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Regional geological and tectonic structures of the North Sea area from potential field modelling

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Abstract

The spatial distribution of large-scale crustal domains and their boundaries are investigated in the North Sea area by combining gravity, magnetic and seismic data. The North Sea is situated on the plates of three continents, Avalonia, Laurentia and Baltica, which collided during the Caledonian orogeny in the middle Palaeozoic. The location and continuation of the collisional sutures are debated. We apply filters and transformations to potential field data to focus on the crystalline crust and uppermost mantle on a regional scale in order to extract new information on continental sutures. The transformations reveal intrinsic features of crustal transitions between the Caledonian plates and their relation to later extensional structures. The transformations include the Hough Transform applied to the gravity field, calculation of fractional derivatives and integrals of the gravity and magnetic fields, the pseudogravity field and the horizontal gradient field as well as upward continuation. The results indicate a fundamental difference between the lithosphere of Avalonia, Laurentia and Baltica. The location of the Mesozoic rift system (the Central Graben and Viking Graben), may have been partly determined by the presence of the sutures between these three plate, indicative of extensional reactivation of compressional structures. A significant lineament across the entire North Sea between Scotland and North Germany indicates that the lower crust of Baltica provenance may extend as far south-westward as to this lineament. Comparison of the power spectra of the gravity field in five selected areas shows significant differences in the long wavelength components between the areas north and south of the lineament corresponding to differences in crustal properties. This lineament could represent the suture between lithosphere of Caledonian origin (Avalonia) versus lithosphere of Precambrian origin (Baltica) in the lower crust and upper mantle. If this is the case, the lineament is the missing link in the reconstruction of the triple plate collision.

Keywords: North Sea; Gravity data; Magnetic data; Potential field modelling; Crustal structure; Lineaments

1. Introduction

Potential field data are a primary source of information on subsurface geology and tectonic features. Gravity and magnetic data may reveal both large and small scale features, including differences in basement type, magmatic intrusions, volcanic rocks, basement surface and fault structures. As such, this type of data provides an invaluable source of information, which is complementary to seismic data.

The North Sea region has been the subject of intense geophysical exploration since the discovery of major hydrocarbon resources. Numerous seismic results have been published on the post-Zechstein deposits, but only

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few publications have targeted the pre-Zechstein deposits beneath the base of the Mesozoic sequences. As such, there are uncertainties as to the existence and thicknesses of Palaeozoic deposits, possible intrusions, differences in crustal domains and location of the continental suture zones.

Until the MONA LISA project in 1993–95 (MONA LISA Working Group, 1997a) there was almost no knowledge about the crustal structure and the configuration of the plates that collided during the early to mid-Palaeozoic amalgamation of the lithosphere in the area. The MONA LISA data identified, along four seismic profiles (Fig. 1 Table 1) (Abramovitz and Thybo, 1999, 2000; MONA LISA Working Group, 1997a), the location of the main sutures in the area, but the main triple junction between the colliding plates could not be identified. In particular, the west and southward extent of Baltica has remained unknown (Thybo et al., 1999, 2002). The relation of the bounding sutures to other plates may be of utmost importance for understanding of the process of subsequent rifting and basin formation. We apply different transformation techniques to potential field data from the area and identify lineaments that may reveal the hidden sutures and thereby provide significant new evidence to the Caledonian and earlier formation of the lithosphere in the area. We further address the importance of early collisional structures in the crust and uppermost mantle for the subsequent tectonic evolution. Identification of main sutures and other structures may hold the key to unravelling later processes of rifting and basin formation, in particular the location and fault structures of rift grabens.

2. Geological setting

The North Sea area was the site of a triple plate collision zone during the Caledonian orogeny (Fig. 2). Four major tectonic events influenced the area since the Cambrian: (i) the Caledonian collision during Late Ordovician to Early Silurian, (ii) subsequent rifting and basin formation mainly identified in the Carboniferous to Permian, (iii) Mesozoic rifting and graben formation and (iv) inversion during Late Cretaceous to Early Tertiary (Ziegler, 1990).

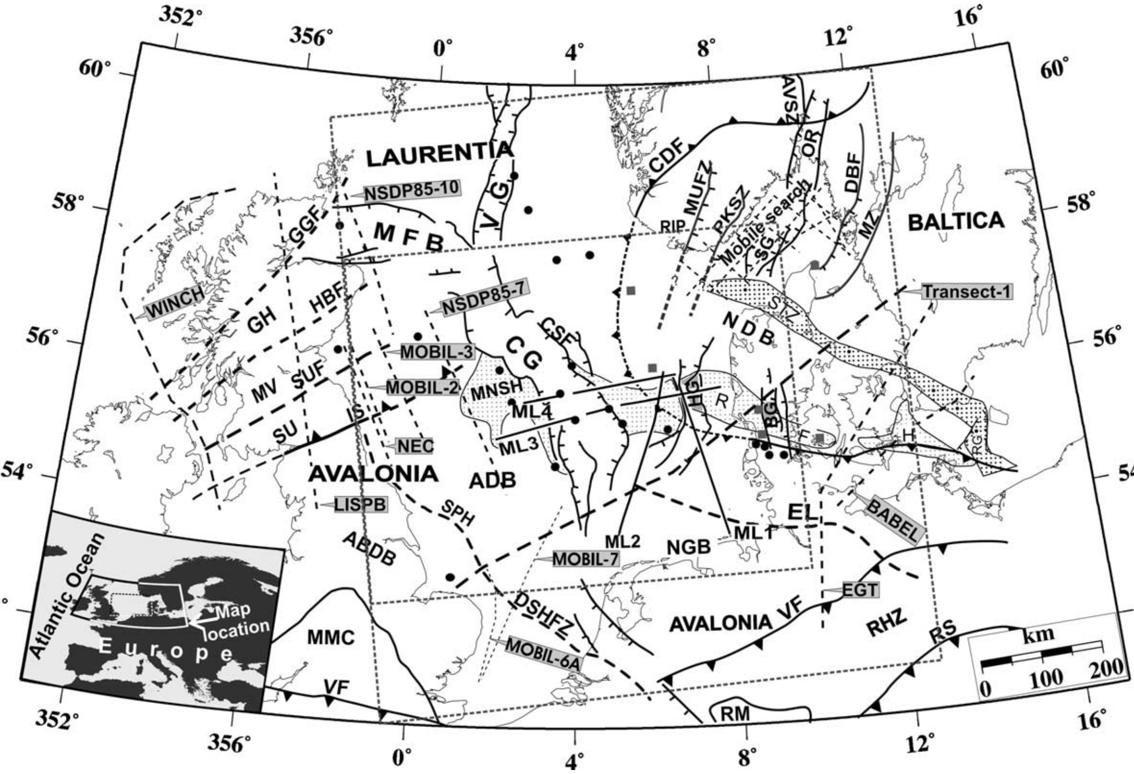


Fig. 1. Main tectonic features and deep seismic lines in the North Sea area. Squares indicate boreholes with Precambrian basement (>825 Ma), circles indicate boreholes with possible Caledonian basement (450–415 Ma). As the authors did not have access to the full gravity and magnetic datasets at the beginning of this study, some of the transformations will show a smaller areal coverage than others. The different areas are outlined by dashed squares. The inner dashed square shows the area used in calculation of the Hough Transform, while the outer dashed square shows the area used in calculation of the pseudogravity transform and the amplitude of the horizontal gradient. Abbreviations as in Table 1.

Table 1
Abbreviations used in the text and figures

AD	Ardennes Massif
ADB	Anglo-Dutch Basin
ABDB	Anglo Brabant Deformation Belt
AVSZ	Amot–Vardefjell Shear Zone
BB	Brabant Massif
BG	Brande Graben
CDF	Caledonian Deformation Front
CG	Central Graben
CSF	Coffeé Soil Fault
CM	Cornubian Massif
DBF	Dalsland Boundary Fault
DSHFZ	Dowsing-South Hewett Fault Zone
EA	Ebbe Anticline
EFZ	Elbe Fault Zone
EL	Elbe Lineament
GGF	Great Glen Fault
GH	Grampian Highlands
GO	Giessen Ophiolite Nappe
HBF	Highland Boundary Fault
HG	Horn Graben
HM	Harz Mountains
HPDB	Heligoland-Pomerania Deformation Belt
IS	Iapetus Suture
LRL	Lower Rhine Lineament
MFB	MorrayFirth Basin
MUFZ	Mandal Ustaoset Fault Zone
MGCH	Mid-German Crystalline High
ML 1–4	MONA LISA profiles 1–4
MMC	Midlands Microcraton
MNSH	Mid-North Sea High
MV	Midland Valley
MZ	Mylonite Zone
NDB	Norwegian Danish Basin
NGB	North German Basin
OR	Oslo Rift
PKSZ	Porsgrunn–Kristiansand Shear Zone
RFH	Ringkøbing Fyn High
RG	Rønne Graben
RHZ	Rhenohercynian Zone
RIP	Rogaland Igneous Province
RM	Rhenish Massif
RS	Rheic Suture
SB	Scania Batholit
SG	Skagerrak Graben
SGH	Silkeborg Gravity High
SH	South Hunsrück
SNF	Sveconorwegian Front
SNSLT	Southern North Sea-Lüneburg Terrane
SPH	Sole Pit High
SU	Southern Upland
SUF	Southern Upland Fault
STZ	Sorgenfrei-Tornquist Zone
VF	Variscan Front
VG	Viking Graben

The Caledonian collision involved two large continents, Baltica to the east and Laurentia to the west, as well as the micro-continent Avalonia to the south which by middle Ordovician times separated from Gondwana (Cocks et al., 1997; Ziegler, 1990). Baltica and Avalonia were prior to the collision separated by the narrow Tornquist Sea while Laurentia was separated from the two opposing continents by the larger Iapetus Ocean. During the Ordovician, the eastern and northern margins of Avalonia were active, related to subduction of the Tornquist Sea and the Iapetus Ocean. The amalgamation of Baltica and Avalonia most likely took place prior to the collision between Laurentia and Avalonia, as indicated by a convergence of palaeolatitudes derived from palaeomagnetic studies and by the onset of faunal mixing (Cocks and Fortey, 1982; Cocks et al., 1997). The collision zone between Avalonia and Baltica in the North Sea can be traced on all four MONA LISA deep seismic normal incidence reflection profiles as a band of south to west dipping reflectors that cuts through crust of Baltica affinity (Abramovitz and Thybo, 2000; MONA LISA Working Group, 1997a). The reflections on the MONA LISA profiles show the deep continuation of the Caledonian Deformation Front (CDF) (defined by Ziegler (1990) as the cratonward limit of Late Silurian to earliest Devonian folding and decollement thrusting that affected Early Palaeozoic sediments and Precambrian basement) in the southern part of the North Sea. The CDF separates more than 825 Ma old Precambrian basement to the north and east from 450 to 415 Ma Caledonian basement and sediments to the south and west (encountered in well-cores sampled from the Mid-North Sea-Ringkøbing Fyn High; Frost et al., 1981; MONA LISA Working Group, 1997b).

Models of seismic velocity and density show that the CDF represents the transition from a two-layered Avalonia type of crust with low P-wave velocities (5.8–6.4 km/s) and low upper crustal density (2715 kg/m^3) to the south of the zone to a three-layered Baltica type of crust with high P-wave velocities (6.1–7.2 km/s) and high upper crustal densities (2775 kg/m^3) to the north of the zone (Abramovitz et al., 1998, 1999; Abramovitz and Thybo, 2000; Williamson et al., 2002). The reflections on profile 2 downlap near Moho into a lower crustal zone of high reflectivity and velocity. Abramovitz and Thybo (2000) interpret the high reflectivity zone as either Baltica lower crust or a remnant of oceanic crust or a former island arc of the Tornquist Sea. The southern edge of the reflective lower crust corresponds to the offshore continuation of the Elbe Lineament (EL) into Northern Germany (Berthelsen, 1992).

