Chapter III

SEISMIC PATTERNS WITHIN THE GLUECKSTADT GABEN

3.1. Introduction

Seismic stratigraphic interpretations of selected lines are given in this chapter. The discussed seismic lines are indicated in Fig. 3.1. Based on the reflection patterns, the main seismic sequences are identified in the multi-channel seismic data. Some sequence boundaries were precisely calibrated with borehole data. This combined data set (seismic lines and well data) was used to define the structure and evolution of the GG from Permian to Cenozoic. However, there are still open questions concerning the correlation of internal reflections of deep strata within the central part of the GG (Fig. 3.2). There are neither deep wells available which provide control, nor is a north-south running seismic line available which could connect the deeper parts with the well-controlled thinner sequence towards the Rinkoebing-Fyn High or the Pompeckij Block. In addition, there are no typical seismic patterns which could help to derive a probable interpretation. Although, Baldschuhn et al. (2001) provided a concise interpretation of the deep reflections, there is an ongoing discussion within the research project SPP-1135 concerning alternative models (Bayer et al., 2003). Furthermore, different interpretations have previously been published by Best et al. (1983) and Baldschuhn et al. (1996).

The crucial reflection seismic profile shown in Fig. 3.2 crosses the central and eastern part of the GG (see Fig. 3.1 for position). This line provides a regional overview of the area under consideration. The thickness differences shown in the profile provide the separation between the Central Triassic Graben and the Eastholstein-Mecklenburg block. Consequently, the cross section can be subdivided into two main structural zones, which represent the Central Triassic Graben with the superimposed Cenozoic Eastholstein Tough and the Eastholstein-Mecklenburg block. The presence of lengthy salt walls hampers seismic correlation between the different structural parts of the basin. The pre-Prepermian strata are only reached by very few wells within the GG. Consequently, the correlations of the pre-Permian reflections are not consistent due to the absence of the well data and due to the presence of huge salt structures (see line 1 in Fig. 3.2; see enlarged version in Appendix A). The base of the salt-rich Rotliegend is the oldest horizon which has been regionally dated

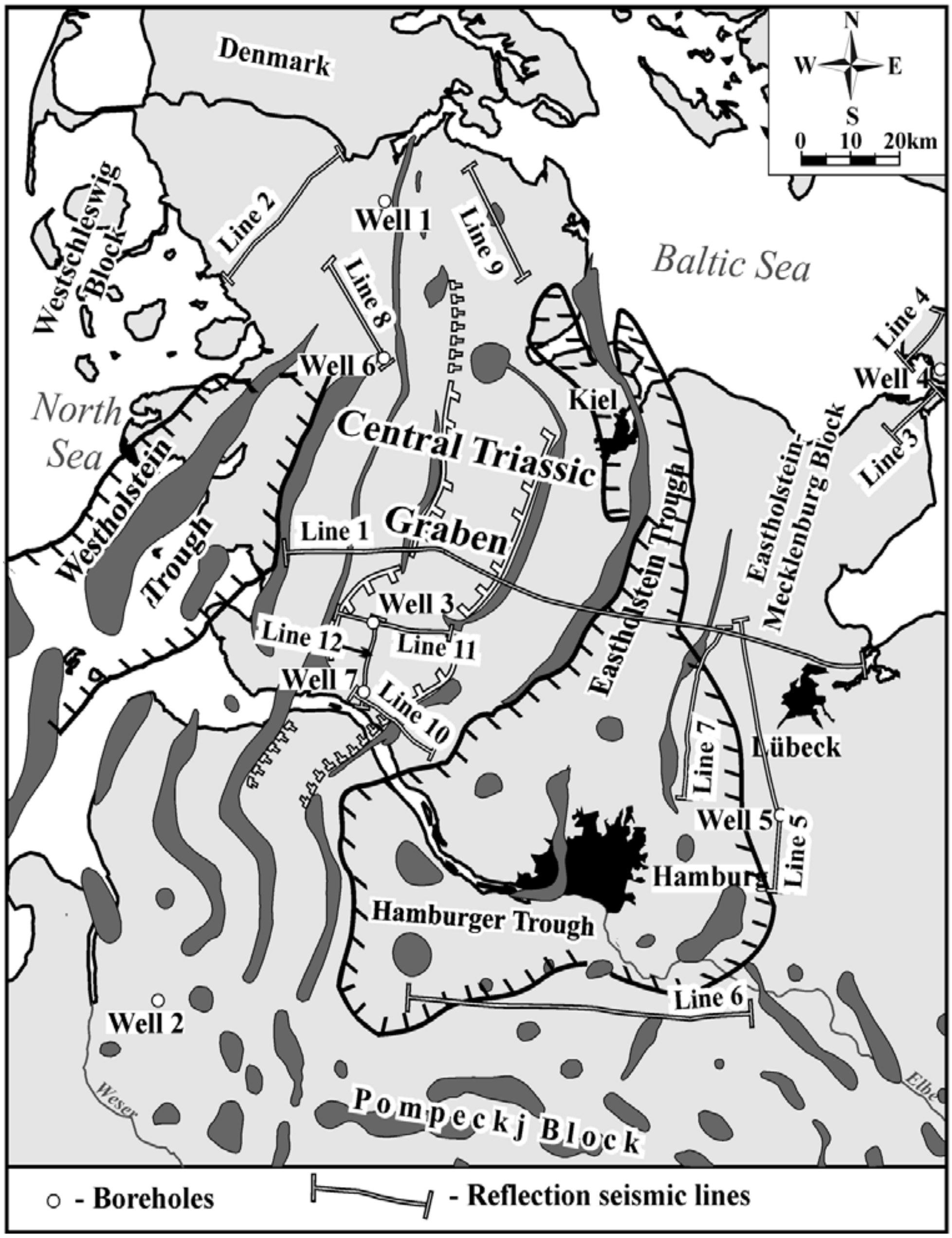
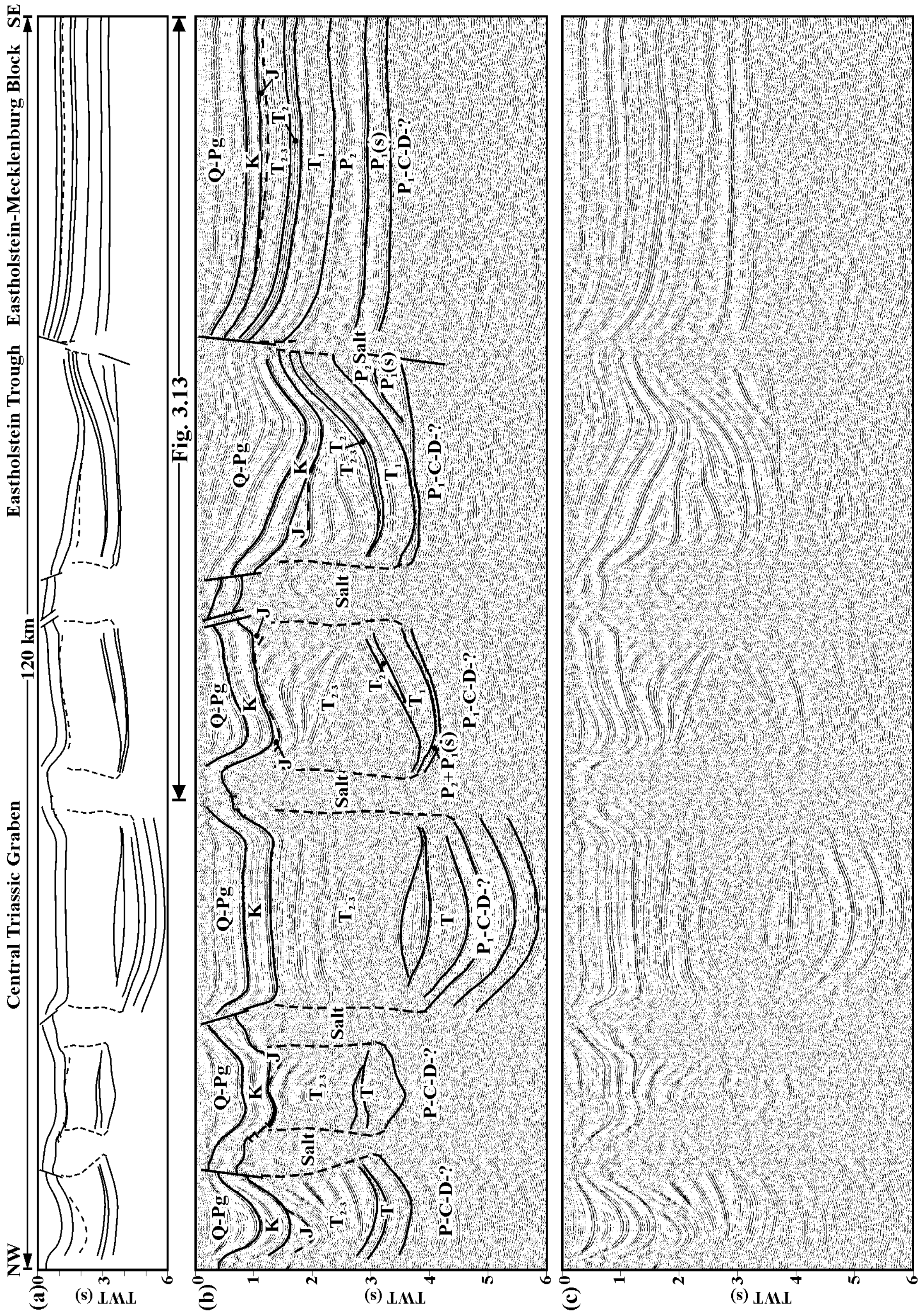


