Folded band of coticula, an extremely fine-grained garnet-bearing whetstone of the Ordovician Salm Group; Regné underground quarry, Vielsalm commune, Stavelot Massif (east Belgium). Photo courtesy of Eric Goemaere.

Chapter 4 Pre-Devonian

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1 Introduction

1.1 Data sources and literature review

This chapter describes the geology, and especially the basin evolution, of the pre-Devonian basement within the SPB area. Geophysical and structural considerations are discussed in the previous chapters.

There is a large amount of literature on the pre-Devonian rocks of the SPB area. In addition to national data and publications, international collaboration has resulted in much new literature and many new insights into the extent and evolution of the sedimentary basins. For example, between 1988 and 1993, researchers from the UK and Belgium collaborated on the correlation of the Caledonides of Wales, the Lake District and East Anglia in England, and the Brabant Massif of Belgium (Verniers & Van Grootel, 1991; Pharaoh et al., 1993b). Another project was the acquisition of a deep geological-geophysical profile across Europe, known as the European Geotraverse (Blundell et al., 1991), which was supported by the European Science Foundation (ESF). This profile extends from the old crust of Scandinavia to the young crust of the Mediterranean region and its main objective was to gain insight into continental accretion.

From 1992 to 2002, the ESF also supported the EUROPROBE programme, which promoted discussion on the geological structure of Europe (Gee & Zeyen, 1996) and in particular the Trans-European Suture Zone (TESZ) where the old, thicker crust of the East European Craton meets the younger and thinner crust of central and southern Europe (see Chapters 2 and 3). Geological and geophysical results of the EUROPROBE research on the TESZ were published in special issues of 'Studia geophysica & geodaetica' (Gee & Beckholmen, 1995), 'Geological Magazine' (Pharaoh et al., 1997), 'Tectonophysics' (Thybo et al., 1999, 2002). A review of lithospheric boundaries of Paleozoic terranes within the TESZ was published by Pharaoh (1999).

The EUROPROBE programme stimulated much new research and resulted in a number of review papers, many of which were published in special volumes. An EU-funded Training and Mobility of Researchers Network called 'Palaeozoic Amalgamation of Central Europe' (PACE) produced a set of research papers relevant to the SPB area (Winchester et al., 2002). The papers include a review of the Cambrian to Mid-Devonian basin development of Eastern Avalonia (Verniers et al., 2002) with an extensive reference section and a comparative stratigraphic column of the Lower Paleozoic from England and Wales to Pomerania in Poland. A special issue of 'Neues Jahrbuch' dedicated to the Rügen Caledonides and southern Baltic Sea was published in 2001 (Giese et al., 2001a), including a review paper by Katzung (2001). A summary of the pre-Devonian geology of the SPB area was published in 'Geologie von Mecklenburg-Vorpommern' (Katzung, 2004).

More recently, a special issue of 'Prace PIG' was published on Pomeranian geology (Matyja & Poprawa, 2006) and a special volume of 'Geological Quarterly' focussed on Poland as the junction of the main geological provinces of Europe (Narkiewicz & Ziegler, 2006); this volume includes a review of the TESZ from the Ediacaran to Early Paleozoic by Nawrocki & Poprawa (2006). The results of the EUROPROBE TESZ project were summarised by Pharaoh et al. (2006) in the 'European Lithosphere Dynamics' volume (Gee & Stephenson, 2006). The pre-Silesian of the Netherlands has been described by Geluk et al. (2007a) in 'The Geology of the Netherlands' (Wong et al., 2007a).

Finally, a new 'Terrane Map of Europe' (Oczlon, 2006) provides a comprehensive synthesis of the different crustal components of the European continent, including those underlying and surrounding the Permian Basin.

1.2 Distribution of pre-Devonian rocks

Pre-Devonian rocks crop out in the north-east, south and west of the SPB. In the centre of the basin, the top of the pre-Devonian is too deep to reach by boreholes. However, rocks of either Proterozoic or Early Paleozoic age have been encountered at the basin margin (**Figures 4.1** & **4.2**).

Areas of pre-Devonian outcrops are found in the Midlands Microcraton of central England and the Brabant Massif and Condroz Inlier in Belgium. In the Rheno-Hercynian Zone, there are outcrops in the Stavelot-Venn Inlier in the Ardennes, the Ebbe and Remscheid anticlines in the Rhenish Massif, and the Harz Mountains. Farther east, pre-Devonian rocks are exposed in the Mid-German Crystalline High, the Saxo-Thüringian Terrane, including the Erzgebirge and the Sudetes, and the Holy Cross Mountains. To the north, pre-Devonian rocks crop out on Bornholm Island and in Scania, southern Sweden (**Figure 4.2**).

