Chapter IV

3D STRUCTURAL MODEL

4.1. Introduction

A 3D structural model has been constructed for the GG and adjacent areas from 53.4^{o}N to 54.8^{o}N latitude and 8.2^{o}E to 10.8^{o}E longitude (Fig. 4.1). This 3D structural model was derived from depth maps extracted from the digital version of the Geotectonic Atlas of NW Germany (Baldschuhn et al. 1996, 2001). The two-dimensional depth maps have been integrated into a three-dimensional structural model after calculation of thickness maps.

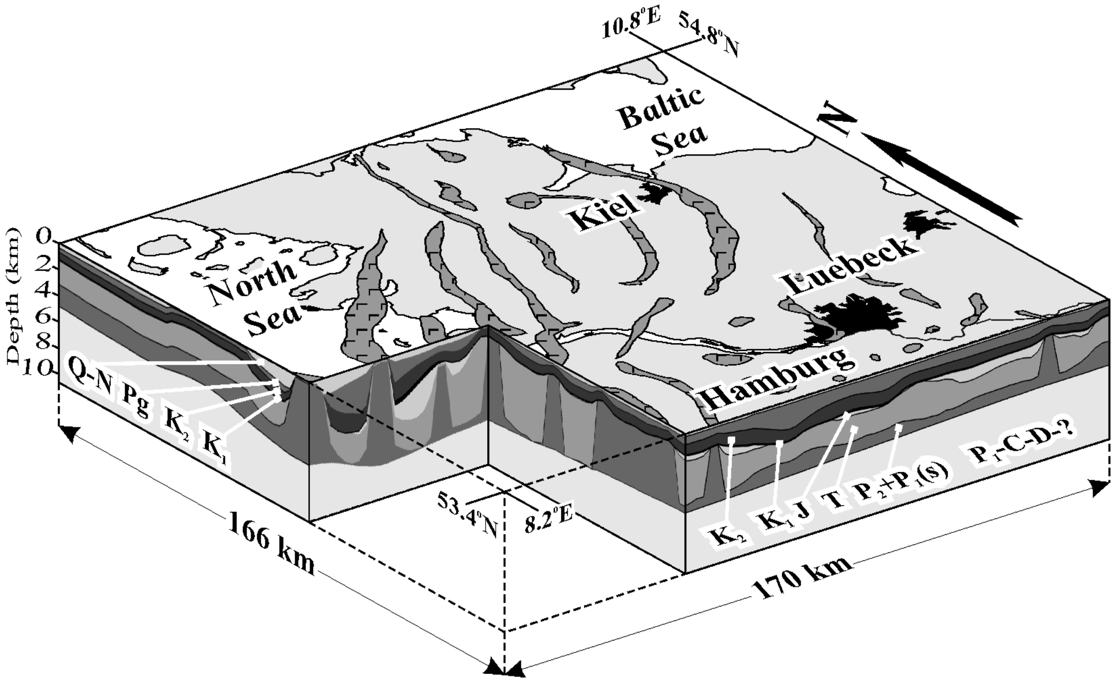


Figure 4.1. 3D structural model of the Glueckstadt Graben and adjacent areas. For stratigraphic key see Figure 1.4.

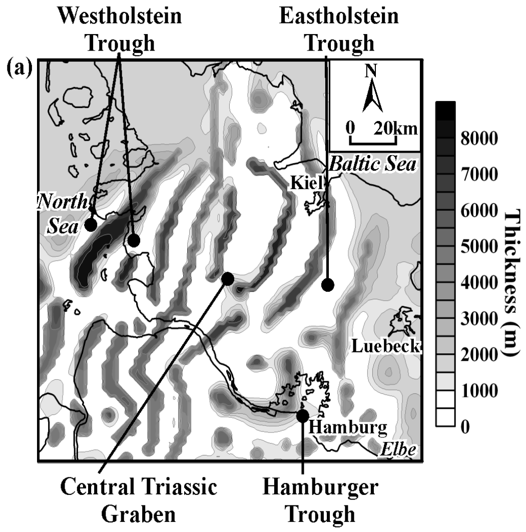
These data were gridded with a cell resolution of 2x2 km. In some areas, where stratigraphic levels intersected, corrections were necessary by the use of well and seismic information. The thickness data of the grids have been compared with the depth sections from the Geotectonic Atlas of the NW Germany (Baldschuhn et al. 1996, 2001), well data and interpreted depth converted seismic sections. In critical areas, additional control points have been added before interpolation, in order to ensure coincidence of contour lines with the original data. The most problematic areas are in the vicinity of salt structures, where steeply dipping beds and strong thickness variations occur. These parts have been recontoured by hand. Finally, the corrected data were interpolated, gridded and merged into the 3D structural model of the GG. The model includes seven thickness maps from the Rotliegend to the Pliocene. The lowest one is the salt-rich Rotliegend plus the Zechstein, overlain by Triassic, Jurassic, Lower Cretaceous, Upper Cretaceous, Paleogene and Quanternary-Neogene.

The present-day structure and the evolution of the GG are discussed in this chapter, describing the Rotliegend to Quaternary in terms of thickness maps and three-dimensional views of the base of appropriate stratigraphic levels. The salt structures represent the present-day state, i.e. the thickness maps have not been corrected for post-sedimentary piercing by rising salt walls. The different areas of the GG have been described in Chapter III by 2D seismic lines. In contrast, plane views of the studied region are presented here for selected stratigraphic levels. In addition, 2D regional slices through the 3D model are analyzed in order to demonstrate the main regional structural features of the area under consideration.

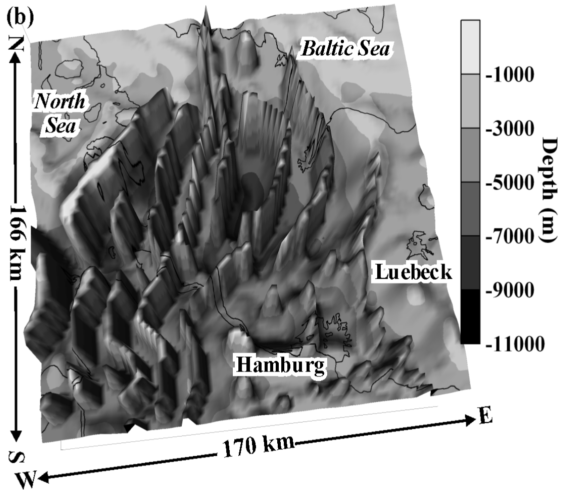
4.2. Present-day structure

4.2.1. Permian salt

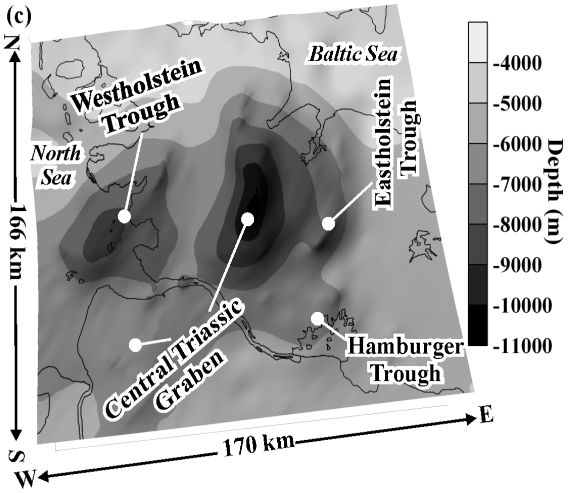
The present thickness of the Permian salt is shown in Fig. 4.2a. Only one layer in the 3D model represents the Permian salt, although, the Permian salt includes two independent layers: salt-rich Rotliegend and Zechstein. The salt-rich Rotliegend and the Zechstein have been merged in one layer because they cannot be distinguished within the Central Triassic Graben and the marginal troughs (West- , Eastholstein and Hamburger) where these layers are mixed in the limits of salt structures. The thickest Permian salt is localized within the salt structures (up to 8500 m). The north-western and eastern parts of the thickness map of the Permian salt (Fig. 4.2) are characterized by almost constant thickness of the Permian salt (about 1500-2000 m). Thus, the 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



Thickness of the Permian salt



Top of the Permian salt



Base of the Permian salt

Figure 4.2. (a) Present-day thickness map of the Permian salt. 3D view on the present-day top (b) and base (c) of the Permian salt in the investigated area.

withdrawn, forming salt structures; and, (2) the north-western and south-eastern flanks where the salt formed salt pillows (Figs. 3.5 and 4.2a) or even is preserved in its original bedding (Figs. 3.3 and 4.2a). In addition, a 3D view of the modelled top of the Permian salt (Fig. 4.2b) 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, salt deformation is less intense at the north-western and south-eastern flanks of the basin (Fig. 4.2). There, the salt- rich Rotliegend is in an almost undisturbed, flat-lying position compared with the displaced Zechstein salt (Figs. 3.2-3.5), whereas both layers have been mobilized in the central part of the basin (Fig. 3.2, 3.9-3.12). The modelled base of the salt is smoothed due to the horizontal resolution of 2x2 km and does not image faults. The isolines of the salt base 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. 3.2). Actually, the modelled 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 low reflectivity within areas occupied by salt structures in the Central Triassic Graben and the marginal troughs (cf. Figs. 3.9 and 3.10). On the other hand, reflections from the base of the Permian salt are easily recognizable at the flanks of the basin (Figs. 3.2-3.4). 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 well defined 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 -10900 m) and the Westholstein trough (depth about -8400 m; Fig. 4.2c). The huge salt walls attain a height of up to 8500 m and the deepest part of the salt base is located in the area where Triassic deposits reach the greatest thickness (Fig. 4.3a).

