Paleostresses of the Groningen area, the Netherlands—Results of a seismic based structural reconstruction

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ABSTRACT

We describe a novel workflow to reconstruct paleostresses in the subsurface where the traditional outcrop-based method that uses fault slip measurements is not possible. We use 3D seismic data and structural restoration to determine fault surfaces and slip vectors. These data are then used as input for paleostress-reconstruction algorithms.

The study area of ca. 750 km² is situated in the Groningen Block, the Netherlands. Excellent quality 3D seismic data were used to interpret 11 horizons and approximately 80 faults between the Tertiary and the Top Rotliegend. Indicators of fault slip direction are fault undulations, sedimentary structures offset by faults and shapes of horizon cut-outs. These indicators were used as a basis of 3D restoration of the interpreted horizons. A stepwise restoration approach was chosen that removed younger deformation to obtain slip vectors for older deformation events. In a following work step, Numeric Dynamic Analysis (NDA) was used to calculate paleostress tensors for the Middle and Lower Tertiary, Upper Cretaceous and Upper Rotliegend sequences.

The results presented in this paper are consistent with existing paleostress interpretations for NW Europe; however, in contrast to previous studies they are derived from a subsurface volume where paleostress information was lacking until now. Issues that need further study include the effect of the size of the study area on the assumptions of a homogenous stress field, and an analysis of the ambiguity of the interpretation of fault slip indicators on 3D seismic data.

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1. Introduction

An understanding of the evolution of the stress field is essential in studies of the tectonic evolution of the crust (e.g. Gruenthal and Stromeyer, 1986). Furthermore, analysis of the paleostress field can help to explain fault reactivation, the timing and patterns of fault leakage and to analyse the migration of geofluids (Du Rouchet, 1981; Gartrell and Lisk, 2005; Henk, 2005).

There are many methods to determine the present-day in-situ stress. Earthquake focal mechanisms (e.g. Hinzen, 2003; Reinecker et al., 2005) provide information on the size and orientation of the stress tensor in seismically active areas. Analysis of borehole deformation and related methods (e.g. Gölke and Brudy, 1996; Reinecker et al., 2003, 2005) are widely used tools to establish the present stress field in the subsurface.

Quantifying stress in the past is much more difficult. Large-scale fault patterns (e.g. Anderson, 1942; Michon et al., 2003) provide a first order estimate of the orientation of the principle stresses, without quantifying stress anisotropy. This Andersonian interpretation for example uses the observation of a newly formed North–South oriented graben system to postulate a vertical $\sigma_1$ (largest principle stress) and an E–W oriented $\sigma_3$, while generally ignoring the possibility of oblique slip. Furthermore, the relative size of the principle stresses remains unknown. Andersonian interpretation has been used to quantify paleostress and the coefficient of static friction from deep seismic lines (see discussion in McBride, 1989). Field-based paleostress studies can provide information on the evolution of the entire paleostress tensor, as fault orientations and slip direction (as indicated by slickensides) can be measured directly. Slickensides should, according to the Wallace & Bott hypothesis (Wallace, 1951; Bott, 1959; Angelier, 1994), be parallel to the maximum resolved shear stress on the fault surface. This allows inversion of the field data to obtain the stress tensor. A correct separation of different fault populations is however essential (e.g. Bergerat, 1987; Larroque and Laurant, 1988; Hibsch et al., 1995; Vandycke, 2002; Reicherter and Peters, 2005; Caiazzo et al., 2006; Sippel et al., 2008-this issue). Some methods (like the NDA used in this work) however calculate the orientation and relative size of the principle strains instead of the principle stresses. Assuming coaxial deformation these strain axes can be considered to coincide with the stress axes (Sperner et al., 1993; Sperner, 1996; Ilic and Neubauer, 2005).
In the subsurface of sedimentary basins, 3D reflection seismic data can be used to map large numbers of fault surfaces in three dimensions. Provided that the slip vectors of these faults can be reconstructed, the paleostress analyses could be extended to much larger fault populations and rock volumes in the crust. The interception of faults with the surface is no longer required for paleostress studies. Previous analyses using this approach were presented by Gartrell and Lisk (2005) for the Miocene in the Timor Sea, and Lohr (2007) for the Rotliegend of the Central European Basin.

In this paper we present a paleostress analysis of a structurally complex, subsurface setting in the Central European Basin System, using 3D seismic data. The high quality and quantity of 3D seismic data available for this study, and existing paleostress studies in the neighbouring countries make the Groningen area suitable for this approach. We estimated for the first time, parts of the paleostress stratigraphy over a period of about 260 Ma exclusively based on subsurface data and compared the results with published paleostress data from NW Europe. For this we studied the 3D seismic data

Fig. 1. The study area in the NW corner of the Groningen Block, a structural high bounded by the Lauwerszee Trough in the west, the Ems Graben in the east and the Lower Saxony Basin in the south (modified from NAM).
set (provided by Nederlandse Aardolie Maatschappij, NAM, a Shell operated 50–50 joint-venture with Exxon Mobil) of the NW corner of the Groningen Block, the Netherlands (Fig. 1). The workflow developed for this study consists of three steps: (i) a high resolution seismic interpretation that defines horizons and fault surfaces, with sufficient detail to locally support the analysis of the paleo-slip directions on individual fault surfaces, (ii) a stepwise 3D reconstruction to incrementally remove younger deformation and determine the direction of slip of earlier faulting, and (iii) the analysis of fault slip and fault orientation data to calculate paleostress tensors. The following paragraphs provide an account of the data analysis and methodology used for this paleostress estimation based on 3D-seismic data, followed by a discussion on the applicability of this approach in settings where fault exposure is lacking and tectonic information is restricted to the subsurface.

