Extra-terrestrial traces at Morasko near Poznañ in the Polish Basin. These meteorite craters are unique in Europe. There are seven craters within a few hundred metres of one another; the largest meteorite was about 100 metres in diameter and 164 kg in weight. The iron meteorites probably impacted about 4700 to 6100 years ago.

Chapter 2 Crustal structure and structural framework

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1 Geological setting

The Southern Permian Basin extends in a west-east direction across the Paleozoic Platform of western and central Europe and encroaches east- and north-eastwards onto the Precambrian East European Craton (EEC) (**Figure 2.1**). The boundary between these major basement provinces is referred to as the Trans-European Suture Zone (TESZ), which represents the most prominent lithospheric boundary in Europe north of the Alpine-Carpathian Orogen (Zielhuis & Nolet, 1994; Pharaoh, 1999; Artemieva et al., 2006; Pharaoh et al., 2006).

The Paleozoic Platform is characterised by crustal thicknesses that vary between 24 and 38 km (Ziegler & Dèzes, 2006) and lithospheric thicknesses of 100 km or less (Artemieva et al., 2006). The crystalline basement of this platform was consolidated during the Caledonian and Variscan orogenies and includes a system of Gondwana-derived continental terranes (Ziegler, 1989; Pożaryski, 1990; Franke, 1990; Pharaoh et al., 2006), as well as some Baltica-derived blocks (Berthelsen, 1992a, 1998; Nawroki & Poprava, 2006).

In contrast, the Precambrian East European Craton, of which the exposed Baltic and Ukrainian shields form part, is characterised by crustal thicknesses in the range of 40 to 50 km, and lithospheric thicknesses of 150 to 200 km, decreasing only along its margins (e.g. in the area of Denmark) to less than 30 km and 150 km, respectively (Artemieva et al., 2006; Ziegler & Dèzes, 2006).

The TESZ is a broad and complex zone of Early Paleozoic terrane accretion that extends over a distance of 2000 km from the central North Sea, along the northern margin of the SPB and through Poland and the Ukraine to Romania. It separates the Precambrian lithosphere of the East European Craton from the Paleozoic lithosphere of western and central Europe (Pharaoh, 1999; Thybo et al., 1999, 2002; Winchester, 2003). For much of its length, this zone is buried beneath Late Paleozoic and younger rocks. The definition of the zone is therefore based on the results of a limited number of deep boreholes and on geophysical data; the latter image the TESZ as a clearly defined lithosphere-scale structure (Zielhuis & Nolet, 1994; Schweitzer, 1995; Grad et al., 2002a; Artemieva et al., 2006). Whereas the North German-North Polish Caledonides mark the suture between the Gondwana-derived East Avalonia Terrane Assemblage and the Precambrian crust of Denmark and the Baltic (Thor Suture, Bertelsen, 1998; closure of the Tornquist Ocean, Cocks & Torsvik, 2006), the TESZ is more complex in Poland, where a number of Baltica-derived blocks were accreted to the East European Craton (EEC) margin during the Cambrian, and during the Caledonian collision of Avalonia with the EEC (Bełka et al., 2002; Dadlez et al., 2005; Nawrocki & Poprawa, 2006; Winchester et al., 2006). Correspondingly, the TESZ is considerably broader in Poland than in the North German-Danish borderlands.

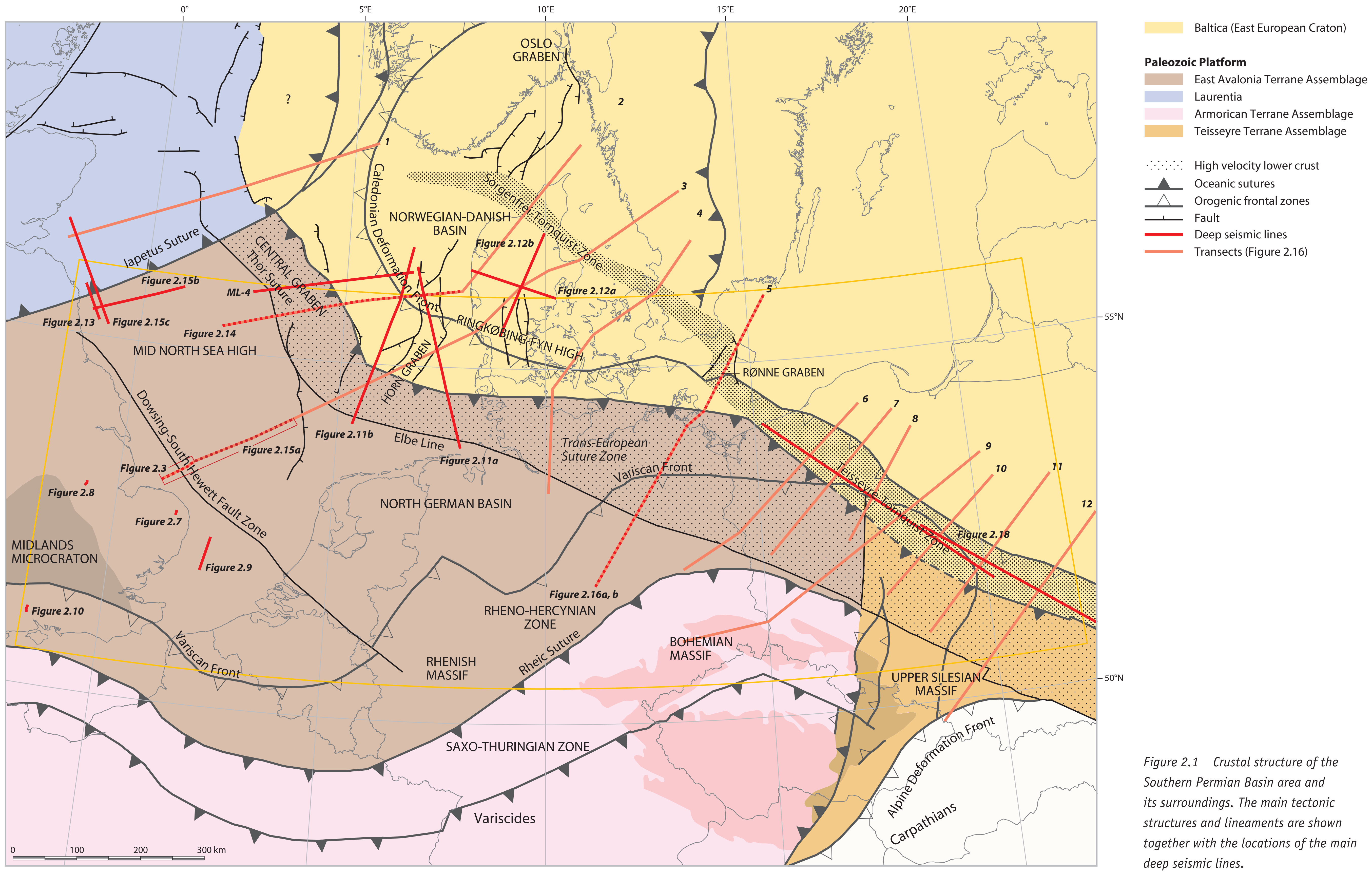


Figure 2.1 Crustal structure of the Southern Permian Basin area and its surroundings. The main tectonic structures and lineaments are shown together with the locations of the main deep seismic lines.

In the area of the North German-North Polish Caledonides, the lower crust of the EEC is interpreted as extending a considerable distance beneath the overriding Avalonia crust to about the Elbe Line, which transects the SPB area in a west-north-westerly direction (Krawczyk et al., 1999; Bayer et al., 2002; Scheck et al., 2002b). The crust of the western parts of the SPB, which is deeply buried beneath Devonian and younger sediments, is probably formed by the composite East Avalonia Terrane Assemblage (Cocks et al., 1997; Pharaoh et al., 2006). The south-western margin of the latter is uplifted and forms the London-Brabant Massif, a stable palaeotectonic feature since Early Devonian times that bounds the SPB to the south-west (Ziegler, 1990a).

The SPB is bounded to the south by the Rhenish and Bohemian massifs, which expose parts of the Variscan orogenic belt. The western and central parts the SPB are essentially confined to the foreland of the external Variscan thrust belt, the Rheno-Hercynian Zone, whereas its eastern parts broadly overstep the latter (Ziegler, 1990a; Narkiewicz, 2007). The composite East Avalonia Terrane Assemblage extends beneath the Rheno-Hercynian Fold Belt up to the Rheic Suture, which marks the contact between the Rheno-Hercynian and Saxo-Thüringian zones (see also latest review of Variscan tectonics in Kröner et al., 2008). This suture was developed by Carboniferous closure of the Rheno-Hercynian back-arc oceanic basin that had opened during the Early Devonian between the East Avalonia Terrane and the Armorican Terrane Assemblage (Ziegler, 1989; Franke, 2000, 2006; Ziegler et al., 2006).

At the end of the Variscan Orogeny, Permo-Carboniferous wrench faulting and related magmatism broadly affected the area of the future SPB and its surroundings (Wilson et al., 2004), causing destabilisation of the lithosphere that had repercussions on the subsequent subsidence of the SPB (Ziegler, 1989, 1990a; Van Wees et al., 2000; Ziegler et al., 2006). During this tectono-magmatic cycle, the TESZ of Poland was reactivated as a major wrench zone (Teisseyre-Tornquist Zone) that extended north-westwards into the Precambrian basement of southern Sweden and Denmark (Sorgenfrei-Tornquist Zone). The Teisseyre-Tornquist Zone is a few tens of kilometres wide and is characterised by distinct gradients in crustal and lithospheric properties, as evidenced by geophysical data (Guterch & Grad, 2006; Królikowski, 2006; Dadlez, 2006). The Teisseyre-Tornquist and Sorgenfrei-Tornquist zones were repeatedly reactivated during the Mesozoic development of the Mid-Polish and North Danish troughs, both of which were inverted during the Late Cretaceous-Early Paleocene phase of intraplate compression (Ziegler, 1990a; Dadlez et al., 1995; Petersen et al., 2003; Krzywiec, 2006; Japsen et al., 2007). Similarly, the basement blocks forming the Bohemian Massif were upthrusted during the Late Cretaceous and Paleocene phase of intraplate compression, and again during the Neogene, causing disruption of the southern margin of the SPB (Ziegler, 1990a; Ziegler & Dèzes, 2007).

The crustal and lithospheric configuration of the western SPB was modified by the Mesozoic crustal extension and wrench faulting that controlled subsidence of the North Sea Central Graben, the Horn and Glückstadt grabens, the Sole Pit, West and Central Netherlands troughs and the Lower Saxony Basin. Lithospheric thinning across the North Sea rift had clear repercussions on the Cenozoic subsidence of the western SPB area (Ziegler, 1990a; Ziegler & Dèzes, 2006). Late Cretaceous and Paleogene partial inversion of some of these basins probably affected their crustal configuration and post-rift subsidence to only a minor degree.

The following information on the crustal configuration of the SPB area is based on extensive hydrocarbon industry reflection-seismic data, academic deep-crustal reflection-seismic profiling, seismic-refraction and wide-angle reflection experiments, and potential-field data.

2 North-west area

2.1 *Overall crustal configuration*

2.1.1 *The Moho*

Moho depths in the UK sector are based principally on interpretation of deep-seismic reflection data (Chadwick & Pharaoh, 1998) together with the results of seismic-refraction studies along the LISP-B profile (Barton, 1992) in the North Sea (Barton, 1986; Nielsen et al., 2000; Lyngsie & Thybo, 2007), as well as by local teleseismic receiver functions (Tomlinson et al., 2006). Lateral variations in Moho topography are therefore resolved quite well, but absolute depths are subject to significant uncertainty due to the lack of velocity information from wide-angle seismics.

The depth of the Moho varies from 27 to 36 km (**Figure 2.2**); it is deepest beneath central and south-east England and shallowest in the north beneath the central North Sea Basin, just inside the SPB area. Beneath the SPB itself, the Moho is not generally faulted, except along the north-west–south-east-trending Dowsing Line, where significant Moho displacements are evident. Here, the Moho seems to have undergone a vertical displacement of up to 5000 m along a south-west-dipping fault, with suggestion of a hanging-wall anticline in the upthrown block (**Figure 2.3**).

2.1.2 *Crystalline basement*

The top of the crystalline basement in the UK coincides with the Caledonian (Scandian) unconformity at the base of Devonian rocks, which essentially are undeformed. In the far south-west, south of the Variscan Deformation Front, where the crystalline basement cannot be mapped, the Variscan Unconformity (top surface of the Variscan Fold Belt) is taken as the top of the basement.

The crystalline basement is shallowest beneath the London-Brabant Massif (**Figure 2.4**), where it occurs at depths of less than 1000 m and outcrops locally. Depths to basement increase north-eastwards to more than 9000 m beneath the SPB, reflecting substantial subsidence during the Devonian and Carboniferous and development of the Permo-Cenozoic basin (**Figure 2.5**). The thickness of the crystalline crust varies from more than 34 km beneath the London-Brabant Massif to less than 21 km beneath the SPB, indicative of crustal thinning since Caledonian times.

2.2 *Details of crustal structure*

The Late Precambrian crust of much of the North Sea sector of the SPB area comprises a mosaic of volcanic and associated sedimentary rocks accreted during the Cadomian Pan-African Orogeny (~600 Ma) and is termed the Avalon Composite Terrane. Closure of the Tornquist Ocean in Late Ordovician - early Silurian times (~435 Ma) brought the continental Gondwana-derived Avalonian Terrane into contact with Baltica along the North German - Polish Convergence Zone (McKerrow et al., 1990; Ziegler, 1990a). South of this zone, most Caledonian thrust-and-fold structures were produced during the latest Silurian (see Figure 3.2), by which time a new continent, Laurussia, the 'Old Red Continent', had been assembled. This was followed by Early and Mid-Devonian, orogen-parallel wrench deformation, which controlled the collapse of the Arctic - North Atlantic Caledonides (Ziegler, 1988, 1989, 1990a). The crust of the southern UK was further modified during the Variscan Orogeny, involving closure of the Rheno-Hercynian back-arc ocean, which had opened during the Early Devonian following the Silurian closure of the Rheic Ocean and the docking of the Armorican Terrane Assemblage against the southern margin of Avalonia (Cocks & Fortey, 1982; Ziegler, 1989). Late Precambrian (Cadomian) crust was accreted together with juvenile Late Paleozoic crust as the Armorican Terrane Assemblage and the Iberian microcontinents successively docked against the southern margin of Laurussia to complete the supercontinent of Pangea (Soper et al., 1992) in Late Carboniferous times (~290 Ma) (see Figure 3.7).

In large parts of the North Sea area, the pre-Permian sedimentary succession attains thicknesses of up to 10 km (Thybo, 1990; Abramovitz & Thybo, 1999; Thybo, 2001, Scheck et al., 2002b; Nielsen et al., 2005). There is little direct control on the age of these deposits. Mid- to Late Paleozoic rifting may have been mainly east-west directed (Scheck et al., 2002b). Preserved Early Paleozoic sedimentary series were probably deposited in the Caledonian foreland and occur in Mid- to Late Paleozoic extensional structures (Abramovitz & Thybo, 1999).

2.2.1 *Upper crust*

The upper crust beneath the sedimentary cover comprises strongly folded, sheared and metamorphosed rocks together with igneous intrusions, which generally form a seismically poorly-reflective layer down to about 6 to 7 s TWTT (two-way travel time) (18-21 km depth). The layer can be divided into a mosaic of blocks separated by major fault zones. A seismic marker is the so-called O-Horizon, which is a characteristic double-amplitude reflector. The O-Horizon is attributed to the lower part of the Baltica Cambro-Silurian shelf and foredeep sequence, and is conceivably related to the abrupt impedance contrast between Lower

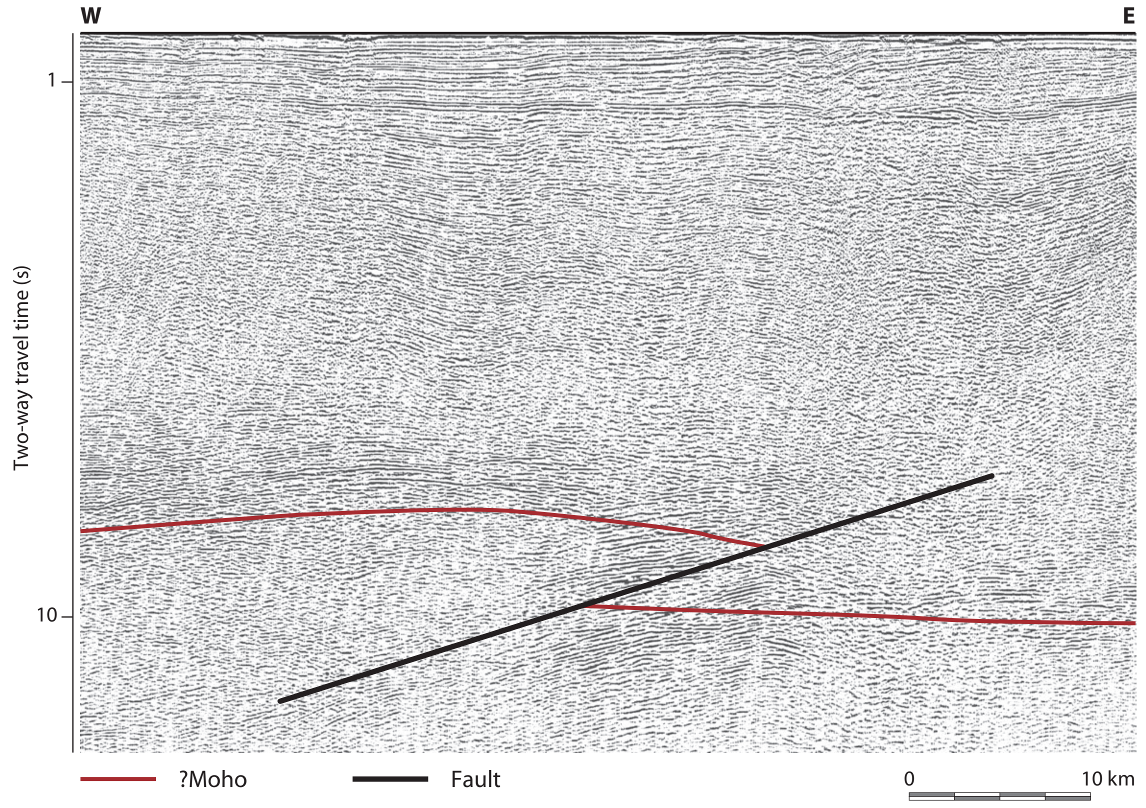


Figure 2.3 Possible Moho displacement along the Dowsing Line (BIRPS seismic data). See Figure 2.1 for location.

Cambrian orthoquartzites and Cambro-Ordovician black shales (Buchardt et al., 1997; Lassen et al., 2001). This marker is considered to be characteristic of crust of Baltica origin (Lassen & Thybo, 2004) and provides evidence that Baltica crust extends far to the south from the Mid North Sea - North German Caledonian Deformation Front (Krawczyk et al., 2002). The Cambro-Ordovician black shales formed a décollement surface for thin-skinned Caledonian thrusting (Lassen et al., 2001).

The Midlands Microcraton was distinctively stable during Early Paleozoic sedimentation and Acadian tectonism, forming a deformation-resistant rigid indenter about which a Caledonian cleavage-arc was moulded (Soper et al., 1987). Acadian deformation was most intense around and adjacent to the microcraton, giving rise to the slate belts of north Wales, northern England and the concealed Caledonides beneath eastern England and the southern North Sea (Pharaoh et al., 1987, 1995). The exact position and nature of the north-east bounding structure of the microcraton is uncertain, but it has been correlated with structures in the sedimentary cover such as the Thringstone Reverse Fault (Smith, 1987) (see Figure 3.6b).

The concealed Caledonides of eastern England are characterised by a pervasive north-west–south-east structural fabric, with a number of discrete thrusts that are visible on seismic-reflection data. A number of intrusive igneous bodies are also present (**Figure 2.6**), ranging in composition from felsic to intermediate; the former is evident as prominent gravity lows (Wybraniec et al., 1998; Williamson et al., 2002; **Figure 2.7**). The clearest images of Caledonian thrusts are from eastern England, where locally the thin sedimentary cover allows good seismic imaging of basement structures. The Broadlands Thrust (Chadwick & Evans, 2005) is well imaged as a north-east-dipping structure in Lower Paleozoic rocks beneath a thin sedimentary cover (**Figure 2.7**). The Glinton Thrust is another well-imaged upper-crustal Caledonian thrust (**Figure 2.8**) showing clear evidence of reactivation during Variscan times as a reverse fault that displaces the Carboniferous sedimentary cover. Evidence of repeated reactivation of these basement thrusts in both extension and contraction modes is provided by the Eakring Fault, which lies along the north-west prolongation of the Glinton Thrust.

Offshore, a number of rather enigmatic mid-crustal reflectors have been identified on deep-seismic reflection data (**Figure 2.9**). These reflectors dip to the north-east and have been interpreted as Mesozoic extensional shear zones (Reston & Blundell, 1987). An alternative, perhaps more likely view, is that they have a Caledonian origin as basement thrusts. Further evidence of control by the north-west–south-east-trending basement fabric is afforded by the geometry of the southern North Sea gasfields (see Chapter 13). The north-west–south-east-trending basement fabric was repeatedly reactivated during the Late Paleozoic, Mesozoic and Cenozoic as evidenced by the evolution of the Sole Pit Basin (see Chapter 3).

The Southern North Sea Terrane (Pharaoh et al., 1995) is bounded to the south-west by the Dowsing Line (**Figure 2.6**), already noted as a major feature at lower-crustal depths. Major contrasts in geophysical properties in the crust on either side of the Dowsing Line led Pharaoh et al. (1995) to infer the presence of a possible suspect terrane incorporated between Avalonia and Baltica during collision in Late Ordovician times.

