1. Introduction

1.1. Overview

In this introductory chapter the objectives and motivation of the project are presented and the different working steps are described. It is not the purpose to introduce the general tectonic setting and the geology of the working area here, because this is already done in detail in the scientific publications that form parts of this thesis in the following way:

Chapter 2 ('Strain partitioning due to salt - insights from interpretation of a 3D seismic data set in the NW German Basin') deals with the general geology of the working area and its surrounding and overlying areas. It discusses the interaction and evolution of tectonic structures, sedimentary features, and salt diapirism in terms of strain and stress.

Chapter 3 ('Prediction of sub-seismic faults and fractures - integration of 3D seismic data, 3D retro-deformation, and well data on an example of deformation around an inverted fault') addresses the 3D kinematic modelling of structure analysed in detail within the studied data set. It demonstrates a combined analysis of different methods (3D seismic interpretation, coherency analysis, 3D kinematic modelling, well data analysis) over several scales, in order to correlate large-scale seismic data with small-scale well data (fractures), and to quantify and qualify sub-seismic strain.

Chapter 4 ('Evolution of a fault-surface from 3D attribute analysis and displacement measurements') concentrates on a detailed displacement and morphology analysis of one large normal fault in 3D, debating about the distribution and orientation of sub-seismic fractures, and assessing its seismic hazard.

Chapter 5 ('Analogue modelling of fault-growth processes') emphasises especially the temporal variations of strain distribution over several scales and documents fault-growth processes such as fault-propagation and segment linkage, as well as alternation of fault activity.

Chapter 6 ('Paleostress analysis from 3D seismic data – an outlook') focuses on the calculation of paleostress data on the basis of detailed 3D interpretations of Permian normal faults.

The results of these chapters are summarised and comprehensively discussed in chapter 7.

1.2. Objectives and motivation

This project is integrated in the DFG-Schwerpunktprogramm 1135 'Dynamics of sedimentary systems under varying stress regimes: The example of the Central European Basin'.

The main objective of this study is the quantification and qualification of strain over a broad scale range, including its distribution, magnitude, and accumulation history during basin evolution. These objectives are important contributions to the questions of stress transfer and deformation processes in the Southern Permian Basin.

Sedimentary basins record a variety of spatial and temporal processes, and exhibit a complex pattern of structural and deformational features and styles. There is a lack of a deeper understanding of how structures and the responsible deformation processes relate to each other across the range of scales from lithospheric faults to grain-scale fractures.

Within the Southern Permian Basin, one of the major problems of unravelling the post-Variscan deformational history is the localised nature of deformation, where initially small isolated grabens were gradually filled by predominantly locally-derived sediments. During the Mesozoic and Cenozoic, crustal subsidence of the intracontinental Southern Permian Basin developed, and a general depositional pattern was established (Fig. 1.1), allowing a correlation between the former sub-basins. Different geological, geophysical or integrated large-scale models are available now covering large parts of the whole Central European Basin System (e.g. Ziegler, 1990; Thybo, 1997; Scheck & Bayer, 1999; Yegorova & Starostenko, 1999; Scheck-Wenderoth & Lamarche, 2005 and references therein; McCann et al., 2006; Krawczyk et al., 2007).