2. Dataset

Our study is based on a high resolution, Pre-Stack Depth Migrated (PSDM) seismic volume of the Groningen Block (Fig. 2), comprising 16 individual seismic surveys acquired between 1984 and 1988, and data from approximately 300 wells. For this study, the NW corner (25 by 35 km, Fig. 1) of this giant survey was selected because of its relative structural simplicity, the high quality of data and the relatively thick accumulation of Cenozoic deposits compared to other parts of the Groningen Block. This allows for a more quantitative analysis of the

![Fig. 2. Representative interpreted seismic in- and cross-line from the Groningen area. Position of the sections is shown in Fig. 6. The stars denote locations of Chalk deposits being truncated by the Base North Sea Super Group. This erosion is not the result of localized fault inversion, but reflects the uplift of the Groningen Block as an internally stable block, sensu Stäuble and Milius (1970).](image-url)
Cenozoic stress field in this area compared to other parts of the Groningen Block.

3. Geological setting

The Groningen gas field is located on the Groningen Block (Fig. 1). The Groningen gas field was discovered in 1959 after drilling of the Slochteren-1 well. This is the largest natural gas accumulation in Western Europe that initiated a revival of hydrocarbon exploration and production in the Netherlands (Breunse and Rispens, 1996). The Groningen Block structure is part of the North Netherlands High (TNO-NITG, 2004; Wong et al., 2007). The Groningen Block is bounded by the Ems Graben in the east, the Lower Saxony Basin (LSB) in the south, and the Lauwerszee Trough in the West.

The Groningen Block has been a relatively stable structure since the latest Jurassic, when the North Netherlands High was formed (Ziegler, 1982; TNO-NITG, 2004; Duin et al., 2006; Wong et al., 2007), and it has probably been a positive structural element since about the Late Carboniferous (Wong et al., 2007). Vitrinite reflectance data and magnetic anomalies have led to the inference of an intrusive body below the Groningen Block of at least Kimmerian age, and apatite fission track data indicate an additional heat pulse in pre-Permian times (Kettel, 1983; Wong et al., 2007). The source rocks for the Groningen gas field are Namurian and Westphalian coals and the reservoir rocks are Rotliegend (Permian) sandstones. The seal is formed by Zechstein evaporites (Van Adrichem-Boogaert and Kouwe, 1993–1997; Wong et al., 2007). The thickness of the Zechstein in this area varies between 500 and 1500 m (TNO-NITG, 2004) due to halokinesis that started in the Early Triassic (Mohr et al., 2005). The Triassic to Lower Cretaceous deposits of the Groningen Block are relatively thin (max. 800 m) due to erosion and non-deposition (Ziegler, 1982; TNO-NITG, 2004; Wong et al., 2007). The Upper Cretaceous Chalk Group is 400 to 1200 m thick (TNO-NITG, 2004) and consists mainly of carbonates and marls. During the (Late Cretaceous) Subhetercynian tectonic phase, parts of the chalks were locally eroded. In the surrounding areas the Laramide inversion (Latest Cretaceous) caused intense uplift, associated with truncation, erosion, fault reactivation and inversion. The NW corner of the Groningen Block however, remained relatively stable with only minor regional uplift, archived in the erosion of the uppermost Cretaceous deposits, while along the southern fringes of the Groningen Block, some minor inversion was documented (Stäuble and Milius, 1970; Ziegler, 1982; Van Wijhe, 1987; Dronkers and Mrozek, 1991; Van Adrichem-Boogaert and Kouwe, 1993–1997; Gras and Geluk, 1999; De Jager, 2003; TNO-NITG, 2004; Worum and Michon, 2005; Duin et al., 2006; Wong et al., 2007). The Cenozoic North Sea Supergroup, deposited from the Early Paleocene onwards is predominantly siliciclastic and between 500 and 1250 m thick (Van Adrichem-Boogaert and Kouwe, 1993–1997; TNO-NITG, 2004).

4. Methods

4.1. Interpretation

The selected seismic PSDM data (Fig. 2) were interpreted with high lateral resolution (25–50 m). Eleven mainly formation bounding horizons were interpreted from laterally continuous high-amplitude reflectors, partly based on interpretations done by NAM (see Table 1). During structural interpretation, particular attention was given to fault shapes, the mapping of en-echelon fault segments as arrays of multiple faults, and exact position and shape of horizons to prepare horizon-fault intersections or juxtaposition maps (“Allan map”, see Table 1). For three horizons no well ties were available and approximate ages are given based on stratigraphic position of the reflector (van Ojik, Personal communication, 2006).

Table 1
Horizons described in this study, with ages based on seismic-to-well ties and their maximum depth

<table>
<thead>
<tr>
<th>Horizon:</th>
<th>Group:</th>
<th>Age:</th>
<th>Max depth (m):</th>
<th>Interpretation by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base upper North Sea</td>
<td>Middle North Sea</td>
<td>Tertiary; Priabonian (19 Ma)</td>
<td>600</td>
<td>Authors</td>
</tr>
<tr>
<td>Brussels Sandstone member</td>
<td>Lower North Sea</td>
<td>Tertiary; Ypresian to Lutetian (52 Ma)</td>
<td>1000</td>
<td>Authors</td>
</tr>
<tr>
<td>Undefined lower North Sea reector</td>
<td>Lower North Sea</td>
<td>Tertiary; E Lutetian (?), approx. 45–48 Ma</td>
<td>1050</td>
<td>Authors</td>
</tr>
<tr>
<td>Base North Sea</td>
<td>Lower North Sea</td>
<td>Tertiary; Thanetian (60 Ma)</td>
<td>1300</td>
<td>NAM / Authors</td>
</tr>
<tr>
<td>Undefined reflector Chalk inside 1</td>
<td>Chalk</td>
<td>L. Cretaceous; M.-U. Campanian (75–80 Ma)</td>
<td>1700</td>
<td>Authors</td>
</tr>
<tr>
<td>Undefined reflector Chalk inside 2</td>
<td>Chalk</td>
<td>L. Cretaceous; Lower Campanian (82–84 Ma)</td>
<td>1900</td>
<td>Authors</td>
</tr>
<tr>
<td>Base Chalk</td>
<td>Chalk</td>
<td>L. Cretaceous; (E) Eocenomanian (97 Ma)</td>
<td>2200</td>
<td>NAM / Authors</td>
</tr>
<tr>
<td>Base Rijnland</td>
<td>Rijnland</td>
<td>E. Cretaceous latest Ryazanian (140 Ma)</td>
<td>2250</td>
<td>NAM</td>
</tr>
<tr>
<td>Top rot salt main evaporite member</td>
<td>Upper Germanic trias</td>
<td>Triassic, E. Anisian (245 Ma)</td>
<td>2800</td>
<td>NAM</td>
</tr>
<tr>
<td>Top Zechstein</td>
<td>Zechstein</td>
<td>L. Permian; Thuringian (251 Ma)</td>
<td>2900</td>
<td>NAM</td>
</tr>
<tr>
<td>Top Rotliegend</td>
<td>Upper Rotliegendes</td>
<td>E. Permian; Saxonian (258 Ma)</td>
<td>3400</td>
<td>NAM</td>
</tr>
</tbody>
</table>

