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A new tectonic model for the Laurentia−Avalonia−Baltica sutures in the North Sea: A case study along MONA LISA profile 3

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Abstract

We present a new model for the lithospheric structure of the transitions between Laurentia, Avalonia and Baltica in the North Sea, northwestern Europe based on 2¾D potential field modelling of MONA LISA profile 3 across the Central Graben, with constraints from seismic P-wave velocity models and the crustal normal incidence reflection section along the profile. The model shows evidence for the presence of upper-and lower Palaeozoic sedimentary rocks as well as differences in crustal structure between the palaeo-continents Laurentia, Avalonia and Baltica. Our new model, together with previous results from transformations of the gravity and magnetic fields, demonstrates correlation between crustal magnetic domains along the profile and the terrane affinity of the crust. This integrated interpretation indicates that a 150 km wide zone, characterized by low-grade metamorphosis and oblique thrusting of Avalonia crust over Baltica lower crust, is characteristic for the central North Sea area. The magnetic susceptibility and the density across the Coffee Soil Fault range from almost zero and 2715 kg/m^3 in Avalonia crust to 0.05 SI and 2775 kg/m^3 in Baltica crust. The model of MONA LISA profile 3 indicates that the transition between Avalonia and Baltica is located beneath the Central Graben with a ramp–flat–ramp geometry. Our results indicate that the initial rifting of the Central Graben and the Viking Graben was controlled by the location of the Caledonian collisional suture, located at the Coffee Soil Fault, and that the deep crustal part of Baltica extends further to the west than hitherto believed.

Keywords: Potential field modelling; Tectonic structures; Lineaments; Suture zones; Rifting

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1. Introduction

The Mesozoic syn- and post-rift activity and fault geometry of the Central Graben and Viking Graben are well described, whereas there is limited data on the pre-Zechstein structures and rift geometry of the sedimentary sequences and crystalline basement. In order to obtain a better understanding of the plate tectonic history of the North Sea area, we use potential field data as a primary source, constrained by seismic reflection/refraction data and borehole data integrated with previous results of transformations of potential fields on a regional scale (Lyngsie et al., 2006). We focus on a part of the North Sea, which is believed to cover the transition between the main continents and terranes involved in the Caledonian orogeny: Baltica, Laurentia and East Avalonia.

The study area is characterized by extensional structures: the Central-and Viking Graben rift system and the Horn Graben and by basement highs: the Mid North Sea High (MNSH), the East North Sea High (ENSH) and part of the Ringkøbing-Fyn High (RFH) (Fig. 1). Recent reprocessing and reinterpretation of

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commercial reflection seismic data and of wide-angle reflection/refraction seismic data have revealed new geological information on: (1) pre-Zechstein, Palaeozoic sequences of substantial thickness (5–7 km) (Zhou and Thybo, 1997; Abramovitz and Thybo, 1999, 2000; Scheck et al., 2002b) and (2) on deformation structures in the crystalline basement (Vejbaek, 1990; Abramovitz and Thybo, 1999; Lassen et al., 2001; Lassen and Thybo, 2004).

Before the MONA LISA project in 1993–1995 (MONA LISA Working Group, 1997b) little was known about the structural relationship between Baltica and Avalonia around the Central Graben. With the MONA LISA data the probable location of the Baltica−Avalonia suture was identified.

We investigate differences in physical parameters of the crust across the Baltica−Avalonia transition by 2¾D gravity and magnetic modelling of the deep seismic MONA LISA profile 3 (location shown in Fig. 1), constrained by existing P-wave velocity models and normal incidence reflection seismic data. To locate continental palaeo-terranes on a regional scale, we use 2D spectral analysis in combination with recently published 2D gravity and magnetic models of the seismic profiles MONA LISA 1, 2 and Transect 1 (Williamson et al., 2002) as well as with regional studies of potential field data (Lyngsie et al., 2006). Knowledge of the locations of the sutures are important for understanding the processes of subsequent rifting and basin formation, and plays an important role in unravelling the tectonic history of the European lithosphere.

In this study we address the following questions:

1. Can integrated potential field modelling techniques be used to differentiate between crustal areas of different affinity and origin e.g. Baltica and Avalonia crust?
2. Did pre-Permian structures exert control on the evolution of the Mesozoic basins?
3. What is the areal extent of Baltica crust beneath the North Sea?

2. Geological setting

The North Sea area shows signs of activity of plate tectonic processes since the Proterozoic (Fig. 1). This is evident in the seismic character of the crystalline crust in

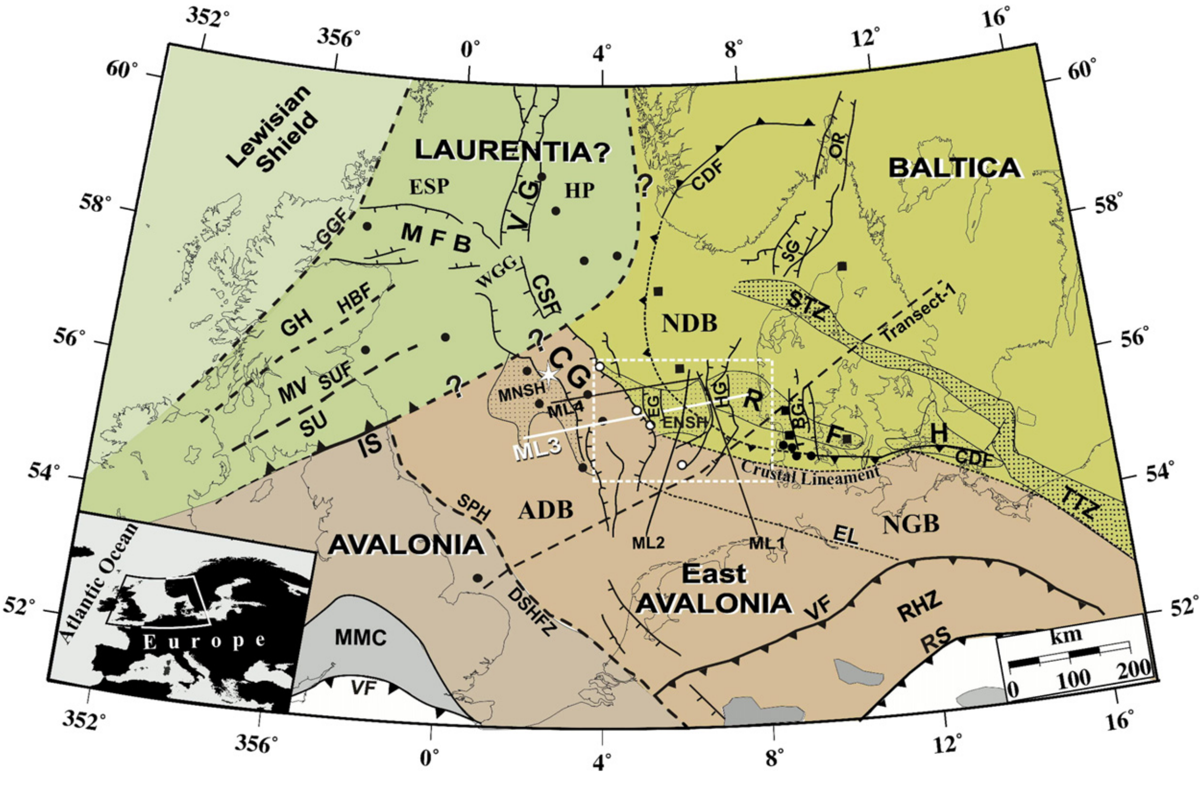


Fig. 1. Main tectonic features and deep seismic lines in the North Sea area. Black squares indicate boreholes with Precambrian basement (880–825 Ma), black dots indicate boreholes with possible Caledonian basement (450–415 Ma) and open circles indicate possible Precambrian basement with a low-grade metamorphic overprint. The white star shows the approximate location of the Clyde oil field. Abbreviations as in Table 1. (After MONA LISA Working Group, 1997b).

Table 1
Abbreviations used in the text and figures

ADB	Anglo–Dutch Basin
ABDB	Anglo–Brabant Deformation Belt
AM	Amorican Massif
BG	Brande Graben
CDF	Caledonian Deformation Front
CG	Central Graben
CSF	Coffee Soil Fault
DBF	Dalsland Boundary Fault
DSHFZ	Dowsing–South Hewett Fault Zone
EG	Else Graben
EL	Elbe Line
ESP	East Shetland Platform
ENSH	East North Sea High
GGF	Great Glen Fault
GH	Grampian Highlands
HBF	Highland Boundary Fault
HG	Horn Graben
HP	Horda Platform
IS	Iapetus Suture
LRL	Lower Rhine Lineament
MFB	I\1orray Firth Basin
ML 1 – 4	MONA LISA profiles 1 – 4
MMC	Midlands Microcontinent
MNSH	Mid North Sea High
MUFZ	Mandal Ustaoset Fault Zone
MV	Midland Valley
MZ	Mylonite Zone
NDB	Norwegian–Danish Basin
NGB	North German Basin
OBH	Ocean Bottom Hydrophone
OR	Oslo Rift
PKSZ	Porsgrunn–Kristiansand Shear Zone
RFH	Ringkøbing-Fyn High
RFZ	Rømø Fracture Zone
RHZ	Rhenohercynian Zone
RIP	Rogaland Igneous Province
RM	Rhenish Massif
RS	Rheric Suture
SB	Scania Batholit
SG	Skagerrak Graben
SGH	Silkeborg Gravity High
SPH	Sole Pit High
SU	Southern Upland
SUF	Southern Upland Fault
STZ	Sorgenfrei Tornquist Zone
TTZ	Teisseyre–Tornquist Zone
VF	Variscian Front
VG	Viking Graben
WGG	Witch Ground Graben

the Scandinavian part of the Baltic Shield, where Gothian or Sveconorwegian orogenic structures indicate episodes of Proterozoic amalgamation of crustal domains which are overprinted by Late Precambrian extension that likely reactivated Sveconorwegian basement shear zones (Lassen et al., 2001; Lassen and Thybo, 2004). During the Cambrian, the Baltica shelf was a passive margin bounded by two oceans. From Early Ordovician to Early Silurian, the oceans were subducted and subsequent triple plate collision resulted in the Caledonian orogeny (Ziegler, 1990a).

The Caledonian collision involved three continents: Baltica, Laurentia and Avalonia (Fig. 1). Prior to collision, the Tornquist Ocean separated Baltica (east) from Avalonia (south), and the Iapetus ocean separated Laurentia (west) from the two opposing continents (Ziegler, 1990a; Cocks et al., 1997). Palaeomagnetic and faunal studies, indicate that the collision between Baltica and Avalonia was prior to the collision between Laurentia and Avalonia (Cocks and Fortey, 1982; Torsvik et al., 1996; Cocks et al., 1997; Cocks, 2002; Cocks and Torsvik, 2002; Verniers et al., 2002; Torsvik and Rehnstrom, 2003).

The Late Ordovician to Early Silurian continental collision resulted in the Caledonian orogeny and created a deep foreland basin in the Danish part of the Scandinavian area (Thybo, 1990; Ziegler, 1990b; Thybo, 2001). The orogeny supplied large amounts, possibly several kilometres, of sediments to the foreland basin (Berthelsen, 1992). In the central and southern North Sea a distal foreland basin had formed during the Devonian in response to the Variscan orogeny (Ziegler, 1990b). This foreland basin possibly also accumulated several kilometres of sediments from the Caledonides. During the Late Silurian and Devonian, both the Scottish−Norwegian and German−Polish Caledonides collapsed. By the end of the Carboniferous, the Variscan orogenic compression activated a system of conjugate shear faults over the entire north-west Europe (Ziegler, 1990b). In the Scandinavian area the extensional tectonic regime created or reactivated the Tornquist Fan, a splay of faults that linked NNE to SSW trending graben structures during this period (Berthelsen, 1992; Thybo, 1997). In the North Sea, extension imposed by the Caledonian and Variscan orogeny resulted in crustal thinning and subsidence of the Northern and Southern Permian Basins. The extension and crustal thinning was associated with widespread intrusive and extrusive magmatism, with an apparent magmatic locus in the North Sea along the southern flank of the Ringkøbing-Fyn High (Dixon et al., 1981). According to Dixon et al. (1981), the petrochemical character of the extrusives in the North Sea has a bi-modal transitional basalt-rhyolitic signature, indicating that the area lies midway between two Carboniferous−Permian volcanic provinces: to the north the Oslo Province with an alkaline petrochemical character and to the south, the northern and central German basins with a more calc-alkaline character. In the central North Sea, along the southern flank of the Ringkøbing-Fyn High, the volcanics are primarily basaltic (Dixon et al., 1981).

By latest Carboniferous–early Permian, the North Sea was affected by regional uplift and deep erosion of the Carboniferous and Devonian sediments (Ziegler, 1990b). The resulting unconformity is a regional seismic reflector and is considered as the traditional acoustic basement in most interpretations of reflection seismic data from the North Sea. During the rest of the Permian, both the northern and southern Permian basins subsided.

By Early Triassic time, most of Europe was subject to regional tensional stresses and reactivation of pre-Permian fracture systems, resulting in, what is commonly regarded as the main rift stage of the North Sea rift system. Regional subsidence continued until the Middle Jurassic, when the central North Sea became uplifted and eroded, a process which contributed to the development of major sandstone reservoirs in the northern North Sea (Ziegler, 1990b). The rate of crustal extension and subsidence of the North Sea rift system accelerated during the Late Jurassic−Early Cretaceous and lasted until the recent inversion phase simultaneous with the Alpine intra plate compression.

