrenko et al. 2005). Thus, some of the Triassic evaporites most likely have their origin in the dissolution and redeposition of the Rotliegend and Zechstein salts. The well-log data highlighted in Fig. 7 illustrate that the gamma log has a serrate shape resulting from alternating beds of claystones and evaporites within the depth interval from 2,400 m to 2200 m. Higher gamma-ray values (up to 65 gAPI) are related to claystone layers, contrasting with the lower gamma-ray minima of salt seams. Salt beds are characterized by variable thickness within the limits of 5–18 m and occupy about fifty percent of the salt-rich interval.

In summary, it can be stated that almost pure salt is prominent in the Zechstein, which dominates in diapiric movements that have influenced the regional evolution of the GG. However, the presence of Rotliegend salt within the salt structures of the GG (Fig. 2) suggests that the initial thickness of Rotliegend salt was greater than is observed at the flanks of the basin today. The role of the Keuper salt is also important but mostly restricted to the area of the Central Triassic Graben where its thickness is significant.

Structural styles and diverse salt structure within the GG

The main deformation mechanism in the area of the GG is salt tectonics. Various structural styles in the GG are related to movements of Permian salt. Details of the evolution are expressed in a variety of salt structures representing different stages of growth such as salt rollers, anticlines, pillows, stocks, and most pronounced elongated salt walls. Based on the tectonic subdivision of the region, different salt structures and related structural features are described. The seismic lines discussed here are indicated in Fig. 2.

Flanks of the basin—Westschleswig and Eastholstein-Mecklenburg blocks

The Westschleswig and Eastholstein-Mecklenburg blocks represent the north-western and south-eastern flanks of the basin. Figure 8 shows the area of the

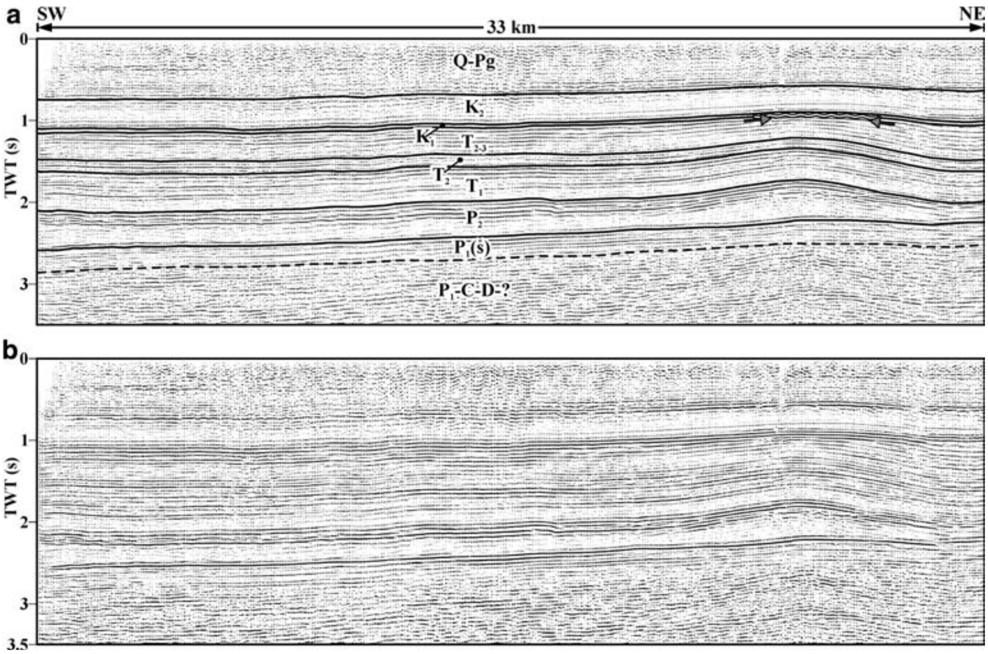

Fig. 8 Interpreted seismic profile 1. A typical structure from the north-western flank of the basin (Westschleswig block) is shown (visible erosional unconformity is indicated by wavy line). See Fig. 2 for location. Stratigraphic key for this and other figures: C-D = Undivided Carboniferous and Devonian deposits; P_1-C_2 = Lower Rotliegend and uppermost Carboniferous; P_1(s) = upper part of the Lower Permian (salt-rich Rotliegend); P_2 = Upper Permian (Zechstein); T_1 = Lower Triassic (Buntsandstein); T_2 = Middle Triassic without uppermost part (Muschelkalk); T_{2-3} = uppermost part of Middle Triassic and Upper Triassic (Keuper); J = Jurassic; K_1 = Lower Cretaceous; K_2 = Upper Cretaceous; *Q-Pg* Paleogene-Quaternary

north-western flank of the GG where the sedimentary cover is mainly characterized by almost horizontal bedding of post-Carboniferous strata with some solitary and low amplitude salt pillows. Bundles of subparallel reflections dominate along the largest part of line 1 with exception of the north-eastern part. There, a salt pillow complicates the subparallel seismic pattern (Fig. 8). The Mesozoic to Cenozoic layers are subparallel to the base of Zechtein. The salt-rich Rotliegend below the salt structure and the constant thicknesses of the uplifted Buntsandstein and Muschelkalk above indicate that the salt pillow developed during the Keuper by mobilization of Zechstein salt. Insignificant reactivation of the Zechstein salt movements occurred in Paleogene–Neogene when a shallow anticline formed (see north-eastern part of the Fig. 8). There is no visible structural unconformity at the base of the Cretaceous within the seismic image with exception of the crest of the salt pillow where an inessential truncation can be observed prior to deposition of the thin Lower Cretaceous. However, the Jurassic sediments are missing along this line. This structural feature can be explained by reduced sedimentation in the Jurassic as well as by low degree Late Jurassic–Early Cretaceous uplift and erosion within the Westschleswig block.