Table 2
Orientation of reconstructed faults for each horizon

<table>
<thead>
<tr>
<th>Horizon:</th>
<th>No significant fault heaves after reconstruction.</th>
<th>Not reconstructed: deposits too thin.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Mid North Sea</td>
<td>No significant fault heaves after reconstruction.</td>
<td>Not reconstructed: deformation not brittle.</td>
</tr>
<tr>
<td>No. of faults: 7</td>
<td>No significant fault heaves after reconstruction.</td>
<td>Not reconstructed: deformation not brittle.</td>
</tr>
<tr>
<td>Base North Sea</td>
<td>All North Sea data No. of faults: 23</td>
<td>Base Chalk</td>
</tr>
<tr>
<td>Chalk inside2 No. of faults: 9</td>
<td>No significant fault heaves after reconstruction.</td>
<td>Top Zechstein</td>
</tr>
<tr>
<td>No. of faults: 15</td>
<td>No significant fault heaves after reconstruction.</td>
<td>Top Zechstein</td>
</tr>
<tr>
<td>Brussels Sandstone</td>
<td>All Chalk data No. of faults: 27</td>
<td>Top Rotliegend No. of faults: 23</td>
</tr>
<tr>
<td>No. of faults: 15</td>
<td>No significant fault heaves after reconstruction.</td>
<td>Top Rotliegend No. of faults: 23</td>
</tr>
</tbody>
</table>

Arrows on the great circles show the reconstructed slip direction for the corresponding fault. For the reconstructed Tertiary and Cretaceous, an additional plot shows the combined data of the entire time period. All stereonets are lower-hemisphere, equal-area projections with North at the top of the circle.

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We interpreted 55 faults in the Supra-Zechstein and 23 at the Top Rotliegend level (Table 2), focussing on faults with sufficient spatial extent and throw to allow the estimation of the displacement vector. Data from 20 wells with (bio-) stratigraphic age constraints were used for accurate dating of the selected marker horizons. An overview of the interpreted horizons is given in Table 1. For one reflector in the Lower North Sea Group and for two reflectors in the Chalk group no well tops were available; the approximate age of these deposits was constrained by their position in wells (van Ojik, personal communication, 2007). The Lower North Sea reflector is of Middle Eocene age, probably Early Lutetian. The younger of the two undifferentiated Chalk reflectors is of Middle to Late Campanian age and the older Chalk reflector is from Late Santonian to Early Campanian age. In some places, poor seismic reflectivity limited horizon interpretation of the deeper reflectors in the Upper Cretaceous sequences.

4.2. Fault slip vectors

We carefully examined the data for all possible indicators of fault slip such as fault intersections, fault bifurcations, the shape of the fault surface (Cartwright et al., 1995; Needham et al., 1996; Marchal et al., 2003), displaced linear objects (Back et al., 2006), and similarities of horizon cut-offs in Allan Maps (Allan, 1989). In the Cenozoic section, the best indicators of fault slip were obtained by a combination of fault undulation (Fig. 3), matching structures on horizons on both sides of the fault (Fig. 4), and occasionally from the asymmetric shape the of the horizon cut-offs on Allan Maps (Fig. 5). Slip vectors were only reconstructed from faults which generated a significant horizon offset (>50 m). Faults that penetrated a horizon with offsets <50 m were classified as “not active” during the timeframe under review.

The high resolution 3D interpretation of faults revealed undulations on many fault surfaces. These undulations are persistent when the interpretation is carried out at different angles to the fault (Fig. 3). The minor overprinting of the undulation by an interpretation-parallel curvature (most clear in Fig. 3c) shows that these features are not strongly influenced by interpretation effects. The fault surface undulations are often described to be parallel to the slip direction (Lee and Bruhn, 1996; Needham et al., 1996; Renard et al., 2006; Lohr, 2007; Kokkalas et al., 2007; Lohr et al., 2008). We interpret the undulations to be parallel to the last direction of fault movement, as only corrugations parallel to the most recent slip direction are likely to be preserved or even amplified, irrespective of their formation mechanism (Kokkalas et al., 2007).

A second method used for fault slip analysis was matching of minor, elongated irregularities in the horizon on both sides of a fault (e.g. Fig. 4a), although it was not always clear what these features were (small faults or sedimentary features close to the limit of seismic resolution). We interpreted these features on the 3D horizons surrounding the fault (see Fig. 4a), rather than on the projection of the horizon on the fault surface (the pure Allan map), as the lateral continuity and 3D shape of the features often indicated whether these features were real or interpretation artefacts.

Thirdly, we analyzed the shape of the horizon-fault intersections in plan view for indicators of the slip direction. In Fig. 4b, the matching of convex and concave shapes on both sides of the fault surface strongly indicates the opening direction of this fault. Similar to the analysis of fault undulations, the geometry matching of fault footwall and hangingwall was very sensitive to the quality of the preceding fault and horizon interpretation.

The fourth method used the shape of the Allan map between the two tips of the fault (Fig. 5), proposing that the obliquity of slip produced an asymmetry in the Allan map of an initially horizontal reflector. The parallelism of the slip arrows in Fig. 5 is an obvious simplification, as slip on normal faults becomes more oblique and rotated in the direction of the centre of the fault towards the tip lines (Roberts, 1996; Morewood and Roberts, 2000; Cowie and Roberts, 2001). Note that the analysis of the asymmetry of the Allan map can be e.g. used to support the slip interpretation presented in Fig. 4.