2.1. The northern North Sea

Deep seismic data in the northern North Sea (i.e. the NSDP, MOBIL and the BIRPS surveys), suggests that pre-existing Caledonian, or possibly older, thrust planes controlled the tectonic development of the Palaeozoic and Mesozoic extensional basins (Frost, 1987; Gibbs, 1987; Cornford and Brooks, 1989). Devonian and Carboniferous rift basins, which may be regarded as precursors to the Viking Graben, are present throughout the northern North Sea (e.g. Ziegler, 1990b; Gluyas et al., 2005; Richardson et al., 2005). The structural style of these basins, indicate that they formed by extensional reactivation of pre-existing basement thrust sheets of Caledonian age in the central and western North Sea and possibly late Precambrian shear zones on the Norwegian margin (Frost, 1987; Gibbs, 1987; Austrheim and Mørk, 1988; Hurich and Kristoffersen, 1988; Tsikalas et al., 2005). After the Caledonian orogeny Late Palaeozoic basins formed as a result of extensional orogenic collapse. Tilted Triassic and Lower Jurassic fault blocks are identified on both sides of the Viking Graben and appear to be controlled by major E and W-dipping faults that sole out in the lower-and middle-crust. They may have formed as a result of extensional reactivation of Caledonian thrusts (Frost et al., 1981; Frost, 1987; Gibbs, 1987; Pinet and Colletta, 1990; Torsvik et al., 1992). The extensional Mesozoic North Sea basins most likely developed by further reactivation of the Caledonian thrust planes and, possibly, with strong influence from stable basement features such as the Horda Platform (Frost, 1987; Gibbs, 1987; Jones et al., 2005).

2.2. The central and southern North Sea

The southern North Sea comprises a collage of terranes, with Gondwana affinity. The two major terranes are Avalonia and East Avalonia (Fig. 1). Avalonia constitutes the central part of Britain. It is separated from East Avalonia by the Dowsing-South Hewett Fault zone (DSHFZ), a presumed Ordovician terrane boundary with strong physical contrast to the crust on either side (Lee et al., 1993; Pharaoh et al., 1995; Pharaoh, 1999; Winchester, 2002). East Avalonia constitutes the central and eastern part of the North Sea and is presumed to extend eastward from the DSHFZ for several hundreds of kilometres beneath the Anglo–Dutch Basin (ADB) and the North German Basin (NGB). However, the geometry and the exact location of the suture between Baltica and Avalonia are uncertain and East Avalonia may extend northwards beyond the Elbe Line (EL) (Pharaoh, 1999; Torsvik and Rehnstrom, 2003). The area between the EL and the Caledonian Deformation Front (Fig. 1) may be defined as a Caledonian marginal thrust belt, which extends from the southwestern North Sea across northern Germany to the island of Rügen and possibly beyond (Meissner et al., 1994; Abramovitz and Thybo, 2000; Lassen et al., 2001; Bayer et al., 2002). The Upper Palaeozoic sediments in this presumed thrust zone represents Caledonian low-grade metamorphosed shelf slope sediments that have been thrusted above a Cambro−Silurian cover which was deposited on the passive margin of Baltica prior to the continental collision (Berthelsen, 1992).

2.3. Southern Scandinavia (the shelf of Baltica)

By Late Silurian, the Caledonian foreland basin covered most of the present day southwestern Scandinavia. The continental collision between Baltica and Avalonia incorporated the Caledonian foredeep in a thrust belt. Analysis of the traces of this thin-skinned tectonic evolution indicates that Ordovician deep marine turbidites, belonging to Avalonia were thrust over a platform of undeformed Baltica shelf type sediments of Lower Cambrian Orthoquartzites and Cambro−Ordovician black shales (Buchardt et al., 1997; Lassen et al., 2001). At the Rotliegendes a changing stress-field, or post-orogenic collapse of the Caledonides resulted in erosion such that the top Rotliegendes seismic horizon today marks a regional unconformity.

2.4. Indications of continental collisions in the study area

The upper crustal collision zone between Avalonia and Baltica has been identified in onshore Denmark and Norway. The northern limit is known as the Caledonian Deformation Front (CDF). It separates 450 to 415 Ma old Caledonian deformed sediments (Avalonia) to the south and west, from more than 825 Ma old Precambrian crystalline basement (Baltica) to the north and east (Larsen, 1971; Frost et al., 1981; Ziegler, 1990a; MONA LISA Working Group, 1997b).

Models of seismic velocity and density along MONA LISA Profiles 1, 2 and 3 show that the CDF represent the transition between an Avalonia type crust, characterized by two crustal layers and a Baltica type crust, characterized by three crustal layers. The two crustal types are clearly differentiated by their P-wave velocity and density values: Avalonia is associated with low crustal P-wave velocities (5.8–6.4 km/s) and low upper crustal density (2715 kg/m^3), whereas Baltica is associated with high P-wave velocities (6.1–7.2 km/s) and high upper crustal densities (2775 kg/m^3) (Abramovitz et al., 1998; Abramovitz and Thybo, 2000; Williamson et al., 2002).

A zone of high reflectivity and velocity is identified to the north of the CDF in the lower crust on MONA LISA Profile 2. Abramovitz and Thybo (2000) interpret this zone as representative of either intruded Baltica lower crust, remnant Tornquist Sea oceanic crust, or a former island arc. The reflective lower crust terminates, towards the north, at the onset of a band of crust cutting SW dipping crustal reflections around the CDF and, towards the south, with the presumed offshore continuation of the Elbe Line (EL).

The EL is a WNW–ESE striking deep crustal boundary. Beneath the North German Basin the lineament represents a lower crustal transition from high P-wave velocities (6.9–7.1 km/s) north of the boundary to low velocities (6.4–6.7 km/s) south of the boundary (Thybo, 1990, 2001; Scheck et al., 2002a). A similar velocity discontinuity is identified in other wide-angle refraction and normal incidence reflection seismic profile (e.g. MONA LISA, EGT, DEKORP BASIN’96, and POLONAISE’97) in Poland (Jensen et al., 1999), northern Germany (Rabbel et al., 1995) and the North Sea (Abramovitz et al., 1998; Abramovitz and Thybo, 2000). It is further identified as a transition between high and low density in potential field data (Banka et al., 2002; Williamson et al., 2002) and it is approximately coincident with a change in the faunal distribution (Cocks et al., 1997). The transition zone between the CDF and the EL is associated with thin skinned tectonics as crust of Avalonia affinity was thrust over the passive margin of Baltica (Thybo, 1990; McCann and Krawczyk, 2001; Thybo, 2001).

The suture between Laurentia and Avalonia is known as the Iapetus Suture zone (IS). It is traceable from offshore western Ireland across the Irish Midlands and the British Isles to the North Sea (Fig. 1). The suture between Laurentia and Baltica in the North Sea is hidden beneath the present shelf to the west of the Scandinavian Caledonides (Soper et al., 1992; Snyder et al., 1997). The hypothesized continuation of the IS across the Central Graben and along the Norwegian coastline (Ziegler, 1990a) is based on a few boreholes reaching crystalline crust (Frost et al., 1981).

3. Data sources

3.1. Gravity and magnetic data

The potential field data (gravity and magnetic) are extracted from grid-compilations made by the Trans-European Suture Zone Potential Field Group (Wybraniec et al., 1998). The gravity database consists of Bouguer anomalies onshore and free-air anomalies offshore (Fig. 2A). 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 already existing data using the USGS potential field software package (Cordell et al., 1992).

The total-field aeromagnetic anomaly data (Fig. 2B) is based on digitised high-resolution aeromagnetic maps of the Danish area provided by the Geological Institute, University of Copenhagen, and of the Polish area provided by Polish Institute of Geophysics, Warsaw, merged with data from the Geological Survey of Canada (Verhoef et al., 1996). The merged magnetic dataset was smoothed in order to minimize edge effects (Wybraniec et al., 1998).

3.2. Borehole data

The borehole data used in this study are based on hydrocarbon exploration data published by the Danish Geological Survey (Nielsen and Japsen, 1991). The boreholes are chosen in the vicinity of MONA LISA profile 3. Direct measurements of magnetic susceptibility on borehole-cores from the area have been carried out by Williamson et al. (2002).

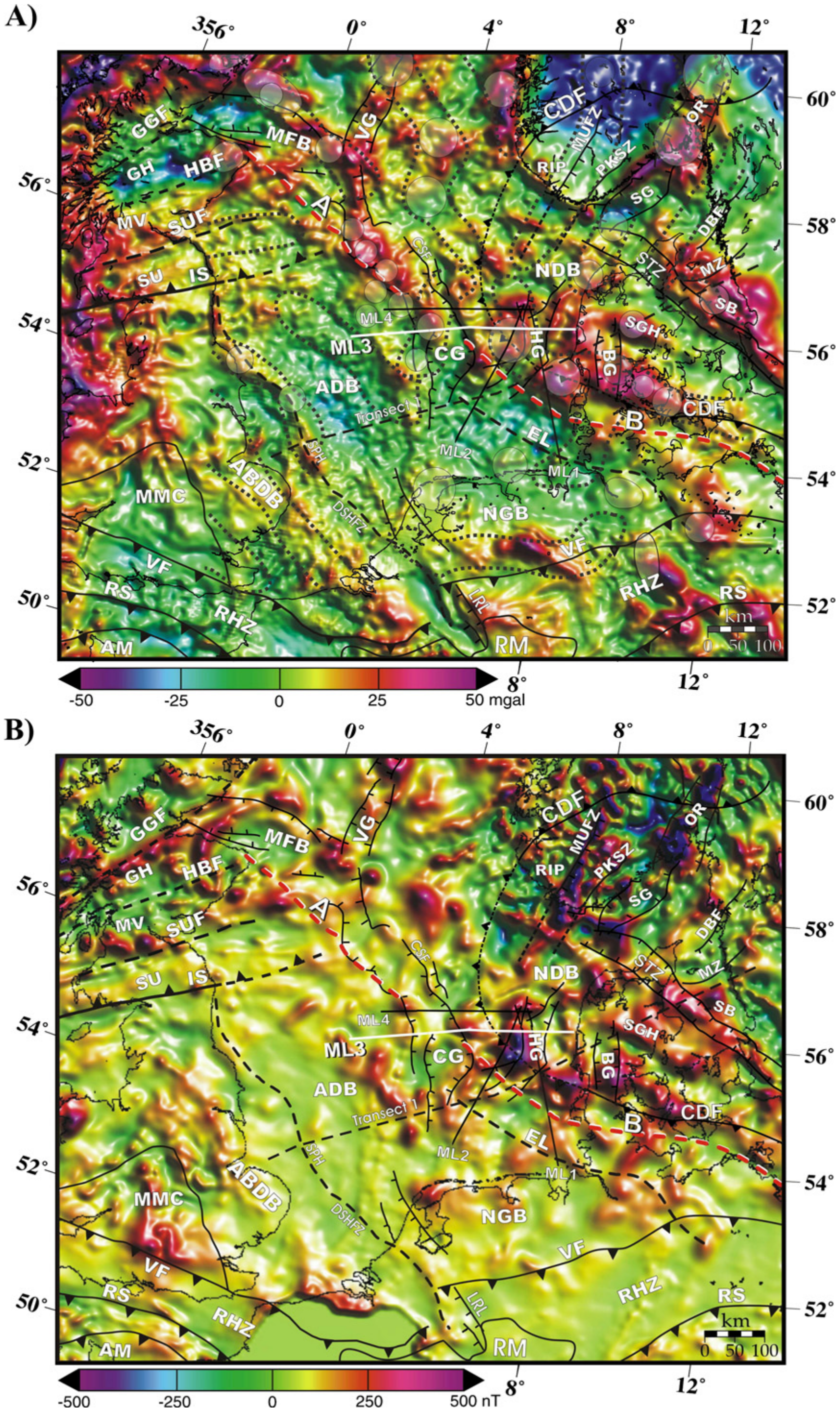


Fig. 2. A) Image of the observed Bouguer and Free-air gravity anomaly with main tectonic features superimposed. The location of local magnetic bodies is shown as circles while the extent of larger magnetic bodies is indicated by dashed lines. The identification of magnetic bodies is based on calculation of the pseudogravity anomaly by Lyngsie et al. (2006). The local magnetic anomalies in the rift zones and at the location of the Caledonian Deformation Front (CDF) are coincident with areas of short wavelength gravity anomalies and possibly relate to magmatic intrusives. Note the regional lineament (lineament A and B) traceable from Germany to Scotland. This lineament was identified and analysed in Lyngsie et al. (2006), but the authors were not able to make a positive correlation across the CG. Illumination direction: 45° declination, 30° inclination. After Lyngsie et al. (2006). Abbreviations as in Table 1. B) Image of the total magnetic field anomaly. The Danish area and the Baltic Shield are characterized by strong high-frequency anomalies associated with shallow crustal and perhaps even sedimentary intrusive complexes. A clear difference in magnetic signature can be observed between Baltica and Avalonia which is only weakly magnetised. Illumination direction: 45° declination, 30° inclination. Abbreviations as in Table 1.