A typical time section along the Eastholstein-Mecklenburg block is shown in Fig. 9. The geological interpretation of the various seismic events on line 2 (cf. Fig. 2) is supported by reliable borehole information (Well 4). The profile extends through the axial part of a salt pillow, demonstrating the structure of the western part of the south-eastern flank of the GG. The section intersects two faults at the base of the oldest detectable reflections (near 4 s TWT). These reflections can be related to the lowest Permian or to uppermost Carboniferous sediments, representing the strong rifting processes which occurred during the Late Carboniferous–Early Permian times within the studied area. The salt-rich Rotliegend shows an almost constant thickness which decreases to the south of the line, perhaps, due to Lower Permian salt withdrawal in the same direction. The base Zechstein reflection is relatively strong, and displays a tiny velocity pull-up underneath the massive salt pillow but is generally subhorizontal. This demonstrates the low degree of activity of the underlying Lower Permian salt beds in this part of the basin. A slight decrease of the Keuper thickness towards the south indicates the initial stage of the salt movements in relation to the salt pillow. The thick Jurassic is characterized by on-lap from below and truncated top-lap from above in the southern anticline limb, showing the next stage of salt pillow formation. This time section also highlights the unconformity at the base of the Lower Cretaceous (northern part of the line) where Jurassic sediments were partially eroded due to a Late Jurassic–Early Cretaceous uplift or sea level fall at that time. The Cretaceous has an almost constant thickness, indicating a rather stable period of sedimentation without strong tectonic activity or salt movements. The Cenozoic sedimentary succession forms three synclines, which are located above the reduced Zechstein salt section (Fig. 9). On the other hand, thinning of the Cenozoic strata occurs at the crest of salt pillows. Such structural features of the Cenozoic succession imply essential salt movements during the Cenozoic along the line. The culmination of the development occurred during the post-Miocene time when the crest of the biggest salt anticline was affected by erosion with rapid subsidence of the southern and northern limbs. In post-Miocene times, the overburden of the salt structure was faulted, possibly due to extension.

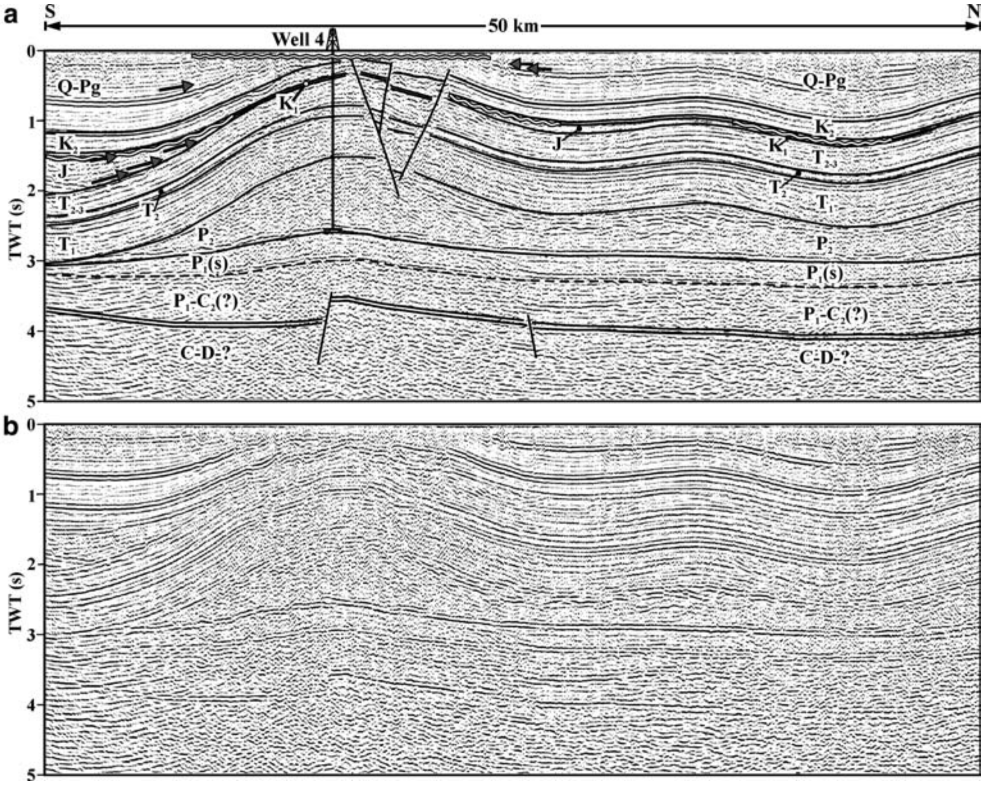

Fig. 9 Interpretation of line 2 showing structural features along the Eastholstein-Mecklenburg block (visible erosional unconformities are indicated by wavy lines; arrows show on- and toplap of the reflection terminations). Late Carboniferous–Early Permian extension tectonics is shown beneath Permian salt pillow. See Fig. 2 for location. For stratigraphic key see Figs. 3 and 8

Marginal Eastholstein trough

The Eastholstein trough is characterized by increased thicknesses of both the Jurassic and the Paleogene–Neogene (Fig. 3b). Line 3 (cf. Fig. 2) runs through the eastern part of this trough along the marginal salt wall, representing an area of extremely thick Paleogene–Neogene succession (Fig. 10). The base of the salt-rich Rotliegend is almost horizontal but the shape of the base Zechstein indicates that it was involved in the formation of the salt structure together with Zechstein salt. Internally, the Permian salt interval shows high- to low-amplitude and sometimes almost disorganized reflections representing a high degree of salt dislocation along this line (Fig. 10). The Buntsandstein, Muschelkalk and Keuper sequences have approximately constant thicknesses, demonstrating the absence of strong salt movements during this time. Jurassic sediments are found

