Chapter I

INTRODUCTION

The study of basin evolution is an aim, which is difficult to achieve in areas of strong salt tectonics. Postdepositional salt flow complicates the recognition of basin evolution both in the local and regional scale. This problem has been analyzed in many different ways. The interpretation of 2D seismic lines is difficult because the seismic pattern is complicated by salt movements. Two main questions of salt tectonics are: (1) the triggering mechanism and (2) the changes in the basin architecture caused by salt flow. Understanding these processes is essential and has to be analyzed by use of additional methods, such as analogue experiments or numerical physical modellenig. During the last decades, 2D and 3D numerical modelling of salt movements together with structural information from seismics has been used for resolving some problems of salt tectonics in basins such as the Gulf of Mexico, North Sea basins, Precaspian basin, Dniepr-Donets basin and many others (e.g. Woidt, 1978; Schmeling, 1987; Roemer and Neugebauer, 1991; Poliakov et al., 1993; Daudre and Cloetingh, 1994; Kaus and Podladchikov, 2001; Stovba et al., 2003; Scheck et al. 2003; Ismail-Zadeh et al., 2004). The Glueckstadt Graben (GG) is one of the sedimentary basins where the sedimentary cover has been strongly affected by salt tectonics. This means that salt movements had an important impact on sedimentation and the subsequent deformation of Mesozoic and Cenozoic strata.

The GG is located between the North Sea and the Baltic Sea, at a transition between areas of different crustal structures (Abramovitz et al., 1999; Meissner et al., 2002; Krawczyk et al., 2002), and between the Ringkoebing-Fyn High in the north and Elbe Fault Zone in the south. Consequently, the GG overprints major structural units in the transition area between Baltica and Caledonian-Variscan Europe. Since the 1990s and until now, the Thor Suture (or Caledonian Deformation Front, Fig. 1.1) has been usually considered as the contact between Baltica and Central Europe (e.g. Pharaoh et al., 1997), while Cocks et al. (1997) favoured the Elbe Line as the major contact zone. A more detailed model of a wedge-like piece of Baltic crust continuing from the Ringkoebing-Fyn High to the Elbe Line has been suggested by the BASIN'96 experiment (DEKORP-BASIN Research Group, 1999) and favoured by Bayer et al. (1999, 2002). Southward of the GG, a block with a low velocity zone in the lower crust was documented between the Elbe Line and the Elbe Fault Zone (e.g.

Aichroth et al., 1992; Thybo, 2001; Scheck et al. 2002). Similar results, concerning the EOL as the southernmost boundary of Baltica have been derived from the TOR-experiment, however, the interpretation is not straight forward and the southern margin of the Ringkoebing-Fyn High may serve as an alternative candidate for the Baltica margin at the level of the upper mantle (Gregersen et al., 2002).

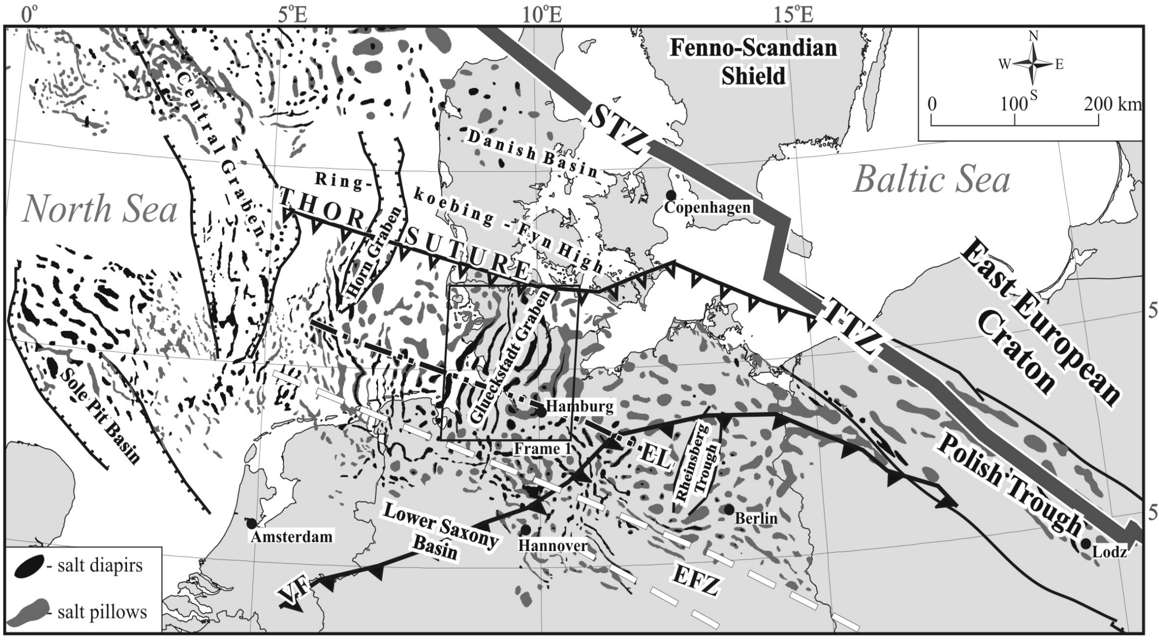


Figure 1.1. Location of the study area (frame 1) in relation to major structural units within the Central European Basin System (compiled after Ziegler, 1990b; Lockhorst et al., 1998; Pharaoh, 1999, Bayer et al., 2002). STZ: Sorgenfrei-Tornqist Zone, TTZ: Teisseyre-Tornquist Zone, EOL: Elbe-Odra Line, EFZ: Elbe Fault Zone, VF: Variscan Front.