3.3. Seismic data

A major source of seismic information on the deep sedimentary cover, the crystalline crust and the upper mantle originates from the MONA LISA survey (MONA LISA Working Group, 1997a,b) in the southeastern North Sea. The main objectives of the MONA LISA project were to locate and evaluate crustal structures of the Caledonian collision suture between Baltica and Avalonia, and to investigate structures related to lithospheric thinning and extension during the formation of basins and grabens of Palaeozoic and Mesozoic age. The data set consists of four deep seismic normal incidence reflection profiles recorded to 26 s (twt) and coincident wide-angle reflection/refraction data recorded by 26 onshore mobile seismometers and 29 ocean bottom hydrophones (OBH's) along profiles 1,2 and 3.

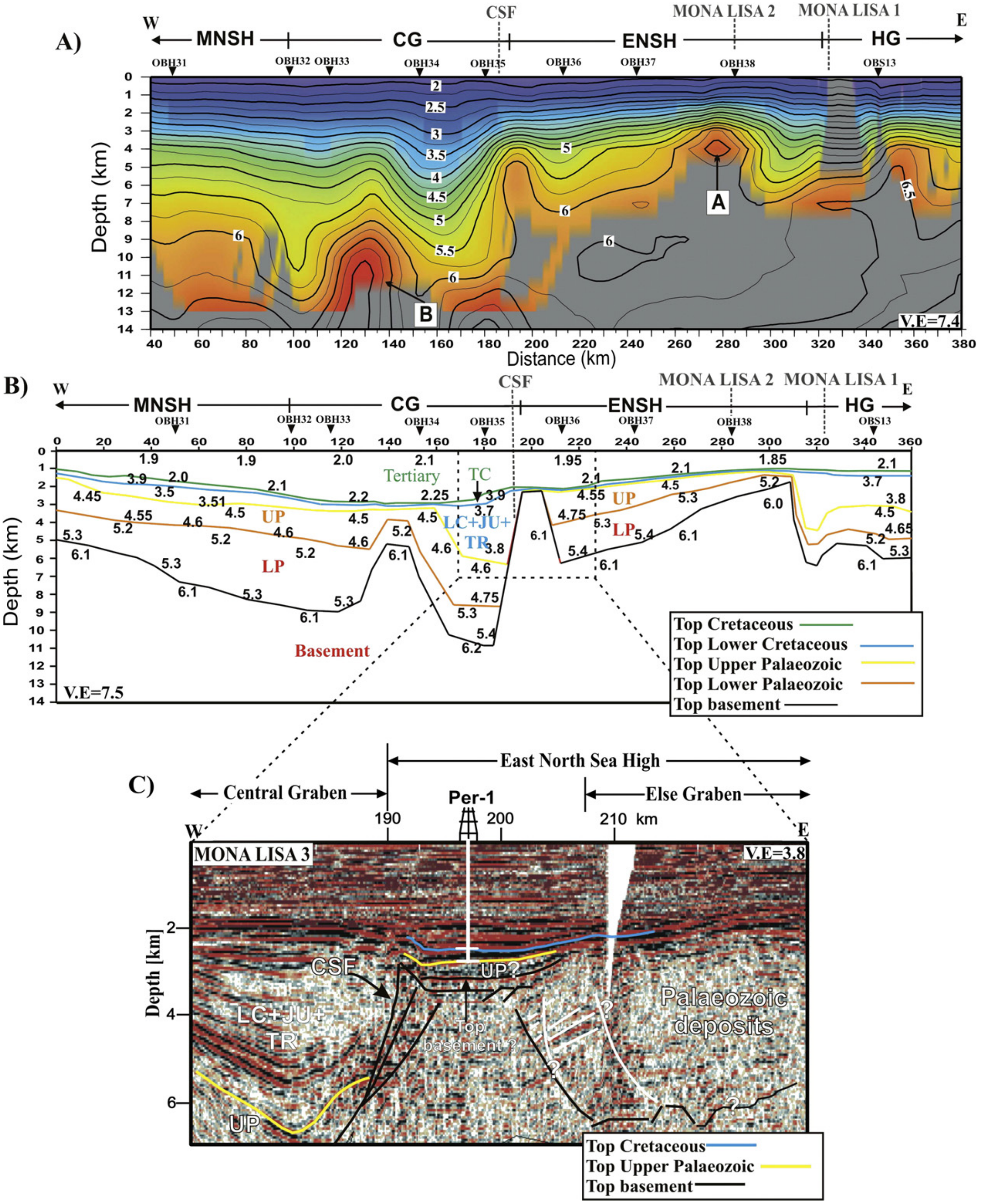
4. Seismic interpretations of the MONA LISA profiles

One of the main results of the MONA LISA project was a set of images of orogenic structures and reflectivity characteristics of the crust and lithospheric mantle, which enabled mapping of the CDF on all four profiles (MONA LISA Working Group, 1997a,b). MONA LISA profile 3 extends along the strike of the Mid North Sea – Ringkøbing-Fyn High (MNSH and RFH), a structural E–W trending high which separates the northern and southern Permian Basins. The profile transects the N−S striking Central Graben (CG), Else Graben (EG) and Horn Graben (HG) (Fig. 1). Based on OBH data recorded along profile 3, Nielsen et al. (2000) presents a P-wave velocity model, which shows a positive Moho relief beneath the CG and a lateral change in P-wave velocities between low crustal velocities of ~6.4 km/s in the western part and ~6.9 km/s in the eastern part of the profile. Substantial amounts of Palaeozoic sedimentary rocks along the entire profile were interpreted by seismic tomography and raytracing (Nielsen et al., 2005). The seismic models show elevated velocities beneath the CG and in parts of the RFH, which may indicate the presence of intrusive complexes.

MONA LISA Working Group (1997a,b) interprets intra-crustal S−W dipping reflections around the CDF and the Caledonian suture zone which cut through the whole crust on all four MONA LISA profiles. On profile 2, the reflections terminate in the lower crust at a zone of high reflectivity. Velocity models along MONA LISA profile 1 and 2 show a distinct change in velocity at the crust cutting reflections, which may represent the deep seismic image of Caledonian deformation structure (Abramovitz et al., 1998; Abramovitz and Thybo, 2000). If so, Avalonia crust was thrust over Baltica lower crust in a ramp–flat–ramp style. Lyngsie et al. (2006) show that the deepest correlated reflections terminate at a distinct lineament, which is traceable across the entire North Sea from the Grampian Highlands of Scotland to northern Germany and that this lineament correlates with the onset of high reflectivity in the lower crust (Abramovitz and Thybo, 2000). The MONA LISA profiles show that this reflective lower crust extends southward to the offshore continuation of the Elbe Line.

A crustal model of seismic velocity, based on joint inversion of density and travel time of MONA LISA profile 3 (Nielsen et al., 2000) shows a change in velocity of the upper and lower crust at the Coffee Soil Fault (CSF): ~6.3/~6.8 km/s to the east of the fault and 6.1−6.2/6.4 km/s to the west of the fault. This velocity distribution supports the hypothesis that crust of Avalonia has been thrust over crust of Baltica. The authors highlight several features in the model, such as positive Moho relief below the CG, high densities in the lower crust in the central part of the profile and elevated velocities and high densities in the upper crust beneath the CG and in the East North Sea High (ENSH). We find that the high density lower crust (~3000 kg/m^3) may correspond to the south-westward continuation of the area of high reflectivity as identified in the reflection seismic profile by MONA LISA Working Group (1997a,b).

Based on first arrival tomography and ray-trace modelling of primary and secondary arrivals, Nielsen et al. (2005) present a detailed model of P-wave velocities along profile 3 to depths of ~14 km showing high velocities in the upper crust beneath the CG and in the ENSH (Fig. 3A and B). However, the lateral extent of the high velocity anomalies beneath the CG are poorly constrained, and may be narrower than shown in the model, as the tomographic method tends to smear the velocity anomalies. The tomographic model (Fig. 3A) indicates the existence of thick sequences of Palaeozoic sedimentary rocks. These sequences extend along almost the entire profile, and include an Upper Palaeozoic sequence with seismic velocities ranging from ~4.5 to ~5.2 km/s and a Lower Palaeozoic sequence with velocities in the range of 5.2 to 6.0 km/s. The Palaeozoic sequences are thickest to the west of the Coffee Soil Fault (model distances km 120 and 180). Palaeozoic sequences are also identified by Cartwright (1990) as present in the Else Graben (EG), located between the CG and the HG. Cartwright (1990) interprets W−WSW dipping imbricated structures as related to reactivated pre-existing basement thrust nappes. The eastern end of the MONA LISA profile 3 is poorly constrained as the ray coverage is sparse and there are no crossing rays between km 300 and 280. The interfaces of the ray-tracing model (Fig. 3B) correlate with the surfaces interpreted from the normal incidence reflection seismic data (Fig. 3C). The Mesozoic



sequences are well constrained by borehole control, whereas the Palaeozoic interfaces are more uncertain.

The two models by Nielsen et al. (2000, 2005) both show: (1) Thick successions of Palaeozoic sedimentary rocks deposited on the Mid North Sea High, in the Central Graben and Horn Graben and on the East North Sea High. (2) High velocities and densities at model distance km 110−150, km 170−200 and km 270−290, which might indicate the presence of mafic intrusions. (3) Palaeozoic deposits reaching thicknesses of ~5.5 km on the MNSH, ~4.5 km in the CG, ~4 km on the RFH and ~2.5 km in the HG. (4) Two basement highs at model distance km 130−150 and km 190−210. The first is likely a basement horst which might be controlled by a mid crustal detachment ramp structure (Gibbs, 1990a,b; Dooley et al., 2005; McClay et al., 2005). The second is also interpreted as a basement high, marking the eastern rift shoulder of the Central Graben i.e. the Coffee Soil Fault (Fig. 3C).

5. 2¾ Dimensional gravity and magnetic modelling along MONA LISA profile 3

We have modelled the distribution of gravity and magnetic parameters along MONA LISA profile 3 by use of the commercial software package GM-SYS™ (Northwest Geophysical Associates, 2002) with algorithms based on Talwani et al. (1959) and Talwani and Heirtzler (1964). The gravity and magnetic data have been extracted from the potential field datasets described above. Depths to the sedimentary interfaces and the top crystalline basement are based on depth conversion of the wide-angle reflection seismic data of MONA LISA profile 3 (MONA LISA Working Group, 1997b) and the seismic velocity model of Nielsen et al. (2005). Depth to intra crustal interfaces and initial crustal densities are based on the seismic velocity model of Nielsen et al. (2000). Initial density values were calculated from velocity by use of the mean conversion curve published by Barton (1986). Densities for the Mesozoic and Cenozoic sedimentary rocks are further constrained by commercial borehole data (Nielsen and Japsen, 1991; Knudsen, 1993). Initial magnetic susceptibility values were based on results from measurements made directly on basement samples in the core archive of the Geological Survey of Greenland and Denmark (GEUS) (Williamson et al., 2002).

The sedimentary interfaces of the velocity model (Fig. 3B) were compared to a depth converted reflection seismic section of MONA LISA profile 3 (Fig. 3C). Horizons from four adjacent boreholes were projected onto the profile and used as constraints for the depth conversion in PROMAX (Landmark Graphics' ProMAX®). Only minor adjustments were needed to fit to the velocity model by Nielsen et al. (2005). In our model the sedimentary layers are constrained by the seismic and borehole-log information. The estimated uncertainties in the modelled depth are within a few hundred meters. The depths to intra crustal interfaces, however, are associated with a higher degree of uncertainty. This uncertainty may be up to 2 km. Tests show that it is possible to replace the density of the lower Palaeozoic sedimentary rocks with crystalline density and still obtain a fit to the observed gravity anomaly trend. However, the observed magnetic anomaly cannot be explained by such a model. Hence, there is compelling evidence for the existence of substantial occurrences of sedimentary rocks of Palaeozoic origin in most of the study area.

The potential field maps (Fig. 2) show that none of the structures causing the observed anomalies have a strike perpendicular to the profile. The computed anomaly response can therefore not be expected to fit the observed anomaly trend perfectly with a 2D modelling approach. In order to minimize the effect of the oblique strike some of the structures are modelled as 2¾D structures, which allow skewed strike directions of the anomalous bodies and allow the structures to be truncated at some distance from the profile. Despite 3D effects, we find that our gravity and magnetic models exhibit a good fit to the observed anomaly values along the entire profile, with a

Fig. 3. A) Image of the P-wave velocity field based on tomographic inversion of first arrival traveltimes, modified after Nielsen et al. (2005). The contours show the values of the velocity field. Colors indicate areas with ray coverage. The likely presence of Palaeozoic deposits across the entire profile is indicated by the velocity range between ~4.5 and 6.0 km/s. The top of the crystalline crust is around the 6.0 km/s contour. The Coffee Soil Fault (CSF) is located at model distance km 190–200 at an abrupt lateral change in velocity. High upper crustal velocities at model distances km 130–190 and km 260–290 are coincident with high densities in the model by Nielsen et al. (2000). B) Image of the P-wave velocity field based on ray-tracing of refracted and reflected seismic phases. The interfaces in the model are partly constrained by well-data. The model shows thick sequences of Palaeozoic deposits. The lithostratigraphy of the Palaeozoic sequences are based on their velocities as no boreholes reaches this level. Modified after Nielsen et al. (2005). C) Tentative line drawing of reflections and faults at the eastern edge of the Central Graben along MONA LISA profile 3. The main faults between km 200–210 have also been identified from backscattered seismic signals (Nielsen et al., 1998). A secondary listric fault attaches to the eastern main fault. The two horizons marked from the well Per-1 are: Top Chalk Group (Blue horizon) and Top Pre-Permian units (Yellow horizon). A possible intra Palaeozoic horizon is marked by orange. Abbreviations: CG: Central Graben, CSF: Coffee Soil Fault, HG: Horn Graben, MNSH: Mid North Sea High, ENSH: East North Sea High, TC: Top Cretaceous, LC: Lower Cretaceous, JU: Jurassic, TR: Triassic, UP: Upper Palaeozoic, LP: Lower Palaeozoic.

maximum magnetic misfit of ±30 nT and a maximum gravity misfit of ±3.5 mGal (Figs. 4 and 5).