Figure 3.1. Simplified tectonic map of the Glueckstadt Graben (frame 1 in the Fig. 1) showing the location of seismic lines and boreholes mentioned in the text (position of salt domes after Baldschuhn et al., 1996).

within the GG. This horizon is quite well constrained by drilling and seismic images. The base of the salt-rich Rotliegend usually marks the deepest correlatable reflections beneath the high-amplitude reflections from the Zechstein base. The geologic identification of the Zechstein base is well established in the GG due to the presence of a strongly reflective package consisting of two- or three-phases. The salt-rich Rotliegend has an almost constant thickness of 0.36-0.38 s TWT within the Eastholstein-Mecklenburg block. Structurally, the upper Rotliegend is characterized by a subhorizontall package of reflections, indicating undisturbed bedding of the salt-rich strata at the basin shoulder. Within the same structural zone, the slightly deformed Mesozoic-Cenozoic sequence and the almost flat base of the Upper Permian indicate the presence of displaced Zechstein salt (see SE part of the Fig. 3.2). Clear evidences of basement fault-controlled subsidence have been recognized at the SE boundary of the Eastholstein Through (Fig. 3.2). There, a steep westward-dipping normal fault is observed, separating the Eastholstein Through from the SE flank of the basin (Eastholstein-Mecklenburg block). Differential movements along the fault suggest a relatively young reactivation of this fault in Late Cenozoic times. Salt movements fold post-Permian strata around the fault. It is important to note that the base of the salt-rich Rotliegend is almost horizontal close to the fault. On the other hand, the Zechstein base is well traceable and folded within the hanging wall, indicating the dislocation of the Rotliegend salt. Thinning of both Zechtein and salt-rich Rotliegend strata further to the NW indicate a depletion of the salt-rich layers. As already pointed out, the presence of salt structures makes the interpretation of the seismic reflections rather difficult, particularly those located in the deepest part of the basin (Fig. 3.2). For the reasons given above, the base of the salt-rich Permian is not traced and the lower part of the Triassic is not subdivided within the deepest part of the Central Triassic Graben. The recognized Lower Triassic (Buntsandstein) strata are characterized by constant thickness with some evidences of postsedimentation erosion near its deepest part (Fig. 3.2). The Muschelkalk shows a constant thickness on the basin shoulder and variable thickness towards the central part of the line. The uppermost Middle-Upper Triassic (Keuper) is characterized by strong variations in thickness and complex reflectivity images (Figs. 3.2). This sequence represents the infill of the GG and shows increasing thickness towards the basin centre. In the SE part of the line, the Keuper interval shows a similar seismic pattern as the Buntsandstein and Muschelkalk sequences. Towards the Central Triassic Graben, the reflection patterns show evidence of strong syn-depositional thickening of the Keuper compare with the underlying strata. This structural difference between the Keuper and older Triassic strata indicates that significant changes of the tectonic setting occurred at the beginning of the latest Middle-Late Triassic



NW
SE
Central Triassic Graben
Eastholstein Trough
Eastholstein-Mecklenburg Block
120 km
Fig. 3.13
(a)
(b)
(c)
TWT (s)
Q-Pg
K
J
Salt
P-C-D-?

(Keuper) within the studied area. The Keuper has a subparallel reflective package at the basin flank. While, the presence of baselapping strata of the thick Keuper sequence indicates rapid subsidence, accompanied by dawnbuilding of the salt structures. Jurassic sediments are only present around the salt structures along the seismic line, indicating the development of rim synclines along the edges of elongated salt walls. The presence of Jurassic on the SE flank of the basin indicates that the original Jurassic infill likely covered a wider area before Late Jurassic-Early Cretaceous erosion. This erosional event is indicated by the angular unconformity beneath the base of the Cretaceous, which provides as a regional unconformity within the GG. The Cretaceous sequence shows an almost constant thickness along the line with thinning from the Eastholstein Through towards the SE flank. The deep Cenozoic Eastholstein Through is observed by thickening of the Cenozoic succession up to 2 s TWT on the eastern side of the line. Generally, the Cenozoic is characterized by thick sequences between the salt structures. Cenozoic rocks have been partially eroded from the crest of most of the salt structures (Fig. 3.2). The Cenozoic depressions between the salt walls indicate that the deposition of sediments occurred simultaneously with the growth of salt structures. In other words, the structure of the Cenozoic demonstrates the rim syncline character of deposition. By contrast, the Cenozoic strata have almost horizontal bedding within the axial part of the line and on the SE termination of the profile (Fig. 3.2). Such subhorizontal bedding indicates a rather weak effect of the salt movements on sedimentation.

Line 1 shows that the post-Permian sedimentary succession of the Central Triassic Graben and the Eastholstein Trough is deformed by salt movements. Thus, one of the main deformation mechanisms 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,

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Figure 3.2. Interpreted northwest-southeast transect through Schleswig-Holstein (profile 1 in the Fig. 3.1). Stratigraphic key for this and other figures: C-D = Undivided Carboniferous and Devonian deposits; P1-C2 = Lower Rotliegend and uppermost Carboniferous; P1(s) = upper part of the Lower Permian (salt-rich Rotliegend); P2 = Upper Permian (Zechstein); P2+P1(s) = upper part of the Lower Permian and Upper Permian (undivided Zechstein and salt-rich Rotliegend); T1 = Lower Triassic (Buntsandstein); T2 = Middle Triassic without uppermost part (Muschelkalk); T2-3 = uppermost part of Middle Triassic and Upper Triassic (Keuper); J = Jurassic; K1 = Lower Cretaceous; K2 – Upper Cretaceous; Q-Pg = Paleogene-Quaternary.

anticlines, pillows, stocks, and most pronounced elongated salt walls. Based on the tectonic subdivision of the region, different salt structures and related structural features will be described below. The seismic architecture of the studied area are presented in terms of key regions: (1) the NW region, which extends along the NW boundary of the GG, named the Westschleswig block; (2) the central domain, which includes the Central Triassic Graben; (3) the marginal domains, that correspond to Eastholstein and Hamburger Throughs; and (4) the SE outer domain, the area of the Eastholstein-Mecklenburg block.

3.2. Flanks of the basin – Westschleswig and Eastholstein-Mecklenburg blocks

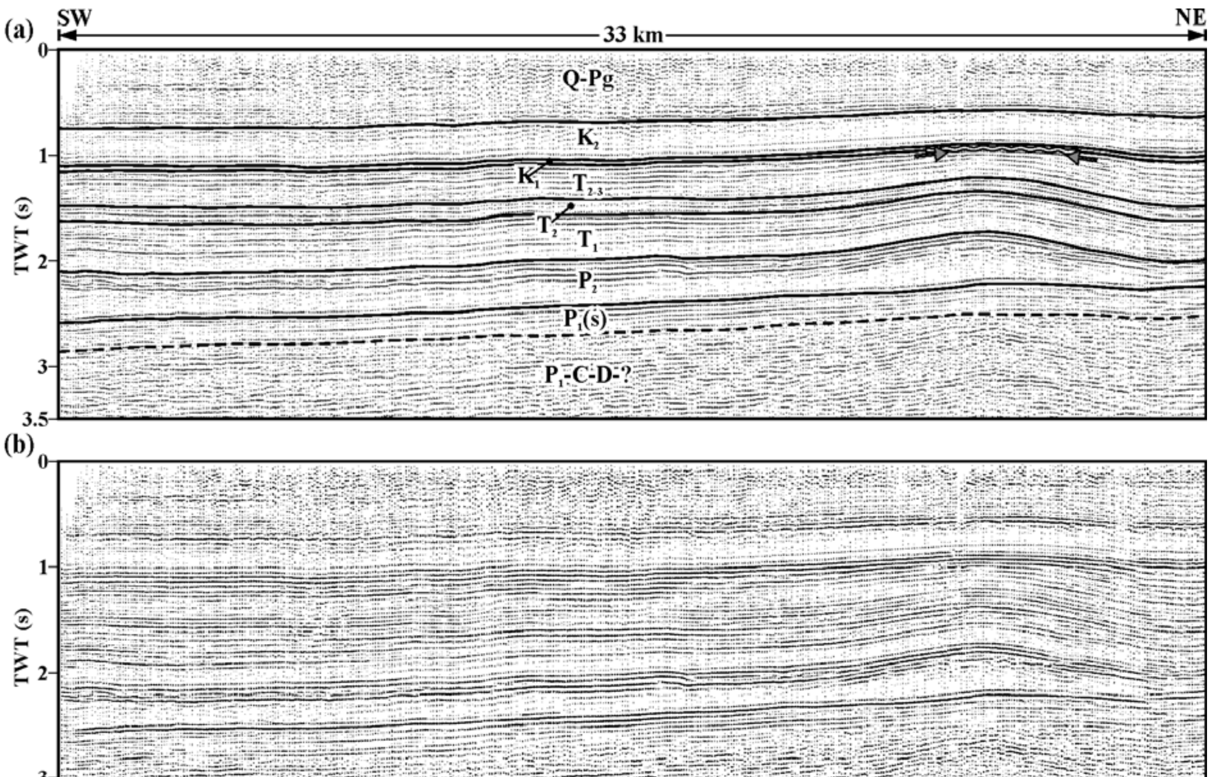


Figure 3.3. Interpreted seismic profile 2. A typical structure from the NW flank of the basin (Westschleswig block) is shown (visible erosinal unconformity is indicated by wavy line). See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

The Westschleswig and Eastholstein-Mecklenburg blocks represent the north-western and south-eastern flanks of the basin. Figure 3.3 shows the area of the 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 are dominating along the largest part of line 2 with exception of the NE part. There, a salt pillow complicates the subparallel seismic pattern (Fig. 3.3; see enlarged version in Appendix A). The Mesozoic to Cenozoic layers are subparallel to base Zechtein. The salt-rich Rotliegend below the salt structure and the constant thicknesses of the uplifted Buntsandstein and Muschelkalk indicate that the salt pillow developed during the Keuper by mobilisation of Zechstein salt. Insignificant reactivation of the Zechstein salt movements occurred in the Paleogene-Neogene, when a shallow anticline formed (see NE part of the Fig. 3.3). 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 within the Westschleswig block.