In summary, a combination of these four approaches can be used directly for slip approximation of the youngest deformation phase. This deformation needs to be sequentially removed from deeper horizons, before Allan lines representing older tectonic phases can be established for these levels.

4.3. Structural reconstruction

The software package 3DMove (Midland Valley Exploration) was used for 3D retrodeformation and the measurement of the slip vectors. The tectonic reconstruction served two goals: (i) to measure and test the azimuth and plunge of the proposed slip vector, and (ii) to remove younger deformation in order to estimate movement vectors on deeper horizons.

Throughout the study area, all interpreted horizons are sub-horizontal in all fault blocks, which justified a sequential restoration by inclined shear. This algorithm was used to move the respective hangingwall blocks to their original position, based on the shape of the associated fault. A restoration was accepted when hangingwall and footwall blocks fitted along the entire length of the fault surface, without significant rotation of the horizon. Since the reconstructed geometry depends on the general shape of the fault surface, an erroneous movement vector could produce rotations or gaps between the footwall and hangingwall, making this an important quality-control tool.

Prior to reconstruction of deeper horizons, the deformation of the overlying horizons had to be removed. This was done using 3DMove’s Unfold-to-Target/Inclined–Shear algorithm that unfolded a selected target horizon to a predefined datum surface by vertical shear, carrying all other objects (both horizons and faults) as passive objects along while maintaining the same vertical distance to the selected horizon. The assumption to justify this step is that all horizons were deposited horizontally. Frequently, an unexpected result after this restoration step was a small area of increased horizon dip on the footwall side of faults. This artefact was produced by an erroneous projection of the vertical restoration vectors across inclined faults. The resulting “pull-ups” were manually removed by deleting the area of increased dip and “snapping” the remaining horizon back to the fault. No decompaction was performed in this study, as estimates of the change in fault dip due to the removal of compaction indicated that these values were less than the uncertainty in orientation due to interpretation.

During the stepwise restoration of the study area down to the Base Chalk level, we collected data on the dip direction and dip of faults together with azimuth and plunge of the slip vector from each restoration step for the subsequent use in paleostress analysis. Because of the presence of the ductile Zechstein salts above the Top Rotliegend, it was not possible to reconstruct all the way down to Top Rotliegend level.

It should be noted that the uncertainty in slip direction determination of faults resulted from the structural reconstruction described above was partly compensated by the fact that almost all horizons contained two types of fault; “Older” faults that penetrate multiple horizons and already underwent restoration, and “fresh” or “blind” faults terminating in the target horizon that remained unaffected by previous reconstructions. An example of the occurrence of these “fresh” faults is the marked increase of faults between the Base Upper North Sea and the Brussels Sandstone (Table 2).

5. Paleostress methods

A number of different methods have been previously developed to calculate paleostress from fault orientations and slip vectors, e.g. the
Direct Stress Inversion (DSI, Angelier, 1990) is based on the inversion of the Wallace & Bott hypothesis (Wallace, 1951; Bott, 1959; Angelier, 1984, 1994). This hypothesis states that slip on a fault surface is in the simplest case parallel to the direction of the maximum resolved shear stress on that plane. Shear stress can be calculated using the stress tensor and the orientation of the plane. Therefore, knowledge of the orientation of a fault surface and the direction of fault slip on this fault allows one to invert the Wallace & Bott hypothesis and to calculate the direction of shear stress on the fault. Combining data from multiple faults then allows the calculation of the paleostress tensor (e.g. Angelier, 1984, 1990). DSI uses a least squares algorithm to calculate the stress tensor, by minimizing the sum of the angles between the measured slip vectors, and the calculated shear stress for all faults. The use of the least squares criterion implies that the method is relatively sensitive to outliers and inhomogeneities in the input data.

The Numeric Dynamic Analysis (NDA, Turner, 1953; Spang, 1972; Sperner et al., 1993) is based on the Mohr–Coulomb criterion and was initially used to calculate stress from twin lamellae in calcite crystals. NDA calculates the kinematic axes that, assuming coaxial deformation, coincide with the stress axes (Sperner et al., 1993; Sperner, 1996; Ilic and Neubauer, 2005). This method involves the calculation of the orientation of the compression and tension axes for each fault. These axes, that are perpendicular to each other, lie in the plane normal to the fault and in the direction of the movement vector. The friction angle theta (θ, the angle between the pressure axis and the fault surface) needs to be defined prior to calculation. In this study, the “best fit angle” was used. This angle is found by analyzing the alignment of the P- and T-axes. A tensor is then calculated (in the coordinate system defined by the fault and slip vector) by assuming a value of +1 in the direction of the compression axis, and a value of −1 in the direction of the tension axis as relative values. A tensor rotation transforms this into a real-world coordinate system, where concentrations of P- and T-axes are then interpreted to represent the orientation of σ1 and σ3, respectively.

In this study NDA was preferred over DSI because NDA was less sensitive to outliers, as shown by a test using synthetic data, and discussed by Sperner et al. (1993). Therefore, data with deviations in the fault slip vector or faults with orientations caused by local stress heterogeneities did not strongly influence the results. A comparison of the calculated DSI-tensors from this study and the faults used to calculate these tensors, often showed that fault systems dominated by normal faults (see Table 2) resulted in the calculation of compressional stress tensors. Tensors calculated with NDA did not exhibit this discrepancy.

Fig. 4. (a) A fault with Allan lines (horizon cut-offs) of a Cenozoic fault from this study illustrating the footwall and hangingwall horizon cut-offs projected on the fault surface. The solid lines represent the hangingwall cut-offs, and the dashed lines are the fault-footwall intersections. For four horizons, parts of the associated 3D surface are shown (shaded for depth). These show the 3D continuation of the corrugations of the Allan lines. These were used to estimate slip direction by the matching of shapes across the fault. Several possible slip directions are indicated by arrows. (b) Top view of the fault cutout of a chalk horizon. The convex and concave shapes on both sides of the fault surfaces can be connected to estimate slip direction.
Neither NDA nor DSI calculate the absolute stress/strain tensor, but only the orientation and the ratio of the principle stresses. In this study, the stress ratio $R$ was defined as

$$R = \frac{(\sigma_2 - \sigma_3)}{(\sigma_1 - \sigma_3)}$$

with $\sigma_1$, $\sigma_2$, and $\sigma_3$ as the principle stresses of the stress tensor, calculated either using DSI or NDA. In this study we used the implementation of the DSI and NDA methods in the program TectonicsFP (Ortner et al., 2002).