The EL is a WNW–ESE striking deep crustal boundary which, in onshore Germany, represents the transition in the lower crust from high velocity (6.9–7.1

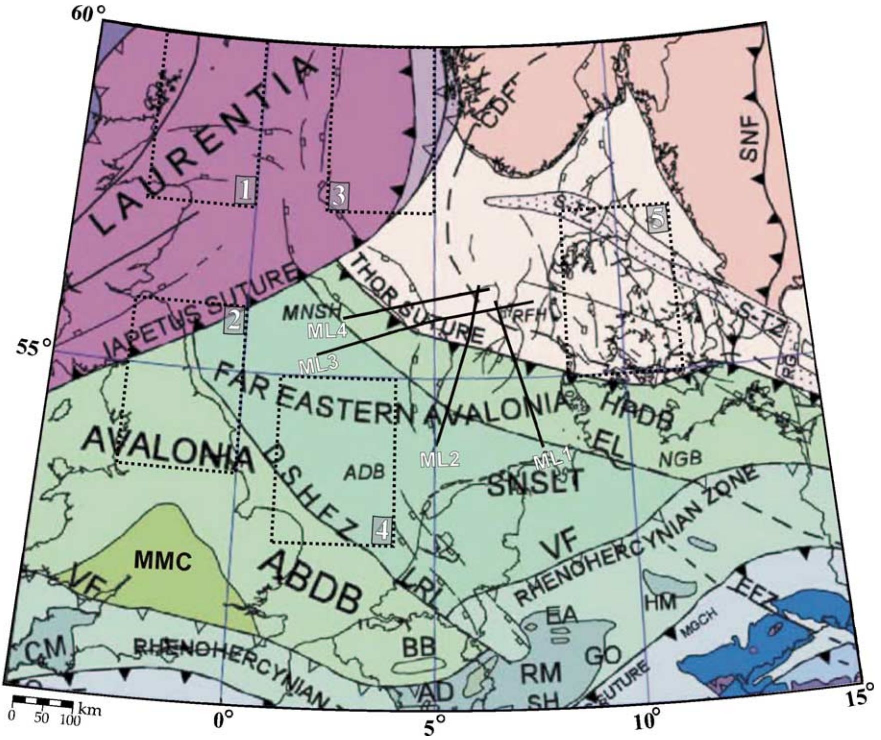


Fig. 2. Sketch map of basement tectonic structures in the study area with the location of the four MONA LISA profiles superimposed. Major terrane boundaries are marked by triangles. The five rectangles show the areas used in calculation of the power spectra of the gravity field. Modified after Banka et al. (2002). Abbreviations as in Table 1.

km/s) north of the boundary to low velocity (6.4–6.7 km/s) south of the boundary (Scheck et al., 2002; Thybo, 1990, 2001). This velocity discontinuity can be traced from the North Sea (Abramovitz et al., 1998; Abramovitz and Thybo, 2000) across northern Germany (Rabbel et al., 1995) and into Poland (Jensen et al., 1999). It is identified in seismic wide-angle and normal incidence seismic data (e.g. MONA LISA, EGT, DEKORP BASIN'96, and POLONAISE'97), potential field data (Banka et al., 2002; Williamson et al., 2002) and in faunal distribution (Cocks et al., 1997). The area between the CDF and the EL is a complex zone with affinities to both Baltica and eastern Avalonia. As such, it can be interpreted as a thrust of Avalonia onto the passive margin of Baltica (McCann and Krawczyk, 2001; Thybo, 1990, 2001).

The suture between Laurentia and Avalonia is known as the Iapetus Suture zone (IS). This zone can be traced eastwards from offshore western Ireland across the Irish Midlands and the British Isles into the North Sea (Figs. 1 and 2), where the suture between Laurentia and Baltica in the crystalline crust most likely is hidden beneath the present shelf west of the Scandinavian Caledonides (Snyder et al., 1997; Soper et al., 1992).

During the Caledonian collision a deep foreland basin developed on the former Baltica plate in front of the Danish-North German Caledonides as indicated by the presence of lower Palaeozoic sedimentary rocks (Thybo, 1990, 2001). The tectonic regime changed from general extension and subsidence in the Devonian to a strike-slip regime during the late Carboniferous to early Permian. During the late Variscan cycle northwestern Europe was transected by a system of conjugate shear faults, which in the Danish area resulted in the development of the Tornquist Fan of faults that form links between NNE to SSW trending graben structures (Thybo, 1997). At the late Carboniferous, the Variscan orogen collapsed and uplift caused truncation of the Devonian–Carboniferous successions.

The late Carboniferous and early Permian extensional wrench tectonics caused crustal thinning and subsidence of the Northern and Southern Permian Basins, which are separated by the Mid-North Sea-Ringkøbing Fyn High. The crustal thinning was associated with magmatic activity, evidenced in Rotliegendes volcanic deposits and associated sedimentary rocks. The Rotliegendes or top pre-Zechstein reflector marks a regional unconformity between pre-rift and syn-rift deposits and defines the traditional acoustic basement in most reflection seismic data from the North Sea.

From the Triassic to the Jurassic the NNW–SSE striking Central, Viking and Horn Grabens developed with extensive normal faulting in the basin areas. In the graben areas the Jurassic and Triassic sediments attain thicknesses in excess of 4 km (Vejbaek, 1992). During the Late Cretaceous Laramide phase of the Alpine orogeny compressional stresses caused inversion and deformation throughout the Danish and the North Sea area. Since the Early Tertiary the geological evolution has been characterized by regional subsidence in the North Sea area and uplift of the Baltic Shield.

3. Data sources and methodology

The potential field data (gravity and magnetic) used in this research are extracted from grid-compilations made by the Trans-European Suture Zone Potential Field Group (TESZ-PFG) (Wybraniec et al., 1998). The gravity database consists of Bouguer anomalies onshore and Free-air anomalies offshore. The Bouguer anomalies have been calculated with a reduction density of 2.67 g/cm^3, with normal gravity based on the 1980 ellipsoid. The grid has an average resolution of 5 × 5 km over most of Europe and a resolution around the Trans-European Suture Zone of 2 × 2 km. It is produced by reprocessing of data using the USGS potential field software package (Cordell et al., 1992).

The total aeromagnetic field anomaly data are based on a digitization of the original 1963 Huntington Aeromagnetic Survey of the Danish Area (Zhou and Thybo, 1997). A Fluxgate magnetometer collected the data with a flight altitude of 762 m (i.e. ~2500 ft) and a N–S line spacing of 3 km onshore and 6 km offshore with tie line spacing of 12 km. The data from the Polish area were provided by the Polish Institute of Geophysics, Warsaw, merged with data from the Geological Survey of Canada (Verhoef et al., 1996). Merging of the different datasets was done by Wybraniec et al. (1998).

As a first approach, we seek to identify and enhance lineaments in the gravity field. The Hough Transform (HT) is very useful for detecting linear features within digital images (Wang and Howarth, 1990). We apply the HT to an image of the observed gravity anomaly field (Fig. 3A). The HT makes use of a parameter space to describe features of a specific geometry in an image, so any curve that may be parameterized can be detected by a generalised HT (Fitton and Cox, 1998). In this study, we apply a linear Hough Transform (Cooper, in press) in which a point in image space maps to a line in the gradient — intercept parameter space with an intensity equivalent to the field value at the point of interest. If a linear feature exists in the data, the result of the HT will be a set of lines which intersect at the gradient and intercept of the equation describing the line (Fig. 3B). Through each point in data space an infinite number of straight lines can be fitted, although not all combinations are possible (vertical lines will have infinite values of intercept and slope), but nevertheless a line may be detected regardless of the fragmentation along it (Fitton and Cox, 1998). This, however, is an effect that should be regarded with care when used on data describing geological structures, as there is a risk that the HT connects independent geological segments. Calculating the inverse HT and thresholding the result (Fig. 3C), the lines with the strongest values will be retained in image space and can be overlain onto the original image as a guide to interpretation (Fig. 3D).

We use a 3D colour shaded relief transformation technique to present features in the gravity and magnetic data (Fig. 4A–E). The basic processing method requires the following input parameters: direction of illumination, a scaling factor applied to the data before the image processing, and two optional reflectivity parameters. This technique visually enhances subtle details as well as large scale lineaments and, as such, aids and facilitates geological interpretation. The computer code used in this study was developed by Pelton (1987) and later refined by Wybraniec (1995, 1999).

A regular colour shaded relief image is often used for display of the measured field strength, with shadows based on the gradient in the direction of an artificial light source. However, a vector representation of the field can be found by calculation of fractional derivatives and integrals in the Hilbert space (Wybraniec, 1999), and it is desirable to image the vector properties. Calculation of the field vectors requires that the field strength is known on the entire surface being analysed and the results are limited to wavelengths smaller than that defined by the size of the area of investigation. A vector representation of the magnetic field is either the three orthogonal components X, Y, Z of the field or the declination and inclination vectors together with the field strength. Similarly, the gravity field can be decomposed with reference to a selected reference coordinate system. Note that the direction of the gravity vector; i.e. the direction defining vertical, varies spatially when referring to the selected reference system. The declination vectors displayed (Fig. 4B and D) are based on the anomalous components only; i.e. the declination is calculated as the angle from true north of the anomalous

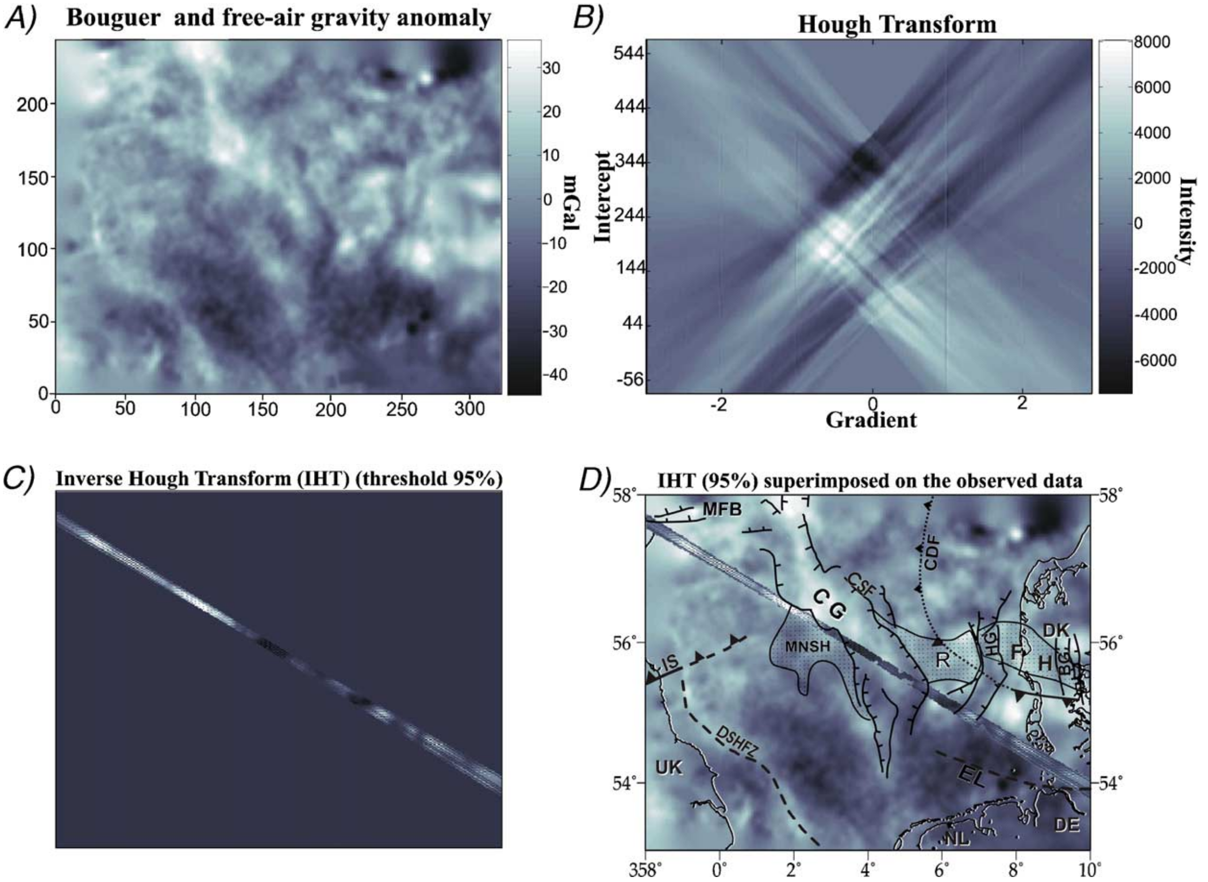


Fig. 3. Results of lineament identification by use of the Hough Transform in the North Sea area. (A) The observed Bouguer and Free-air gravity field. The axis shows the number of bins used in the sampling. The location of the area is marked by a dashed square in Fig. 1. (B) Hough Transform parameter space. (C) The Inverse Hough Transform (IHT) with a threshold of 95%, where only the strongest linear structures are retained. (D) The IHT with a threshold of 95% superimposed onto the observed data. This result indicates the presence of a lineament across the entire North Sea between Scotland and Germany.