Seismic lines 3 and 4 (Fig. 3.4; see enlarged version in Appendix A) show the structure within the outer NE part of the Eastholstein-Mecklenburg block. The interpretation of these lines is based on the geological information of the nearby situated Well 4 (see Fig. 3.1 for location). The salt-rich Rotliegend sequence has been interpreted only on line 3 (Fig. 3.4a). On the other hand, the salt-rich Rotliegend is not interpreted along line 4 (Fig. 3.4c) due to an almost chaotic seismic pattern beneath the base of the Zechtein. The salt-rich Rotliegend is characterized by a subparallel package of reflections with thickness up to 0.4 s TWT. The internal structure of the salt-rich Rotliegend does not indicate any salt movements of the upper Rotliegend salt in the area around the lines. In contrast, the variable thickness and the complex internal seismic pattern of the Zechstein clearly show that Zechstein salt was mobilized during post Permian times. Furthermore, the outflow of Zechstein salt created additional space for the deposition of Cenozoic deposits in the SW part of line 3 (Fig. 3.4). There, the thickness of the Cenozoic strata is more than doubled compared with the NE part of line 3 and line 4. The Jurassic sediments are only present on the SW limit of line 3 and the

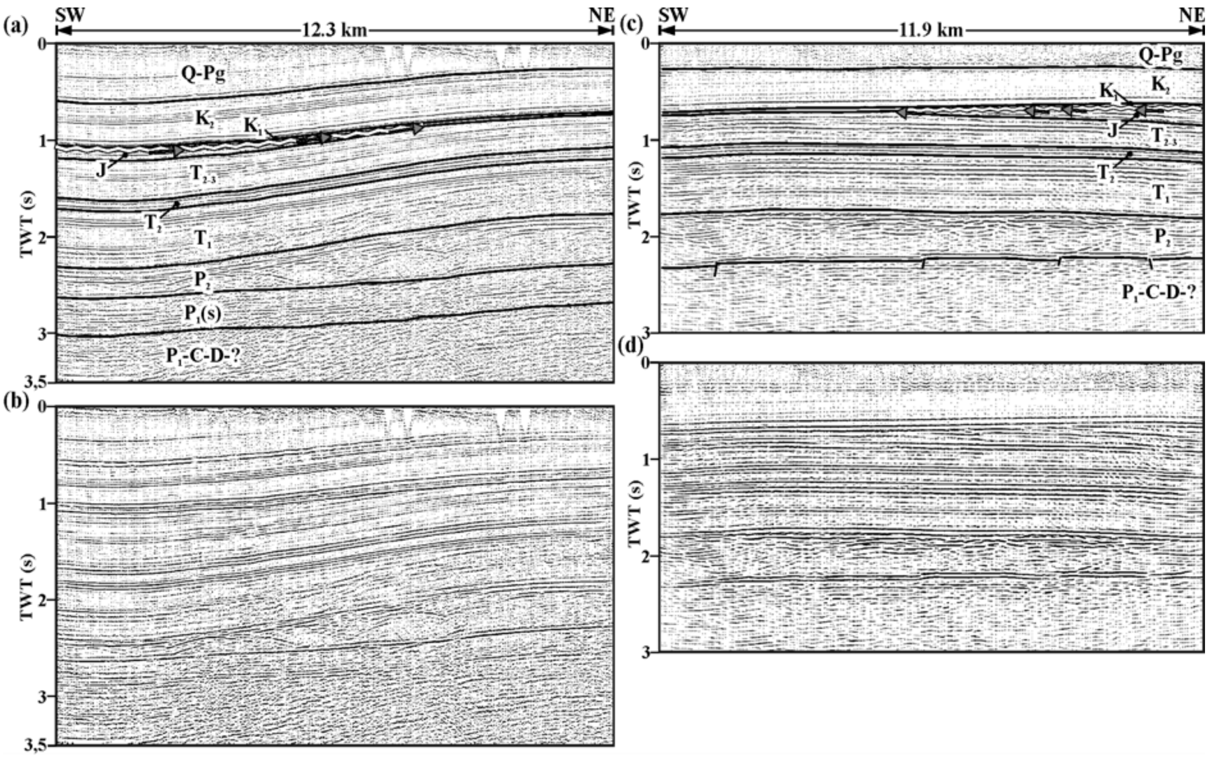


Figure 3.4. Interpreted seismic profiles 3 and 4. A typical structure from the NE part of the SE flank of the basin (Eastholstei-Mecklenburg block) is shown (visible erosinal unconformity is indicated by wavy lines). See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

NE limit of line 4. Possibly, they had a much broader distribution before the Late Jurassic – Early Cretaceous erosion. The visible truncation is indicated in terms of an angular unconformity by wavy lines along the lines. The borehole data (Well 4) indicate that the Keuper was also eroded but not so essentially. This can indicate a minor amplitude of erosion or the presence of thick Jurassic sediments before erosion. Triassic and Createceous sequences have an almost constant thickness along the lines, indicating minor or no movements of salt during the Triassic and Cretaceous times within this part of the basin (Fig. 3.4).

The geological interpretation of the various seismic events on line 5 (Fig. 3.5; see enlarged version in Appendix A) is supported by reliable borehole information (Well 5). The profile runs 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, possibly representing the 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 "activity" of the underlying Lower Permian salt beds in this part of the basin. The Buntsandstein and Muschelkalk sediments have approximately constant thickness, indicating rather flat bedding during sedimentation. The Keuper sequence shows almost constant thickness along the line with slight thinning towards the southern termination of the profile. Thick Jurassic (about 0.5 s TWT) is interpreted within the southern limb of the salt anticline. The Jurassic infill pattern is characterized by onlap from below and truncated toplap from above in the southern anticline limb. 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 Late Jurassic-Early Cretaceous uplift or sea level fall at that time. The well data show that the Keuper sediments at the crest of the salt pillow have been also eroded. However, it is not obvious that Upper Triassic sediments were mainly eroded during the Late Jurassic-Early Cretaceous. Possibly, some part of the missing Triassic sediments was eroded during the formation of the relatively deep Jurassic depression on the southern termination of the profile. Furthermore, the presence of the Jurassic onlaps onto the top of the Keuper can indicate that northward lying Triassic strata were uplifted. Thus, there are no direct indications concerning the presence of thick Jurassic sediments at the crest of this salt anticline before Late Jurassic-Early Cretaceous erosion.

The Cretaceous strata have 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 Upper Permian (Zechstein salt) section (Fig. 3.5). 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 5. The culmination of the development occurred during the post-Miocene when the crest of the biggest salt anticline was affected by erosion with rapid subsidence of the southern and northern limbs.