The Southern Permian basin, the Danish Basin and the Mid-Polish Trough together with the superimposed Mesozoic graben and basin structures (e.g. the GG, the Horn Graben, the Rheinsberg Trough and the Lower Saxony Basin) form the Central European Basin System (CEBS). The sedimentary cover of the CEBS is pierced by Permian salt, which has been mobilized during the Mesozoic and Cenozoic to form a variety of salt structures (walls, stocks and pillows). One of the significant stages of salt movements occurred during the Triassic. The Triassic corresponds to a period of global plate boundary and plate kinematics reorganization, marking the beginning of the break-up of Pangea (Ziegler, 1990). From the thickness map of the Triassic in the CEBS it is obvious that sediments extended from the western part of the North Sea to Eastern Poland (Fig. 1.2). The largest Triassic subsidence occurred in the different sub-basins surrounding the Ringkoebing-Fyn High (Fig. 1.2), in the Horn Graben, the GG and the Danish Basin. Another center of Triassic subsidence is located within the Polish Trough where the thickness of Triassic reaches up to 5000 m. The Sole Pit Basin, the Central Graben and the Rheinsberg Trough are characterized by minor thickening of the Triassic strata in comparison with the mentioned Triassic basins. The thickest Triassic succession is observed in the GG where it reaches about 9000 m (Fig. 1.2). The last strong

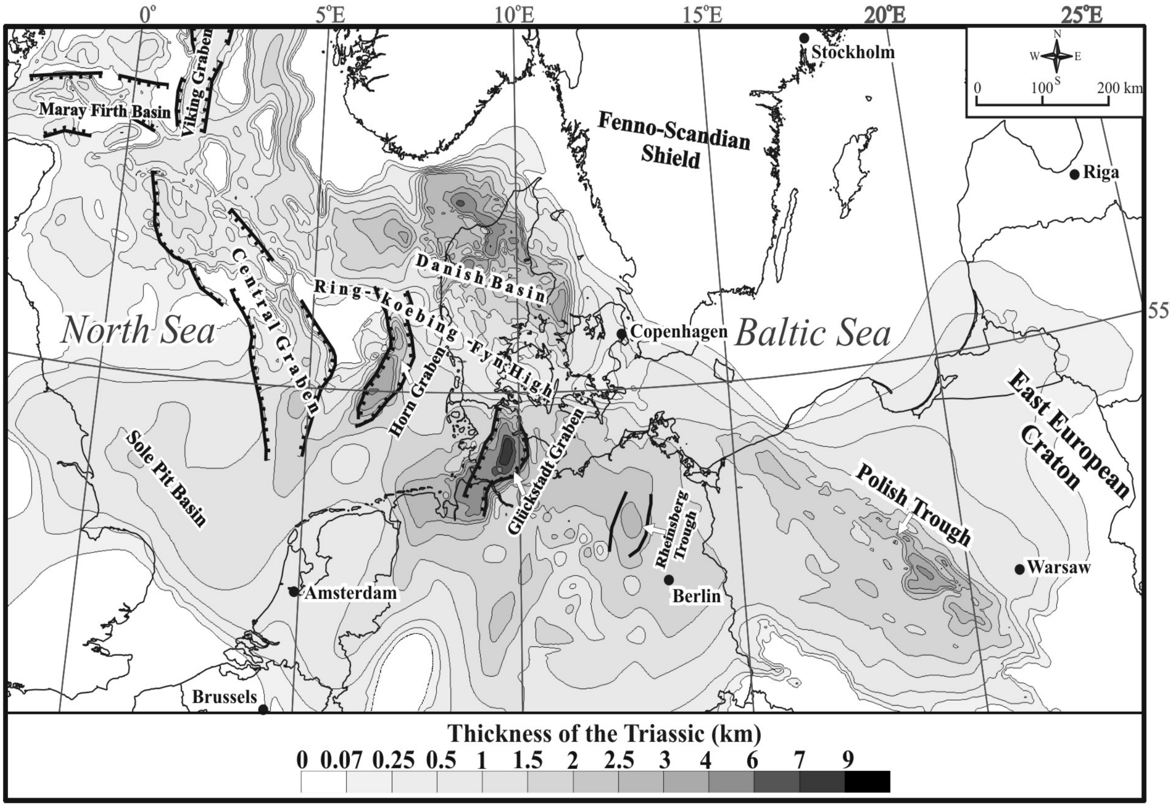


Figure 1.2. Location of the study area in relation to major Triassic subsidence centers within the Central European Basin System (compiled after Van Horn, 1987; Ziegler, 1990; Britze and Japsen, 1991; Vejbaek and Britze, 1994; Baldschuhn et al., 1996 and 2001; Šimkevičius et al., 2001; Evans et al., 2003; Scheck et al., 2003; Dadlez, 2003; Bayer et al., 2003; Sliaupa, 2004; Lamarche and Scheck-Wenderoth, 2005).

