Magnetic Anomaly Interpretation of the North German Basin: Results from Depth Estimation and 2D-Modeling

Bachelor of Science Thesis

by

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This is a modified version of the original report.

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Abstract

This guided research project demonstrates and reconstructs the occurrence of magnetic minerals within Cretaceous sediments of the North German Basin. The analysis of an aeromagnetic survey covering large parts of Lower Saxony revealed the existence of a Lower Cretaceous high susceptibility horizon within the lower Albian or Aptian. The magnetic sources surrounding a salt diapir in the area of Hannover must reside within shallow sediments, as their wavelength is comparatively small. The depth estimation results obtained by the 3D Euler method in combination with the seismic interpretation locate the high susceptibility source horizon within Lower Albian or Aptian sediments. With a high susceptibility layer of 150 μegs in the lower Albian, we could reconstruct the magnetic profile across the mentioned salt diapir in a North-South as well as in a West-East model. A linear trend of short-wavelength anomalies running in a WNW-ESE direction through the whole survey area follows in most parts the outcropping Albian or Aptian sediments underlying the Upper Cretaceous. This suggests a continuous occurrence of magnetic material within the Lower Cretaceous along the northern margin of the Lower Saxony Basin.

Additionally it was shown that numerous linear, short wavelength anomalies can be correlated with fault structures suggesting a susceptibility contrast within the displaced shallow sediments. Most of the low susceptibility salt structures are also present in the magnetic signature and partly rimmed with magnetic anomalies caused by the inclination of the magnetization carrying sediments. The application of 3D Euler deconvolution to the Bramsche anomaly yielded depth estimates between 5.5 and 7 km, confirming the scenario of an igneous intrusive body at approximately 6 km depth.

The analysis and the subsequent 2D modeling could proof the general potential of aeromagnetic data to improve the outline of the contact zone between the sedimentary strata and intrusive salt bodies, given a susceptibility contrast within the sediments.
Bachelor Thesis on Magnetic Anomalies

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1 Introduction

Aeromagnetic data allow fast coverage of large and inaccessible areas for subsurface reconnaissante, which makes magnetic data analysis an essential tool of geophysical exploration. In general, magnetic surveying is used in many different studies targeting all kinds of objects from kimberlite pipes to unexploded ordnance. Magnetic anomaly studies in Germany have mainly been interpreting large scale subsurface structures with high magnetic susceptibility such as volcanic intrusions. As long wavelength anomalies are caused by igneous, iron-rich rocks, they can well be resolved and interpreted in magnetic surveys. Numerous magnetic anomaly interpretations have used this characteristic for location and depth estimation of these mostly intrusive bodies. Another achievement of magnetic anomaly studies is the confirmation of the theory of geomagnetic polarity reversals and ocean spreading. The observed lineation of magnetic anomalies parallel to ocean spreading zones is caused by the remanent magnetization of oceanic crust. On the other hand, high resolution magnetic surveys are also applicable for short wavelength analysis, which can reveal fault structures in the sediments, though they have a significantly lower susceptibility than basement rocks. Many countries, including Great Britain and Canada, have already been covered by high-sensitivity aeromagnetic surveys. In Germany however, a high-resolution aeromagnetic survey covering the whole country has not been conducted yet. The aeromagnetic survey analyzed in this report is one of the largest existing within Germany.

In March 2008, RWE Dea AG bought a license for the use of a high resolution aeromagnetic dataset of Lower Saxony, Germany, which had been acquired by Sanders Geophysics Limited, Canada, in the years 2004 and 2005. The survey area covers most of Lower Saxony including well-known, large-scale anomalies such as the Bramsche Anomaly and the Fulda-Celle Minimum. The analysis of the dataset should identify possible magnetic sources within the sediments and verify the gain of additional information for subsurface interpretation by magnetic anomaly investigation. The two objectives of the investigation were the depth estimation of magnetic sources, i.e. their assignment to a specific horizon in the sedimentary sequence, by the application of the 3D Euler method and the 2D modeling of possible scenarios with the GM-SYS software extension, based on the results of the depth estimations.

In November 2008, RWE Dea AG has suggested the realization of the analysis of the aeromagnetic data on the Lower Saxony Basin area within the framework of a guided research project with subsequent presentation of the findings in a Bachelor Thesis. Jacobs University Bremen has been chosen as partner for this Bachelor thesis project and this final report is the successful outcome of the cooperation. Most of the analysis of the magnetic data has been carried out with the analysis tool provided by the software Geosoft Oasis montaj.

A particular emphasis of the analysis was on the area of a salt diapir, north of Hannover. This salt dome, which ascended during the late Jurassic or early Cretaceous, was intensely investigated during the 1930’s on the search for oil. Numerous drillings to depth of up to 2000 meters are placed at the flanks of the salt body, but no petroleum accumulation was encountered in the trap structures formed by the inclined sedimentary layers and the salt. Nowadays the focus of the petroleum exploration industry has shifted towards the occurrence of Permian gas, which resides in much deeper reservoirs. Though the volume of the known reservoirs in the North German Basin is relatively low, exploration activity has been intensified within the last decade. In the area of the salt diapir, the exploration activity comprises the reprocessing of 3D seismic data due to the improvement of the processing techniques and the integration of long-offset recordings and
a gravimetric modeling of the salt dome conducted by TERRASYS (Müller and Krieger, 1999). Both contributed to a more exact interpretation of the outline of the salt dome. The problem is, that the seismic data do not allow for a precise location of the sediment - salt contact zone, as the seismic velocity in salt is higher than in the surrounding sediments. Therefore the objective of the gravimetric modeling and the combination of all data in a 2D model, as presented within this report, is an improvement of the localization of the salt contact outline.

In the following the regional geology in the survey area is shortly summarized and the basic theory of magnetic anomaly interpretation is introduced together with a more detailed discussion of the 3D depth estimation based on Euler deconvolution. Afterwards we will introduce the analyzed and available geophysical datasets and outline their major characteristics. Thereafter the aeromagnetic dataset over Lower Saxony is investigated for anomaly trends with the aid of different derivatives and we will present the depth estimation results by Euler Deconvolution of the Bransche Anomaly. As the results approve the potential of the method, it is applied for a more detailed investigation of the area around the salt dome, which reveals the occurrence of magnetic sources in Lower Cretaceous sediments. In order to test this aspect of the data analysis results, we constructed two models across the salt dome. Finally, the results are assessed and a possible geological scenario to explain the occurrence of magnetic minerals within the Cretaceous is discussed.

2 Regional Geology

The North German Plain is characterized by low topography. The Northern edge is delimited by the coastline of Baltic Sea and the North Sea, which comprises runoff areas of a number of major rivers (Elbe, Weser, Aller, Ems, etc.). In the South, the North German lowland is delineated by the shallow mountain chains of the Weser- and Wiehengebirge and the Harz mountains. Especially the Northwest German Basin as part of the Central European Basin system has been intensively investigated by the petroleum industry during the last century.

According to Walter (2007) the north west German part of the North German Plain is structured in the Niedersächsische Scholle (Lower Saxony block) and the Pompeckjsche Block. Mainly during the Jurassic and the Cretaceous, the area of the Lower Saxony block was an independent sedimentation region. In the Upper Jurassic and Lower Cretaceous, the Lower Saxony block was in large parts covered by a shallow marine sea. The deposition during this period accounts for 2,000 to 3,000 m of sediments. During the Upper Cretaceous and later on during the Paleocene the Lower Saxony block has been subject to inversion, whereas the northern part of the North Germany Basin, including the Pompeckjsche Block is now covered by a thick layer of tertiary and quaternary sediments due to continuous subsidence. During this inversion process, the sediments of the Lower Saxony block were partially thrusted over the Pompeckjsche Block.

The Lower Saxony basin is a 300 km long and 65 km wide Early Jurassic to Late Cretaceous trough, which was spreading over large parts of the area of the Lower Saxony block and marked transgression area of a shallow marine sea. To the south and to the west of the Weser, the edge of the Lower Saxony block is pervaded by the mentioned system of WNW - ESE striking thrust faults. To the east of the Weser, along the Aller river, the border of the Lower Saxony tektogen is marked by a number of linear salt structures parallel to the Aller lineament. In the south the Lower Saxony block is delineated by the Nordwestfälisch-Lippische Schwelle and the Weser- and
Figure 1: The Lower Saxony block (Niedersächsische Scholle) and its delineation by the Pompeckjsche block in the north and the Nordwestfälisch Lippische Scholle in the south, according to Walter (2007). The map describes the occurrence of sediments below the Tertiary.

Wiehengebirge. Figure 1 illustrates the geologic setting of the Lower Saxony Tektogen. During the Permian a WNW-ESE and NNE-SSW trending basement fault system became apparent. Especially the WNW-ESE trending faults are continued within the overlying sediments. Figure 7 shows the fault structures in the basement block pattern after the Geotectonic Atlas of Baldschuhn et al. (1996). During the inversion of the Lower Saxony tectogen, these WNW-ESE striking bundled faults were reactivated as thrust faults.

A general stratigraphic sequence of the sediments of the Lower Saxony basin is given in the appendix in table 6. However not all stratigraphic horizons are continuously present in the North German Basin. The differences in the stratigraphic sequence over Northern Germany are due to a number of inversion and transgression events. The Cretaceous sediments of the North German Basin are mostly marine depositions of a period of high sea-level. There is a distinct facies differences between the Lower and Upper Cretaceous sediments. Whereas the Lower Cretaceous sediments consist mainly of clay and sandstones, the Upper Cretaceous sediments are dominated by carbonates. A comprehensive discussion of the geologic setting of the North German plain can be found in the textbook by Walter (2007).

2.1 Salt Tectonics in Northern Germany

The structural geology of the North German plain is determined by numerous salt structures. During the Zechstein, the North German basin was covered by a shallow sea. In this shallow marine area up to 2.000 m of salt was deposited by evaporation during a prolonged period of
warm, arid climate (Henningsen and Katzung, 2006). The sedimentation of evaporites on the WNW-ESE striking basin margin in NW Germany began in the Upper Rotliegend (Mohr et al., 2005), subsequent deposition of Zechstein salt produced an approximate thickness of at least 800 m (Jaritz, 1973). These evaporites were covered with ensuing sedimentation from Buntsandstein (Triassic) till Tertiary and finally Quaternary.

Rock salt deforms plastically when it is subjected to low compressive or tensile stress. This property in combination with the low density of salt, compared to the overlying sediments, can lead to the rise of salt and finally to the formation of salt domes, which are characteristic for the Northern German Basin. A first movement of salt is described by (Jaritz, 1973) in the middle to late Bunter (Buntsandstein). The peak of the salt diapirism in North Germany was probably at the end of the Late Jurassic and came to an end during the Lower Cretaceous. During the ascent of the salt, the overlying horizontal layer were heavily inclined, furthermore, the rise of salt diapirs was associated with the formation of salt edge basins. The temporal sequence of the rise of the salt can be evaluate by analysis of the structure of the surrounding sedimentary layers. A more complete discussion of the halokinesis in Northern Germany can by found in Jaritz (1973) and a more recent discussion of periods of active salt tectonics based on seismic interpretation is given by Mohr et al. (2005).