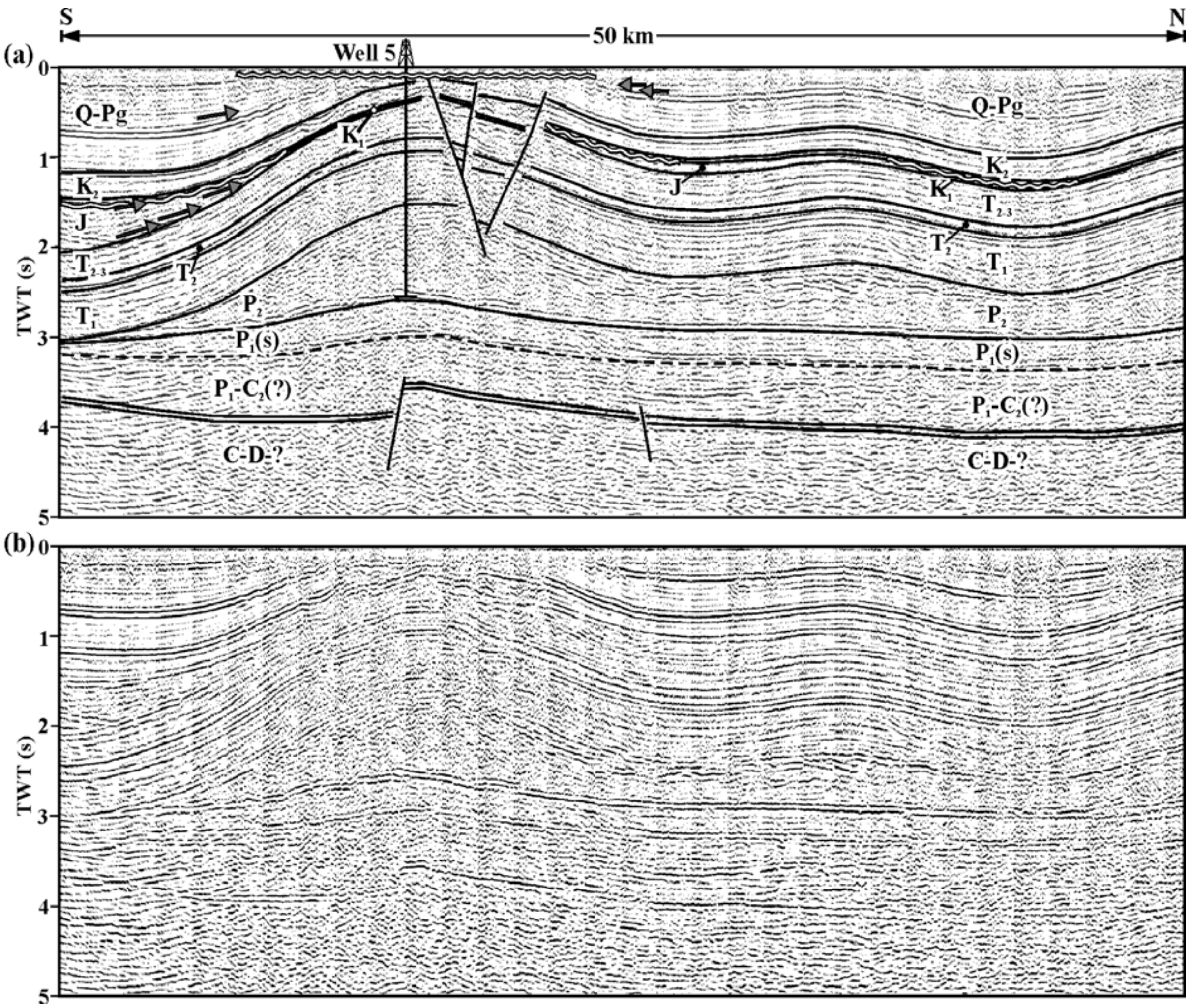
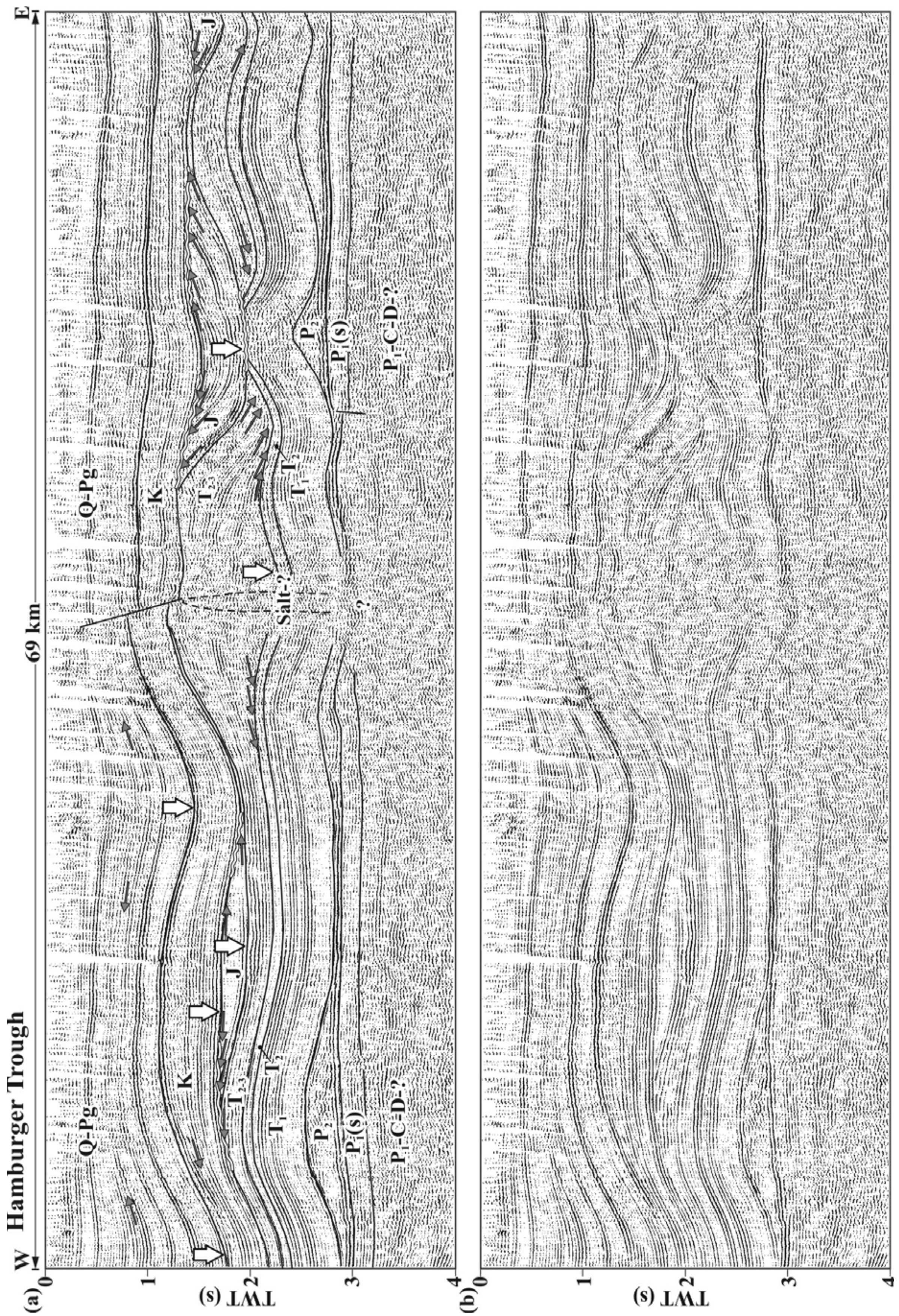


Figure 3.5. Interpretation of line 5 showing structural features along the Eastholstein-Mecklenburg block (visible erosinal unconformities are indicated by wavy lines; arrows show on- and toplap of the reflection terminations). Late Carboniferous-Early Permian extension tectonics is shown beneath Permian salt pillow. See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

In post-Miocene times, the overburden of the salt structure was faulted, possibly due to an extension. It is noteworthy that the southern limb of the salt anticline has steeper dipping layers at the Triassic level than at the Cretaceous level. This difference in dipping indicates two periods of anticline growth, suggesting the main phases of the salt activity during the Jurassic and during the Cenozoic, with interruption during the Cretaceous. A slight decrease in thickness of the Keuper towards the south indicates the initial stage of salt movements. On the other hand, the deposition of the Buntsandstein and Muschelkalk sequences were not affected by salt movements but these strata were involved into the salt anticline during postdepositional times.

3.3. Marginal Hamburger Trough

The structure of the southern margin of the Hamburger Trough is shown by the west-east running seismic line 6 (Fig. 3.6; see enlarged version in Appendix A). The salt-rich Rotliegend sediments deposited as a huge flat blanket without prominent deformation in the western and eastern parts of the profile (Fig. 3.6). In the central part, the upper Rotliegend deposits are not correlated due to the presence of a salt diapir. The overall reflection pattern features high parallel and high coherency along the line, however beneath the salt diapir, the upper Rotliegend reflectors generally become chaotic and wormy. This can indicate that upper Rotliegend salt together with the Zechstein salt was involved in the formation of the salt stock. Zechstein deposits are geneally thinned. Thinning of the Zechstein occurred during the formation of salt structures such as three salt pillows and the mentioned salt diapir. The Buntsandstein-Muschelkalk deposits have constant thickness of about 0.6 s TWT with the exception of the salt anticline within the eastern part. There, the Buntsandstein and Muschelkalk have been truncated in the crest of this anticline. The western part of the line is characterized by the presence of the thin Keuper, which concordantly covers the underlying Middle-Lower Triassic strata. In contrast, the internal Keuper reflections are not in phase with the underlying bedding within the area around the salt diapir and towards the east. In the central part of the line, the Keuper sequence is extremely thickened up to 0,9 s TWT in comparison to 0,24 s TWT on the westward margin. The thickened Keuper sequence is characterized by the presence of clinoforms onlaping onto the top of Muschelkalk. These baselaps indicate a main phase of salt movements, which occurred at the beginning of the Keuper. In addition, the onlap of the Keuper onto the Muschelkalk demonstrates that structural highs were formed due to salt movements. Some of these structural highs were in existence until the Jurassic. Figure 3.2 shows one of these highs where thick Jurassic sediments discordantly cover eroded Buntsandstein and Mushelkalk sediments at the crest of the salt anticline. Jurassic strata are present within the seismic profile, forming three depocenters of sedimentation. The top of Jurassic is characterized by an angular


(a)
W
Hamburger Trough
69 km
E
Q-Pg
K
J
T
Salt-?
P2
P1(s)
P1-C-D-?
TWT (s)
(b)
TWT (s)

unconformity within these depocenters. Clearly, some parts of the Jurassic sediments have been eroded (Fig. 3.6), implying a major hiatus at the base of the Cretaceous. This major hiatus is traceable along the entire line, indicating a considerable long-term erosional process. On the other hand, thickening of the Jurassic sediments within the depositional centres does not necessarily indicate the distribution of equally thick Jurassic prior to the Late Jurassic – Early Cretaceous erosion along the entire profile. It is rather a consequence of progradation of clastic wedges following salt outflow. This is illustrated by the change from steeply-dipping seismic reflection pattern of the old Jurassic strata to an almost horizontal reflection pattern within the youngest Jurassic sediments, indicated by arrows within the Jurassic sequence in Fig. 3.2. The Cretaceous covers an erosionally leveled surface with thickness variation from 0.3 s up to 0.6 s TWT. Along line 6, the Cenozoic sequence reaches a thickness of 1-1.8 s TWT. A high angle normal fault cuts the Cretaceous and the Cenozoic through the anticline above the salt diapir, but stops within the Upper Cenozoic. This fault divides the line into two segments. The Eastern segment is characterized by approximately subparallel Cretaceous and Cenozoic reflections. There, a distinct angular unconformity separates folded Triassic and Jurassic deposits from subhorizontal Cretaceous-Cenozoic sediments. In contrast, the Cretaceous and Cenozoic successions are folded within the western segment of the line.