6. Fault interpretation results

6.1. Supra–Zechstein Faults

The mapped faults above the Zechstein mainly define graben or half-graben structures, and there are three main trends visible (Fig. 6). In the SW, a clear NW–SE orientation prevails parallel to the Lauwerszee Trough and the Rotliegend fault pattern. Along the western border of the study area, the structural trend of the interpreted fault orientation is N–S. In the N part of the studied volume, the fault orientation is generally NE–SW (Fig. 6). In the central and eastern part of the volume, no faults extending into the Tertiary succession were observed and faults in the Cretaceous where only interpreted when they had a significant throw (>50 m).

Many faults in the Upper Cretaceous Chalk and Tertiary clastics show indications of growth such as increased sediment thickness in the hangingwall (see Fig. 2). The number of faults in the Cretaceous is larger than the number of faults in the Cenozoic.

The supra–Zechstein faults in this dataset have a length between 1 and 6 km, with throws generally ranging between 50 and 200 m. Their location correlates in many cases with underlying Zechstein salt structures. In 3D the faults are slightly elliptical to rectangular, with a concave upward shape. Many of these fault surfaces, particularly in the Cretaceous section, are undulated, with the corrugations being independent of the orientation of the interpretation cross-section (see Fig. 3). Segmented faults were only observed in the Upper Rotliegend. For Mesozoic and Cenozoic faults that were not undulated we used the other methods described above to determine fault slip (Figs. 4 and 5). Additionally, complex fault assemblages, antithetic fractures and the geometries of splays were mapped as a secondary slip direction indicator.

Fig. 5. (a) Theoretical Allan Map of a circular fault with pure dip-slip displacement cutting three horizontal horizons. Dashed line is the footwall cutoff, the continuous line is the hangingwall cutoff and the bold line is the tip-line (zero-displacement line) of the fault. (b) Theoretical Allan Map of a circular fault with oblique-slip displacement cutting three horizontal horizons. Note the asymmetry in the Allan map that can be used as an indication of fault slip.

Fig. 6. Oblique view of the model with all supra-Zechstein faults and the Top Rotliegend horizon. Note the agreement of the NW–SE fault trend with the general Top Rotliegend fault orientation. N–S oriented plane indicates position of inline cross section in Fig. 2 (a); the E–W oriented plane is the position of crossline (b). The circle encloses the fault shown in Fig. 3. The vertical exaggeration of the model is 3×.
Reactivation of a fault during later deformation may change the shape of the undulations on the fault surface. Therefore, we only used data on the direction of undulations for faults that were not reactivated.

6.2. Rotliegend faults

The Rotliegend faults consist of a number of linked concave and convex fault segments, with some relay ramps. These segmented faults directly indicate fault slip direction. The segments are an indication of the first stage of faulting before the fault was formed by subsequent fault linkage (see e.g. Needham et al., 1996; Walsh et al., 1999; Schöpfer et al., 2007; Lohr, 2007; Lohr et al., 2008). The Rotliegend faults generally are longer than the survey, and have a NW–SE orientation. In Fig. 6 and Table 2 the orientation of the Rotliegend faults are shown. The ductile overlying salt makes it difficult to accurately time the deformation of the Top Rotliegend reflector. Well data showed that the strong reflector directly above the Top Rotliegend reflector (Fig. 2), represents Zechstein deposits up to and including the Z2 Basal Anhydrite Member (267.5 Ma, Van Adrichem-Boogaert and Kouwe, 1993–1997). This Zechstein reflector is clearly faulted by the same event as the Top Rotliegend, and no syntectonic deposition is observed, documenting that the studied faulting of Top Rotliegend did not start before mid-Zechstein time.

6.3. Retro-deformation and paleostress results

After retro-deformation, from the 7 Cenozoic and Upper Cretaceous horizons only the two top Tertiary and the two top Upper Cretaceous horizons exhibited sufficient fault displacement (>50 m) for further analysis. The Top Rotliegend Horizon was not reconstructed due to the uncertainties in the timing of faulting due to the decoupling effect of the Zechstein salts. The segmented faults, however, provided a slip direction for the time of fault formation. The orientation and slip direction of the retro-deformed Post-Zechstein faults in the reconstructed horizons and the Rotliegend faults are given in Table 2.

Table 3 shows the paleostress results calculated using the NDA-method. The stereoplot provides the estimated orientations of the principal stress axes. The R-value is the ratio between the principle stresses. In the histogram of residuals the difference between calculated and measured lineations is depicted. A homogeneous dataset (data from a single tectonic event and reasonably homogeneous stress field) may be assumed to have normally distributed residuals. Residuals with bimodal or skewed distribution indicate a stress field that is heterogeneous or that faults moved during different phases.

6.4. Top Rotliegend

Results from the 23 reconstructed faults at Top Rotliegend indicate a near-vertical σ2, with σ2 oriented NW–SE (Table 3). R has a value of 0.40. The best-fit theta angle for this horizon is 32°.

6.5. Upper Cretaceous

Results from the 18 reconstructed faults of the first horizon in the Cretaceous shows a vertical σ1 and a NNE–SSW oriented σ2 (Table 3). The second reflector of the Cretaceous Chalk also has a near vertical σ1 and a NNE–SSW oriented σ2. For both horizons, the minimum stress σ3 is oriented WNW–ESE. At Base Chalk, fault displacement became zero when the overlying deformation was removed. This indicates that deformation of this horizon started after the deposition of the succeeding Chalk horizon. This period of tectonic quiescence in the early Late Cretaceous in the Netherlands is also observed in other studies (Ziegler, 1982; Van Wijhe, 1987; De Jager, 2003). R-values of both horizons are 0.38. The stress results for the two Upper Cretaceous horizons are similar, and are interpreted to reflect the same tectonic phase. The combined data from these horizons shows a stress tensor with a vertical σ1, a NNE–SSW oriented σ2, and σ3 at WNW–ESE (Table 3). The R-value for the combined data is 0.38.