2.2 Bramsche Massif

At the transition from the Upper Jurassic to the Lower Cretaceous, a rifting event in the North Atlantic rifting system together with a tectonic setting of low sea level led to a temporary change in sedimentation in Middle and Northwest Europe. Wide ridges of land were rising among them the Rheinische Massif and the sedimentation in the North German plain was limited to small zones subjected to depression (Walter, 2007). In the course of the Lower Cretaceous, the marginal troughs including the Lower Saxony Tektogen underwent enhanced subsidence. Deep-reaching crustal faults enabled the rise of basement volcanic rocks and the intrusion of laccoliths in the North German basin such as the suggested Bramsche Massif north-west of Osnabrück. Furthermore, igneous intrusions of Cretaceous age at Uchte, Vlotho and Neustadt are matter of discussion (Bosum et al., 1995). The Bramsche Massif shows a significant magnetic and gravimetric anomaly (Brink, 2001). Based on the magnetic anomaly an igneous intrusion scenario has been discussed by Hahn and Kind (1971) with an intrusion depth of 5 km. In addition, the Bramsche Massif is associated with a thermal anomaly (Senglaub et al., 2006) and a high maturity area as indicated by vitrinite reflectance (Kus et al., 2005). However there has been vivid discussion of the intrusion scenario and an alternative interpretation of the Bramsche anomaly has been proposed. Brink (2001) compares the Bramsche Anomaly to the anomaly of Pritzwalk and discusses both, an inversion and intrusion scenario. The high thermal maturity might be better explained by an inversion scenario, however the general belief tends to favor an intrusion for which the intrusion depth is still matter of debate. Hahn and Kind (1971) assumed a deep-lying igneous intrusion at more than 5 km, and the refraction seismic measurements show a refractor of high velocity at a depth of approximately 6 km. Senglaub et al. (2006) however argues that a burial by approximately 4 km of now-eroded Cretaceous rocks was revealed by calibrated numerical modeling to be the probable cause for the anomaly.

A more recent publication by Bilgili et al. (2009) tests both scenarios and comes to the result, that the Bouguer anomaly of the Bramsche Massif cannot be modeled without a high-density,
intrusive-like body at depth. [Bilgili et al. (2009)] also applied the 3D Euler Method to the gravity field, finding solutions at depths between 5 and 15 km.

3 Theory

Magnetic anomaly maps provide an insight into subsurface structures, the composition of the Earth’s crust and the distribution of magnetic minerals - primarily magnetite - in the crust. The most universal application of magnetic data has been to detect igneous intrusions and to determine the depth to the top of magnetic sources. The plotting of magnetic anomaly trends preserved by the oceanic crust in the 1950s and 1960s were another indication for the proposed theory of geomagnetic reversals. A more detailed mapping of the symmetric magnetic anomalies about the oceanic ridges revealed the temporal evolution of the oceanic crust. In Mineral exploration depth estimates are usually used to provide the depth of ore bodies, which contain magnetic minerals. In search of diamonds, aeromagnetic surveys are flown to look for kimberlite pipes, which are diamond carrying igneous intrusions.

3.1 Magnetic Anomalies

The gain of information by the application of the magnetic method depends on the contrast in magnetic properties of the types of rock in the survey area. Most common rock-forming minerals exhibit only limited magnetic properties. The magnetic response of rocks is due to the presence of magnetic minerals such as magnetite, pyrrhotite, ilmenite, franklinite and specular hematite. The magnetic properties of rocks arise almost entirely from the widely distributed mineral magnetite.

The fundamental rock parameter in magnetic prospecting is the susceptibility. How easily a body can be magnetized, is determined by its magnetic susceptibility $k$. The magnetic susceptibility $k$ is the proportionality factor, by which the induced intensity of magnetization depends on the strength of the magnetizing force $H$ of the inducing (geomagnetic) field. This proportionality between the magnetization $M$ and the magnetizing field $H$ is expressed by:

$$M = kH$$  \hspace{1cm} (1)

In the SI system the magnetization $M$ and the magnetizing field $H$ are both measured in [A/m]. The susceptibility $k$ is dimensionless, but differs in the c.g.s. system from that in the SI units by the factor $4\pi$:

$$k_{SI} = 4\pi k_{cgs}$$  \hspace{1cm} (2)

Table 2 lists the susceptibility ranges and average values of common rock types. Magnetic susceptibility can vary as much as four to six orders of magnitude. This variation of susceptibility does not only exist between different rock types, but great variations also occur within a given rock type. Basement rocks have usually high susceptibilities due to their high magnetite content (iron), whereas sedimentary rocks have much lower susceptibilities. Metamorphic rocks are
variable in their magnetic character and basic igneous rocks have generally a higher magnetite content than acid igneous rocks. Overall, the magnetic susceptibility of rocks is strongly variable and depends extremely on lithology. In the north German basin, magnetic susceptibility values of sedimentary rocks are in the range of 0-200 \( \mu \) cgs, with 80 \( \mu \) cgs being already a high value. The magnetic properties of sediments are determined by their iron content, though the iron content is not a direct measure of the magnetite content.

The measured parameter of magnetic surveys is the total magnetic field, which is the magnetic induction \( B \) (measured in nT) including the effect of magnetization \( M \). It can be written by consideration of equation \[I\] as:

\[
B = \mu_0 (H + M) = \mu_0 (1 + k) H = \mu \mu_0 H
\]

with \( \mu_0 = 4\pi \times 10^{-7} \) H/m the permeability of free space.

Magnetized matter can be considered as an assortment of microscopic magnetic dipoles which result from the magnetic moments of individual atoms and dipoles. Magnetization \( M \) is defined as volume density of magnetic dipole moments per unit volume (Telford et al., 1990). For the interpretation of magnetic anomalies, there are two main types of magnetization. Induced magnetization, \( M_{\text{ind}} \), is the magnetic response produced by induction of the external applied field. The induced magnetization depends on the susceptibility and the strength of the applied (geomagnetic) field and vanishes, when the external field is switched off (equation \[I\]). Residual magnetism called remanence or remanent magnetization, \( M_{\text{rem}} \), is the inherited, permanent magnetization of a rock, which remains even when the external field is removed (Kearey et al., 2002). When rock forms at high temperature, its magnetic components align with the external applied field and retain this magnetic orientation if the rock cools below the Curie temperature. This is the main type of remanent magnetization, which accounts also for the isochronic magnetic lineation of the ocean’s crust. This thermoremanent magnetization is the main mechanism of residual magnetization of igneous rocks. The total magnetization is the sum of induced and remanent magnetization. In sedimentary rocks, the effect of induced magnetization is generally much more pronounced than the effect of detrital (DRM) or chemical remanent magnetization (CRM). In order to quantify the respective contribution a detailed study of the sedimentary conditions would be necessary.

A thorough discussion of magnetic theory is given in the textbooks by Kearey, Brooks, and Hill (2002); Mussett and Khan (2000); Telford, Geldart, and Sheriff (1990).

### 3.2 Basic Interpretation of Magnetic Anomalies.

Most of the maps of the total magnetic intensity and its derivatives in this report are presented as shaded relief maps to improve the visibility of features. Especially near surface, i.e. small scale anomalies, are better resolved in this type of map. In geophysical analysis of gridded data, derivatives are used to enforce high wavenumber components of the spectrum by suppressing
Table 1: Characteristic magnetic susceptibility values for sedimentary and basement rocks, (After Dobrin and Savit (1988) and Kearey et al. (2002))

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Susceptibility Range [µ cgs]</th>
<th>Average [µ cgs]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sedimentary Rocks:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td>0 - 75</td>
<td>10</td>
</tr>
<tr>
<td>Limestone</td>
<td>0 - 300</td>
<td>25</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0 - 1670</td>
<td>30</td>
</tr>
<tr>
<td>Shale</td>
<td>0 - 1500</td>
<td>50</td>
</tr>
<tr>
<td><strong>Basement Rocks:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metamorphic</td>
<td>0 - 5800</td>
<td>350</td>
</tr>
<tr>
<td>Acid igneous</td>
<td>0 - 6500</td>
<td>650</td>
</tr>
<tr>
<td>Basic igneous</td>
<td>40 - 10000</td>
<td>2600</td>
</tr>
</tbody>
</table>

Deep-seated long wavelength anomalies. The visibility of these high wavenumber components can even be increased by higher-order derivatives. However, due to limitation of significance, usually only the first vertical (FVD) and the second vertical derivative (SVD) are applied. In addition to vertical derivatives, a variety of functions is used as tools to locate and interpret magnetic anomalies.

The Analytic Signal is expressed as:

$$\text{AS}(x,y) = \sqrt{\left(\frac{\delta T}{\delta x}\right)^2 + \left(\frac{\delta T}{\delta y}\right)^2 + \left(\frac{\delta T}{\delta z}\right)^2}$$  \hspace{1cm} (4)

with $T$ the measured field. This artificial parameter is completely independent of the direction of magnetization and the direction of the inducing field and therefore very helpful and interesting in the context of interpretation (Riedel, 2008). The analytic signal is used to locate the edges of magnetic source bodies, particularly where remanence and low magnetic latitude complicate interpretation. A map of the analytic signal over Lower Saxony is given in figure 22 in the appendix. Another tool suitable enhancing the mapping of shallow structures is the so called tilt derivative, which is defined as:

$$TDR = \arctan\left(\frac{VDR}{THDR}\right)$$  \hspace{1cm} (5)

where VDR and THDR are the first vertical and total horizontal derivatives of the total magnetic intensity $T$:

$$VDR = \frac{\delta T}{\delta z}$$  \hspace{1cm} (6)

$$THDR = \sqrt{\left(\frac{\delta T}{\delta x}\right)^2 + \left(\frac{\delta T}{\delta y}\right)^2}$$  \hspace{1cm} (7)

A complete discussion of magnetic filtering techniques based on the common Fourier domain filters for gridded data is given in the Geosoft tutorial by Whitehead and Musselman (2007).
3.3 Depth Estimation by 3D Euler Deconvolution

The objective of the 3D Euler deconvolution process is to produce a map showing the locations and the corresponding depth estimations of geologic sources of magnetic or gravimetric anomalies in a two-dimensional grid (Reid, 1990).

The Standard 3D Euler method is based on Euler’s homogeneity equation, which relates the potential field (magnetic or gravity) and its gradient components to the location of the sources, by the degree of homogeneity \( N \), which can be interpreted as a structural index (Thompson, 1982). The method makes use of a structural index in addition to producing depth estimates. In combination, the structural index and the depth estimates have the potential to identify and calculate depth estimates for a variety of geologic structures such as faults, magnetic contacts, dykes, sills, etc. The algorithm uses a least squares method to solve Euler’s equation simultaneously for each grid position within a sub-grid (window). A square window of predefined dimensions (number of grid cells) is moved over the grid along each row. At each grid point a system of equations is solved, from which the four unknowns \((x, y\) as location in the grid, \(z\) as depth estimation and the background value) and their uncertainties (standard deviation) are obtained for a given structural index. A solution is only recorded if the depth uncertainty of the calculated depth estimate is less than a specified threshold and the location of the solution is within a limiting distance from the center of the data window (Whitehead and Musselman, 2008).

Thompson (1982) showed that for any homogenous, three-dimensional function \( f(x, y, z) \) of degree \( n \):

\[
f(tx, ty, tz) = t^n f(x, y, z) \tag{8}
\]

it can be shown that, the following equation, which is known as Euler’s homogeneity relation can be satisfied:

\[
x \frac{\delta f}{\delta x} + y \frac{\delta f}{\delta y} + z \frac{\delta f}{\delta z} = nf \tag{9}
\]

In geophysics, the function \( f(x, y, z) \) can have the general functional form:

\[
f(x, y, z) = \frac{G}{r^N} \tag{10}
\]

where \( r^2 = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \), \( N \) a real number (1,2,3,...) and \( G \) a constant (independent of \( x,y,z \)). Many simple point magnetic sources can be described by equation (10) with \((x_0, y_0, z_0)\) the position of the source whose field \( F \) is measured. The parameter \( N \) is dependent on the source geometry, a measure of the fall-off rate of the field and may be interpreted as the structural index (SI). Clearly equation (10) is homogeneous and thus \( N \) is equivalent to \(-n\) in Euler’s equation (9).

Considering potential field data, Euler’s equation can be written as:
Table 2: Structural Indices for simple magnetic and gravity models used for depth estimations by Euler Deconvolution. The number of infinite dimensions describes the extension of the geologic model in space.

<table>
<thead>
<tr>
<th>Geologic Model</th>
<th>number of infinite dimensions</th>
<th>magnetic SI</th>
<th>gravity SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>sphere</td>
<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>pipe</td>
<td>1 (z)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>horizontal cylinder</td>
<td>1 (x-y)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>dyke</td>
<td>2 (z and x-y)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>sill</td>
<td>2 (x and y)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>contact</td>
<td>3 (x,y,z)</td>
<td>0</td>
<td>NA</td>
</tr>
</tbody>
</table>

with $B$ the regional value of the total magnetic field and $(x_0, y_0, z_0)$ the position of the magnetic source, which produces the total field $T$ measured at $(x, y, z)$.