4.2.2. Triassic deposits

The Triassic is one of the thickest stratigraphic units of the 3D structural model (Fig. 4.3a). A broad area of the thick Triassic sediments occupies the whole Central Triassic Graben and is chracterized by a gradual increase of thickness from less than 3500 m at the margins to more than 6500 m towards the basin centre. The thickness of the Triassic in the axial part of the GG is characterized by an intense oviform zone of high thickness with a predominant SW–NE trend. The thickness ranges from 6500 to 9300 m within this zone, which represents the thickest Triassic deposits within the GG. Salt walls bound this oviform zone from the NE and SE. Within the basin flanks and marginal troughs, the Triassic thickness varies between 1300 and 2300 m in general, which locally increases up to 3000 m. Some local decreases of Triassic thickness occur around some salt structures. These local decreases of Triassic thickness can be related to syndepositional salt movements in the Triassic or to post Triassic salt activity. Most isopachs of Triassic delineate the contours of salt structures in the horizontal plane, indicating a strong influence of salt movements on the distribution of the Triassic.

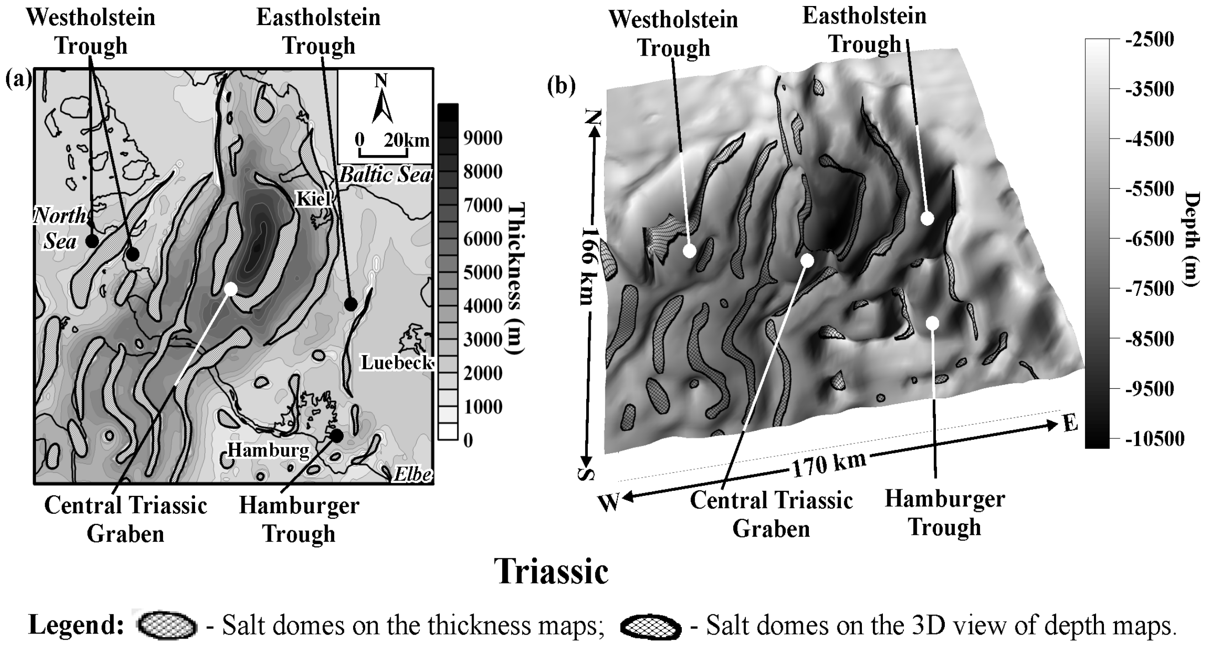


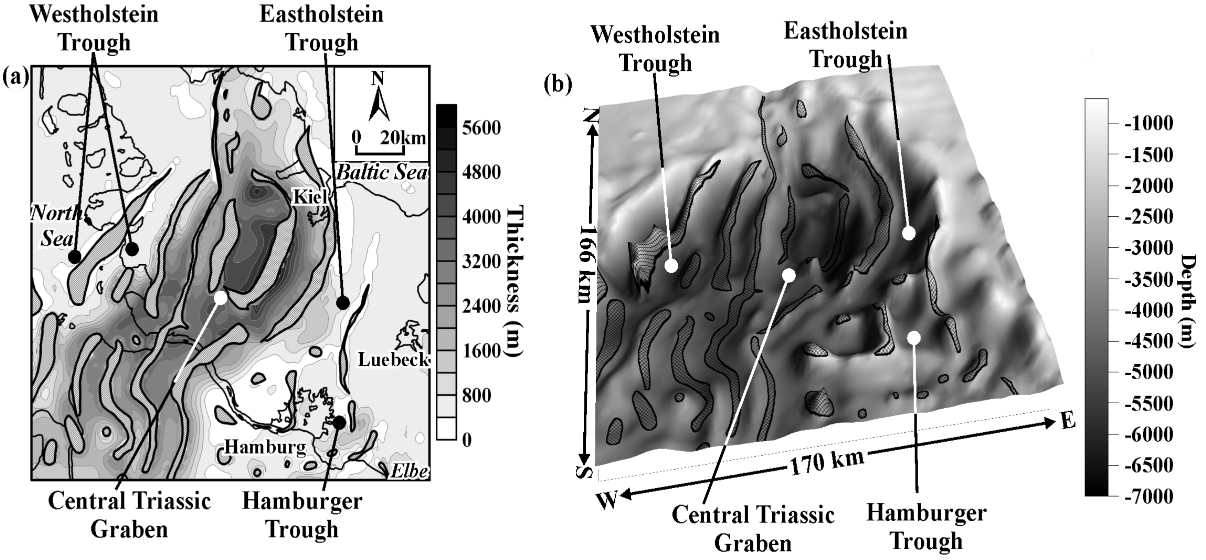
Figure 4.3. (a) Present-day thickness map of the Triassic. (b) Present-day depth position of the base of the Triassic, taken from the 3D structural model of the GG.

The base of the Triassic is located between 2500 and 4000 m depth, increasing to 7000-9000 m in the Central Triassic Graben. The base of the Triassic is complicated by many lows and rises (Fig. 4.3b), indicating salt induced deformation of the sedimentary cover. The base of the Triassic is strongly deformed within the central part of the GG where elongated salt walls are present. On the other hand, the base topography within the flanks of the GG is more or less smooth, with local rises due to the presence of salt pillows (Fig. 4.3b). There is a visible relation between the isopach map and the Triassic base in Fig. 4.3. Relatively thin Triassic deposits occur at the almost flat north-western and north-eastern parts of the GG, where only some local irregularities are present. In contrast, thick Triassic corresponds to the area with high amplitude anticlines. It was inferred from the seismic data that salt movements created these anticlines mainly during the Keuper. Particularly, the thickest Triassic is underlain by a broad syncline, which reaches 10600 m depth. This syncline corresponds to the deepest area of the present-day Triassic base (Fig. 4.3b). However, the anticline and syncline structures of the present-day Triassic base are not obviously reflected in the thickness variation of the Triassic within the West-, Eastholstein and Hamburger Troughs. This indicates post Triassic deformation of the Triassic base within the marginal troughs.

4.2.2.1. Uppermost Middle Triassic plus Upper Triassic (Keuper)

The thickness map of the uppermost Middle Triassic plus Upper Triassic (Keuper) and the present-day depth position of the Keuper base are shown in Fig. 4.4. It is important to note that the depth position of the base of the Keuper can not be identified with confidence within the central part of the GG. The reason is a poor available seismic coverage of the central part of the GG and a complex seismic pattern within the Keuper. Meaning, that the localized thickening of Keuper, undoubtedly exists in the central part of the GG, is badly defined in the present map. For that reason, the Keuper was not separately included into the 3D structural model of the GG.

The first-order difference between the central part of the GG and the surrounding regions is evident on the thickness map. Two zones of relatively thin Triassic on the NW and SE are separated by the area of the very thick Triassic of the Central Triassic Graben. The thickness pattern within the Central Triassic Graben is complex, reflecting the main phase of the subsidence within the GG. On the other hand, simpler patterns dominate within the basin flanks and marginal troughs (Fig. 4.4a). An almost constant thickness of the Keuper suggests that the Westschleswig and the Eastholstein-Mecklenburg blocks were not strongly affected by Middle-Late Triassic extension (Fig. 4.4a). At these basin flanks, the thickness varies from 370-400 m up to about 600 m, reflecting a rather regional component of subsidence.