In addition, this seismic line demonstrates a prominent feature of the distribution of sediments thickening at the different stratigraphic levels. It is clearly seen, that the axial parts of the thickened sediments at the different stratigraphic layers never vertically aligned (see white arrows in Fig. 3.6a). For instance, two segments of the thick Keuper are separated by thick Jurassic sequence (Fig. 3.6a), and both thick successions are covered by ordinary Cretaceous and Cainozoic. Furthermore, an unusual extensive thickening of the Cretaceous strata is observed between two Cenozoic depressions on the western part of the line. These two Cenozoic depression are characterized by thickening of the strata, indicating rapid subsidence in comparison to other parts of the time section. The thickened Cretaceous is

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Figure 3.6. Interpreted seismic profile 6. A typical structure along the southern margin of the Hamburger Trough is shown (visible erosinal unconformity is indicated by wavy line; grey arrows show on- and toplap of the reflection terminations; white arrows indicate the depocentres of sedimentation). See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

underlain by thick Jurassic but without vertical alignment of those axial parts. It is possible to conclude that thickening was strongly controlled by depletion of the Permian salt layer along the line. Thus, the seismic data reveal that thickening of the sediments was associated with simultaneous salt movements.

3.4. Marginal Eastholstein Trough

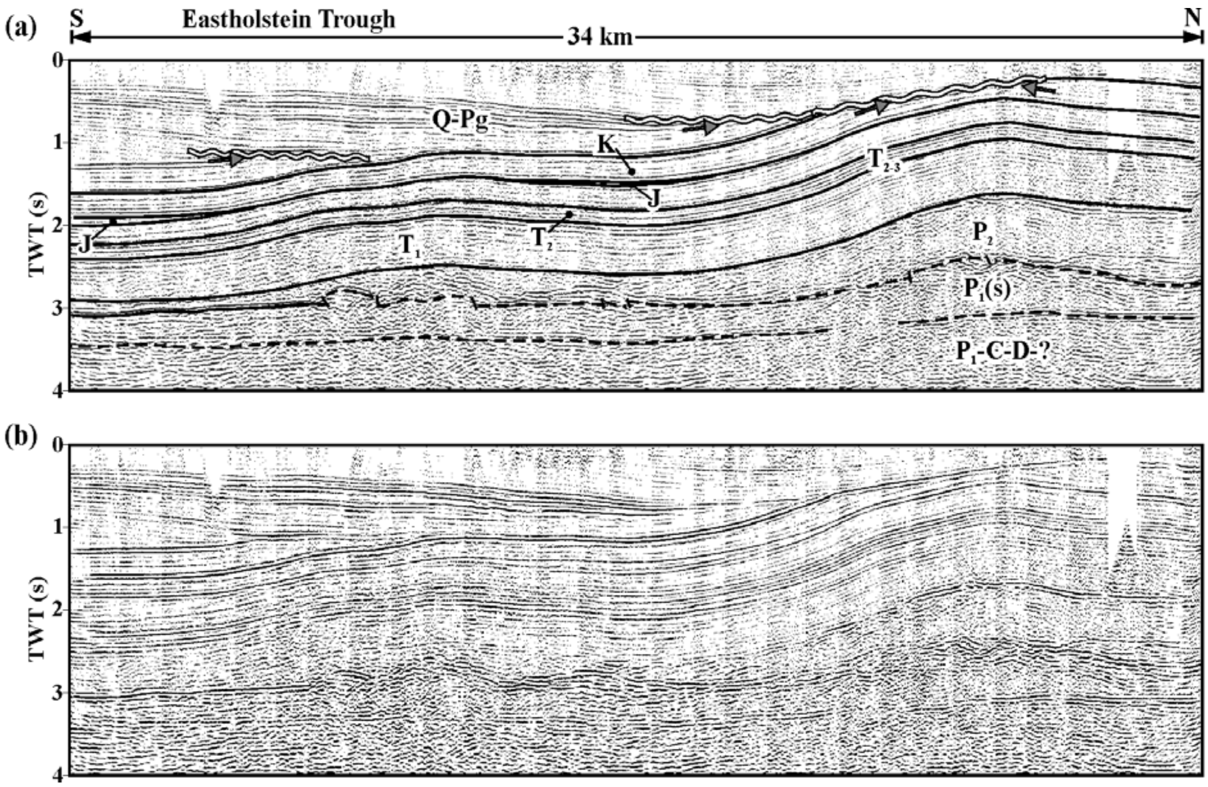

Figure 3.7. Interpreted seismic reflection line 7 from the Eastholstein Trough. Two Cenozoic unconformities are shown by wavy lines. See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

The Eastholstein Trough is characterized by increased thicknesses of both the Jurassic and the Paleogene-Neogene (Figs. 1.4b and 3.2). Line 7 (Fig. 3.7; see enlarged version in Appendix A) runs through the eastern part of this trough along the marginal salt wall, representing an area of extremely thick Paleogene-Neogene succession. The high-amplitude reflections at the base of the Zechstein are continuous and subhorizontal along the southern part of the line. Northward from the Eastholstein Trough, reflections at the Zechstein base are transformed from a strong coherent seismic phases into a number of discontinuous and sporadic phases which are commonly folded and even faulted. 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. 3.7). Thus, the presence of almost horizontal reflections at the base of the salt-rich Rotliegend and continuous reflection package of Triassic strata indicate the presence of a ductile layer between. Partially, this ductile layer is obviously represented by Zechstein salt. On the other hand, the structural features of the Zechstein base imply the presence of an additional ductile layer below. According to the litho-stratigraphic column of the GG, this lower part of the ductile layer can be only be the salt-rich Rotliegend. Consequently, the salt beds of the salt-rich Rotliegend together with Zechstein salt were involved in the formation of the two observed salt anticlines along the seismic profile (Fig. 3.7). The Buntsandstein, Muschelkalk and Keuper sequences have approximately constant thicknesses, demonstrating the absence of strong salt movements during this time. Jurassic sediments are found 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, an another erosional unconformity is observed during the Cenozoic. These two distinct erosinal 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 250 to 1680 ms two-way travel time. The thickest package of the Paleogene-Neogene sequence corresponds to the thinnest Permian salt beds and vice versa (Fig. 3.7). 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. 3.7) as well as parallel to the salt wall towards the west (Fig. 3.1). Thus, the syn-kinematic stratigraphic thickening of the Paleogene-Neogene interval indicates mainly Cenozoic salt movements along the entire line. In contrast, the whole Mesozoic interval is only deformed without considerable thickness variations related to salt-cored anticlines and synclines.

3.5. Transition zone from the NW flank to the Triassic graben

The NW-SE running line 8 (Fig. 3.8; see enlarged version in Appendix A) intersects the collapsed termination of a salt wall (Fig. 3.8) which continues towards the south (Fig. 3.1). This line commences in the north-western flank of the basin and further to the east

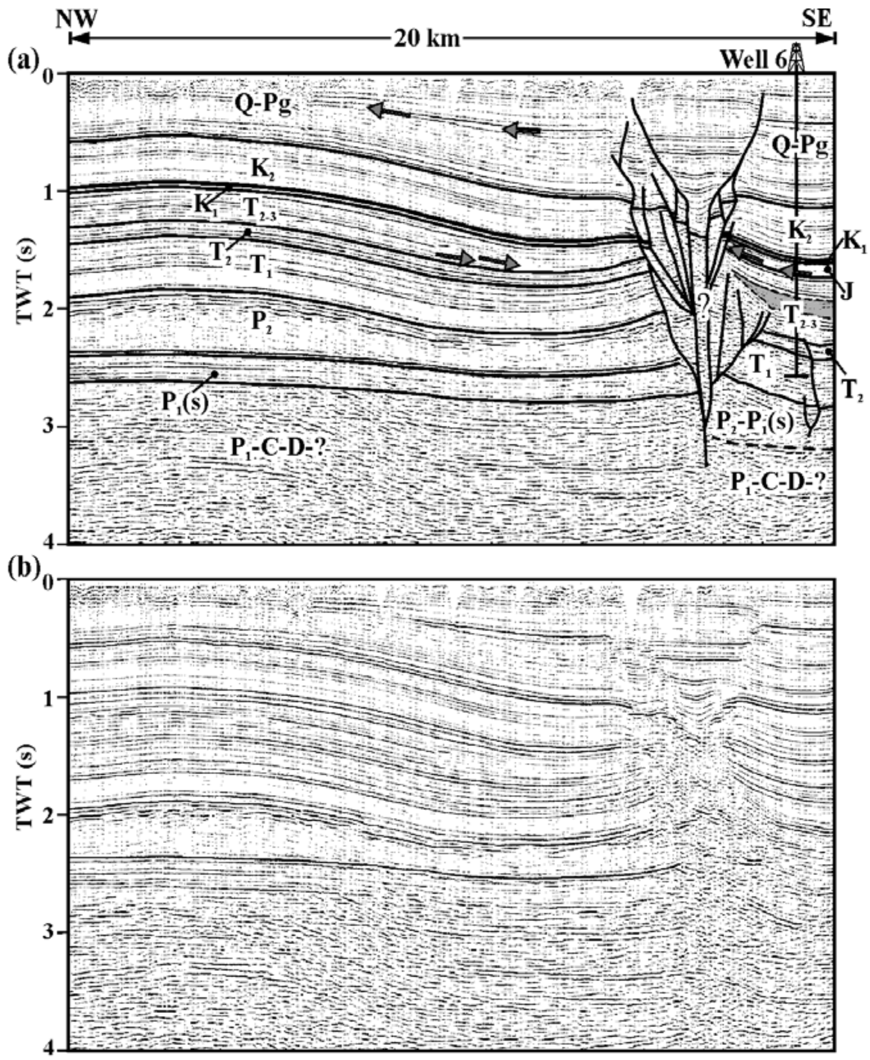

Figure 3.8. Interpreted seismic profile 8 showing a salt structure which collapsed during Paleogene-Neogene. The section shows the transition from the NW flank towards the center of the GG (arrows show onlap of the reflection terminations). The gray wedge corresponds to the salt-rich Keuper sequence. See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

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 may have formed along basement faults (Sanemann, 1968; Maystrenko et al., in press). 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 6. Moreover, this seismic line across the western boundary of the GG (cf. Fig. 3.1) 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 NW flank of the basin and their presence south-eastward from the fault (Fig. 3.8), it is suggested that the fault experienced more than one phase with reactivation in the Jurassic. Onlap at the base Jurassic (SE part of the profile) points toward further salt flow and continued fault movements in this area. During the Paleogene-Neogene, this part of the salt wall (cf. Fig. 3.1) collapsed probably due to salt outflow towards its southern continuation, causing the formation of a complicated fault system above the former salt structure (Fig. 3.8). This complex fault system has the features of a flower structure, pointing toward 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-Createceous 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 1200 to 600 ms. Internally, the unit shows moderate- to high-amplitude clinoforms onlaping onto the underlying strata within the central part of the profile. These clinoforms could be due to 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.