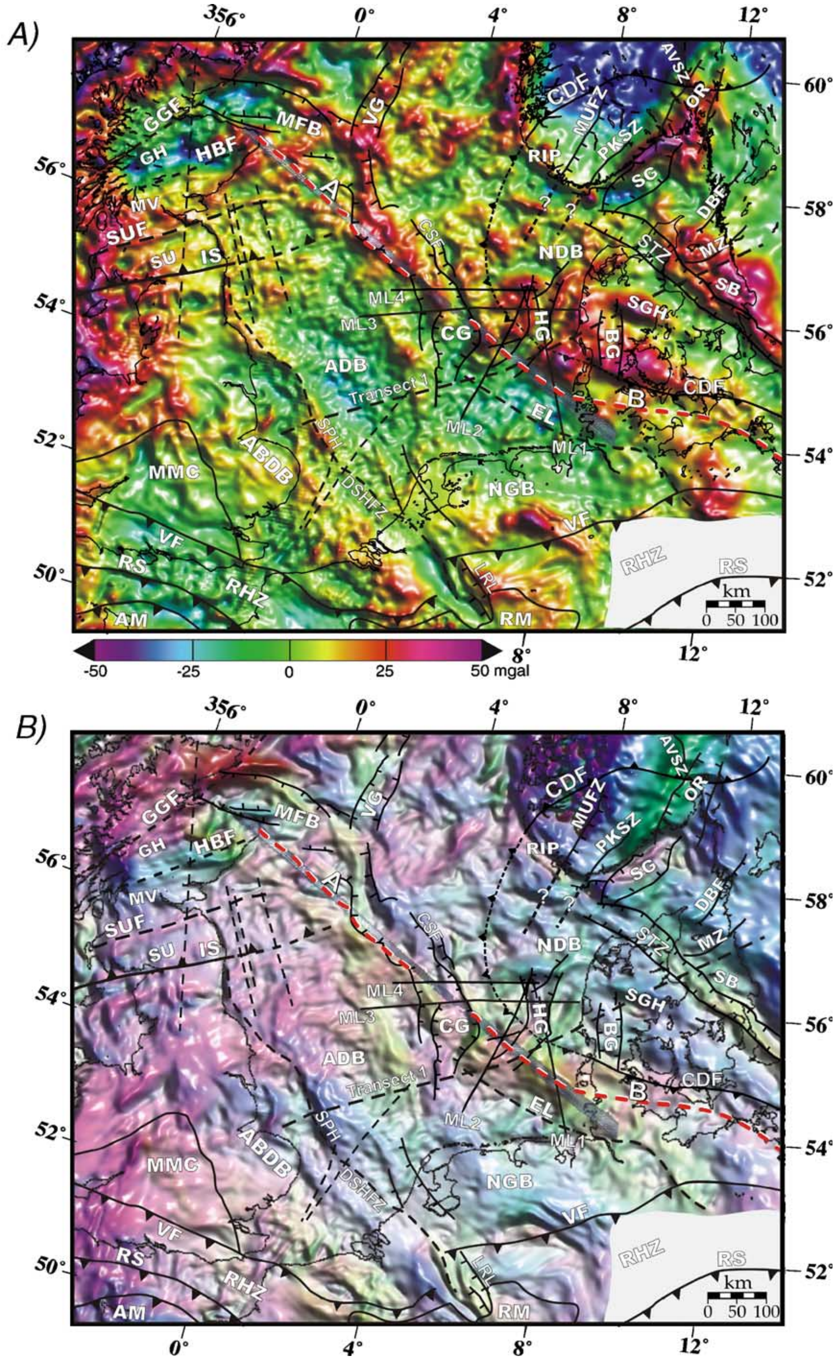
horizontal vector field. Using the HUE colour scheme (conic colour space) and working in polar coordinates, we assign the radial component (length) of the vectors to the colour saturation and the angular component (azimuth) to the HUE. The third component of the HUE colour space — the intensity is superimposed on the vectorial image to create a 3D shaded relief. This type of imaging is used as directional filtering and enhances tectonic structures perpendicular to the illumination direction and many details not otherwise seen.

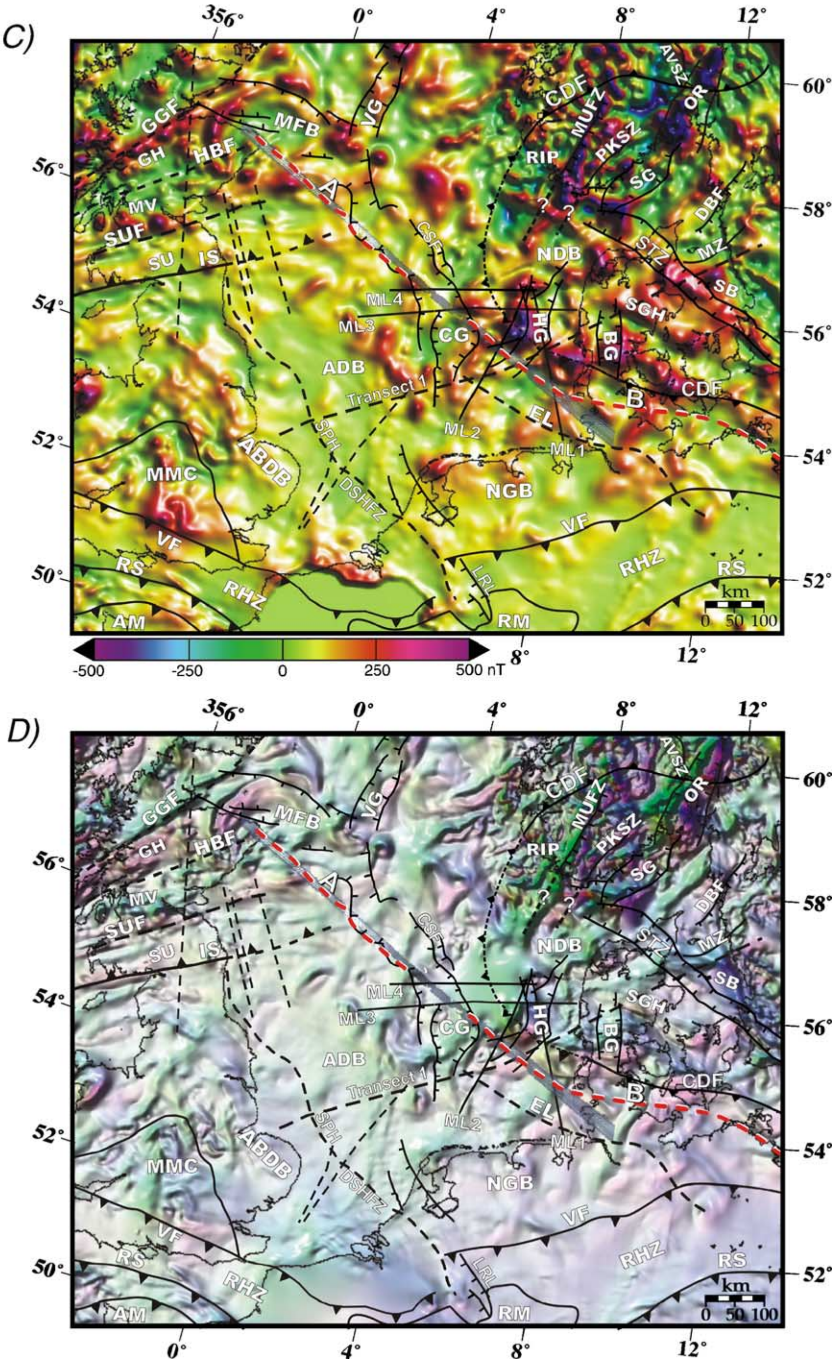
As magnetic anomalies very rarely are centred above their source, transformation techniques must be applied in order to locate and outline crustal magnetic sources. This can be done by calculating the horizontal gradient of a pseudogravity anomaly transform. First, we calculate the pseudogravity anomaly from the total magnetic field with a Fourier transform; the effect is a change of phase, which centres the magnetic anomalies above their causative bodies, provided that only induced magnetization is considered (Fig. 5). In order to focus on gross crustal structures, the pseudogravity field is band pass filtered, using a cosine roll-off and retaining wavelengths between 75–100 and 450–475 km. To outline the edges of the magnetic sources, we then calculate the horizontal gradient of the pseudogravity field and apply an automatic window search routine, which locate the peak values of the horizontal gradient field. The located magnetic sources may be correlated with the gravity field by applying a similar band pass filter to the observed Bouguer–Free air gravity anomaly data. All transformations were calculated by use of USGS potential field software (Cordell et al., 1992).

We use upward continuation of the gravity and magnetic fields and apply the theory of Jacobsen (1987), stating that the field resulting from upward continuation to a level of Z focus on sources situated at a minimum depth of $Z_0 = 1/2Z$. This way, the potential field is low-pass filtered as short wavelengths are attenuated more than long wavelengths, while still keeping the physical character of the field intact.

We choose to apply the upward continuation technique as a tool of regional/residual separation in order to investigate the orientation of regional structures of the lithosphere. The interpretation of the upward continued gravity anomaly field will be somewhat ambiguous without having modelled and subtracted the response from near surface structures as shallow, large bodies or closely spaced small bodies may produce long wavelength anomalies. However, sufficient information on shallow sedimentary surfaces is not available and the influence of the shallow sources cannot be fully eliminated.

Interpretation of upward continuation to the magnetic field requires estimates of maximum depth of magnetization. The depth of magnetization varies not





only with temperature, but also with the mineralogy of the lower crust and upper mantle. Minerals in the hematite–ilmenite (Fe_2O_3–$FeTiO_3$) solid solution series may produce strong lower crustal magnetic anomalies (Frost and Shive, 1986; Shive et al., 1992). Furthermore, the presence of small amounts of native alloys (mostly Fe–Ni) makes upper mantle magnetization possible (Shive et al., 1992). Serpentinization may affect the crystallization of magnetite. This process can take place in the lower crust and upper mantle at tectonic settings such as in orogens, forearc regions or at subducting oceanic slabs (Kido et al., 2004; Toft et al., 1990). Serpentinization processes may produce magnetic minerals with Curie points in excess of 580 °C, and will effectively deepen the Curie isotherm (Haggerty, 1978; Toft et al., 1990). Serpentinized upper