6.6. Tertiary

In the Tertiary succession only few faults have sufficient throw for reconstruction. The faults in the Base Upper North Sea Group horizon show a near vertical σ1 and a NW–SE σ2 after the paleostress inversion (Table 3). The R-value for the Base Upper North Sea is 0.29. The Brussels Sandstone also has a near vertical σ1 and near NNNW–SSE oriented σ2 (Table 3), with an R-value of 0.17. The undeformed Lower North Sea horizon and Base North Sea horizon were flat after the removal of the deformation of the overlying horizons. This indicates that after the deposition of these horizons no tectonic activity occurred until after the Brussels Sandstone member was deposited and deformed. This period of tectonic quiescence clearly separates the deformation of the Upper Cretaceous horizons from the deformed Tertiary horizons. The Upper Cretaceous deformation thus most likely represents a different tectonic phase than the phases that deformed the Base Upper North Sea and Brussels Sandstone horizons. On basis of the differences in stress axis orientation and R-value, the Base Upper North Sea and Brussels Sandstone paleostress results were also interpreted as two different phases of deformation.

7. Discussion

7.1. Methodology

A basic assumption of nearly all paleostress methods is that of a homogeneous stress field on the scale of the study. The first order validity of this assumption is based on consistent results of field studies (e.g. Bergeret and Geyssant, 1983; Bergeret, 1987; Larroque and Laurant, 1988; Bles et al., 1989; Sperner et al., 1993; Hibsch et al., 1995; Vandycke, 2002; Hinzen, 2003; Reicherter and Peters, 2005), but also on the basis of numerical studies for the case of the lack of fault interaction (Dupin et al., 1993; Pollard et al., 1993). Nevertheless, there are a number of possible situations where these assumptions do not hold. Stress fields are generally not homogeneous, and fault tips, fault irregularities and fault bends, as well as anisotropies such as a deep rooted structural elements, sedimentary inhomogeneities and batholiths may result in local stress deflections on different scales (e.g. Dupin et al., 1993; Angelier, 1994; Gruenthal and Stromeeyer, 1994; Maerten et al., 2002).

An important issue in this respect is the large size of the study area (25 km by 35 km) whilst the scale of outcrops is typically 5 to 50 m. Paleostress analyses based on field measurements can be considered as point datasets, whereas this study calculates the paleostress for an area of 750 km². Therefore, we needed to test the assumption of a homogeneous stress field. This was done in a bootstrapping study of the data, subdividing the study area in 4 parts as shown in Fig. 6, and re-calculating the paleostress for these individual parts, using only those faults that were present in that part. The results from these analyses were internally very similar and compared well with the original data of the entire survey. This supports the assumption of a homogeneous stress field on the scale of the study area.

In this study, slip direction was established by analysis of fault surface undulations, interpretation of Allan maps, and matching of irregularities in the horizons on both sides of a fault. Faulted channels and unconformities (Back et al., 2006) were absent in this dataset. Segmented faults (Cartwright et al., 1995; Roberts, 1996; Marchal et al., 2003; Lohr, 2007; Lohr et al., 2008) are only observed in the Rotliegend horizon. The mechanism by which the undulations used in this work to constrain paleo-slip are formed however remains unclear.
The coalescence of older faults (sensu Schöpfer et al., 2007; Lohr et al., 2008) is a possibility, or it could reflect an inherent roughness of fault planes which forms during initial failure. Irrespective of the formation, corrugations in the most recent slip direction have the highest potential to be preserved or even amplified (Lee and Bruhn, 1996; Renard et al., 2006; Kokkalas et al., 2007).

<table>
<thead>
<tr>
<th>Table 3</th>
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<tbody>
<tr>
<td>Paleostress results for the horizons reconstructed in this study showing the principle stress orientations and histograms of residuals together with the best fit $\Theta$-angle and the $R$-value (ratio of the principle stresses)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Paleostress axes:</th>
<th>Histogram</th>
<th>Paleostress axes:</th>
<th>Histogram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top mid North Sea</td>
<td>$48^\circ$</td>
<td>0.40</td>
<td>$54^\circ$</td>
</tr>
<tr>
<td>Brussels sandstone</td>
<td>$50^\circ$</td>
<td>0.12</td>
<td>$48^\circ$</td>
</tr>
<tr>
<td>All North Sea data</td>
<td>$52^\circ$</td>
<td>0.20</td>
<td>$52^\circ$</td>
</tr>
<tr>
<td>All chalk data</td>
<td>$52^\circ$</td>
<td>0.38</td>
<td>$52^\circ$</td>
</tr>
<tr>
<td>Top Rotliegend</td>
<td>$32^\circ$</td>
<td>0.40</td>
<td>$32^\circ$</td>
</tr>
</tbody>
</table>

Stereonets are lower hemisphere, equal-area projections with North at the top of the circle.

Gartrell and Lisk (2005) have published paleostress results based on 3D seismic data from the Neogene deposits of the Timor Sea. They unfolded horizons to remove ductile deformation effects and bed rotations, after which both the flatted hangingwall and footwall horizons were restored to a specified level. In a following step, a rigid body translation was used for the restoration of the remaining...
horizontal separation. This two-stepped approach does not differ much from the restoration used in this work. However, the flexural slip unfolding might introduce errors during restoration, especially at fault tips and relay ramps, and when fold axes are non-parallel (Gartrell and Lisk, 2005). This unfolding step was not part of this study as horizons within all studied fault blocks were almost horizontal.