Uppermost Middle Triassic and Upper Triassic (Keuper)

Figure 4.4. (a) Present-day thickness map of the uppermost Middle Triassic and Upper Triassic (Keuper). (b) Present-day depth position of the base of the uppermost Middle Triassic and Upper Triassic (Keuper).

In the marginal troughs, the thickness is more variable. The area of increased Keuper thickness within the Central Triassic Graben is characterized by an almost SW-NE trend. This broadly curvilinear area is up to 65-km wide with thickness variations from 1500 m up to 5800 m. The total length of the Central Triassic Graben is approximately 220 km from the Ringkoebing Fyn High to the Pompeckj Block. In the northern part of the Central Triassic Graben, the thickness map (Fig. 4.4a) offers a good view of the rapid thinning of the Keuper towards the north where the Ryngkoebing Fyn High is located. A distinctive region of high thickness gradients is located within the central part of the GG. The reason for the localization of the highly increased Keuper thickness is salt movements during the Keuper within the central part of the Triassic Graben. This is supported by the thickness map in Fig. 4.4a, where the thickness gradient is always higher in the vicinity of salt walls. In addition, the increased Keuper thickness of the southern part of the Central Triassic Graben is running parallel to the curved salt walls. This structural feature indicates that the Keuper sedimentation was accompanied by strong salt movements and was even controlled by salt outflow.

The shape of the Keuper base is very similar to the base of the Triassic (cf. Figs. 4.3b and 4.4b). The differences are the absolute value of depths and local changes variations in shape. The central part is pierced by Rotliegend-Zechstein salt, forming anticline folds close to the salt structures. Within the basin flanks, the base of Keuper is mainly deformed by Zechstein salt pillows. The Keuper base reaches 7000 m depth in the Central Triassic Graben. The depth position of the Keuper base shallows towards the north-western and the south-eastern flanks of basin where it is located at 1200-2000 m depth.

4.2.3. Preserved Jurassic sediments

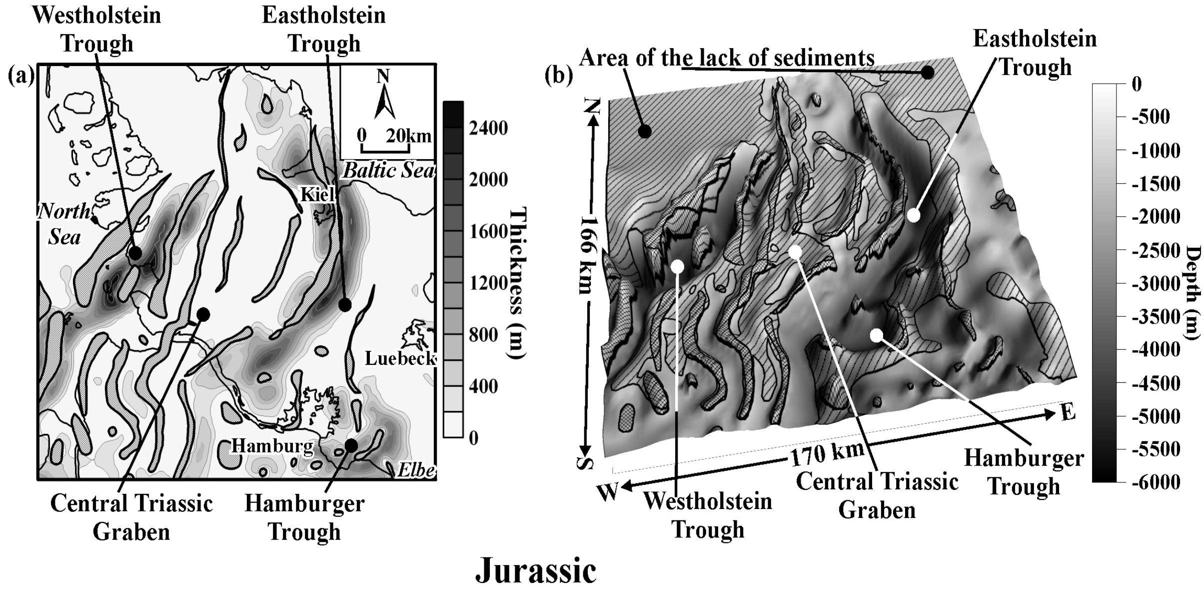


Figure 4.5. (a) Present-day thickness map of the Jurassic. (b) Present-day depth position of the base of the Jurassic, taken from the 3D structural model of the GG.

The thickness and structural maps of the Jurassic show only the present-day distribution of the sediments which remained after the Pre-Cretaceous erosion (Fig. 4.5). Therefore, the distribution of the preserved thicknesses of Jurassic strata can be explained by Late Jurassic-Early Cretaceous erosion or alternativly by variable syndepositional subsidence due to salt tectonics. From the seismic data discussed in Chapter III it is inferred that the remaining sediments represent areas where sedimentation and subsidence were most intensive. Fig. 4.5 illustrates that the centre of sedimentation is shifted from the central part towards adjoining areas compared with the Triassic, forming two centres in the north-west and south-east. The Central Triassic Graben area is characterized by a lack of Jurassic sediments or by relatively thin deposits reaching 400 m thickness (Fig. 4.5). The Westholstein Through delineates the NW margin of the Central Triassic Graben (Fig. 4.5a). It has an estimated width of about 20 km and is associated with relative thick Jurassic sediments. The maximum thickness of the Jurassic is about 2500 m in the Westholstein Through. The Hamburger and Eastholstein Troughs were formed at the SE margin of the Triassic Graben (cf. Figs. 4.3a, 4.4a and 4.5a). The Eastholstein syncline is characterized by a SW-NE elongated band of sediments along the marginal salt walls. The Jurassic is locally 1800-2200 m thick with an average thickness between 1000 and 1200 m in the Eastholstein Trough. The distribution pattern of sediments is very similar to the West- and Eastholstein Troughs where thickening of the Jurassic is observed along salt walls, implying a strong influence of the salt movements on deposition. The complex Jurassic thickness pattern with almost circular and elongated zones near Hamburg defines the extent of the Hamburger Trough. This trough is filled by Jurassic sediments, reaching a thickness up to 1600 m. In contrast to the West- and Eastholstein troughs, the thickness distribution of the Hamburger Trough is not clearly SW-NE elongated, probably due to the presence of differently shaped salt diapirs. The thickness distribution of the Jurassic strongly coincides with salt structures, displaying a rim syncline character of sedimentation.

The deep synclines of the Jurassic base coincide with the areas of the thick Jurassic strata in the West-, Eastholstein and Hamburger Troughs (cf. Figs. 4.5a and 4.5b). Areas without Jurassic sediments are associated with an elevated Jurassic base in comparison to the deep synclines (Fig. 4.5b). Jurassic sediments are not observed within the NW and NE parts of the map in Fig. 4.5. Generally the distribution patterns of the Jurassic match well with the areas where complex relief prevails (see Fig. 4.5b).

4.2.4. Lower Cretaceous

The Lower Cretaceous sediments are wider distributed than the Jurassic sediments, because they cover most salt structures which already existed at the beginning of the Cretaceous (Fig. 4.6a). The Lower Cretaceous thickness does not strongly vary (about 90 m) within the basin with the exception of the areas near salt diapirs in the north-west and south-east (Fig. 4.6a). Therefore, the regional trend shows very slow subsidence after the Late

Jurassic-Early Cretaceous erosion (Fig. 4.6a). As a result, the present-day thickness of the Lower Cretaceous is considered to be partly controlled by predepositional regional erosion and/or interruption of the sedimentation during Late Jurassic- Early Cretaceous times.

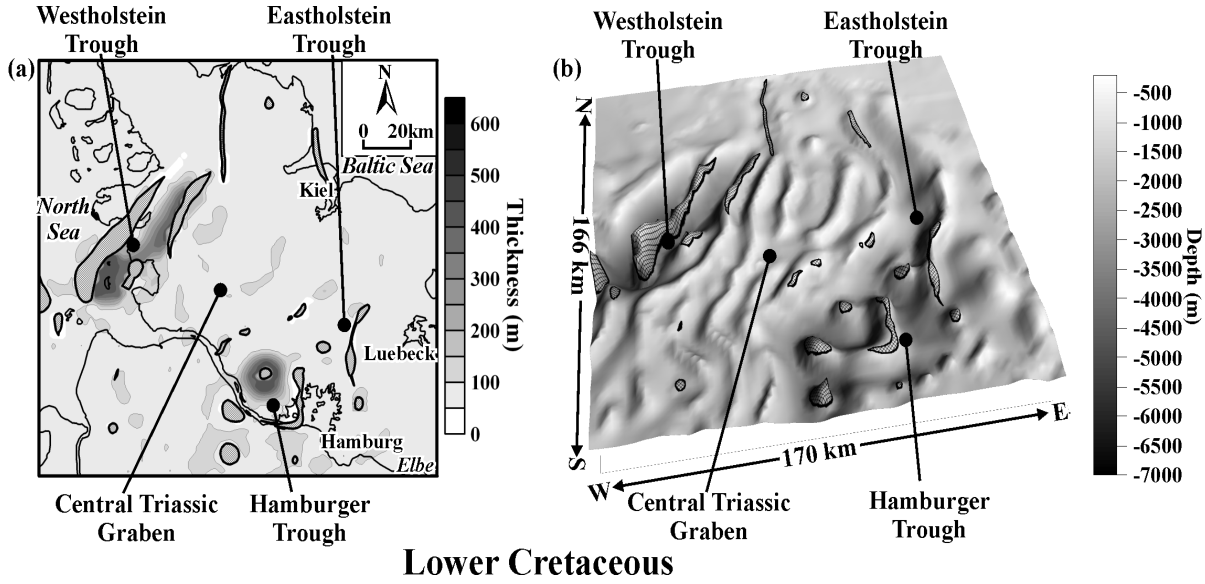


Figure 4.6. (a) Present-day thickness map of the Lower Cretaceous. (b) Present-day depth position of the base of the Lower Cretaceous, taken from the 3D structural model of the GG.