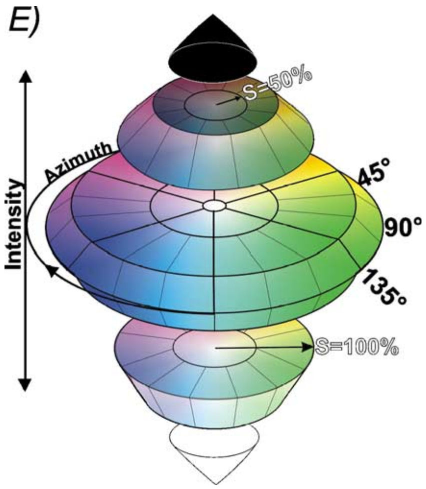


Fig. 4. (A) Image of the Bouguer (onshore) and Free-air (offshore) gravity anomalies. Several features are prominent, such as the deep sedimentary basins at gravity lows, the N–S striking graben systems and a lineament traceable from Scotland across the North Sea to northern Germany (lineament A and its possible continuation at lineament B or the EL). The lineament resulting from the Hough Transform has been superimposed. The southeastern corner of the map lacks data coverage. Abbreviations as in Table 1. Illumination direction: 45° declination, ~10° inclination. (B) Declination vector image of the gravity field. The rift structures define a change in the colour pattern indicating a change in crustal properties. As such a NW–SE trending crustal gradient observed as a yellow to green lineament (B) just south of the presumed location of the CDF, may mark the transition between different crustal types. The southeastern corner of the map lacks data coverage. The lineament resulting from the Hough Transform has been superimposed. Colour image created by S. Wybraniec (personal communication 2002). Illumination direction: 45° declination, 30° inclination. (C) Image of the total magnetic field anomaly. The Danish area and the Baltic Shield are characterized by numerous short wavelength anomalies associated with shallow crustal and perhaps even intrusive complexes within the sediments. A clear difference in magnetic signature can be observed between Baltica and Avalonia. The lineament resulting from the Hough Transform has been superimposed. Illumination direction: 45° declination, 30° inclination. (D) Declination vector image of the magnetic field. The difference between Baltica, Laurentia and Avalonia is pronounced. The anomalies of Baltica show a strong magnetic signature, likely caused by shallow magnetic structures whereas Avalonia has a very weak magnetic signature. Laurentia shows intermediate amplitude signals. The NW–SE trending lineament observed in the gravity declination vector image is not as evident in the magnetic field. The lineament resulting from the Hough Transform has been superimposed. Colour image created by S. Wybraniec (personal communication 2002). Illumination direction: 45° declination, 30° inclination. (E) Colour scale used in the declination vector images (Fig. B and D), where S = saturation.

mantle rocks may have high magnetic susceptibilities to depths greater than 70 km, depending on the heat flow (Toft et al., 1990). Assuming an old craton with a low heat flow, as the present day East European Craton with a heat flow of ~40 mW/m^2 (Chekunov et al., 1992), the limit for lithospheric ferromagnetism may be as deep as 95 km (Toft and Haggerty, 1988).

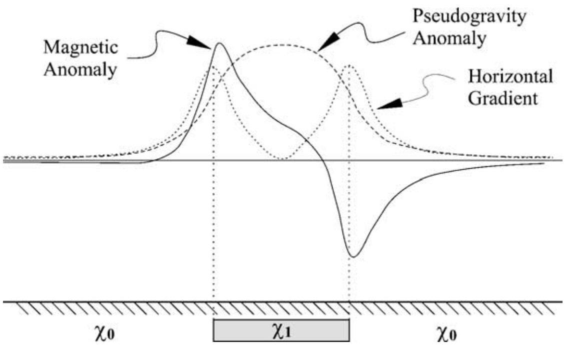


Fig. 5. Sketch of the relation between the magnetic anomaly, pseudo-gravity anomaly and the horizontal gradient anomaly given a magnetic body with susceptibility χ_1 situated in a non-magnetic crust ($\chi_2 = 0$).

Surface heat flow values for the North Sea and Danish areas are between 60 and 75 mW/m^2 (Balling, 1995; Baumann and Rybach, 1991; Hurtig, 1995). Balling (1995) calculates the 2D crustal temperature field in the Baltic Shield and the Danish Basin and estimates the maximum depth of magnetization (at about 600 °C for magnetite (Shive et al., 1992)) to be at depths between 60 and 70 km in the northern shield area, 35 and 40 km in the southern shield area and 25 and 35 km in the Danish Basin. However, if the magnetite minerals have been subjected to serpentinization, the Curie isotherm may be deeper seated at the Baltica margin. If so, application of upward continuation to the magnetic field may enable differentiation between the cold lithosphere of the Baltic Shield and the younger and hotter lithosphere of Phanerozoic Europe.

We finally apply spectral analysis to the characterization and comparison of areas of presumed different tectonic domains. The Fourier analysis is a quantitative approach in which anomalies of a selected region are transformed into the wavenumber domain, where they can be interpreted in terms of their spectral properties and compared with spectral properties of neighbouring regions.

We calculate the power spectra after upward continuation of the observed gravity field to 5 km. This will result in smoother spectra and may outline the different lithospheric regions. The upward continued gravity data were extracted in five selected areas (for locations see Fig. 2), each spanning 3° in longitude and 2 1/2° in latitude. The data for each area were tapered with a 10−20% expansion along the edges using a cosine bell on a grid with 640×640 data points. The radial power spectra were calculated for each area by averaging the amplitudes of the Fourier transform within bands of width $dk = 0.02\ \mathrm{km}^{-1}$, concentric about the origin. The rate of decrease of the power spectra is plotted against the wavenumber $|\mathbf{k}|$, where $\mathbf{k} = (k_x, k_y)$ is the horizontal wavenumber component. The rate of amplitude decrease with $|\mathbf{k}|$, is largely controlled by the depth of the sources, but can also be influenced by the nature of the density distribution (Simpson et al., 1986).

4. Interpretation of the potential field maps

The transformations of the potential field data from the North Sea area reveal large-scale tectonic structures that support and complement previous interpretations of deep seismic data. We relate the results from the transformations to the deep seismic profiles of the North Sea (locations shown in Fig. 1).

Applying thresholds to the Hough Transform of the observed gravity anomaly field where only 65%, 30% and the top 5% of the highest amplitude transforms are retained, a very strong and hitherto undescribed lineament remains across the entire North Sea (Fig. 3). The lineament is outlined between the Grampian Highlands in Scotland and northern Germany and is also present in the shaded relief map of the gravity vectorial image (Fig. 4B). Comparison with Fig. 2 shows that the lineament crosses the presumed location of the Iapetus Suture, implying a possible different tectonic setting for the northern North Sea area than previously assumed.

4.1. Basins and lineaments

The gravity and magnetic anomaly maps indicate that the effects of younger structures are superimposed on, and partly mask, the effects of structures from the Caledonian triple plate collision in the study area. The gravity anomaly map (Fig. 4A) shows strong positive anomalies in much of the Danish region, associated with crustal intrusions of Carboniferous–Permian age. These intrusions are large magmatic masses in the crystalline crust and the sedimentary sequences (Thybo and Schonharting, 1991; Thybo, 1997; Ziegler, 1990). Strong positive anomalies of long wavelength characterize the westernmost part of the map (to the west of the central parts of England and Scotland), probably related to deep seated sources. Negative gravity anomalies are associated with relatively young features, e.g. the North German Basin (NGB), the Anglo-Dutch Basin (ADB), the Skagerrak-Oslo Graben (SG and OR), the Norwegian Danish Basin (NDB), Brande Graben (BG), Horn Graben (HG) and the southern Central Graben (CG). In the Viking Graben (VG) and the northern part of the CG, local and large positive gravity anomalies indicate high density from magmatic intrusions or underplating.

The magnetic anomaly map (Fig. 4C) shows a clear contrast between crust of Avalonia affinity and crust of Baltica and Laurentia affinity. Avalonian crust is characterized by low amplitude anomalies which correlate with known tectonic structures such as the Anglo Brabant Deformation Belt (ABDB), the Midlands Microcraton (MMC), the Rheic Suture (RS) and the Variscan Front (VF). Even though to a large extent covered by sedimentary rocks, Avalonia crust must exhibit extremely low susceptibility values. The Baltica and Laurentia crust, in contrast, exhibits numerous high amplitude anomalies of which several correlate with known intrusive complexes. This contrast is even more pronounced in the magnetic declination vector image (Fig. 4D) where the crust of Baltica and Laurentia is characterized by short wavelength anomalies compared to long wavelength anomalies of Avalonia crust. The southern part of the Caledonian Suture and Deformation Front (CDF) follows a distinct series of positive magnetic anomalies (Fig. 4C) at a pronounced change in the field at the transition from the Precambrian shield-platform area into the younger regions of Europe.

A roughly N–S striking graben system including the Viking Graben, Central Graben, Horn Graben and Brande Graben dominates the post-Zechstein basin evolution. On the vectorial images (Fig. 4B and D) this graben system clearly intersects the NW–SE striking Mid-North Sea-Ringkøbing Fyn High and, judging from the change in colours and colour saturation, the system seems to be superimposed on older structures and intersects the edge of the Baltic Shield.

The Central Graben changes direction from NNE–SSW to NNW–SSE where it intersects the edge of the Baltic Shield. It has a much stronger contrast to the shield edge than e.g. Horn Graben on both vectorial images. This difference may be related to the difference in graben structure, sedimentary thickness and amount of Palaeozoic strata below the two grabens (Abramovitz and Thybo, 2000; Nielsen et al., 2000; Nielsen and Jacobsen, 2000).

Negative Bouguer anomalies are associated with the sedimentary North German and Anglo-Dutch Basins. The lack of short wavelength anomalies is probably due to thick accreted early Palaeozoic sequences and a weakly magnetized crust (Banka et al., 2002). The Norwegian Danish Basin (NDB) is characterized by local high-amplitude and short-wavelength gravity and magnetic anomalies that may be related to basement morphology of the Sveconorwegian crystalline crust below the basin area together with the effects of Late Palaeozoic volcanic rocks. A similar, but weaker magnetic character is found in the North German Basin (NGB), reflecting the presence of thick sedimentary sequences above the basement rocks (Banka et al., 2002; Williamson et al., 2002). The Norwegian Danish Basin and the North German Basin are separated by the Mid-North Sea-Ringkøbing Fyn High (MNS-RFH). The MNS-RFH and the inverted Sorgenfrei-Tornquist Zone (STZ) are evident in both the gravity and the magnetic images as NW–SE striking lineaments with high amplitude and short wavelength.

The lineament identified by the Hough Transform must have deep sources due to its large lateral extent. It crosses the North Sea between Scotland and northern Germany (segments A and B) and is evident in both gravity maps (Fig. 4A and B). We hypothesize that this lineament represents the deep crustal suture between Avalonia and Baltica/Laurentia. It crosses the hypothesized offshore continuation of the Iapetus Suture in the northwest (segment A, Fig. 4) and continues east of the Central Graben along a trend parallel to the Caledonian Deformation Front (segment B, Fig. 4). Its presence indicates that lower crust of Baltica affinity may extend as far westward as to this lineament which as such, may be the missing link in the reconstruction of the plate geometry of the Caledonian orogeny.

4.2. Pseudogravity and the horizontal gradient

Basic potential field theory shows that any anomaly may be the combined result of the effects of several sources, with the strongest effects of the shallowest sources. By calculating the horizontal gradient of the pseudogravity field, we are able to outline crustal magnetic sources. Superimposing the structures onto the gravity image adds constrains to the geological interpretation.