It is important to discuss the effect of errors in slip direction determination from seismic data. Although interpretation uncertainties are more than compensated by the large volume of structural data available for the study, individual determinations are less accurate than those measured in the field using slickensides. Therefore, we carried out a Monte Carlo analysis with the slip direction in three datasets. We introduced normally distributed errors with a standard deviation of 2°, 9° and 20° in a set of 20 randomly selected faults from the present data set, as well as a homogeneous set of fault measurements based on field data from the Mammendorf Quarry (Southern Inverted Margin of the Southern Permian Basin, Germany, Sippel et al., 2008-this issue) and an artificial dataset from Shan et al. (2003). The slip vector was rotated around the normal vector of the fault surface. This way, 50 modified datasets were prepared for every combination of data source and standard deviation. Results show that with increasing standard deviation of the introduced errors, the NDA method produced results where the average orientations of the principle stresses and the stress ratio remained roughly constant, but the variance increased significantly with increasing standard deviation. Using the same data with DSI produced similar results but with an even higher variance. For about 5% of the Mammendorf results and 10% of the data set of this study, a completely different stress tensor was calculated, which did not fit the observed faults. We believe this results from the least squares criterion based calculation of the DSL, where outliers strongly influence the result. This might also be the reason why the DSL method did not produce internally consistent tensors in this study.

Discussions of the validity of the basic paleostress assumptions by e.g. Dupin et al. (1993), Pollard et al. (1993) and Gapais et al. (2000) focus on outcrop scale studies. It is reasonable to assume that the data in NW Europe, two different kinds of stress fields are generally recognized for the Mesozoic-Cenozoic (Bergerat and Geyssant, 1983; Bergerat, 1987; Bles et al., 1989; Hibsch et al., 1995; Vandycke, 2002); an extensional stress field, interrupted by short, compressional stress states associated with the Alpine tectonic phases. Numerical modeling has shown that the present-day stress field of NW Europe is the result of the combined forces exerted by the European-African collision and ridge push at the Mid Atlantic Ridge (Gruenthal and Stromeyer, 1994, Gölke and Coblenz, 1996). When comparing the temporally closely spaced, but tectonically very different, extensional and inversion stress fields for the Cretaceous (Vandycke, 2002), it is common to find the maximum horizontal compressive stress (σ3) to have the same orientation (see also Fig. 7). This can be explained by that the stress ellipsoid during the Cretaceous is almost purely constrictional (σ1 < σ2 < σ3, and σ3 is horizontal, oriented NW–SE) so that small changes in the horizontal stress σ3 result in a switch or permutation (sensu Larroque and Laurant, 1988) in the principle stress directions. These changes might result from a variation in the contributions of tectonic forces and ridge push on the stress field of NW Europe. Our Cretaceous paleostress results show values of R of roughly 0.4, more representing a stress state with σ1 > σ2 > σ3. The fact that we do not find R values supporting this model might be explained by the inherent uncertainty in slip direction determination, as suggested by our Monte Carlo analysis.

8. Geology

8.1. Rotliegend

Hibsch et al. (1995) and Bles et al. (1989) describe an earliest Zechstein N–S extension in the UK and France. However, the coeval faulting of ZZ Basal Anhydrite member and the Top Rotliegend Horizon shows that the oldest tectonic phase interpreted in the Groningen dataset did not start before the Mid Zechstein, but its upper limit is not well constrained. A thickness analysis between the Top Rotliegend and the ZZ Anhydrite reflectors shows that the E–W trending faults in the survey were not active between the depositions of these strata (Table 2). Paleostress data from Southern Germany, Southern France (Reicherter et al., 2008 and references cited therein), and the UK (Hibsch et al., 1995) (Fig. 7) shows that the late Triassic to Jurassic stress field is described by a vertical σ1 and a NW–SE oriented σ2 (since σ1 is vertical, σ2 is equal to the maximum horizontal compressive stress, σh). The paleoextension of the Top Rotliegend horizon in this study is therefore interpreted to represent Triassic extension (Fig. 7). Lohr (2007) published a paleoextension state based on 3D seismic data from the Aller Lineament with comparable orientation.

8.2. Late Cretaceous

As mentioned above, the tectonic state during the Cretaceous in NW Europe was characterized by prolonged extensional periods that were interrupted periodically by strike-slip/compressional events (Vandycke, 2002). Paleostress results from Sussex and Kent (UK), Boulonnais (N France) and the Mons Basin (Belgium) showed E–W to NW–SE extension (Vandycke, 2002), very similar to the results of the present study. The studied Upper Cretaceous Chalk reflectors are below the Subhercynian unconformity (see Fig. 7) but no evidence is found for tectonic inversion or fault reactivation within the seismic volume. Vandycke (2002) and De Jager (2003) showed furthermore that the effects of inversion events in the Upper Cretaceous were restricted to a few areas, while others experienced continued deposition. Effects of the Subhercynian inversion phase are only documented in Kent and Boulonnais, while in the other studied areas E–W to NW–SE extension prevailed (Fig. 7). In Sussex, Kent and Boulonnais, Vandycke (2002) did not observe any effects of Laramide inversion. During the Jurassic and Early Cretaceous, the stress field in Southern Germany and France was controlled by rifting in the Central Atlantic (Ziegler, 1982). Rifting in the South Atlantic and building of the Pyrenees began during the Late Cretaceous (Ziegler, 1982). These events corresponded to a stress field with a vertical σ1 and an N–S oriented σ3 that rotated to a NW–SE σh and shifted from extension to compression (Bergerat, 1987; Bergerat and Geyssant, 1983; Hibsch et al., 1995; Reicherter et al., 2008) (Fig. 7). Note that the σh from this study corresponds both to the pre-Laramide extension as published by Vandycke (2002) for the Mons Basin, Kent, Boulonnais and Sussex, as well as to the S3H of the Laramide inversion phase in the Mons Basin, although the tectonic setting of the later is completely different.

8.3. Tertiary

The Brussels Sandstone (52 Ma) paleostress shows a near E–W extensional stress field, very similar to the Late Paleogene extensional
deformation observed by Vandycke (2002) (Fig. 7). In Sussex and the Isle of Wright, coeval strike-slip and thrust tectonics are respectively described by Vandycke (2002), with a N–S oriented compression direction. Also Hibsch et al. (1995) published “Post-Paleocene” N–S-oriented thrusting in England and Wales. Hibsch et al. (1995) describe a W–E stress permutation is observed in Europe, during the Late Paleogene. This transition with N–S thrust/strike-slip deformation to the west and E–W extensional faulting to the east runs roughly N–S through France. The Groningen area was on the extensional side of this pan-European trend, as only extension is observed here. In this study we have no evidence that the reconstructed North Sea Group horizons were subject to the documented major inversion; however, minor depositional gaps are observed between the different North Sea Groups in Groningen (Duin et al., 2006).