However, prominent thick Lower Cretaceous deposits are observed around the salt structures within the Westholstein and Hamburger Troughs (Fig. 4.6a). The thickness of the Lower Cretaceous sequence increases from less than 90 m to more than 500 m within the Westholstein and Hamburger Troughs (Fig. 4.6a). A large zone of Lower Createceous thickening of the Westholstein Trough stretches in the SW-NE direction between two elongated salt walls. It is likely that the reason for this thickening is the simultaneous growth of the salt walls. In contrast, the Lower Cretaceous thickening zone is almost circular within the Hamburger Trough, reflecting sedimentation in the vicinity of the circularly shaped salt diapir. In addition, the described two areas of thick Lower Cretaceous have increasing thickness gradients towards the salt structures, reflecting salt induced sedimentation (Fig. 4.6a). Such thickening occurs in areas where German “Wealden” sediments are present, which represent the Berriasian and the lower Valanginian intervals of the lowest part of the Cretaceous (Boigt, 1981). The Berriasian and the lower Valanginian are not observed in the other parts of the area under consideration, but they occur in the south, in the Lower Saxony Basin (Baldschuhn et al., 1996 and 2001). Thus, these two pronounced areas of the Westholstein and Hamburger Troughs indicate the continuation of salt movements during the Early Cretaceous, following the strong Jurassic salt activity in the same areas.

The Lower Cretaceous sediments of the marginal troughs are all characterized by deep burial depth (Fig. 4.6b). The base is locally below -6000 m within the Westholstein Trough and -4000 m within the Eastholstein and Hamburger Troughs. Such deep burial indicates strong post Cretaceous subsidence during the Tertiary. The position of the salt walls is easily recognizable from the presence of the elongated highs within the Central Triassic Graben (Fig. 4.6b), demonstrating postdepositional salt flow. A similar situation is observed within the marginal troughs and the basin flanks where the development of most synclines and anticlines took place in the Tertiary with the exception of a few salt structures which were also active in the Early Cretaceous. This means that the present-day base topography of the Lower Cretaceous does not reflect the correct relationship between thickness distribution and the shape of the base.

4.2.5. Upper Cretaceous

The thickness of the Upper Cretaceous indicates regional subsidence with local disturbance due to salt tectonics (Fig. 4.7a). The Cretaceous succession slightly varies between 500 and 700 m thickness within the Central Triassic Graben and the basin flanks. However, pronounced thickening occurs within the Westholstein and Hamburger Troughs. A slight thickening is also observed within the Eastholstein Trough but it has less intensity. The thickness of the Upper Cretaceous is characterized by a narrow band of thick sediments in the Westholstein Trough. In the Hamburger Trough, the relatively thick Upper Cretaceous forms two synclines, which are almost symmetrically situated towards the west and the east of a salt diapir (Fig. 4.7a). The structural features of the isochors indicate that the deposition of the thick Upper Cretaceous occurred simultaneously with salt movements within the relatively shallow rim synclines. The maximum thickness of Upper Cretaceous deposits ranges from 1400 to 1600 m within the Westholstein Trough and from 1200 to 1300 m within the Hamburger Trough. The thick Upper Cretaceous in the Westholstein Trough coincides with the Jurassic and Lower Cretaceous areas of thickenning (cf. Figs. 4.5a, 4.6a and 4.7a). However, the thick Upper Cretaceous covers a wider area towards the northwest within the NW marginal trough. In the Hamburger Trough, the thick Upper Cretaceous sediments have a similar setting but the thickness maximum is shifted to the south in comparison with the Jurassic and Lower Cretaceous thickness maxima (cf. Figs. 4.5a, 4.6a and 4.7a). These features point to a long-term salt activity since the Jurassic within the north-west and the south-east marginal troughs.

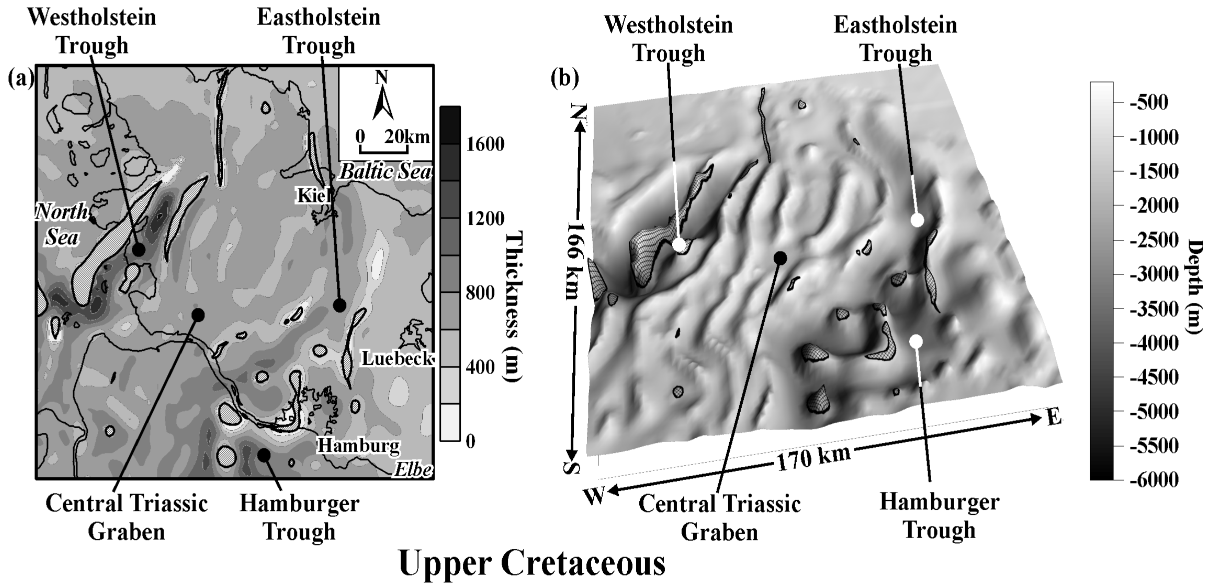


Figure 4.7. (a) Present-day thickness map of the Upper Cretaceous. (b) Present-day depth position of the base of the Upper Cretaceous, taken from the 3D structural model of the GG.

The comparison of the isochore map of the Upper Cretaceous and depth position of the base of the Upper Cretaceous shows good agreement. Where the Upper Cretaceous is relatively thick, synclinal structures are present at the base topography. Where the Upper Cretaceous is relatively thin, anticlinal structures are observed. It is obvious that the anticlines of the present-day depth position of the Upper Cretaceous base represent the location of salt structures within the study area. Therefore, the narrow areas of present-day reduced thickness reflect the position of the salt walls within the GG. Therefore, the present-day thickness distribution is considered to be partly controlled by later erosion of the crest of some salt structures (cf. Figs. 4.7a and 4.7b).

4.2.6. Paleogene

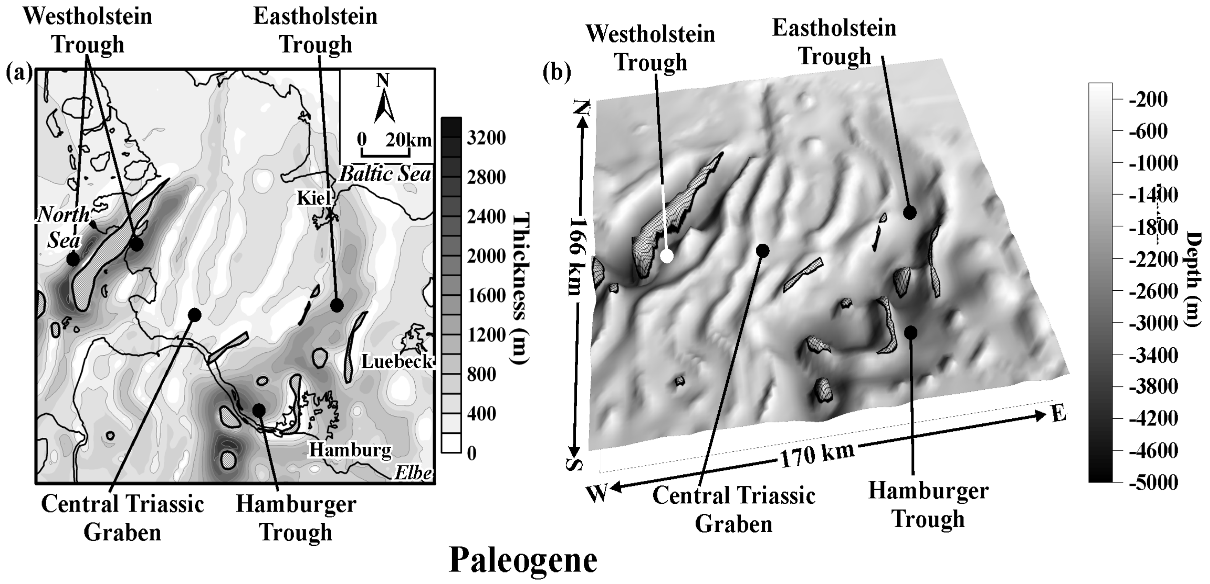


Figure 4.8. (a) Present-day thickness map of the Paleogene. (b) Present-day depth position of the base of the Paleogene, taken from the 3D structural model of the GG.