4.2.1. Pseudogravity

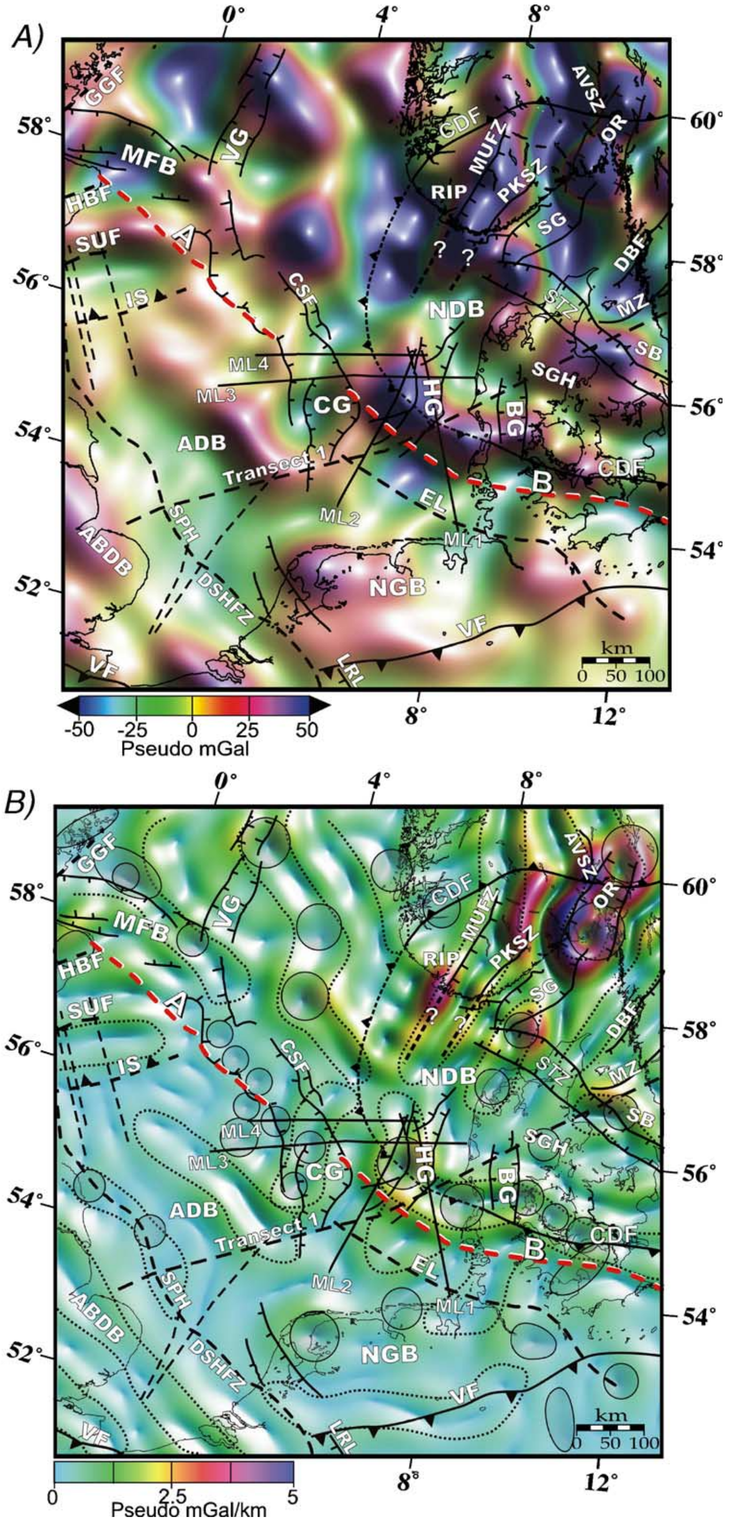
From the pseudogravity anomaly map (Fig. 6A) it is clear that the crust of Avalonia is less magnetic than the crust of Baltica and Laurentia, although there are distinct magnetic provinces in the Avalonian crust. The pseudogravity map shows high amplitude anomalies in the Baltic Shield proper. A zone of strong anomalies is coincident with the Rogaland Igneous Province (RIP) with a strike parallel to the Late Proterozoic Mandal Ustaoset Fault Zone (MUFZ). These anomalies extend into the Danish Area in accordance with the Precambrian age of the crystalline basement in this area (Bingen and Stein, 2003; Frost et al., 1981). As such, the pseudogravity transformation may be a tool for assessing basement provenance.

Strong positive pseudogravity anomalies are present over the entire Danish area with a trend that matches the expected location of the Caledonian Deformation Front in the Horn Graben area (e.g. MONA LISA Working Group, 1997b). In the northern North Sea the positive anomalies extend far to the west from the Norwegian coast, perhaps as far as to the west of the Viking Graben where the basement is of Laurentia origin. In the southwestern part of the pseudogravity image, a positive anomaly correlates with a small segment of the Variscan Front. Parallel and approximately 100 km further north, another positive lineament is observed which correlates with the Anglo Brabant Deformation Belt. The Dowsing-South Hewett Fault Zone (DSHFZ) is hardly identifiable in the pseudogravity image except for its southern continuation into the Lower Rhine Lineament (LRL). The LRL coincides with a positive anomaly that marks a southward step in the continuation of the Variscan Front (see Fig. 2).

4.2.2. The horizontal gradient of the pseudogravity

Gravity and magnetic anomalies of the crust are not necessarily correlated. We use the horizontal gradient method to estimate the locations of the magnetic contacts. This is a simple and robust procedure compared to other location methods. Local peaks in the magnitude of the horizontal gradient give the locations of the magnetic contacts. However, as the method is based on the assumption of near vertical contacts, the locations of non-vertical contacts will generally be imprecise.

The horizontal gradient indicates contacts that are continuous and generally parallel to the contours of the pseudogravity field. We use a 10 × 10 km search window in order to locate the peak values in the horizontal gradient grid, which are situated at the edges of the magnetic sources (see Fig. 5) (Phillips, 1997). Super-



imposing the points of calculated peak values onto the horizontal gradient map enables us to outline both local and regional anomalies (Fig. 6B).

The amplitude map of the horizontal gradient (Fig. 6B) shows the differences in magnetic character between the three continents: Avalonia, Baltica and Laurentia. The Baltic Shield is characterized by high amplitude anomalies. Four elongated NNE–SSW striking regional anomalies are outlined to the east of the Caledonian Deformation Front. These anomalies coincide in southwestern Norway with the onshore Rogaland Igneous Province (RIP), Mandal–Ustaoset Fault Zone (MUFZ) and Porsgrunn–Kristiansand Shear Zone (PKSZ). They extend for at least 200 km into the Norwegian Danish Basin (NDB) and across the Cretaceous–Tertiary Sorgenfrei-Tornquist inversion zone. The northern part of the Skagerrak Graben and its continuation into the Oslo Rift are also associated with strong anomalies. North of the Oslo Rift, the strike of the anomalies changes from NNE–SSW to NNW–SSE, at the exposed Amot–Vardefjell Shear Zone (AVSZ). In southwestern Sweden and in Kattegat the anomalies can be associated with the Dalsland Boundary Fault (DBF) and the Mylonite Zone (MZ). A WNW–ESE trending anomaly correlates with the Ringkøbing Fyn High and the southern part of the Caledonian Deformation Front as defined by MONA LISA Working Group (1997a,b).

The orientation and strike of the regional magnetic anomalies appear to be related to the basement type: Avalonia crust is characterized by a NW–SE strike and Baltica crust has a dominantly NNE–SSW direction to the east of the Caledonian Deformation Front. Local anomalies around the Sorgenfrei-Tornquist Zone, north and south of the Skagerrak Graben and along the Ringkøbing Fyn High correspond to the locations of known and interpreted intrusive complexes. The Central Graben and its continuation northward into the Viking Graben are also associated with local magnetic sources probably related to mafic intrusion during rifting.

Laurentia crust is characterized by a few elongated mainly EW striking anomalies that correspond to the locations of the major tectonic provinces such as the MorayFirth Basin and Southern Upland Fault. The location of the Iapetus Suture and segment A of the lineament across the North Sea from Scotland to northern Germany are not directly identifiable in the horizontal gradient image. The lack of signature may be because the related continental collision structures mainly exist in the lower crust where the magnetization is weak due to high temperatures. However, the locations of both lineaments coincide with significant changes in the general strike direction of the anomalies (Fig. 6B).

In Avalonia the amplitudes are significantly lower than in the two other continents, indicating that either the crystalline basement is very deeply seated or that it may have lost its magnetic character due to tectomagmatic processes. In the southern and southwestern part of the horizontal gradient amplitude map (Fig. 6B) elongated NW−SE striking magnetic anomalies correspond in parts to the location of the Variscan Front (VF), the Caledonian Anglo Brabant Deformation Belt (ABDB) and the Dousing-South Hewett Fault Zone (DSHFZ) (Pharaoh, 1999; Winchester, 2002). Two anomalies further to the north outline the edges of the Anglo-Dutch Basin. Both of the basin bounding anomalies correlate with magnetic complexes in the gravity/magnetic model of Transect 1 (Williamson et al., 2002).

4.3. Correlation of crustal domains

The pseudogravity transformation of the magnetic anomaly field amplifies long wavelengths and attenuates short wavelengths. A band-pass filter, similar to that applied to the pseudogravity anomaly field, is applied to the observed Bouguer–Free air gravity anomaly field in order to correlate between magnetic and the gravity sources (Fig. 7). Most of the interpreted magnetic sources coincide with gravity anomalies, although there are exceptions such as in the Norwegian Danish Basin. These exceptions indicate deeply seated sources and thick sedimentary successions, which have strong effects on the gravity field, or that the sources have lost their magnetic signature due to tectonic processes or elevated temperatures.

Fig. 6. A) Pseudogravity anomaly field, band pass filtered (cosine roll-off) between 75–100 and 450–475 km. The areal extent of the map is shown in Fig. 1. There are evident differences in crustal magnetic character between Laurentia, Baltica and Avalonia: Baltica is characterized by strong anomalies, Laurentia by intermediate anomalies and Avalonia by a weak magnetic character with only a few elongated magnetic complexes. Illumination direction: 45° declination, 30° inclination. B) Amplitude of the horizontal gradient of the pseudogravity anomaly. Interpreted edges of regional magnetic sources are indicated by stippled lines, local magnetic sources by closed curves. There are clear differences between Baltica, Laurentia and Avalonia, e.g. in the strike direction of the anomalies. Baltica is associated with several large elongated NNE-trending anomalies as well as several local sources that correlate with known exposed structures in southern Norway and southern Sweden. The southern part of the CDF as defined by interpretations of deep seismic profiles (MONA LISA Working Group, 1997a,b) correlates with a NW–SE trending anomaly fabric. The dominating trend in Laurentia is SE–NW to E–W. Illumination direction: 45° declination, 30° inclination.

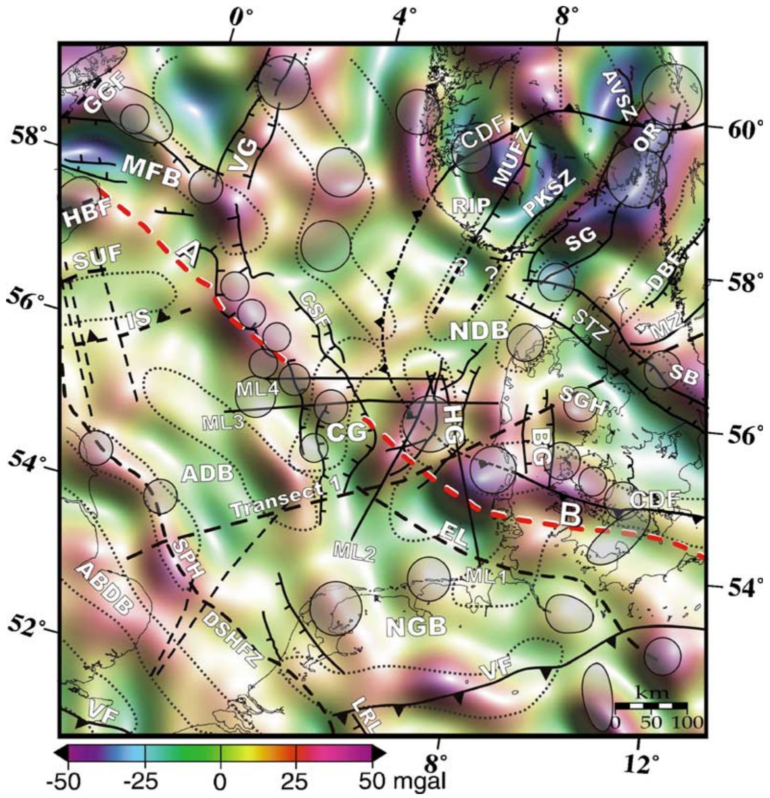


Fig. 7. Image of the filtered Bouguer and Free-air gravity anomaly (band pass filter with a cosine roll-off passing wavelengths between 75–100 and 450–475 km). The interpreted locations of local (shaded circles) and regional (stippled lines) magnetic sources from the horizontal gradient of the pseudogravity transform (Fig. 6B) are superimposed. Most of the magnetic anomalies are associated with density contrasts within the crystalline part of the crust. A clear correlation between magnetic and gravity anomalies are found along all the areas of rifting. Illumination direction: 45° declination, 30° inclination.

The Viking Graben and Central Graben are associated with positive gravity anomalies, which correlate to local magnetic sources. The positive gravity anomaly of the central part of Central Graben has several short wavelength features coinciding with local magnetic anomalies (compare Fig. 4A with Fig. 7). This indicates the presence of high density rocks which are partly offset from the axis of the rift structure and probably originate from ultra-mafic intrusion during rifting and coeval shallow volcanic rocks of Rotliegendes age.