In the far south-west of the area, the Variscan Front Thrust defines the northern limit of pervasive Variscan deformation and metamorphism in the Variscan fold/thrust belt. The Variscide Rheno-Hercynian Zone comprises Upper Paleozoic rocks metamorphosed at relatively low grade, which developed in a foreland

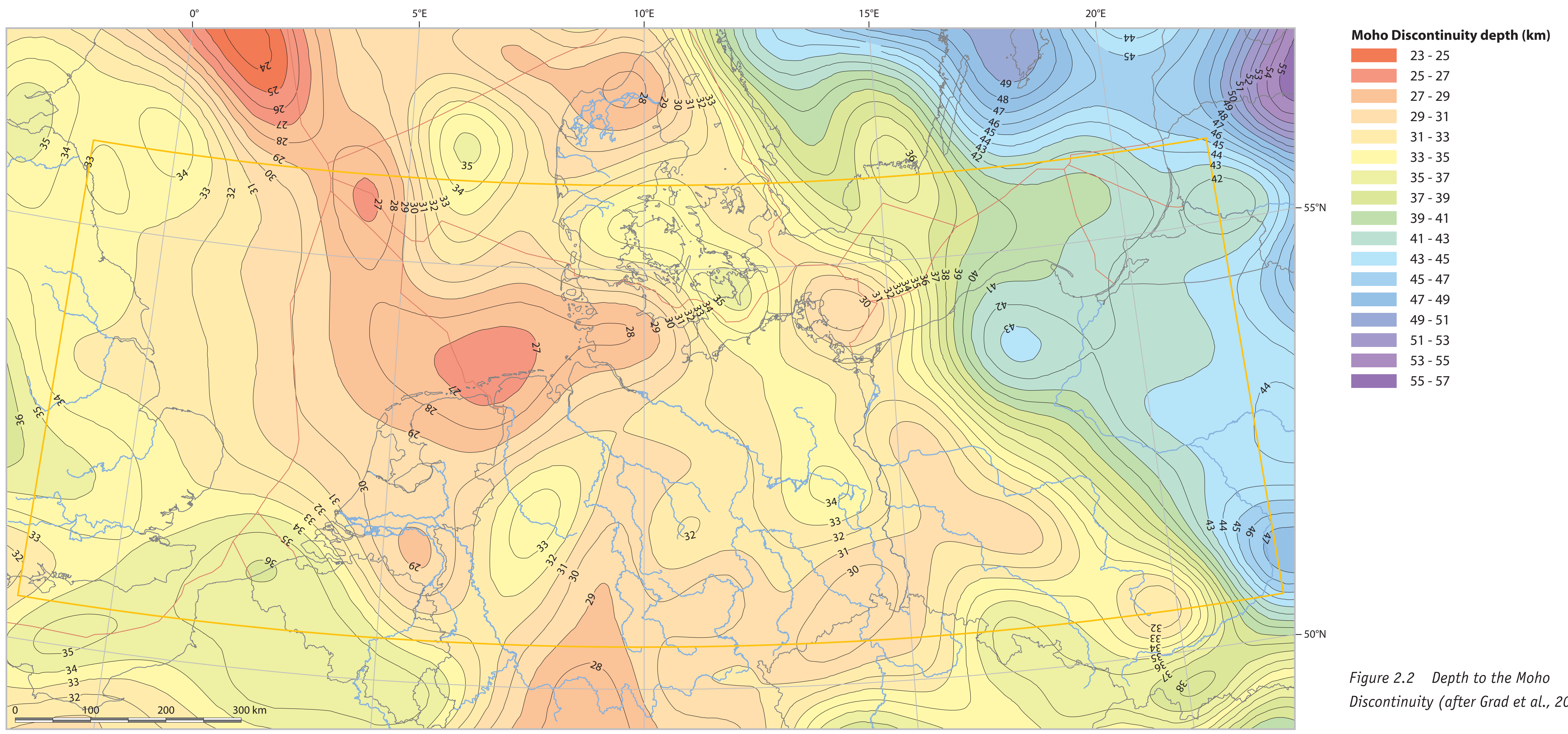


Figure 2.2 Depth to the Moho Discontinuity (after Grad et al., 2009).

thrust belt. A number of south-dipping thrusts are evident on seismic data. These were notably susceptible to reactivation (e.g. **Figure 2.10**), and controlled evolution of the Mesozoic-Cenozoic Wessex Basin of southern England. The Variscan external thrust belts of Belgium and southern England overprinted the Mid-European Caledonides (Ardennes) (Ziegler, 1990a).

In the south-eastern North Sea area, the upper-crustal fabric is dominated by Caledonian deformation structures. The suture between Baltica and Avalonia has been imaged by a gently south- to west-dipping reflective band in four deep seismic profiles (**Figure 2.1**) (MONA LISA Working Group, 1997a, 1997b). This band marks the transition between the upper, high-velocity crust of Baltica affinity and the low-velocity crust of Avalonia affinity (**Figure 2.11**) (Thybo, 1990; BABEL Working Group, 1993; Abramovitz et al., 1998, 1999; Abramovitz & Thybo, 2000). This crustal suture continues into a series of thrust structures in the sedimentary sequence and uppermost crystalline crust (Abramovitz & Thybo, 1998; Lassen et al., 2001). The reflectivity of the suture may have been enhanced by intrusion of mafic magma during later extensional tectonic events, as indicated by the magnetic and gravity signals around the suture (Lyngsie & Thybo, 2007).

The upper crust of the Baltica part of the North Sea area is surprisingly reflective, showing a series of reflection bands with variable dips and dip directions. Mapping of these reflections shows that they can be interpreted as remnant structures of Proterozoic collisional events, including the Gothian and Sveconorwegian orogenies, and that these structures may have been reactivated during later extensional events (Lassen & Thybo, 2004). Comparison with the BABEL deep-seismic reflection line in the Baltic Sea (BABEL Working Group, 1993) shows that these upper-crustal reflections may have extended deeper than they are today, indicative of significant post-orogenic erosion in the Danish area. Such upper-crustal reflections are seen up to the Caledonian Deformation Front, where they disappear.

Within the area of Baltica crust, a series of strike-slip faults have been interpreted as the Tornquist Fan (Thybo, 1997). These faults, which probably extend to the base of the crust, branch out from the Tornquist-Teisseyre Zone in the Baltic Sea to form a triangular fan of faults across the Danish region with west to north-west strike directions. The southernmost of these faults may mark the edge of the former Baltica Plate at upper-crustal levels at the Trans-European Suture Zone (EUGENO-S Working Group, 1986;

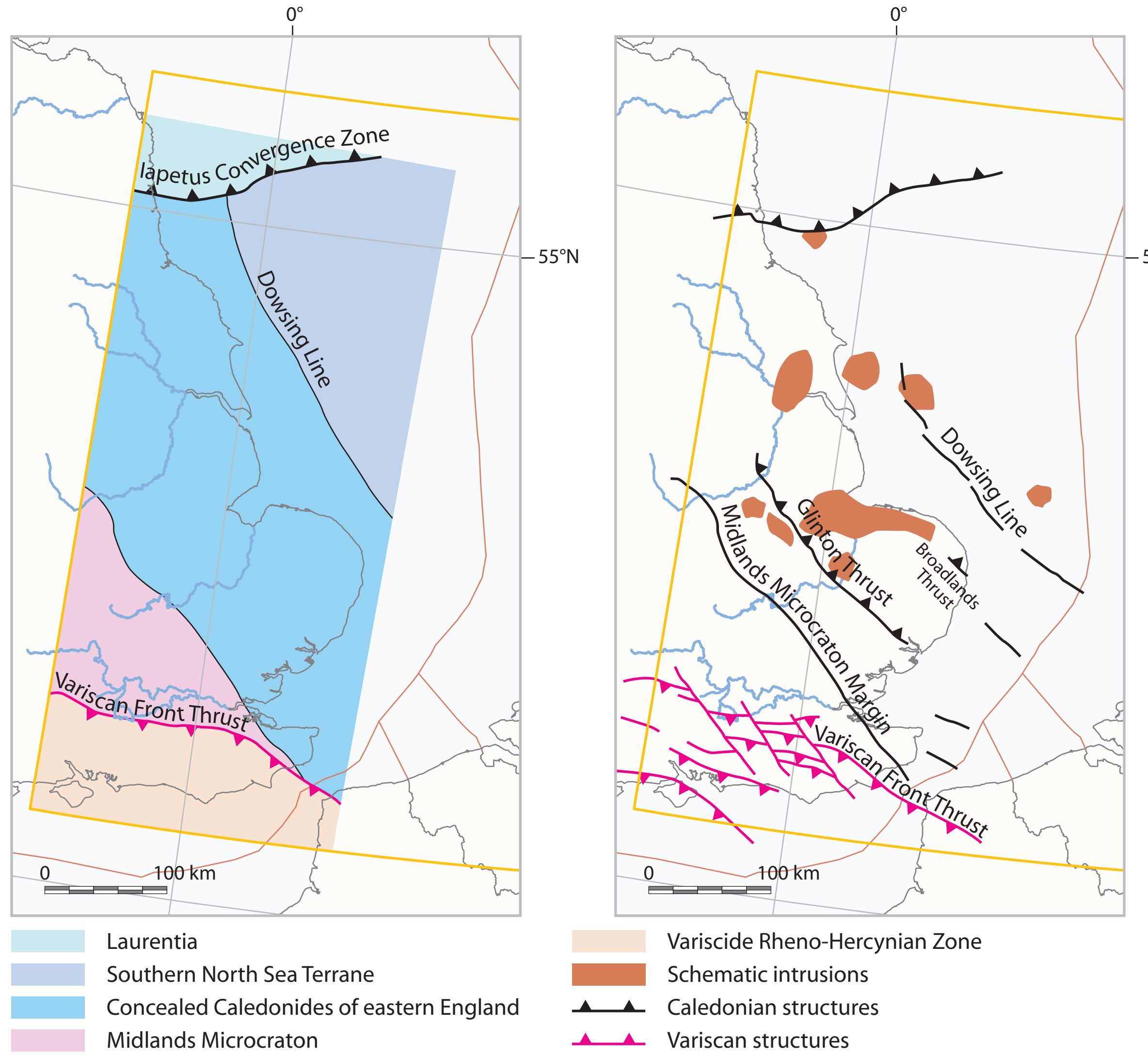


Figure 2.6 Major upper-crustal structural provinces and structures.

Berthelsen, 1992a). This system of faults had significant influence on the tectonic development of the region, including the Late Carboniferous to Permian extension that initiated the Northern Permian Basin. These faults presumably accommodated the transfer of right-lateral displacement between individual extensional structures such as the Brande Trough, Horn and Central grabens (Thybo, 1997). Moreover, they may have provided pathways for several magmatic intrusions in the area during Late Carboniferous-Permian extension. These intruded batholiths are generally identified as ~50 mGal positive gravity anomalies, for example in central Jylland (Thybo & Schönharting, 1991), Scania and the south-eastern Kattegat (Thybo, 2001). The intrusion at the Silkeborg gravity high in Jylland has been imaged in detail by deep-seismic investigations as a 20 to 30 km-wide, 20 km-high and more than 100 km-wide body beneath a depth of ~10 km, with extremely high seismic velocities (6.6-7.7 km/s); as such, its volume is more than 100 000 km^3

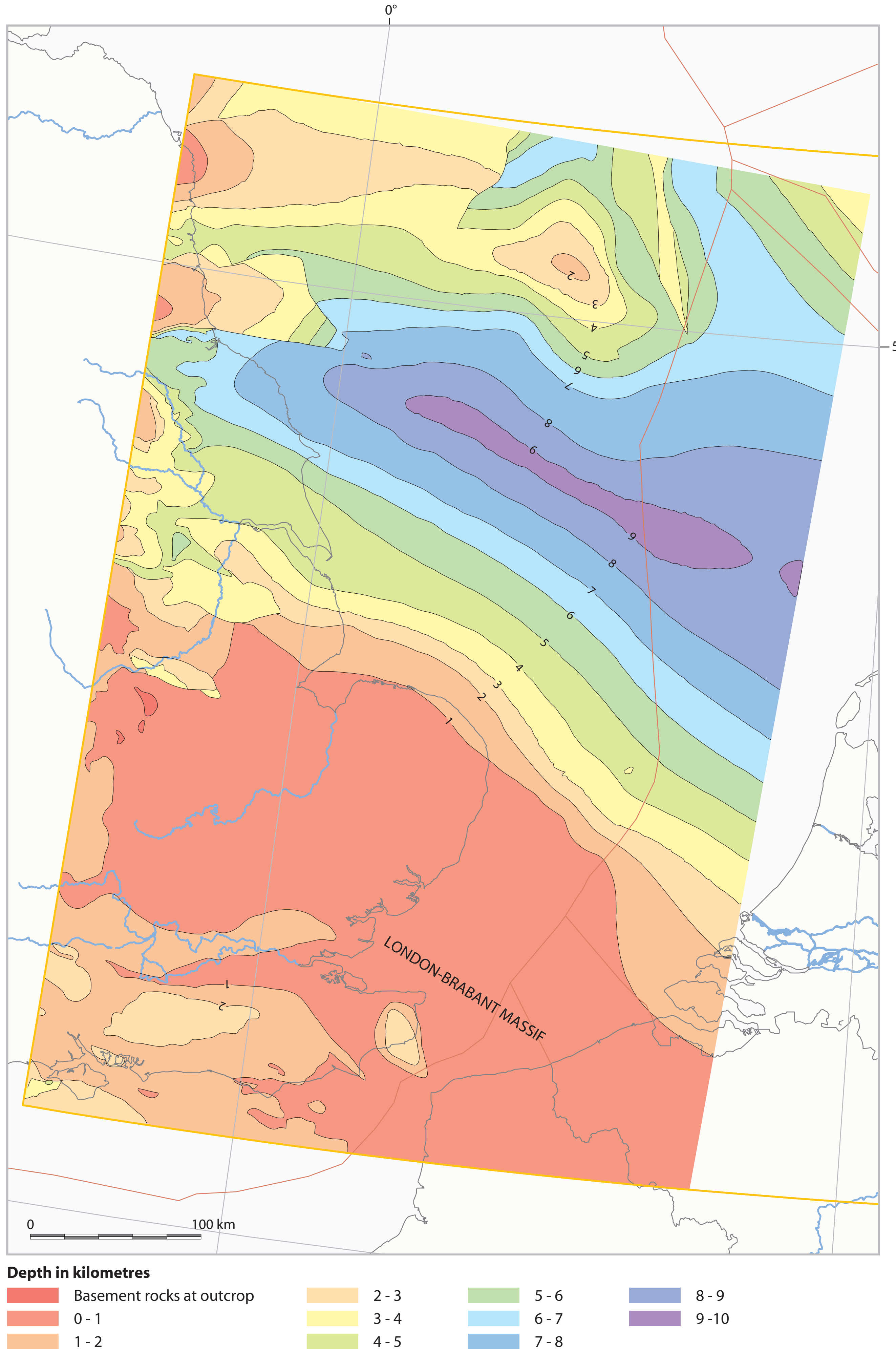


Figure 2.4 Depth to the top of the crystalline basement in the North Sea area.

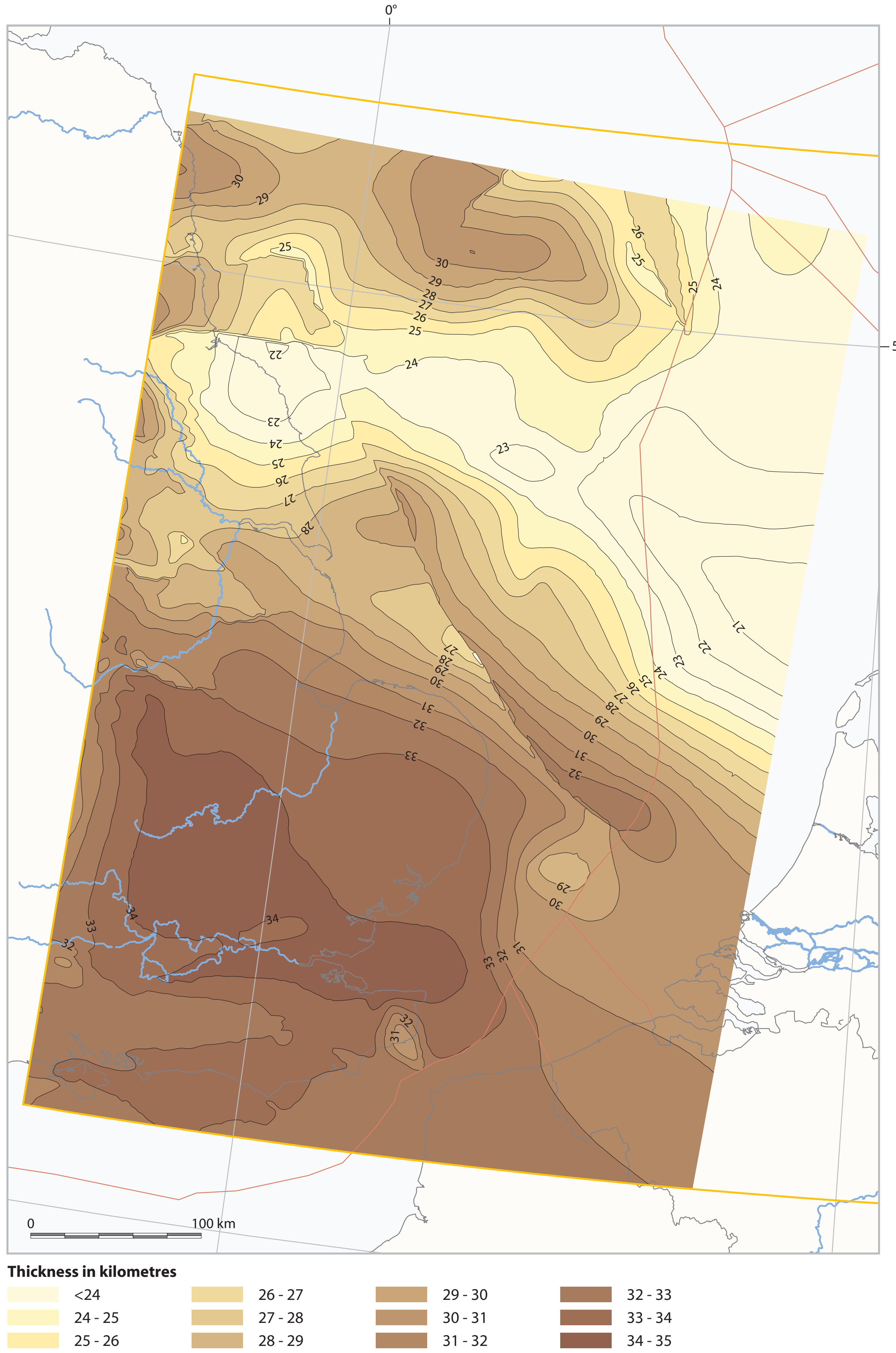


Figure 2.5 Thickness of the crystalline crust in the North Sea area.

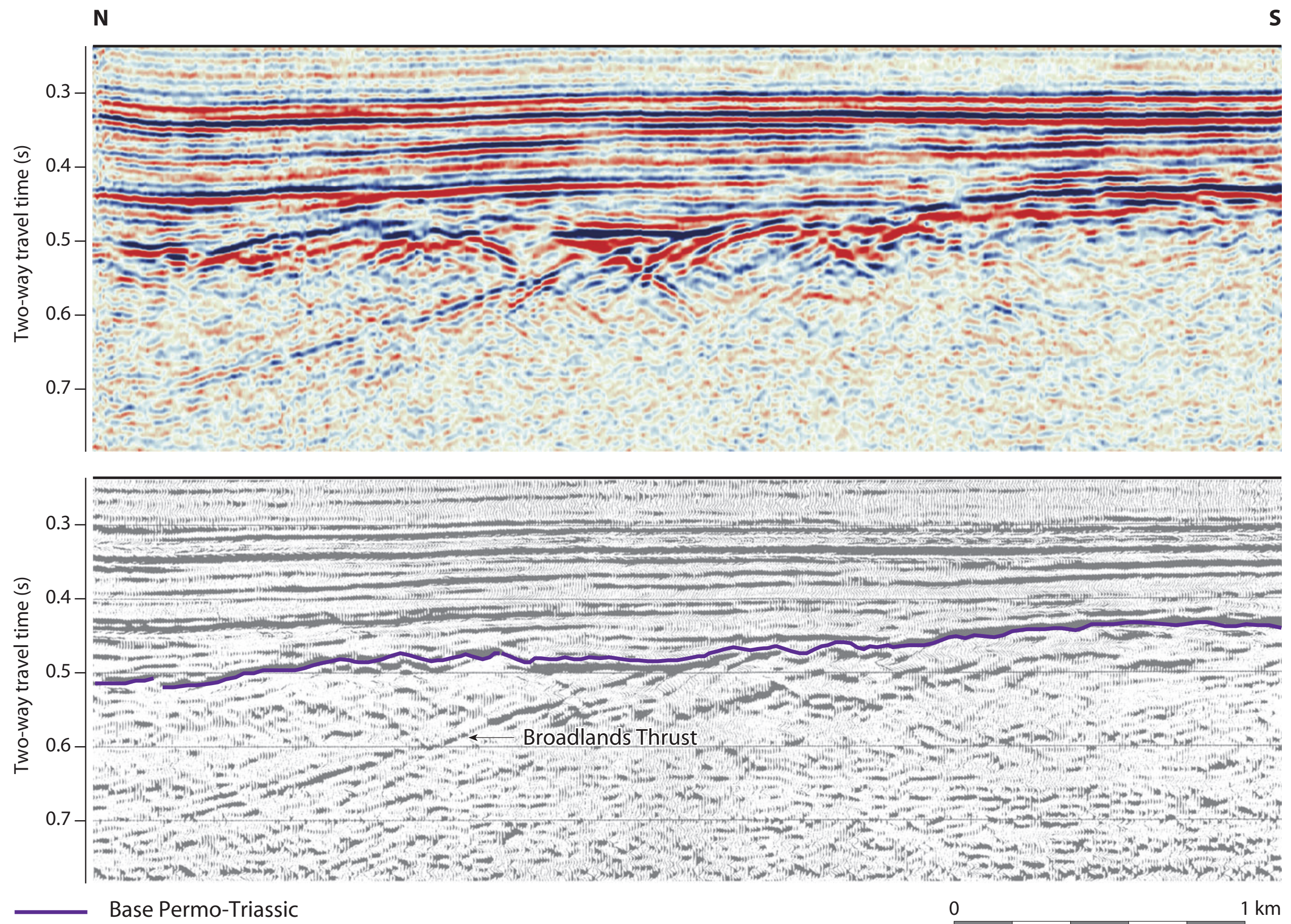


Figure 2.7 The Broadlands Thrust. A Tornquist-trending structure from the concealed Caledonides of eastern England (from Chadwick & Evans, 2005). See Figure 2.1 for location.