The isochore map of the Paleogene (Fig. 4.8.a) shows two thickness maxima in the West-, Eastholstein and Hamburger Troughs. This indicates that Paleogene subsidence occurred mainly within the marginal sub-basins, while, sedimentation was much less in the axial part of the GG and on the basin flanks. The zones of Paleogene thickening are in the same areas as the highest thickness values of the Jurassic, Lower Cretaceous and Upper Cretaceous, indicating further increased sedimentation rates in the marginal troughs. However, the thick Paleogene extends further to the west within the Westholstein sub-basin compared with the Jurassic and Cretaceous, where the zone of thickening is located only around the eastern margin of the salt wall. According to the map in Fig. 4.8., the Paleogene reaches locally 2500-3000 m thickness with a strong isochore gradient from the salt wall towards the centres of the rim synclines. The thickness varies between 200 and 2000 m within the 10 km wide synclines. In the Eastholstein and the Hamburger Troughs, the entire area of the former Jurassic and Cretaceous troughs was affected by increased rates of subsidence with the strongest thickness gradient in the south-western part of the Hamburger Trough. The Eastholstein Trough is a pronounced NW striking zone of thick Paleogene with a maximum thickness between 1300 and 1700 m. Two circular thickening zones are visible within the western part of the Hamburger Trough, where the highest isochore values vary between 2300 and 2900 m. The area of the Central Triassic Graben is characterized by narrow bands of reduced Paleogene thickness (Fig. 4.8a). These areas of low Paleogene thickness within the axial part of the GG coincide with highs of the base, which correspond to the crests of salt walls and diapirs. A similar coincidence can be recognized at the basin flanks, where the areas of thinned sediments are located above the locally elevated base topography (cf. Figs. 4.8a and 4.8b). Thinning of the Paleogene occurs mainly above the salt structures in the area under consideration. The coincidence is in agreement with the seismic lines (e.g. see Figs. 3.2, 3.9 and 3.10), indicating growth of the salt structures during the Paleogene and a post-Paleogene erosion of the crests. In the Central Triassic Graben and on the basin flanks, the Paleogene thickness varies from 0-200 m above the crest of salt structures, and reaches 400-900 m between the salt structures (Fig. 4.8a).

The base topography of the Paleogene is characterized by the presence of two deep synclines surrounding the Central Triassic Graben from the NW and SE. The Paleogene base reaches locally depth greater than 5200 m in the Westholstein Trough and greater than 3300 m in the Hamburger Trough. The north-western and north-eastern parts of the map in Fig. 4.8b demonstrate an almost flat base of the Paleogene with depth values vary between 300 and 600 m. In contrast to the Cretaceous, the present-day thickness distribution and depth position of the Paleogene base are in a good agreement. The position of the relativly thick Paleogene correlates with the low base topography and thinning of this stratigraphic unit occurs above elevated areas (cf. Figs. 4.8a and 4.8b).

4.2.7. Quaternary -Neogene

The thickness map and a 3D view of the base of the Quaternary-Neogene are shown in Fig. 4.9. The structural map of the base Quaternary-Neogene (Fig. 4.9b) is the “negative” of the thickness of the Quaternary-Neogene sediments (Fig. 4.9a) within the German lowlands. This means that the present-day thickness distribution and 3D view on the depth position of the Quaternary-Neogene base are in an excellent agreement with each other. The areas of the elevated base precisely correspond to the minima of Quaternary-Neogene thickness and vice versa (cf. Figs. 4.9a and 4.9b). The uplifted SW-NW elongated highs on

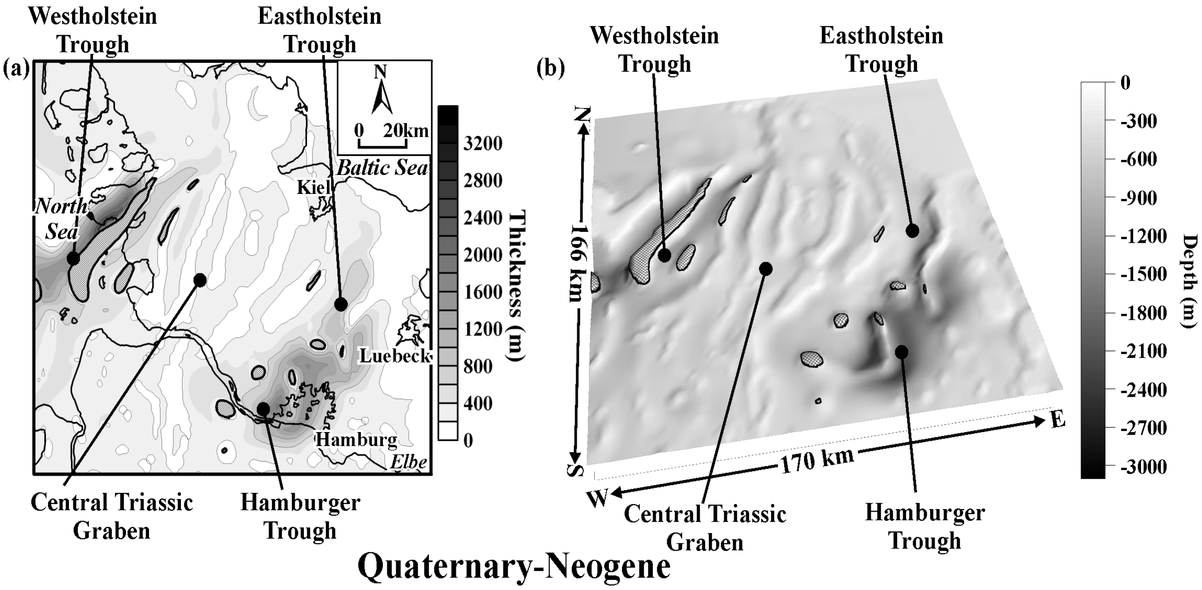


Figure 4.9. (a) Present-day thickness map of the Quaternary-Neogene. (b) Present-day depth position of the base of the Quaternary-Neogene, taken from the 3D structural model of the GG.

the base in Fig. 4.9b indicate growth of salt walls within the Central Triassic Graben during the Neogene. On the basin flanks, the roundish highs reflect the formation of the salt pillows. SW–NE-oriented deep synclines are visible within the north-western and south-eastern parts of the map in Fig. 4.9b. The location of the zones of Quaternary-Neogene thickness maxima overlaps with the areas of the Paleogene maximum within the marginal troughs (cf. Figs. 4.8a and 4.9a). The thick Quaternary-Neogene occupies only a restricted area on the western wing of the most-marginal salt wall in the Westholstein Trough. This indicates a migration of the subsidence centre to the west in comparison to the Paleogene. This zone of high thickness values of the Westholstein sub-basin forms a 9 km wide syncline parallel to the salt wall with more than 3000 m of sediment fill. In the Hamburger Trough, the centre of subsidence is shifted to the east in comparison to the Paleogene. The thickness of the Quaternary-Neogene reaches 1500-1800 m. In the Central Triassic Graben and on the flanks of the basin, the thickness varies between 80-120 m above the salt structures and 280-350 m elsewhere (Fig. 4.9a). The thinning of the Quanternary-Neogene above salt structures reflects syndepositional growth of most of the salt-related anticlines.

4.3. Regional structural features of the GG

Here, the regional features of the basin structure are analyzed by use of a set of 2D vertical slices from the 3D structural model. The position of the vertical slices is shown in Fig. 4.10, also indicating their position relative to major tectonic units. The NW-SE cross-sections 1–4 show the large-scale structure across basin strike (Fig. 4.11). In contrast, the SW- NE profiles 5-9 demonstrate the structural features of the GG along basin strike (Fig. 4.12).