The location of the rift shoulder of the CG at the Coffee Soil Fault (at model distance km 190), has been shifted westward by 2 km as compared to the original velocity model. The rift shoulder (CSF) cannot be uniquely identified in the reflection seismic section (Fig. 3C) as it most likely represents a fault zone. This is also supported by the loss of magnetic signature of the basement at Mid North Sea High close to the rift shoulder, which may be caused by faulting and metamorphosis of the top basement.

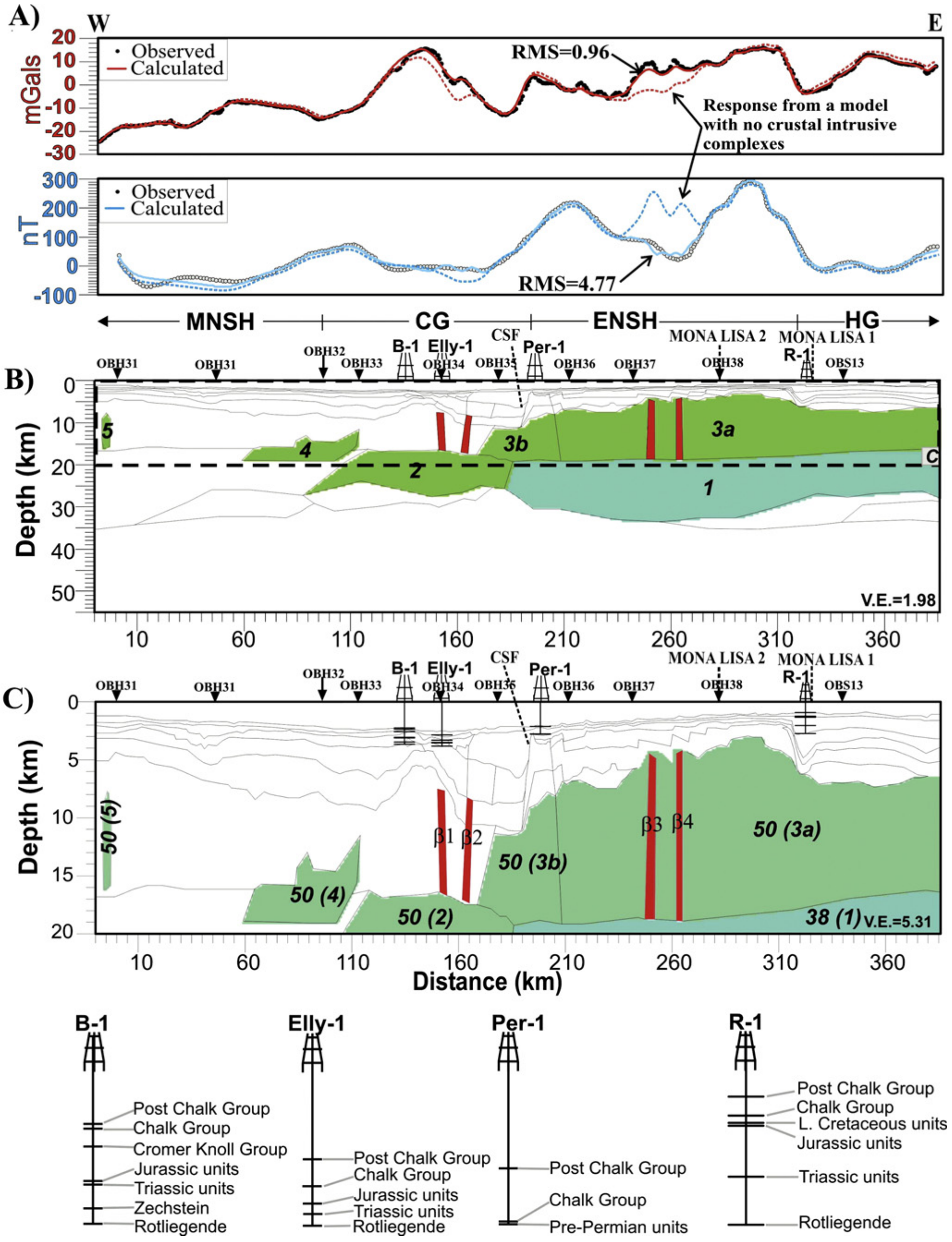


Fig. 4. Magnetic model of MONA LISA profile 3. The model indicates thrusting of Avalonia crust over Baltica crust. A) Observed magnetic and gravity anomalies (dots) and calculated model response (line). The dashed line shows the response from a model without the crustal intrusive complexes β_{1-4}. B) Full model view, colours indicate crustal elements associated with a magnetic susceptibility. Notice the non-magnetic character of the Avalonia crust. C) Section zoomed to a depth of 20 km. Magnetic values are shown in Table 2. Abbreviations as in Table 1.

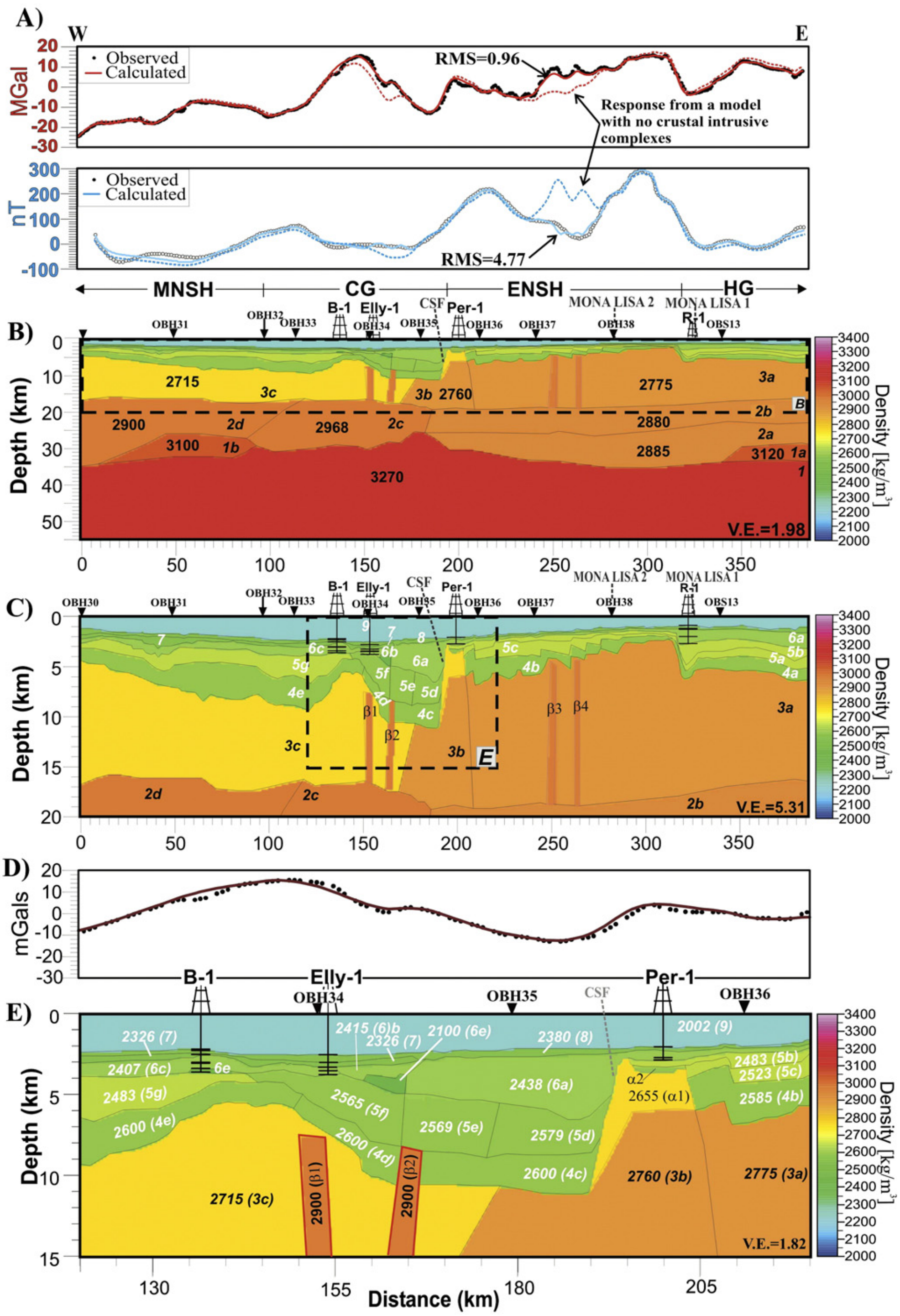


Fig. 5. Gravimetric model of MONA LISA profile 3 with values in kg/m^3. All sedimentary interfaces are based on the velocity model by Nielsen et al. (2005), deeper surfaces are based on the velocity model by Nielsen et al. (2000). A) Observed (dots) and modelled (line) gravity and magnetic response. The dashed line shows the response from a model without the crustal intrusive complexes β_{1-4}. B) Full crustal view of the model. C) Full length view zoomed to 20 km depth. D) Observed and modelled gravity of the Central Graben area relating to the zoomed section in figure) The gravity model zoomed in on the Central Graben. Structures shown in red are modelled in 2¾D and has, as such, a finite extension in the direction perpendicular to the profile. Density values are shown in Table 3. Abbreviations as in Table 1.

Table 2

Body no.	Layer	Susceptibility (10^{-3} SI)	Modelled remanent magnetic values		
			J (A/m)	Declination	Inclination
1	Baltica mid- and lower crust	38			
2	Baltica extended lower crust	50			
3a	Baltica upper crust	50			
3b	Transitional Baltica crust	50			
4	Mid crustal Magmatic arc	50			
β_1	Mafic Intrusion		3	−15°	15°
β_2	Mafic Intrusion		3	0°	15°
β_3	Mafic Intrusion		5	0°	10°
β_4	Mafic Intrusion		5	0°	10°

Modelled magnetic values adopted for the 2¾D magnetic modelling along MONA LISA profile 3.

5.1. Sediments and the top of the crystalline basement

At the western end of the East North Sea High (ENSH) (km 200 to 210), we interpret the presence of two faults from the reflection seismic section, one defining the transition between crystalline crust and sedimentary rocks and the other controlling a half graben system of possible Palaeozoic age (Fig. 3C). These faults have been located by interpretation of back-scattered energy in the MONA LISA refraction seismic data (Nielsen et al., 1998). Their locations are coincident with the western shoulder of the Else Graben (Cartwright, 1990).

The modelled morphology of the crystalline basement indicates strong block faulting. The gravity anomaly from this surface fits the short wavelengths of the observed gravity field. However, the upper part of the crystalline basement of the MNSH may be non-magnetic, as the magnetic anomaly curve lacks high frequency components (Fig. 4A). A smooth magnetic response that fits the observed magnetic anomaly trend is obtained by modelling the top 0.3−1.5 km of crystalline basement as non-magnetic in accordance with the results by Thybo (2001). Due to the non-magnetic, low-density character of the basement on the eastern CG rift shoulder (Fig. 4C), we assume that the crystalline basement was: (1) either exposed and metamorphosed in pre-Carboniferous times, (2) lost its magnetic character during the collision of Avalonia and Baltica or (3) Late Palaeozoic−Early Mesozoic extensional faulting destroyed the magnetic fabric of the uppermost crystalline crust.

According to our model, sedimentary rocks of Palaeozoic age cover almost the entire East North Sea High (ENSH) with thicknesses of up to 5 km. The lower Palaeozoic sequences (4a−e in Fig. 5) have a density range between 2585 and 2600 kg/m^3, whereas the middle- and upper Palaeozoic sequences (5a−g in Fig. 5) range between 2480 and 2580 kg/m^3, which are comparable to results obtained by Williamson et al. (2002). The presence of block faulted Palaeozoic rocks is supported by the residual gravity anomaly calculated by wavelength filtering with a band-pass of 10−50 km (Fig. 6A), which shows an irregular pattern at the ENSH. Besides from the CG and HG, the thickness distribution of the Mesozoic and Cenozoic sedimentary rocks are relatively even in the area. We therefore infer that the short wavelength gravity anomalies must be caused by lateral density variations in the sub-Zechstein level. The presence of pre-Permian sedimentary rocks have also been encountered in the borehole PER-1 (Nielsen and Japsen, 1991).

5.2. The crystalline crust

The modelled densities of the crystalline crustal are comparable to results by Williamson et al. (2002), Nielsen et al. (2000) and Thybo (2001). The upper crust is modelled with a density of 2715 kg/m^3 and negligible magnetic susceptibility in Avalonia (model distance km 0−170), and a density of 2775 kg/m^3 and 0.05 SI in Baltica (model distance km 170−385). It appears from both the gravity and magnetic models that the transition between Baltica and Avalonia occurs below the Central Graben in the upper and middle crust and that Baltica lower crust extends for 70 km further westward.