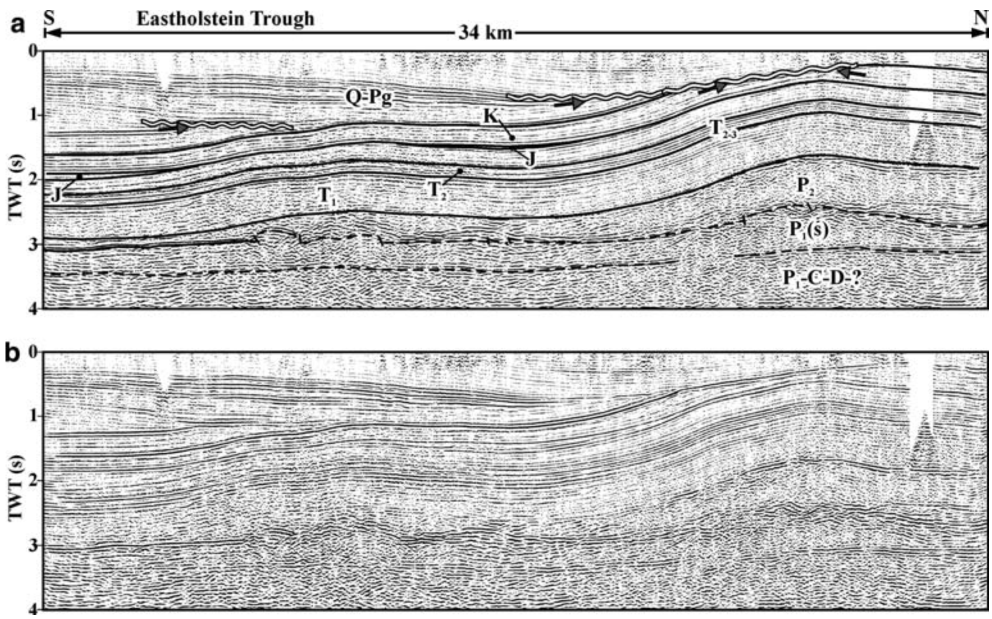

Fig. 10 Interpreted seismic reflection line 3 from the Eastholstein Trough. Two Cenozoic unconformities are shown by wavy lines. See Fig. 2 for location. For stratigraphic key see Figs. 3 and 8

along the profile within the southernmost and central parts of the line where thin Jurassic strata were interpreted. The Cretaceous is the youngest interval with almost constant thickness along the entire line but it is truncated at the crest of the salt anticline within the northern part of the line. This erosional truncation occurred during the postsedimentation period in the Cenozoic. South of the line, another erosional unconformity is observed during the Cenozoic. These two distinct erosional unconformities indicate two main pulses of salt movements with migration of the crest of the salt anticline from south to north during the Paleogene–Neogene. It is a great pity, that these unconformities cannot be precisely dated due to missing well data. The thickness of the Paleogene–Neogene succession varies from less than 0.25 to 1.68 s two-way travel time. The thickest package of the Paleogene–Neogene sequence corresponds to the thinnest Permian salt beds and vice versa (Fig. 10). This structural feature demonstrates that the deposition of Paleogene–Neogene sediments was strongly controlled by gradual salt outflow towards the salt pillow in the northern part of the profile (Fig. 10) as well as parallel to the salt wall towards the west (Fig. 10). Thus, the syn-kinematic stratigraphic thickening of the Paleogene–Neogene interval indicates Cenozoic salt movements along the entire line.

Transition zone from the north-western flank to the Triassic graben

The northwest-southeast running line 4 (cf. Fig. 2) intersects the collapsed termination of a salt wall (Fig. 11) which continues towards the south (Fig. 2). This line commences in the north-western flank of the basin and further to the east crossing a major vertical normal fault, visible at the base of the salt-rich Rotliegend (offset is about the 0.5 s TWT). The thickness of the Keuper increases significantly, almost doubling within the footwall block, in comparison with the hanging wall, indicating activity of the fault during the Keuper. This normal fault can be related to the Triassic Graben border-faults which extend along the basin margin beneath the salt wall. The interpretation of this line supports the concept that NNE-SSW-trending salt structures, controlling abrupt changes of sediment thicknesses which may have formed along basement faults (Sanemann 1968; Maystrenko et al. 2005). The onlapping Keuper reflections along the flank of the basin indicate that a salt wall was formed above the fault during Triassic extension. On the hanging wall, the thick Keuper is characterized by the presence of a salt-rich layer with a thickness up to 450 m as known from well 5. Moreover, this seismic line across the western boundary of the GG (cf. Fig. 2) shows clear evidence of syntectonic salt movements in response to normal faulting in the Keuper. However, taking into account the lack of Jurassic sediments on the north-western flank of the basin and their presence south-eastward from the fault

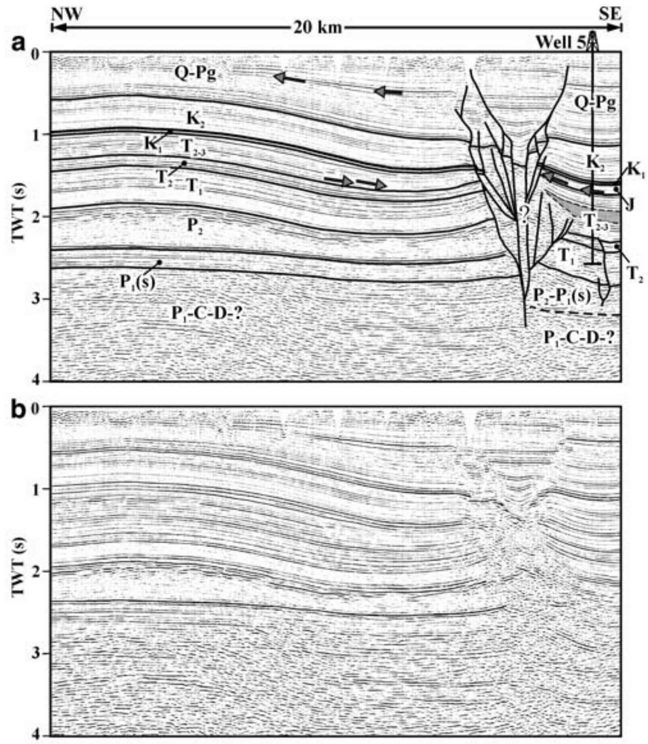

Fig. 11 Interpreted seismic profile 4 showing a salt structure which collapsed during Paleogene–Neogene. The section shows the transition from the north-western flank towards the centre of the GG (arrows show onlap of the reflection terminations). The grey wedge corresponds to the salt-rich Keuper sequence. See Fig. 2 for location. For stratigraphic key see Figs. 3 and 8

(Fig. 11), it is suggested that the fault experienced more than one phase with reactivation in the Jurassic. Onlap onto the base Jurassic (SE part of the profile) points towards further salt flow and continued fault movements in this area. During the Paleogene–Neogene, this part of the salt wall (cf. Fig. 2) collapsed probably due to salt outflow towards its southern continuation, causing the formation of a complicated fault system above the former salt structure (Fig. 11). This complex fault system has the features of a flower structure, pointing towards a horizontal strain component in Paleogene–Neogene times. Similar structures have been described by Brink et al. (1992) within other marginal salt structure of the GG. Therefore, the trigger of post-Cretaceous salt movements in the study area was most likely the reactivation of former boundary faults of the Central Triassic Graben under a possible strike-slip regime in the Paleogene–Neogene. The thickness of the Paleogene-Quaternary varies from more than 1.2–0.6 s. Internally, the unit shows moderate- to high-amplitude clinoforms onlapping onto the underlying strata within the central part of the profile. These clinoforms could be due to the salt outflow in the direction of the salt pillow imaged on the western part of this profile. Based on these data, south-eastward thickening of the Paleogene-Quaternary can be, at least partially, explained by salt movements. Due to strong salt tectonics, the tectonic development cannot be investigated in as much detail as in other parts of the basin, but it is unlikely that the central segment of the GG behaved significantly different during the Meso-Cenozoic tectonic history.