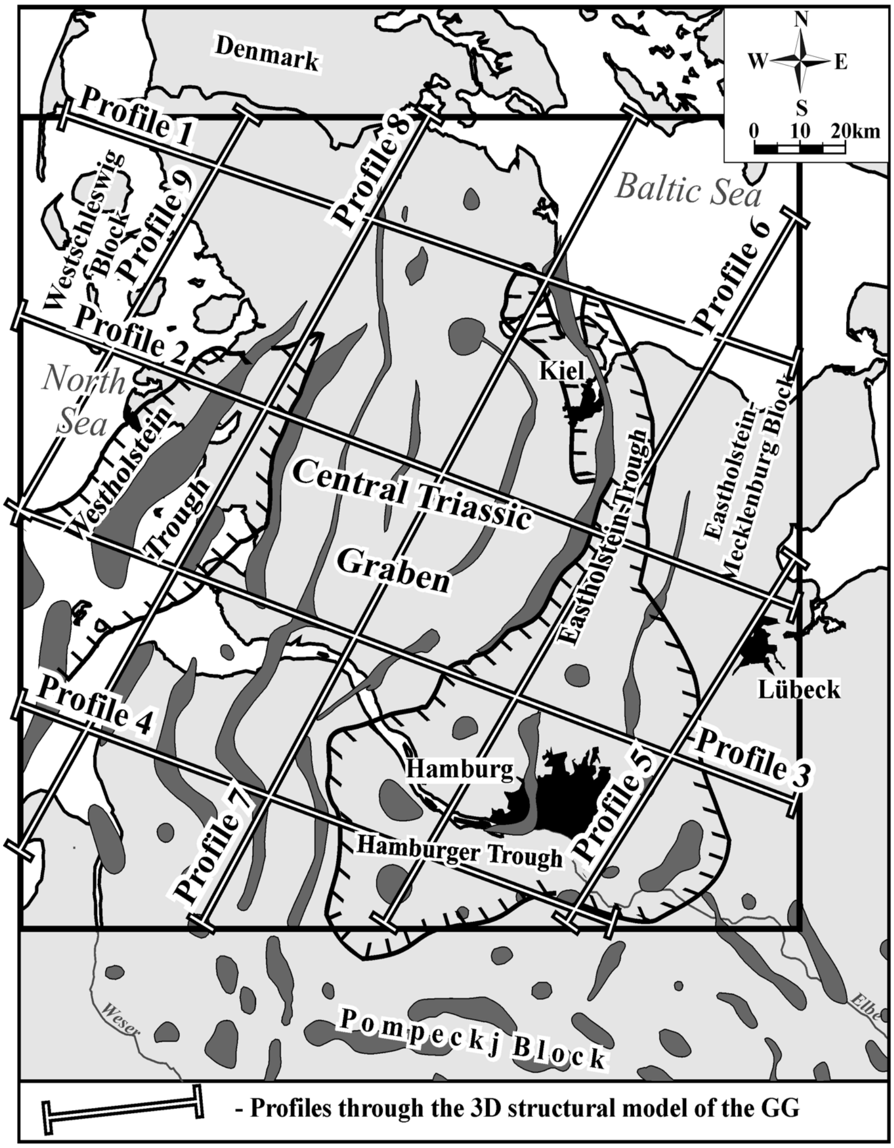
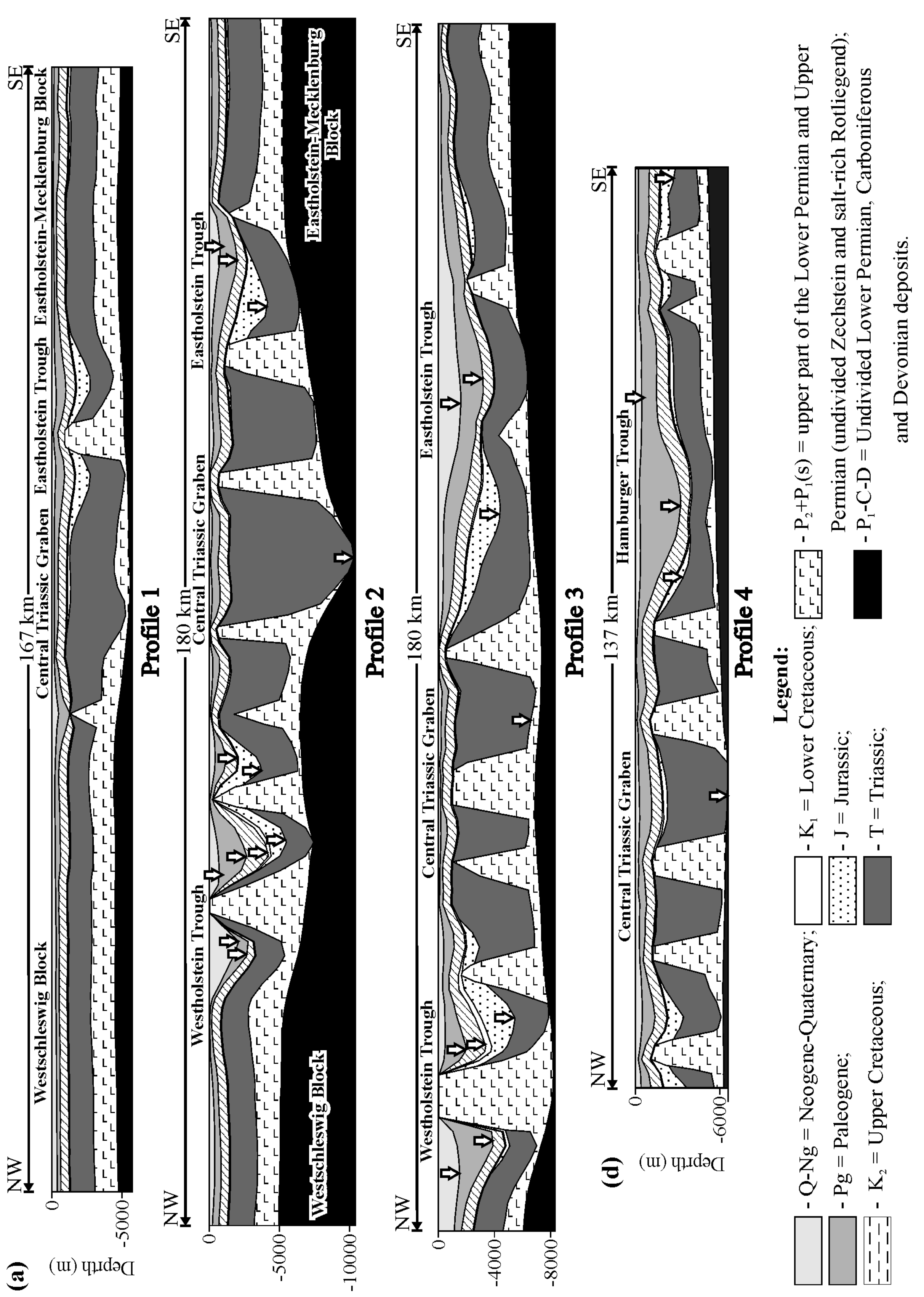


Figure 4.10. Location of the 2D large-scale regional slices projected onto the specified vertical planes through the 3D structural model of the GG (position of salt domes after Baldschuhn et al., 1996).

Figure 4.11 provides cross-sectional views, showing the structural relations between the Central Triassic Graben, the marginal troughs (the West-, Eastholstein and Hamburger troughs) and the basin flanks (Westschleswig and Eastholstein-Mecklenburg blocks) from the north-east to the south-west. Profile 1 in Fig. 4.11a shows the NE continuation of the GG where the Central Triassic Graben is narrow and strikes more southnortherly, but the zone of Triassic thickening can still be recognized. Along this profile (Fig. 4.11a), the Central Triassic Graben is characterized by a relatively thick Triassic within restricted zone between two salt walls. The Triassic sequence does not show obvious thickening in the Westschleswig and Eastholstein-Mecklenburg Blocks. The marginal Eastholstein Trough is evident at the south-eastern part of this section where it is mainly displayed by thickening of Jurassic strata around a salt wall.

The central segment of the 3D model (see Profile 2 in Fig. 4.11b) indicates close relations between the thick sequences of the Triassic, Jurassic and Tertiary across the GG. The thick Triassic succession of the central part overlying the Permian evaporites thins towards the West- and Eastholstein Troughs. Significant thinning broadly coincides with the axial parts of these marginal troughs. In contrast, the Jurassic deposits are cut by the Late Jurassic-Early Cretaceous erosion and are significantly thinning towards the Central Triassic Graben. Profile 2 demonstrates the deformation of post Triassic units due to the growth of the salt structures. Prominent thickening of the Paleogene and the Quaternary-Neogenere occurs in limits of the West- and Eastholstein Troughs along Profile 2 (Fig. 4.11b). Along Profile 3 (see Fig. 4.11c), marginal Jurassic-Cenozoic sub-basins at the north-western and the south-eastern edges of the Central Triassic Graben are most broadly extended in comparison to other parts of the GG. In addition, Profiles 2 and 3 show thick Upper Cretaceous within the SE syncline of the Westholstein Trough. This contrasts with the basin-wide thickness distribution of Upper Cretaceous sediments within other parts of the GG, e.g. they are a much thinner further to the southeast (Figs. 4.11 b, c). Profile 4 demonstrates the thickest part of the Hamburger Trough where only the Paleogene is thickened (Fig. 4.11c).