(Tompson 1982) showed that simple magnetic and gravimetric models are consistent with Euler's homogeneity equation. Thus Euler Deconvolution provides an excellent tool for providing good depth estimations and locations of various sources in a given area, assuming that appropriate parameter selections are made. Applied to aeromagnetic surveys, the 3D Euler process is a fast method for obtaining depth and boundary solutions of magnetic sources for large areas.

Though it is a general advantage of the Euler Deconvolution method, that it is applicable to all geologic models and that it is insensitive to magnetic remanence and geomagnetic inclination and declination, an initial assumption of the source type has to be made. Dependent upon the potential source type, a structural index is chosen. This structural index is also a measure of the distinctive fall-off rate of the geologic feature. For example, the best results for a contact are obtained by structural indices of 0 to 0.5, while for thin two-dimensional dyke structures a structural index of 1 yields the best estimates. Table 2 summarizes the structural indices (SI) for given geologic models, which proved to provide the best results.

The significance of the location and depth estimates obtained by 3D Euler Deconvolution is given by the specificity of the chosen parameters like the grid cell size, window size, structural index, chosen depth uncertainty tolerance, etc. The selection of the grid cell size should be based on the grid spacing and the wavelength of the anomalies to be analyzed, as the software Geosoft Oasis montaj allows a square window size of up to 20 grid cell units. If the wavelengths of the anomalies are significantly longer or shorter than the window size, the 3D Euler method does not yield appropriate results. On the other hand, the limiting distance from the centre of the algorithm window, in which solutions are still recorded, should be chosen with respect to the wavelength of potential anomalies. In general, 3D Euler Deconvolution yields results for each window position, therefore it is necessary to eliminate solutions with high uncertainties.

A reliable tool for the limitation of results is the specification of a threshold value for depth and horizontal uncertainties. Geosoft Oasis montaj reports the depth and location uncertainties as percentage of the depth below the recording sensor position. As matter of principle, low SI values are associated with source bodies which give rise to low gradients, thus depth estimation...
solutions with low SI values have high uncertainties. The data quality determines the general level of uncertainty, so an examination of the recorded solutions will define the selection criteria. The consideration of appropriate solutions should be guided by two aspects. On the one hand, the position (and depth) anomalies should be kept low to improve the accuracy of the computations, on the other hand a sufficient number of solutions must be retained in order to delineate geologic features sought and provide meaningful solutions.

The results of the Euler method are displayed in ordinary maps as point solutions combining the location (position of solution) and the depth (colour range). Given the choice of an appropriate structural index, 3D Euler Deconvolution will lead to a clustering of solutions, which can be interpreted. A vertical pipe structure will for example be shown as a cluster of solutions around a specific point, whereas an elongated dyke structure, will be recognized as a linear trend of solutions.

Another approach to limit the solutions obtained by the Euler method, is the Located Euler 3D method, which, unlike the Standard Euler method, tests and limits grid locations before calculating depth estimations by Euler deconvolution. The Located Euler method calculates the analytic signal and finds peaks in the analytic signal grid. The normal depth estimation by Euler Deconvolution is then only applied to these peak locations. As this method however produces far fewer solutions than the Standard Euler method, it is only applicable for very prominent anomalies and does not yield solution clusters.

\[
ASig = \sqrt{(dx \cdot dx) + (dy \cdot dy) + (dz \cdot dz)}
\] (12)

A more thorough discussion of the discussed 3D Euler Deconvolution method is given by Reid (1990); a new approach to combine Euler Deconvolution and Werner deconvolution in the Extended Euler Deconvolution algorithm is reported by Nabighian and Hansen (2001).
4 Data

4.1 Aeromagnetic Surveys

Aeromagnetic surveys are flown with aircrafts equipped with cesium magnetometer sensors which are placed in tail stingers, that are sticking out behind the empennage of the aircraft. Cesium magnetometers are so-called optically pumped magnetometers, which allow for high recording frequency and for measurements of magnetic field variations as small as 0.01 nT (Telford et al., 1990). The development of airborne anomaly detectors was boosted during World War II, as they were used for submarine detection. The aircrafts have normally reduced iron components such as aluminum wings, etc., which are only slightly influencing the magnetic field measurements. In rough topography areas for high-resolution aeromagnetic surveys, which are flown in a height of only a few hundred meters, helicopters with a towed magnetometer are also used.

For the recording of the magnetic field data, the aircrafts are flying in a grid-like flight pattern with constant flight-line orientation, usually perpendicular to the regional geological strike and with constant line spacing. The flying height, i.e. the distance from the magnetic sources, and the line spacing determine the resolution of the survey. Continuous recording of GPS positional data and the height by radio and barometric altimeters guarantee for constant elevation and post-mission data referencing. A stationary ground magnetometer, whose exact position is known, is used for correction of slowly varying diurnal effects. Usually large magnetic variations of magnetic storms are not corrected, as magnetic recording is stopped during such magnetic events.

The main advantage of airborne surveying is the fast and low cost data collection over large and even inaccessible areas. The speed of the aircrafts decreases the effects of time variations of the magnetic field and flight elevation and grid spacing can easily be chosen to favor the geologic structures in the survey area. However, magnetic surveys are generally susceptible to interference from cultural features such as steel pipes, artificial waterways with steel piled walls and other infrastructure.

4.2 Aeromagnetic Dataset over Lower Saxony

During the months of December 2004 and January 2005, Sander Geophysics Limited (SGL) conducted a high-sensitivity aeromagnetic survey over northwest Germany. A license for the use of this aeromagnetic dataset was acquired by RWE Dea AG, Hamburg, in 2008. The analysis of this dataset was the vital objective of this Bachelor Thesis and the preceding Guided Research.

4.2.1 Survey Area

The survey area, as given in figure 2, extends approximately 325 km in an east-west direction and 125 km in the north-south direction and covers Lower Saxony in large part. The survey block includes a small part of the Netherlands in the Northwest corner and many urban, built-up areas among them the cities Hannover, Bremen, Celle, Osnabrück, Minden, Braunschweig and Münster. The relief within the survey block, consisting of large agricultural areas and low forested hills(Weser- and Wiehengebirge) is gentle, with the exception of the Harz Mountains in the southeast. The rivers Weser, Aller and Ems are crossing the survey block and a few small
lakes are scattered throughout the block. The survey area is pervaded by a significant number of transportation infrastructure such as highways, railway lines and waterways including the Mittellandkanal, which crosses the survey block in an east-west direction.

4.2.2 Data Recording & Processing

The aeromagnetic survey over Lower Saxony was performed with two Cessna 208B Grand Caravan and one Cessna 404 Titan aircrafts by Sander Geophysics Limited (SGL). The flying speed of the survey flights was indicated between 150 knots and 170 knots respectively. A total of 44 production flights were conducted, during which a total of 40,008 line kilometers were flown. The survey was flown at a height of 320 m above ground level using a drape surface. The traverse line were flown in an orientation of 170° and with a line spacing of 1 km, the control lines spacing was 3 km and oriented at 80°. The grid-like flight pattern of the survey is illustrated in figure 2.

During the course of the survey a number of parameters were recorded. The aircraft altitude was measured by the barometric altimeter and terrain clearance was provided by radar altimeter at intervals of 0.25 s. The GPS positional data of the aircraft and of the ground station was recorded.
Table 3: Geomagnetic Field Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Strength</td>
<td>48852 nT</td>
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<tr>
<td>Inclination</td>
<td>67.235°</td>
</tr>
<tr>
<td>Declination</td>
<td>0.948°</td>
</tr>
</tbody>
</table>

The airborne magnetometer data were recorded at 10 Hz and the recording frequency of the ground total magnetic field measurements was 2 Hz. The survey flights were subject to technical flight specifications in order to ensure the quality of the data. The influence of the aircraft on the magnetic field recording was tested in a number of aircraft manoeuvres (pitching, rolling, yawing of the aircraft) at high altitude over magnetically quiet areas and appropriate compensation was applied. Differential correction was applied to the position of the ground station. These corrected positional data of the ground station were then used for post-mission differential corrections of all survey flights. The field parameters of the geomagnetic field in the survey area are listed in Table 3.

The data processing including editing, filtering, quality control and final processing was performed by SGL (Bates and Rucareanu, 2004). Diurnal variations in the airborne magnetometer data were corrected by subtraction of the filtered and IGRF corrected ground station data. In a next step, the magnetic data were IGRF corrected using the IGRF 2000 model. After the diurnal and IGRF correction, a levelling procedure was applied to account for a number of effects including data differences at intersections of control and traverse line recordings. The final data products were interpolated onto a regular grid. Furthermore a cultural editing was applied to the total magnetic intensity (TMI) grid provided by SGL to correct for rough effects due to interference from substantial infrastructure in the area. The data required from Sanders Geophysics Limited include a table containing all recorded and levelled data and two grid files of the Residual Total Magnetic Intensity in nT and of the First Vertical Derivative. All grids are referred to the WGS-84 datum in the Universal Transverse Mercator (UTM) projection zone 32 North. The supplied Total Magnetic Intensity grid served as the basis for most of the applied interpretation methods. Figure 3 shows the total magnetic intensity grid after reduction to the pole.

More details of the instrument setup, the flight specifications and recordings and the data processing can be found in the technical report (Bates and Rucareanu, 2004) provided by Sanders Geophysics Limited together with the dataset.

4.2.3 Total Magnetic Intensity Map

The total magnetic intensity grid provided by Sanders Geophysics Limited was reduced to the pole using geomagnetic field values given as in Table 3. The survey area is characterized by a number of major long wavelength anomalies and linear short wavelength anomalies mainly in the central part of the survey area. The negative anomaly of up to -60 nT on the lower eastern edge of the map is part of the so-called Fulda-Celle minimum and has been described by Bosum et al. (1995) before. As the name already tells, this NNE trending anomaly extends from Fulda in the south to Celle in the north and shows the highest amplitude in the north eastern part (Bosum et al., 1995). The whole trend of the anomaly is clearly visible in the EMAG2 total magnetic intensity map in Figure 4. The anomaly with the highest amplitude of 140 nT is situated north...
Figure 3: Total magnetic intensity map of the survey area over Lower Saxony. The magnetic anomaly data is reduced to the pole.
of Osnabrück and is caused by the Bramsche Massif for which an inversion and an intrusion scenario are discussed as pointed out in section 2.2. The positive anomaly at Oldenburg has been described as Oldenburg High by Wonik (1992). The Oldenburg High has a roundish shape and a maximal amplitude of 55 nT. The positive anomaly in the north-east (100 nT) is a branch of a positive magnetic anomaly north of Hamburg with high amplitude of up to 250 nT. The positive anomaly at the south eastern corner of the dataset is caused by the rocks of the Harz mountains. The north-south trending positive anomaly in the western part of the survey has not been matter of thorough investigation yet. For the magnetic anomaly north-west of Hannover at Nienburg (Weser) an amplitude of 40 nT was recorded. This anomaly could also be caused by an intrusion, as investigations in the area showed a high thermal maturity. The intrusion scenarios discussed for Uchte, Vlotho and Neustadt am Rübenberge (Bosum et al., 1995) could not be identified as magnetic anomalies, though all locations lie within regions of positive anomalies. Compared to other regions with significantly higher amplitude anomalies in northern Europe, the survey area is largely magnetically calm.

4.3 EMAG2: Earth Magnetic Anomaly Grid

EMAG2 is a magnetic anomaly grid of the magnetic intensity at an altitude of 4 km above mean sea level with a global 2-arc-minute resolution. The EMAG2 dataset was compiled from satellite (CHAMP), marine, aeromagnetic and ground magnetic surveys Maus (2009). The EMAG2 is a significant update compared to the first global magnetic anomaly grid, EMAG3. The name reflects the improvement of the resolution from 3 arc minutes to 2 arc minutes. The altitude has also been reduced from 5 km to 4 km above geoid. An extensive description of the compilation and processing of the EMAG2 dataset is given by Maus et al. (2008).