tectonic event before the Triassic took place during the end of Late Carboniferous-Early Permian times and was accompanied by extensive igneous activity and faulting within the entire CEBS (Gast, 1988; Plein, 1990; Ziegler, 1990b; Dadlez et al., 1995; Bachmann et al., 1997; Bayer et al., 1999; Abramovitz and Thybo, 1999). Apparently, the Late Carboniferous - Early Permian rifting initiated the deposition of a thick Upper Permian succession that is stratigraphically complex and contains thick salt layers. Later, the Permian salt was mobilized, creating significant space for additional sedimentation in the Triassic. This period of salt tectonics was associated with extension, reflecting a discrete pulse of tectonic activity in the Triassic (Ziegler, 1990; Vejbaek, 1990; Kockel, 2002; Scheck et al., 2003; Krzywiec, 2004; Maystrenko et al., in press). Particularly, the area of the GG is not only the thickest Triassic structure within the CEBS, but it provides a large “natural laboratory” concerning the effects of salt tectonics in space and time. Although the large-scale tectonic evolution of the region has been highlighted by Sannemann (1968), Brink et al. (1990), Brink et al. (1992), Baldschuhn et al. (1996), Bachmann and Hoffmann (1997), Baldschuhn et al. (2001), Kockel (2002), the relation between salt movements and tectonic events is still poorly understood.

The main objective of this work is to examine the evolution of the GG, with emphasis on the influence of salt tectonics during the Mesozoic and Cenozoic periods. The origin and development of large salt walls and intrabasinal structural features in the region are analyzed by selected deep wells, 2D reflection seismic lines and a 3D structural modelling approach.

In particular, the ultimate aim of this study is to analyze the following aspects of the post-Carboniferous basin evolution:

(1) the recognition of the major tectonic events;

(2) the timing of salt movements;

(3) the relationship between salt structures and styles of sedimentation both in time and in space;

(4) the development of salt structures through time;

(5) the initial thickness distribution of the Permian (Rotliegend and Zechstein) salt within the basin.

1.1. Geological setting

1.1.1. Structural framework

The basin structure and fill of the GG have been systematically studied since the beginning of the last century, mainly in the view of oil and gas exploration. Some results of the scientific investigations within this area have been discussed in several publications (Sannemann, 1968; Dohr et al., 1989; Brink et al., 1990, 1992; Baldschuhn et al., 1996, 2001; Kockel, 2002). Nevertheless, it is useful to discuss some aspects of the major structures since they are important for understanding basin development.

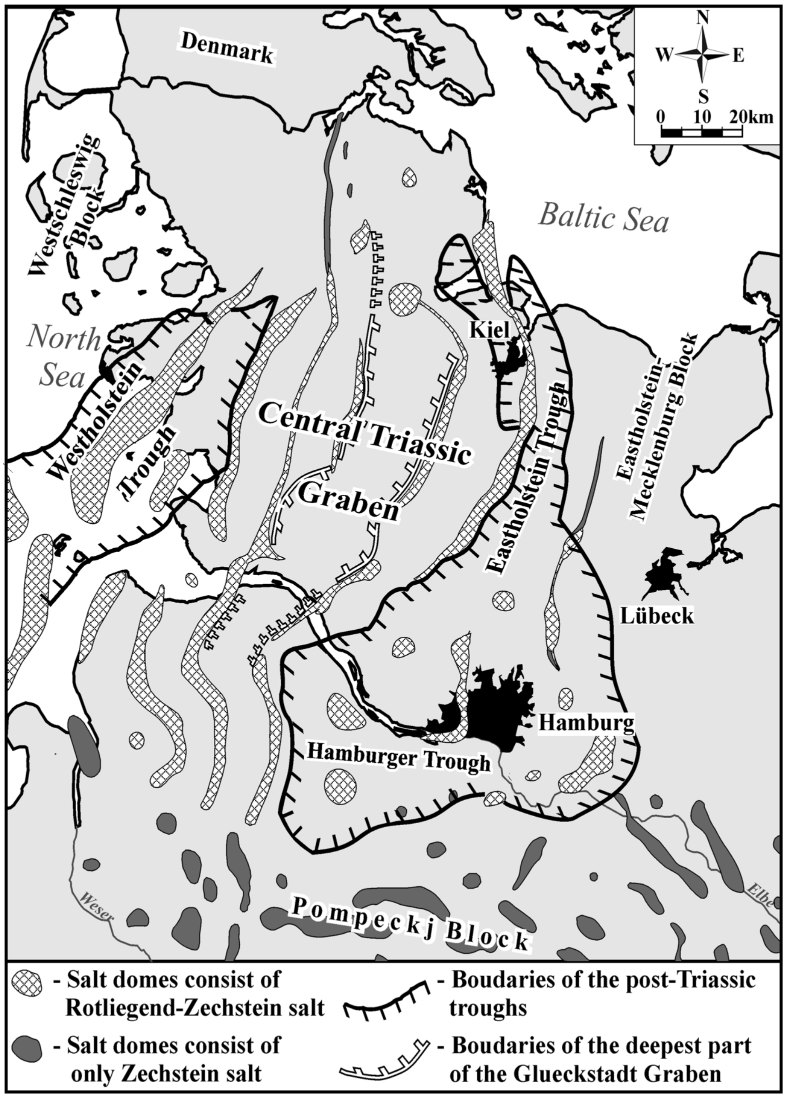


Figure 1.3. Tectonic map of the Glueckstadt Graben (frame 1 in the Fig. 1.1; position of salt domes after Baldschuhn et al., 1996).