A small upper crustal magnetic body (magnetic susceptibility 0.05 SI) at the extreme western end of the profile (polygon 5 in Fig. 4) is introduced in order to fit the observed positive magnetic anomaly. It has a vertical extent of 5−7 km. The horizontal gradient of the observed magnetic field (Fig. 6B in Lyngsie et al., 2006) shows that the body may be part of a larger magnetic complex at the northern edge of the Anglo–Dutch Basin (ADB). The magnetic complex continues to the NNW and SSE of MONA LISA profile 3. It crosses Transect 1 at a position coincident with the location of a magnetic complex (Williamson et al., 2002).

Table 3

Body no.	Layer	Vp range (km/s)	Modelled density (kg/m^3)
1	Upper mantle	8.0 – 8.3	3270
1a	Eclogite	7.8 – 8.0	3120
1b	Intruded ultra-mafic lower crust	6.4 – 6.9	3100
2a	Baltica lower crust	6.9 – 7.1	2885
2b	Baltica mid-crust	6.6 – 6.9	2880
2c	Baltica extended lower crust	6.8 – 7.1	2968
2d	Avalonia lower crust	6.4 – 6.9	2900
3a	Baltica upper crust	6.2 – 6.4	2775
3b	Transitional Baltica crust	5.9 – 6.2	2760
3c	Avalonia upper crust	6.1 – 6.2	2715
$\beta_{1-2-3-4}$	Mafic intrusions	~7.0	2900 – 2930
α_1 and α_2	Metamorphosed Baltica upper crust	5.9 – 6.1	2655 and 2600
4a–b–c–d–e	Lower Palaeozoic sedimentary rocks	5.2 – 5.4	2585 – 2606
5a–b–c–d–e–f–g	Mid Pal. or U. Pal. sedimentary rocks	4.5 – 5.2	2483 – 2579
6a–b–c	Triassic + Jurassic sedimentary rocks	3.5 – 3.8	2407 – 2438
6e	Zechstein salt	2.2	2100
7	L. Cr. + Mid Cr. sedimentary rocks	3.7	2326
8	U. Cr. sedimentary rocks	3.9	2380
9	Tertiary sedimentary rocks	1.9 – 2.25	2002
Seawater			1030

Modelled density values adopted for the 2¾D gravity modelling along MONA LISA profile 3, based on direct conversion of P-wave velocities (Abramovitz et al., 1998; Abramovitz and Thybo, 2000; Nielsen et al., 2000; Nielsen et al., 2005) using the mean conversion curve of Barton (1986).

A mid-crustal magnetic complex (susceptibility 0.05 SI) with a sheet like structure is modelled at km 60–110 (polygon 4 in Fig. 4). This complex has an irregular upper surface and an average depth of ~15 km. The complex does not coincide with any density or velocity contrast. Similar mid crustal magnetic complexes are modelled in Transect 1, MONA LISA 1 and MONA LISA 2 (Williamson et al., 2002). The complexes modelled by Williamson et al. (2002) exhibits an irregular top surface around depths of 15 km and are interpreted as possibly buried magmatic complexes representing arc complexes related to the inferred southward subduction of the Tornquist Sea.

A significant mid to lower crustal magnetic complex (susceptibility 0.05 SI) is modelled beneath the central part of the Central Graben (polygon 2 in Fig. 4) at km 100–185. The extent of this complex corresponds to the extrapolated position of the zone of lower crustal high reflectivity (Abramovitz and Thybo, 1999) and high density (2968 kg/m3). The high density and reflectivity could relate to mafic intrusions emplaced in lower crust of Baltica affinity during late Palaeozoic rifting. We believe that the western extent of this magnetic and reflective complex (at model distance km 100) corresponds to the off-shore continuation of the Elbe Line (identified on MONA LISA Profile 1 and 2).

Tests have shown that the long-wavelength gravity anomaly trends at the ends of the profile cannot be described by the Moho relief only. We therefore introduce two lower crustal, high-density bodies at Moho level (polygons 1a and 1b in Fig. 5). The bodies are 4–6 km thick and have densities between 3100 to 3120 kg/m^3. They may represent mafic to ultra-mafic intrusives in the lower crust or eclogite–facies rocks created during tectonic loading of the foreland basin or alternatively remnant exotic elements emplaced during the collision between Baltica and Avalonia (Abramovitz and Thybo, 2000).

5.3. Intrusions

Four vertical structures, interpreted as intrusive dikes, are modelled beneath the Central Graben and in the crystalline crust of the East North Sea High (polygons β_{1-4} in Figs. 4 and 5) with high density of 2900−2930 kg/m^2 and strong remanent magnetization of 3–5 A/m, inclinations from 10 to 15°, and declinations from 0 to −15°. The presence of such intrusive features is supported by local high velocity anomalies in the tomographic model (area A and B in Fig. 3A), by positive gravity anomalies evident in the residual gravity field (Fig. 6A) and by circular, local magnetic anomalies observed in the total magnetic anomaly map between OBH 37 and 38 (Fig. 6B).

The two shallow near vertical intrusive dikes beneath the Central Graben (polygons β_1, β_2) are identified as a short wavelength anomaly with low amplitude at km 160–170 superimposed on the large gravity anomaly at km 100–180 (Fig. 5A). However, these intrusive bodies are not evident in the total aeromagnetic field (Fig. 6B), probably due to the flat magnetic orientation of the complexes and their short horizontal extent, although non-magnetic properties of the intrusions cannot be ruled out.

The high-density lower crust (km 100–190) and the Moho relief describe the long wavelength of the observed gravity anomaly. The intrusions create a shift that aligns the observed and the calculated anomaly and further lead to the correct amplitude without the need for changes to crustal interfaces and Moho surface as compared to the seismic model.

The vertical structures in the East North Sea High are located at the onset of the band of S–W dipping

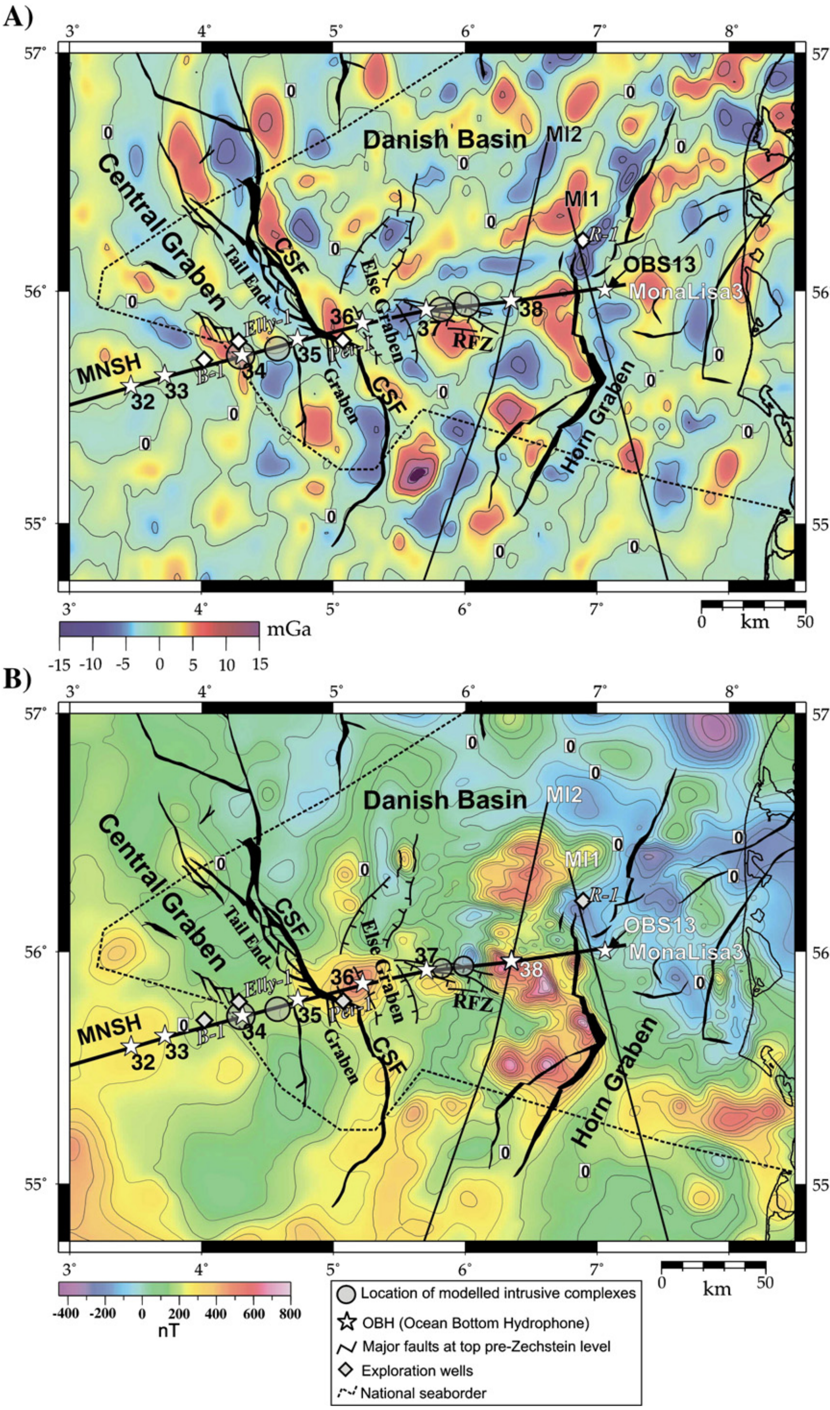


Fig. 6. A) Residual gravity anomaly showing the effect of shallow density contrasts, based on wavelengths between 10 and 50 km. The image supports the gravity/magnetic model of MONA LISA profile 3 with crustal intrusions between OBH 34 and 35 and between OBH 37 and 38. White stars show locations of Ocean Bottom Hydrophones (OBH). Abbreviations as in Table 1. B) Total aeromagnetic anomaly field. The image supports the gravity/magnetic interpretation of MONA LISA profile 3 in which crustal intrusions are modelled at OBH 37. However, the intrusions modelled between OBH 34 and 35 are not evident in the image. The local magnetic anomalies between OBH 34 and 35 also show a clear correlation with positive density anomalies in the residual gravity field. Abbreviations as in Table 1.

crust cutting reflections identified by MONA LISA Working Group (1997a,b). The reflections are possibly related to the Caledonian or older deformation structures, but judging from the orientation of the remanent magnetization, the vertical intrusions are likely related to a later extensional phase during the Carboniferous and Permian, when the area was situated at equatorial latitudes. The intrusive complexes are located close to the southern margin of the East North Sea–Ringkøbing-Fyn High which is regarded as the locus of Permian magmatism (Dixon et al., 1981).

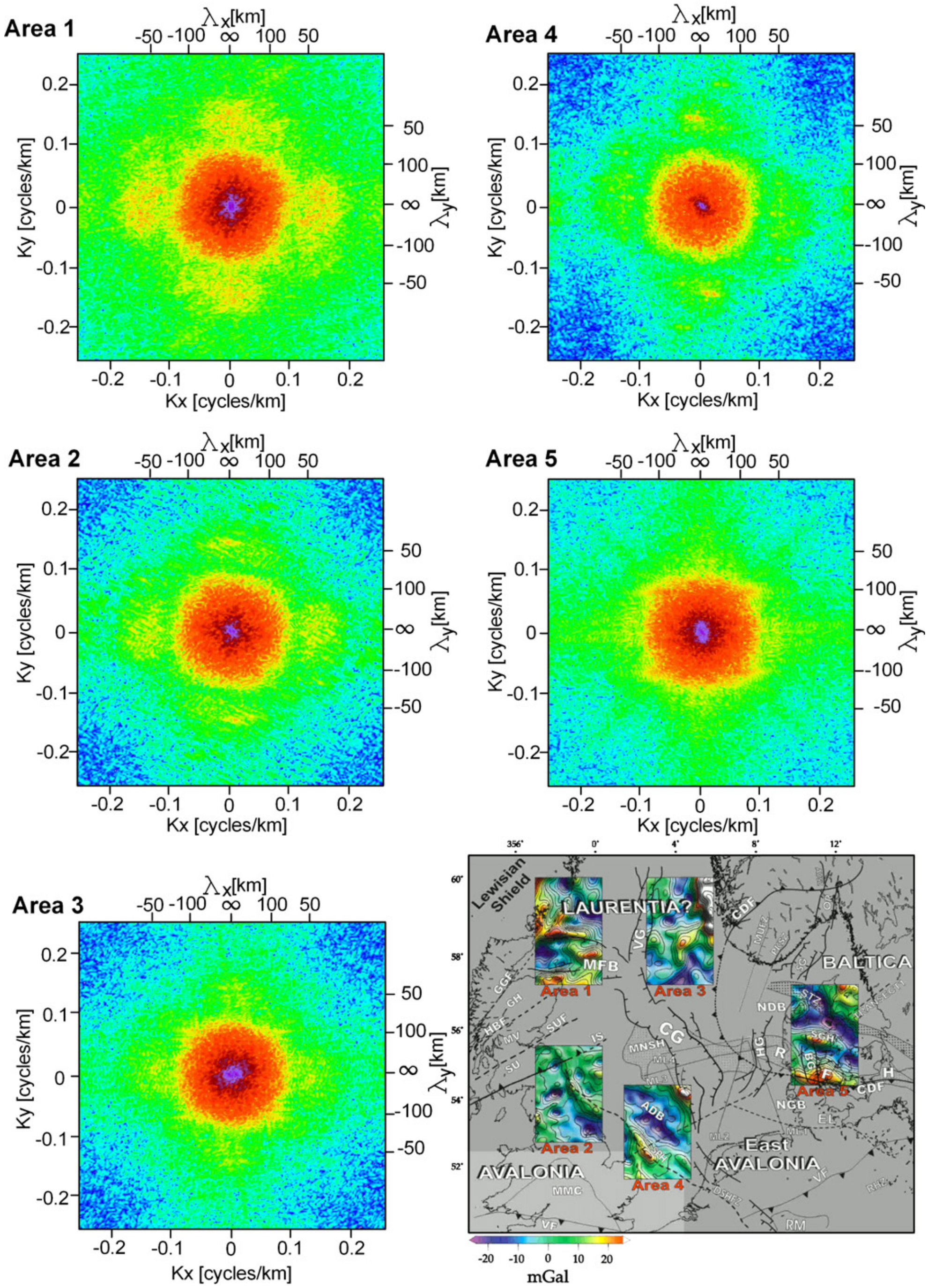


Fig. 7. Map showing areas used in spectral analysis and their respective 2D Fourier power sprectrum.