The northern boundary anomaly of the Anglo-Dutch Basin (ADB) is touched by MONA LISA profile 3 at its western end. The anomaly only partly correlates with a density contrast and might relate to a mid- to lower crustal magnetic complex, as modelled on Transect 1 (Fig. 3 in Williamson et al., 2002). The southern boundary of the Anglo-Dutch Basin shows strong correlation between the interpreted magnetic anomaly and the gravity field at the Dowsing-South Hewett Fault Zone (DSHFZ). This significant long wavelength component likely relates to the suture between East Avalonia and Far Eastern Avalonia (Pharaoh et al., 1995). Two local magnetic anomalies (marked by circles) at the DSHFZ, correlate with local gravity highs and may represent structures related to the Alpine inversion. The southernmost anomaly coincides with the Sole Pit High (SPH in Fig. 7) (Donato, 1993; Vanhoorn, 1987).

4.3.1. Upward continuation of the gravity and magnetic field

We have applied a standard upward continuation technique to both the observed gravity and magnetic fields (Figs. 8 and 9). The chosen levels of upward continuation for the gravity and magnetic fields are: 6, 30, 50, and 100 km. If viewed as a tool for separation filtering (Jacobsen, 1987), this implies that the maps focus the regional response from sources located at depths below 3, 15, 25, and 50 km respectively, and as such the upward continued anomalies retain responses from sources located in the upper, middle and lower crust as well as the uppermost mantle.

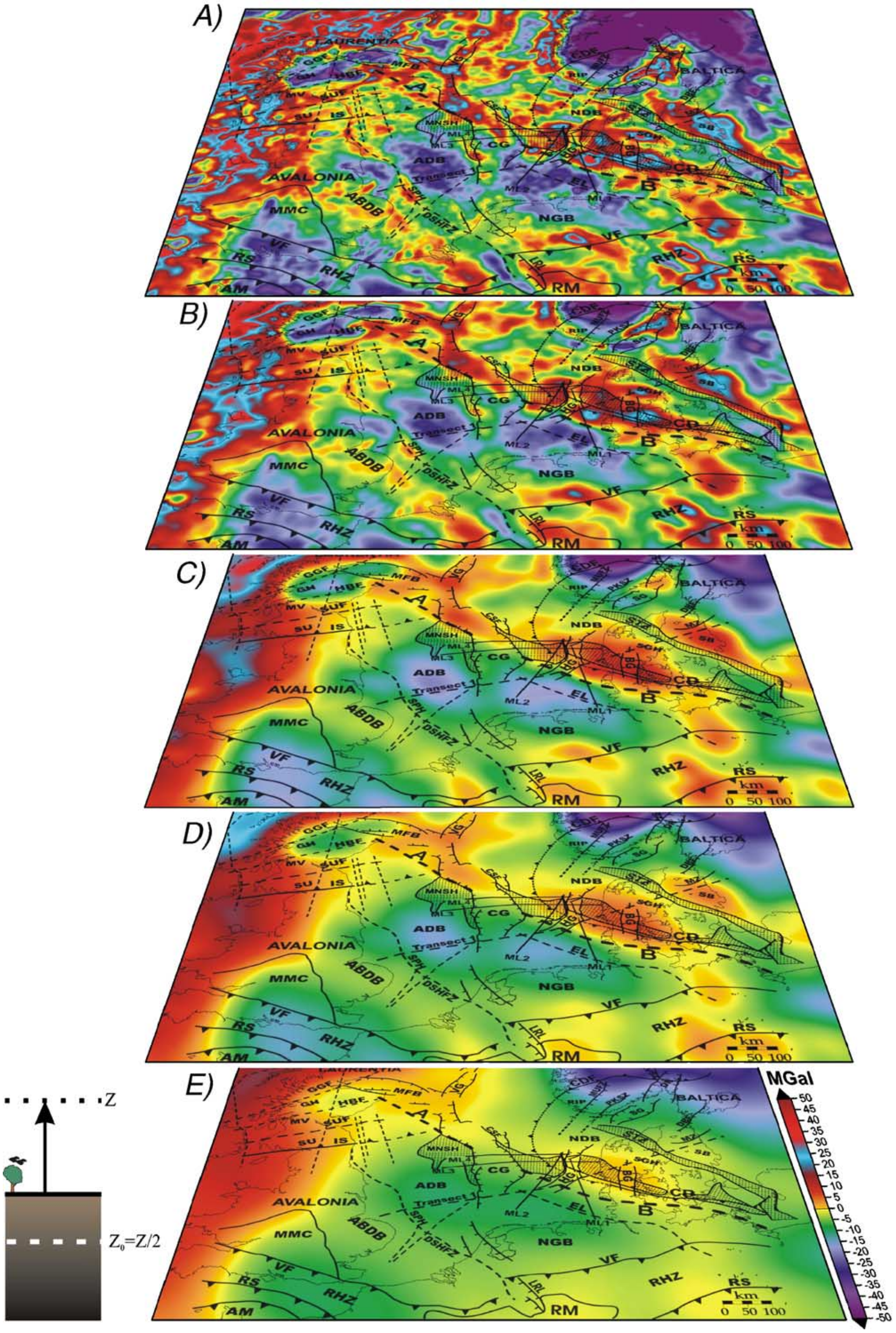


Fig. 8. Upward continuation of the observed gravity field. According to Jacobsen (1987), the resulting field from an upward continuation level of 'Z' retains anomalies from sources below a depth of $Z_0 = 1/2Z$, whereas sources above are more attenuated. The level of upward continuation (Z) and associated depth (Z_0) are: A) $Z=0$, the observed Bouguer and Free-air gravity field, B) $Z=6$ km, $Z_0=3$ km, C) $Z=30$ km, $Z_0=15$ km, D) $Z=50$ km, $Z_0=25$ km, E) $Z=100$ km, $Z_0=50$ km. Compare with Fig. 1 to locate the seismic lines described in the text.

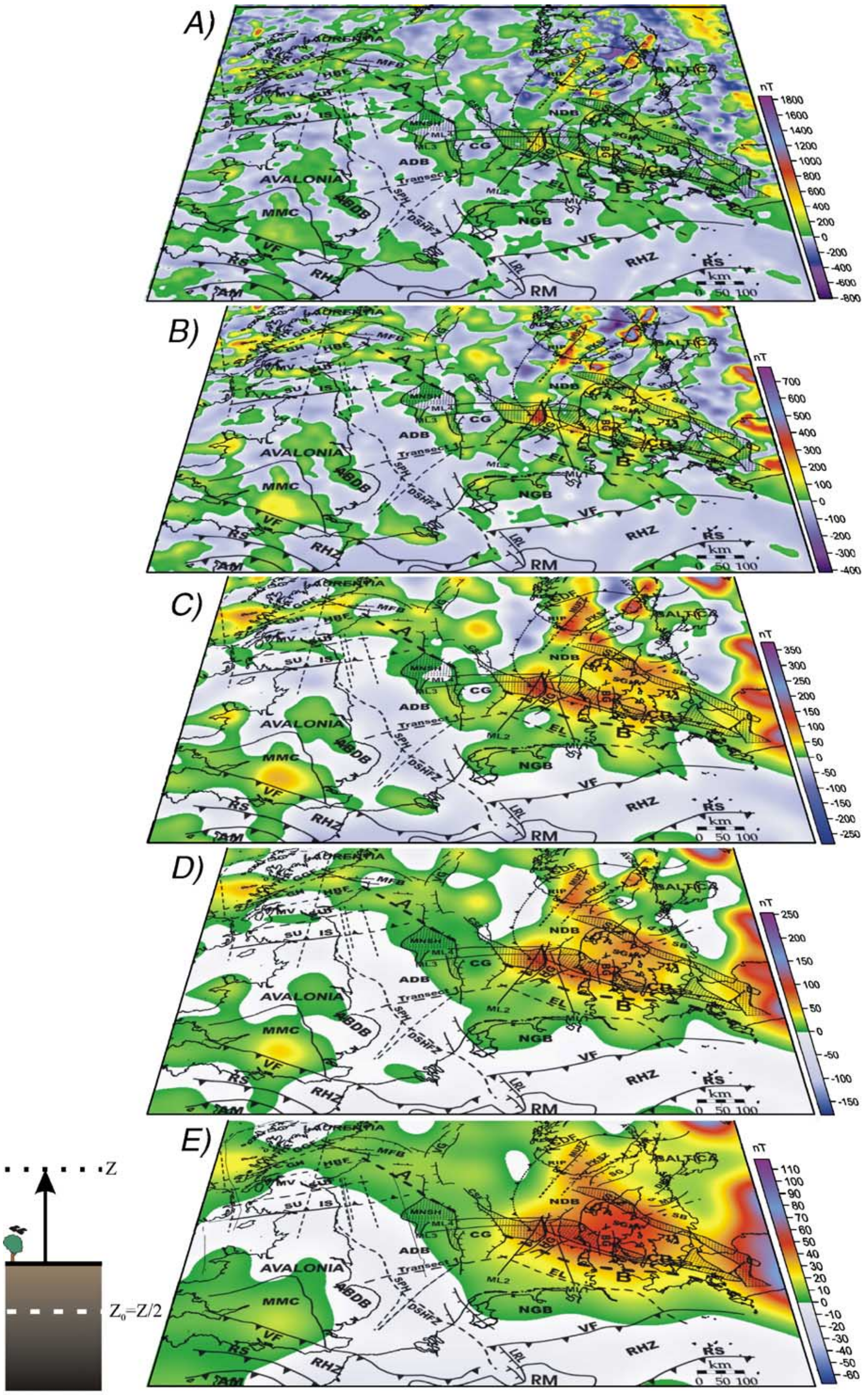


Fig. 9. Upward continuation of the observed total aeromagnetic anomaly field. The level of upward continuation (Z) and associated depths (Z_0) are: A) $Z=0$, the observed total aeromagnetic anomaly field, B) $Z=6$ km, $Z_0=3$ km, C) $Z=30$ km, $Z_0=15$ km, D) $Z=50$ km, $Z_0=25$ km, E) $Z=100$ km, $Z_0=50$ km. Compare with Fig. 1 to locate the seismic lines described in the text. Notice: the colour scale varies with upward elevation.

Subject to the incompleteness of separation filtering, several structural grains should be noticed in the upward continued images. From the upward continued gravity field, it is likely that the source of the anomaly at the ABDB reaches deep (Fig. 8). The location and depth extent of the source correlate with the mid and lower crustal reflectivity observed on the deep reflection seismic profiles MOBIL 6A and 7 (Blundell et al., 1991). The strong anomalies at the Scania Batholith (SB), the Silkeborg Gravity High (SGH) and the Oslo Rift (OR) are all observable to depths of more than 15 km in particular for the former two features. The sources of the SB and the SGH together with the RFH, can even be traced to depths of 25–30 km. The whole area of the Tornquist Fan exhibits strong positive anomalies through most of the crust to depths larger than 25 km. Further to the south in the Polish and German area, positive anomalies exist but with sources in the upper and middle crust. We associate these characteristic anomalies to sources from the intensive late Palaeozoic, regional magmatic activity (Ziegler, 1990). Similar sources of large magnetic anomalies can be followed through the crust of the Tornquist Fan, and this whole area exhibits a strong magnetic signal.

The large gravity anomaly values in the western part of the area appear to have a strong source in the mantle. Apparently the density contrast divides Britain into two parts along a NS direction with sources in both the crust and the mantle.

In the central part of the North Sea the CG and VG are well defined by positive anomalies in both the gravity and magnetic fields originating from depths of 3–25 km, indicating that the VG and the northern part of the CG likely are associated with large intrusive complexes in the lower and middle crust which in several places may reach shallow levels. The southern part of CG (south of MONA LISA profile 3) shows negative gravity anomalies in the NGB. The NGB and ADB have significant low anomaly values corresponding to depths of 25 to 50 km (Fig. 8D and E). This may be surprising considering that the MONA LISA profiles 1 and 2 show high seismic velocities in the upper most mantle (Abramovitz and Thybo, 2000) and may therefore rather be ascribed to low density values of the crust, in agreement with the low seismic velocity throughout this area.