The GG is mainly located in Schleswig-Holstein and in the northern part of Lower Saxony, NW Germany. It can be subdivided into three structural domains (Fig. 1.3):

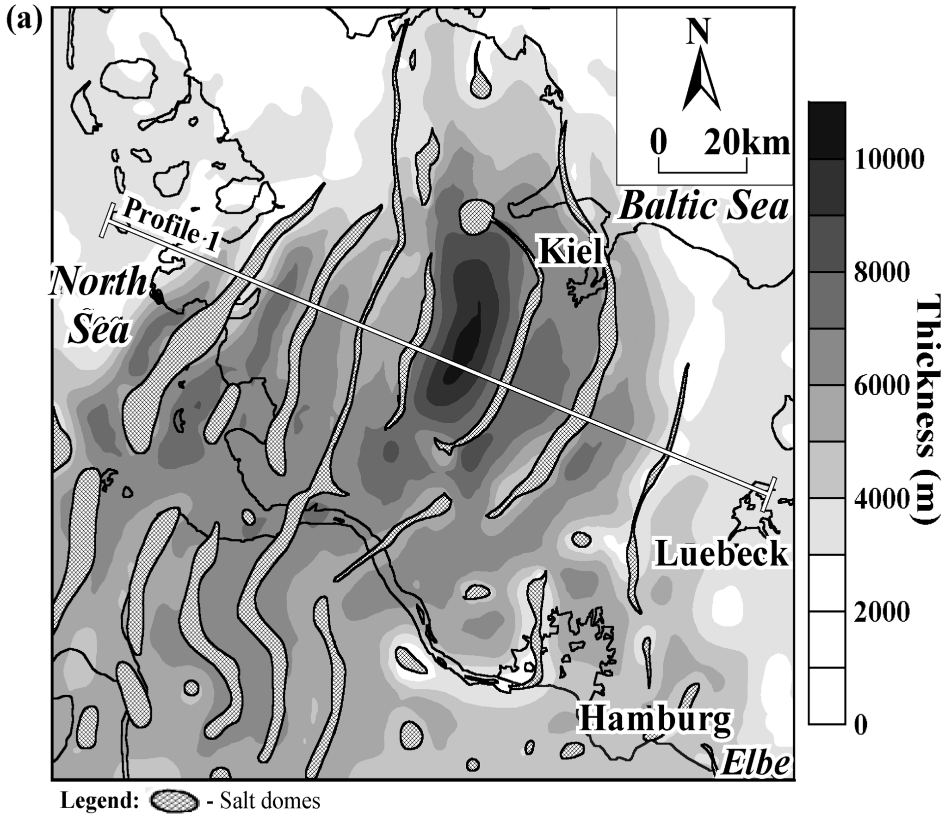
(1) the central Triassic graben;

(2) the marginal Jurassic and Cenozoic troughs – Westholstein, Eastholstein and Hamburger;

(3) the flanks of the basin – Westschleswig and Eastholstein-Mecklenburg blocks.

Direct information on the nature of the lower crust is scarce, but available indirect evidence indicates that the crust below GG was consolidated during the Caledonian orogeny (Bayer et al., 2002) and that the structural grain within the Caledonian basement may have influenced later structural development of the crust in the Schleswig-Holstein area. According to the interpretation of an east-west running reflection line, the central part of the GG is characterized by a thinned lower crust due to a Moho uplift of up to 25 km in comparison with the flanks where the Moho is located at a depth of more than 30 km (Dohr et al., 1989; Brink et al., 1992). This Moho uplift is associated with a steep gravity gradient culminating in a broad maximum located in the GG area, which appears in the gravity field, reduced to the base of Zechstein (Dohr et al., 1989).

The isopach map of the Meso-Cenozoic sedimentary cover, provided in Fig. 1.4a, illustrates the variation of sediment thickness across the different sub-basins of the GG. The Central Triassic Graben is by far the deepest part of the GG. In its central area, the base of Triassic sediments is located at more than 10000 m depth (Fig. 1.4b). At its south-eastern margin, the Triassic depocenter is separated from the Eastholstein-Mecklenburg block by the Eastholstein and Hamburger Troughs (Fig. 1.4b), which exhibit increased thicknesses of Jurassic (more than 1900 m) and Cenozoic (more than 3300 m) sediments. The Westholstein marginal through is also characterized by thick Jurassic (more than 2400 m) and Cenozoic (more than 5000 m) deposits and separates the Central Triassic Graben from the Westschleswig block (Fig. 1.4b). The Westschleswig and Eastholstein-Mecklenburg blocks bound the GG from the northwest and the southeast accordingly and are covered by post-Permian sediments of up to 4000 m thickness. These structural zones have small dip (sometimes almost horizontal) at the base of Upper Permian (Fig. 1.4b), little salt mobilisation and the salt overburden is characterized by relatively undeformed rocks.