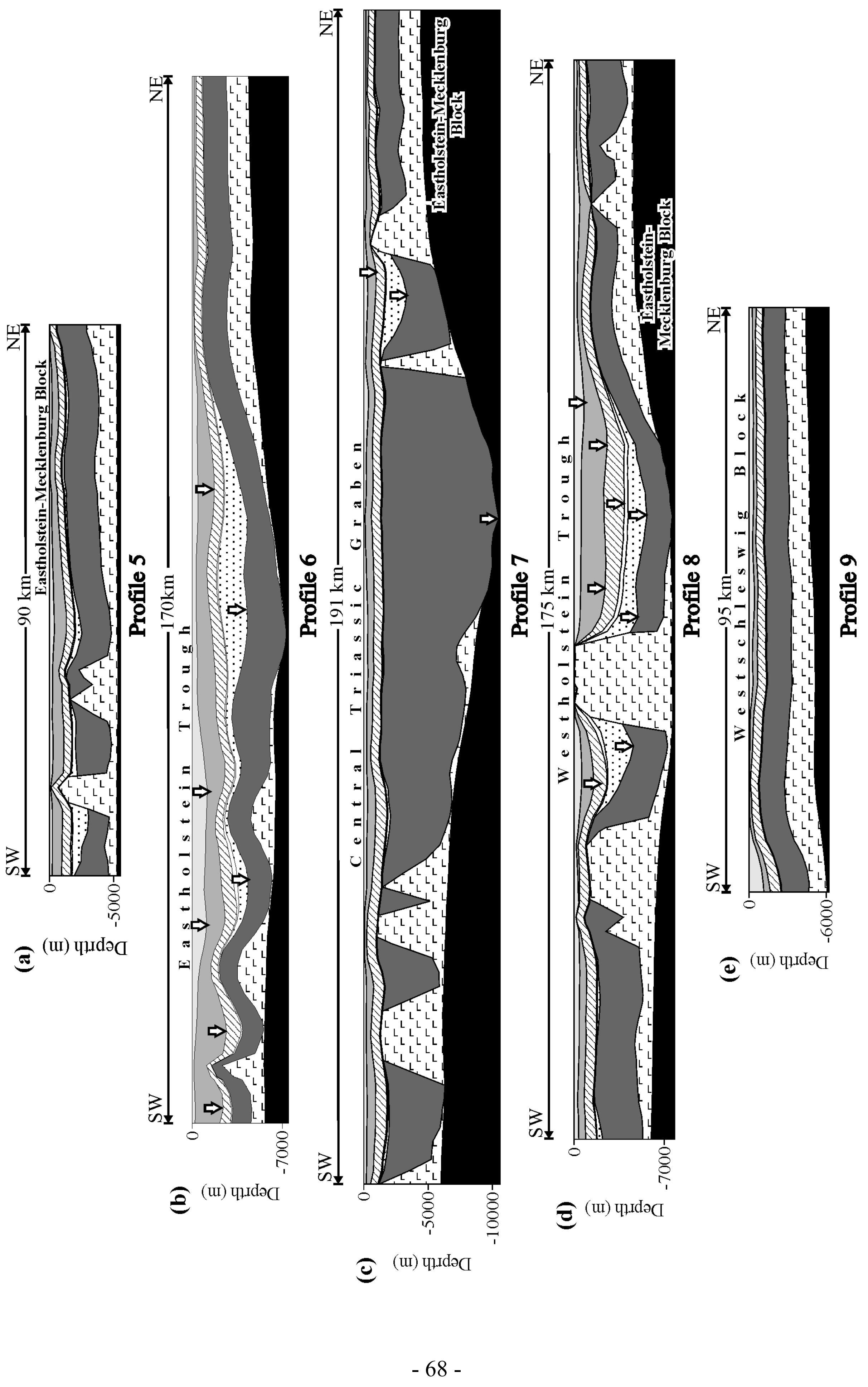
The location of profiles 5-9 was chosen to display an individual structure of each tectonic unit (for location see Fig. 4.10). This was done in order to show the structure of the tectonic zone parallel to strike of the GG (Fig. 4.12). Along the Profiles 5 and 9 (Figs. 4.12 a, e), the Mesozoic-Cainozoic sedimentary cover of the Westschleswig and Eastholstein-


(a)
Depth (m)
0
-5000
NW
SE
167 km
Westschleswig Block
Central Triassic Graben
Eastholstein Trough
Eastholstein Trough
Eastholstein-Mecklenburg Block
Profile 1
(b)
Depth (m)
0
-5000
-10000
NW
SE
180 km
Westholstein Trough
Central Triassic Graben
Central Triassic Graben
Eastholstein Trough
Eastholstein Trough
Westschleswig Block
Eastholstein-Mecklenburg Block
Profile 2
(c)
Depth (m)
0
-4000
-8000
NW
SE
180 km
Westholstein Trough
Central Triassic Graben
Eastholstein Trough
Eastholstein Trough
Profile 3
(d)
Depth (m)
0
-6000
NW
SE
137 km
Central Triassic Graben
Hamburger Trough
Profile 4
Legend:
- Q-Ng = Neogene-Quaternary;
- Pg = Paleogene;
- K_2 = Upper Cretaceous;
- K_1 = Lower Cretaceous;
- J = Jurassic;
- T = Triassic;
- P_2+P_1(s) = upper part of the Lower Permian and Upper Permian (undivided Zechstein and salt-rich Rotliegend);
- P_1-C-D = Undivided Lower Permian, Carboniferous and Devonian deposits.

Mecklenburg blocks has an almost constant thickness (Figs. 4.12a, e), reflecting a regional component of subsidence with some solitary complications during post Permian times. Profile 7 in Fig. 4.12c shows the Triassic depocenter along the axial part of the GG, consisting of SW-NE trending thick Triassic sediments, which are underlain by extremely depleted Permian salt. The longitudinal view of Central Triassic Graben is characterized by thinning of the Triassic from the central part of the GG to the southwest and to the northeast (Fig. 4.12c). The thickness pattern along Profile 7 (see Fig. 4.12c) shows that the post Triassic succession thins significantly within the axial part of the Central Triassic Graben. Furthermore, Jurassic sediments are almost absent within the central part of the basin (Fig. 4.12c) but the deep Jurassic synclines overlap the thick Triassic within the West- and Eastholstein Troughs (Profiles 6 and 8 in Figs. 4.12 b, d). Extremely thick Quaternary-Neogene and Paleogene deposits notably extend into the area of the marginal synclines between the Central Triassic Graben and the basin flanks (Profiles 6 and 8 in Figs. 4.12b, d). Profiles 6 and 8 (Figs. 4.12b, d) show that thick Jurassic and Tertiary successions extends along the Central Triassic Graben, and that the deformation following the salt movements, resulted in the formation of the deep rim synclines within the marginal troughs. In addition, Profiles 6 and 8 run along the Eastholstein and Westholstein Troughs, providing evidence for a major discordance between the Jurassic and Cretaceous strata (Figs. 4.12b and d).

The cross-sections in Fig. 4.11 are not indicative of a clear boundary between the Central Triassic Graben towards the marginal troughs. Furthermore, the transition from the Central Triassic Graben towards the marginal troughs is smoothed. Additionally, the profiles displayed in Figs. 4.11 and 4.12 indicate a important relationship between the depocentres of sedimentation for different stratigraphic units of the Meso-Cenozoic sedimentary cover. The observation indicate that the axial parts of the thickened sediments are not vertically aligned, indicating displacement of the depocenteres of sedimentation in time and in space (see arrow's indications in Figs. 4.11 and 4.12). A similar observation was already discussed for individual lines in the Chapter III; but here, this regularity is described for the entire GG.

Figure 4.11. Cross-sectional views are taken through the 3D structural model of the GG. Regional profiles 1-4 demonstrate the main structural features across strike of the GG (white arrows indicate the depocentres of sedimentation). For stratigraphic key see Figure 1.4.


(a)
Depth (m)
0
-5000
SW
NE
90 km
Eastholstein-Mecklenburg Block
Profile 5
(b)
Depth (m)
0
-7000
SW
NE
170km
Eastholstein Trough
Profile 6
(c)
Depth (m)
0
-5000
-10000
SW
NE
191 km
Central Triassic Graben
Eastholstein-Mecklenburg Block
Profile 7
(d)
Depth (m)
0
-7000
SW
NE
175 km
Westholstein Trough
Eastholstein-Mecklenburg Block
Profile 8
(e)
Depth (m)
0
-6000
SW
NE
95 km
Westschleswig Block
Profile 9

The West-, Eastholstein and Hamburger Trough are separated by thick Triassic (mainly Keuper) within the Central Triassic Graben and prominent thickening towards the axial part of the GG (e.g. Fig. 4.11b). On the other hand, the area of the Central Triassic Graben is characterized by relatively thin Cretaceous and Cainozoic sediments and partly by the absence of the Jurassic. Furthermore, the internal structure of the Westholstein Trough demonstrates that the thick Jurassic is covered by thickened Cretaceous, Paleogene and Neogene but without the vertical alignment of those axial parts (see arrows in Figs. 4.11 b, c and 4.12d). Along profile 6 (Fig. 4.12b), the thick Paleogene of the SW part generally thins to the northeast, where its thinned continuation is covered by thickened Qunternary-Neogene. Zone of Jurassic thickening is observed within the central part of this profile but without thickened younger strata above (Fig. 4.12b). It is possible to conclude, that these profiles document of the subsidence following reactivation of salt tectonics, and suggest that a greater amount of subsidence occurred close to the active salt structures, and may have resulted in gradual depletion of Permian salt from the source layer. Thus, this observation indicates that the source of the long-term subsidence is derived from gradual depletion of the Permian salt, which began within the axial part of the basin and further move away towards the basin flanks.