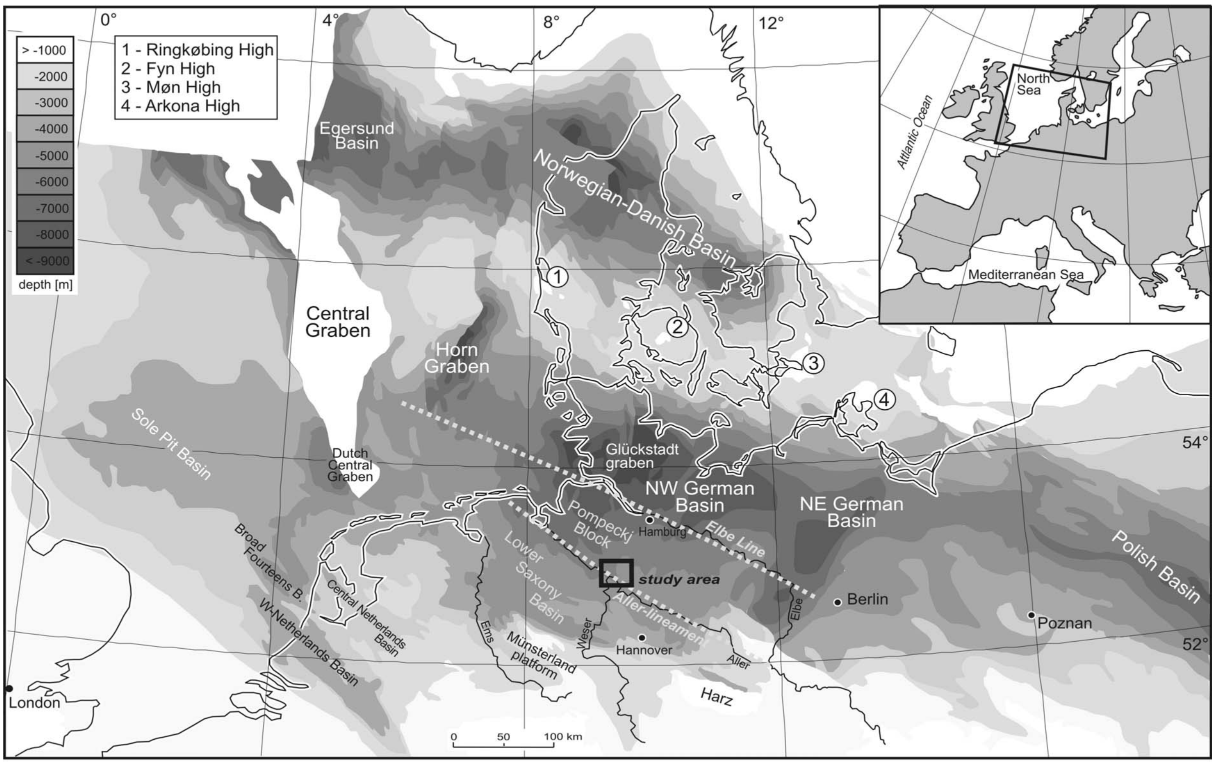

Figure 1.1: Depth map of the Southern Permian Basin and location of the study area. Modified after Kossow (2001) and the NW European Gas Atlas (Lockhorst 1998).

An order of magnitude lower, depth-sections are used as input for the setup of basin-wide structural models, but the correlation of different depth-sections is often inconsistent because of non-unified basic data. In sedimentary basins the restoration of such seismic depth-sections are used to reveal the sub-surface structures, the nature of basin-forming mechanisms, and the kinematic evolution of the area under consideration, but also to understand facies and source-reservoir relationships. In the North German Basin, the only available palinspastic reconstructions are in the NE (Kossow & Krawczyk, 2002), and forward modelling of the initial phase of basin formation was applied in combination with detailed analysis of core material (Rieke et al., 2001).

Conventional restorations typically yield minimum deformation values. However, valid results for restoration and retro-deformation based on seismic data require the consideration of sub-seismic-scale deformation, which has an important impact on basin evolution (e.g. Pickering et al., 1996; Tanner et al., subm.). Whereas the interpretation of reflection seismic data allows especially the analysis of brittle large-scale deformation, structures below the seismic resolution (hereafter referred to sub-seismic) and ductile strain components may also accommodate a significant amount of the total strain (Marrett & Allmendinger, 1991; Scholz & Cowie, 1990), reaching up to 40-50 % on both local and regional scale (Walsh et al., 1996; 1998 and references therein; Tanner et al., subm.).

The understanding of the structural inventory of the North German Basin as observed today, and especially quantitative modelling of the deformation processes and their time-dependent interactions occurring in this dynamic setting, however, require an integrated approach over a large range of scales to understand the complexity mentioned above, and to provide appropriate predictions in terms of e.g. strain distribution, fault connectivity, and fluid migration. Quantitative seismic interpretation, calibration with well data, 3D retro-deformation, and analogue modelling provide information on the strain geometry over a broad range of scales, between the mm (borehole) and 10 m (seismic) scale, and on the processes of its accumulation through geologic time.

The data set here analysed in the North German Basin (for location see Fig. 1.2) is one of the rare cases where geophysical data are available together with well data within one volume from the Quaternary down to the Carboniferous. RWE Dea AG (Hamburg) provided a high-resolution 3D reflection seismic data set together with well data, containing 14 wells with deviation data, log data, partly FMI (Formation Micro Image) and core data. For confidentiality reasons the location is not defined in more detail.

Figure 1.2: Topography of Germany and adjacent countries with location of the study area. Alpine deformation did not affect the surface topography near the study area, but it is recognised in the subsurface. Data source: http://commons.wikimedia.org/wiki/Image:Deutschland_topo.png (modified).

1.3. Working procedure

1.3.1. 3D reflection seismic interpretation

The analysed 3D reflection seismic data set was provided as a pre-stack depth migrated (PSDM) volume by RWE Dea AG, Hamburg. The volume covers an area of 22 x 17 km and reaches down to a depth of ca. 7.5 km. The grid spacing is 25 m by 25 m, and approx. 30 m vertical resolution is reached, depending on the depth in the volume.

The first working step was loading of the seismic volume into the seismic interpretation software GeoFrame/IESX (Schlumberger). Subsequently, well data were loaded together with their log information (LAS files), and corresponding deviation files needed to be integrated in order to position the bore-hole data correctly. To calibrate the well data with the seismic volume, stratigraphic markers from composite logs were imported into GeoFrame and checked for consistency throughout the volume.

After loading, numerous horizontal slices have been created from the seismic volume, which allowed a better correlation of faults and horizons not only along vertical sections (inlines, crosslines, diagonal lines, zig-zag lines), but also in map view during the subsequent interpretation process (Fig. 1.3).