Central Triassic Graben

The central Triassic deep trough is the most complicated part of the basin; however, it is the most remarkable in terms of salt tectonics. This part of the basin is illustrated by two seismic lines (5 and 6; cf. Fig. 2) represented in Figs. 12 and 13.

A NNW–SSE oriented profile running through a salt diapir is presented in Fig. 12. The diapir rises from the base salt level and reaches a height of more than 4000 m. The diapir displayed in Fig. 12 is slightly asymmetric (north-westwards leaning). The reflectors from the Buntsandstein to the Jurassic terminate against the diapir, while the base Cretaceous reflector is continuous and covers the structure. Minor half graben structures are observed both in the north-western and south-eastern part of the profile at the base of the Permian salt. This normal faulting can be related to the Keuper extension which caused strong salt movements around the diapir. The Lower Triassic (Buntsandstein) is characterized by various thicknesses at both sides of the salt diapir (Fig. 12), indicating initial salt movements already in the Buntsandstein. Within the SSE part of the profile, the Buntsandstein has been truncated near the salt stock during Middle–Late Triassic times. The truncation of the Buntsandstein implies that the overburden might have been penetrated in the Keuper. The Keuper sequence shows clinoforms on- and down-lapping onto the top of Buntsandstein and Muschelkalk. In addition, downlaps are interpreted at the base of the Muschelkalk, indicating the initial pillow stage of this salt diapir. Jurassic sediments appear only in the SSE part of the profile demonstrating a synclinal geometry close to the salt stock and they bend sharply upwards further away from the salt structure. The structural character indicates the formation of rim synclines in the Jurassic at the SSE wing of the salt stock. In contrast, the NNW wing is characterized by the absence of Jurassic sediments, possibly due to erosion. However, the structural features at the NNW part of the line (subhorizontal Keuper strata underlay the Lower Cretaceous) do not allow us to suppose the existence of thick Jurassic sediments as observed at the SSE part of the line. The Late Jurassic–Lower Cretaceous unconformity is well imaged on both sides of the diapir by an angular erosional unconformity underneath the base of the Lower Cretaceous. In spite of the angular erosional unconformity, toplapping Jurassic strata are still recognizable within the SSE rim syncline, representing the proximal depositional limit of the Jurassic in some distance of the salt structure. The last stage of diapir

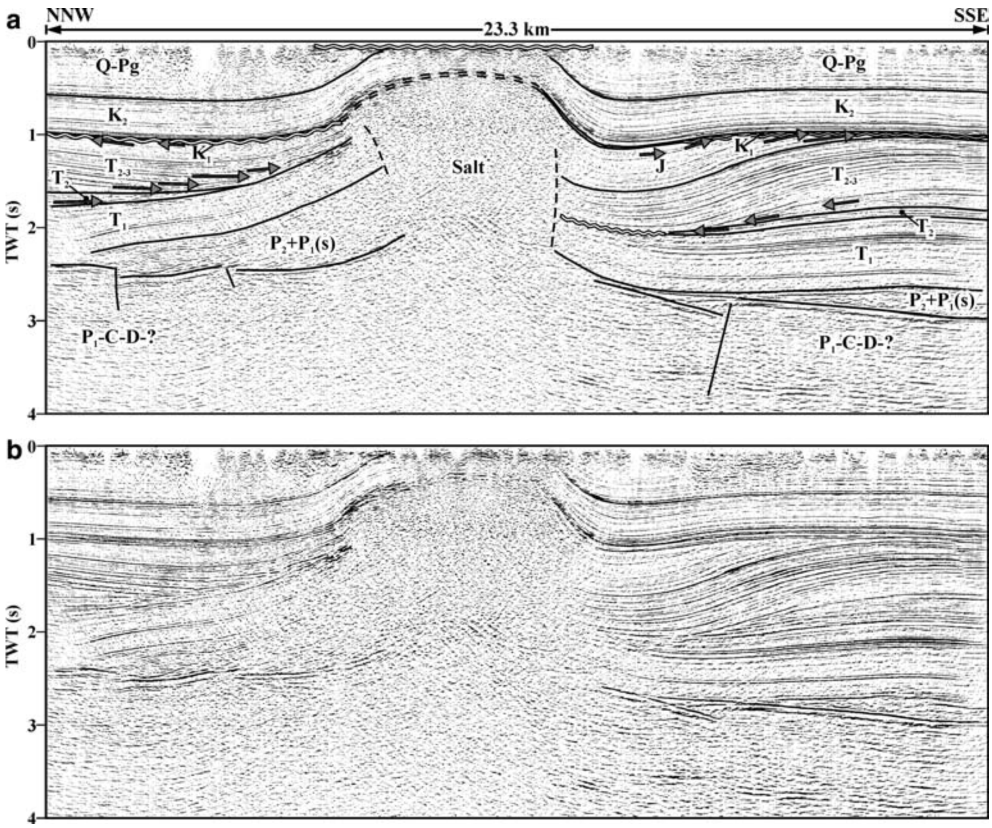

Fig. 12 Interpreted seismic profile 5 showing the structure of a salt diapir within the northern part of the Central Triassic Graben (visible erosional unconformities are indicated by wavy lines; arrows show on-, down- and toplap of the reflection terminations). See Fig. 2 for location. For stratigraphic key see Figs. 3 and 8