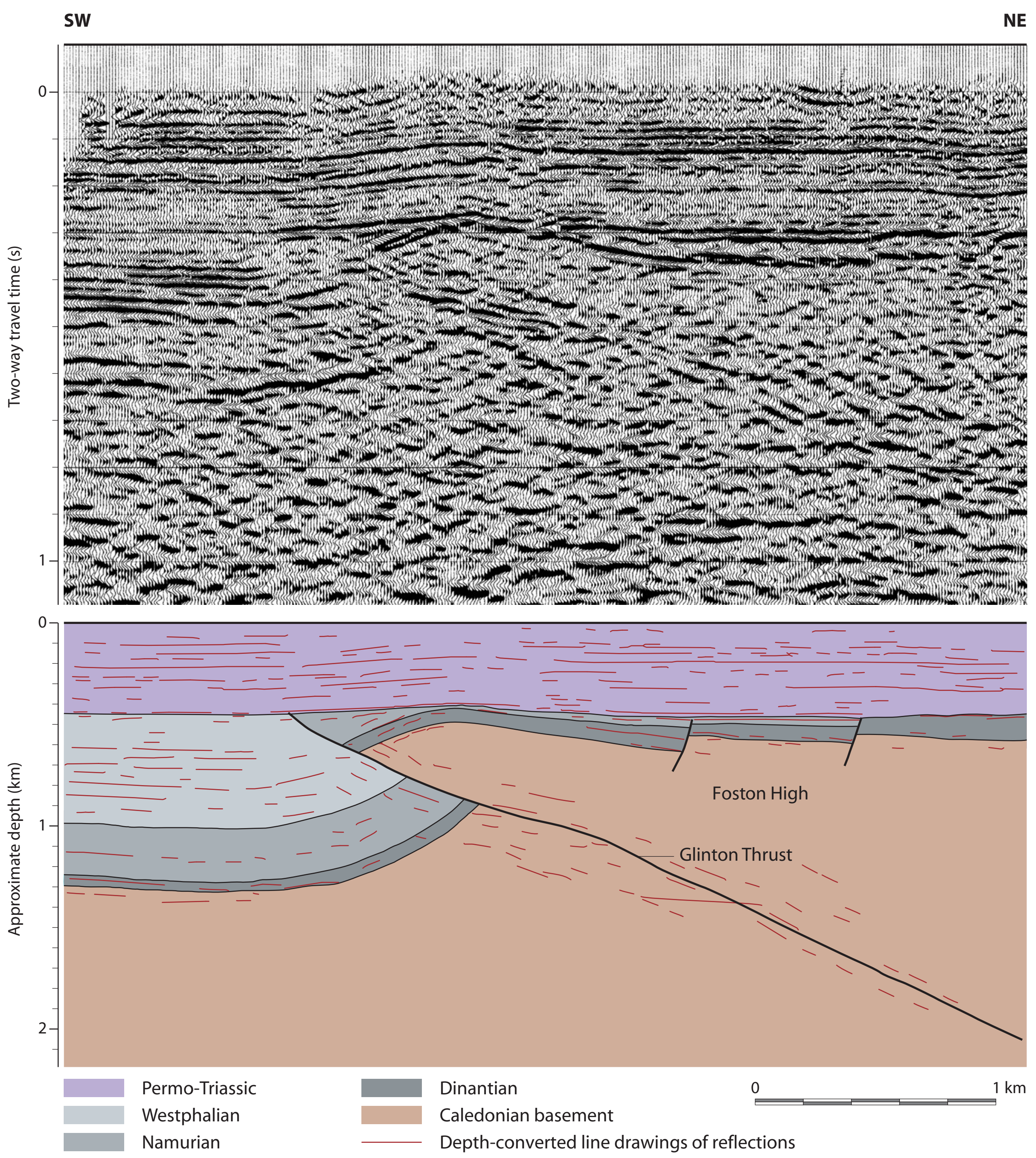


Figure 2.8 The Glinton Thrust. A Caledonian structure reactivated in Variscan times to displace Carboniferous sedimentary cover rocks (from Chadwick & Evans, 2005). See Figure 2.1 for location.

(Thybo et al., 2006; Sandrin & Thybo, 2008a, 2008b). The body is seismically transparent, which indicates that it may have been intruded over a short period in a single or very few events (**Figure 2.12**). The existence of a hot magmatic body of these dimensions may have initiated thermal subsidence of the Danish-Norwegian Basin (Sandrin & Thybo, 2008b).

2.2.2 Lower crust

In general, the lower crust of the UK sector is seismically layered, though with some geographical variation. Layering is best developed beneath the Variscan Fold Belt, not so well developed beneath the Caledonides of eastern England and the southern North Sea, and possibly only faintly evident beneath central England (Chadwick & Pharaoh, 1998). The lower crust lies typically between 6 and 10 s TWTT (18-30 km depth). The top of the lower crust can be readily identified in places where layering is well developed. The base of the lower crust corresponds to the seismic-reflection Moho. Where lower-crustal layering is well developed, the Moho is readily identified as the base of this layering (**Figure 2.13**). In some areas, the Moho corresponds to a discrete seismic reflection. There are only a few deep-seismic data records where the Moho can not be clearly identified (**Figure 2.15**).

The nature of the lower crust is largely a matter of conjecture. The well-developed seismic layering noted above has been ascribed to igneous differentiation during partial melting, the presence of basic igneous intrusions, or even the presence of fluids. Of greater significance may be the fact that the well-developed sub-horizontal reflections suggest a dominantly sub-horizontal structural fabric, consistent with lower-crustal rocks showing severe ductile flattening beneath dominant vertical-loading forces. Further evidence of a ductile lower crust lies in the fact that many of the upper-crustal faults or shear zones flatten out within the uppermost part of the lower crust, or die out within it. However, prominent dipping thrusts of the upper crust do penetrate locally deep into the lower crust as shear zones. The main structure that cuts from upper-crustal levels down to the Moho is a north-west-dipping fault associated with the Caledonian Iapetus Suture (Chadwick & Holliday, 1991; **Figure 2.13**).

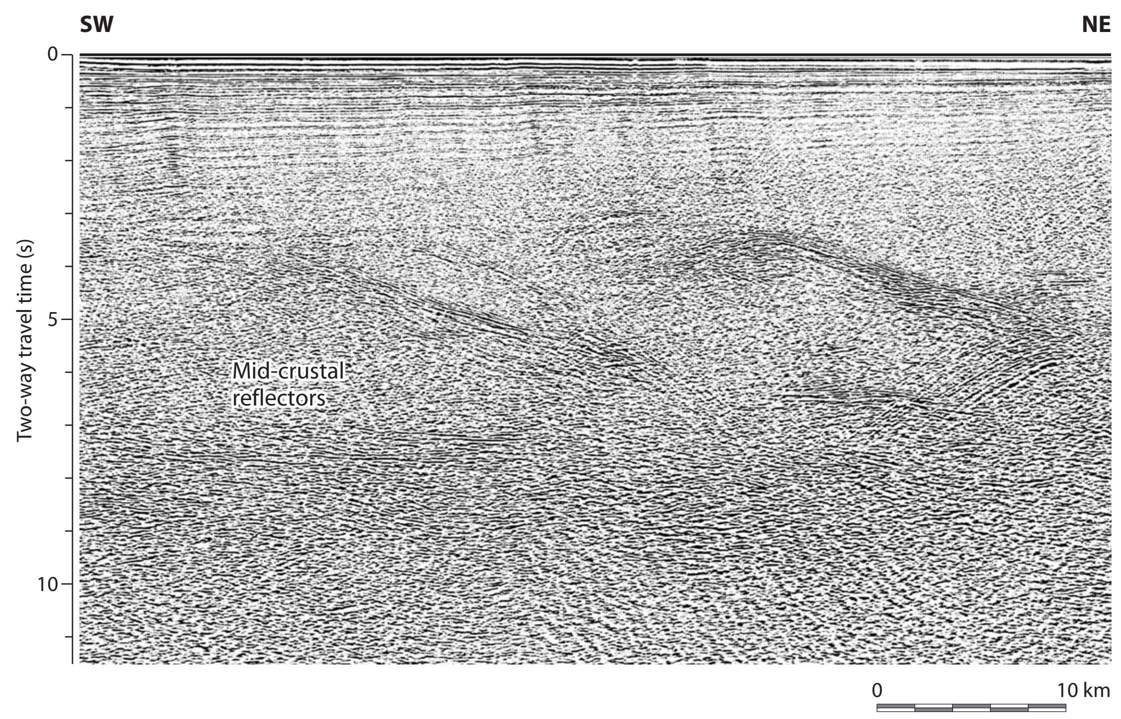


Figure 2.9 Mid-crustal reflectors from the concealed Caledonides beneath the southern North Sea. Interpreted as shear zones of enigmatic origin (BIRPS seismic data). See Figure 2.1 for location.

The lower crust of Precambrian Baltica is generally non-reflective with a few exceptions (BABEL Working Group, 1993; MONA LISA Working Group, 1997a, 1997b). This allows the lower-crustal transition between Baltica and Avalonia/Laurentia to be identified. Furthermore, the lower crust of Baltica origin has generally high velocity (>7.0 km/s) as demonstrated in a number of deep-seismic profiles (e.g. EUGENO-S Working Group, 1986; Thybo, 1990, 2001; BABEL Working Group, 1993; Abramowitz et al., 1998; Abramowitz & Thybo, 2000). There are considerable variations in the depth of the Moho in the Precambrian crust of Denmark, ranging between 26 and 38 km depth within the basin area (Thybo, 1997, 2000) (**Figure 2.2**). Most of this variation may be attributed to crustal thinning during extensional events, mainly during Late Paleozoic times. Based on seismic data and significant anomalies in the gravity field, Lyngsie et al. (2006) interpreted the Baltica lower crust as extending across the central and northern North Sea to the coast of Scotland.

The transition between the lower crust and Moho in the area around the large mafic batholiths in the Precambrian crust of Denmark was apparently modified significantly during the related extensional events. A ~4000 m-thick band of reflective basal crust with very high velocity has been identified, extending up to 100 km from the batholith in central Jylland. The internal structure of these bands is layered, with characteristic thicknesses of individual high-velocity layers of 300 to 600 m (Sandrin et al., 2009). These internal layers are interpreted as mafic sills that were intruded along the Moho during the late phase of magmatism due to increased pressure from the cooling intrusive body (**Figure 2.12**).

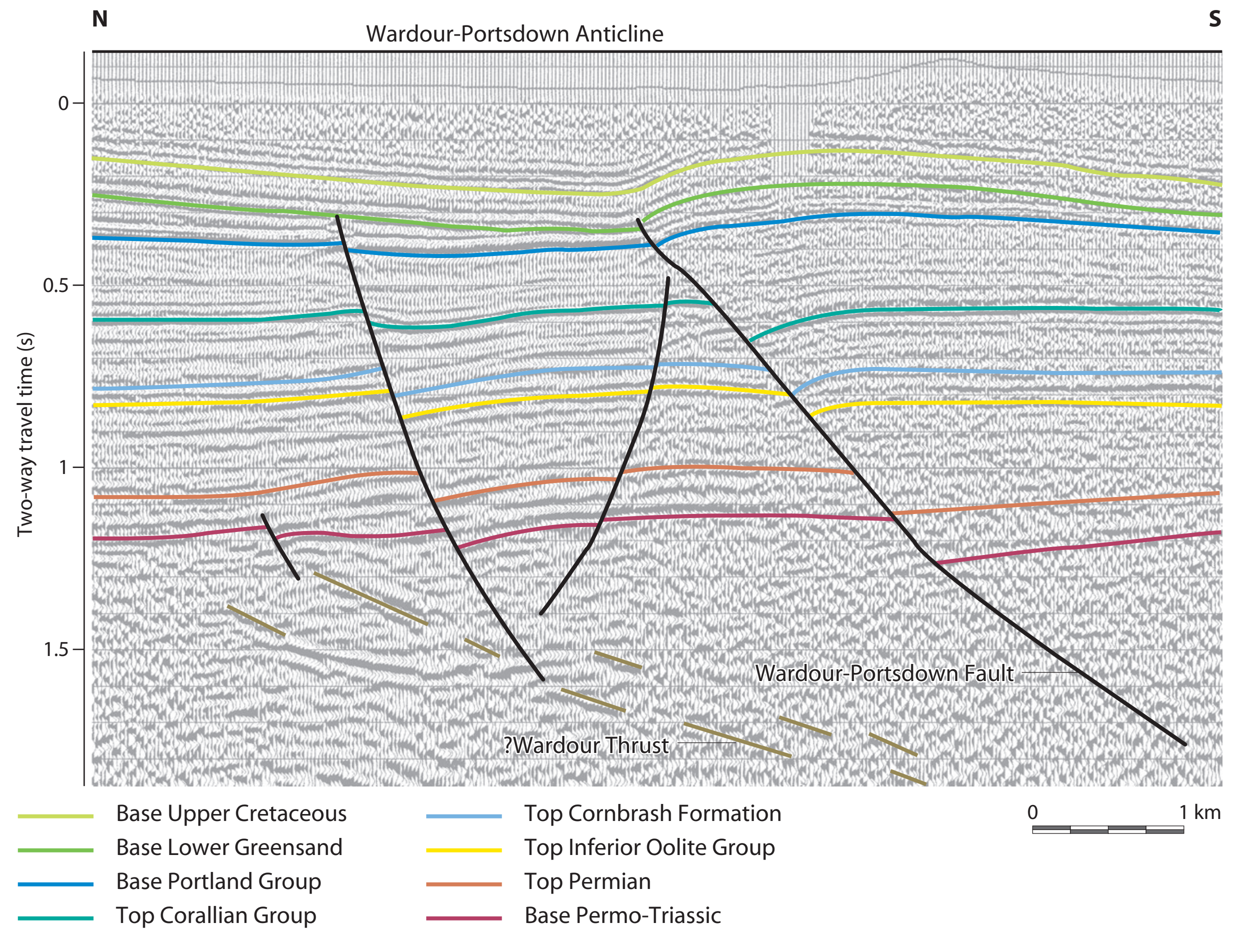


Figure 2.10 Variscan basement thrusting. The Wardour-Portsdown Thrust reactivated in extension in the Mesozoic and contraction in the Cenozoic to form the Wardour-Portsdown inversion structure (from Chadwick & Evans, 2005). See Figure 2.1 for location.

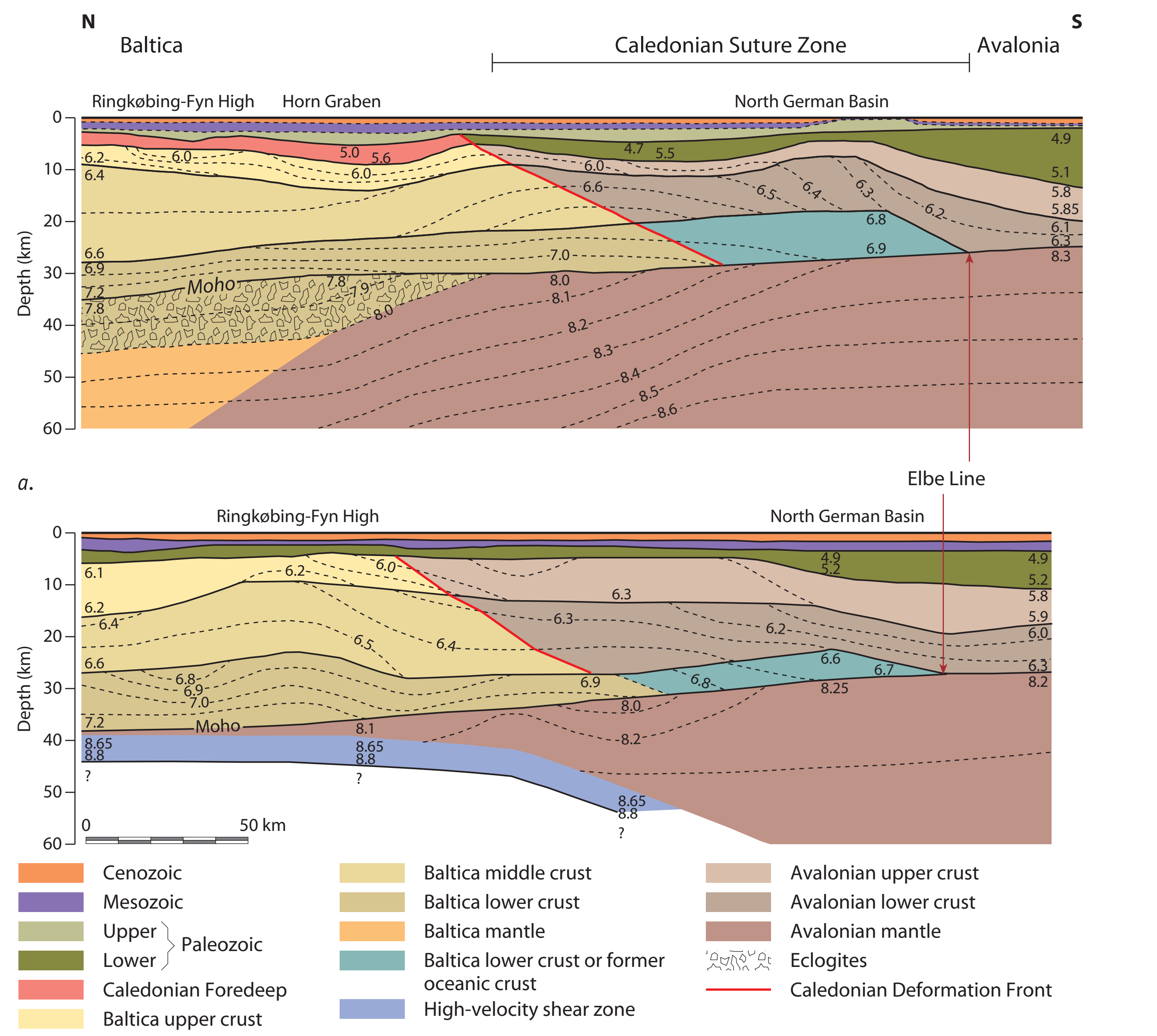
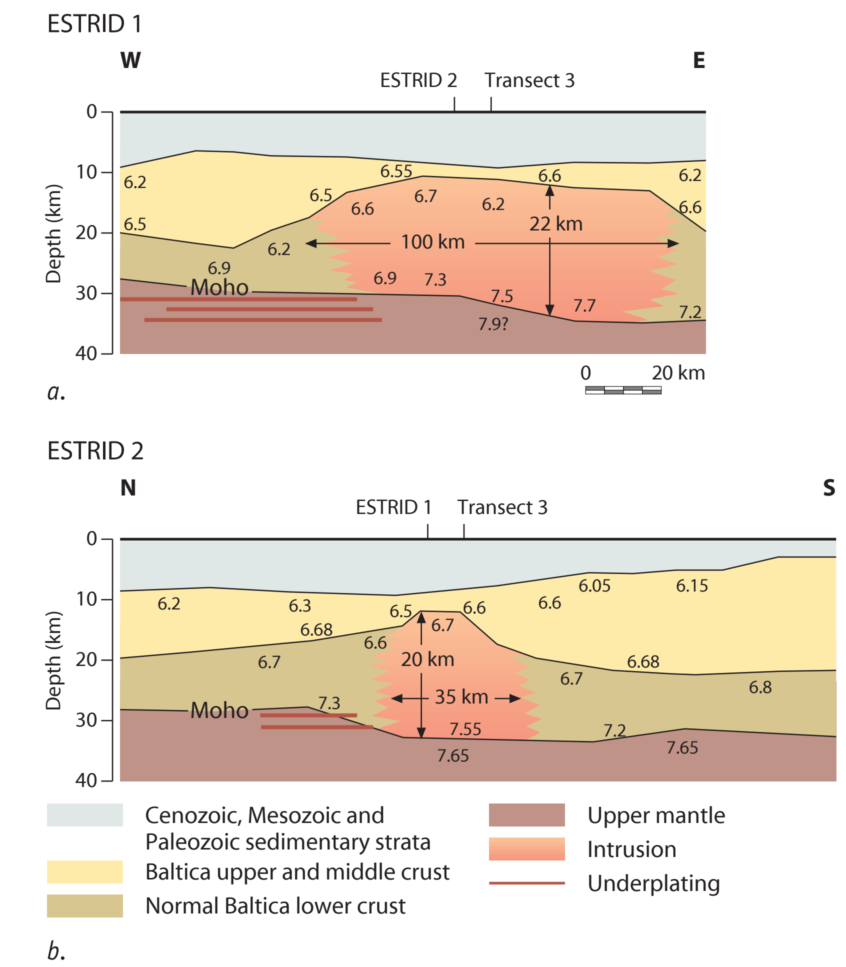


Figure 2.11 Seismic velocity profiles along MONA LISA Profiles 1 (a) and 2 (b)(after Abramowitz et al., 1998; Abramowitz & Thybo, 2000). See Figure 2.1 for locations. The crustal structure is generally similar in both profiles, which extend from the Baltica crust in the north across the suture zone to the Avalonia crust in the south. The area of lower crust interpreted as being of Baltica origin could also represent oceanic crust beneath the metasedimentary basement sequences. The mantle structures are completely different in each profile, even though they are only ~100 km apart. The mantle beneath the Avalonia crust has very high velocity (>8.3 km/s) in both profiles. In Profile 1, the upper ~12 km of mantle beneath Baltica has low velocities (7.8-8.0 km/s). This mantle wedge is interpreted as former lower crust, which has been transformed into eclogite facies while being subducted during the Caledonian Orogeny. In Profile 2, the uppermost mantle includes a 5000 m-thick zone of extremely high velocity (>8.6 km/s), which has been interpreted as a shear zone where olivine minerals are aligned such that the recorded high velocity is due to anisotropy.