The start of the neotectonic period for central and northern Europe is estimated to have occurred around 10 Ma (e.g. Becker, 1993; Van Balen et al., 2005). The Base Upper North Sea Group was deposited around 19 Ma (Van Adrichem-Boogaert and Kouwe, 1993–1997). Despite the obvious gap between the deposition of this horizon and the start of the Neotectonic period, we have compared the paleostress result of the Base Upper North Sea with the present-day stress field, as published in the World Stress Map (WSM, Reinecker et al., 2005, Fig. 8). Becker (1993) notes that the onset of the Neotectonic period is not strict but a range. The line symbols in Fig. 8 represent the orientation of the maximum horizontal compressive stress ($S_H$). Since in our study $\sigma_1$ is observed to be near vertical, we assume the orientation of $\sigma_2$ to be parallel to $S_H$. The general present-day stress trend for the Netherlands is an NW–SE $S_H$. In the north of the Dutch offshore (Central Graben area) the $S_H$ is oriented roughly E–W, as well as in parts of the southern Netherlands and Belgium. These different stress orientations might result from stress deflections around the London Brabant Massif and the Central Graben (Gruenthal and Stromeyer, 1994). The data from this study are quite similar to the general trend of the neotectonic data of the WSM (Reinecker et al.

Fig. 7. General overview of the stratigraphy in the Netherlands, including the tectonic phases (based on Van Adrichem-Boogaert and Kouwe, 1993–1997; Duin et al., 2006) and the paleostress results of this study, compared with outcrop-based data from (1) Vandycke (2002) and (2) Bergerat (1987), Bles et al. (1989), Becker (1993), and Reicherter et al. (2008). The general consistence of subsurface-based stress reconstruction and surface data emphasizes the value of detailed 3D seismic structural analysis in areas lacking rock exposure.
2005) in the Netherlands. However, the WSM data point closest to the study area (Lauwerszee Trough, Fig. 8) shows a NE–SW oriented maximum horizontal stress ($S_H$). This data point is clearly an outlier if compared to the general regional trend. This data point is located between the Lauwerszee Trough bounding faults, and local stress deviations often occur over faults (Dupin et al., 1993; Pollard et al., 1993; Gapais et al., 2000).

Vandycke (2002) showed that for 6 locations in the southern UK, France and Belgium, extension NE–SW extension dominated during the Quaternary (equal to the minimum horizontal stress, $\sigma_h$). This trend fits very well with the observed NW–SE $\sigma_H$ from the Upper North Sea Group studied in this study. Furthermore, based on borehole hydraulic fractures, Friksen (1999) shows that the present-day maximum compressive horizontal stress ($\sigma_H$) from the Friesland platform (roughly 60 km to the west of the Groningen area, Fig. 8) is oriented at 152°. This measure is a 7° clockwise deviation with respect to the $\sigma_H$ of the Base Upper North Sea horizon measured in this study.

A stress permutation is observed in the Late Neogene stress axes in Fig. 7 and the European present-day stress maps (www.wsm.physik.uni-karlsruhe.de, Reinecker et al., 2005). While this study and Vandycke (2002) calculate a normal faulting stress state in Groningen and Belgium, France and the UK. The stress state described by Reicherter et al., 2008, based on e.g. Bergerat and Geyssant, 1983; Bergerat, 1987; Becker, 1993) is a strike slip stress tensor, with a similar maximum horizontal stress ($\sigma_H$). This stress tensor is based on field observations in the south of Europe, close to the African Indentor. Further north, the strike slip fault setting changes into normal faulting, while maintaining a NW–SE oriented $S_H$ (see also Gruenthal and Stromeyer, 1994).

8.4. The lack of tectonic inversion on the study area

In the study area, no tectonic, fault-related effects for Meso- and Cenozoic inversion phases are observed in the data. Erosional features represented by reflector truncations are present, showing that these features are not related to tectonic inversion.

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Fig. 8. Data from the World Stress Map compared to results of this study and data from Friksen (1999). Lines represent the orientation of the present-day maximum horizontal compressive stress ($S_H$). Shape of the data point indicates method, point fill indicates tectonic regime (NF=normal faulting; SS=strike slip; TF=Thrust faulting; U=undefined). Modified from Reinecker et al. (2005).

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phases did affect the study area. As discussed by Stäuble and Milius (1970), Van Wijhe (1987) and De Jager (2003), the bulk of the Tertiary and Cretaceous inversion events are found in the West Netherlands Basin, Lower Saxony Basin and Central Netherlands Basin, the Broad Fourteens Basin and Dutch Central Graben, and to a lesser degree in the basins surrounding the Groningen area. In other areas deposition continued. The Groningen Block was predominantly uplifted as homogenous rigid block, and only slightly eroded, but the faults within the Groningen Block were not reactivated. With the exception of erosional features, the post-Zechstein deposits of the studied region of the Groningen Block exhibits only deformation related to extensional events during the Upper Cretaceous and Tertiary.

8.5. Salt

Van Balen et al. (2005) points out that in the northern and eastern Netherlands most of the faults are associated with salt movements. In this NW-Groningen case study there is also a clear link between the Top Zechstein topography and the general fault locations and orientations. Many of the faults detected are located directly above the faults formed.

In this NW-Groningen case study there is also a clear link between the orientations. Many of the faults detected are located directly above the faults formed. The Groningen Block was predominantly uplifted as homogenous rigid block, and only slightly eroded, but the faults within the Groningen Block were not reactivated. With the exception of erosional features, the post-Zechstein deposits of the studied region of the Groningen Block exhibits only deformation related to exten- sional events during the Upper Cretaceous and Tertiary.

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