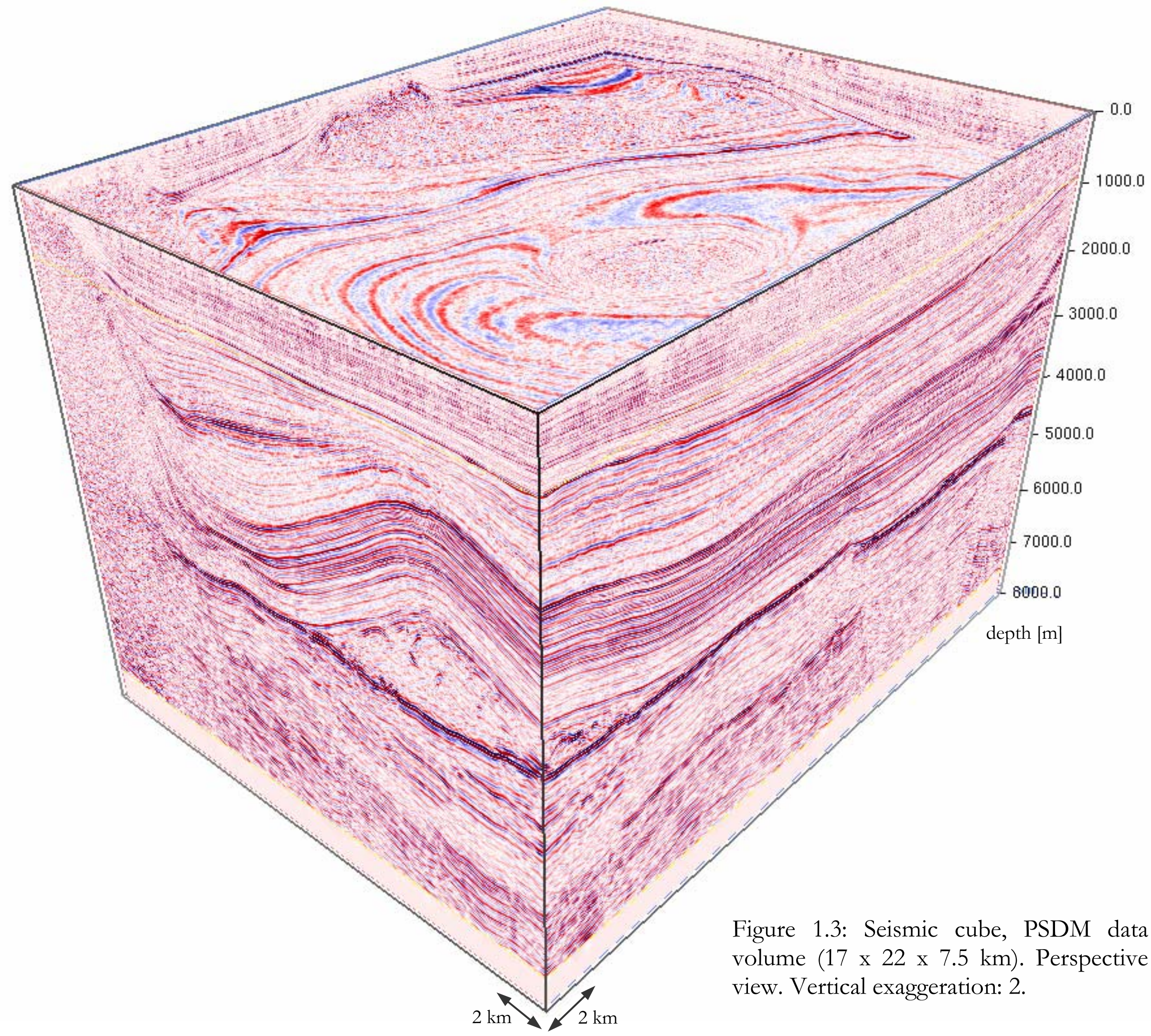

Figure 1.3: Seismic cube, PSDM data volume (17 x 22 x 7.5 km). Perspective view. Vertical exaggeration: 2.

The next step was the interpretation of important stratigraphic horizons and good correlative seismic reflectors (Fig. 1.4) by tracing and picking of a reflector phase-consistently along its peak amplitude (Fig. 1.5). First, horizon interpretation was carried out using a coarse grid with a line spacing of 125 m (picking every fifth inline and crossline). Depending on strong faulting and quality (low-amplitude signal) of the analysed reflector, in some cases the mesh needed to be tighter by choosing a line spacing of 75 m (every third inline and crossline). After this manual interpretation (75 to 125 m grid) the non-interpreted inlines and crosslines were interpreted automatically (autotracking) resulting in a 25 m grid. Subsequently, after autotracking, the horizons were checked for accuracy, and improved manually if required. The key reflectors that have been interpreted are: Top Reflective Carboniferous, Base Rotliegend, Top A2, Top Zechstein salt, Base Jurassic, Jurassic/Cretaceous unconformity, Base Upper Cretaceous, and Base Tertiary.