Figure 2.12 Interpretation of a large batholith in the Danish Basin and underplating layers at its rim. Based on 2D-seismic-velocity structure along the ESTRID seismic profiles (1 and 2; see Figure 2.1 for locations) (after Sandrin & Thybo, 2008a). The geometric properties of the interpreted intrusions are: total thickness in the order of 18-22 km; total length (E-W) at least 80-100 km; total width (N-S) between 15-20 km at the top and 30-35 km at Moho level. Strong seismic reflectivity is observed from a 4000 m-thick layer at the Moho level, extending 50-100 km from the edge of the crustal batholith. This underplated layer is interpreted as originating from the late stage of mantle cooling.



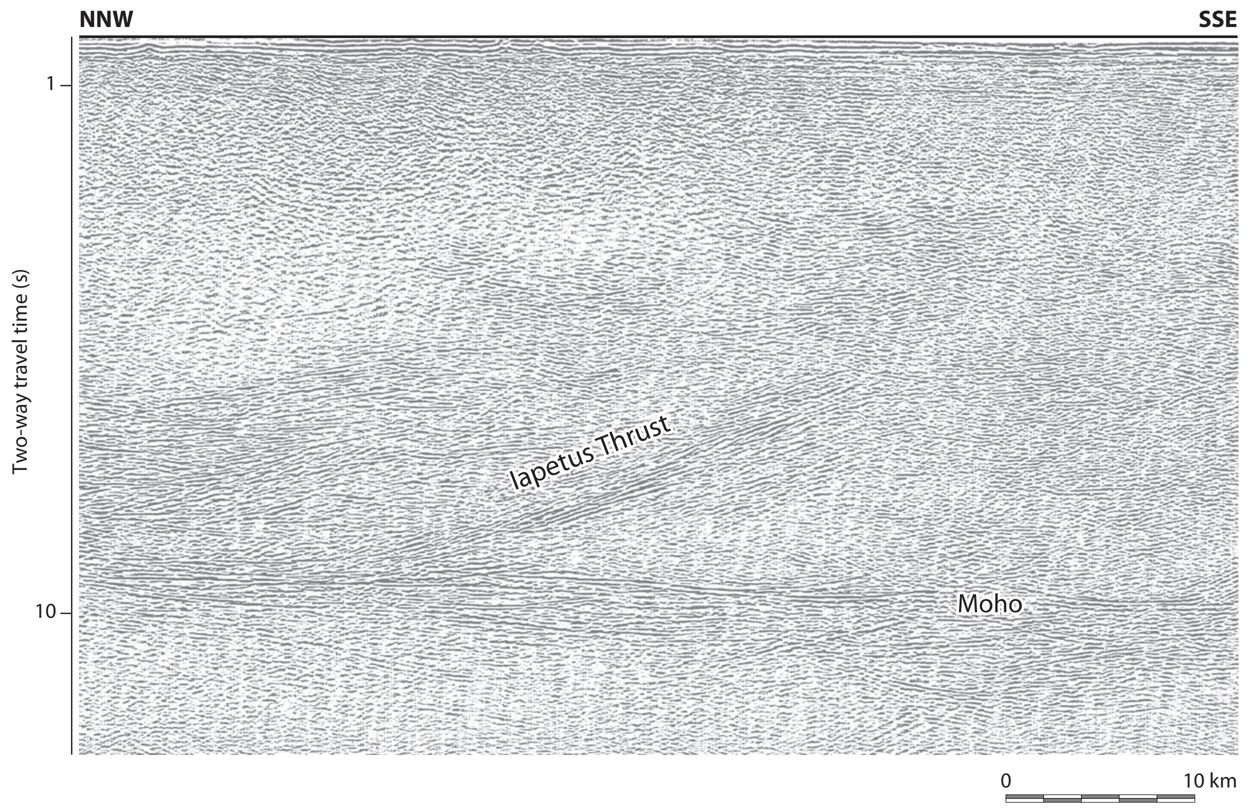


Figure 2.13 Lower crustal faulting on the Iapetus Thrust (BIRPS seismic data). See Figure 2.1 for location.

3 Central area

3.1 MONA LISA transects in the south-eastern North Sea

The MONA LISA (Marine and ONshore Acquisition for LIthospheric Seismic Analysis) project was designed to provide images of lithospheric-scale structures related to Caledonian collision and basin formation in the south-eastern North Sea (MONA LISA Working Group, 1997a, 1997b). The seismic profiles are approximately oriented perpendicular to the Caledonian Deformation Front and the Mesozoic Central Graben (**Figure 2.1**). The data include high-quality, deep-seismic reflection profiles up to 24 s TWTT and a large set of seismic-refraction/wide-angle reflection data recorded at, along, and between the profiles. The project allowed imaging of structures close to the base of the lithosphere in a region where spectacular reflections from 21 to 22 s TWTT may originate close to the asthenosphere-lithosphere boundary.

The profiles have provided images of the crustal structure, which indicate that Baltica crust extends southwards as far as the projection of the Elbe Line into the North Sea. The Caledonian suture between the Avalonia and Baltica crust (Thor-Tornquist suture) has been imaged as a slightly listric fault structure with a dip of about 25°. The images of the mantle lithosphere show both north-easterly and south-westerly dipping structures that may be related to the Caledonian collision and later extensional events.

Three different crustal types have been identified from the MONA LISA data: (1) a three-layered crust, typical of the Precambrian Baltica shield in the north; (2) a transitional crust (suture zone) in the central part; and (3) a two-layered Avalonia crust of Caledonian origin to the south, which is characterised by very low velocities throughout the crust (Abramovitz & Thybo, 2000) (see Section 3.1.2).

3.1.1 The Moho

The depth to the Moho generally varies by only a small amount at about 30 to 32 km, but rises to 26-28 km beneath the Mesozoic Central Graben and the Avalonia crust of the North German Basin (**Figure 2.2**). In the southern part of the area, the Moho reaches maximum depths of 38 km beneath the Precambrian crust of the Ringkøbing-Fyn High (Abramovitz et al., 1998).

The Moho gives rise to a distinct and sharp reflector in the southernmost Avalonian part of the profile area, where it represents a sharp contrast between crust with a velocity of 6.3 km/s and mantle with a velocity of ~8.2 km/s. Reflections from the Moho are even identified at near-normal incidence on single-station seismic recordings (MONA LISA Working Group, 1997a). This distinctive feature of the Moho has been interpreted as being characteristic of the Caledonian Avalonia Terrane (Abramovitz et al., 1998).

Farther north, reflections from the Moho are still identifiable as individual events with smaller amplitude and with a longer duration waveform. In a few locations, the sections show banded reflections in the lowermost crust, with the Moho corresponding to the base of the reflective band (**Figure 2.12**). Layering around the Moho beneath the Ringkøbing-Fyn High may be related to sills that were intruded along the crust-mantle boundary during the intrusion and cooling of the Permo-Carboniferous Silkeborg batholith (Abramovitz et al., 1998; Lyngsie & Thybo, 2007; Sandrin & Thybo, 2008a).

The MONA LISA data image a sub-horizontal Moho across the Caledonian collision zone, which implies that the present Moho is a late- or post-Caledonian feature. The sub-Moho velocity is characteristically low (<7.9 km/s) beneath the Baltica crust in the north-eastern part of the MONA LISA area. This indicates that the upper part of the mantle in this area may contain eclogitised lower-crustal material that, owing to its high velocities, has been transferred across the geophysically defined Moho to now form part of the seismic upper mantle (**Figure 2.11**) (Abramovitz & Thybo, 1998, 2000; see also Griffin & O'Reilly, 1987; Mengel & Kern, 1992; Le Pichon et al., 1997; Ziegler et al., 1998).

3.1.2 Crustal structure

The upper crust is generally non-reflective with only localised individual dipping reflectors. The lower crust is slightly more reflective in the south-west than in the north-east part of the region. Distinct lower-crustal reflectivity occurs only locally.

Three characteristic crustal types have been identified around the Caledonian collision zone (**Figure 2.11**):

- A characteristic *three-layered crust* with high average crustal velocities in the north-east of the area is interpreted as Proterozoic shield-type Baltica crust. Its velocity structure is comparable to findings from other deep-seismic projects in the Danish area, where a similar basement crust has been identified beneath most of the North Danish Basin to the north and east (Thybo et al., 1990; BABEL Working Group, 1993; Thybo, 2000). The upper-crustal velocities of 6 to 6.25 km/s may represent a mixture of gneissic and granodioritic rocks, as encountered in boreholes penetrating basement in the Danish area. A thick mid-crustal layer with velocities of 6.3 to 6.6 km/s may represent felsic rock assemblages, similar to upper-crustal rocks under high metamorphic conditions, such as amphibolite to granulite facies. The weakly reflective, thick, high-velocity lower crust has velocities of 6.8 to 7.2 km/s, which are consistent with rocks of a mafic composition in high-grade amphibolite or granulite facies.
- The *transitional crust* in the central part of the area is characterised by deep-reaching, southerly dipping reflectors. This domain is interpreted as the crustal suture zone between the Baltica crust to the north-east and the Avalonia crust to the south-west. This interpretation implies that, during the Caledonian Orogeny, Avalonia and/or its accretionary wedge was thrusted northwards and eastwards over Baltica crust. Distinct southerly dipping reflections may represent the northern and eastern frontal parts of the Caledonian Deformation Front within the crystalline crust, i.e. the northernmost limit of the area affected by the collision between Baltica and Avalonia (Abramovitz & Thybo, 2000; Lassen et al., 2001). The southerly dipping reflectors may be images of crustal shear zones within the suture zone, which correspond to a diffuse and distinct change in crustal velocity structure. Very high seismic velocities beneath this transition zone indicate that Baltica lower crust clearly extends beneath this suture.
- The *two-layered crust*, with remarkably low average crustal velocities in the southern part of the profile, is interpreted as an Avalonia-type crust similar to that beneath most of the North German Basin, which extends southwards to the Variscan Front (Thybo, 1990, 2001; Aichroth et al., 1992; Bayer et al., 2002; Krawczyk et al., 2008a). The very low velocities (<6.3 km/s) above the Moho may represent a mixture of north-eastward thrusted metasedimentary rocks and intercalated granitic intrusions. These metasedimentary rocks may have formed in the accretionary wedge of the Avalonia fore-arc complex (Abramovitz et al., 1998; Abramovitz & Thybo, 2000).

Mapping the extent of the reflective, high-velocity lower crust between the Caledonian crustal suture and the projection of the Elbe Line into the North Sea suggests that the lower Baltica crust was overridden by Avalonia or related terranes during docking against Baltica and the related closure of the Tornquist Ocean. However, a possible alternative explanation is that this lower crust represents oceanic Tornquist crust (**Figure 2.11**) (Abramovitz & Thybo, 2000).

Combined magnetic and gravity modelling shows that the crust of Avalonia affinity is weakly magnetic, whereas Baltica crust is strongly magnetic (Williamson et al., 2002; Lyngsie & Thybo, 2007). Interpretation of the potential field across the North Sea indicates that Baltica crust extends westwards, at least to the coast of Scotland, and that a large part of Baltica crust was overridden during the Caledonian Orogeny in a 200 to 300 km-wide belt (Lyngsie & Thybo, 2007). Short wavelength magnetic anomalies around the location of the presumed Caledonian suture indicate that faults of this suture zone represented weakness zones during the Permo-Carboniferous extensional events, forming conduits for the intrusion of mafic magmas (Lyngsie & Thybo, 2007).

The east–west profiles show slight crustal thinning beneath the Mesozoic Central and Horn grabens (Nielsen et al., 2000). Interpretation of the magnetic field along one of the profiles further shows that Baltica lower crust extends farther west than the Central Graben, and that development of this segment of the Central Graben apparently involved tensional reactivation of the Caledonian suture (**Figure 2.14**) (Lyngsie & Thybo, 2007). There is no sign of underplating directly beneath the Central Graben as often observed around rift zones (e.g. Thybo & Nielsen, 2009). However, a 2 to 4 km-thick reflective layer with high density, observed about 70 to 100 km farther west, may be related to Permo-Carboniferous mafic intrusions.

3.1.3 Mantle structure

The mantle in the south-eastern North Sea shows significant variation in both seismic velocity and seismic reflectivity. The MONA LISA profiles all show dipping bands of mantle reflections (MONA LISA Working Group, 1997a, 1997b). Due to the configuration of the four profiles, these reflections can be correlated between the different profiles, and it appears that one set of mantle reflections dips to the north-east. This set is cut by another set of mantle reflections, which dip to the south-west and must therefore be younger. The north-east-dipping set of events extends from the Moho into the mantle where the crustal suture reaches the Moho, thus describing a 'crocodile' type structure (Abramovitz et al., 1998; Abramovitz & Thybo, 2000). Similar structures are also seen farther east along the BABEL and BASIN96 profiles where they have been interpreted as having a Caledonian collisional origin (BABEL Working Group, 1993; Meissner & Krawczyk, 1999). Alternatively, these reflections may be related to eclogitised crustal material contained in the Sveconorwegian lithospheric mantle (see Section 3.2.1). Although the origin of the apparently younger, south-westerly dipping reflections is unknown, it is likely that they represent a shear zone that developed during post-Caledonian extension and basin formation (Abramovitz & Thybo, 2000).

Seismic velocities are highly variable in the mantle of the area, as seen on the two north-south profiles of the MONA LISA experiment (1 and 2), which show very different structures (Abramovitz & Thybo, 2000). The easternmost profile (Profile 1) shows a high (8.2 km/s) sub-Moho velocity at its southern end and a low (<7.9 km/s) velocity at its northern end, whereas the westernmost profile (Profile 2) shows a significant southerly dipping zone with an exceptionally high seismic velocity (>8.6 km/s) (**Figure 2.14**). The latter zone coincides with the band of south-west-dipping mantle reflections, interpreted as an anisotropic shear zone (Abramovitz & Thybo, 2000). Similar to Profile 1, high mantle velocity is seen at the southern end of Profile 2. No similar variation has been observed in the east–west profile (Nielsen et al., 2000), perhaps due to lower resolution of the mantle velocity.

Beneath the Ringkøbing-Fyn High, sub-horizontal reflections are imaged on two profiles in the deeper mantle at 20 to 21 s TWTT. These depths are close to the lithosphere-asthenosphere boundary (LAB) (Artemieva & Thybo, 2008); however, it is unlikely that these reflections originate from the LAB, which may be defined from variations in temperature (Eaton et al., 2009). These unique reflections are therefore interpreted as sill-like intrusions in the lower part of the lithospheric mantle (Thybo, 2006) slightly above the LAB. Similar reflections have been observed globally (Steer et al., 1998), but only the North Sea profiles demonstrate uniquely that they cannot be ascribed to side swipe.

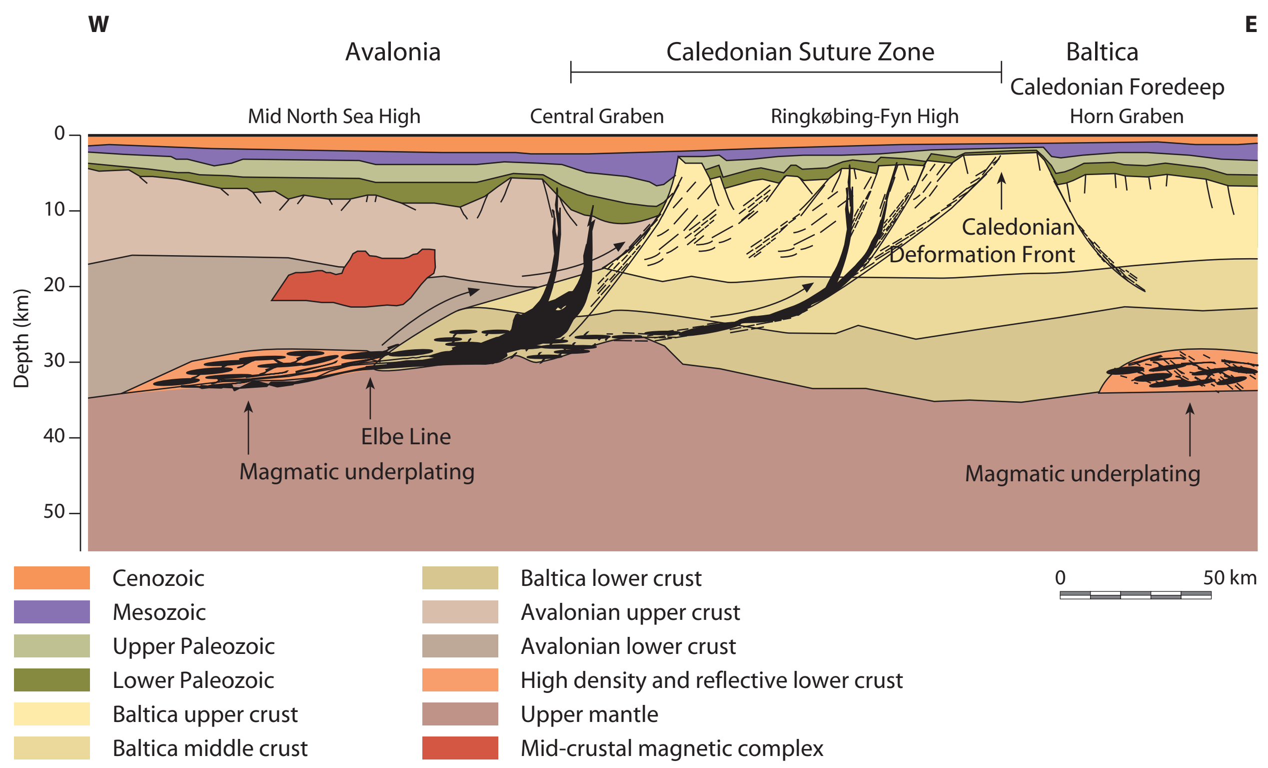


Figure 2.14 Tectonic model along MONA LISA Profile 3. Based on interpretation of seismic normal-incidence and refraction data and gravity and magnetic information (after Lyngsie & Thybo, 2007). See Figure 2.1 for location. The profile crosses the Central Graben, which is situated within the suture zone of Caledonian collision. The reflection profile images intensive westerly dipping reflectivity interpreted as faults that were active during collision and that were possibly reactivated during later extension. Their reflectivity may be intensified by magma that was intruded during later extension, as there are clear magnetic anomalies around the faults (Lyngise & Thybo, 2007). The locations of the intrusive magmatic complexes are constrained by the gravity and magnetic model, whereas the linking between the high-density lower crust and the magmatic complexes are 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 levels and forms the upper part of a ramp-flat-ramp system that was probably reactivated during Late Paleozoic extension. The area between the Central Graben and the Caledonian Deformation Front is interpreted as a Caledonian foreland thrust belt.

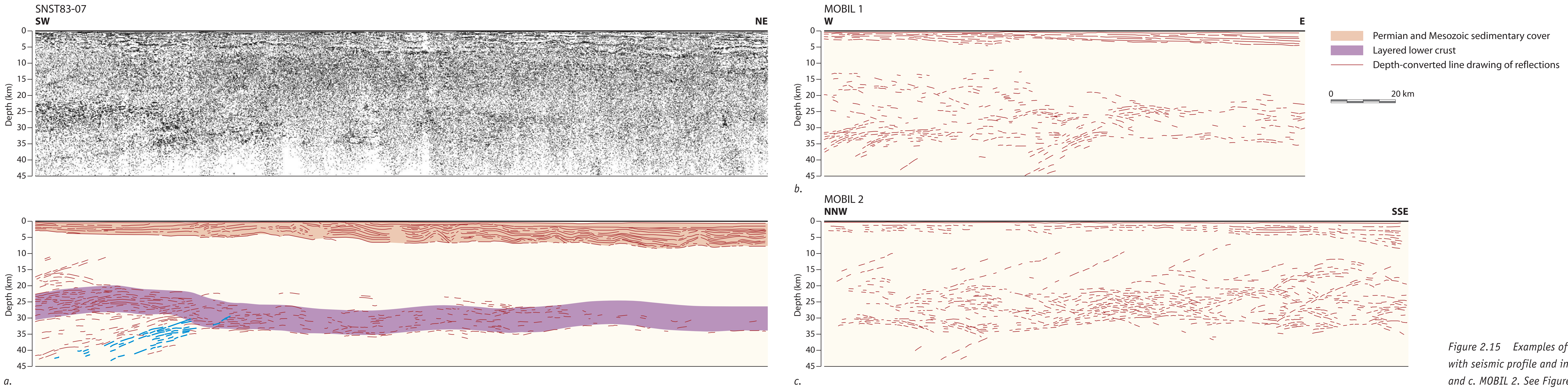


Figure 2.15 Examples of regional deep sections: a. SNST83-07 with seismic profile and interpreted line drawing; b. MOBIL 1; and c. MOBIL 2. See Figure 2.1 for locations.

3.2 North German Basin

The BASIN96 survey provides a unique crustal-scale transect across the north-east German part of the SPB. This transect extends from the Precambrian crust of the Baltic Sea across the North German-Polish Caledonides and the external parts of the Variscan Orogen (Krawczyk et al., 1997, 1999; DEKORP-BASIN Research Group, 1998, 1999). Regional (Bayer et al., 1999) and profile-oriented (Krawczyk et al., 2008a) integration of magnetotelluric (MT), gravity and magnetic datasets are combined into a consistent model showing the different crustal and tectonic domains, as well as the overlying Mesozoic basin fill (**Figure 2.16 a** & **b**).