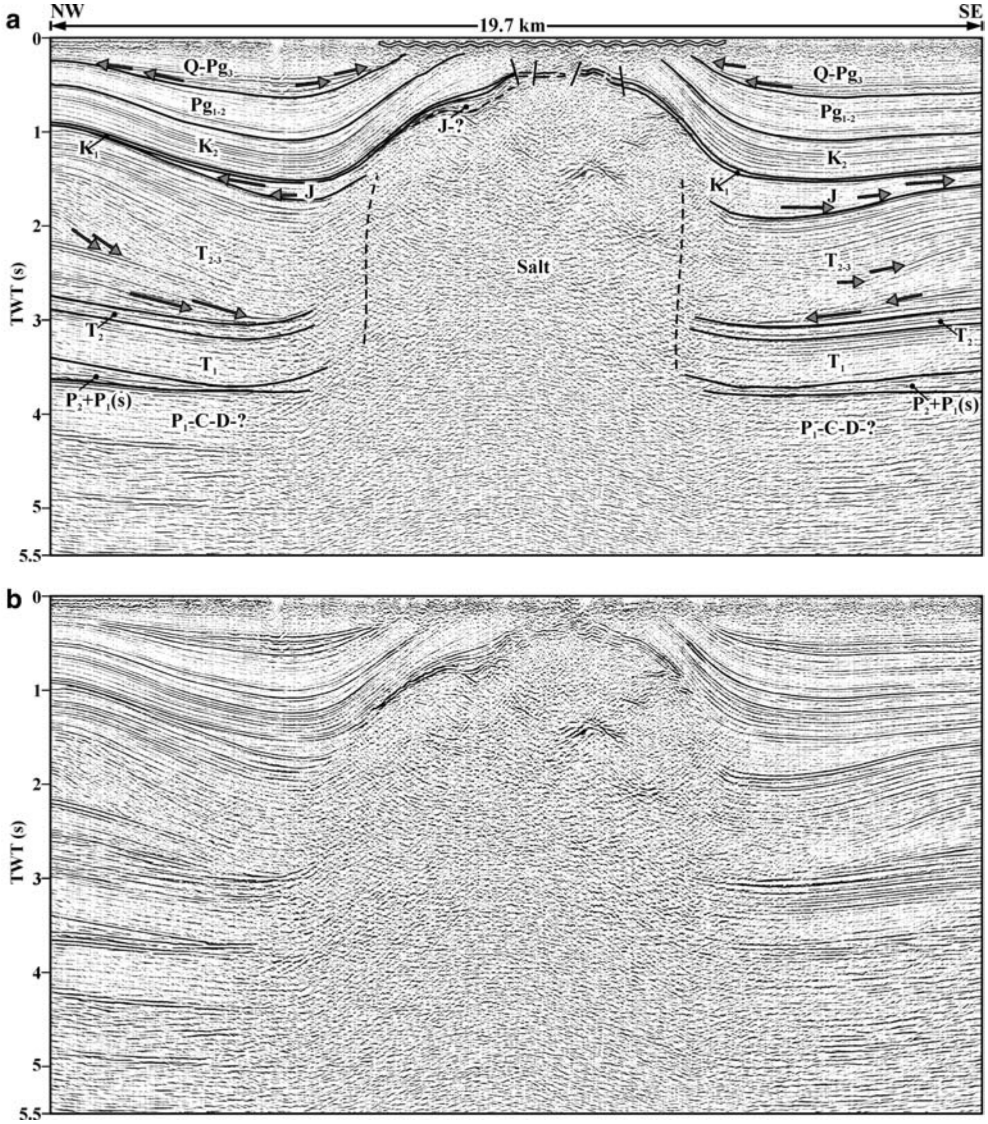

Fig. 13 Interpreted seismic profile 6 across the central part of the Glueckstadt Graben, showing onlapping strata due to salt diapir formation within the Keuper, Jurassic and Paleogene–Neogene (on- and downlapping strata are indicated by arrows; visible erosional unconformity is shown by wavy line). See Fig. 2 for location. For stratigraphic key see Figs. 3 and 8

growth occurred in Paleogene–Neogene when the crest of the salt structure was uplifted and partially truncated in comparison with the subsided NNW and SSE wings.

A typical salt structure within the deep part of the GG is displayed by line 6 crossing one of the salt walls (for location see Fig. 2). This seismic line demonstrates a vertical slice through an almost symmetrical salt wall, which reaches more than 5,000 m height (Fig. 13). Like in the diapir described above, the salt has penetrated its cover layer up to the Lower Cretaceous succession. Strong reflectivity in the upper part of the salt diapir corresponds to the caprock. Usually, caprocks consist of displaced clastic rocks of Lower Permian age which were moved together with the salt-rich Rotliegend according to borehole information. The Buntsandstein and Muschelalk show constant thicknesses on both sides of the salt structure. The Keuper is the thickest sequence (up to 3,400 m) along the line, indicating the main phase of subsidence within the Central Triassic Graben. An analysis of the seismic data shows that the Keuper clinoforms onlap onto the top of the Muschelkalk, highlighting the character of basin-fill associated with the initial growth of the salt structure during the Keuper. Onlaps in the interior of the Keuper succession point towards subsequent extrusions of Permian salt which represent the next stage of the salt structure development—the penetration of the overburden. Considerable amounts of Jurassic sediments are localized mainly around the salt structure with rim syncline character of sedimentation. Onlaps of the Jurassic reflections onto the underlying Keuper demonstrate a progradation of the sedimentation away from the salt wall due to the gradual withdrawal of the Permian salt. The Late Jurassic–Early Cretaceous erosional unconformity is almost invisible in terms of seismic stratigraphy but it has been indicated by well data in this part of the basin. The Paleogene-Quaternary sequence shows thickening near the salt structure and is almost missing at the crest of the salt wall due to erosion. Internal onlaps within the Paleogene-Quaternary highlight the culmination of salt movements at the beginning of the Oligocene.

These two interpreted sections illustrate different intensities of salt tectonics in the limits of the Central Triassic Graben: Permian salt is almost completely extruded from the source layer along line 6, while great amounts of salt are still preserved along line 5.