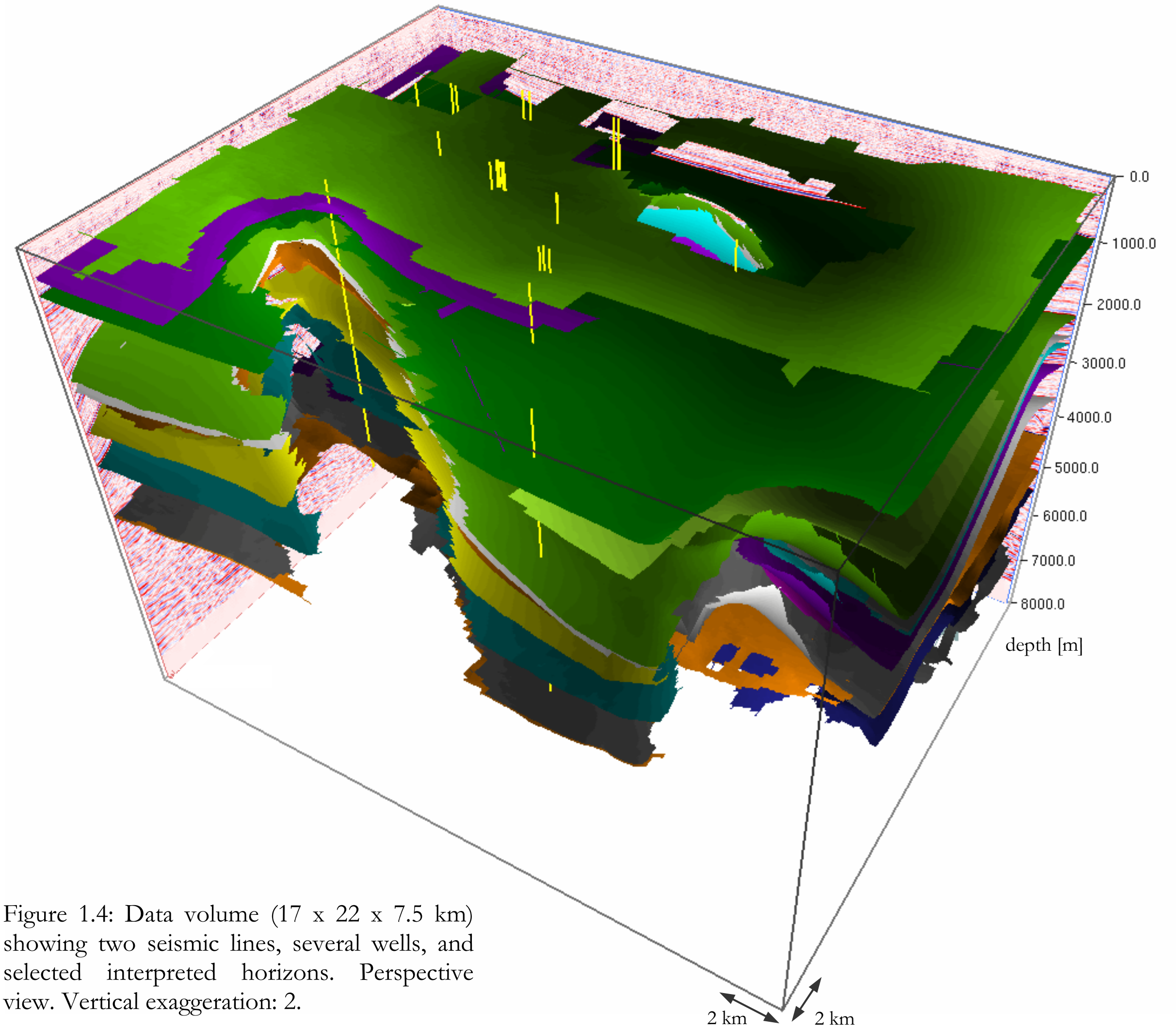

Figure 1.4: Data volume (17 x 22 x 7.5 km) showing two seismic lines, several wells, and selected interpreted horizons. Perspective view. Vertical exaggeration: 2.

After compilation of complete horizons, numerous dip-, azimuth- (Fig. 1.6), and thickness maps (Fig. 1.7), as well as horizon slices (Fig. 1.8) were created. A thickness map can be done by subtracting the depth of a horizon from that of a deeper horizon. Variations in thickness refer then to tectonic or sedimentary changes during sedimentation. Dip and azimuth maps highlight subtle changes in the dip of a horizon, direction variations, and folded or fractured areas. Horizon slices (= amplitude maps) can be created by flattening the seismic volume at an interpreted horizon. In map view, slight changes in amplitude of this horizon are highlighted, and subtle lineaments (faults or sedimentological features) can thus be identified (Figs. 1.6, 1.8).

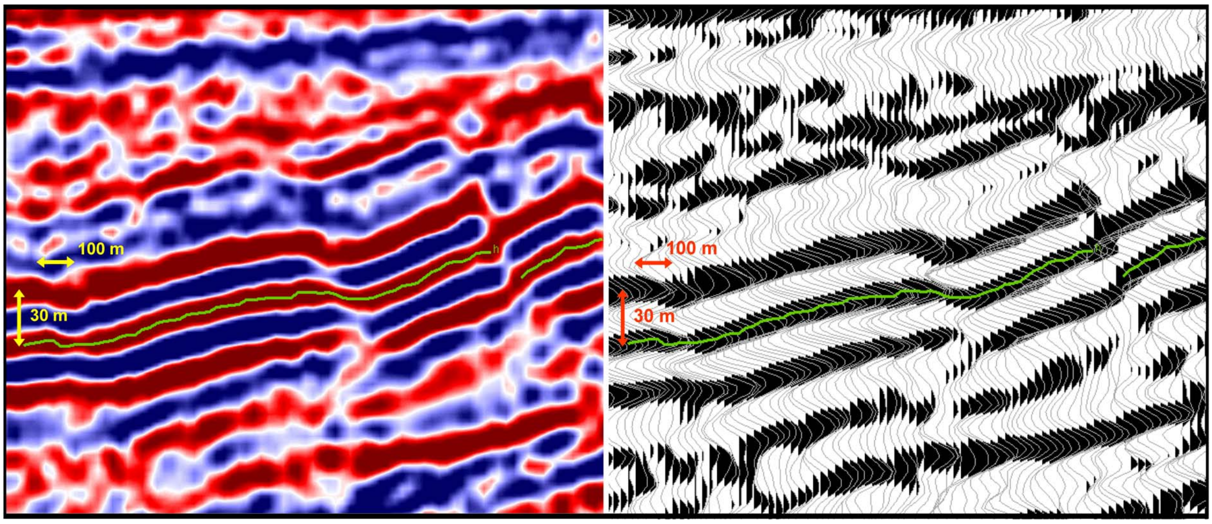

Figure 1.5: Detailed example of the seismic data in 2 km depth. Left: colour-coded seismic amplitudes demonstrating the high resolution and one interpreted reflector (green line). Right: same image but without colour-coded amplitudes. Here, all traces are visible and positive amplitudes are filled with black. See scales for resolution.