A major result of the BASIN96 campaign was to provide evidence for the southward continuation of Baltica crust beneath the northern parts of the North German Basin. This is based on: (1) reflection patterns on the offshore profiles (DEKORP-BASIN Research Group 1998; Meissner & Krawczyk, 1999; Krawczyk et al., 2002), and (2) a distinctive mid-crustal reflection that can be traced onshore (Krawczyk et al., 1997, 1999; DEKORP-BASIN Research Group 1999). Further evidence comes from velocity models based on wide-angle seismic data (Thybo, 1990; Bleibinhaus et al., 1999) and receiver functions (Gossler et al., 1999). The Baltica crust, which extends beneath the northern parts of the North German Basin, probably consists of a series of Proterozoic terranes, some of which were interpreted from BABEL seismic data (Abramovitz et al., 1997).

3.2.1 The Moho

The combined reflection and refraction-seismic survey of BASIN96 revealed that the Moho can be traced across the entire North German Basin as a smooth and continuous interface (**Figure 2.16a** & **b**). In large parts of this transect, the Moho is interpreted to lie at the base of an approximately 2000 to 4000 m-thick lower-crustal reflection band that rises from 35 km at the margins of the North German Basin to 30 km beneath its central parts (Krawczyk et al., 1997, 1999) (**Figure 2.2**).

North of Bornholm, the Moho pattern becomes very diffuse (**Figure 2.16b**; Meissner & Krawczyk, 1999), which is consistent with observations on the BABEL transect (BABEL Working Group, 1993; cf. Krawczyk et al., 2008b). A number of north-easterly dipping upper-mantle reflection bundles are evident in the Baltic Sea. These extend up to the Moho, above which the crustal fabric generally displays similar dip directions as the upper-mantle reflections. In the western Baltic Sea, the reflection-seismic Moho is located at depths between 28 to 35 km, and in many areas appears to truncate the dipping crustal fabric (e.g. north-east of Bornholm; BABEL Working Group, 1993). This suggests that, during the Sveconorwegian consolidation of the Baltica crust, crustal material was subducted to depths at which it was eclogitised and transferred across the geophysically defined Moho into the upper mantle. During the post-orogenic erosional unroofing of the crust, and the re-equilibration of the Moho to its present depth and configuration, retrograde eclogite to granulite transformation may have also played an important role (cf. Le Pichon et al., 1987). The imaged north-easterly dipping upper-mantle reflection bundles presumably arise from lithology-related impedance contrasts associated with subducted continental or oceanic crust. Such dipping upper-mantle reflection bundles are typical of the Precambrian Baltica crust (for other examples, see Ziegler et al., 1998), and are also evident on three of the PQ2 profiles that were recorded in the westernmost Baltic Sea (Meissner & Krawczyk, 1999).

Farther south in the North German Basin, two zones of weaker Moho reflectivity occur beneath the depocentre of the Permian Basin and beneath the Flechtingen High (**Figure 2.16a**). As the wide-angle data do not show any gap in the PmP-arrivals (P reflections from the outer side of the Moho) in the Pritzwalk area (**Figure 2.16b**; Bleibinhaus et al., 1999), the Moho can be regarded as a continuous feature across the entire profile. The major PS-converting boundaries in the receiver-functions data of the teleseismic experiment are the crystalline basement and Moho (Gossler et al., 1999), which agree well with the wide-angle and vertical-incidence seismic observations of the coincident part of the BASIN9601 profile. The pre-Permian basement thickness is therefore only 20 km beneath the basin centre and 35 km at its margins.

The appearance of the Moho beneath a 2 to 4 km-thick reflective band suggests a compositional or fabric change in the lower crust with respect to the overlying layer. As noted, the Moho is continuous, although the reflective pattern in the basin centre is weaker than at the margins. This may be related to the extent of Baltica crust beneath the North German Basin. Alternatively, this may suggest that processes affecting the petrophysical properties of the crust occurred prior to or during the early stage of basin subsidence, including modification by enrichment in mafic components. The presence of mafic rocks in the lower crust would imply a higher density, which is supported by refraction-seismic data showing a P-wave velocity of 6.7 to 7.0 km/s for the lower crust in the basin centre, versus 6.4 km/s towards the basin margins (Bleibinhaus et al., 1999), and by three-dimensional gravimetric modelling (Scheck & Bayer, 1999). This is consistent with the concept of Permo-Carboniferous magmatic underplating and interaction of mafic melts with the lower crust (Ziegler, 1990a; Bachmann & Hoffmann, 1997; Krawczyk et al., 1999; Ziegler et al., 2006).

3.2.2 Crustal structure

In general, the combined BASIN96 and PQ2 surveys show the sedimentary basin fill of the North German Basin in the middle part of the transect, and its asymmetric margins with a northern, smoothly on-lapping margin, and a southern, prominently fault-controlled margin. The mid-crustal depth level is dominated by large-scale traces of the amalgamation of Baltica and Avalonia (**Figure 2.16**).

The base and top of the Zechstein salt are clearly imaged across much of the region. However, the base of the Rotliegend series, marking the initial phase of basin subsidence, is essentially non-reflective (**Figure 2.16b**; see Chapter 3).

At the northern margin of the basin, the Zechstein reflectors shallow from 3000 to 1500 m depth and are truncated by the overlying Triassic strata (Krawczyk et al., 1997, 2002; DEKORP-BASIN Research Group, 1998; Meissner & Krawczyk, 1999). Beneath them, moderate-amplitude, south-west-dipping reflections are observed down to depths of ~20 to 25 km on BASIN9601 in the northern third of the basin. Offshore, and on Rügen Island, deep wells calibrated these reflectors as arising from imbricated Ordovician sediments, which were thrusted over the Precambrian Baltica basement (Krawczyk et al., 2002). The Baltica crust thins progressively southwards where it appears to wedge out towards the Elbe Line and is overridden by Avalonia crust (Krawczyk et al., 1997, 1999, 2008a, 2008b; Bayer et al., 2002; Pharaoh et al., 2006; Hoffmann et al., 2009). This marks the Caledonian Thor-Tornquist suture. The deformed and thrusted Ordovician rocks are interpreted as an accretionary wedge that developed in front of the advancing Avalonia Terrane. South-westerly dipping structures may be related to Caledonian thrusting.

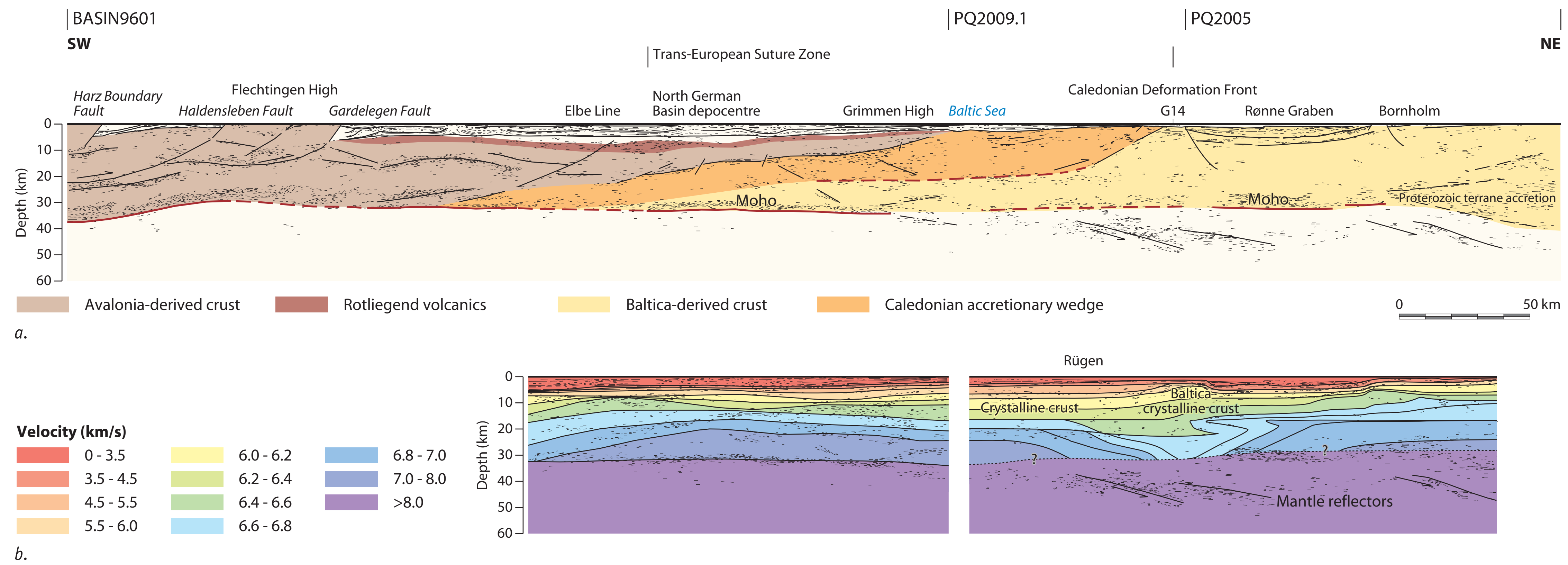


Figure 2.16 Combined offshore and onshore seismic profiles of the BASIN96 transect: a. interpreted line drawing of depth-migrated reflection-seismic profiles BASIN9601, PQ2-9.1 and PQ2-5; b. corresponding refraction-seismic velocity profile (after Krawczyk et al., 2008a, 2008b). G14 is a well in the Baltic Sea (see Chapter 4). See Figure 2.1 for locations.

This change in crustal origin from Baltica crust in the north to Avalonia crust in the south is also confirmed by the crustal velocity structure that changes in the North German Basin across the Elbe Line (along the European Geotraverse (EGT): Thybo, 1990, 2001; Rabbel et al., 1995; along BASIN9601: Bleibinhaus et al., 1999; cf. compilation in Krawczyk et al., 2008b).

In the area of the Caledonian suture off Rügen Island, a reflection pattern is observed with opposing dips in the upper crust and the uppermost mantle (**Figure 2.16a**). Detailed analysis of the dipping reflections in the upper crust provides evidence for two different sets of reflections, which are separated by the O-Horizon, the basal detachment of the Caledonian deformation complex. Southerly dipping reflections beneath the sub-Permian discontinuity, and above the O-Horizon, are interpreted as Caledonian thrust structures. Beneath the O-Horizon, south-westerly dipping reflections in the upper crust are interpreted as the Sveconorwegian crustal fabric. The Caledonian deformation complex is subdivided into (1) southerly-dipping foreland thrusts in the north, (2) the southerly dipping suture itself, which shows increased reflectivity, and (3) apparently north-easterly dipping downfaulted sedimentary horizons south of the Avalonia-Baltica suture, reflecting post-orogenic normal faulting (Meissner et al., 2002; Krawczyk et al., 2002, 2008b; **Figure 2.16**). The north-dipping reflections in the upper mantle are probably of Sveconorwegian origin, as postulated also for the upper-mantle reflectors in the Bornholm area (see above), rather than to collisional interaction of Avalonia and Baltica as postulated by Meissner et al. (2002).

In the foreland of the North German-Polish Caledonides, undeformed Early Palaeozoic Platform sediments are preserved in downfaulted structures of the Sorgenfrei-Tornquist Zone, which was activated during the Permo-Carboniferous. This fault system was transtensionally reactivated during the Mesozoic, controlling the subsidence of, for example, the Rønne Graben and the North Danish Basin (Petersen et al., 2003a; Japsen et al., 2007).

The sedimentary fill of the North German Basin onshore, as imaged in the central part of the SPB, contains salt-pillow structures with amplitudes increasing from the north-east to the south-west. These are overlain by Triassic rocks, which are partially truncated by Jurassic to Cenozoic reflectors indicating increasing halokinesis during the Late Mesozoic and Cenozoic (Kossow et al., 2000). Significant reflectivity is observed near the depocentre beneath the basal Zechstein reflector, decreasing in intensity to the north and south (**Figure 2.16a**). This interval is interpreted as Namurian-Rotliegend sedimentary and volcanic rocks (DEKORP-BASIN Research Group, 1999).

Along the southern margin of the North German Basin, Variscan deformed series and their Permian and Mesozoic cover sequences were involved in Late Cretaceous and Paleocene intraplate compressional structures, such as the upthrust Calfoerde, Flechtingen and Harz blocks (**Figure 2.16a**). At the level of the base-Zechstein reflector, the vertical offset at the Gardelegen Fault is about 5000 m (Kossow et al., 2000), whereas offsets of 2500 m are seen at the Haldensleben Fault and the Harz Boundary Fault (see Figure 3.39b). These steep reverse faults are interpreted to sole out at approximately 20 km depth into strong mid-crustal reflectors. Kinematic modelling shows the mid-crustal expression of these surface structures and the offsets along their controlling fault zones (Kossow, 2001).

North of the Elbe Line, the crustal velocity structure changes in the North German Basin (Rabbel et al., 1995; Bleibinhaus et al., 1999). The most striking feature is a ~10 km-thick, high-velocity layer in the lower crust between ~20 and 30 km depth (see compilation in Krawczyk et al., 2008b). The P-wave velocity of this layer is 6.9 to 7.5 km/s, which is typical for shield crust. This high-velocity lower crust extends between the Elbe Line and the Caledonian Deformation Front (Thybo 1990, 2001; Rabbel et al., 1995; Abramovitz & Thybo, 2000). The EGT and other surveys in the North German Basin support this finding (EUGENO-S Working Group, 1988; Aichroth et al., 1992; Schulze & Lück, 1992). Whereas Hoffmann (1990) suggested that the area south of the Elbe Line was underlain by a separate microcontinent involved in the Caledonian collision, its interpretation as an important tectonic element was only later stated more precisely to mark the southernmost extent of Baltica evident in the North German Basin (Thybo, 1990, 2001; Hoffmann & Franke, 1997; Bayer et al., 1999; DEKORP-BASIN Research Group 1999; Krawczyk et al., 1999). High-velocity lower crust is also found farther west in the North Sea on MONA LISA Profile 1 (Abramovitz et al., 1999), and to the east in Poland in the POLONAISE '97 data (Grad et al., 1999, 2002a, 2002b; Janik et al., 2002).

The extension of Baltica crust under the North German mainland has also been modelled by gravity data. The results suggest the presence of an Avalonian accretionary wedge on top of Baltica crust, which thins out towards the North German Basin depocentre (Krawczyk et al., 2008a). An alternative interpretation suggests the presence of a low-density body beneath the northern margin of the SPB. However, this model is less convincing, as reprocessing of seismic data clearly indicates the presence of an accretionary wedge (Krawczyk et al., 2001; Lassen et al., 2001; McCann & Krawczyk, 2001).

On a more regional scale, 2D- and 3D-gravity modelling has been performed in the North German Basin. Along the DEKORP-BASIN96 profiles, the 3D-gravity model suggested a high-density lower crust beneath the centre of the basin and an increased thickness of low-density upper crust beneath its margins to fit observed and modelled data (Barrio-Alvers et al., 1998; Scheck & Bayer, 1999). The occurrence of such a high-density lower crust may be related to Permo-Carboniferous injection of mantle-derived melts into the crust and to its magmatic underplating. Indications corroborating this hypothesis are provided by seismic data (Rabbel et al., 1995; Krawczyk et al., 1999), studies on magmatic activity (Benek et al., 1996) and subsidence analysis (van Wees et al., 2000).

4 South-east area

4.1 Crustal and lower lithospheric structure of the Trans-European Suture Zone

In northern Poland, the Trans-European Suture Zone (TESZ) area has been investigated over the last decade by a number of seismic-refraction and wide-angle reflection profiles: LT-7, TTZ and P1-P5 profiles recorded during the POLONAISE'97 experiment (Guterch et al., 1994, 1999; Grad et al., 1999; Jensen et al., 1999; Środa and POLONAISE Working Group, 1999; Wilde-Piórko et al., 1999; Krysiński et al., 2000; Czuba et al., 2001; Janik et al., 2002; Grad et al., 2003; Grad et al., 2007; Guterch et al., 2007). The locations of profiles referred to in the following description are shown in **Figure 2.17**. Seismic data provided by the LT-7 line (**Figure 2.17f**) in north-west Poland show that the crustal thickness in the TESZ is intermediate between that of the East European Craton to the east (about 42 km) and that of the area to the south-west of the Variscan Front (approximately 30 km) (Guterch et al., 1994; Guterch & Grad, 1996). This initial finding provided the framework for the succeeding seismic survey undertaken during the POLONAISE'97 experiment. The main results of this experiment are summarised below.

The crustal structure of the East European Craton (EEC) is represented by the north-eastern parts of profiles in **Figure 2.17f** to **l**. All models of the crust for this area are characterised by a nearly horizontal, uniform seismic structure. The crystalline crust consists of three parts: upper, middle and lower, with P-wave velocities of 6.1 to 6.4, 6.5 to 6.7 and 7.0 to 7.2 km/s respectively. The crystalline basement lies at depths of 500 to 5000 m and plunges strongly in a south-westerly direction, almost perpendicular to the edge of the craton. In the north-western part of Profile P5 (Czuba et al., 2001), a body with high seismic velocities of about 6.6 km/s was found at depths between 2000 to 10000 m. The body coincides with the rapakivi-like and anorthosite Mazurian Complex, well known from borehole data. The depth of the Moho boundary ranges from 39 to 45 km in north-eastern Poland, reaching 50 km beneath Lithuania (**Figure 2.2**). The sub-Moho P-wave velocity is 8.5 to 8.1 km/s.

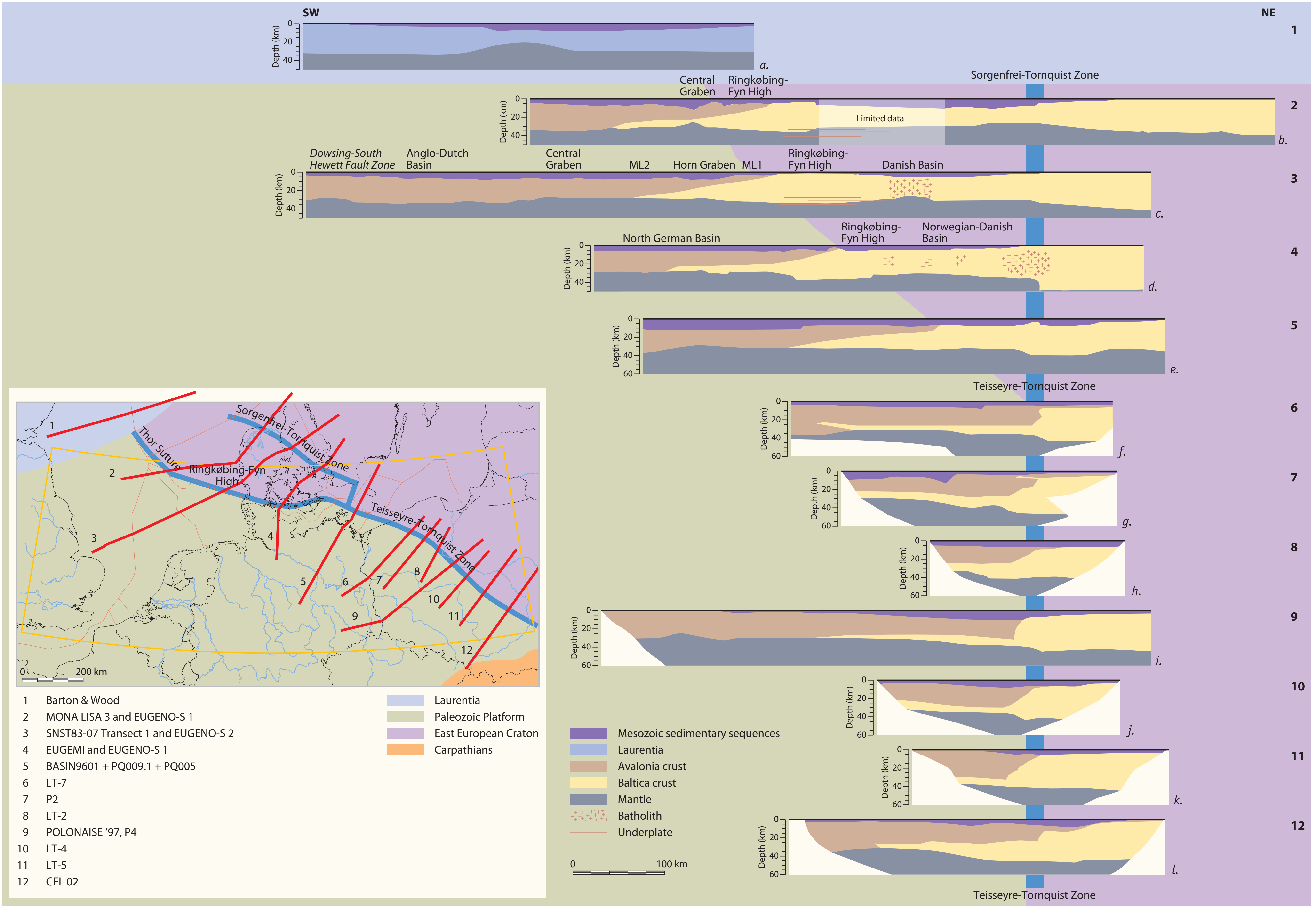


Figure 2.17 Interpreted seismic profiles in the transition between the East European Craton and Paleozoic Platform.

The crustal structure of the Paleozoic Platform beneath the Polish Basin is represented by the south-western parts of all profiles in **Figure 2.17f** to **l**. The upper crust of the Paleozoic Platform between the edge of the EEC and the Wolsztyn High is generally characterised by low P-wave velocities (<6.1 km/s) down to a depth of 20 km and low reflectivity (Guterch et al., 1992). These low velocities are interpreted to be indicative of low-grade metamorphic volcano-sedimentary rocks. In contrast, the lower crust is characterised by P-wave velocities in the range 6.5/6.8 to 7.3 km/s, a high-velocity gradient and strong, ringing reflectivity. This layer has a distinctly laminar seismic structure, interpreted as being associated with the Moho; a flat and horizontal first-order velocity discontinuity (Guterch et al., 1992; Jensen et al., 1999). The velocity of the sub-Moho uppermost mantle is high (>8.2-8.3 km/s). The high-velocity lower crust was previously identified on a number of seismic-refraction profiles recorded on the Fore-Sudetic Monocline (Guterch et al., 1986, 1992). The south-western limit of this type of lower crust coincides with the Odra Fault. Typical two-layer, Variscan-type crust was observed to the south-west of the Odra Fault on Profile VII (Guterch et al., 1986) and at a depth of about 40 km on profile LT-7 (see **Figure 2.17f**; Guterch et al., 1994).