Thickness of the Meso-Cenozoic sedimentary cover

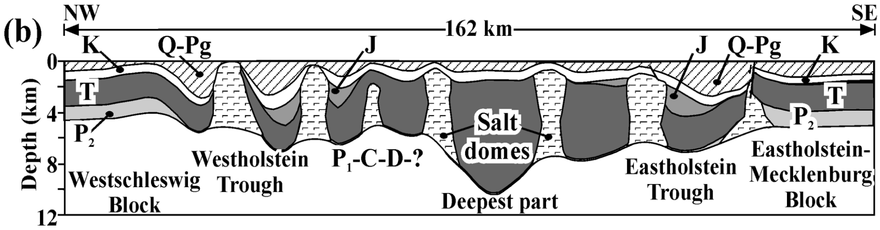


Figure 1.4. (a) Present thickness of the sedimentary cover down to top Upper Permian (Zechstein) in the Glueckstadt Graben and its surrounding area (based on Baldschuhn et al., 1996). (b) Regional NW–SE cross-section across the Glueckstadt Graben, showing main structural features (vertical slice from the 3D model of the Glueckstadt Graben). Stratigraphic key: P_1 -C-D = Undivided Lower Permian (Rotliegend), Carboniferous and Devonian deposits; P_2 = Upper Permian (Zechstein); T = Triassic; J = Jurassic; K = Cretaceous; Q-Pg = Paleogene-Quaternary (including Neogene).

The generalised northwest–southeast cross-section of Fig. 1.4b runs through the main structural zones described above. It is oriented approximately perpendicular to the central Triassic depocentre where the thickness of the Triassic reaches more than 8500 m. The cross section has been extracted from the 3D model discussed later, in order to illustrate the key features of salt tectonics on the regional scale. The cross section shows that the formation of three centers of maximum subsidence (in Triassic, Jurassic and Cenozoic) was strongly controlled by salt movements through time: the centre of sedimentation was moving away from the central part of the original Central Triassic Trough towards its margins due to gradual withdrawal of Permian salt (Sannemann, 1968). In this sense, the GG was formed at least partially as a “basin-scale rim syncline” during post-Permian times.

1.1.2. Tectono-stratigraphic sequence

The sedimentary succession of the GG reflects the major stages in the tectonic development of the basin. Fig. 1.5 shows the post-Carboniferous lithostratigraphy of the GG, together with some major tectonic events. The post-Carboniferous basin fill may be divided into three major sedimentary sequences: Prepermian deposits, Permian salt and Meso-Cenozoic overburden. Unfortunately, the oldest known sedimentary strata, Upper Devonian and Lower Carboniferous (Tournasian and Visean), have been penetrated only in one deep well within the limits of the GG. The Precambrian crystalline rocks have only been reached within the Westschleswig block in the Nordsee Q-1 deep well (Best et al., 1983). Late Carboniferous-Early Permian rifting is reflected in the lithology of Lower Permian deposits by the presence of conglomerate series and volcanics. The known total thickness of the Lower Permian succession, including up to 450 m thick salt-rich layers, varies along the basin’s flanks from 1500 meters to more than 2200 m. The Upper Permian (Zechtein) is characterized by carbonate-evaporite successions, dominated by rock salt. The Lower Triassic (Buntsandstein) consists mainly of clastics and thin layers of evaporites, whereas the Middle Triassic (Muschelkalk) contains carbonates and evaporites. It was postulated that the GG could have been affected by rifting towards the end of the Early Triassic (late Buntsandstein; Brink et al., 1992; Kockel, 2002), when a very narrow trough was formed within the central part of the basin. However, the main extension occurred during the latest Middle Triassic and Late Triassic (Keuper) when thick sediments (up to 5800 m in the basin depocenter) were deposited (Brink et al., 1992; Baldschuhn et al., 1996; Baldschuhn et al., 2001). The Keuper succession has a very complicated structure due to rapid subsidence and due to the presence of thick salt-rich layers (Bayer et al., 2003). It is important to note, that there is no direct evidence of Late Triassic volcanism, which could have accompanied the deposition of thick Keuper sediments within the GG.