The EMAG2 anomaly grid allows for recognition of characteristic magnetic anomalies. Parallel trending anomalies to isochrons of the ocean crust can be observed as well as various anomalies caused by formation of continental crust, large scale volcanism or massive iron ore accumulation (Kursk Magnetic Anomaly, Russia). The EMAG2 dataset is available from the internet as an ASCII grid of the total magnetic intensity at 4 km above the WGS84 ellipsoid. This dataset was gridded for the area of Northern Germany and shows the continuation of the later discussed magnetic anomalies beyond the edges of the aeromagnetic survey of Lower Saxony. An extract of the EMAG2 dataset over Northern Germany is given in figure 4.

4.4 Bouguer Gravimetric Survey & Modeling

In order to improve the subsurface model suggested by the seismic data, a gravimetric survey was performed in an area of approximately 725 km$^2$ between Celle in the east and Schwarmstedt in the West. The point distance was 375 m (7.1 measurement points per km$^2$). In order to improve the resolution in the area around the salt diapir, an additional number of gravimetric measurements were conducted, such that in the end 25 measurements per km$^2$ had been recorded close to the salt structure. An extract of this gravimetric dataset above the salt diapir is shown in figure 5. For the correct positional referencing of gravimetric measurements, GPS positional data were recorded at each measurement point. A topographic correction to mean sea level as well as a latitudinal correction were applied to the data. A complete description of the measurements procedure and the data processing can be found in the technical report by Seidemann (1999).
Figure 4: Total Magnetic Intensity Grid over Northern Germany based on the EMAG2 dataset. The black rectangle outlines the area of the aeromagnetic survey performed over Lower Saxony.
Figure 5: Bouguer Gravity data from survey of Salt Diapir. The blue line defines the outline of the caprock of the salt diapir. The negative anomaly caused by the salt dome in the centre is clearly visible. The negative anomaly in the north-east is caused by a nearby salt structure. Bouguer gravimetric values are given in mGal.

Figure 5 shows the negative anomaly caused by the salt diapir in the centre. The thin blue line marks the outline of the caprock, which extends further towards the sides, especially towards the south, than the deeper, narrower column of the salt structure. The negative anomaly in the Northern edge of the map is caused by another salt intrusion. From refraction seismic measurements most of the salt structures in Northern Germany are mapped. As suggested by the seismic data there is a flat salt pillow extending in a western direction from the salt diapir. The orientation of this salt pillow is given by the negative anomaly on the western side of the salt diapir in figure 5.

Based on this gravimetric survey, a 3D gravity modeling of the salt diapir was performed by Terrasys in 1999 (Müller and Krieger, 1999) with the objective to investigate the near-surface geometry of the salt diapir in detail. The focus was on the resolution of the geometry and the depth of the top and base of the anhydrite caprock.
4.5 3D Seismic Data

Seismic data acquisition in the concession area around Celle including the salt diapir has been conducted during two surveys. From July to September 1995 one survey and during the months of October 1998 to February 1999 another long offset seismic survey were carried out. A final seismic bin with a line inline and crossline distance of 25 meters was produced. The salt dome discussed in this report is situated in the South-Western edge of the acquisition area and thus seismic data covering the flanks of the salt dome are available.

In the period from 2006 to 2008 a reprocessing of the seismic data was performed by CGG-Veritas. The depth volume is based on a pre-stack depth migration using anisotropy. The applied migration algorithm is a Beam-Migration algorithm (Controlled-Beam-Migration). Stratigraphic depth information of specific horizon from drill hole logging in the area were implemented as constraints for the migration. The creation of an improved velocity model resulted in an interpretation which comes closer to the true geological depths. A comparison of the interpretations
<table>
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Table 4: Stratigraphic Information from drill holes at the flanks of the salt diapir. The depth values are given as measured depth (MD). A is located on the northern rim and the drillings B and C are placed on the southern edge. Position coordinates are given for the DHDN datum based on the old and new data processing revealed an uplift of geologic structures closer to the surface. The available dataset shows a particularly good image quality.

Starting from the mapping of sedimentary horizons conducted by [Baldschuhn et al. (1996)](#), a number of horizons were defined and adjusted over the seismic profile. These seismic horizons were used as a basis for the modeling part of this report. In the case of the salt diapir, there is a remarkable thickening of the Lower Cretaceous horizon at the flanks of the salt diapir, that could be interpreted as edge basins in the seismic data and might suggest a rise of the salt structure in the transition period from Jurassic to Cretaceous. Figure 6 shows a 3D cube of the seismic data with an interpreted Lower and Upper Cretaceous horizon (after [Baldschuhn et al. (1996)](#)).

### 4.6 Stratigraphy of drill holes

Beyond the availability of all major geophysical data for the modeling area, numerous drill holes are placed at the flanks of the salt diapir. However, most of the drilling was done in the 1930s on the search for oil at the flanks of salt diapirs and most holes have not been drilled deeper than a few hundred meters. Furthermore stratigraphic information is not available for all drillings. As for the modeling of the magnetic anomaly at the salt diapir, a model of the North-South profile (and a West-East profile) was intended, stratigraphic information from close-by drillings was retrieved. Table 4 summarizes the stratigraphy of the drilling sites A on the northern flank of the salt dome and of the drill holes B and C on the Southern flank of the salt structure. The stratigraphic information from C proved to be particularly helpful, as it contains a depth value for the base of the Albian horizon.
5 Data Analysis

In petroleum exploration, the focus of interest is on sedimentary rocks. However in magnetic anomaly maps, iron rich basement rocks have significantly higher susceptibilities and therefore higher amplitudes than sedimentary rocks. These higher amplitudes outreach magnetic anomalies caused by high susceptibility horizons in the sediments. Therefore their influence is generally reduced by application of high-pass or band-pass filters. In the survey area over Lower Saxony, the long wavelength anomalies have rather low amplitudes compared to the positive anomalies in the North Sea or Denmark of approximately 400 nT and the major negative anomalies seen in figure 4. This already allows to recognize short wavelength anomalies in the total magnetic intensity grid shown in figure 3. A high-pass filtered (10 km) total magnetic intensity grid, which enhances short wavelength anomalies, is attached in the appendix in figure 19. The characteristic structures in the magnetics of the survey area are perspicuously present in the first vertical derivative and the tilt derivative presented in the following sections. The second vertical derivative does not allow the identification of further structures (figure 21).

5.1 Fault Structures as Magnetic Anomalies

Figure 3 shows besides the obvious long-wavelength anomalies linear, short-wavelength anomalies whose visibility is essentially enhanced by the shaded relief image. A further enhancement of the short wavelength trends in the data set is achieved in the first vertical derivative of the reduced to the pole, total magnetic intensity grid, as shown in figure 7. A system of WNW-ESE trending anomalies of short wavelengths of 5 km at most is clearly visible, extending from the Dutch border towards the ESE between Bremen and Hannover. Furthermore the cultural editing by SGL applied to the built-up areas of Bremen and Hannover can be recognized. In the Northern part of the survey area a number of mostly roundish, negative anomalies (dark blue) is shown. These anomalies result from the low susceptibility of salt structures. Some of these negative anomalies have remarkable positive anomalies at the edges, though not all of the salt structures are lined with these positive anomalies. The presence of linear, negative and positive anomalies next to each other is due to the general geometry of magnetic anomalies (Telford et al., 1990). Though this first vertical derivative map is significantly enhancing the small scale structures in the magnetic dataset, the data appears to be noisy in large parts. Thus the process of improvement of resolution (by the computation of derivatives) came along with a loss of significance.

The first vertical derivative in figure 7 is overprinted with the basement block pattern in Northern Germany after Baldschuhn et al. (1996) and shows numerous Pre-Permian fault structures which are continued within the overlying sediments. The lengthy, negative anomaly between Oldenburg and Bremen is associated with the rise of linear salt structures along the Bremen lineament. In the southern edge between Osnabrück and Hannover the trend of a positive magnetic anomaly correlates strongly with the course of the Wiehen - Wesergebirge flexure. The central WNW-ESE trending system of anomalies lies exactly in the area of a WNW-ESE striking fault system that is confined in the east by the Steinhuder Meer Lineament. Though the majority of linear magnetic anomalies show good spatial correlation with fault structures, not all anomalies can be explained by faults. Approximately 20 km north of Hannover there is a linear magnetic anomaly which cannot be related to a fault structure. It is also noteworthy, that not all fault structures are present as magnetic anomalies in the first vertical derivative map.
Figure 7: First Vertical Derivative (FVD) of the reduced to the pole, total magnetic intensity grid. Red and blue colours describe regions with high local derivatives. The FVD map is overlain by the basement block pattern in Northwest Germany mapped by R. Baldschuhn, U. Frisch & F. Kockel (BGR Hannover, 1997). A good portion of the linear magnetic anomalies shows good local correlation with fault structures. The pattern is dominated by a system of WNW-ESE striking thrust faults (Walter 2007) in the centre of the figure. The Wiehen- and Wesergebirge system is visible as a linear magnetic anomaly.
5.2 High susceptibility horizon in the Cretaceous

The presence of linear trending, short-wavelength anomalies in the Lower Saxony dataset must be caused by the magnetic response in shallow sediments, as deeper-lying sources would have longer wavelength effects. Figure 8 shows the tilt derivative of the total magnetic intensity, which is another mean to enhance the distribution of prominent structures with positive susceptibility contrast in the dataset. The tilt derivative is adequate for mapping shallow basement features, thus the Bramsche anomaly as well as most of the other long-wavelength anomalies are identified in the map. The elongated short-wavelength anomalies discussed in the previous section are also present in the tilt derivative grid. The salt diapir, 25 km north of Hannover, is very pronounced and rimmed with positive anomalies.

The overprint of the tilt derivative in figure 8 is the base of the Upper Cretaceous horizon after Baldschuhn et al. (1996). Contour lines with corresponding depth values indicate a rise of the base of the central Lower Saxony basin, resulting from the inversion of the Lower Saxony block. Concentric contour line bands above the Pompeckjsche Block in the North, are caused by the uplift of the Cretaceous horizon due to salt structures. The Münsterländer Cretaceous basin lies in the south-eastern part of the survey area and is bounded by the Osning Lineament (figure 7) on the northern edge. The end of the Upper Cretaceous horizon in the northern part runs over the whole map with a WNW-ESE aligned trend. This trend of the end of the Upper Cretaceous horizon coincides with a continuous system of linear magnetic anomalies, that can be followed over the complete grid. It is striking to observe the good correlation of both structures. In the area between Hannover and Wolfsburg, at the Northern part of the Fulda-Celle anomaly, the magnetic anomaly trend is clearly following the base of the Upper Cretaceous horizon and cannot be explained by the presence of fault structures, which were shown in figure 7.

This trend of magnetic anomalies suggests the presence of a high-susceptibility in the Cretaceous either in the earlier part of the Upper Cretaceous or in the upper part of the Lower Cretaceous. Though this trend is clearly visible along the northern edge of the Lower Saxony block, the northern edge of the Münsterländer Cretaceous basin, marked by the Osning lineament, does not go along with a magnetic anomaly trend.

5.3 Depth Estimation by Euler Deconvolution

After the recognition and description of the substantial magnetic anomalies in the survey area, the question of the depth of the sources of the magnetic anomalies arises. There is a complete tool box of depth estimation methods available; a very convenient one, which can easily be applied to 2D maps is the depth estimation by 3D Euler Deconvolution. The basic theory of the method and a general discussion of the necessary and selectable parameters as well as the cavities of the method has been given in section 3.3.