The 3D-velocity model of the crust, obtained using a tomographic inversion method, shows substantial horizontal variations of the crustal structure across the study area of the TESZ (Środa et al., 2002). Modelling results reflect the complex structure of the Earth's crust in the TESZ region and provide insights into the physical characteristics of tectonic units juxtaposed in that area. The horizontal slices of the 3D-velocity distribution clearly show the differences between the areas of the Paleozoic Platform to the south-west, the TESZ, and the East European Craton to the north-east (Środa et al., 2002). At a depth of 10 km, P-wave velocities of less than 6 km/s, typical of sedimentary rocks, characterise the TESZ and in parts the adjacent Paleozoic Platform to the west, whereas on the EEC, velocities typical of crystalline rocks exceed 6 km/s. In the slice cutting the model at 40 km depth, there is a distinct difference in the velocity distribution in the Paleozoic Platform, which is characterised by velocities of 8 km/s or more, and the EEC with velocities of about 7 km/s. Velocities in the EEC area are consistent with the presence of lower-crustal rocks, whereas velocities significantly higher than 8 km/s in the Paleozoic Platform area indicate the upper mantle. This variability is also conspicuous on the vertical slices in the Y-plane, especially for Y = 130 km, cutting the model near the location of the P4 profile (**Figure 2.17i**). From south-west to north-east, the slice crosses the Paleozoic Platform with a relatively thin crust (about 35 km), the Teisseyre-Tornquist Zone comprising a deep asymmetrical Polish Basin underlain by a thin crystalline layer, and finally the EEC with a thin sedimentary cover and a crust about 45 km thick.

The lower lithosphere under the TESZ is characterised by a series of seismic reflectors in depths ranging from the Moho to about 90 km (Guterch et al., 1994; Grad et al., 2003). A seismic reflector generally occurs about 10 km beneath the Moho, and the reflectivity of the uppermost mantle is stronger beneath the Paleozoic Platform and TESZ than beneath the EEC (Grad et al., 2003). As this stratification disappears laterally on both sides of the TESZ towards the East European Craton and Paleozoic Europe, it seems to be directly linked to the lithospheric mobility at this transition zone. Consequently, the low-velocity upper-mantle layer may represent an upwelling of relatively lighter material into the mobile zone at the mantle-rooted craton margin, due to thermal softening of the lithosphere during the Late Paleozoic / Mesozoic.

A tomographic analysis of the shear-wave velocity structure of the mantle under Europe shows that, in Poland, the TESZ is a deep-seated structure separating regions with high S-wave velocities beneath the Precambrian Platform from low-velocity regions under the Paleozoic Platform (Zielhuis & Nolet, 1994). Further confirmation of the TESZ influence on the propagation of regional seismic waves was obtained from observations of several hundred earthquakes and man-made explosions located in Europe. To explain the blockage of the seismic energy propagation of regional seismic events across the TESZ, the structural anomaly between eastern and western Europe must reach a depth of at least 200 km (Schweitzer, 1995).

The seismic structure of the basement underlying central Poland to the west of the EEC margin has several common features. It comprises three main layers, including a thick upper crust and a reflective lower crust characterised by high P-wave velocities (**Figure 2.17f** to **l**). The seismic structure of this crustal domain is very different to those of the EEC to the north-east, and of the Variscan Orogen to the south-west. Its remarkable characteristics have already been determined in earlier seismic surveys (Guterch et al., 1984, 1986, 1994, 1999). The south-west boundary of the three-layer basement of central Poland is reflected on seismic profiles as a relatively sharp vertical discontinuity. It seems to coincide with the west-north-west-trending Dolsk Fault documented beneath the Permo-Mesozoic cover by borehole data (Znosko, 1979; Wierzchowska-Kicułowa, 1984). This fault defines the north-eastern boundary of the Wolsztyn High and separates it from the deeply buried basement farther to the north-east (Dadlez, 2006).

The seismic structure of the crust between the TESZ and the Dolsk Fault generally resembles that of northern Germany and southern Denmark (Aichroth et al., 1992; Rabbel et al., 1995; Abramowitz et al., 1998; Krawczyk et al., 2008a). The structure is typical of the basement domain that extends between the Caledonian Deformation Front in the north-east and the Elbe Line to the south-west. Like the basement of central Poland, this domain has low P-wave seismic velocities down to a depth of about 20 km and relatively high velocities below. Furthermore, its lower crust is characterised by a high vertical-velocity gradient and strong, ringing reflectivity (Aichroth et al., 1992; Rabbel et al., 1995; Abramowitz et al., 1998). Jensen et al. (1999) pointed out these similarities with reference to the POLONAISE P1 profile.

Figure 2.18 shows the general seismic crustal characteristics along the 700 km-long profile TTZ-CEL03, together with a tectonic interpretation of the TESZ in Poland. This profile is located in the central part of the Polish Basin, parallel to the trend of the EEC. The crustal structure of the units defined here reveals some close similarities to the three-layered structure of the EEC cratonic crust. In the Kuiavian Unit, the crustal thickness is very comparable to that in the external zone of the EEC (the region affected by extension during the break-up of Rodinia), but it is thicker in the Radom-Łysogóry Unit. However, there are also essential differences between these areas. A lower-crustal layer with velocities of 7 km/s occurs only in the Pomeranian Unit, and also shows considerable reflectivity and a high-velocity gradient. The middle crust in the Kuiavian and Radom-Łysogóry units has lower velocities than the other two units. The upper-crystalline crust is also characterised in all four blocks by velocities lower than in the EEC area, exceeding 6 km/s in only a few places.

These similarities and dissimilarities indicate an EEC origin for all of the units. However, this does not necessarily mean that the cratonic crust of these units was attenuated *in situ*. The very sharp boundary of the intact craton to the north-east of the transect suggests that strike-slip movements along the boundary played a role in its development, and that allochtonous terranes were accreted to it. These do not apparently form part of Avalonia, as expressed earlier by Dadlez et al. (1994) and Dadlez (2000) and more recently summarised by Dadlez et al. (2005). In this scenario, proximal terranes were detached from Baltica farther to the south-east during the Vendian and were reattached to it in the Late Ordovician / Silurian. Quick counter-clockwise rotation of Baltica during the Ordovician (Torsvik et al., 1996) may have caused strong, right-lateral transtensional stresses along the edge of the relatively young crust of Baltica, particularly at the south-eastern limit (the present-day Dobrogea area of Romania and Black Sea). The detached narrow lithospheric slivers of the so-called Teisseyre Terrane Assembly then moved along the edge of Baltica towards the north-west and, together with the exotic Avalonia Terrane, were accreted during the Late Ordovician and Silurian Caledonian Orogeny to the sheared passive margin of the EEC (Nawrocki & Poprawa, 2006). At least two crustal blocks of this origin can be postulated based on our results, the Pomeranian and Kuiavian units. The position of the Radom-Łysogóry Unit, with a crustal section that mostly resembles the EEC crust, is debatable. It has been proposed that the unit is part of the margin of the EEC (Dadlez et al., 1994), or that it represents a separate terrane (e.g., Belka et al., 2000). The same discussion applies to the Narol Unit, which may be either part of the Małopolska Terrane (Dadlez et al., 1994) or the EEC.

5 Potential-field data

Potential-field data provide an overview of crustal structures, terranes and sutures in an area. The latest compilations for Central Europe document the most fundamental features of the entire crust, thereby allowing structures from the overlying sedimentary basins to be separated from the underlying Paleozoic basement (Krawczyk et al., 2008b). In this section, maps with special emphasis on substantial changes in the crustal structure of the SPB area are presented, which also show the significant gravity, magnetic and geothermic anomalies in the SPB (**Figures 2.19** to **2.29**).

5.1 Gravity data

The most recent and consistent gravity map of Europe (Wybraniec et al., 1998) synthesised the existing data with Bouguer anomalies onshore and free-air anomalies offshore, at a general resolution of 5 × 5 km. All major large-scale tectonic features and suture zones can be recognised on this map, with pronounced gravity lows along the western side of Fennoscandia and the Alps (Krawczyk et al., 2008b). In the SPB, the gravity maps (**Figures 2.19** to **2.22**) show to the first order that the morphology of the Bouguer anomalies in the TESZ area coincide with the tectonic structure, and that it has a clear south-east–north-west lineation. The Caledonian Deformation Front is generally associated with a north-west–south-east-trending, sharp gravity lineament extending across the North Sea and into northern Germany (**Figure 2.19**). This lineament is probably caused mainly by lower-crustal density anomalies (Lyngsie et al., 2006). To the south-east, a similarly oriented feature is evident beneath Poland along the strike of the Teisseyre-Tornquist Zone. In the Polish Basin, an extensive depression down to −60 mGal can be seen, superimposed by a short-wavelength linear anomaly of up to +15 mGal corresponding to the Mid-Polish Swell. The areas of the EEC in the north-east, and Fore-Sudetic Monocline in the south-west (see Figure 3.13), are characterised by positive Bouguer anomalies of up to +10 mGal and +20 mGal respectively. Whereas the structural detail is better revealed in the free-air anomaly map (**Figure 2.20**), lineaments and their continuity are best shown by the residual maps (**Figures 2.21** & **2.22**).

The Avalonian accretionary wedge, which overrides Baltica crust that wedges out beneath the northern flank of the North German Basin, has been confirmed by gravity modelling (Krawczyk et al., 2008a).

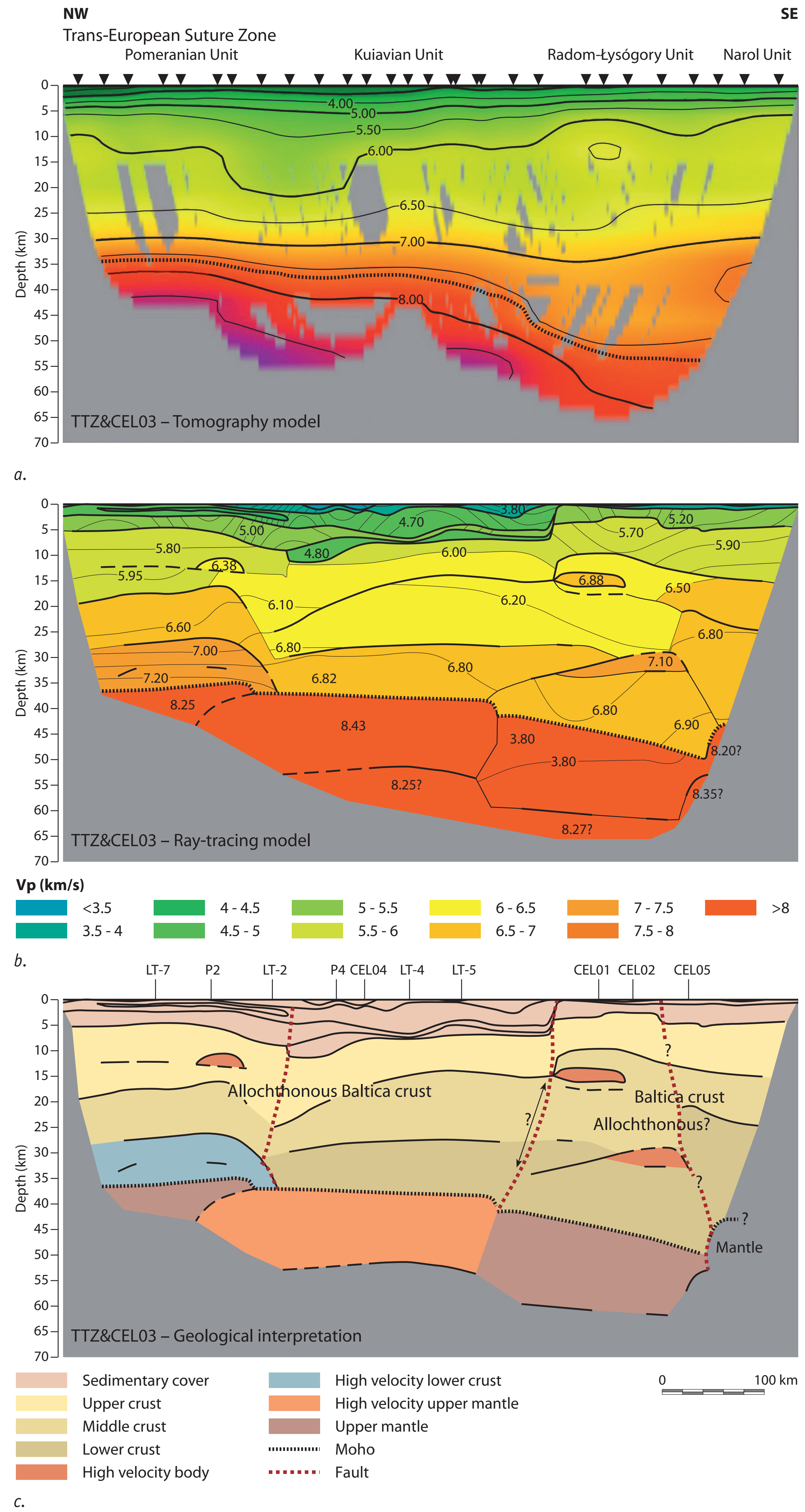


Figure 2.18 Seismic models based on the TTZ-CEL03 profile (after Grad et al., 1999; Janik et al., 2005): a. Model obtained by 'smooth' tomography of first arrival times; b. Model obtained using ray-tracing technique for refracted and reflected waves; c. Tectonic interpretation. See Figure 2.1 for location.

Modelling of the gravity field in the North Sea shows a similar geometry, with the Avalonia Terrane overriding Baltica lower crust that may extend as far west as Scotland (Lyngsie et al., 2006; Lyngsie & Thybo, 2007).

In north-west and central Poland, where Baltica basement is also largely concealed beneath the Mesozoic cover, a detailed gravity model of the crustal structure along the TESZ (based on the 'Gravimetric Atlas of Poland' (Królikowski & Petecki, 1995)) has been constructed (Królikowski & Petecki, 1997). This Bouguer

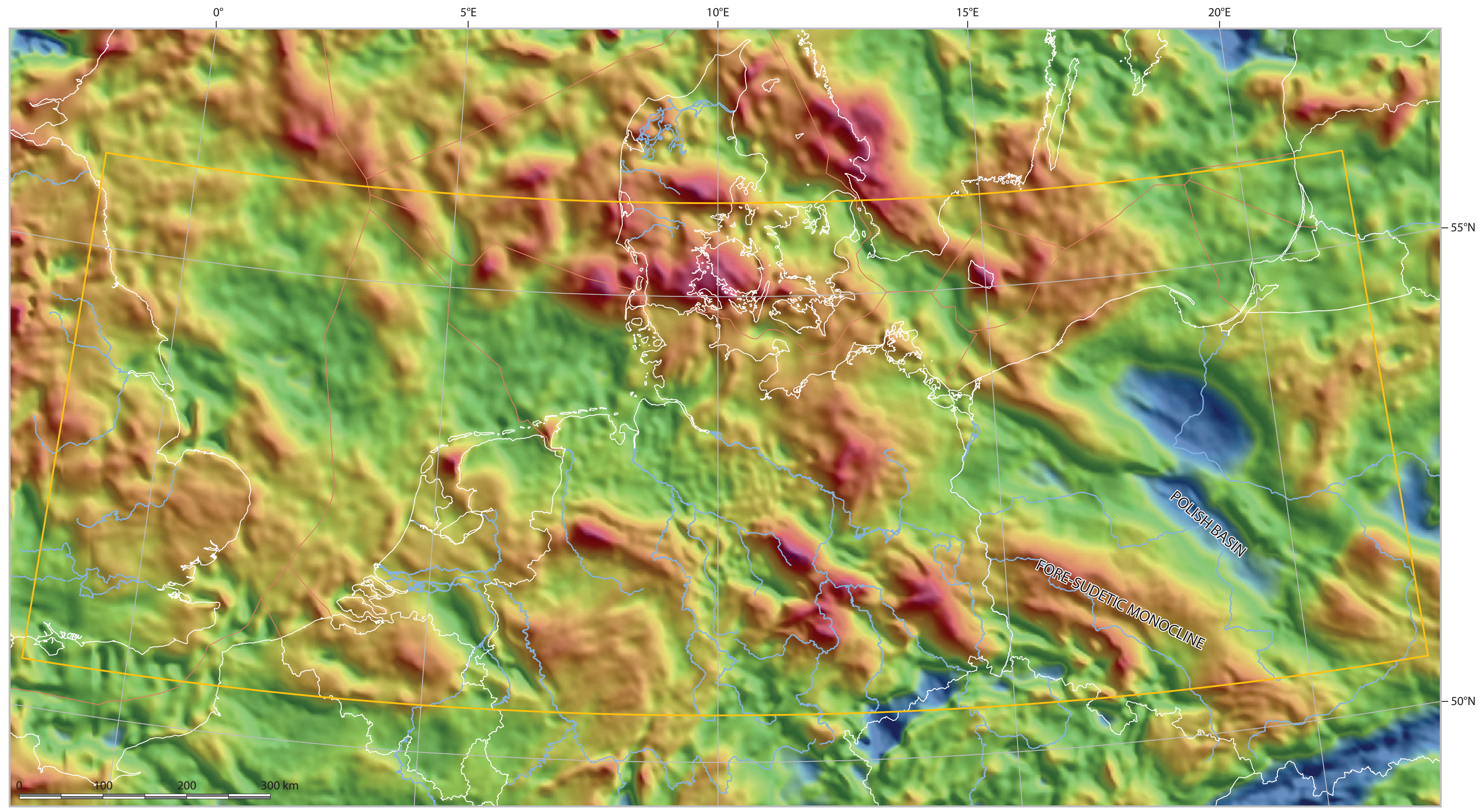


Figure 2.19 Gravity. Bouguer (onshore) and free-air (offshore) anomaly. Data sources (onshore) for Bouguer anomaly data: United Kingdom – based on UK gravity database (British Geological Survey; 5 × 5 km grid); Belgium – Belgian gravity database (Service Geologique de Belgique / Belgische Geologische Dienst; 22 260 data points). Netherlands – gravity database (1053 gravity stations); Denmark – Danish gravity database (Geological Institute, Copenhagen University); Germany – gravity data from the digitised gravity map of Germany, 1 : 500 000 scale (Geo-ForschungsZentrum Potsdam on behalf of DEKORP; about 500 000 data points); Poland - Polish gravity database (Polish Geological Institute; 1 × 1 km grid based on ~900 000 data points); Adjacent areas – 'Global gravity data. Land data' Version 1. (Bureau Gravimetrique International, Toulouse, France; 1996). Scandinavla and Baltic countries – 21 138 data points from KMS, Copenhagen. Data sources (offshore) for free-air anomaly data: KMS2002 Global marine free-air gravity field (2 minute grid) (2003); Andersen & Knudsen (1998).

anomaly map suggests the presence of anomalous masses in the Lower Paleozoic successions. In order to interpret these anomalies, a zone of 35 km-thick crust overlying a dense upper mantle has been suggested for the region along the TESZ (Krolikowski & Petecki, 1997). This model is supported by seismic data (Guterch et al., 1994, and references therein), as well as by the most recent potential-field maps of Poland (Petecki et al., 2003a, 2003b). These maps show a clear separation between the Paleozoic Platform and the EEC.

5.2 Magnetic-field data

The magnetic field in the SPB has been compiled using a 2 × 2 km grid from various datasets. There is a strong contrast between the highly magnetic crust of the EEC and the less magnetic, Paleozoic-accreted terranes of Central Europe (Krawczyk et al., 2008b). The TESZ area is characterised by a lack of magnetic anomalies (±100 nT; **Figures 2.23** to **2.25**), which may result from the deeply buried magnetic basement. On the EEC, strong (−1500 to +1500 nT) and large-scale (in the order of 100 km), oval and elongated magnetic anomalies correspond to granitoid massifs, metamorphic belts and metamorphic-magmatic complexes of the crystalline basement, which is covered by only 1000 to 2000 m-thick sedimentary rocks (Ryka, 1984). The south-westernmost area of Poland within the Paleozoic Platform shows the pattern of small-scale magnetic anomalies (in the order of 10 km). Moreover, there is an irregular pattern across Baltica (**Figures 2.23** & **2.24**). The Avalonia crust is more weakly magnetised than the Baltica crust, which makes the magnetic-field data ideal for identifying the location of the Caledonian suture (Williamson et al., 2002; Lyngsie & Thybo, 2007). The Caledonian Deformation Front can be traced along this prominent pattern of magnetic anomalies from northern Poland to the North Sea, where it either fades out towards the west, or is offset northwards and continues to Scotland.

Combined structural, magnetic and gravimetric modelling was carried out with the aim of unravelling the possible evolution of observed structural features (see Krawczyk et al., 2008b for more detail). Integrated modelling of the Lower Paleozoic Anglo-Brabant Belt suggests that the Caledonian Deformation Front flanks the Brabant Massif to the south-west (Woodcock, 1991). Cratonic basement is assumed to be present to the south-west of this zone (Verniers et al., 2002). A compressional-wedge model has been proposed for the Brabant Massif, with Precambrian basement controlling its kinematics (Sintubin & Everaerts, 2002). This is in contrast to the classic interpretation of an anticlinal culmination (van Grootel et al., 1997).