The strong seismic reflectivity observed at MONA LISA profiles 1 and 2, between the EL and lineament B is not associated with any positive gravity anomalies (Figs. 4A and 8). This leads us to speculate that the reflectivity in this area may not only originate from lower crustal intrusions (sills) but also from tectonic deformation. Apart from intrusive sills, the high amplitude reflectivity may be caused by contrasting rock types produced by either deformation (compression and/or extension) or by very strong internal deformation that leads to metamorphic reactions (e.g. mylonitization).

The offshore location of the CDF at the MONA LISA profiles (Abramovitz et al., 1998; Abramovitz and Thybo, 2000) coincides with both positive gravity and magnetic anomalies that constitute part of the RFH. From the magnetic upward continuation, there is a clear difference between lithosphere of Avalonia and Baltica origin (Fig. 9E). The Avalonia lithosphere does not show any magnetization in the upper mantle, as also expected from a young terrane with a high heat flow. However, the lithosphere of Baltica may be associated with positive magnetization values in the upper mantle. Apparently, the transition between the Precambrian (Baltica) and the Caledonian terrane in the upper mantle (Fig. 9E) is located to the west of the hypothesized lower crustal suture, as defined from the gravity anomalies. From Fig. 9E, the transition from Avalonia to Baltica at upper mantle levels can be divided into four zones: (1) the non-magnetic Avalonia, (2) a transition zone of low magnetization at the margin of Baltica, (3) a zone of stronger magnetization beneath the Danish Basin and (4) a zone of high upper mantle magnetization in the East European Craton. These results are supported by 3D gravity modelling of mantle density differences in Yegorova et al. (submitted for publication).

4.3.2. Spectral analysis

We apply the method of spectral analysis in order to quantify the differences between the tectonic domains of the North Sea area and to test the hypothesis that the lineament, marked by A and B, coincides with a lower crustal suture as detected in the gravity data and detailed by the Hough Transform and the upward continuation results.

We identify three characteristic types of curves (Fig. 10): (a) curve 1 in the Laurentian area, (b) curves 2 and 4 mainly in the Avalonian area and (c) curves 3 and 5 in areas with Baltica and Laurentia crust. The curve for area 1 is distinctly different from the other curves for wavenumbers larger than 0.025 rad/km but may differ for even lower wavenumbers. However, we have chosen $|\mathbf{k}|=0.025$ rad/km as a distinct marker point for the comparison, also because the region near $|\mathbf{k}|=0$ is the most poorly defined region in the Fourier domain.

From the power spectral properties is evident that area 1 must have a significantly different density distribution. We conclude that area 1 must have a lithosphere distinguishable from the other areas. The spectral properties between areas 2–4 and 3–5 diverge for wavenumbers larger than 0.0625 rad/km (≈ 100 km) indicating that the crustal density properties are

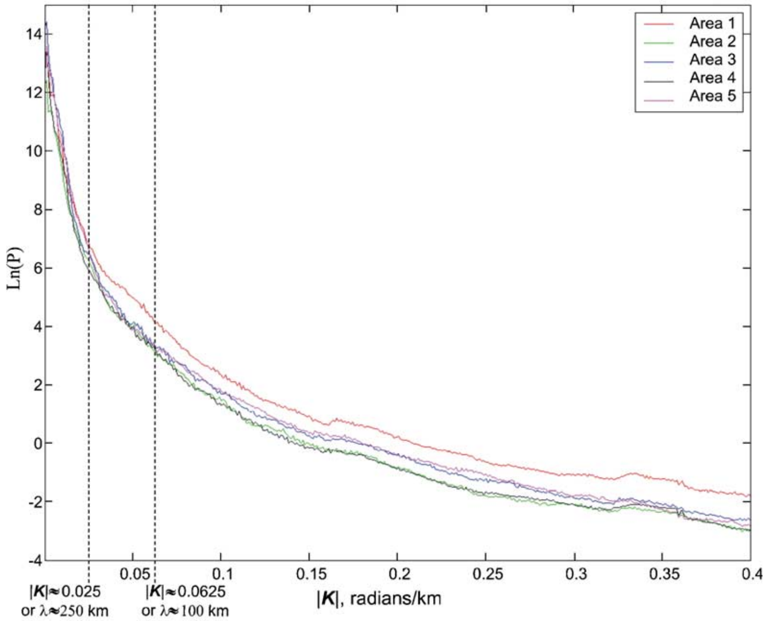


Fig. 10. Radial power spectra for five selected areas, calculated by averaging the Fourier amplitudes calculated from a 5 km upward continued gravity field. The similarity between area 3 and 5 indicates a strong resemblance in density distribution, suggestive of the same middle and lower crustal tectonic provenance (Baltica) of the two areas. Likewise, areas 2 and 4 show similar trends distinctively different from areas 3 and 5, indicating that both areas belong to the same tectonic regime (Avalonia). Area 1 exhibits a clear difference from the other four areas and is interpreted to belong to crust of Laurentia origin. The locations of the areas are shown in Fig. 2.

not similar for these areas. Areas 2 and 4 show a very similar trend and we interpret that the two areas have the same tectonic provenance (Avalonia). The trends of area 3 and 5 are strikingly similar. This is a surprise, since area 3 is in an area with surface of Laurentia origin as defined by the location of the Iapetus Suture (see Fig. 2 and related references). This is a significant result, as it indicates that the crust of area 3 is likely of Baltican, rather than Laurentian affinity.

5. Discussion

5.1. Lower crustal reflectivity

MONA LISA Working Group (1997a,b) presents seismic normal-incidence and wide-angle reflection images of a reflective lower crust beneath the Central Graben (CG) and Horn Graben (HG). S−SW dipping intra crustal reflections around the Caledonian Deformation Front and suture zone transect the whole crust on all four MONA LISA profiles, terminating in the lower crust at a zone of high reflectivity on profile 2. Seismic velocity models along MONA LISA profiles 1 and 2 show a distinct transition at the crust cutting reflections which might represent the deep seismic image of Caledonian deformation structures (Abramovitz et al., 1998; Abramovitz and Thybo, 2000).

The deepest correlated reflection terminates at a distinct anomalous lineament which is characterized by yellow to green colours in the image of the gravity declination vector (marked B in Fig. 4B). These anomalies indicate a deep-seated source that correlates with the onset of high reflectivity in the lower crust. Abramovitz and Thybo (2000) show that the highly reflective lower crust extends southward to the seaward extension of the Elbe Lineament (Fig. 11).

A model based on joint inversion of density and travel time (Nielsen et al., 2000) along MONA LISA profile 3 shows different velocities in the upper and lower crust: ~6.3 to ~6.8 km/s to the east of the Coffeé Soil Fault and 6.1 to 6.2–6.4 km/s to the west of the fault. The authors highlight several features in the model, such as a positive Moho topography in relation to crustal thinning, high lower crustal densities in the central part and elevated velocities and high densities in the upper crust beneath the CG and just west of the HG. We find the velocity of 6.4 km/s significant as similar velocities are found south of the Caledonian suture further to the east. These low velocities are probably responsible for a large part of the differences in the potential field spectra between areas of the North Sea as well as for the existence of the new lineament A + B. The high density (~3000 kg/m^3) lower crust corresponds to the westward continuation of the area of high reflectivity.

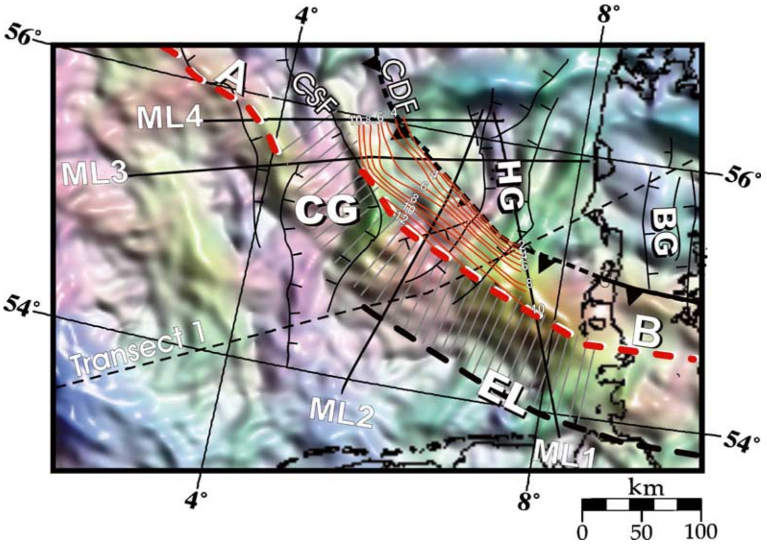


Fig. 11. Zoomed section of the gravity declination vector field with superimposed contours (in s/twt) of the dipping crustal reflections from the MONA LISA deep seismic profiles (contours after Abramovitz and Thybo, 2000). The contours define the depth in s/twt to the reflection from the crustal Caledonian Deformation Front (CDF). Gray hatching defines the area of highly reflective lower crust. A correlation between lineament A and the B appears likely. Illumination direction: 45° declination, 30° inclination.

5.2. Regional tectonic structures

5.2.1. Southern Scandinavia

Southern Scandinavia is characterized by NE–SW trending magnetic anomalies (Fig. 6B). The trend of the anomalies corresponds to the onshore trend of the main Palaeoproterozoic to Mesoproterozic lithotectonic contacts and shear zones of the Sveconorwegian Orogen (Bingen et al., 2001; Bingen et al., 2002; Park et al., 1991). The horizontal gradient amplitude image (Fig. 6B) shows that the Rogaland Igneous Province (RIP) corresponds to a strong positive gradient. RIP is interpreted by Bingen et al. (2003) as a series of mid-crustal intrusions related to the Sveconorwegian Orogenic event (1.03–0.97 Ga). The RIP is set in a belt of magnetic Precambrian granites with ~1.05 Ga intrusions (Bingen et al., 2003) and bordered to the east by the large and deeply seated Late Proterozoic Mandal–Ustaoset Fault Zone (MUFZ). East of, and parallel to, the MUFZ the Porsgrunn–Kristiansand Shear Zone (PKSZ) is believed to be a Gothian (~1.58 Ga) suture zone that was active during the Sveconorwegian Orogenic event (Starmer, 1993). A possible offshore continuation of the MUFZ and PKSZ has been debated, but until now there has been no clear evidence. Our horizontal gradient image shows clear indications of an offshore continuation of both fault zones at a lower to mid-crustal level into the Farsund Basin and the Norwegian Danish Basin across the Sorgenfrei-Tornquist Zone (STZ).

Northeast of the PKSZ the Amot–Vardefjell Shear Zone (AVSZ) is a major late Sveconorwegian boundary, located at the western border of the Palaeozoic Oslo Rift. The AVSZ is regarded as an amphibolite-facies shear zone (Bingen et al., 2003). Trace element analysis indicates an episode of extensive magmatism between 1.19 and 1.13 Ga with intrusion along the AVSZ (Bingen et al., 2003). The horizontal gradient image indicates that this shear zone extends offshore, into the Norwegian Danish Basin.

Southeast of the Oslo Rift the Dalsland Boundary Fault (DBF) and the Mylonite Zone (MZ) are parts of prominent Proterozoic steeply dipping fault zones. The outline of the DBF magnetic anomaly indicates an offshore continuation across the Kattegat to onshore Denmark where it is cut by the STZ. The trend of the MZ apparently changes from NE–SW to E–W at the Swedish coast (Lassen and Thybo, 2004). Also this zone is cut by the STZ. These zones may originally have extended further south and westwards, but the development of the Mesozoic basins and inversion zones may have destroyed their magnetic signature.