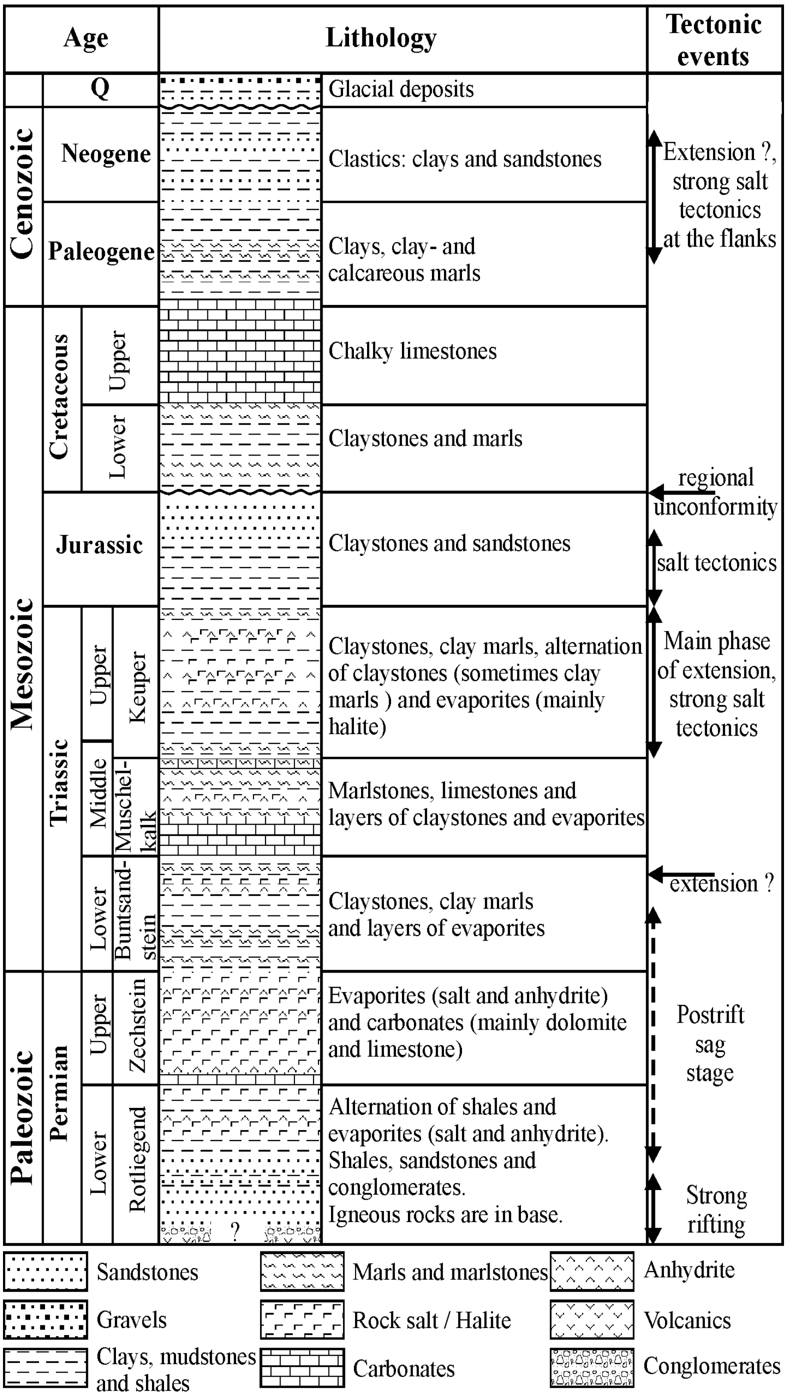


Figure 1.5. Lithostratigraphic chart and main tectonic events of the Glueckstadt Graben. Lithologies are taken from well data.

The Jurassic sequence includes clastics consisting of claystones and sandstones. Its thickness is significantly controlled by salt tectonics. The area around the GG was uplifted in Late Jurassic-Early Cretaceous times, indicated by a regional erosional unconformity.

Sedimentation resumed in the Cretaceous, a time of tectonic quiescence and rising sea level. Lower Cretaceous strata unconformably overlie the Triassic and Jurassic sequences and consist of marine and continental sediments. During the Late Cretaceous, the sediments were deposited in a gentle platform-type depression that extended far beyond the boundaries of the GG. The Upper Cretaceous succession comprises mainly chalky limestones.

Finally, the collision between Africa-Arabia and Eurasia caused the formation of the Alpine orogen during the Late Cretaceous-Tertiary. The collision-induced compression affected whole Europe, with some basins undergoing compression and inversion. Nevertheless, in contrast to other basins of the CEBS, such as the Polish Trough, Lower Saxony Basin, or North-East German Basin, the GG was not essentially inverted. At the same time, it can be infered from structural data that the area around the Glueckstadt Trough has been affected by an accelerated tectonic subsidence rate within the marginal Westholstein, Eastholstein and the Hamburger troughs. Interestingly, a regional Upper Cretaceous unconformity is not obvious from the seismic data, although it is a prominent feature in other parts of the North German Basin.

The Cenozoic succession consists mainly of clastics with some marls and reaches a maximum thickness of more than 5000 m. During the Paleogene-Neogene, the basin was tectonically reactivated with rapid subsidence along the northwestern and southeastern margins of the Triassic trough (Sannemann, 1968; Baldschuhn et al., 1996; Maystrenko et al., in press). This event coincides with rapid subsidence in the central North Sea (Kockel, 1988; Ziegler, 1990b; Evans et al., 2003) and most likely is related to almost E-W directed extension. Quaternary glacial deposits cover all older strata regionally.