Evolution of the GG in relation to salt movements

The evaluation of the diverse deformation patterns of the sedimentary cover and their relations to salt structures show that the strongest salt movements occurred at the beginning of the Keuper when the area under consideration was affected by extension. The NNE-SSW trending salt walls may have formed above normal faults within the pre Permian bedrock, implying a WNW-ESE directed Middle–Late Triassic extension. Minor primary salt-withdrawal synclines interpreted within the Buntsandstein and Muschelkalk deposits point towards earlier salt movements (Baldschuhn et al. 1996, 2001). Some evidence of the initial salt movements in the Muschelkalk is illustrated in Fig. 12, where the Muschelkalk downlaps onto the Buntsandstein. The analysis of seismic data from the GG showed that the Middle–Late Triassic extension and associated normal faulting are the principal mechanisms for tectonic subsidence during the Keuper. Basement faulting could have been a main trigger for the development of salt pillows and diapirs at that time. The internal seismic pattern of the Keuper, lithostratigraphic data and the results of palynological investigations (Trusheim 1960) indicate that Permian salt extruded on the paleosurface and was dissolved and redeposited within the Keuper strata. Krzywiec (2004) observed similar patterns in the Mid-Polish Trough, where the Permian salt also extruded on the paleosurface in the Keuper.

In the GG, many questions remain unresolved concerning the salt tectonics which produced the marginal troughs (Hamburger, West- and Eastholstein; Fig. 2), where up to 1,900–2,400 m of Jurassic sediments and up to 5,000 m of Cenozoic were accumulated (Fig. 3b). Sanemann (1968) postulated that the formation of the marginal Jurassic and younger rim-synclines occurred as a consequence of the Keuper extension by subsequent wave-front-like growth of salt stocks in post-Triassic time. In other words, the salt-induced deformation persisted in the Jurassic when rapid subsidence continued mainly around the former Triassic salt structures by gravity driven flow. This concept is not strictly consistent with the onlap patterns of the Jurassic sediments at the top of the Keuper succession (see Figs. 9, 11, 13) indicating essential changes of the sedimentation style during the Jurassic. Kockel (2002) has documented the Early Jurassic extension and related normal faulting, which affected the entire sedimentary succession within the Lower Saxony Basin and the Pompeckj Block. Although, there is no direct evidence of normal faults in the Jurassic of the GG, one of them can be inferred from structural features of the Jurassic strata in Fig. 11. Thus, the Jurassic tectonic event documented in the Lower Saxony Basin and within the Pompeckj Block (Kockel 2002) may have also affected the GG. However, post-Keuper salt tectonics occurred mainly along the north-western and the south-eastern margins of the GG (Fig. 3b) where Permian salt was not depleted during the Triassic. Thick Jurassic sediments are only observed around salt structures and are thinning away from salt walls or salt stocks. Possibly, parts of the Jurassic might be missing due to erosional truncation in the Late Jurassic–Early Cretaceous times. However, the Keuper strata were eroded mainly in the vicinity of salt structures (Figs. 8, 12) or are transgressively covered by Lower Cretaceous sediments (e.g. see Fig. 8 and the NW part of the Fig. 13). The low degree of erosion of the Keuper (only up to the first 100 m), the presence of truncated toplaps within the Jurassic strata (Figs. 9, 12), and the absence of visible unconformities within the north-western flank of the basin (Fig. 8), suggest a minor erosion during Late Jurassic–Early Cretaceous times. According to vitrinite reflectance data (Radon and Littke, this volume), the estimated thickness of the eroded sediments can vary from 200–400 m within the basin flanks and locally up to 700 m within the central part of the GG. Therefore, the present day thinning of the Jurassic sequence could reflect the proximal depositional limit near rising salt structures. Furthermore, the present day remains of thick Jurassic still represents the areas of intensive subsidence, which was strongly controlled by withdrawal of the Permian salt from the source layer.

Sedimentation continued in the Early Cretaceous (mainly during Barremian-Hauterivian stages) when thin clays and marls (the prevalent thickness is about 70–80 m) have been deposited. The Upper Cretaceous strata have an approximately constant thickness and the parallel reflections pattern indicates a quiet tectonic setting with very minor salt movements in the Late Cretaceous within the area under consideration. In contrast to other parts of the CEBS, the GG was not inverted during the Late Cretaceous and Tertiary, when up to 4–5 km of sediments were eroded during inversion of the Lower Saxony Basin (Petmecky et al. 1999) and along the southern margin of the north-eastern German basin (Scheck et al. 2002). Renewed salt flow during the Paleogene–Neogene (mainly Eocene–Miocene) caused rapid subsidence along the marginal parts of the Central Triassic Graben in the Westholstein, the Eastholstein and the Hamburger troughs. Also many salt structures continued to rise within the centre of the GG. These movements were much less intense in comparison to the marginal troughs. Permian salt continued to intrude into existing salt domes at this time promoting the growth of large anticlines over salt structures, as seen in Figs. 9, 12 and 13. The continued rise of salt in almost north–south-striking salt walls indicates an east–west directed extension. This is consistent with the assumed regional stress field during Late Cretaceous–Early Tertiary inversion within the other parts of the CEBS. For this period, the stress field is characterized by north–south compression and east–west extension, derived from the regional structural analysis of Central Europe (Ziegler 1990a, 1992). The GG was parallel to the principle strain direction and therefore was not prone to an inversion in Late Cretaceous–Early Tertiary. The data interpreted in this study also show that Paleogene–Neogene salt tectonics in the GG was most likely triggered by reactivation of Triassic structures due to horizontal movements (Fig. 11). The thick Paleogene–Neogene strata within the marginal troughs (Figs. 3b and 10) may also be related to a regional component of tectonic subsidence in the area, contemporary with the rapid subsidence in the North Sea (Sclater and Christie 1980; Jordt et al. 1995; Garetsky et al. 2001).