5.2.2. The southern North Sea

The southwestern part of the study area is a region of complex basement tectonics. The southern border of East Avalonia was in latest Ordovician times subject to accretion of several Gondwana derived terranes (Banka et al., 2002), the effects of which are evident in the processed maps. The Midlands Microcraton (MMC), a mildly metamorphosed Neoproterozoic basement, is distinguishable in the magnetic declination vector image (Fig. 4D), but less pronounced in the gravity declination vector image (Fig. 4B). A similar signature marks the Anglo Brabant Deformation Belt (ABDB), visible in both declination vector images (Fig. 4B and D) as a NW–SE striking zone. The ABDB represents a zone of basement weakness that can be traced from Wales across the English Channel into Belgium where it is exposed in the Brabant Massif (Banka et al., 2002; Winchester, 2002). The anomalies of the MMC and ABDB in the magnetic declination vector image (Fig. 4D) indicate basement with significant magmatic intrusions to shallow depths. The possibility of lower crustal intrusives is supported by a correlation between strong positive gravity anomalies of long wavelength and the outline of the magnetic zone of the ABDB (Fig. 7).

North of the ABDB, the Dowsing-South Hewett Fault Zone (DSHFZ) likely controlled the Permian to Jurassic development of the Sole Pit Trough and the Anglo-Dutch Basin (Pharaoh, 1999; Winchester, 2002). The northern part of the fault zone is associated with a positive gravity anomaly observed in the long wavelength gravity field (Fig. 7), but the zone almost lacks magnetic signature, only the northernmost part is outlined by the horizontal gradient field (Fig. 6B). The upward continued gravity field (Fig. 8) indicates that the fault is constrained to the upper crust (in accordance with Blundell et al., 1991). The downward projected trace of the fault, however, marks a transition in seismic reflectivity of the mid and lower crust from high reflectivity to the southwest of the fault to low reflectivity or non-reflective north of the fault (Pharaoh, 1999). The positive gravity and magnetic anomaly in the northern part could be caused by mafic or ultra-mafic rocks which were emplaced in the fault plane, indicative of a deep reaching fault zone in the northern part.

The Variscan Front (VF) is not pronounced in the gravity and magnetic images, but coincides with a few elongated anomalies in the horizontal gradient field (Fig. 6B). The VF shows a NE−SW trend parallel to the ABDB and the DSHFZ in its western part and an E−W trend at the southern margin of the North German Basin (NGB).

5.2.3. The Central North Sea

The Viking Graben (VG) and Central Graben (CG) are both associated with positive long wavelength gravity anomalies (Fig. 7). We interpret the cause of these anomalies as high density intrusives at lower to mid-crustal level. Similar magmatic intrusions in the form of sills have been interpreted at several rift structures, e.g. the Pripyat–Dniepr–Donets palaeorift in Ukraine (DOBREfraction Working Group et al., 2003) and the Palaeogene Kenya Rift (Searle, 1970; Thybo et al., 2000). Short wavelength, positive gravity anomalies in the VG and CG, coincide with local magnetic anomalies indicating that magmatic materials have penetrated to shallow levels as intrusive and possibly extrusive complexes. This is supported by the gravity and magnetic model of MONA LISA profile 3 (Lyngsie et al., submitted for publication), which shows high density (~2900 kg/m^3) near vertical intrusions which reaches shallow levels beneath the CG. The model also shows that the upper and mid-crustal transition between rocks of Baltica and Avalonia affinity is located below the Mesozoic CG. Based on the gravity and magnetic model along MONA LISA 3 and the data images presented in this study, we find that the development of the structures related to the Mesozoic CG and VG system, to a large part, may have been determined by pre-existing Caledonian collisional structures.

The Ringkøbing Fyn High (RFH) shows correlation between long wavelength gravity components and a large elongated magnetic anomaly (Fig. 7), with several local magnetic anomalies superimposed. The local anomalies correlate with positive short-wavelength gravity anomalies, and are likely to be graben related tectonic features as well as magmatic intrusives or extrusives (Thybo, 2001).

The Elbe Lineament (EL), which may mark the transition from Avalonia to Baltica in the lower crust does not correspond to any lineament directly observable in the potential fields. However, the position inferred at the MONA LISA profiles from reflection seismic interpretation (Abramovitz and Thybo, 2000) is parallel to a lineament in the gravity declination vector image (Fig. 4B). This lineament (annotated by the letter B in Fig. 4) coincides with the termination of crust cutting reflections and the onset of a reflective/high density lower crust. We interpret it as the onset of high density Baltica lower crust further south and west than the upper crustal Caledonian Deformation Front. Segment B represents, as such, the suture zone between overthrusted Avalonia crust and Baltica crust at a mid to lower crustal level. The area between segment B and the CDF experienced thin-skinned Caledonian crustal deformation.

The observed gravity and declination vector images (Fig. 4A and B) indicate that there may be a continuation of the EL across the CG and a possible link to lineament A (Fig. 11). If lineament A relates to a tectonic structure, lower crust of Baltica affinity extends as far across the northern North Sea as to Scotland and underneath the Iapetus Suture in the lower crust. This implies that the southeastern part of lineament A represents the lower crustal suture zone between Avalonia and Baltica and the northwestern part of lineament A represents the lower crustal suture zone between Laurentia and Baltica.

The northwestern part of lineament A transects a complex tectonic region. We argue that the lineament defines the eastern limit of an accretionary wedge, bounded by the Highland Boundary Fault (HBF) to the north and the Iapetus Suture (IS) to the south. This wedge comprises several terranes of which the two largest are the Midland Valley and the Southern Uplands terranes. The Midland Valley terrane accreted to southern Scotland in Late Ordovician accompanied by large strike-slip movements along the HBF which separates the Grampian Highlands from the Midland Valley complex (McKerrow and Soper, 1989; Soper and Hutton, 1984). Ocean floor trench assemblages are believed to have accreted to the Midland Valley terrane along the Southern Uplands Fault (SUF) during the Late Ordovician and Silurian as part of the northwestward subducting oceanic plate, creating the Southern Uplands (Leggett et al., 1983). Both the HBF, the SUF and the IS are believed to have undergone major strike-slip movements during the Late Ordovician or Silurian (the time during which accretion of the Southern Uplands took place), likely as a response to oblique subduction at the northern margin of the Iapetus Ocean (Hutton, 1987; Leggett et al., 1983; McKerrow and Soper, 1989; Soper and Hutton, 1984).

The SUF is, by some researchers believed to be a deeply penetrating structure, possibly crust cutting (e.g. Leggett et al., 1983 and Freeman et al., 1988), while other researchers argue in favour of an upper crustal thrust structure (e.g. Bluck, 1985 and Needham and Knipe, 1986). There is a feature at the fault in the LISPB model (Bamford et al., 1978), but is hard to identify in the deep reflection seismic profiles (LISPB, NEC, MOBIL 2 and 3), probably due to the steep inclination of the fault plane and the fact that the profiles are aimed at imaging the lower crust. The offshore continuation of the SUF has not been described in the literature, but Blundell et al. (1991) correlate a reflective pattern on profiles NEC and MOBIL 2 and 3 with the offshore projection of the SUF, indicative of an eastward extension of the SUF to the MOBIL 3 profile.

The IS has been interpreted as a dipping reflection in the lower crust rather than a contrast in geophysical properties. The reflection is generally believed to be the southern limit of a northward subduction complex in the lower crust (Freeman et al., 1988; Soper et al., 1992). The reflection has been correlated in the deep reflection seismic profiles WINCH, LISPB and NEC (Bamford et al., 1978; Barton, 1992; Freeman et al., 1988; Klemperer and Matthews, 1987). On all three profiles the authors correlate reflective seismic patterns and there seems to be a general consensus of a subdivision of the lower crust into four terranes: (1) Midland Valley lower crust bounded to the north by the HBF and to the south by the SUF, (2) a highly reflective subcontinental subduction complex bounded by the SUF to the north and the IS to the south, (3) Lake District lower crust bounded by the IS to the north and possibly underthrusted by (4) the Midland Platform to the south (Freeman et al., 1988). The continuation of the structures further into the North Sea has been investigated by Freeman et al. (1988), Blundell et al. (1991) and Soper et al. (1992) who correlate the reflectivity on the deep seismic profiles NEC, MOBIL 2, 3 and NSDP85-7. The IS looses amplitude between the NEC profile and the NSDP85-7 and is difficult to identify on the latter. The direction of the NSDP85-7 profile is perpendicular to the expected strike direction of the IS suture and the same reflection characteristics as on NEC are observed, although less distinct. The dip of the suture changes from about 25° west of Britain to about 40° at the NSDP85-7 profile. The increased dip at NSDP85-7 could be a response to the proximity to the hypothesized lineament A.

5.2.4. Tectonic implications

The scenario described above for the accretionary wedge includes oblique subduction, large sinistral strike-slip movements along the HBF, SUF and IS, possible termination of the SUF at the location of lineament A, and increased dip and weakening of reflectivity of the IS. We believe that these are indications for the presence of lower crust of Baltic affinity to the west of the Mesozoic rift structures in the northern North Sea. The closure of the Iapetus Ocean between Norway and Greenland took place during Wenlock and Ludlow and the subduction under Scotland and accretion of terranes continued during the Early Devonian. The final closure between Scotland and England most likely did not occur until late in Early Devonian times (Leggett et al., 1983). If the Tornquist Sea already closed by Late Ashgillian, as indicated by benthic ostracodes and non-marine fish (Cocks and Fortey, 1982; McKerrow, 1988), our hypothesized lineament A would most likely be a lower crustal tectonic structure, which acted as the eastern boundary during the last stages of continental collision and subduction between Avalonia and Laurentia. The presence of this lower crustal boundary may, as such, explain the strike-slip movements of the HBF, SUF and IS, the rotation of the Southern Uplands and the oblique subduction below Scotland, as compensation for the triangular geometry.

We suggest that the IS continue across the North Sea with the same trend as proposed by Ziegler (1989) (see Fig. 2) but that the suture, where it crosses lineament A, is confined to upper and mid-crustal levels, whereas the lower crust beneath the CG and the southern part of the VG is of Baltica origin. The Caledonian tectonic scenario to the north-east of segment A would therefore be thick-skinned, and thin-skinned tectonics would be restricted to the upper crustal regions situated between the Iapetus Suture and the front of the Caledonian deformation. Lyngsie and Thybo (submitted for publication) show by 2 1/2D gravity and magnetic modelling along MONA LISA profile 3 that northward thrusting of Avalonia upper crust over Baltica lower crust has a ramp-flat-ramp geometry, and that Avalonia upper crust extends eastward to lineament B. Baltica lower crust has high density values (~2968 kg/m^3) between lineament B and the EL on MONA LISA 3 and correlates with a zone of high reflectivity interpreted in the reflection seismic section (Abramovitz and Thybo, 1999). It seems likely that lineament A and B are connected across the CG (Fig. 11) and that they mark the westward extent of Baltica lower crust. However, they are likely not related in time as the southern Caledonian deformation took place prior to the closure of the Iapetus Ocean.

Based on the presented results we suggest that the enigmatic lineament A–B is the lower crustal expression of the continental suture between the three juxtaposed continents and that thick-skinned tectonics dominated the Caledonian orogeny to the east of lineament A and south of lineament B in the northern and central part of the North Sea.

6. Conclusions

We have shown that transformation techniques applied to the gravity and magnetic fields can reveal detailed structures of both regional and local scale. The potential field data indicate fundamental differences between crustal domains of the North Sea. We have shown that tectonic structures observed onshore correlate with lineaments observed in the potential fields beneath the Norwegian Danish Basin and the Skagerrak–Kattegat Platform. Based on the transformation images, we hypothesize that the Caledonian suture zone continue as a lineament in the lower crust across the North Sea between Scotland and northern Germany and that the Central Graben and Viking Graben rift systems coincide with the upper crustal suture between Avalonia and Baltica in the central parts of the North Sea. This interpretation indicates a generic connection between Caledonian collisional structures and the later rifting events in the area.

We present a new model of the long debated collisional history of the three continents Avalonia, Laurentia and Baltica, and hypothesize that Baltica lower crust extends across the entire northern part of the North Sea. We further suggest that the Iapetus Suture defines the southern extent of a thick-skinned tectonic regime. This implies that Laurentia crust has been thrust over Baltica lower crust, and that the enigmatic lower crustal lineament is the missing link in the interpretation of the docking history between Baltica, Avalonia and Laurentia.

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