1.2. Database

The available database consists of reflection seismic profiles supplemented by deep well data (Fig. 1.6). This database has been provided by the German oil and gas industry through the German Society for Petroleum and Coal Science and Technology (DGMK) in the frame of the research project “Dynamics of sedimentary systems under varying stress conditions by example of the Central European Basin system” (DFG-SPP 1135, DGMK

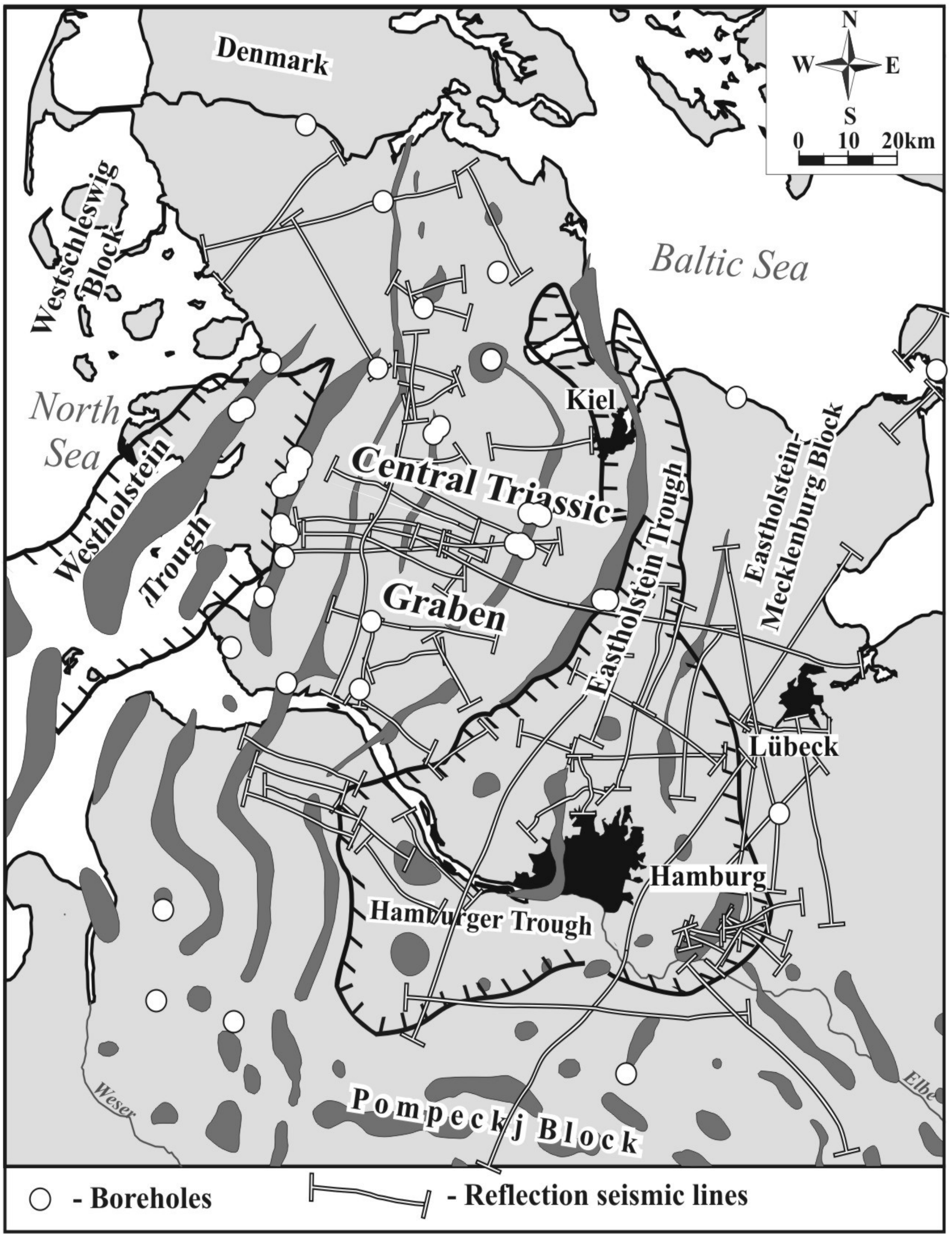


Figure 1.6. Available seismic data coverage of the study area and the location of available wells.

Project 577). The quality of the seismic data varies within the study area, but in general the data are of high to medium quality. The medium data quality seems to be at least partly related to the complex structural style of the GG. Generally, the resolution of seismic images decreases beneath the salt structures because the salt dissipates much of the seismic energy.

In some places, the deep reflections may be represented by Devonian or Carboniferous rocks but it is very difficult to correlate them due to missing deep well data in the GG. This study highlights mainly nine sequences which have been correlated using the seismic profiles and available well data, these being:

(1) P_1(s) = upper part of the Lower Permian (salt-rich Rotliegend);

(2) P_2 = Upper Permian (Zechstein);

(3) T_1 = Lower Triassic (Buntsandstein);

(4) T_2 = Middle Triassic without uppermost part (Muschelkalk);

(5) $T_{2\text{-}3}$ = uppermost part of Middle Triassic and Upper Triassic (Keuper);

(6) J = Jurassic;

(7) K_1 = Lower Cretaceous;

(8) K_2 = Upper Cretaceous;

(9) Q-Pg = Paleogene-Quaternary.