3.6. 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 (9 and 10) represented in Figs. 3.9 and 3.10.

A NNW–SSE oriented profile running through a salt diapir is presented in Fig. 3.9 (see enlarged version in Appendix A). The diapir rises from the base salt level and reaches a height of more than 4000 m. The diapir displayed in Fig. 3.9 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 to the salt stock during Middle-Late Triassic times. The observed truncation of the Buntsandstein implies that the overburden might have been penetrated during the Keuper. The Keuper sequence shows clinoforms onlaping onto the top of Buntsandstein and Muschelkalk. In addition, onnlaps are interpreted at the base of the Muschelkalk, indicating the initial pillow stage of this salt diapir. On the NNW wing of the salt structure, the Buntsandstein strata are tilted to NNW. 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 (sub-horizontal 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 erosinal unconformity underneath the base of the Lower Cretaceous. In spite of the angular erosional unconformity, toplapping Jurassic strata are still recognizable within the

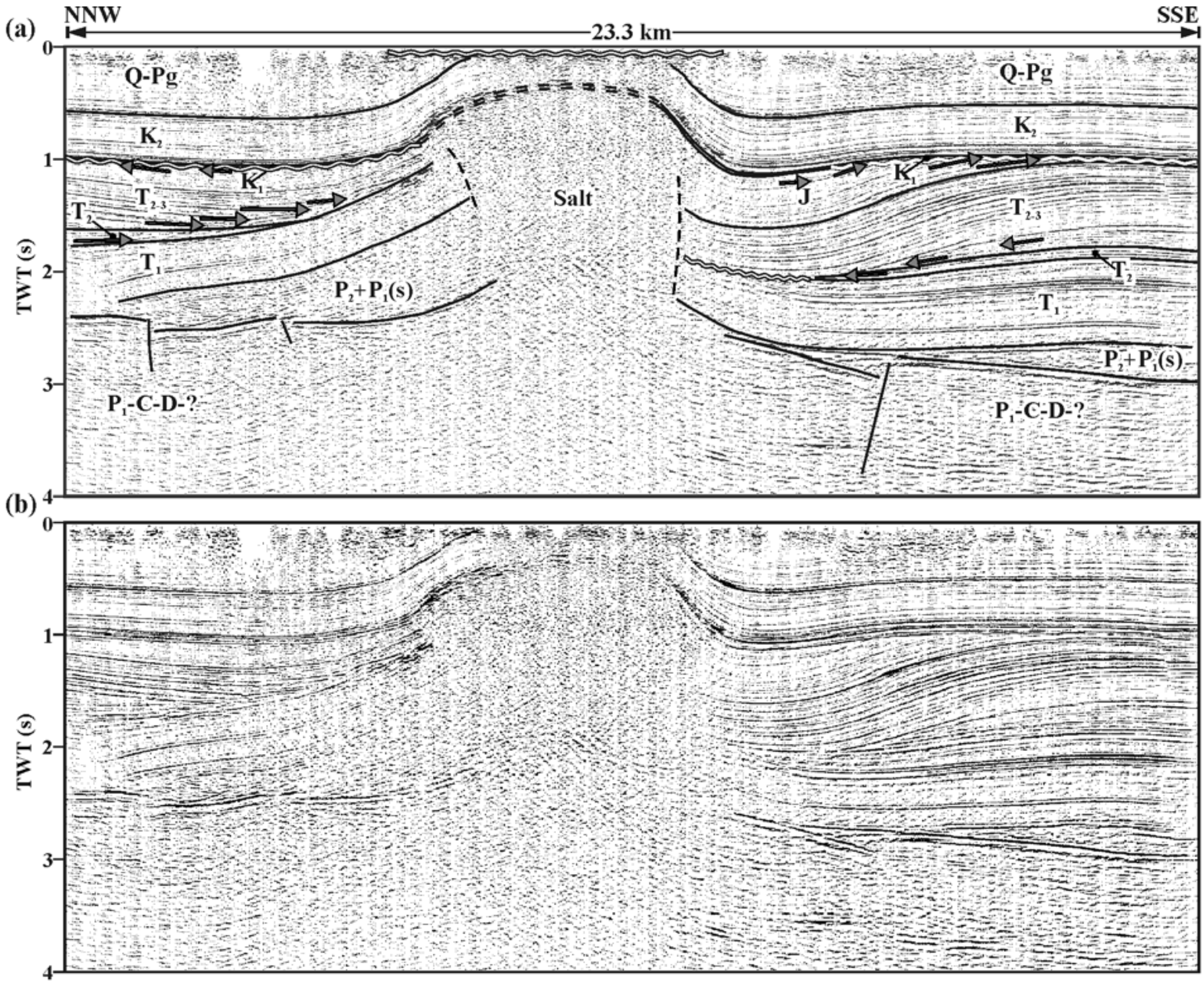

Figure 3.9. Interpreted seismic profile 9 showing the structure of a salt diapir within the northern part of the Central Triassic Graben (visible erosinal unconformities are indicated by wavy lines; arrows show on- and toplap of the reflection terminations). See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

SSE rim syncline, representing the proximal depositional limit of the Jurassic in some distance of the salt structure. The last stage of diapir 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 10 crossing one of the salt walls (Fig. 3.10; see enlarged version in Appendix A). This seismic

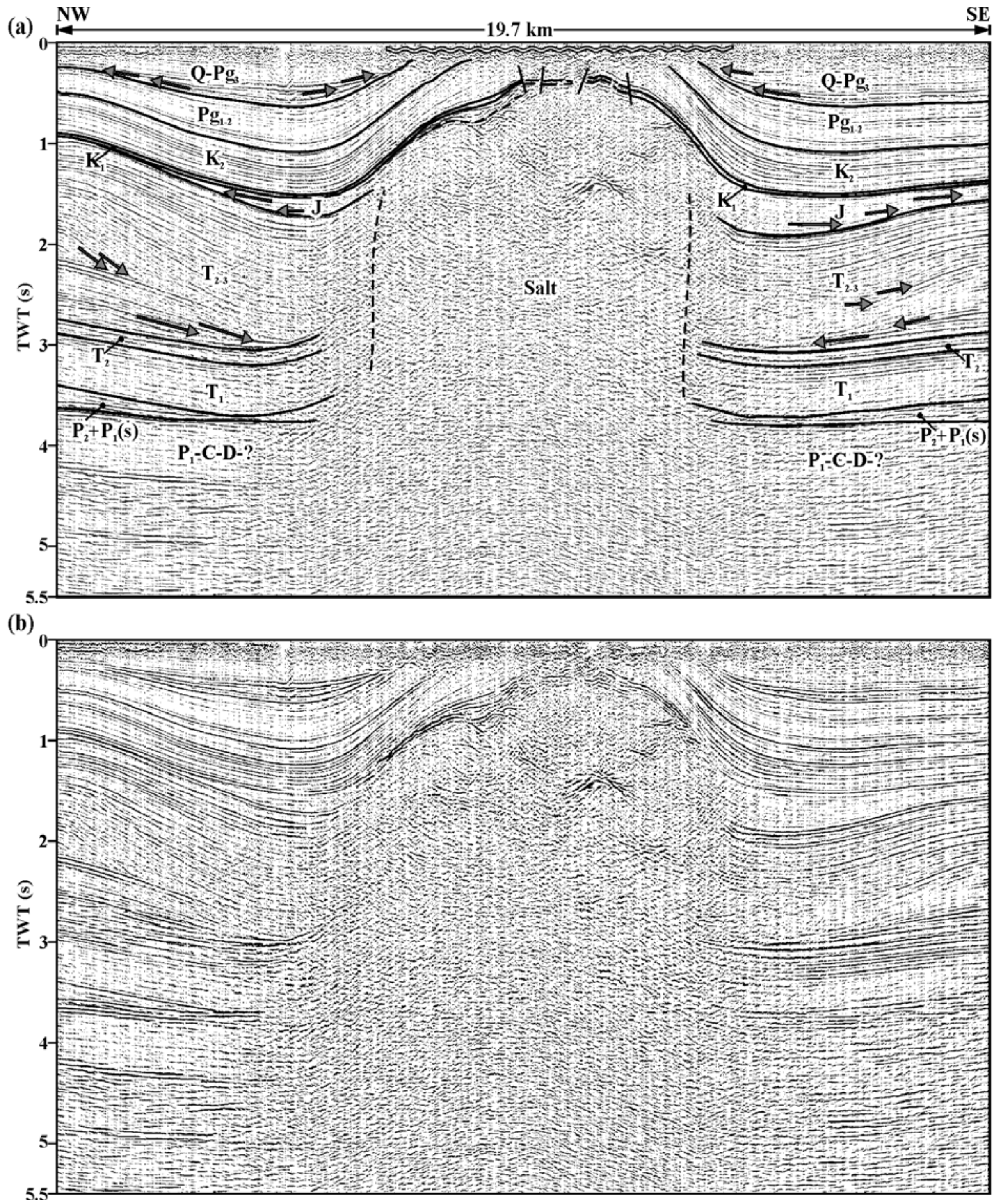

Figure 3.10. Interpreted seismic profile 10 across the central part of the Glueckstadt Graben, showing onlapping strata due to salt diapir formation within the Keuper, Jurassic and Paleogene-Neogene (onlapping strata are indicated by arrows; visible erosinal unconformity are shown by wavy line). See Fig. 3.1 for location. For stratigraphic key see Figure 3.2.

line demonstrates a vertical slice through an almost symmetrical salt wall, which reaches more than 5000 m height (Fig. 3.10). 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 well information. The Buntsandstein and Muschelalk show constant thicknesses on both sides of the salt structure. The Keuper is the thickest sequence (up to 3400 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 onnlap 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 toward subsequent extrusions of Permian salt which represent the next stage of the salt structure development – the penetration of the overburden. Considerable amount of Jurassic sediments are localized mainly around the salt structure with rim syncline character of sedimentation. Onlaps of the Jurassic reflections onto 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 10, while great amounts of salt are still preserved along line 9.