In the southern North Sea, combined magnetic-gravimetric 2.5D modelling reveals anomalies related to a sharply defined Avalonia-Baltica suture along the EUGENO-S and MONA LISA 1 and 2 profiles (Williamson et al., 2002) and MONA LISA Profile 3 (Lyngsie & Thybo, 2007). Here, the magnetic Baltica basement dips to the south-west through the entire crust to depths of 30 to 35 km beneath an overriding non-magnetic Avalonia basement wedge. The internal structure of Baltica is interpreted as being imbricated. Low-amplitude magnetic anomalies to the west and south of the suture zone are interpreted as being related to a mid-crustal magnetic body, which might represent the 'missing arc', beneath which the Tornquist Ocean was subducted southwards (Abramovitz & Thybo 2000; Williamson et al., 2002). Short-wavelength magnetic anomalies at the location of fault zones, which are imaged in the MONA LISA deep-seismic reflection profiles, indicate that mafic magmas were intruded along these fault zones, probably during the Permo-Carboniferous tectono-magmatic event (**Figure 2.14**) (Lyngsie & Thybo, 2007).

Images from deep-seismic data between the North Sea and Poland reveal a variety of structural features in the crust. These are also indicated in the magnetic-field and pseudogravity map (**Figure 2.25**). This map gives the spatial integration of magnetic anomalies under the assumption that the magnetic signature correlates with density. From these data, the Caledonian Deformation Front is interpreted to coincide with the continental slope of Baltica, which terminates at the lower Elbe Line (Abramovitz & Thybo, 2000; Bayer et al., 2002). This lineament is interpreted to form the boundary between Baltica- and Avalonia-dominated domains, with high lower-crustal velocities characterising Baltica to the north. The potential-field data suggest that Baltica extends under the northern flank of the SPB, and so supports a concept that was earlier formulated on the basis of seismic data only (e.g. Thybo, 1990, 2001; Rabbel et al., 1995; Krawczyk et al., 1999).

5.3 Thermal structure

The thermal structure of the SPB shows low surface heat-flow values between 30 and 50 mW/m^2 for the Fennoscandian area, whereas higher values, typically 60-80 mW/m^2, are noted from younger units located farther south (**Figures 2.26** to **2.29**; Majorowicz et al., 2003). Low temperatures are characteristic of the Baltic Shield area, where there is also a stable temperature-depth distribution. In contrast, the area south of the Caledonian Deformation Front is characterised by strong lateral temperature variations in the upper kilometres of the sedimentary successions (Norden et al., 2008; **Figures 2.26** to **2.29**).

3D-geothermal modelling of specific areas reveals the different character of underlying terranes (see Krawczyk et al., 2008b, and references therein). Along the length of the European Geotraverse (Cermak et al., 1991) generally low crustal temperatures (400-500°C at the Moho) and low heat-flow values (~30 mW/m^2) characterise the Baltic Shield and the North German Caledonides, whereas higher values are typical of the Mediterranean area (50-60 mW/m^2) (Artemieva et al., 2006). This difference reflects the strong contrast

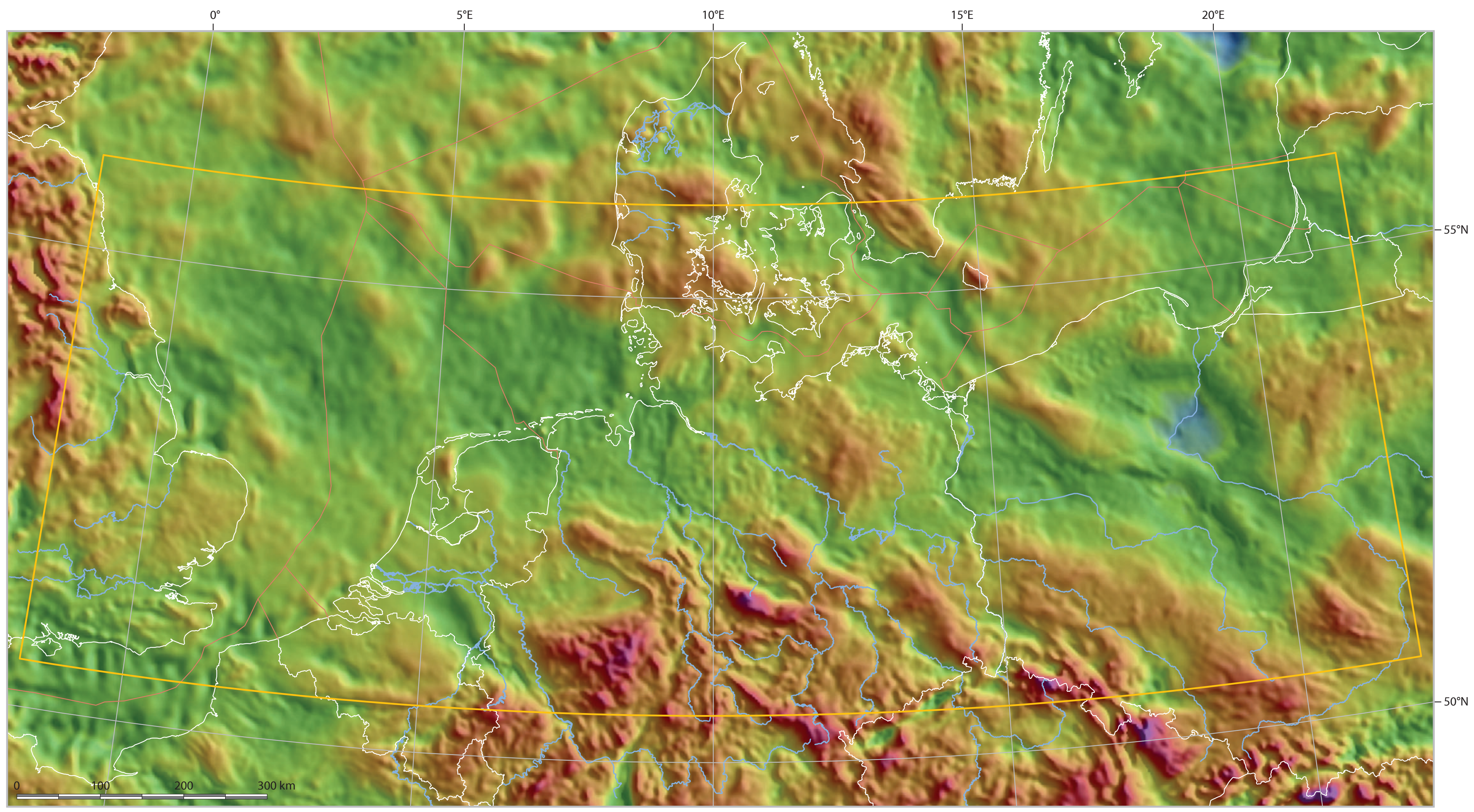


Figure 2.20 Gravity. Free-air anomaly.

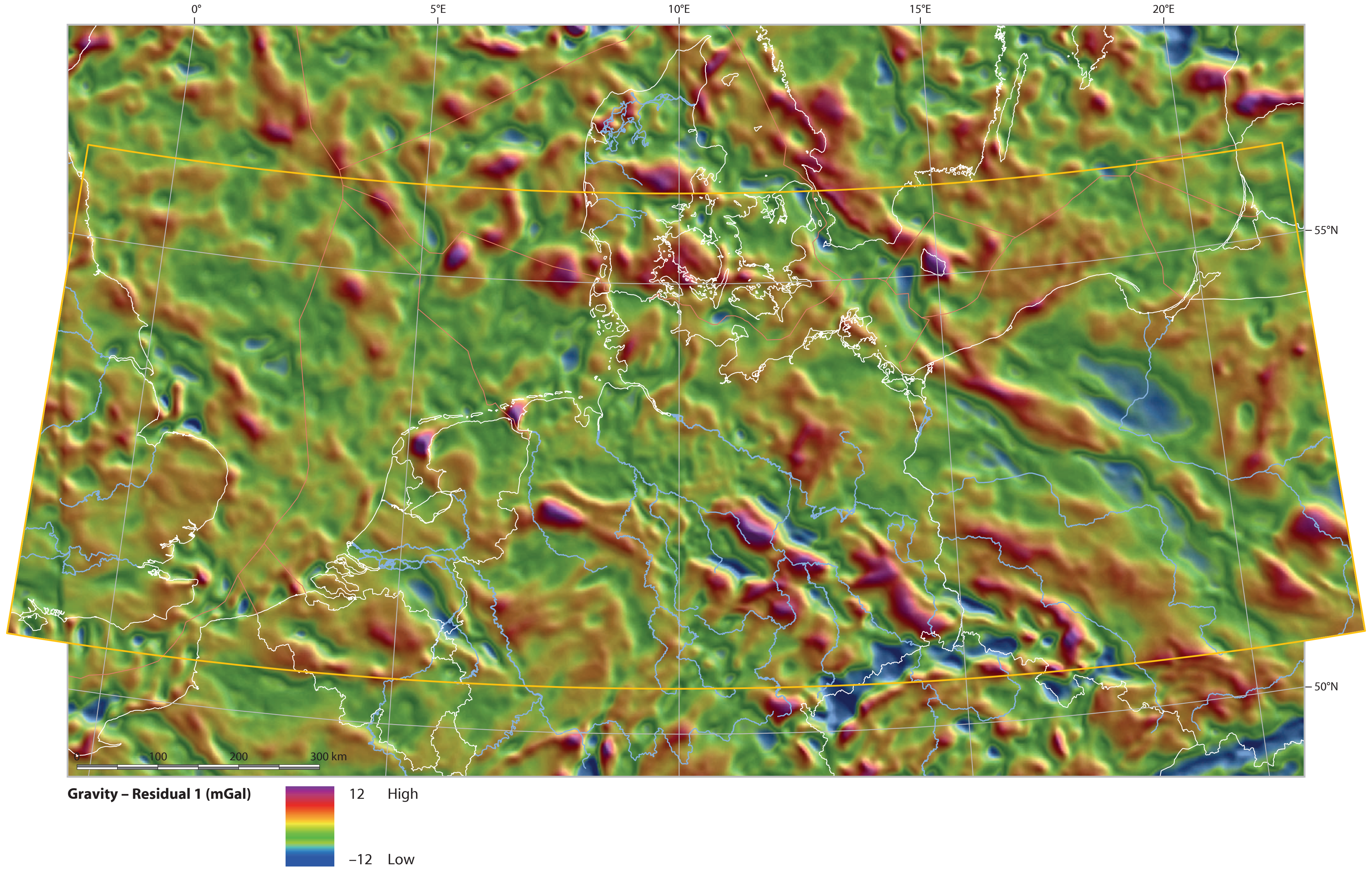


Figure 2.21 Gravity. Residual 1 (upward 2 km – upward 10 km)

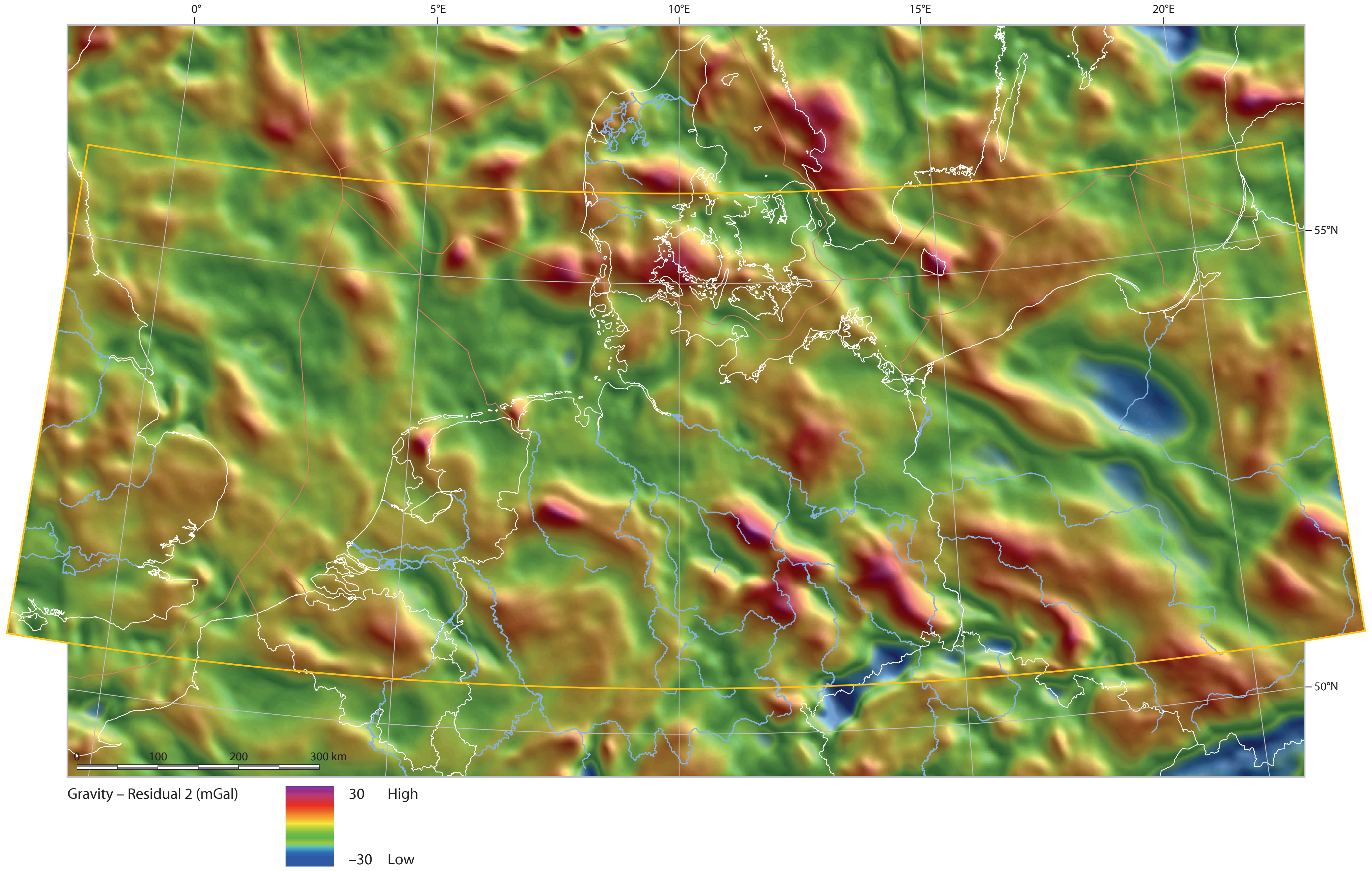


Figure 2.22 Gravity. Residual 2 (upward 5 km – upward 40 km).

between the thin lithosphere of Phanerozoic Central Europe and the thick lithosphere of the Precambrian East European Craton (Artemieva et al., 2006; Artemieva & Thybo, 2008). In addition, the Caledonian Deformation Front marks the northern boundary of the transitional zone from low to high heat-flow values (Cermak & Bodri, 1995).

A comprehensive 2D-numerical analysis of the thermal structure of the lithosphere across the Baltic Shield and Sorgenfrei-Tornquist Zone is available for the FENNOLORA and EUGENO-S/EUGEMI profiles (Balling, 1995). Heat-flow densities were compiled along 2300 profile-kilometres for the Fennoscandian Shield, the Danish area and northern Germany. Upper-mantle heat-flow values in southern shield areas (i.e. close to the Caledonian Deformation Front) are in the range of 30 to 40 mW/m^2 and are interpreted to be related mainly to heat flux from the upper mantle rather than to upper-crustal heat generation. Petrological considerations suggest that the present-day deep crust is at lower temperature-pressure conditions than during the early stages of Proterozoic consolidation. However, the lowermost parts of the present-day East European Platform (EEP) crust are still located within the eclogite stability field. Combined with the absence of significant gravity anomalies, it is therefore likely that eclogites are abundant in the shield-type EEP Baltica crust.

The Paleozoic Platform of south-west Poland is characterised by an up to 8000 m-thick sedimentary cover, a relatively thin crystalline crust (28-34 km), and 'hot' lithosphere with a heat flow of 40 to70 mW/m^2 and an age of about 450 to 270 Ma. In contrast, the EEP of north-eastern Poland is characterised by a 500 to 5000 m-thick sedimentary cover, 42 to 47 km thick crystalline crust, a 'cold' lithosphere with relatively low heat flow (<40 mW/m^2) and an age of about 2000 to 800 Ma (Guterch et al., 1986; Guterch & Grad, 1996, 2002).

The relationship between near-surface heat-flow density and the depth to the Moho may differ for various tectonic units (compare **Figures 2.1** & **2.26**; see also Hurtig (1995) and Artemieva (2003)). Schellschmidt et al. (1999) corroborated this relationship in greater detail for the area between Rügen and Flechtingen in the North German Basin. They noted that temperatures down to 1500 m depth are colder on Rügen Island (40-50°C) than in southern parts of the SPB (three isolated maxima of 70°C occur in 60°C background temperature).

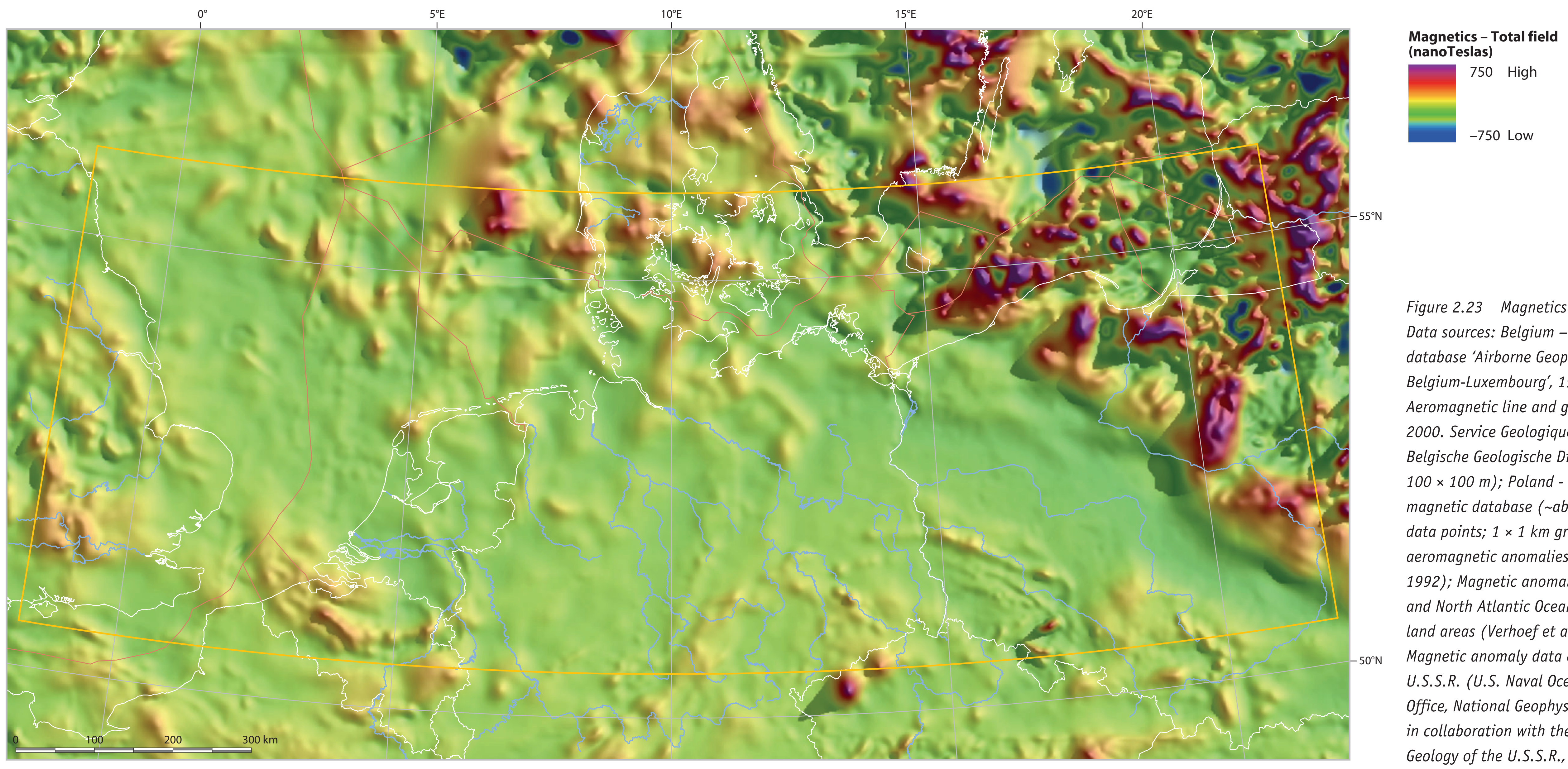


Figure 2.23 Magnetics. Total field. Data sources: Belgium – Belgian magnetic database 'Airborne Geophysical Survey Belgium-Luxembourg', 1994. Aeromagnetic line and gridding CD-ROM, 2000. Service Geologique de Belgique / Belgische Geologische Dienst (Grid 100 × 100 m); Poland - based on Polish magnetic database (~about 1.5 million data points; 1 × 1 km grid). Other areas – aeromagnetic anomalies (Wonik et al., 1992); Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas (Verhoef et al., 1996); Magnetic anomaly data of the former U.S.S.R. (U.S. Naval Oceanographic Office, National Geophysical Data Center in collaboration with the Ministry of Geology of the U.S.S.R., 1996).