The seismic lines have been interpreted in terms of seismic stratigraphy and some of them were migrated in the frequency domain by using a software for digital processing of 2D and 3D seismic data (SPS-PC: the software package developed for Windows-based PCs and was provided by the Russian company Nord-Express). Migration in the frequency domain has been chosen because it allows to migrate seismic lines with steeply dipping reflections without loosing important dynamic characteristics of the reflections compared with the finite-difference scheme or Kirchhoff. Moreover, additional seismic processing procedures have been applied to selected lines and some seismic reflectors have been flattened. The additional processing includes f-k filtering in order to amplify the seismic image of strongest reflections by removing low-amplitude reflections in the frequency domain, automatic gain control (AGC) and finally band-pass filtering.

In addition to well and seismic data, structural maps were provided by the Federal Department of Geosciences and Mineral Resources (BGR; Baldschuhn et al., 1996) which cover the area under consideration. The digital versions of depth maps from the Geotectonic Atlas of NW Germany (Baldschuhn et al., 2001) was integrated into a three-dimensional structural model after calculation of thickness maps. This 3D model was finally adjusted by using the results from seismic interpretation.

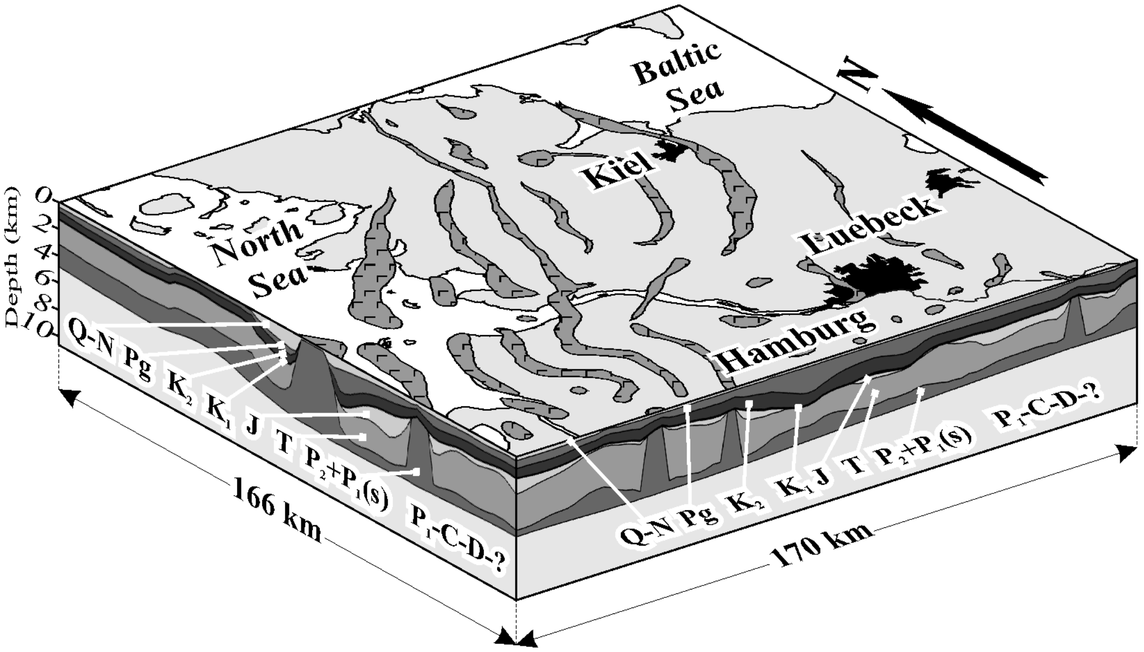


Figure 1.7. 3D structural model of the area under consideration. For stratigraphic key see Figure 1.4.

The constructed three-dimensional model covers an area which is 170 km long and 166 km wide (Fig. 1.7) and has a 2x2 km grid spacing. It includes seven layers from the Rotliegend to the Quaternary:

(1) $P_1(s) + P_2$ = salt-rich Rotliegend plus Zechstein;

(2) T = Triassic;

(3) J = Jurassic;

(4) K_1 = Lower Cretaceous;

(5) K_2 = Upper Cretaceous;

(6) Pg = Paleogene;

(7) Q-N = Quaternary-Neogene.

The 3D structural model has been used to calculate the initial Permian salt thickness within the limits of the GG by using software developed at the GeoForschungsZentrum Potsdam by Ulf Bayer, Magdalena Scheck-Wenderoth and Björn Lewerenz. In addition, the 3D modelling approach has been used to determine salt distribution at certain paleo-levels in response to unloading during sequential removing of the stratigraphic layers. The salt flow has been determined by a finite-element method, depending mainly on the sedimentary load and the shape of the isostatically-balanced base of the salt. A basic assumption in this approach is that the behaviour of salt is similar to a viscous fluid that is usually in hydrostatic equilibrium with the overburden and that its volume is conserved. This modelling was already successfully applied within the NE German Basin by Scheck et al. (2003).