5.3.1 Depth Estimation of Bramsche Anomaly

In a first step, the depth estimation by 3D Euler Deconvolution has been applied to the total magnetic intensity grid of the Lower Saxony dataset by SGL. The search window of the Standard
Figure 8: Tilt Derivative enhancing shallow basement structures including the Bramsche Anomaly and the distribution of high susceptibility contrasts. An overlay of the base of the Upper Cretaceous horizon (after Baldschuhn, Frisch, and Kockel (1996)) shows good correlation with the end of the Upper Cretaceous horizon and a WNW-ESE striking trend of magnetic anomalies, that can be followed over the whole survey area.
Figure 9: Euler Deconvolution applied to aeromagnetic dataset of Lower Saxony. Grid spacing: 2 km. Structural Index SI = 0.0.
Euler Deconvolution should be chosen, such that it is large enough to include the entire anomaly being analyzed, but should not extend over multiple anomalies. As the Geosoft Oasis montaj software limits the area of the Euler window to a size of 20 in grid cell units, with a grid cell size of 100 m used for the general analysis, the window size would be limited to an edge length of 2 km, and would thus not comprise the major long-wavelength anomalies which have wavelength of up to 40 km and more. So the total magnetic intensity grid was regridded with a grid spacing of 2 km, which would allow for a maximum grid cell size of 40 km.

In an initial tryout phase of the 3D Euler method, different structural indices, depth tolerance and "maximum distance to accept" (from the centre) values were tested. The depth estimate solutions are given as coloured point solutions. As the Euler Deconvolution is a very good method, but leaves the interpretation of the significance of a calculated solution to the interpreter [Thompson, 1982], an additional assessment of the solution is crucial. Figure 9 shows the computed depth estimates for a structural index of 0.0. The best results yielded a window size of 7 corresponding to 14 km, a maximum distance of the source from the centre of the window of 20 km and a maximum depth tolerance of dz: 15%. The suggested solutions calculated by the 3D Euler method, which also accounts for the flying height, give the depth in the ground to the top of the anomaly causing source body. A structural index for a geologic setting with fault structures as sources is used, which explains, why the solutions in figure 9 are concentrated along the edges of the anomalies. The suggested source depths are in the range of 1600 to 9000 m, however the solutions are too shallow to be realistic solutions. For instance the solutions at the northern rim of the Bramsche anomaly, which are in the range of 1500 to 2800 meters, are far too shallow to explain the width of the observed long wavelength anomaly. The obtained values are thus not realistic, as the magnetic anomalies are not caused by fault structures assumed by a structural index of 0.0. The distribution and clustering of solutions along the rims of the anomalies is a good illustration of the functioning of the method, whereas the few scattered solutions are not significant.

In order to obtain valid solutions, a different structural index must be selected, which accounts for the geologic setting in the survey area. As the presence of an igneous intrusion is discussed as potential source for the magnetic anomaly observed in the area of Bramsche (see section 2.2), a structural index of 1.0 is selected, which applies for the simple model of a magnetic field caused by a sill or dyke structure (table 2). Figure 10(a) presents the depth estimation solutions calculated for a structural index of 1.0. Using the same parameters as for the previous calculations with a structural index of 0.0, the application of the Euler deconvolution yields a cluster of source points in the Bramsche region and in the region of the Oldenburg High and above other large scale anomalies, which are fully present in the dataset. The brands of the positive anomaly in the north eastern edge are not showing significant solution clusters. Besides these areas of clustered solutions, there are numerous source points spread over the whole dataset, though none of these appear in a significant solution cluster, which could be interpreted. Apart from the Bramsche anomaly and the Oldenburg High, the two anomalies east and south of the Bramsche anomaly show clustering of solutions. The corresponding depth estimations are in the range of 3000 to 6000 m and 4000 to 7000 m respectively. The dense clustering of solutions in the range of 6000 to 7000 m above the Bramsche anomaly suggests a depth to the top of the source between 6-7 km.

A significance improvement of the obtained solutions shown in figure 10(a) is achieved by a change of the depth and horizontal uncertainty limitations. In figure 10(b) the selection criteria are further constraint by lowering the accepted position uncertainties. Only solutions with a
Figure 10: Euler Deconvolution applied to aeromagnetic dataset of Lower Saxony. Structural Index SI = 1.0, Window Size: 7, limiting distance from center of window MaxD: 20 km. Please note the different colour scales for both depth solutions.

(a) Structural Index SI = 1.0, depth uncertainty dz: 15%

(b) Structural Index SI = 1, solution selection: dz: 10%, horizontal uncertainty dxy: 20%
depth uncertainty of $dz \leq 10\%$ and a horizontal uncertainty of $d_{xy} \leq 20\%$ are retained, which results in an obvious reduction of solutions, although the clustering of solutions at the Bramsche anomaly remains. This confirmation of solutions in the range of 6 to 7 km above the Bramsche anomaly is significant enough to serve for discussion. The reduction of solutions by an adaptation of selection criteria involved the elimination of solutions with high uncertainties, which were scattered over the whole survey area before.

To verify the retrieved solutions of the depth estimation applied to the SGL dataset of Lower Saxony, the 3D Euler method is also applied to an extract of the EMAG2 grid showing the anomaly caused by the Bramsche Massif. Therefore the EMAG2 dataset was gridded with a grid spacing of 2 km for the area of the Bramsche anomaly as shown in figure 11. The altitude of the EMAG2 magnetic anomaly grid is 4 km above geoid, hence the short-wavelength features recognized in the aeromagnetic dataset are not resolved by the EMAG2 grid. Nevertheless, the Bramsche anomaly as a large scale structure is clearly visible in figure 11. For the Standard Euler deconvolution method a window size of 20 km was used with a structural index of 1.0. The maximum distance from the centre of the Euler window in which solutions are recorded was set to $MaxD \leq 10\text{km}$ and a depth uncertainty criteria of 15% was chosen. The results for the Bramsche anomaly, plotted in figure 11, range between 5600 and 7000 m. The higher values at the rims of the clustering are disregarded, as their distribution does not show the dense clustering associated with significant solutions.

Depth estimation by 3D Euler deconvolution of the Bramsche anomaly yields results in the range of 5.5 to 7 km for the top of the source body both, for the aeromagnetic survey by Sanders Geophysics Limited (SGL) as well as for the EMAG2 dataset.

5.3.2 Depth estimation solutions in restricted area around salt diapir

The application of Euler deconvolution to the long-wavelength anomalies in this study lead to meaningful results, so that the method can be applied in a step forward to a local extract of the total magnetic intensity centered on the salt dome. Therefore an area of approximately $50\text{km} \times 50\text{km}$ was gridded with a grid spacing of 500m. Figure 12 reveals the negative anomaly of the salt dome in the centre. The base of the Upper Cretaceous horizon is wedging out along the northern flank of the salt dome. A south-east trending anomaly extends from the eastern edge of the salt structure. Two parallel west-east directed positive anomalies are visible on the western flank, which correlate with the edges of the previously mentioned salt pillow on this side of the salt dome. The negative anomaly on the eastern part of the map is part of the Fulda-Celle Minimum, the high values on the western margin of the map belong to the discussed positive anomaly at Nienburg.

As the stratigraphy in the displayed area especially around the salt dome is well described and known from the seismic data, depth estimation solutions of the anomalies could help to locate source horizons. The focus of the regional interpretation in this study area is on identifying contact and fault structures, so that a structural index (SI) between 0 and 1 should be used.

An initial testing of different parameters, showed that the 3D Euler method yields the best results with the following parameters. The window size was fixed with a value of 10, such that the edge lengths of the Euler window with a grid spacing of 500 m was 5 km. Solutions with a maximum distance of MaxD: 10 km were accepted and a depth uncertainty constraint of $dz$: 30
15% was chosen. Figure 12 shows the depth estimates by Standard Euler Deconvolution for the Structural Indices SI = 0, 0.25, 0.5, 0.75 and 1.0 in the scenarios (a) to (e) respectively. For a better comparison of the obtained solution, only solutions in the depth range between 0 m to 2000 m were kept, which entailed an elimination of a few spurious solutions. The overall increase of the number of solutions for higher structural indices (SI), is a property of the Euler Deconvolution mechanism. Low SI values are associated with bodies giving rise to low gradients, so solution for low structural indices have high uncertainties. However the used threshold for the depth uncertainty was kept constant for all structural indices, which accounts for the increase of the quantity of solutions for higher structural indices.

Under the assumption of a geologic setting determined by contact structures and a structural index of 0.0 as given in figure 12(a). There are only few solutions and the majority of solutions runs parallel to the edge of the survey area, which might be a side effect of the method. These solutions should be disregarded. What is interesting to see, are the solutions on the northern flank of the salt dome, which are also present in figure 12(b). For a structural index of 0.25, many more solutions are recorded and the linear anomaly extending from the western margin to the south eastern part of the map is already lined with numerous solutions. In figure 12(c) a continuous band of solutions around the salt diapir is observed with SI = 0.5. The clustering of solutions around the salt diapir is even increased for higher structural indices as in the figures 12 (d) and (e). A structural index of 1.0 comes along with numerous solutions along the linear anomaly trend in the map and around the salt structures, however including a deviation of the location of solutions from the clear lining observed for SI values of 0.5 and 0.75. Most of the other solutions spread over the map can not be explicitly correlated with source bodies.
Figure 12: Depth Estimations by Euler Deconvolution for different structural indices applied to the regional magnetic intensity map around the salt diapir (central low of magnetic intensity map). Standard Euler deconvolution has been applied for the structural indices 0, 0.25, 0.5, 0.75 and 1. For better comparison, the solutions have been limited to depth estimates between 0 and 2000 m.
The depth estimation values along the linear anomaly extending westwards from the edge of the salt dome are in the range of 300 to 800 m. Of special interest are the depth estimations of the positive anomaly surrounding the salt diapir. The source horizon on the northern flank seems to lie significantly deeper than on the southern edge. The range of the depth estimations on the northern flank is between values of 600 m and 1600 m, taking into account the depth solutions at this point for all five structural indices. In consideration of the fact, that an structural index that is too low gives depths that are too shallow and one that is too high gives estimates that are too deep, one has to decide which geological setting and hence which structural index is most appropriate. If the index is correctly chosen, depth estimates are more precise for high-index sources than for low (Reid 1990). As in this study, a continuous pattern of solutions along the major anomalies is obtained with a structural index of SI = 0.5 and higher structural indices are not yielding significantly different solutions in terms of location and depth range, the results obtained with an SI of 0.5 and 0.75 are accepted as best estimates.

Thus the Euler Deconvolution suggests a depth of the source horizon of 300 m to 700 m in the south of the salt dome and a depth between 900 m and 1600 m on the northern flank. Comparing these depth estimates with the stratigraphic information known from the seismic data, the source horizon would be situated in the upper part Lower Cretaceous horizon. The depth range of 900 to 1600 m in the north of the salt intrusion falls into the upper part of the Lower Cretaceous. From the stratigraphic record of the Adolfsgück 11 drilling located on the southern margin of the salt dome (see table 4) it is known that, the base of the Albian is in a depth of 575 m, which falls in the range of the depth estimation of the source horizon south of the salt structure. Figure 6 shows the wedging out of the Upper Cretaceous on the northern rim of the salt diapir, thus the magnetic anomaly in the south cannot reside within this horizon. As a conclusion, it is assumed that the high-susceptibility source body, which causes the anomaly lies within the upper part of the Lower Cretaceous, probably in the Albian or Aptian.
6 Modeling

The identification of a high susceptibility horizon in the Albian by the Euler Deconvolution and the linear anomaly correlation with the end of the upper Cretaceous horizon encouraged the test of this result, building a 2D model across the salt diapir. The precondition of modeling the magnetic response of the sedimentary layers in the area of this salt structure was the availability of gravimetric and seismic data. The 2D modeling was performed with the *GMSYS Intermediate Profile Modeling* software extension of the Geosoft Oasis montaj software package. GM-SYS is a registered trademark of Northwest Geophysical Associates, Inc.