3D structural modelling

Present structure

A 3D view on the modelled top Permian salt surface (Fig. 14a) demonstrates that the high amplitude salt walls are located mainly within the Central Triassic Graben and the Westholstein trough with decreasing amplitudes towards the Eastholstein and Hamburger marginal troughs. Accordingly, the salt deformation is less intense at the north-western and south-eastern flanks of the basin (Fig. 14a). There, the salt-rich Rotliegend is in an almost undisturbed, flat-lying position compared with the displaced Zechstein salt (Figs. 8, 9), whereas both have been mobilized in the central part of the basin. The modelled base of the salt is smoothed due to the horizontal resolution of 2×2 km and does not image faults. The isolines of the base salt surface show merely an elongated trough with NNE-SSW orientation. However, it is known from seismic data that faults are present on this interface (e.g. Fig. 12). The modelled sedimentary cover above the salt is well constrained, with the sedimentary layers derived from the Geotectonic Atlas of north-western Germany (Baldschuhn et al. 1996; Baldschuhn et al. 2001) and multichannel reflection seismic data. Actually, the modelled detailed shape of the base of the Permian salt is more complex because of the lack of a unique phase correlation underneath the salt structures. This is due to a low reflectivity within areas occupied by salt structures in the Central Triassic Graben and the marginal troughs (cf. Figs. 12 and 13). In contrast, reflections from the base of the Permian salt are easily recognizable at the flanks of the basin (Figs. 8 and 9). The wave image is inconsistent within the salt diapirs and walls. Therefore, the base of salt cannot be determined from seismic data as there are no regular reflections. This provides a main source of uncertainty in estimating the base of the Permian salt under some salt structures. For that reason, the depth position below these salt structures was determined by interpolation of the definite depth around salt walls and diapirs.

The modelled base of the Permian salt is characterized by two deep minima which correspond to the Central Triassic Graben (depth up to −10,900 m) and the Westholstein trough (depth about −8,400 m; Fig. 14b), while the base is almost flat at 3,500 up to 5,500 m depth on the basin flanks. The huge salt walls attain a height of up to 8,500 m and the deepest part of the salt base is located in the area where Keuper deposits reach the greatest thickness (Fig. 15a). The modern thickness of the Permian salt shows that the basin can be subdivided into two parts: (1) a central part where most of the Permian salt was withdrawn to form salt structures, and, (2) the north-western and south-eastern flanks where the salt formed salt pillows (Figs. 9, 15b) or even is preserved in its original bedding (Figs. 8, 15b).

Results of the restoration

The reconstruction of the initial salt thickness takes into account that the Permian salt partially extruded during the Keuper and was redeposited due to superficial dissolution. This phenomenon of salt tectonics has also been observed in other basins of the world. In the

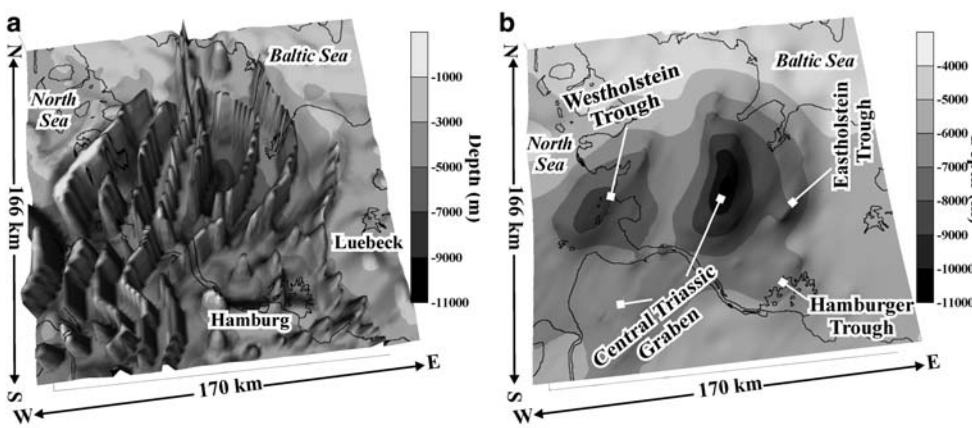

Fig. 14 The 3D view on the present day top (**a**) and base (**b**) of the Permian salt in the Glueckstadt Graben and adjacent areas

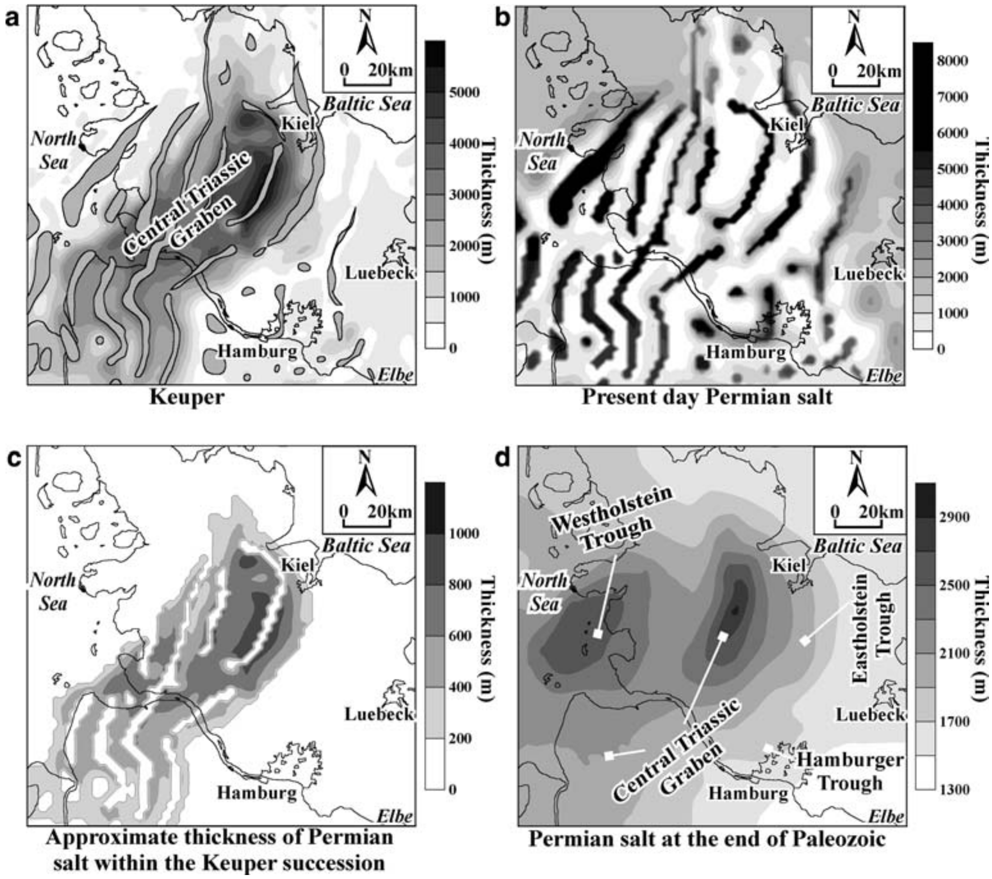

Fig. 15 Thickness maps: (**a**) uppermost Middle Triassic and Upper Triassic (Keuper) and (**b**) Permian (Zechstein plus salt-rich Rotliegend) salt layer; (**c**) suggested thickness of the Permian salt within the Keuper strata; (**d**) reconstructed map of initial salt thickness obtained from 3D salt redistribution within the studied area