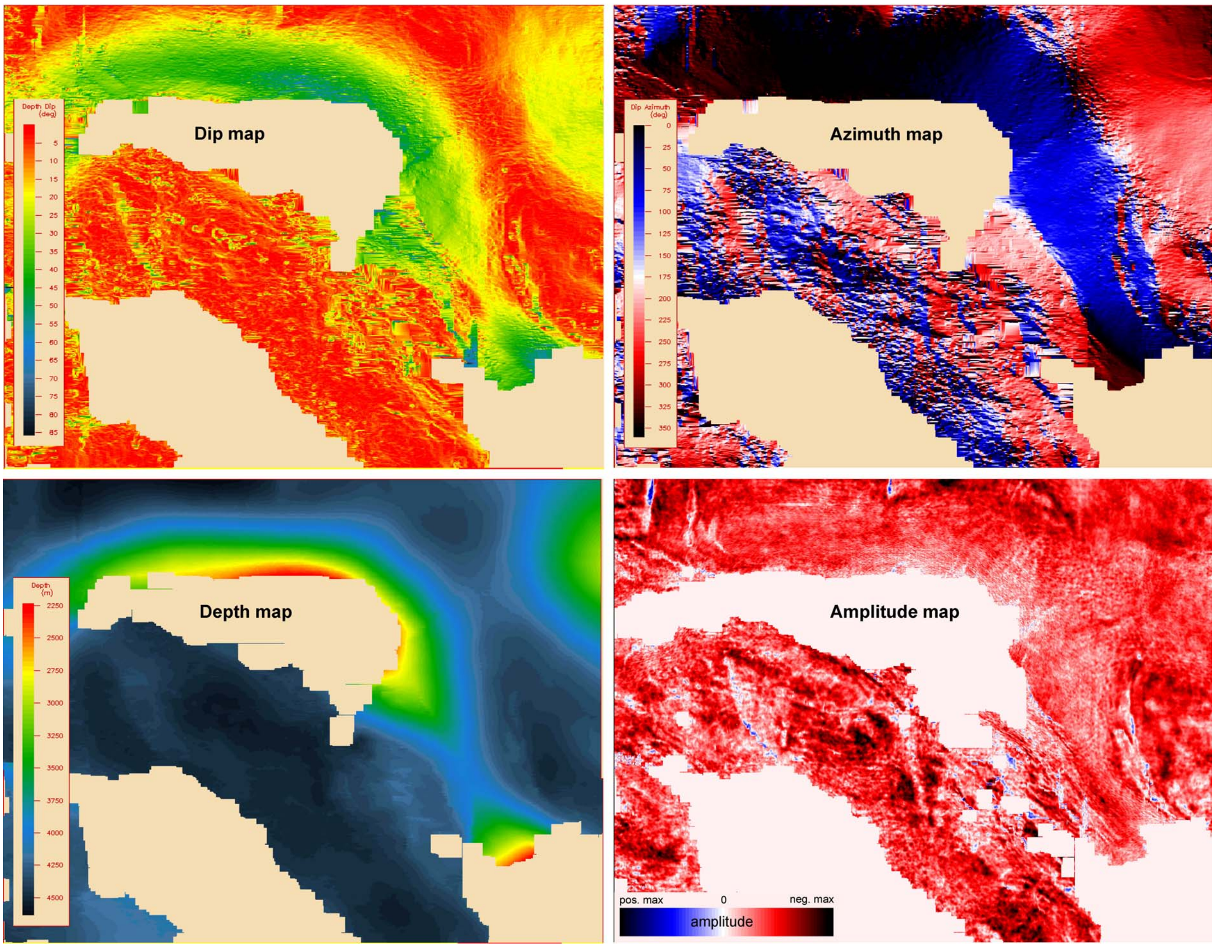

Figure 1.6: Several attribute maps of Top Zechstein salt horizon showing the detailed structured surface. Blank colours are uninterpreted areas, because here salt rose into diapirs, and the amplitudes of the reflector are too low for being suitable for interpretation. The dip map indicates the amount of dip, the azimuth map illustrates the direction to which the reflector is dipping, and the depth map shows the depth range where the horizon is located today. The amplitude map (horizon slice) shows the intensity of reflections, and can highlight tectonic features along which usually the amplitude decreases. Area size: 17 x 22 km.