6.1 Modeling with GM-SYS

GM-SYS™ Profile is a program for calculating the gravity and magnetic response of a geologic cross-section model. A step-by-step introduction to the software is available in the User Guide (Anonymous 2006). The software allows to digitize a profile from maps in Geosoft. In general, the extent (x-coordinate) and depth (z-coordinate) of the profile to be modeled and the Earth’s Magnetic Field parameters (Strength, Inclination, Declination) are defined. With the given coordinates a topography, gravity and magnetic profile can be extracted from georeferenced grids or maps. The presented models are pure 2D models, though GM-SYS also enables an enhanced 2.5 modeling. Subsequent testing of the 2.5 modeling parameters did not lead to a significant improvement of the models. A tool implemented in the GM-SYS environment also allows for Inversion calculations to improve the model. For the inversion setup of this function, given parameters, such as susceptibility or coordinates defining the horizons, are freed and then adapted in numerous runs to yield a best fit model. However, the application of this inversion tool did not yield acceptable results in this small-scale scenario and thus it was disregarded for the improvement of the models. The inversion calculations offered by this tool are rather designed for case studies without seismic information, where it can significantly improve the subsurface interpretation.

6.2 General Model Setup

The magnetic anomaly across the salt dome was modeled in two profiles in a north-south and a west-east direction crossing the central anomaly of the salt structure. Both profiles were directly digitized from the total magnetic intensity grid (figure 13) after choosing an appropriate starting coordinate, which simplified the referencing procedure of the seismic backdrop. An initial number of 50 profile points was chosen and the magnetic field parameters were defined as given in table 3. The salt body and the sedimentary horizons were digitized by means of a seismic backdrop, which included interpreted seismic horizons (after Baldschuhn et al. 1996) and the outlines of the salt diapir and the caprock as defined by the gravity modeling discussed in section 4.4. These horizons were digitized and partially adapted according to the seismic backdrop. As the modeling area is characterized by flat topography, a constant elevation was assumed. Stratigraphic information from drilling sites at the flanks of the salt dome as shown in table 4 were manually entered for the North-South model and their exact location was calculated as distance from the starting point of the profile. The spatial deviation of the drilling locations from the actual profile section is no more than one kilometer and thus the depth values for the sedimentary layers were used as
additional input and showed a good correlation with the interpreted horizons and the outline of the salt diapir. For the West-East modeling section, there was no appropriate drilling site with stratigraphic information within a spatial range of 1 km deviation.

After the stratigraphic buildup, density and susceptibility values were defined for the individual horizons as given in table 5. The assumed density values were adapted from the gravimetric model presented in section 4.4. Susceptibility values were chosen according to the values given in the aeromagnetic study over Mittelplate (Anonymous, 1999), but as the variability of susceptibility can be in the order of magnitudes over short distances even within a single horizon, they were adapted for a best fit model keeping them in a realistic range of significance between 0 and 200 $\mu$ cgs. The horizons that were assigned a susceptibility are the Upper Cretaceous with a susceptibility of 30 $\mu$ cgs, the lower Cretaceous with a susceptibility of 63 $\mu$ cgs and the Lias with a susceptibility of 30 $\mu$ cgs. The magnetic influence of the sediments below the Lias was neglected and their susceptibility was set to zero, as the observed short wavelength anomaly trend must be produced by shallow sources. A test of this assumption by variation of the susceptibilities of the deep-lying sediments, did not lead to a significant change of the magnetic profile. Though the model basically disregards the deeper layers below 3000 m, they are shown in the models to depth of 5000 m for completeness. The susceptibility and density of air was also disregarded.

The profiles presented in this report show a vertical exaggeration (V.E.) of 2. It is important to notice, that the Upper Cretaceous horizons wedges out along the northern flank of the salt diapir and thus no Upper Cretaceous sediments are found south of the salt dome. Furthermore, there is a remarkable thickening of the Lower Cretaceous horizon in the southern part. In order to test the assumption of a layer with high susceptibility sediments in the Lower Cretaceous, a thin horizon of a susceptibility of 150 $\mu$ cgs is introduced in both models in the lower Albian and is denoted just as ”Albian” in the model sections. Its exact location and thickness was part of the improvement of the model and is discussed in the following sections for each profile respectively.

Table 5: Susceptibility Values and Density Values used for 2D-Modeling

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Susceptibility [$\mu$ cgs]</th>
<th>Density [g/cm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Quaternary</td>
<td>0</td>
<td>1.80</td>
</tr>
<tr>
<td>Tertiary</td>
<td>0</td>
<td>2.07</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>30</td>
<td>2.42</td>
</tr>
<tr>
<td>Albion horizon</td>
<td>150</td>
<td>2.37</td>
</tr>
<tr>
<td>Lower Cretaceous</td>
<td>63</td>
<td>2.37</td>
</tr>
<tr>
<td>Lias</td>
<td>30</td>
<td>2.42</td>
</tr>
<tr>
<td>Keuper</td>
<td>0</td>
<td>2.45</td>
</tr>
<tr>
<td>Muschelkalk</td>
<td>0</td>
<td>2.55</td>
</tr>
<tr>
<td>Bunter</td>
<td>0</td>
<td>2.55</td>
</tr>
<tr>
<td>Zechstein Salt</td>
<td>0</td>
<td>2.22</td>
</tr>
<tr>
<td>Caprock</td>
<td>0</td>
<td>2.85</td>
</tr>
</tbody>
</table>

35
Figure 13: Locations of the modeled profile sections with respect to the total magnetic intensity map (RTP). Both the North-South profile (black) as well as the West-East profile (blue) are crossing the central magnetic anomaly caused by the salt structure. The offset of the drillings from the North-South Profile is clearly visible.
6.3 North-South Profile across salt dome

The North-South Profile is displayed in figure 14. It extends over 20 km starting approximately 6 km north of the salt dome. The starting coordinates for the southward extending profile were: X-coordinate = 3545537 and Y-coordinate = 5842517. The exact orientation of the profile, which crosses the centre of the negative anomaly caused by the salt, is shown in figure 13. The model was based on a total magnetic intensity grid, which was reduced to the pole. It can be seen in the profile section that the general trend of the magnetic anomaly could be reproduced. The gravimetric trend could also be followed, though for the gravimetric data the lateral extent of the stratigraphic layers is important. Therefore, the gravimetric curve was just used as a control parameter in order to see, if the assumed stratigraphy with the respective density values gets close to the observed real world data. In general, the discrepancy between the observed and calculated profiles is greater for the gravity data than for the magnetics.

Based on the values presented in the report of the aeromagnetic survey over Mittelplate (Anonymous, 1999) and according to the earlier analysis of a high-susceptibility source horizon in the Upper part of the Lower Cretaceous, it was assumed that the major contribution to the observed magnetic anomaly across the salt dome resides within the Lower Cretaceous. As the Upper Cretaceous and the Tertiary wedge out on the northern flank of the salt structure, they can not serve as sources to explain the steep magnetic anomaly on the southern flank. A variation of the susceptibility of the Upper Cretaceous sediments between 0 and 100 $\mu$ cgs only shifts the total magnetic intensity north of the salt intrusion up or downwards. The sediments of the Lias were assigned a susceptibility of 30 $\mu$ cgs to account for the high susceptibility values measured at the drilling cores of Mittelplate (Anonymous, 1999). A major increase of the Lias susceptibility could not reproduce the short wavelength of the anomaly south of the salt structure, therefore the source must lie within the Lower Cretaceous. As the seismic record at the flanks of the salt diapir does not yield any significant information about the exact position of the salt sediment contact zone, the stratigraphy of the drilling sites was of great help to confirm the suggested outline of the salt dome and the depth of the Lower Cretaceous stratigraphy. As it can be seen in figure 14, the measured depths of the Base of the Salt Diapir and the Base of the Albian at the A drilling do not correspond with the model. This is mainly due to the spatial offset of the drill hole locations (table 1) with respect to the profile section, nevertheless the deviation is only small. On the southern edge of the dome, the measured depth of the B and C drill holes are in very good agreement with the interpreted seismic horizons and the outline of the salt dome. Both drill locations are relatively close to the profile section.

The central objective of the adjustment of the model to the observed anomaly was achieved by the introduction of an Albian high susceptibility layer. As there was no initial geologic information about the source, a rather thin layer was introduced in the Lower Albian. A range of susceptibilities were tested, but did not lead to a change of the general waveform and thus in order to keep the susceptibility in a realistic range it was fixed at 150 $\mu$ cgs. A susceptibility of 150 $\mu$ cgs is a comparatively high value for sediments. The variation of susceptibility and the thickness of the introduced Albian layer resulted in similar effects on the calculated profile and did not lead to an improvement of the model. The measured depth of the Albian at the C drill hole location was used to defined the base of the horizon, which was then continued over the whole southern part of the profile with the aid of the seismic backdrop. Furthermore a minor thickening of the Albian in the edge basin of the salt diapir was implemented. The modeled magnetic profile in figure 14 corresponds well with the curve of the observed anomaly.
Especially the waveform on the southern edge of the negative anomaly is followed by the model, which is an indication, that the sources are modeled at correct depths. Differences between the computed response and the observed profile at the edges of the profile section could be minimized by further adjustment. Overall, the deviation of the calculated and the observed profile is only in the range of a few nT, which is definitely acceptable for a magnetic profile. To account for the very low values in the central part of the negative anomaly, the lateral extent of the layers would have to be implement in the model. This could only be achieved by 3D or enhanced \(2\frac{3}{4}\) modeling, which was beyond the scope of this project. On the northern flank, an Albian high susceptibility horizon was not introduced, as the sediments of the Lower Cretaceous in the southern part are considerably thicker than in the north indicating a different depositional history, as will be discussed later. Additionally, in the north, the concentration of sources in the upper part of the Lower Cretaceous would not have such a significant impact on the profile, as the lower Cretaceous lies much deeper on this side than in the south.

In the presented final model in figure 14 reduced to the pole magnetic data were used with a declination of 0° and an inclination of 90° of the geomagnetic field. This was necessary, as the initial model based on the provided total magnetic intensity grid with the geomagnetic parameters as given in table 3 yielded a great offset between the calculated and observed profile, which could not be explained and might be due to a software problem. The model based on the original total magnetic intensity data is shown in the appendix in figure 26. Although, there is an offset in both profiles, the general waveform is reproduced. Generally the north-south profile could reproduce the observed anomaly with the assumption of an Albian high-susceptibility horizon.

6.4 West-East Profile across the salt dome

The selection of a second profile for 2D Modeling was motivated by the results of the prior North-South Model. The section was chosen in a West-East direction to include major positive anomalies on both sides of the salt dome, whereas in the North-South direction, the southern flank of the salt structure is rimmed with a more positive anomaly than in the north. Furthermore 3D seismic data were used to set the location of the Albian horizon, as it should be present on the western as well as on the eastern edge. The orientation of the digitized profile is shown in figure 13. It crosses the negative anomaly at its centre and is aligned with one of the linear anomalies in the western part. Towards the east it gets close to another salt structure which can be seen north-east of the salt intrusion as negative anomaly. The profile was digitized starting from a position in the west with X-coordinate: 3535000 and along the Y-coordinate: 5830512. The setup of the model is illustrated in figure 15, which shows only an extract of the model centred on the salt diapir from west(left) to east (right). The stratigraphic record was lifted up by the rise of the salt. The rise of the deeper layers towards the east is due to another salt intrusion, which was also modeled, but is not shown here.

Sediments above the Lower Cretaceous are wedging out along the displayed west-east direction and are just present in the first hundred meters. The effect of the Upper Cretaceous with a susceptibility of 30 \(\mu\) cgs is negligible, but shown for integrity. In contrast to the north-south profile, there was no additional stratigraphic information of drill holes available. The position of the Albian was adjusted by means of identifying major amplitudes in the seismic record of the Lower Cretaceous, which could be correlated with the Albian in the prior model. The profile runs over the overhang of the salt dome, but is very close to the central, deep rooting salt body.
Figure 14: North-South Modeling Profile across salt dome, the profile extends approximately 20 km from north(left) to south(right). The observed profiles are displayed as station measurements with dots. The straight lines are the calculated magnetic and gravimetric profile of the model. (Ad.g. 1 = Adolfsglück 1)
The calculation of the gravimetric profile does not account for this effect, which explains the offset with respect to the observed profile over the anomaly.