6. Identification of crustal domains by spectral analysis

In order to identify terranes of different origin and tectonic history we apply Fourier analysis to the observed Bouguer and Free-air gravity anomaly field in five regions selected based on their presumed location in different tectonic domains (Fig. 7). By transforming the gravity anomalies of a region into the wave number domain, the spectral properties can be interpreted and compared with spectral properties of the neighbouring regions. As signals from deep sources tend to be overprinted by high-amplitude signals from shallower sources in the Fourier domain (Simpson et al., 1986), and as our focus is on differences of the crystalline crust, we have upward continued the observed gravity field to 5 km before calculating the 2D power spectra. Each region spans 3° in longitude and 2½° in latitude. The extracted data were tapered with a 10−20% expansion along the edges using a cosine bell function on a grid with 640 × 640 data points. A 2D power spectrum was calculated for each region (Fig. 7).

Differences in wave number amplitudes may be influenced by the depth to sources and the nature of the lateral density distribution. As a quantitative analysis of the five power spectra, we calculate and compare the Cross-Correlation Coefficients (CCC) of each region (Table 4). In case of complete correlation, that is if an area is correlated with itself, the CCC equals one. As the gravity data used in this study is contaminated in several ways (e.g. by near surface effects not related to the crustal terrane structure), the CCC will never be close to 1.0 (Lyngsie et al., 2006). We find values in the range of 0.5–0.65.

The cross-Correlation Coefficients indicate that region 2 and 4 are strongly correlated (CCC = 0.6035) reflecting a similarity between Avalonia and East Avalonia. The correlation between region 3 and 5 (CCC = 0.6128) is significantly larger than the correlation between region 1 and 3 (CCC = 0.5192). This indicates the presence of a Precambrian basement of Baltica origin in region 3, rather than Caledonian basement of Laurentia Origin.

Table 4
Cross-correlation coefficient of the upward continued Bouguer anomaly gravity field

R^2	Area 1	Area 2	Area 3	Area 4	Area 5
Area 1	1	0.5658	0.5192	0.5333	0.5275
Area 2		1	0.5468	0.6035	0.5509
Area 3			1	0.5488	0.6128
Area 4				1	0.5565
Area 5					1

Wavenumber cross-correlation analysis. The wavenumber correlation coefficients (R^2) are calculated by method of linear regression of the wave number distribution given by the 2D power spectrum of the low-passed Bouguer gravity anomaly field.

7. Discussion

The oldest structures observable in the Precambrian basement in the study area can be related to the Gothian or early Sveconorwegian orogeny, and structures of younger orogenic events are superimposed onto the original structures (Lassen et al., 2001; Lassen and Thybo, submitted for publication). It is likely that inherited Proterozoic and Caledonian basement structures may have influenced the formation of the Permian−Mesozoic basins and their faulted margins in the North Sea (Frost, 1987; Gibbs, 1987; Faerseth et al., 1995).

7.1. The northern North Sea

In the Viking Graben (VG), Sveconorwegian or Caledonian basement thrust structures had significant influence on the geometry and location of the Permian−Mesozoic basins (Frost, 1987; Gibbs, 1987; Faerseth et al., 1995). The N−S trending orientation of the major faults of the VG is likely inherited from pre-rift deformation of crystalline basement, and a Devonian or Carboniferous precursor to the Viking Graben could have developed along Caledonian lineaments (Gibbs, 1987; Cornford and Brooks, 1989).

Most of the Norwegian off-shore platform is covered by pre-Mesozoic syn-rift sediments as interpreted on the Horda Platform (HP), off-shore Norway. On the HP, syn-rift sedimentary rocks are deposited on top of Caledonian metamorphic basement in half-grabens with thicknesses of up to 3–4 km (Brun and Tron, 1993; Fjeldskaar et al., 2004). It is advocated by several authors that early post-Caledonian extension reactivated pre-existing Caledonide thrust planes which resulted in tilted fault block structures and sub-basins of Late Palaeozoic age (Frost, 1987; Gibbs, 1987; Brun and Tron, 1993; Faerseth et al., 1995; Fjeldskaar et al., 2004).

High-grade metamorphosis of the Laurentia−Baltica continental collision has been demonstrated in boreholes between the VG and the Norwegian shoreline. This area was a zone of thin-skinned tectonics during the middle Palaeozoic, in which the initial collision of Laurentia with the passive margin of Baltica caused foreland intraplate compressional deformation, followed by emplacement of Laurentia crystalline nappes onto the Baltica foreland. The shelf sediments of the pre-existing passive Baltica margin may have acted as decollement surface. This scenario implies that, the deep boreholes in the northeastern North Sea that bottom in Caledonian metamorphosed crust, only sampled the thrusted nappes of Laurentia. Crust of Baltica affinity may still exist beneath the nappes. The Horda Platform likely acted as a stable Precambrian basement barrier which was over thrust by thin sheets of Caledonian basement during the Caledonian orogeny (Frost et al., 1981; Frost, 1987). These hypotheses are in agreement with our spectral analysis results, which show that the area east of the Viking Graben is more likely of Precambrian (Baltica) origin than of Caledonian (Laurentia) origin.

7.2. The southern North Sea

Analysis of borehole data shows a marked difference in the grade of metamorphosis of the crystalline basement between the northern and southern North Sea (Dixon et al., 1981; Frost et al., 1981). The difference between the high-grade (northern North Sea) and low-grade (southern North Sea) metamorphosed basement may reflect the differences in collisional tectonic style. The low-grade metamorphosed foreland thrustbelt between Avalonia and Baltica may be a function of oblique collision, strike–slip convergence and a decollement surface at the top of Cambro−Silurian shelf slope deposits (McKerrow et al., 1991; Berthelsen, 1992; Meissner et al., 1994; Torsvik and Rehnstrom, 2003). Clockwise rotation of Avalonia was initiated by Late Ordovician (450 Ma) when the eastern tip of Avalonia arrived at the Baltica passive margin (Meissner et al., 1994; Mac Niocaill, 2000). As Avalonia pivoted towards Baltica, trans-tensional stresses likely created considerable strike–slip faulting as observed in, especially, the Belgian terranes (Cocks et al., 1997) and perhaps also created a precursor to the Coffee Soil Fault zone. The clockwise rotation of Avalonia might also explain the major Late Ordovician to Silurian sinistral displacement faults observed in the British and Scottish Caledonides: the Iapetus Suture (IS), the Southern Uplands Fault (SUF), the Highland Boundary fault (HBF) and the Great Glen Fault (GGF) (Leggett et al., 1983; Soper and Hutton, 1984; Hutton, 1987; Freeman et al., 1988; Kneller, 1991).

7.3. Interpretation of the gravity and magnetic model of MONA LISA profile 3

7.3.1. Long wavelength anomalies

A prominent feature of our gravity and magnetic model is the large lateral thickness variation of the crystalline crust. This variation is reflected in the long wavelength anomalies of the profile and is pronounced in the central part of the profile at the Central Graben (CG). This part of the crust has been subject to substantial extension and crustal thinning. Nielsen et al. (2000) estimate the effect of the elevated Moho relief to +64 mGal, but it is not possible to fit the observed long wavelength anomaly without introducing high density values in the lower crust beneath the CG. We therefore interpret the long wavelength anomaly in the central part of the profile to be caused by a combination of igneous intrusions and crustal thinning.

In order to fit the long-wavelength gravity anomaly trend at the ends of the profile, we model two lower crustal, high-density bodies around Moho level (polygons 1a and 1b in Fig. 5B). Tests have shown that the anomaly trend cannot be described by the Moho relief itself, because this will result in large deviations from the seismic model. Also, the gravity effect of the late Mesozoic uplift of the Horn Graben rift shoulder at the eastern end of the model cannot explain the anomaly. The density of the lower crustal bodies is ~3100 kg/m^3 and may represent mafic to ultra-mafic intrusions or eclogites in the lower crust. Abramovitz et al. (1998) and Abramovitz and Thybo (2000) interpret lower crustal rocks in eclogite facies just below Moho in the northern part of MONA LISA profiles 1 and 2, based on P-wave velocity modelling. We therefore interpret the eastern lower crustal body (structure la in Fig. 5) to represent rocks in eclogite facies. These rocks may have been subject to high-pressure metamorphosis due to lithospheric flexure in response to the loading and tectonic stacking by the Caledonian orogeny. We interpret the western lower crustal body (structure 1b in Fig. 5) to represent mafic or ultra-mafic rocks which intruded as sills into the ductile lower crust during the Late Palaeozoic–Early Mesozoic rifting of the Central Graben. The location of this body coincides with a lower crustal zone of relatively strong sub-horizontal seismic reflectivity (MONA LISA Working Group, 1997b; Nielsen and Jacobsen, 2000).

7.3.2. Upper crustal intrusive dikes

Four vertical structures interpreted as upper crustal dikes are modelled beneath the CG and in the crystalline crust of the East North Sea High (Figs. 4 and 5). The observed Bouguer and Free-air gravity anomaly fields show correlation between short wavelength gravity anomalies and the interpreted intrusive bodies (indicated by circles in Figs. 2A and 6A). The correlation with the magnetic anomaly map (Figs. 2B and 6B) is less obvious. However, local magnetic anomalies along MONA LISA profile 3, found by calculation of the horizontal gradient of the pseudogravity transform (shown as closed circles in Fig. 2A), correspond to the location of the modelled intrusive complexes. The magnetic anomalies along MONA LISA profile 3 are situated in the Central Graben (CG) and East North Sea High (ENSH), to the west of the Caledonian Deformation Front (CDF).

The residual gravity field (Fig. 6A) shows strong gravity anomaly values (~5 mGal) at OBH 34 and locally between OBH 34 and 35 in the CG. Tests show that the residual gravity anomaly values cannot be described by elevated basement alone. With P-wave velocities of 6.5–7.0 km/s at shallow level (Fig. 3A — area B), we believe that near vertical intrusive dikes are present beneath the CG. The depths to these intrusive complexes cannot be uniquely determined from the potential fields and seismic data. We have modelled intrusion β_2 as penetrating into the lower Palaeozoic unit at model distance km 165, but it may also be located deeper with a higher density. However, when considering the observed short wavelength anomaly located at model distance km 165, which is modelled by intrusion β_2, we find that increasing the depth and density will yield a worse fit as it also increases the wavelength.

East of OBH 37 a zone of positive gravity values is observed (Fig. 6A), ranging from ~3 mGal at the profile to ~15 mGal south of the profile. This zone coincides with an area of high magnetic anomaly values (−250 nT, Fig. 6B) and P-wave velocities exceeding 6.2 km/s (Fig. 3A — area A). This area is coincident with the position of the intrusive complexes modelled in the upper crust of the ENSH. No borehole data is available to constrain the depth and densities of the intrusions. However, our results are supported by reprocessed and pre-stack depth migrated sections of MONA LISA profiles 2, 3 and 4 (Fernandez Viejo et al., 2002), which show possible intrusive bodies in the eastern part of the ENSH, to levels as shallow as ~4 km. Intrusions are interpreted on all three profiles, coincident with the location of the Rømø Fracture Zone (RFZ) and the presumed Caledonian Deformation Front (CDF) (Fernandez Viejo et al., 2002).

We model the intrusions with a remanent magnetization of 3 to 5 A/m, inclinations of 10 to 15°, and declinations of 0 to −15°. The relatively flat to reverse orientation of the remanent magnetization direction can be explained if intrusion took place during the Kiaman period of magnetic reversal in the Late Carboniferous−Early Permian, in accordance with the interpretation of the Silkeborg gravity and magnetic anomaly onshore Denmark (Thybo and Schonharting, 1991) and analysis of cores from boreholes (Dixon et al., 1981). Analysis of igneous rocks from cores in the Central Graben, Horn Graben and on the East-North Sea High (ENSH), indicates that the southern flank of the ENSH-RFH was the locus of a bi-modal basalt−rhyolite volcanic field in Lower Permian Times (Dixon et al., 1981).