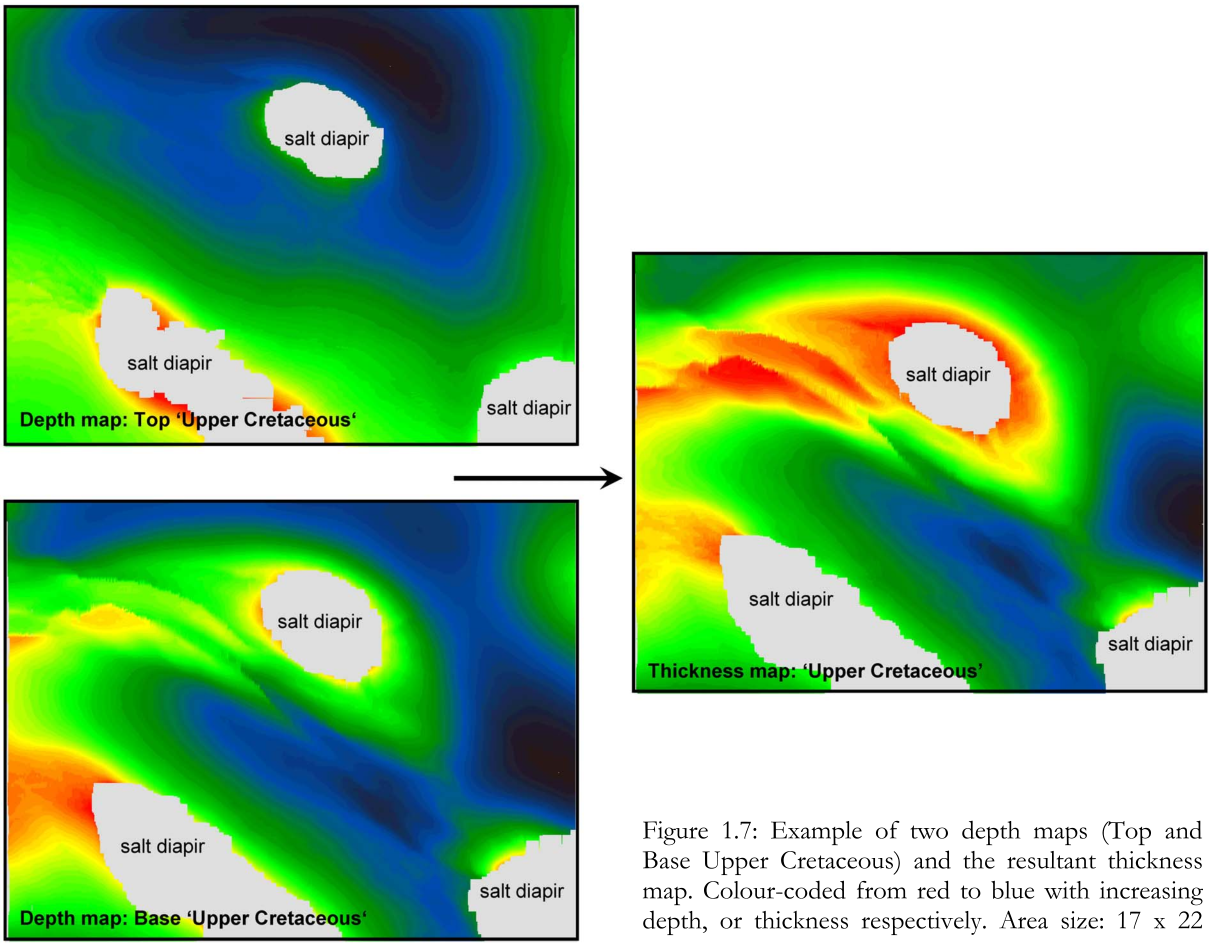

Figure 1.7: Example of two depth maps (Top and Base Upper Cretaceous) and the resultant thickness map. Colour-coded from red to blue with increasing depth, or thickness respectively. Area size: 17 x 22

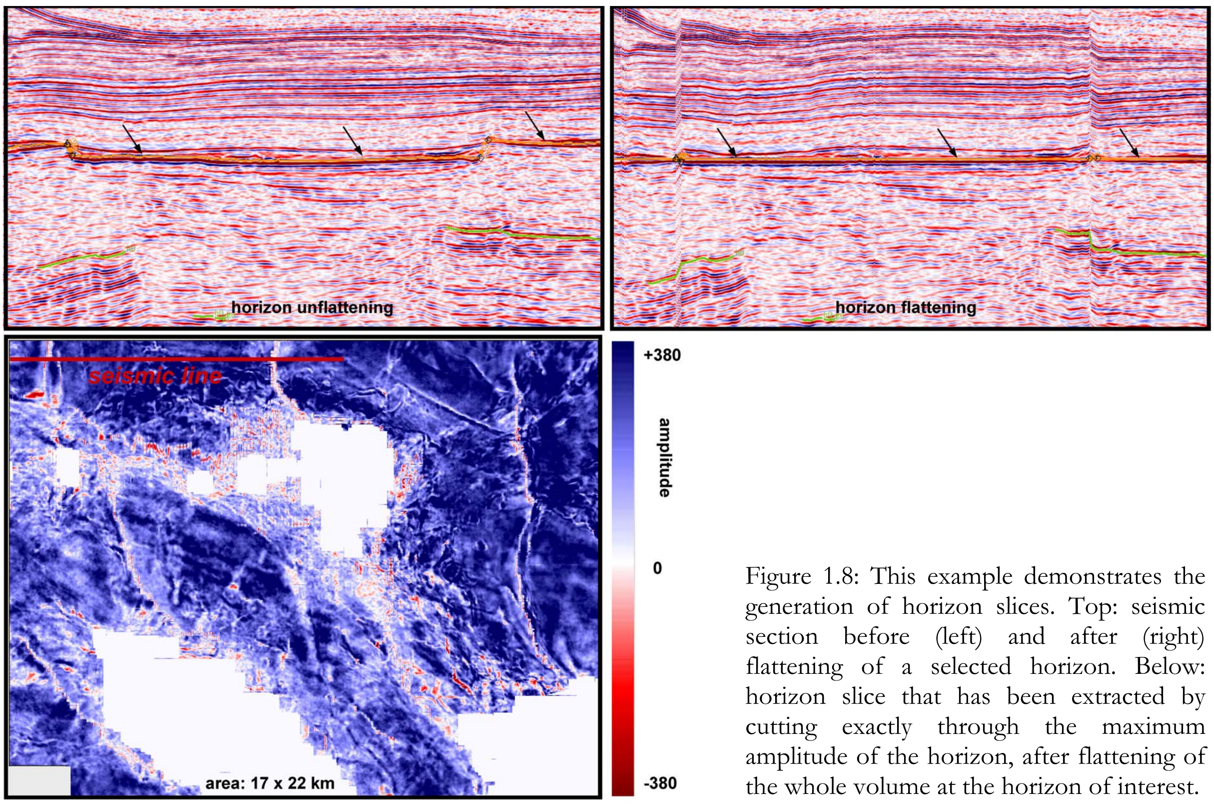

Figure 1.8: This example demonstrates the generation of horizon slices. Top: seismic section before (left) and after (right) flattening of a selected horizon. Below: horizon slice that has been extracted by cutting exactly through the maximum amplitude of the horizon, after flattening of the whole volume at the horizon of interest.