3.6.1. Detailed structure of the internal Keuper sequence

The detailed image of the Keuper sedimentary infill is illustrated in Figs. 3.11 and 3.12 by NW-SE and N-S seismic lines at the depositional centre of the Glueckstadt Graben (seismic profiles 11 and 12; see enlarged version in Appendix A). The salt beds are very thin

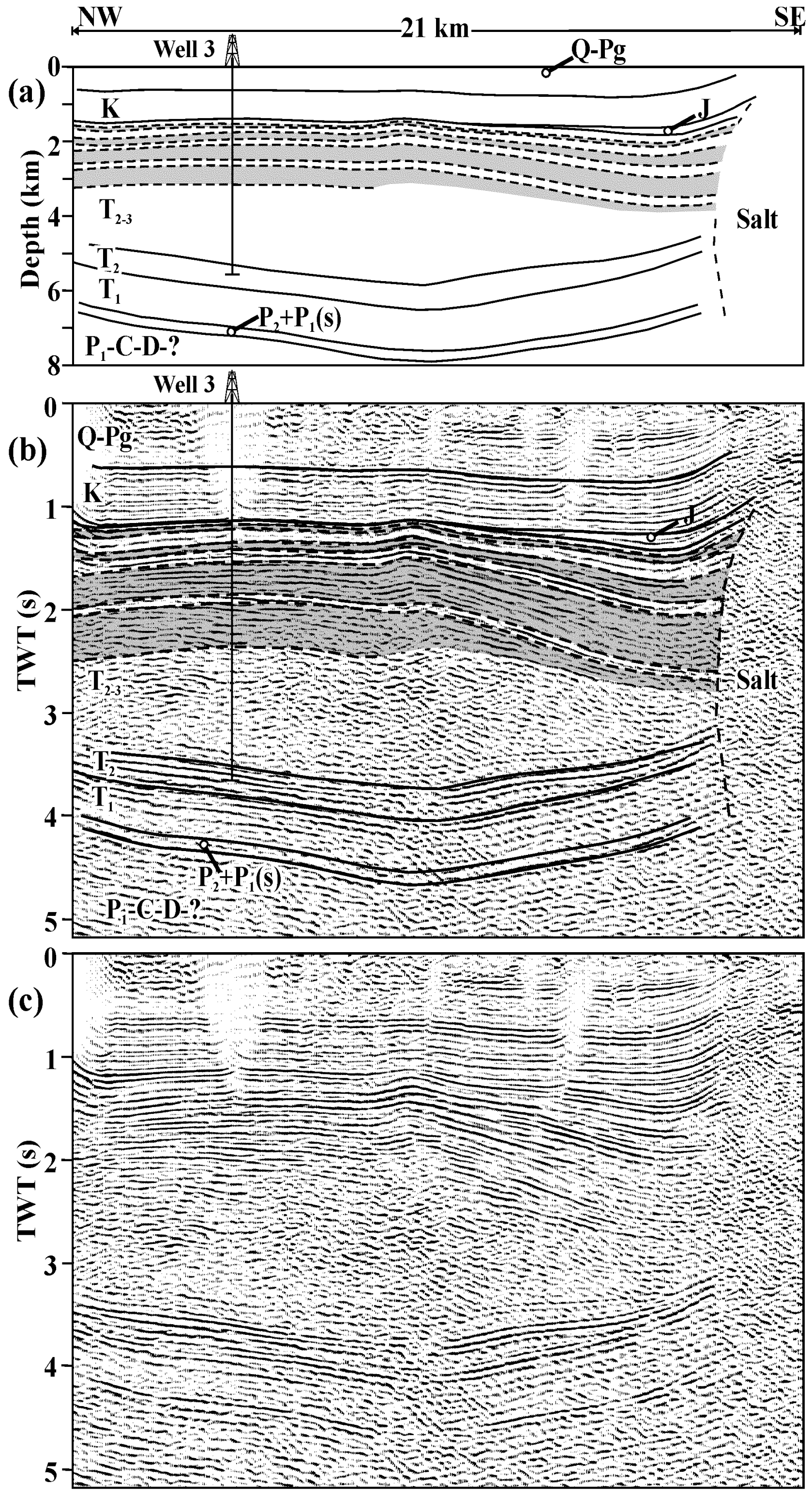

Figure 3.11. Structural features of the Keuper salt-rich layers across the Central Triassic Graben Depth. (a) Depth converted seismic section 11 (see Fig. 3.1 for location). (b) Interpreted time section 1. (c) Time section 11 without an interpretation. Grey areas correspond to salt rich layers. For stratigraphic key see Figure 3.2.

within the limits of 5-18 m except certain areas, where the Permian salt was extruded onto paleosurface. Therefore, it is not possible to show single salt beds in the seismic data, due to the limits of vertical resolution. The most prominent intervals of salt are shown by grey areas on the time sections. In general, the salt-rich layers within the Keuper are characterized by basinwide distribution within the Central Triassic Graben and by thinning towards the flanks of the basin. The internal seismic pattern of the salt-rich Keuper is dominated by concordant and subparallel clinoform beds (Figs. 3.11 and 3.12). The seismic profile 11 across the Central Triassic Graben of the GG shows the presence of four intervals where halite is interbedded with clastic sediments (Fig. 3.11). The deep part of the Keuper syncline was filled mainly by claystones (thickness up to 2000 m). This part of the line is characterized by non-regular reflectivity. The thickness of salt-rich layers is almost constant along the profile. However, the thickening of salt-rich layers is visible near the Permian salt diapir at the SE part of the line. Possibly, this increase of thickness occurred due to the presence of thicker salt beds, indicating an extrusion of Permian salt from the salt diapir. Therefore, some of the salt domes may have reached the surface providing a source for salt deposition within the Keuper sequence. Trusheim (1960) reported Permian spores within the Keuper salt rich layers somewhat south of the area under consideration. Thus, it is possible that the Permian salt partially extruded on the paleosurface 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 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 the Triassic and Jurassic (Ismail-Zadeh et al., 2004). Finally, present-day extrusions of salt are observed in the Zagros Mountains of Iran (Talbot et al., 2000).

The sedimentary infill in line 12 shows typical concave and sigmoidal reflections (base- and top-lapping) which can be identified as alternations of clay and salt layers by comparison with two wells (Wells 3 and 7) indicated in Figure 3.12. The seismic profile 12 is running from the south to the north along the strike of the axial part of the GG. In contrast to the cross section 11, the thickness of salt-rich layers strongly varies along line 12. Thinning of the salt-rich layers at the base of Keuper indicate a pinching-out of the