7.4. A tectonic model along MONA LISA profile 3

Reflection seismic data around the Else Graben (EG), show W−WSW dipping fault planes to depth of around 10 km (Cartwright, 1990). The fault planes are imaged as bands of reflections, which indicate that W−WSW dipping shear zones dominate the upper to middle crust at the East North Sea High (ENSH). The Else Graben terminates at a WNW trending zone of rotated basement blocks, the Rømø Fracture Zone (RFZ) (Cartwright, 1990). The RFZ coincides with the location of the modelled intrusive complexes of the ENSH (β_3 and β_4, Figs. 4, 5, and 6).

MONA LISA Working Group (1997b) interprets SSW-dipping shallow, possibly Caledonian thrust planes on all four MONA LISA profiles, and identifies a SSW dipping crust cutting zone of reflections which terminates at a highly reflective lower crust beneath the Central Graben. They interpret the zone as the easternmost extent of crustal Caledonian deformation. Lyngsie et al. (2006) show, that the Caledonian suture zone (the SW-ward edge of Baltica) may be traced as a lower crustal lineament, across the North Sea between Scotland and northern Germany. They identify this lineament on several images of transformations of the gravity and magnetic fields although the correlation across the Central Graben (CG) may be uncertain (Fig. 8). Based on our 2¾D modelling results, the Elbe Line (EL), as identified on MONA LISA Profiles 1 and 2 (MONA LISA Working Group, 1997a,b) can be correlated across the CG to coincide with the western limit of the high density, highly reflective Baltica lower crust (polygon 2c in Fig. 5B), which also appears plausible from the gravity declination vector image (Fig. 8). This implies that upper and mid Laurentia crystalline crust has been thrusted ~100 km over Baltica lower crust in a, presumably, thin-skinned tectonic regime, and that the crust cutting reflections identified by MONA LISA Working Group (1997b) represent the eastern most limit of Caledonian crustal deformation.

Based on our potential field model along MONA LISA profile 3, together with the results of Cartwright (1990) and the MONA LISA Working Group (1997a,b), we construct a tectonic model (Fig. 9). The model indicates the existence of a detachment surface between the Caledonian terrain of East Avalonia and the

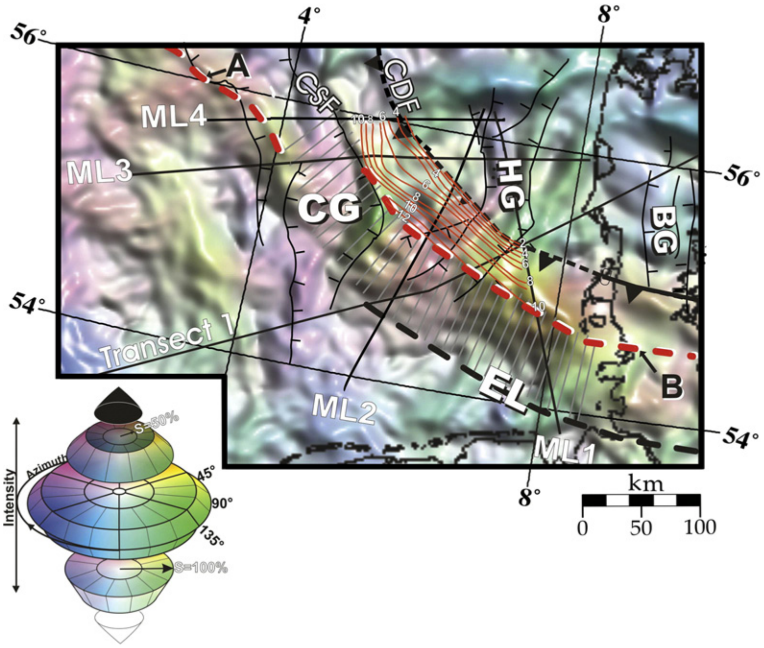


Fig. 8. Zoomed section of the gravity declination vector field with superimposed contours (in s/twt) of the dipping crustal reflections interpreted from the MONA L1SA deep seismic profiles (contours after Abramovitz and Thybo (2000)). The declination vector image is based on the gravity components. The declination is calculated as the angle from true north of the anomalous horizontal vector field. The radial component (length) of the vectors is assigned to the colour saturation and the angular component (azimuth) to the HUE (conic colour space). The third component of the HUE colour space is the intensity which is superimposed on the vectorial image to create a 3D shaded relief. This type of vectorial imaging enhances tectonic structures perpendicular to the illumination direction (for further details see Lyngsie et al. (2006)). The red contours define the depth to the deep seismic image of the Caledonian Deformation Front (CDF). Note the location of the deepest contours, which coincide with the regional lineament (lineament A and B) traceable from Germany to Scotland (see also Fig. 2). Gray lines define the area of highly reflective lower crust. The colour scale shows the intensity and saturation (S) as a function of declination and azimuth. Modified after Lyngsie et al. (2006). Illumination direction: 45° declination, 30° inclination. Abbreviations as in Table 1.

Precambrian lower crust of Baltica. The extensional Central Graben is situated above a ramp−flat−ramp structure representing a mid crustal and a base crustal detachment with a horizontal scale of ~100 km. The tectonic model reflects a simple shear tectonic rift scenario (Wernicke, 1985). The simple shear model predicts the crust-penetrating low-angle detachment fault plane and the asymmetric rift basin with steeply dipping basin-bounding faults in the upper crust, which are two significant observed features. The main arguments in favour of this tectonic interpretation are: (1) the modelled differences in magnetization of the crust. (2) The spectral analysis of the density distribution which shows a statistical difference across the Central Graben area and (3) the borehole analysis of Frost (1981, 1987). The model geometry is supported by cross sections interpreted from reflection seismic data at the Clyde field in the central part of the Central Graben (Fig. 10) (Gibbs, 1984; Gibbs, 1990b).

In our model, the CDF as suggested by Ziegler (1990b) and identified by MONA LISA Working Group (1997b) in the reflection seismic data, continues into dipping thrust structures in the upper to mid crustal level of the RFZ. It is possible that the presumed mild collision as indicated by low-grade metamorphic basement encountered in boreholes, between Baltica and the clockwise rotating Avalonia, created a roughly 100 km wide orogenic crustal wedge or foreland thrust belt. The internal crustal structures beneath the ENSH would then be expressions of Caledonian compressional low-angle thrust or shear zones. The orogenic wedge, with its western limit at the Coffee Soil Fault (CSF) and its eastern limit at the crust cutting band of reflections may be a transtensional accommodation zone, which also explains the loss of magnetic character at the CSF. On the ENSH our tectonic model shows rotated block structures and half grabens at the top of the crystalline basement. These structures could reflect late Palaeozoic syn-rift sedimentary rocks deposited in half grabens that developed during brittle extensional reactivation of pre-existing shear zones (Cartwright, 1990; Fernandez Viejo et al., 2002;

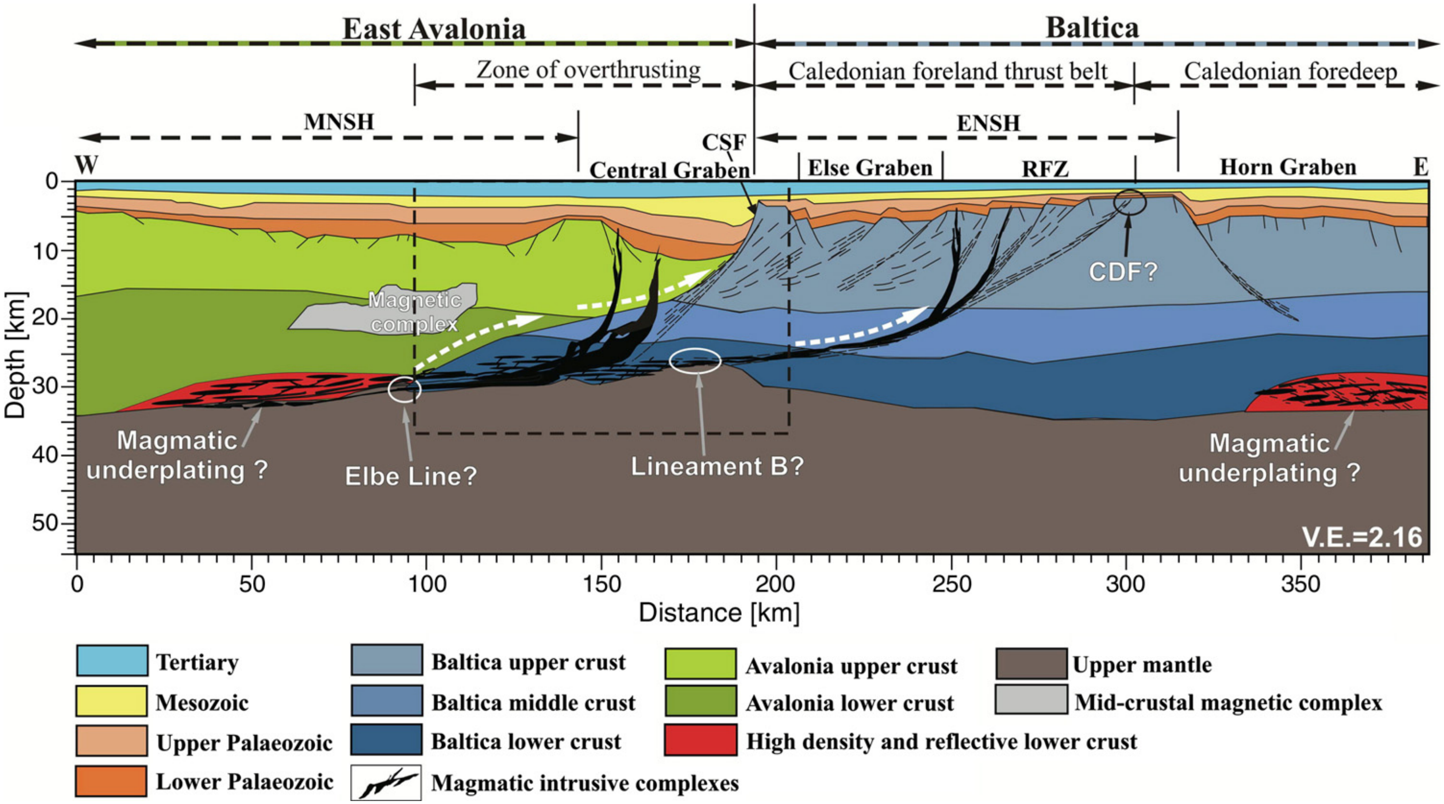


Fig. 9. Tentative tectonic model along MONA LISA profile 3. Structures and depths are obtained form the gravity and magnetic model. Superimposed seismic reflectors within the East North Sea High are based on Cartwright (1990) and Abramovitz and Thybo (1999). The locations of the intrusive magmatic complexes are constrained by the gravity and magnetic model, the linking between the high density lower crust and the magmatic complexes are, however, purely speculative. The model includes an asymmetrical basin created by simple shear and shows characteristics of faulted margins such as tilted horst and terrace systems developed on both planar and listric faults. The Central Graben system developed in the hanging wall complex above a westward-dipping crust penetrating detachment surface. The master detachment is, at upper crustal level, coincident with the Coffee Soil Fault (CSF) and forms the upper part of a ramp–flat–ramp system that was likely reactivated during Late Palaeozoic extension. The area between the CSF and the Caledonian Deformation Front (CDF) is interpreted as a Caledonian foreland thrust belt. The black dashed box outlines the area shown in Fig. 10.

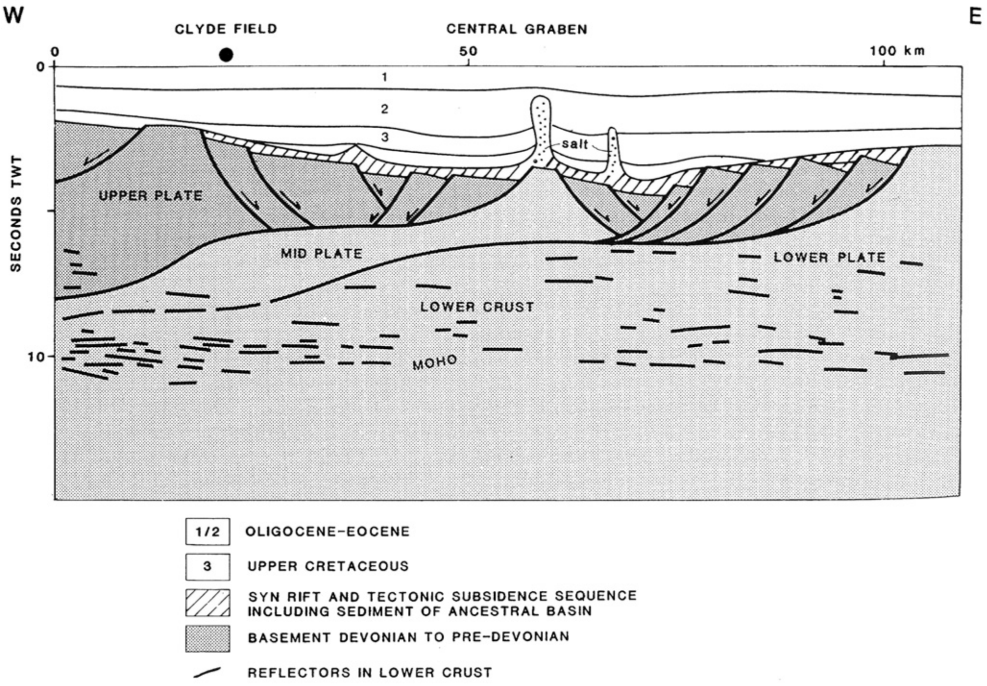


Fig. 10. Crustal model of Central Graben at the location of the Clyde oil field (see Fig. 1 for location). The model reflects simple shear crustal deformation and a mid-graben high developed in response to extension along a pre-existing ramp which is part of a crust cutting detachment surface. Adopted from Gibbs (1990b).