Faults have been interpreted first in map view, using a combination of depth maps, thickness maps, dip maps, and horizon slices, to obtain an overview about the general structural style in the working area. Later, faults have been interpreted along appropriate cross-sections in detail. For modelling purposes, the major Permian faults were interpreted in 3D as detailed as possible.

3D seismic interpretation is the base for the subsequent tectonic modelling. During interpretation of the data set numerous evaluations were necessary in order to interpret the evolutionary model correctly, e.g. seismic reflections were analysed whether they represented relevant geological features or seismic artefacts, tectonic structures needed to be identified and distinguished from sedimentological features, regional unconformities needed to be evaluated in space and distinguished from local unconformities caused by salt diapirism, and the interaction of faulting and deformation overprint had to be defined for later kinematic restorations (see chapter 2).

1.3.2. Tectonic modelling

After seismic volume interpretation, surfaces have been loaded into the modelling software GoCad (GoCad Consortium) and 3Dmove (Midland Valley). GoCad was used especially for surface triangulation of horizons and faults, cutting or merging of objects, surface attribute calculations (dip, azimuth, curvature), and finally construction of tectonic models. In GoCad, the surfaces were analysed and cross-checked with the seismic data for consistency, and, if necessary, reinterpreted. Depending on the purpose and the modelling procedure, several smaller models have been created, rather than one large model of the whole study area (Fig. 1.9).

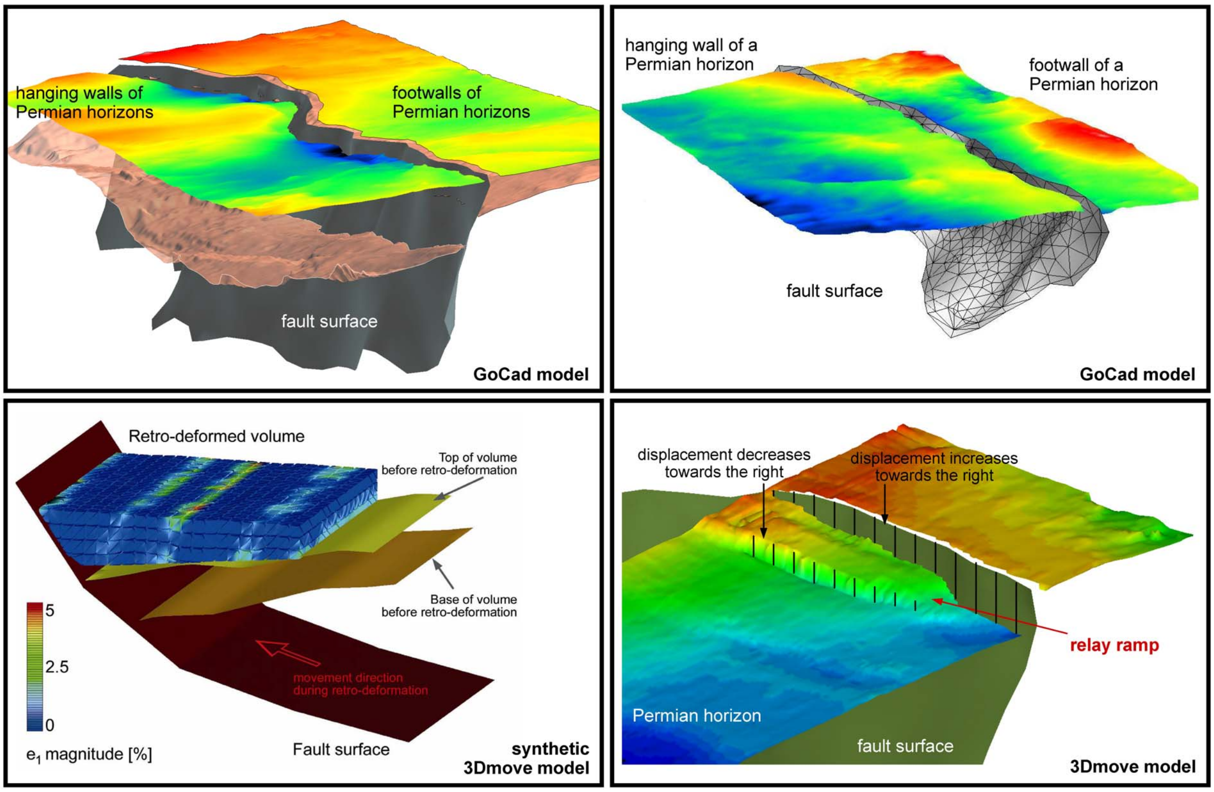

Figure 1.9: Several selected models constructed with GoCad and 3Dmove software. Horizons are colour-coded from red to blue with increasing depth. No vertical exaggeration.