The measured magnetic field is characterized by a central low over the salt and the sources in the shallow sediments yield to steep gradients on both flanks of the intrusion. The model is based on the original total magnetic intensity data, which has not been reduced to the pole. The slight rise of the observed profile towards the west, is probably caused by a long-wavelength anomaly at Nienburg (Weser), which was discussed before. The slight offset between the measured and computed values could therefore not be reproduced but is within an acceptable range of a less than 5 nT. The modeled thickening of the Albian high susceptibility horizon on the western (left) margin of the model tries to account for the mentioned rise of observed profile, there is however not geologic reason for a thickening of this layer. The form of the calculated positive anomalies on both sides of the salt are in good agreement with the waveform of the observed profile, approving the choice of the high susceptibility layer in the lower Albian. The observed anomaly east of the salt dome shows a slightly higher peak, which appears a few hundred meters further east than in the modeled profile. A thickening of the Albian horizon in the salt edge basin and thus a concentration of sources in this area could compensate for this effect. As the difference between the observed and calculated profile is only in the range of a few nT an adjustment of the model is omitted, since it would just lead to an over-complication of the model. In order to account for the low values of the anomaly on the western margin of the salt structure, an additional low susceptibility body was introduced. The introduction of this low susceptibility body was justified by the ambiguity of the seismic record below the salt overhang. Though the modeled outline of the salt body corresponds to the salt body suggested by the gravimetric modeling (Müller and Krieger [1999]), the stratigraphic record below the salt overhang is matter of interpretation.

Both models confirm the assumption of magnetic sources in the Lower Cretaceous. The observed anomaly profile was modeled within a few nT in both 2D models, which is an excellent result. The gradients of the magnetic profile on the edges of the anomaly could be simulated with a high susceptibility profile in the Albian. The distribution and origin of magnetic sources within this horizon is an aspect of further discussion and the concentration of sources in the salt edge basins could lead to a further improvement of the model.
Figure 15: West-East Modeling Profile (Left to Right) across southern flank of the salt intrusion. Dotted curves are observed profiles and straight lines the calculated ones.
7 Results

7.1 Major Magnetic Anomalies in Lower Saxony

The major long wavelength magnetic anomalies in the survey area as discussed in section 4.2.3 are in the scale of tens of kilometers and are mapped by both the aeromagnetic survey by SGL and the EMAG2 dataset. A depth estimation of the Bramsche anomaly by the 3D Euler method yielded results in the range of 5.5 to 7 km as shown in the figures 10 and 11. This depth range supports the idea of an igneous intrusion to depth of up to 6 km and demonstrated the potential of this method. Previous studies among them Wonik (1992) have already identified and described the large scale anomalies in the survey area with the Bramsche anomaly and the Fulda-Celle minimum being the most prominent ones. The outline of the anomalies was significantly improved by the higher resolution of the aeromagnetic survey compared to the contour maps of earlier studies and the resolution of the EMAG2 dataset.

Besides the long wavelength anomalies which are caused by deep lying sources in the basement and igneous intrusions, short wavelength anomalies with linear trends extending over the whole survey area stand out. Their existence could only be revealed with the high resolution of the aeromagnetic survey. Most salt structures and intrusions in the survey area are denoted by negative anomalies, which are partially rimmed by positive anomalies. These positive anomalies are caused by the uplift of high susceptibility horizons, which had been inclined by the rise of the salt. The distribution of salt structures correlates well with the existence of fault zones, as the salt rises along these zones of weakness.

7.2 Recognition of Fault Structures

The comparison of the system of linear anomalies along the Northern margin of the Lower Saxony block with mapped basement fault structures strongly suggests a geologic correlation. Magnetic anomalies in figure 7 seem to be related to fault structures. This relation is also very pronounced for the Weser- and Wochengebirge structure. The high pass filtered total magnetic intensity map in figure 19 in the appendix demonstrates that most of these magnetic anomalies are strong positive anomalies, which are rimmed with negative anomalies on both sides. Since the alignment of the majority of these linear anomalies is in a WNW-ESE direction, these negative anomalies are located to the north and south of the positive anomalies. This shape of the anomalies, is what one generally expects for fault structures (Telford et al., 1990), where magnetic source horizons show a displacement. This offset within the stratigraphic record causes the observed linear anomalies. The location of the positive anomalies will not be right above the fault structures, which is an effect of the inclination of the geomagnetic field. However, it is wrong to conclude, that each fault structure will automatically produce such a magnetic anomaly. A magnetic anomaly along a fault structure is only caused by the vertical offset of sedimentary strata with different susceptibility. On the other hand, it could be shown, that salt structures, which produce negative anomalies can often be correlated with a fault setting. The data analysis has shown, that the existence of fault structures is revealed in the magnetic signal due to the susceptibility contrast in the geologic record. The short wavelength of the linear magnetic anomalies suggests very shallow sources, which must reside within the upper 1000 m. Thus an outcropping high susceptibility horizon in the Albian would explain the linear
magnetic anomaly trend along the margin of the Lower Saxony block marking the northern boundary of the Lower Saxony basin. Furthermore, it is known that this fault system between the Lower Saxony block and the Pompeckjsche Block is dominated by overthrust faults due to the inversion of the Lower Saxony block (Jaritz 1973; Walter 2007), thus an overthrust of magnetic sources in the Albian could even account for parallel anomalies. However, it does not serve as an explanation for the short wavelength anomalies in other parts of the survey area, where the Albian lies either in greater depth or is not present in the stratigraphic record at all.

7.3 High susceptibility horizon in Albian or Aptian

A first indication of a high susceptibility horizon within the Upper or Lower Cretaceous record was established by the finding of a linear magnetic anomaly trend following the end of the upper Cretaceous horizon (figure 8). Since for magnetic anomaly interpretation, it is crucial to keep in mind, that the anomaly does not appear directly over the sources, the magnetic source horizon can not directly be deduced from this finding. Furthermore this trend was only observed along the northern margin of the Lower Saxony basin and not along the base of the Upper Cretaceous sediments in the Münsterländer Cretaceous basin. The lack of magnetic sources within the Cretaceous sediments suggests a different geologic composition of the sediments in this area. From susceptibility measurements of drill holes of the oil platform Mittelplate (Anonymous 1999), it is known that there are relatively high susceptibility values in the Jurassic and the Cretaceous. However there is a strong local deviation of susceptibility values over small distances within individual horizons.

The depth estimation solutions by Euler Deconvolution, applied to the salt dome as presented in figure 12 located magnetic sources in a depth of 900 to 1600 m in the north and in a depth range between 300 and 700 m in the south. A comparison with the seismic data showed, that the magnetic sources must thus reside within the Lower Cretaceous, as no Upper Cretaceous sediments exist south of the salt diapir. The sediments in the south at depth of 300 to 700 m belong to the Aptian and mainly the lower Albian as known from stratigraphic information of the drill holes and the seismic interpretation. As the magnetic anomaly at the southern flank of the salt dome is part of the linear anomaly extending in a WNW-ESE direction as discussed for figure 8, it was assumed, that the suggested magnetic sources in the Lower Albian exist within the whole horizon in the survey area.

The shape of the North-South Profile and of the West-East Profile across the salt dome correspond with the theoretical profiles of a semi-infinite horizontal sheet or slab as shown by Telford et al. (1990). To test for such a scenario of a contact or sheet like structure with two infinite dimensions, the appropriate structural index for the Euler deconvolution lies between 0.5 and 1.0. It could be shown in figure 12 that the choice of a structural index within this range yields the best results. The depth estimates of the linear magnetic anomaly trend including the southern margin anomaly of the salt dome are all within a range of 300 to 700 m, supporting the assumption of a continuous horizon outcrop. In the western part this anomaly trend has a parallel component approximately 5 km in the north. It is known, that a salt pillow is located right within the area between both anomalies, which confirms the idea of a high susceptibility horizon, which was uplifted on both sides due to the rise of the salt.

The two models introduced in figure 14 and 15 running respectively in a North-South and West-East direction over the salt dome as shown in figure 13 confirmed the existence of a high
susceptibility horizon in the lower part of the Albian in the Lower Cretaceous stratigraphy. An assumed susceptibility of 150 \( \mu \) cgs for the Albian high susceptibility horizon proved to be a good estimate. Both models could reproduce the observed anomaly profiles and especially the rise at the rims of the salt diapir. The overall deviation of the calculated profiles from the measured values is very low and nowhere more than 5 nT. None of the models required a major adjustment of the given stratigraphy based on seismic interpretation. Only in the West-East model an additional low susceptibility body was introduced to account for the low magnetic values in the western part of the anomaly.

The sum of the findings including the depth estimation as well as the subsequent modeling confirmed the existence of magnetic sources, probably iron accumulations, within the lower part of the Albian or Aptian. Though susceptibility can greatly vary even within one layer, a continuous horizon containing magnetic sources could be identified in the Albian. A theoretical scenario of the formation and geological composition of the magnetic sources is discussed in the following.

8 Discussion

8.1 Assessment of igneous intrusion scenario for Bramsche Anomaly

The existence or non-existence of the so-called Bramsche Massif is still an unsolved question of regional importance for the evolution and structure of the Northwest-German Basin. In order to obtain further insight into the crustal structures in the region of the Bramsche Massif and a future verification of either scenario - inversion vs. intrusion, a more detailed investigation is required based on the combination of all available geophysical and geochemical data. Our findings of a magnetic source body at depths of 5.5 to 7 km adds to the long list of models and indications supporting the idea of an igneous intrusion at approximately 6 km depth.

Brink [2001] summarizes the geophysical and geochemical indications for an intrusive body and shows that though the gravimetric anomaly can also be reproduced in a 2D model by a high density body in a depth of 15-30 km, the most likely scenario is an intrusion, which falls within the period of the inversion of the Lower Saxony block. The concept of a mafic intrusion would also explain the high thermal maturity, the \( \text{CO}_2 \) risk and lack of reservoir rocks in the southern part of the North West German Basin in the area of the Bramsche Massif, which is supposed to have risen in the Upper Cretaceous period as mafic pluton at depths of about 6 km. Both, an inversion and intrusion scenario, have been modeled in 3D density models by Bilgili et al. [2009], who found that the Bouguer anomaly could not be modeled without a high-density, intrusive-like body at depth.

The depth estimates of the top of the magnetic source of the Bramsche Anomaly presented in this report confirm the general idea of a source body in a depth of approximately 6 km. As an extensive discussion of the geologic setting of the Bramsche Massif is not objective of this project and goes beyond the scope of this report, we will limit the discussion to the interpretation of our findings. All obtained depth solutions for both analyzed data sets strongly support an intrusion scenario at depth of 6 km. As this result is consistent with most of the depth estimations and models presented in the literature, it demonstrated the potential of the 3D Euler deconvolution method for the depth estimation of magnetic sources. Though, the depth of the magnetic sources
has been verified, the question of the geologic scenario remains. Is it possible, that the magnetic anomaly is due to an inversion scenario with metamorphosed rocks of high susceptibility at depths of approximately 6 km? Even if the gravimetric anomaly can be modeled by an inversion scenario, at least in 2D models (Brink, 2003), and the thermal influence of a magmatic intrusion is not evident (Senglaub et al., 2006), it is very unlikely that a tectonic inversion with metamorphic rocks can cause such a prominent magnetic anomaly. However, the process of metamorphism and the production of subsequently emerging, strong magnetic sources is subject of further studies. For a thorough discussion of the Bramsche Massif and the related anomalies, it should be referred to Brink (2001) and a recent publication by Bilgili et al. (2009).

8.2 Ferromagnetic minerals in the Albian and Aptian

During the analysis of the aeromagnetic data and the modeling, the focus of this Bachelor project was shifted towards the high susceptibility horizon in the Lower Cretaceous. The comparison of the depth estimates and the available seismic information gave already a first hint for a concentration of magnetic sources within the lower Albian or Aptian. As it is generally known, that susceptibilities can significantly vary within individual horizons even over short distances, it is very surprising to find a continuous anomaly trend over the whole survey area extending over more than 300 km. Though there are numerous publications analyzing and describing Albian sediments, only the analysis of the high-resolution aeromagnetic survey over Lower Saxony could reveal the presence of these comparatively weak, short-wavelength anomalies. The report of the aeromagnetic analysis conducted in the Elbe estuary area including the oil rig Mittelplate (Anonymous, 1999) mentions high susceptibilities in the Lower Cretaceous, however suggesting a strong spatial variation. This spatial variation could be explained by differences in the depositional behaviour of the sediments hosting the magnetic sources.