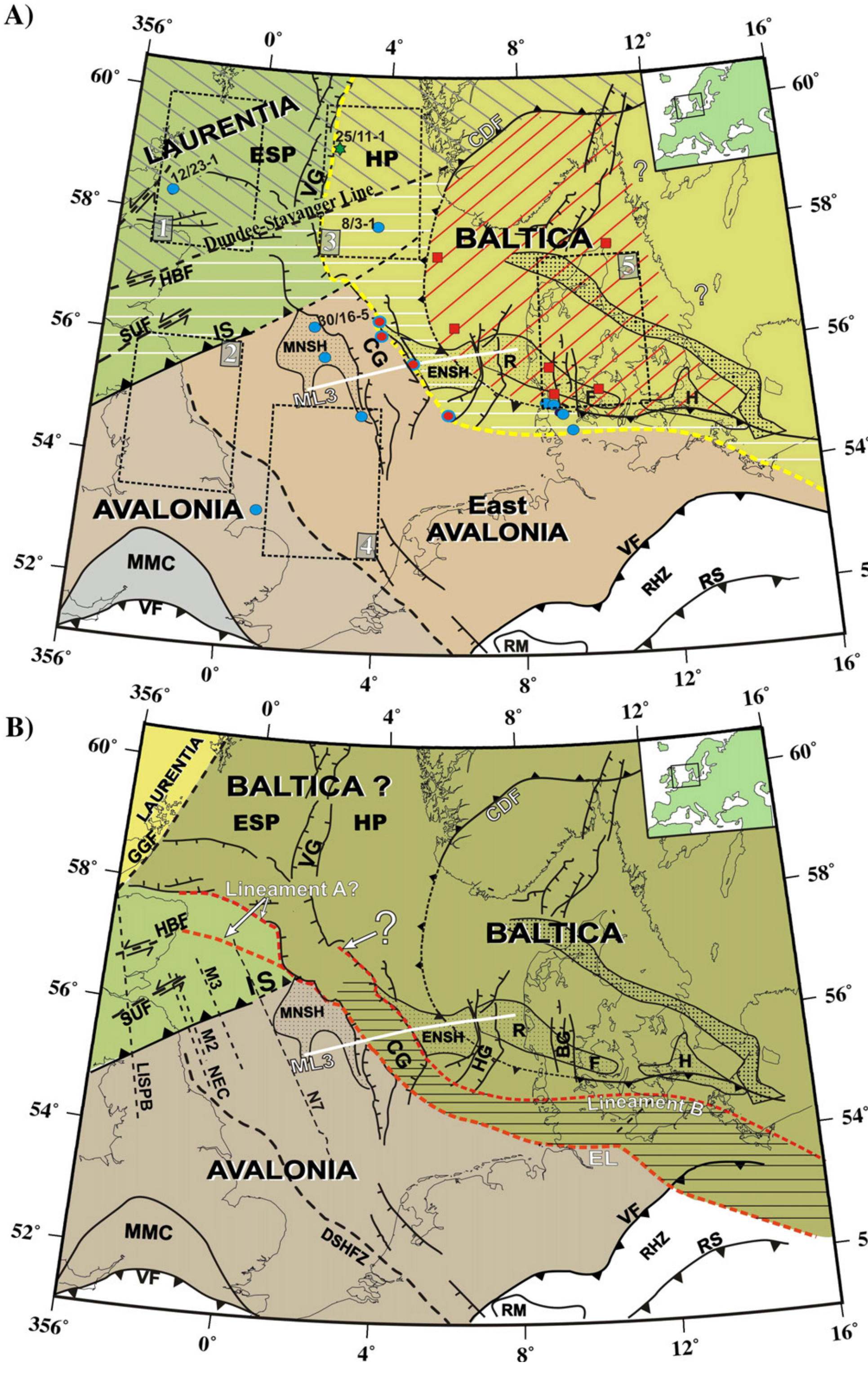
Scheck et al., 2002b). It is likely that Late Carboniferous−Early Permian extension reactivated pre-existing basement faults of Caledonian age and thereby created sub-basins and half grabens. Alternatively, the crustal reflections and the block faulted structures could be related to older tectonic events such as the Gothian or Sveconorwegian orogenic events or have been created in response to Late Palaeozoic wrench movements.

Along the southern flank of the ENSH-RFH the late Palaeozoic extensional tectonics was accompanied by widespread intrusive and extrusive magmatism (Dixon et al., 1981). We interpret the intrusions modelled along MONA LISA profile 3 as intruded through reactivated shear zones or thrust planes in relation to late Palaeozoic extension of the lithosphere.

7.5. A regional tectonic interpretation

It is likely that allochthon Caledonian metamorphic basement in the northern North Sea was emplaced as thrust sheets or nappes over older shelf sediments that belong to the passive margin of Baltica (Frost, 1987; Gibbs, 1987; Ziegler, 1990b). This is evidenced in well 25/11-1 (Frost et al., 1981), where highly metamorphosed augen−gneiss of Caledonian age is encountered above sedimentary rocks of the Baltica passive margin. These two rock types cannot be from the same thrust assemblage and it is therefore plausible that the Horda Platform acted as a stable Precambrian basement barrier which was overthrusted by nappes of Caledonian basement and thus define the eastern edge of the Viking Graben (Frost et al., 1981; Frost, 1987). Our results supports the hypothesis that Late Carboniferous−Early Permian extensional tectonics reactivated pre-existing Caledonian or older shear zones and initiated the formation of the Viking and Central Graben along the Caledonian suture at the Coffee Soil Fault. It is also likely that the north−south trending fault orientation of the Jurassic and Cretaceous basins in the northern North Sea area partly were controlled by reactivated Caledonian detachment surfaces as advocated by e.g. Frost (1987), Gibbs (1987), Brun and Tron (1993), Faerseth et al. (1995) and Fossen et al. (2000). In our regional tectonic model of the upper crust (Fig. 11A), the Precambrian basement of Baltica extends to the eastern edge of the Viking-and Central Graben, a location which we believe was determined by the Caledonian suture zone. This is in agreement with Gibbs (1990a,b,c) who, based on analysis of balanced sections in the North Sea, hypothesises that the type of crustal extensional geometry in our 2D model normally coincides with older lineaments and may be part of a unified system spanning the entire North Sea rift system.

For the upper crustal part of our regional tectonic model (Fig. 11A), we believe that Caledonian crust of Laurentia Origin is present only in thin nappes to the



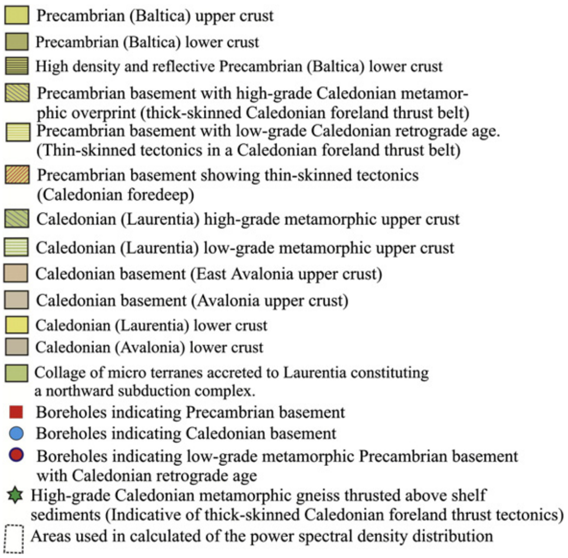


Fig. 11. A) Regional tectonic model of upper crustal domains in the North Sea, where Precambrian crust of Baltica affinity extends westwards to the Central-and Viking Graben. The northern area at the Horda Platform (HP) was a zone of thick-skinned tectonics with nappes of Caledonian basement thrust above Precambrian basement and shelf sediments as indicated by deep boreholes showing high-grade metamorphic rocks of Caledonian age thrust above Baltica shelf slope sediments (borehole 25/11-1 cf. Frost et al., 1981). The Dundee–Stavanger line is coincident with the Highland Boundary Fault (HBF) and separates high-grade metamorphic Caledonian basement from a collage of accreted terranes showing low-grade Caledonian metamorphic overprint (Frost et al., 1981). The Iapetus Suture may continue east of the Central Graben as proposed by Ziegler (1990a,b), but it will be constrained to the Palaeozoic sediments defining the eastern extent of thin skinned Caledonian tectonics and will as such not be a crust penetrating structure as observed in onshore and offshore Britain. B) Regional model of the lower crustal tectonic setting in the North Sea. The model shows Baltica lower crust present beneath the rift systems in the North Sea. The deep seismic MONA LISA profile 3 constrains the central part of the North Sea, where the lower crust beneath the Central Graben is associated with high-density and strong reflectivity. The westernmost extent of Baltica lower crust is defined by the Elbe Line (EL). The north-westward continuation of the EL is based on transformation of the potential field data and it is uncertain whether Baltica lower crust is present beneath the East Shetland Platform (ESP) or terminates beneath the Viking Graben rift system. The Iapetus Suture (IS) is, in this model, truncated by the EL and does not continue east of the Central Graben as in the upper crustal model. The termination of the IS is indicated by the change of dip and reflectivity as observed in the deep seismic profiles LISPB, NEC, MOBIL 2 and 3 (M2 and M3) and NSDP85-7 (N7) (Klemperer and Matthews, 1987; Freeman et al., 1988; Blundell et al., 1991; Barton, 1992; Soper et al., 1992).

east of the Viking Graben (VG) and that the Iapetus Suture (IS) therefore does not continue across the Central Graben (see also discussion in Lyngsie et al., 2006). For the lower crustal part, our 2¾D potential field model shows that the lower crustal lineament described by Lyngsie et al. (2006) can be connected across the Central Graben (Fig. 11B). The offshore continuation of the Elbe Line (EL) correlates with lineament A to the west of the Central Graben. Lineament B defines the northern limit of a zone of lower crustal high density and high reflectivity, which coincides with the lower part of a band of crust cutting reflections identified by MONA LISA Working Group (1997b). We believe that this lower crustal structure extends further northward beneath the Viking Graben and perhaps even, though speculative, that lower crust and upper mantle of Baltica provenance extends as far across the North Sea as to the western edge of the Moray Firth Basin (Fig. 11B). This infers that a detachment surface between Baltica lower crust and Laurentia mid and upper crust must exist beneath the East Shetland Platform (ESP). This hypothesis is partly supported by interpretation of reflection seismic profiles at the Witch Ground Graben (WGG) (Beach, 1986; Gibbs, 1987).

8. Conclusions

We differentiate between crustal areas of different affinity and origin on a regional scale by integrated potential field modelling. By combination of results from spectral analysis of the gravity field together with results by Lyngsie et al. (2006), we show that the crystalline crust situated between the Viking Graben and the Norwegian shoreline (the Horda Platform) is more likely of Precambrian (Baltica) than of Caledonian (Laurentia) origin.

By 2¾D modelling of the gravity and magnetic fields we have shown indications of upper crustal intrusive complexes, the presence of Palaeozoic sedimentary rocks, and a Caledonian suture zone situated beneath the Central Graben and the Ringkøbing-Fyn High. The East North Sea–Ringkøbing-Fyn High has earlier been regarded as a structural high of crystalline basement rocks. Our studies demonstrate that the sub-Mesozoic basement consists of sedimentary rocks of Palaeozoic origin, and that most of the Eastern North Sea basins may contain substantial sequences of upper and lower Palaeozoic sedimentary rocks with thicknesses up to 3–6 km, indicative of a pre-Mesozoic rift stage of this economically important structure (cf. Thybo, 1990; Zhou and Thybo, 1997; Abramovitz and Thybo, 1999; Thybo, 2001).

Our model shows a clear difference between the crustal properties of Avalonia and Baltica. The crustal part of the model is consistent with the hypothesis that Avalonia upper crust has been thrust over Baltica lower crust in a ramp–flat–ramp geometry, where the northern and eastern limit of Avalonia crust defines the Caledonian collisional sutures. We further find that Laurentia crust is only present in the area as a thin alloctoneous sheet over Baltica crust.

We argue that the Late Palaeozoic extensional stress regime triggered the intrusion of magmatic complexes along Caledonian or older thrust and shear planes.

We suggest that the location of the Caledonian suture in the upper crust is coincident with the Coffee Soil Fault, which acted as a transpressional shear zone during continental collision in the Ordovician–Silurian. Late Carboniferous−Early Permian extensional tectonics reactivated pre-Permian crustal structures and the Mesozoic rifting of the Viking and Central Graben was controlled by the Caledonian ramp–flat–ramp detachment surface. The location of the Caledonian collisional suture was thus the controlling factor for the location of the Viking and Central Graben rift systems.

We show that the crystalline crust beneath the Horda Platform is of Precambrian origin (Baltica) and not of Caledonian origin (Laurentia). Baltica upper crust may have acted as a stable barrier during the Caledonian orogeny such that the area to the east of the Viking and Central Graben is defined by thin-skinned tectonics. For the lower crustal part, we argue that Baltica lower crust reaches at least to the western edge of the Viking and Central Graben and, in the northern North Sea, possibly also further in a crocodile tectonic style beneath the East Shetland Platform.

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