After constructing the tectonic models in GoCad, several objects (surfaces, lines) were loaded into the software 3Dmove, which was then used for orientation measurements (pole-point plots of surface triangles), fault morphology analyses (definition of the kinematic vector), 3D displacement calculations (Allen maps), volume generation between surfaces, 3D restorations (retro-deformation) of natural and synthetic models, as well as strain analyses. Excel and SpheriStat software were used for the subsequent evaluation of results from kinematic, displacement, and strain analyses.

With the constructed it was possible to quantitatively assess geometrical quantities such as fault displacement, kinematic vectors and sequences, and the pattern and magnitude of deformation from seismic-scale structures. The relations between horizons and fault surfaces reveal the relative ages of single kinematic increments. 3D retro-deformation of the constructed model validated its geometric and kinematic characteristics. Furthermore, the validated model allowed the prediction of distribution and magnitude of strain within the retro-deformed volume. Model validation encompasses an incremental retro-deformation of the different deformation stages during basin evolution (see chapters 3 and 4).

1.3.3. Analogue modelling

In addition to the prediction of distribution and orientation of strain from 3D retro-deformation, scaled analogue experiments were performed, designed on the basis of the results from seismic interpretation and model building. The analogue modelling was based on a parameter analysis and mechanical properties related to the structural types comparable to the North German Basin. This analysis allowed a better understanding of distribution, accumulation, and scaling of deformation during crustal extension, and provides constraints on the temporal evolution and structural processes responsible for the patterns identified in the 3D seismic data and 3D retro-deformation models.

During analogue modelling (chapter 5), the evolution of normal faulting was studied in terms of distribution and accumulation of strain, which refers to the observation of fault-linkage, small-scale strain, and the time-dependent activation and deactivation of faults. These experiments were detected and analysed with an optical high-resolution digital camera and were subsequently processed with the PIV technology (Particle Image Velocimetry) of LAVISION software DaVis, which allows to quantify the deformation at all scales and to measure all components of the displacement-gradient tensor (chapter 5).

Before starting the appropriate experiments and constructing the suitable deformation box (see experiment study in chapter 5), parameter experiments have been carried out to test different materials (sand, cement, starch, gypsum, and mixtures among them) and their physical behaviour under extensional conditions (Fig. 1.10). We recognised that pure sand was not suitable for our purpose because its cohesion is very low and it develops no tensile fractures. However, pure starch, cement, and gypsum are characterised by a high cohesion and tensile fractures, but shear fractures developed only secondarily. By testing different material mixtures, we found that a mixture of sand and gypsum in relation 3:1 was the most suitable analogue material, as it showed steep structures, open fractures, and shear fractures. These structures represent well the upper brittle crust, and are therefore suitable for comparing the structures of our working area. Additionally, the sand-gypsum mixture has a small grain size which is necessary for a detailed observation of fault-growth processes also at a small scale.

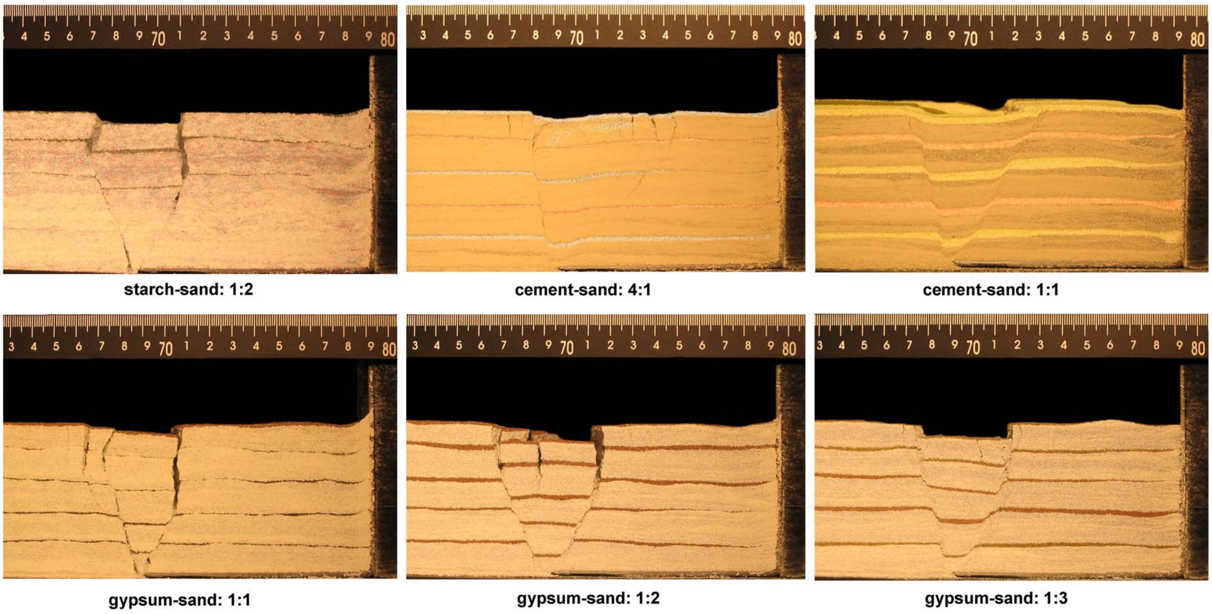

Figure 1.10: Selected preliminary extensional experiments testing different materials and showing a different faulting behaviour. All experiments have been done under the same boundary conditions. Horizontal measure is in cm; vertical extent of entire box is 12.5 cm.