The susceptibility of 150 $\mu$ cgs used for the modeling is just an assumed theoretical value, which lies within a realistic range. Unfortunately, susceptibility logging is not performed for most petroleum exploration drillings, so that no information about susceptibilities was available in the area of the salt intrusion. The magnetic response of the introduced high susceptibility horizon in the models (figure 14 and 15) is mainly dependent on its susceptibility and the thickness of the layer. Admittedly, it could be argued that the chosen susceptibility value is too high, but on the other hand the thickness of the layer is little. The stratigraphic morphology at the flanks of the salt dome is another issue of debate. The interpretation of the seismic information (figure 6) suggests a thickening of the Lower Cretaceous sediments at the edges of the diapir. As this thickening is very pronounced for the Lower Cretaceous sediments, but not for the deeper horizons, it could be concluded, that the salt rose within the beginning of the Lower Cretaceous. This would implicate the existence of salt edge basins during the Lower Cretaceous and serve as a possible explanation for the observed thickening of the Lower Cretaceous sediments. If such a salt edge basin was still existent during the Albian, magnetic sources could be concentrated in these basins causing the positive anomalies, encountered at the rims of the salt structures. This could also explain, why not all anomalies at the rims of salt intrusions are as pronounced as for the salt dome. Having said that, it is known that the northern margin of the Lower Saxony block defines roughly the margin of the shallow marine sea covering the Lower Saxony basin during the Lower Cretaceous until the inversion of the Lower Saxony Block in the Upper Cretaceous (Walter, 2007). Hence the salt dome and its neighbouring salt structures were positioned in a coastal area with possibly strong sedimentation. All in all, this is very theoretical, so we will
As the interpreted high susceptibility layer in the Albian was not explicitly mentioned in previous work, the high resolution magnetic susceptibility measurements on the Research Cores Kirchrode I and II by Rose et al. (1996) are an important reference of support. The susceptibility measurements of the Albian sediments in these research cores taken at the edge of the Lehrte-Sehnde salt dome near Hannover show a striking peak in the susceptibility profile in the Middle to Late Albian, as it can be seen in figure 16. According to Rose et al. (1996) the material of the two cores consists of entirely marine, mainly grey marly claystone with interbedded high susceptibility carbonatic Fe-, P- and Mn-concretions. Kirchrode I was drilled to a depth of 245 m and KII to a depth of 279 m, respectively. The drillings are 2 km apart and due to the dipping of the beds 92 m could be added to the depth values of KII to obtain the continuous profile of figure 16. The susceptibility signal from 325 to 300 m distinctly deviates from the average signal of the profile and reaches values beyond 1000 $\mu$ SI which corresponds to values of 80 $\mu$ cgs. Rose et al. (1996) explains the increase of susceptibility in this part with the presence of red marls with increased content of ferromagnetic minerals and the increased occurrence of high susceptibility carbonatic Fe-, P- and Mn-concretions. This measurement of magnetic susceptibility data verifies the presence of ferromagnetic material in the Albian. Though the profile does not include the Lower Albian, it confirms the occurrence of Albian high susceptibility layers within the Lower Saxony Basin close to the salt diapir; yet their geologic origin is still not explained.
Motivated by the finding of a high susceptibility measurement in the Albian, the stratigraphy records of drillings close to the salt intrusion were checked for the occurrence of ferromagnetic material in the Albian. In the stratigraphic record of the *Hassel Z1* drilling, approximately 20 km north-east of the salt dome, a strong iron enrichment in the lowest Albian sediments is explicitly mentioned. Pyrite, brown haematite debris and iron claystones are described within a clay stone and marly clay bed of only a few meters thickness. Below this layer a sandstone bed in the Aptian showed a similar enrichment of iron claystone and a general high iron-content. The occurrence of iron rich sediments is limited to a 50 meter thick bed comprising the Lower Albian and the Aptian. A few kilometers north of the salt dome, no Albian sediments occur in the stratigraphic records of the drillings. (Otternhagen Z1, Benthe Z1, Kolenfeld Z1, Husum Z1, Lehrte Z1), which confirms our expectation, since we identified the outcrop of the Albian horizon as the magnetic source causing the observed linear magnetic anomaly. The *Texas Z1* drilling, just a few kilometers north of the discussed linear magnetic anomaly, contains also a significant iron-enrichment in its stratigraphic record of the Lower Albian and Aptian. The lithology of these sediments includes iron claystones and pyrite. The iron is mostly present in brown haematite debris, iron claystones and partially pyrites. The sum of this stratigraphic information, supporting the enrichment of iron, would be a possible explanation for the existence of high susceptibility layers within the Albian and Aptian sediments.

The existence of the Lower Cretaceous iron ores in the Salzgitter area in the southeastern part of the Lower Saxony Basin has been known for a long time (Mutterlose and Bornemann, 2000). The deposition of these sedimentary iron ores was controlled by a marine, near-shore environment. The Harz massif, only a few kilometers in the south, was probably not covered by sea in the Early Cretaceous, and so the area was under the depositional regime of the Harz mountains. A similar scenario could have been the prevailing geologic setting in the near-shore areas of the Lower Saxony basin along the northern margin of the Lower Saxony block. Iron claystone geodes, deposited during the Jurassic, were taken up during the transgression of sea water and reworked in the tidal areas along the margins of the Lower Saxony basin. These iron debris ores accumulated in the salt edge basins of the risen Zechstein salt structures as iron ooids.

This scenario of iron ore geodes, which were deposited during the Lias, reworked during the Lower Cretaceous and then deposited in the edge basins of salt structures, could also explain the discussed positive anomalies surrounding the salt structures. The climax of the halokinesis in the North German Plain lies within the Upper Jurassic and Lower Cretaceous (Jaritz, 1973). In addition, the seismic data around the salt dome indicate the presence of salt edge basins during the Lower Cretaceous in the area (Mutterlose and Bornemann, 2000) describe oolitic iron ores within the Aptian but not within the Albian. This is confirmed by the stratigraphic record of the *Hassel Z1* drilling, which showed high iron content only within few meters of the earliest Albian sediments, but for a significantly thicker layer in the Aptian. The reworking in the tidal areas destroyed the iron ore geodes, which were then accumulated as oolithic iron in the salt edge basins. As the salt dome lies at the Northern margin of the Lower Saxony block, it is very likely, that the salt diapir was in the coastal area of the Lower Saxony basin and might even have formed a small island, which was not flooded. In such a scenario we would expect that the deposited oolithic iron would cause magnetic anomalies, which are particularly strong at depositional traps caused by fault structures or salt edge basins. Furthermore we would expect an alignment of magnetic anomalies along the original tidal, near-shore area of the shallow marine sea in the Lower Cretaceous. This idea would theoretically explain the observed anomaly trend.
If this scenario of reworked iron claystone geodes does not apply, one has to search for other possible sources of the iron found in the system. Brockamp (1976) has analyzed the Montmorillonit content of various Cretaceous sediments in the Eastern part of the Lower Saxony Basin and interpreted it as an indicator for volcanic tuff. At an outcrop in the area of Salzgitter, he measured a strong peak of the Montmorillonit concentration in the Lower Albian. Moreover, a high $Fe_2O_3$ concentration of 8.7 % was measured in the Albian. If this scenario of volcanic activity during the Lower Cretaceous and an associated input of iron by igneous material or hydrothermal fluids is realistic and holds for the whole Lower Saxony Basin, is debatable.

The amount of publications referring to oolithic iron and iron claystone geodes within the Lower Cretaceous supports the idea of deposited ferromagnetic minerals as magnetic sources within the Albian or Aptian (Bayer (1989); Brandt (1985); Littke et al. (1998); Mutterlose and Bornemann (2000); Schmidt and Götze (1999)). However a geologic scenario, which can explain the extent of the observed anomaly and thus of the wide-spread distribution of the iron-rich sediments along the northern edge of the Lower Saxony basin requires further discussion.

9 Conclusion and Outlook

The analysis of the aeromagnetic survey conducted by Sanders Geophysical Ltd. revealed the existence of a Lower Cretaceous high susceptibility horizon in the lower Albian or Aptian. The application of the 3D Euler Deconvolution to the whole survey could demonstrate the applicability of the method for depth estimations, confirming the literature values of the depth of the source body of the Bramsche Anomaly of approximately 6 km. Subsequent analysis of an extract of the dataset around the salt structure led to the recognition of a high susceptibility horizon in the Lower Cretaceous. The presented 2D models support the idea of an accumulation of magnetic sources in the Albian or Aptian. The observed anomaly could be reproduced using a thin, 150 µ cgs susceptibility horizon in the lower Albian with an error of less than 5 nT. Ferromagnetic minerals seem to reside within this high susceptibility horizon, as a linear magnetic anomaly trend running throughout the whole survey area in a WNW-ESE direction could be identified along the "wedging out" of this layer.

Moreover, the high-resolution aeromagnetic data contains the signature of linear anomalies along fault structures caused by the displacement of high susceptibility horizons. In the survey area numerous mapped fault structures were correlated with anomalies. In new exploratory areas, aeromagnetic data could be used to reveal the presence of fault structures and to determine their orientation given the existence of a susceptibility contrast between displaced horizons. Furthermore we verified the use of aeromagnetic data for the recognition of salt structures. High-sensitivity aeromagnetic data reveal the intrusion of salt of low to negative susceptibility. In addition, uplift and overthrusting of magnetization carrying sedimentary layers at the flanks of the salt structures cause a visible magnetic anomaly encircling the intrusion.

The demonstration of the functional capability of the 3D Euler method encourages the application of the 2D method to the magnetic profile. The method was not tested during this guided research project, as the license was not available. The results obtained by this method could help to improve the already acceptable model of the salt dome’s magnetic anomaly. The next level would be the setup of a 3D model with the enhanced GM-SYS software package. Though the setup of a 3D model is more complex than in the 2D case, the availability of well processed and
referenced seismic data speeds up the model setup significantly. All in all the GM-SYS software proved to be a reliable tool for testing of magnetic susceptibility models and the software Oasis montaj by Geosoft could provide fast and direct analysis tools for magnetic data.

The identification of the Lower Cretaceous high susceptibility horizon, hosting the accumulation of ferromagnetic minerals, could be achieved by a susceptibility logging in one of the drillings located north of the observed magnetic anomaly trend. The geochemical analysis of a core pulled on the southern flank of the salt dome in a depth between 300 and 800 m would not only identify the depth of the sources, but also help to find an explanation for the source of the iron.

10 Acknowledgements

This guided research project and the Bachelor thesis, which you’ve almost finished to read, would not have been possible without the help of Dr. Matthias König. His expertise in the analysis of potential field data, his helpful assistance and references played a crucial part in the completion of this work. I would like to express my sincere gratitude to Dr. Matthias König and RWE Dea AG, who had always confidence in me to complete my work given restricted amount of time and limited previous knowledge about magnetic field data.

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Finally I would like to extend my appreciation to Sanders Geophysical Limited for providing us with helpful information and a fantastic aeromagnetic dataset and especially for allowing the realization of this scientific report. Moreover I appreciated the work with Oasis montaj, developed by Geosoft, and GM-SYS, a registered trademark of Northwest Geophysical Associates, Inc.
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Table 6: Stratigraphic Profile of Northern Germany
Figure 17: Total magnetic intensity map of the survey area over Lower Saxony. The magnetic anomaly data is reduced to the pole.
Figure 18: High Pass Filtered (10 km) total magnetic intensity map of Lower Saxony
Figure 19: Band pass filtered (1.6 to 10 km) total magnetic intensity grid of the eastern half of the survey area. The overlay shows the occurrence of salt structures, which are particularly in the area around salt structure (blue contour line) rimmed with positive anomalies.
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Analytic Signal (of TMI (RTP))

GS: 100 m
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Figure 24: Extract of tilt derivative map showing the area around salt dome.
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