4.4. Summary

During the Triassic (mainly in the Keuper), rapid subsidence occurred within a central band (Figs. 4.3a, 4.4a, 4.11 and 4.12c) which provides the “core” of the GG. However, already in the Jurassic the subsidence pattern deviates strongly from typical post-rift thermal subsidence. Instead of a typical thermal subsidence, we observe the evolution of two subsidence centres at the former shoulders of the initial Graben (Figs. 4.5, 4.11 and 4.12b, d). These narrow secondary subsidence centres persisted until present, slowly departing outward from the initial subsidence centre, one to the west, the other to the east. Presently, these depocentres are located within the western Westholstein, the southern

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Figure 4.12. Longitudinal views are taken through the 3D structural model of the GG. Regional profiles 5-9 demonstrate the main structural features along strike of the GG (white arrows indicate the depocentres of sedimentation). For stratigraphic key see Figure 1.4.

Eastholstein and the Hamburger Troughs (Figs. 4.9, 4.11b-d and 4.12b, d). In contrast, there is no post Triassic accelerated subsidence within the Keuper depocentre besides some minor salt reactivations as most of the salt was already consumed in the Keuper period. The post tectonic subsidence, therefore, does not show the typical thermal subsidence following a stretching event. The Jurassic subsidence and associated reactivation of the salt movements occurred simultaneously with extension in the Lower Saxony Basin and the Pompeckj Block (Kockel, 2002), but were interrupted by the Late Jurassic-Early Cretaceous erosinal event. This truncation is reflected by lack of the Jurassic sediments in some parts of the GG (Fig. 4.5). This development is especially surprising because the adjacent areas were affected by the development of the Lower Saxony Basin during the Late Jurassic (Betz et al., 1987), as well as by stretching events in the North Sea Central Graben (Nielsen et al., 2000), the Central and Western Netherland Basins (Wijhe, 1987) and the Polish Trough (Dadlez et al., 1995; Stephenson et al., 2003). Thus, the Late Jurassic extension mainly occurred along the margins of the CEBS, while its central part (North German Basin) was stable at that time. Since, the area was uplifted and strongly eroded, at the Jurassic-Cretaceous boundary; the remaining Jurassic sediments may represent the areas where sedimentation and salt tectonics were most intensive during that time. This assumption is in agreement with the results from seismic data in Chapter III. The Lower Cretaceous deposits are separated by a regional hiatus from Jurassic succession. The regional sedimentation was renovated in the Hauterivian when the relatively thin Lower Cretaceous covered the entire GG with very slight thickness variations. However, salt tectonics-controlled subsidence is recognized in the Westholstein and Hamburger Troughs. In these sub-basins, the accumulation of comparatively thick Lower Cretaceous seems to be concentrated in the Valanginian and Berriasian (Fig. 4.6). There is no evidences of fault tectonics during the Early Cretaceous in the GG. Thus, this time interval was tectonically quiet, while salt-induced deformation persisted within the Westholstein and Hamburger Troughs where rapid subsidence continued. Tectonic quiescence continued into the Late Cretaceous and deposition of carbonates and marls took place in the GG. In general, the thickness of the Upper Cretaceous does not strongly vary and reflects a regional component of subsidence through the wider region (Figs. 4.7, 4.11 and 4.12). On the other hand, thickened Upper Cretaceous is observed within the Westholstein and Hamburger Troughs just as in the Early Cretaceous. The structural data reveal that this thickening was associated with simultaneous local salt movements (Figs. 4.11b, c and 4.12d). The thickness of the Paleogene implies further growth of salt structures with the formation of deep synclines near the flanks of the GG. These troughs formed around salt walls (Figs. 5a-d and 9). The Tertiary to recent development coincides with the formation of rifts of similar orientation in Central Europe like the Rhein Graben, Leine Graben, and Eger Graben.

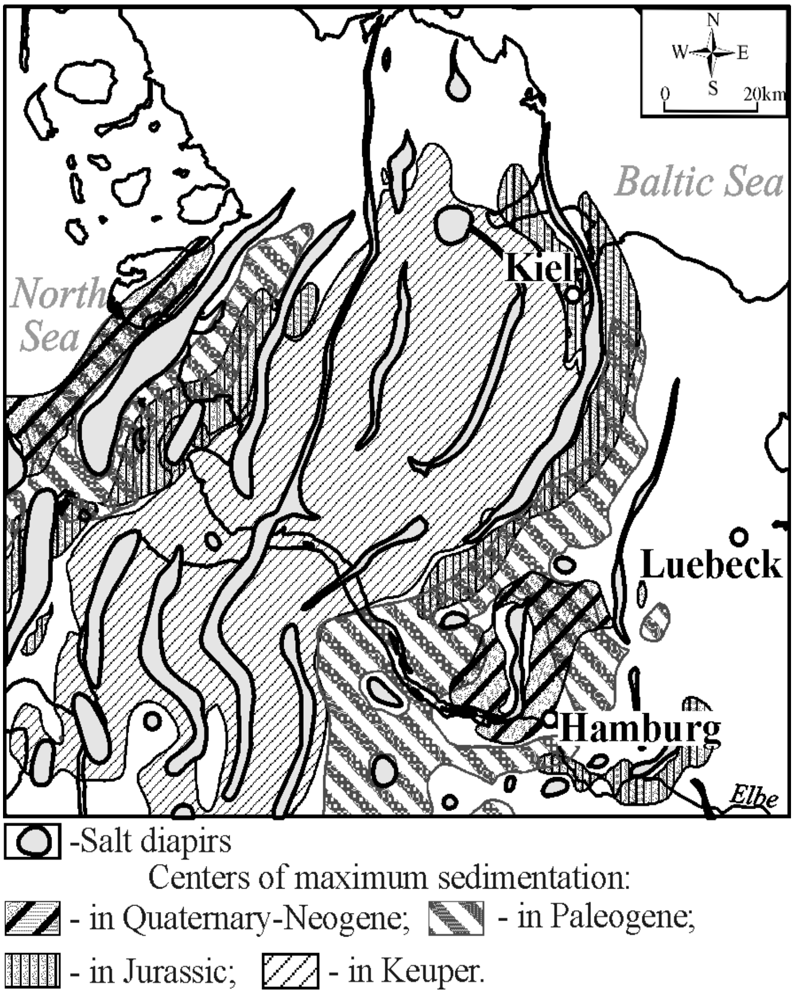

Figure 4.13. Summarized map of maximum sedimentation centres from the Keuper to Neogene-Quaternary within the Glueckstadt Graben.

In summary, it can be stated that the centre of the sedimentation was moving away from the central part of the original Graben structure towards its margins (Fig. 4.13). Starting with the Jurassic, the subsidence-centre was partitioned into two parts located adjacent to the Central Triassic Graben (Figs. 4.4, 4.11b, c and 4.12b, d). Later, the two centres of sedimentation moved gradually towards the flanks of the Central Triassic Graben during Cretaceous and Paleogene (Figs. 4.5-4.9 and 4.11b, d). Such a pattern was already observed by Sannemann (1968, 1983) who called it “salt-stock families”, meaning that salt stocks spread in time becoming gradually younger away from the axial part of the graben. Indeed, the data point to salt mobility as controlling factor for the post-Permian evolution, which was triggered by the initial removal of salt along the axis of the Keuper subsidence centre. In this sense, the Glueckstadt Graben was formed at least partially as a “basin-scale rim syncline” during post-Permian times. However, as indicated by the Tertiary acceleration of subsidence, large-scale changes in the stress field may have interacted with the local evolution. Within the Tertiary and Quaternary sequences, the general subsidence pattern remains stable, although, the total amount of subsidence increases in the Paleogene as well as in the Quaternary-Neogene (Figs. 4.8, 4.9 and 4.11). The Tertiary acceleration of subsidence in the GG coincided more or less with the development of a major subsidence centre in the North Sea during the Miocene-Oligocene (Kockel, 2002, 1988, Garetsky et al., 2001), which may have been active until today. Thus, the present-day Hamburger, East- and Westholstein Troughs are the actual state of the long term salt tectonics which still may continue and may play a role in terms of young processes and e.g. for costal protection within NW Germany.