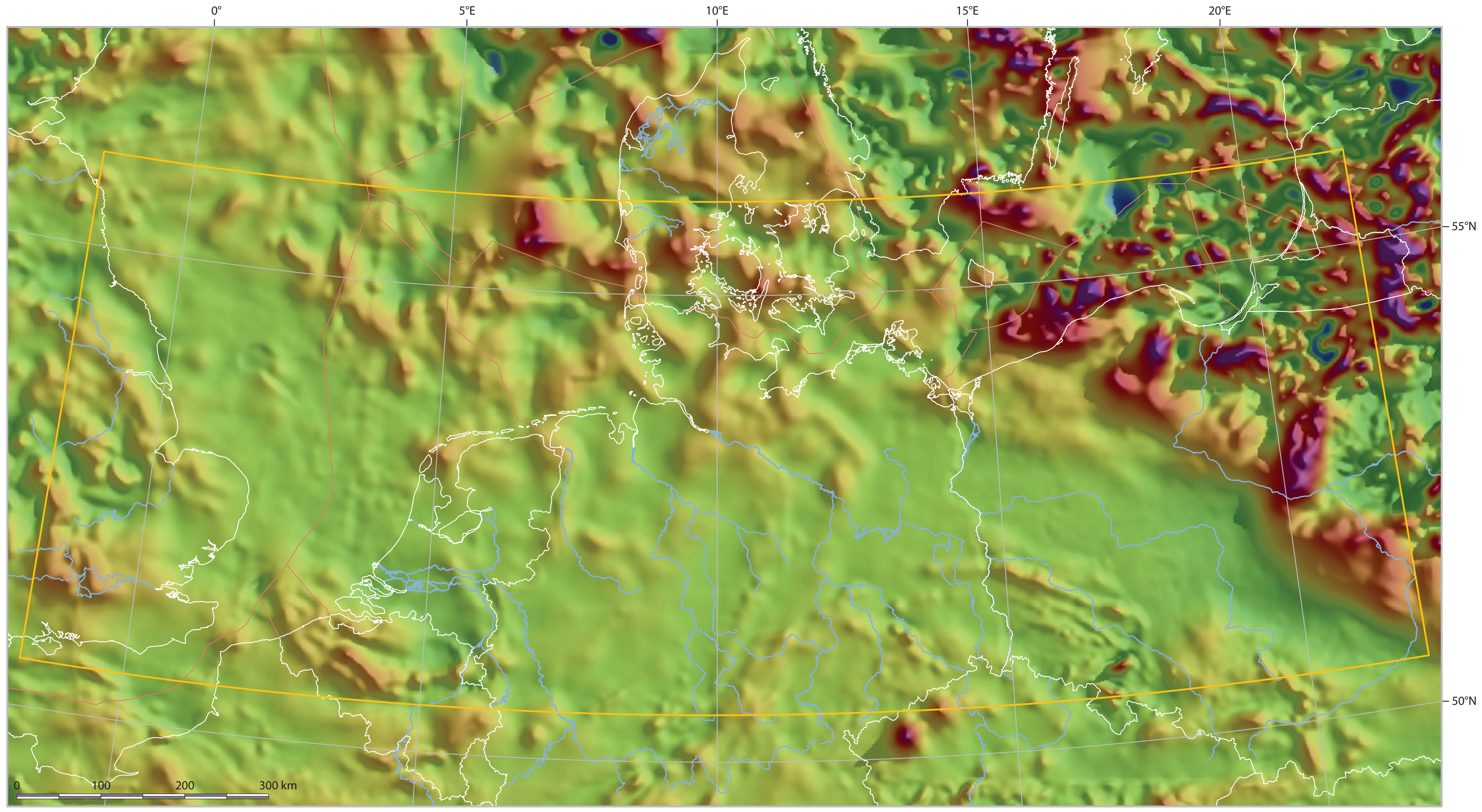


Figure 2.24 Magnetics. Total field reduced to the North Pole.

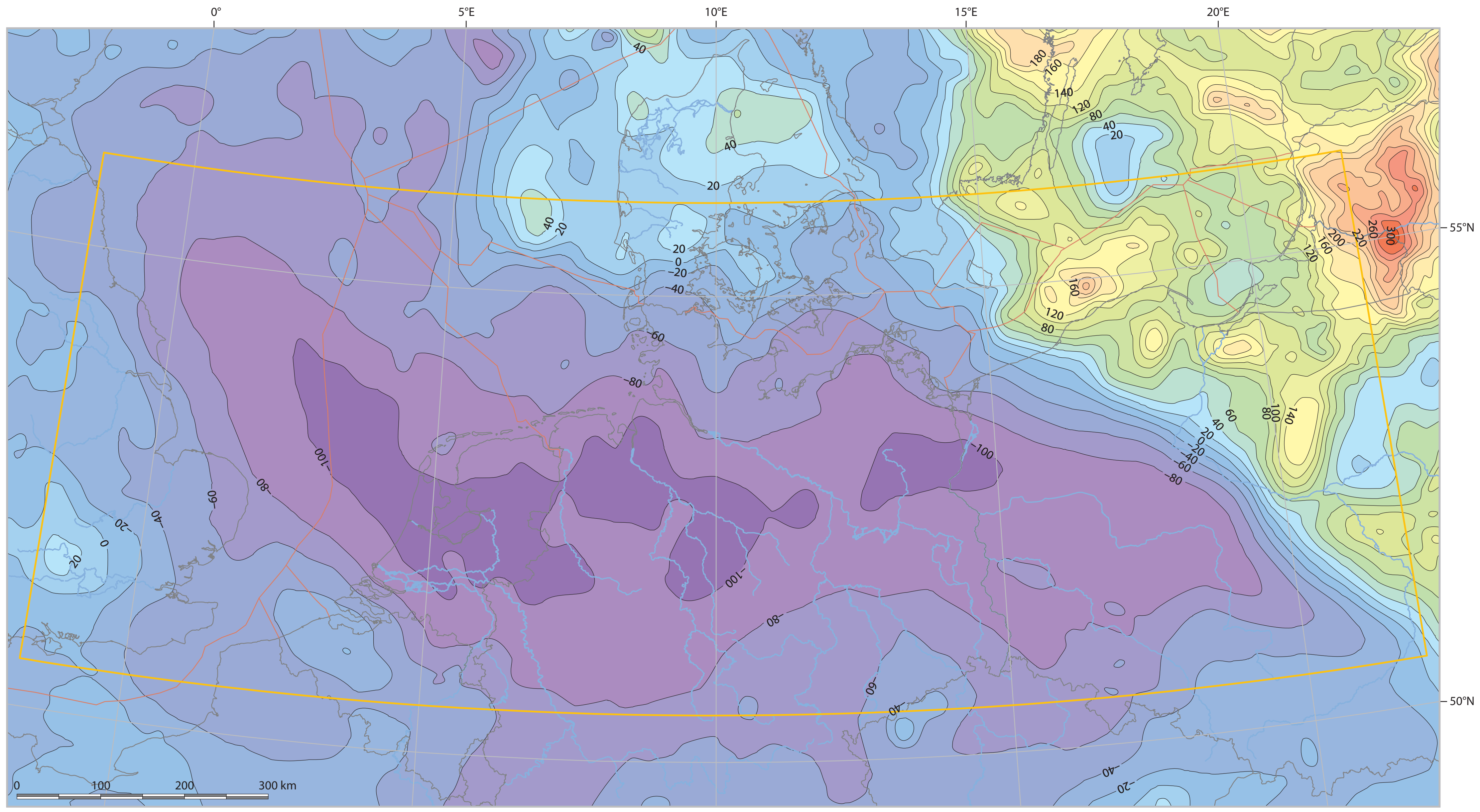


Figure 2.25 Magnetics. Total field – pseudogravity.

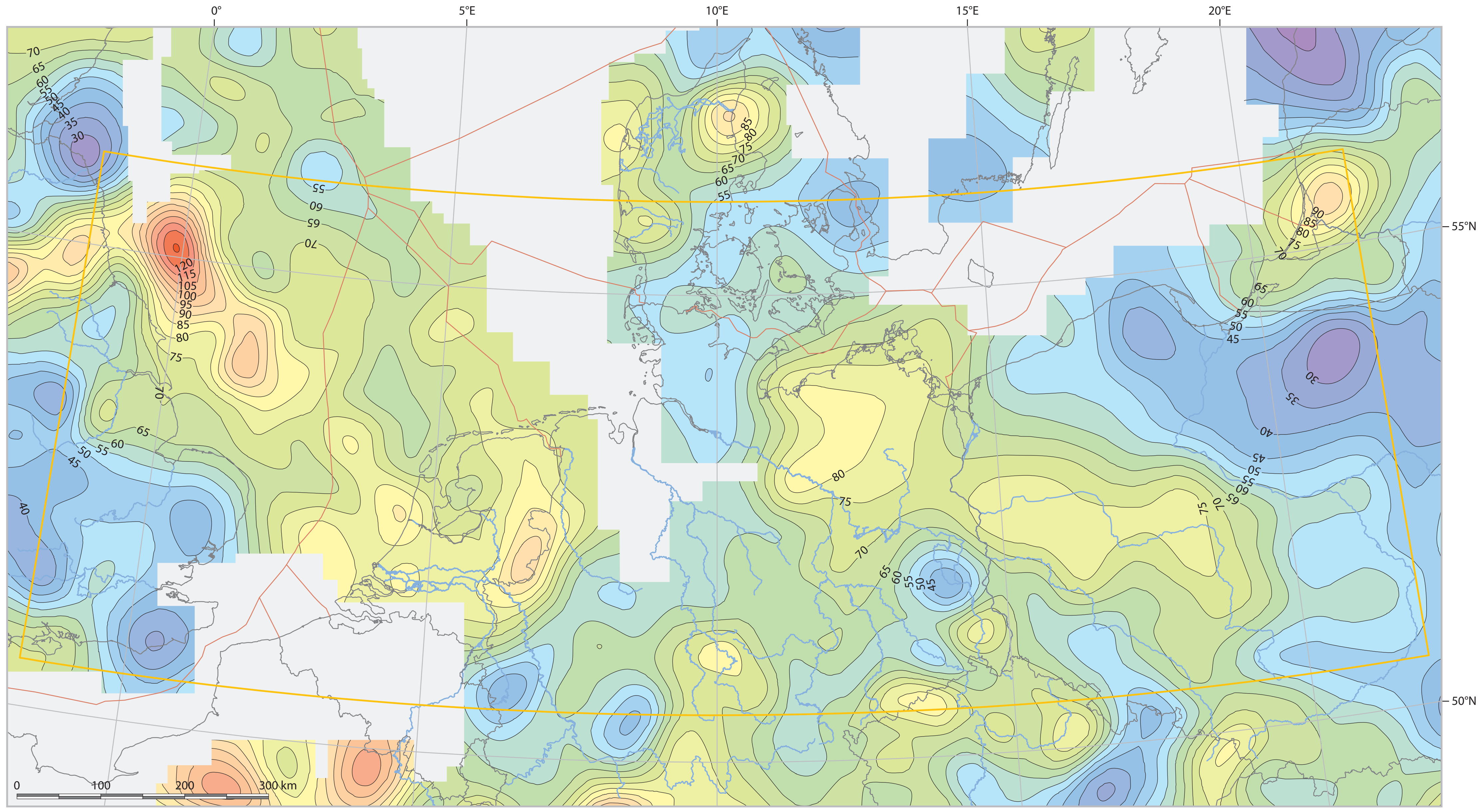


Figure 2.26 Geothermal. Heat-flow density (uncorrected). Data sources: Hurtig et al.(1991/1992); Hurter & Haenel (2002); The Global Heat Flow Database of The International Heat Flow Commission. Site: www.heatflow.und.edu/index2.html.

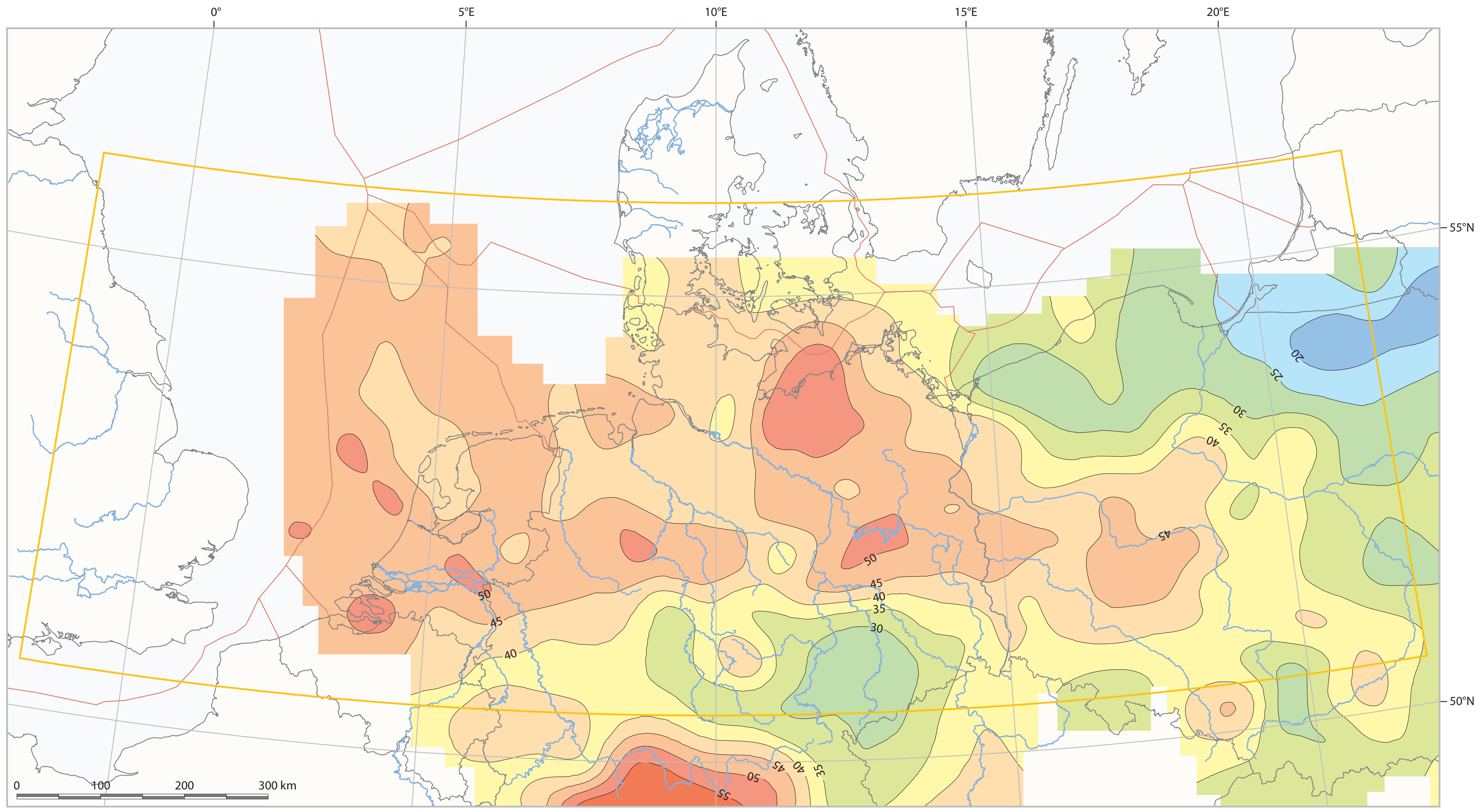


Figure 2.27 Geothermal. Temperature level at 1000 m. Data sources: Belgium – Legrand (1975); Vandenberghe & Fock (1989); Netherlands – temperature data from bottom-hole temperature measurements (from TNO); Germany – Schellschmidt (2007); Poland – deep drillhole temperature data from Polish geothermal database (Polish Geological Institute).

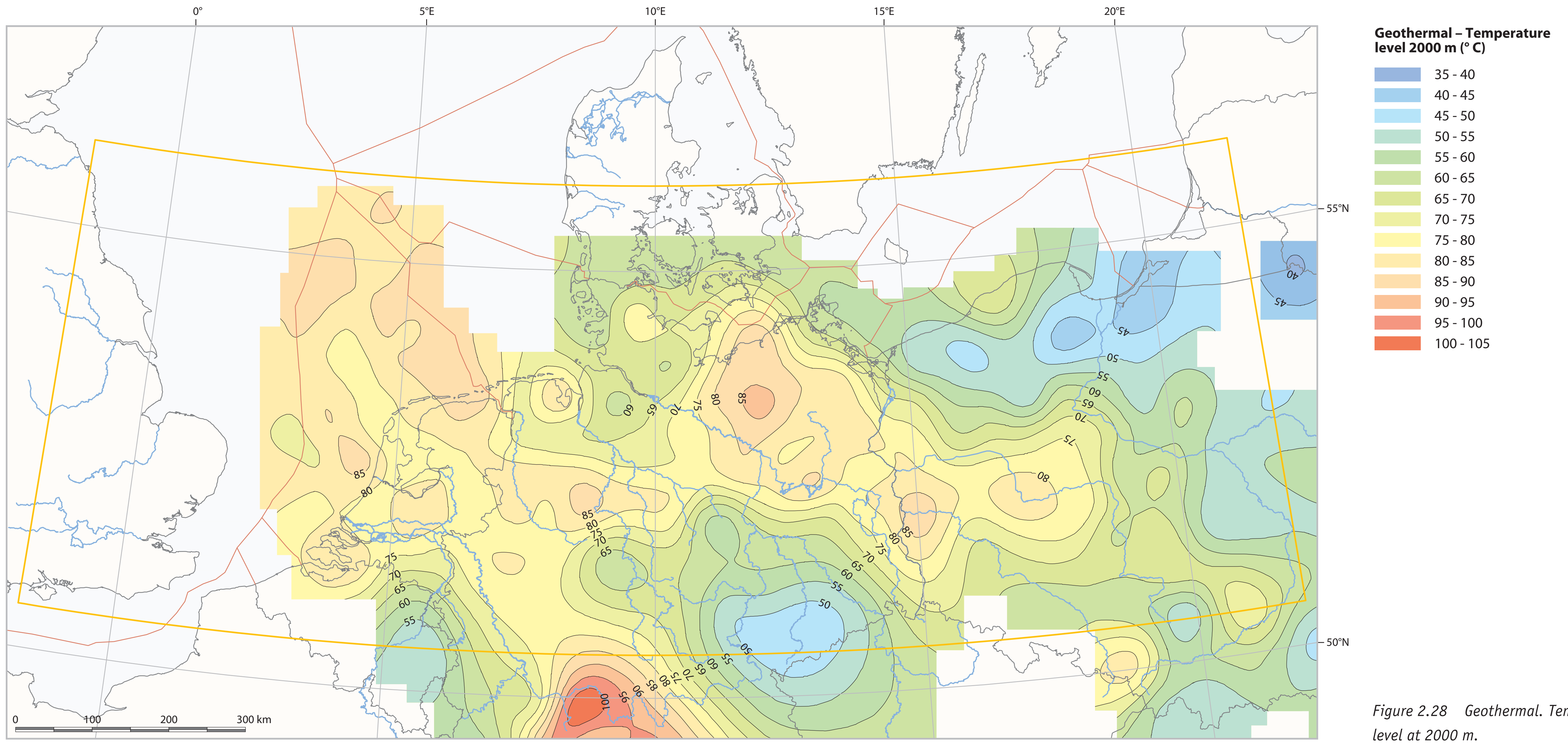


Figure 2.28 Geothermal. Temperature level at 2000 m.

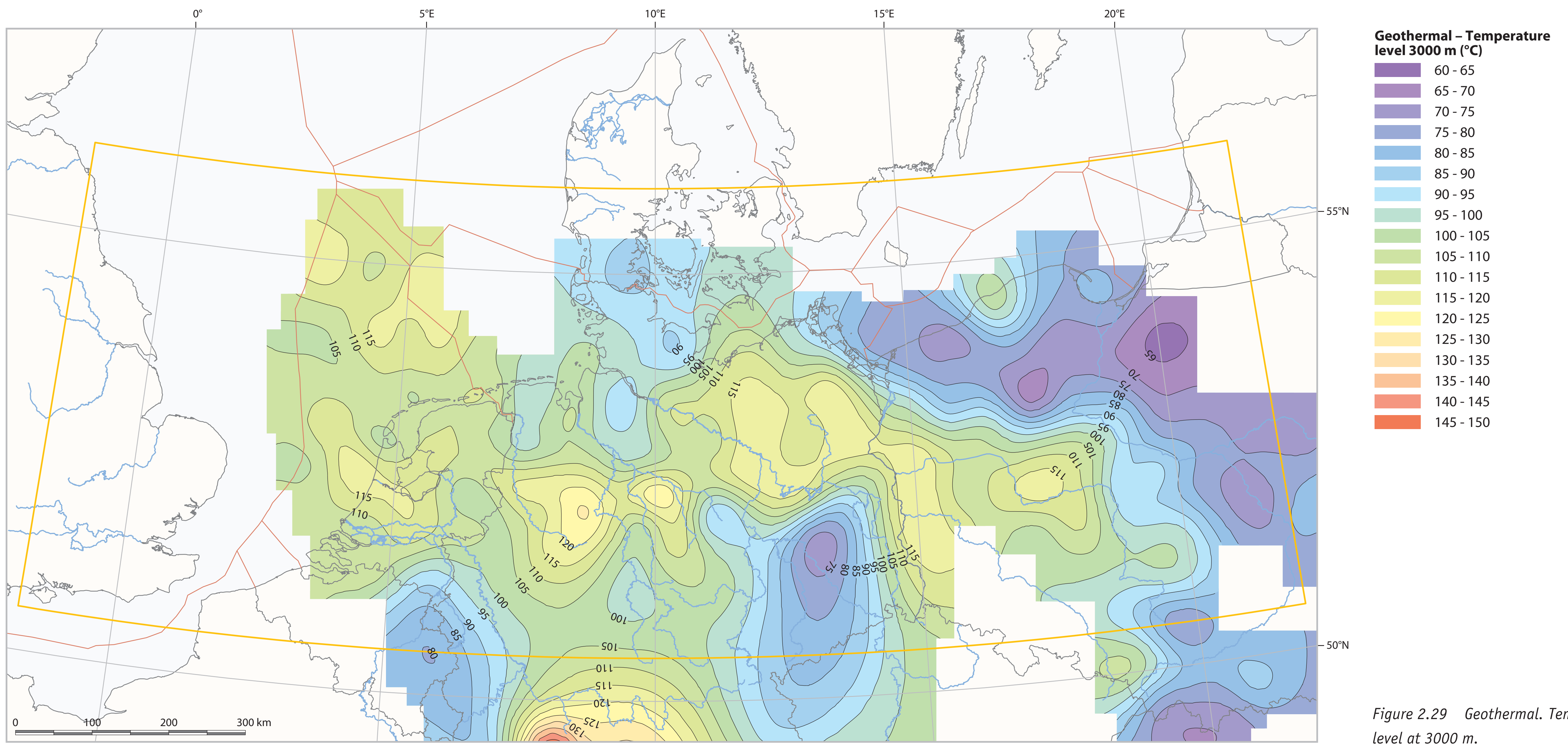


Figure 2.29 Geothermal. Temperature level at 3000 m.