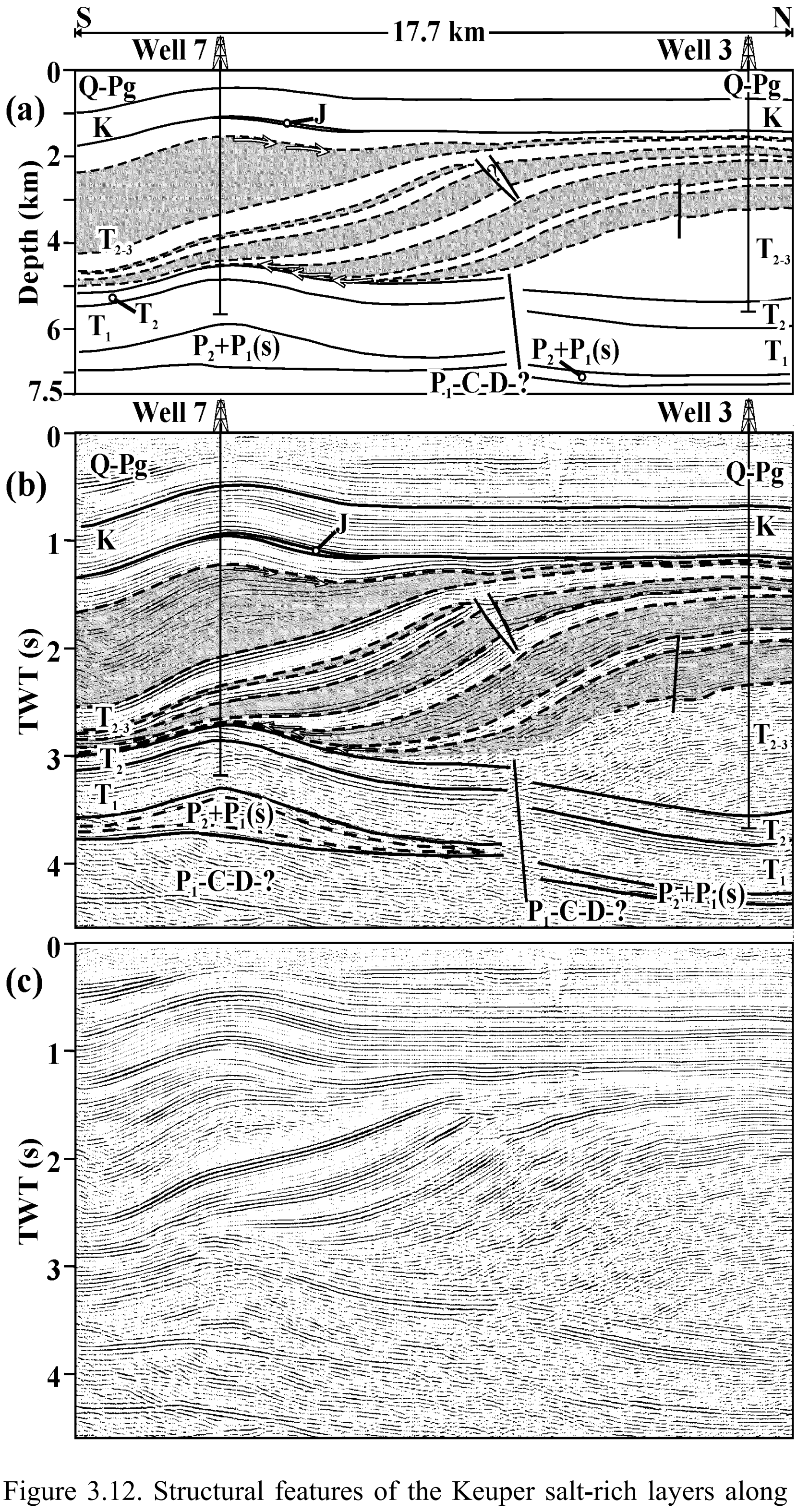

Figure 3.12. Structural features of the Keuper salt-rich layers along the Central Triassic Graben. (a) Depth converted seismic section 12 (see Fig. 3.1 for location). (b) Interpreted time section 2. (c) Time section 12 without an interpretation. Grey areas correspond to salt rich layers. For stratigraphic key see Figure 3.2.

sediments southward with exception of the youngest salt-rich interval. The sigmoidal layers indicate sediment progradation from north to south into a rapid subsided trough, which was subsequently filled from a source area in the north, perhaps the Ringkoebing-Fyn High. The present-day dips of the sigmoidal reflections are 18-25 degrees. Such steeper inclination of the reflections indicates a possible change after the deposition. Therefore, this values do not reflect true dipping at the time of sedimentation. It can indicate postsedimentation subsidence within the southern part of the profile. A possible reason for this subsidence can be salt movements during late Keuper times. Structural features of the salt-rich layers show that the salt movements created additional space, which was partially filled by extruded or redeposited Permian salt. The structural analysis indicates that polyphase movements of the Permian salt accompanied basin subsidence during the Keuper. Furthermore, the results of the interpretation show that the Permian salt was continuously near the paleosurface during the Keuper.

3.7. Summary

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 toward earlier salt movements (Baldschuhn et al., 1996 and 2001). Some evidences of the initial salt movements in the Muschelkalk are illustrated in Fig. 3.9, where the Muschelkalk onlapps onto the Buntsandstein. The analysis of seismic data from the GG shows that the Middle-Late Triassic extension and associated normal faulting are the principle mechanisms for the 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 possible syn-rift structure (apparent normal faulting) provides, therefore, the typical signature of a tectonically subsided graben while typical post-rift structures are missing as well as a typical subsequent thermal subsidence. Nevertheless, some faults at the margin of the subsidence centre can be related to syn-rift erosion as indicated in Figure 3.13c by seismic flattening. Thereby, Figure 3.13 corresponds to the eastern part of Figure 3.2, an area where the correlation of the internal strata of the Triassic can be performed with some confidence. The palinspastic reconstruction of seismic reflections at the time before deposition of a particular layer was done by flattening its basal interface to the zero level of two-travel time. This kind of reconstruction provides structural snapshots for the time of deposition of each interface, and two of them are displayed in addition to the present-day image (Fig. 3.13a). The steeply dipping normal fault separates the Eastholstein Trough from the East-Mecklenburg Block on the present-day section (Fig. 3.13a). In contrast, the same fault is not observed on the sections flattened to the base of the Cretaceous and to the base of the Keuper (Figs. 3.13b, c), indicating rather young faulting in that place. The absence of fault can be inferred from the identical thicknesses of the Triassic sequences on both sides of the present position of the marginal salt dome. On the other hand, the Keuper section is characterized by the presence of mobile salt, which could have been deposited within the Eastholstein Trough during the Keuper. Subsequently, the Keuper salt could have beeen extruded from the section during post Triassic times, smoothing the thickness difference of the Keuper. This assumption is supported by the presence of the salt pillow within the Keuper sequence of the Eastholstein Trough to the south of the line 1 (Baldschuhn et al., 1996). Therefore, the probable displacements along this fault could have occured already in the Keuper times with following reactivation during the Cenozoic (Fig. 3.13a).

The internal seismic pattern of the Keuper, lithostratigraphic data and the results of pallinological 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. 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. 3.2, 3.9, 3.10 and 3.13a, b). 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. Sedimentation continued in the Early Cretaceous (mainly during Barremian-Hauterivian

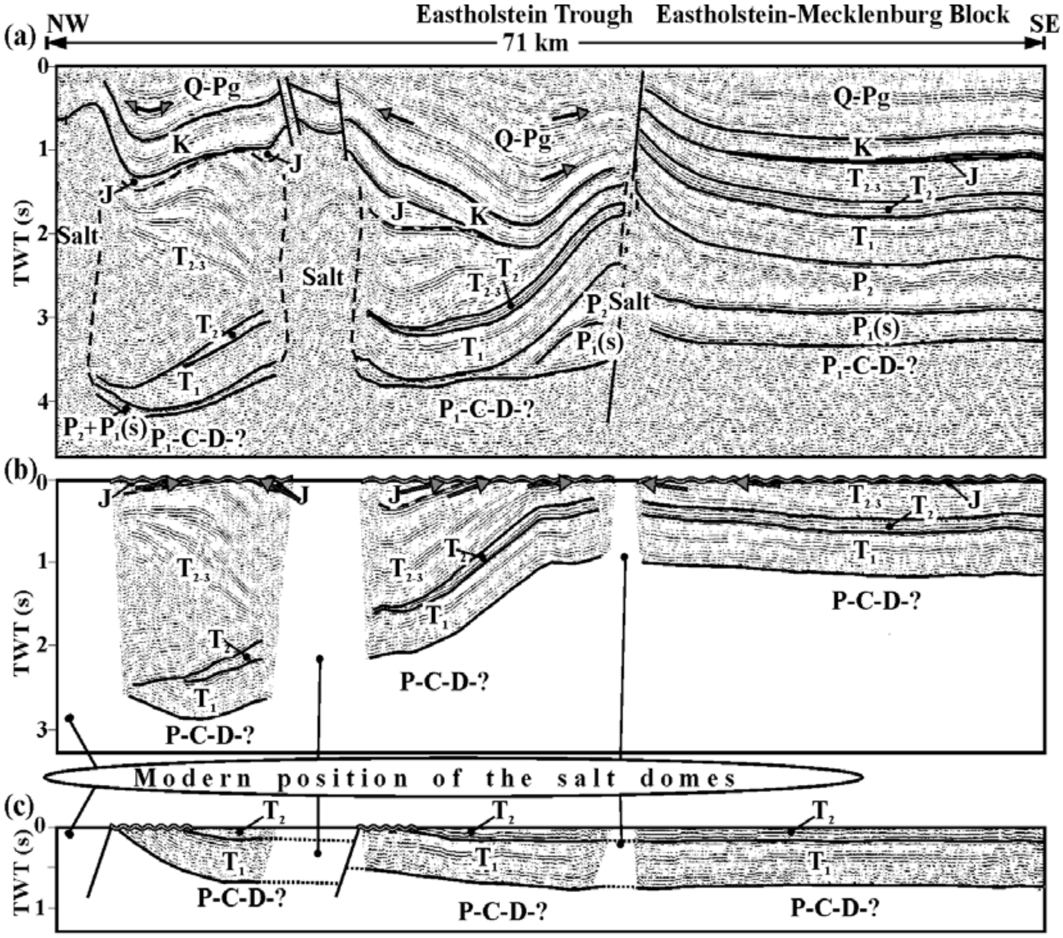

Figure 3.13. Structural evolution of the Glueckstadt Graben along south-eastern part of the seismic reflection profile 1 as visualized by flattening the SE part of line 1 to selected stratigraphic levels (for location see Figs. 3.1 and 3.2; visible erosinal unconformity is indicated by wavy line; arrows show on- and toplap of the reflection terminations). (a) Present-day structure; (b) Reconstruction to the base of Cretaceous. Late Jurassic – Early Cretatious regional erosional event is shown; (c) Reconstruction to the base of Keuper. Possible syn-rift faults and erosion are shown. For stratigraphic key see Fig. 3.2.

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 NE 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. Although many salt structures continued to rise within the centre of the GG. These movements were much less intense compared with 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. 3.5, 3.9 and 3.10. The continued rise of salt in almost N-S-striking salt walls indicates an E-W 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 N-S compression and E-W extension (Scheck and Lamarche, 2005) that is generally derived from the regional structural analysis within the 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. 3.8). The thick Paleogene-Neogene strata within the marginal troughs (Figs. 1.4b, 3.2 and 3.7) 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).