Dniepr-Donets basin, the Lower Permian salt was partially deposited due to an extrusion and redeposition of the Devonian salt during Early Permian extension (Averiev 1962; Stovba et al. 2003). In the Precaspian Basin—Permian salt extruded and was possibly redeposited within Triassic and Jurassic (Ismail-Zadeh et al. 2004). Finally, present-day extrusion of salt is observed in the Zagros Mountains of Iran (Talbot et al. 2000). The quantity of Permian salt redeposited during the Keuper can be approximately derived from lithostratigraphic and structural features of the Keuper succession. The amount of salt in the Keuper has been estimated as twenty percentage in the thickest part of the section which occupies the central part of the GG (Fig. 15c).

The modelling approach aims to reconstruct the original Permian salt distribution immediately after deposition. This reconstruction of the initial thickness of salt was carried out in the following sequence: (1) backstripping of Meso-Cenozoic sediments, including Permian salt, (2) calculation of an isostatic response of the salt base without sediment infill, (3) restoration of the Permian salt layer above the backstripped and isostatically balanced base of salt, (4) addition of the redeposited Permian salt from Keuper (20% of thickest Keuper) to the Permian salt, (5) redistribution of the total Permian salt onto the restored base like a viscous fluid until the salt layer was in hydrostatic equilibrium with the salt load and, finally, (6) calculation of an isostatic response due to the new load conditions. The obtained initial thickness is displayed in Fig. 15d. It shows a spatial correlation between the present-day minima within the Westholstein trough and the central part of the GG (Fig. 14b) and two modelled maxima of the initial salt thickness distribution (Fig. 15d). The modelled two maxima of initial salt thickness are separated by thinned salt, reflecting the presence of the relative structural high within the centre of the basin. The initial salt thickness varies from 1,300 m at the flanks of the basin up to 3,000 m within the central part and demonstrates a clear NNE-SSW trend of the basin. The regional trend of the restored salt distribution points to a westward continuation of the Permian salt basin (Fig. 15d). In addition, the map displayed in Fig. 15d shows that the low degree of salt-tectonic activity within the flanks of the basin may have been predetermined by relatively thin initial salt thickness. Thus, the initial thickness of the Permian salt may have controlled the structural style of the basin. Where salt was thick, salt diapirs were formed and the overburden rocks were subjected to have high-amplitude folding. Where salt was relatively thin, simple salt pillows and shallow anticlines developed.

As the modelling approach assumes the volume of salt to be constant through time, the initial thickness of the Permian salt bears an error in the sense that a possible salt loss due to underground dissolution is not considered. The significance of this process is highlighted by Clark et al. (1999) and Cartwright et al. (2001) in the North Sea basin. Most probably, considerable superficial dissolution did occur not only in the Keuper but also in later times. For instance, the considerable superficial dissolution could also have occurred in the Jurassic and during the Late Jurassic–Early Cretaceous interruption of the sedimentation (Jaritz 1980). The Lower Cretaceous sediments cover almost all salt diapirs and walls within the GG (Figs. 12 and 13). This indicates that salt structures could be very close to the surface or even have reached the surface in the Jurassic with a main phase of superficial dissolution during the Late Jurassic–Early Cretaceous erosion. On the other hand, some of dissolved salt re-entered the system via redeposition during the Keuper—a process considered in the modelled salt volume. However, the aspects of the salt dissolution are too complex, preventing a reliable estimate of the dissolved Permian salt and therefore, have been postponed to future studies.

Conclusions

The results from interpretation of seismic data and borehole data as well as from 3D numerical modelling allow the following conclusions:

Three main phases of growth of the salt structures have been identified by the analysis of the seismic pattern. A major phase of growth occurred during the Keuper extension in response to normal faulting of the salt base. This activation of salt tectonics was followed by a Jurassic pulse of salt movements which temporally correlate with an extensional event in the Pompeckj Block and Lower Saxony Basin. The third, Paleogene–Neogene tectonic event caused significant growth and amplification of the salt structures mainly at the margins of the basin. This event is extensional with possible horizontal component of the tectonic movements. These three phases of salt tectonics were separated by intervals associated with very low degree of salt mobility, especially in the Late Cretaceous.

Triassic extensional faults have been identified on the salt base below salt walls and diapirs which formed in the same time interval. This fault activity most likely controlled the location and orientation of the NNE-SSW elongated salt walls. In this case, the formation of the salt walls and diapirs was triggered by salt movements above active extensional faults in Keuper. During the Jurassic and the Cenozoic, the tectonic events played a minor role in the location of the diapirs, but aided in their growth.

The present day thinning of the Jurassic sequence reflects the proximal depositional limit in some distance of the salt structures. Therefore, the present day remains of thick Jurassic still represents the areas of intensive subsidence, which was strongly controlled by withdrawal of the Permian salt from the source layer.

Zechstein salt is the main component involved in the diapiric movements that have influenced the regional evolution of the GG. Rotliegend salt is not significantly disturbed within the flanks of the basin where it is still characterized by flat-laying strata. However, Rotliegend salt could have played an important role in the formation of salt structures in the central part of the GG, where it contributes in addition to the Zechstein salt to the total volume of some salt structures. Thus, Rotliegend salt could have been much thicker within the central part than on the flanks of the basin.

Initially Permian salt may have been up to 3,000 m thick within the central part of the basin and about 1,300–1,900 m at the flanks. Possibly, the initial thickness distribution of the Permian salt controlled the structural style of the basin, regionally. Where salt was thick, salt diapirs and walls formed. Where salt was relatively thin, simple salt pillows and shallow anticlines developed.

Finally, the results show that salt withdrawal may have played an important role during the Meso-Cenozoic evolution and that the effects of the salt driven subsidence during the Meso-Cenozoic may be considered a main reason for formation of the deep Central Triassic Graben and the subsequent Jurassic-Cenozoic marginal troughs.

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