In the Anglo-Brabant Deformation Belt, several hundred boreholes have reached the Lower Paleozoic basement in Belgium, about 150 of which are important to the understanding of basin evolution and mapping of the subsurface geology; there are 300 boreholes within the SPBA area in England. Elsewhere, there are few that encounter pre-Devonian rocks: for example, there are two boreholes in the UK sector, two in the Dutch sector, and two in the German sector of the southern North Sea. There are five boreholes in the Danish offshore sector, but only two are in the SPBA area. Onshore, there is one borehole that reaches pre-Devonian rocks in the Netherlands (Kortgene), six in Denmark within the SPB area, and two in Schleswig-Holstein in northern Germany.

Along the southern margin of the Permian Basin, there are several boreholes in the Condroz and Stavelot-Venn inliers and surrounding area, one of which is north of the Rhenish Massif. In south-eastern Germany, more than 50 deep boreholes penetrated the pre-Devonian basement in the eastern part of the Northern Phyllite Zone in the Mid-German Crystalline Rise and the Saxo-Thüringian Terrane. Seven deep boreholes in Germany reached Permian volcanics containing xenoliths or zircons of Proterozoic age.

In the western Baltic Sea, two boreholes reached the basement in the Danish sector near Bornholm, whereas in the German sector there are three boreholes offshore and six on land in the Rügen-Vorpommern area. There is much more information from Poland, where more than 35 offshore boreholes reached Lower Paleozoic sedimentary rocks in the Baltic Basin. Several hundred reached Ordovician or Silurian strata in Pomerania and about one hundred encountered pre-Devonian rocks in the East European Platform area. South of the Polish Trough, several hundred boreholes reached pre-Devonian rocks in and around the Holy Cross Mountains, mostly in the Małopolska Massif, in the coal-bearing region of Katowice in the Brunovistulian Terrane, and in the Sudetes.

The depth to the top of the pre-Devonian rocks in the SPBA area with individual borehole locations indicating the depth to the top of the pre-Devonian below (or above) sea level is shown in **Figure 4.3**. Outcrops of pre-Devonian rocks are also shown. In the south, the most important folded Paleozoic massifs are outlined; these are either exposed or are present in the shallow subsurface. Where there is a high borehole density, interpolated depth contour lines have been drawn in England, Belgium, north-east Poland and the Baltic Sea.

The East European Platform dips to the south-west and is bordered by the central Polish Basin, a graben filled with Permian and younger sediments. Directly north of the graben, some boreholes reached pre-Devonian rocks at about 5000 m depth. According to seismic data the top of the pre-Devonian strata is estimated to be at a depth of about 7000 to 10 000 m within the central Polish Basin (Znosko et al., 1998).

In the Rønne Graben, Silurian rocks were reached at 3212 m in the Pernille borehole, more than 1000 m deeper than in the nearby Stina borehole, which is outside the graben. In the Danish sector, the Ringkøbing-Fyn High is an elongated Mesozoic high with basement uplift of 1000 to 2000 m.

No boreholes have penetrated the pre-Devonian in the central area, where the SPB is deepest. However, in the seven boreholes indicated on **Figure 4.3**, xenoliths or zircons of pre-Devonian age were found in Permian volcanics encountered at great depth (see section 2.4.3); the depths at which the inclusions were found are given.

2 Stratigraphy and lithology

A tectonostratigraphic correlation chart for the Ediacaran (latest Proterozoic) to Lower Devonian in the SPB area is shown in **Figure 4.1**. On the left, the stratigraphic columns represent deposition on the Avalonian Microplate (seven columns), and in the centre they represent deposition on Baltica (ten columns). The column of the Rügen boreholes has been placed between Avalonia and Baltica as these represent the collision between both microplates (see **Figure 4.12**). The two columns on the right illustrate deposition on Gondwana. The sedimentary basins were far apart until Devonian times when they were joined during the Caledonian and Variscan orogenies to form the crust of central Europe (Chapter 3).

2.1 The Midlands Microcraton and the Anglo-Brabant Deformation Belt

The Midlands Microcraton in England constitutes the core of the eastern part of the Avalonian Microplate. The pre-Devonian rocks in the Anglo-Brabant Deformation Belt were deposited from the Midlands Microcraton to the Brabant Massif in Belgium. These folded, slightly metamorphic rocks are Cambrian to Silurian in age and can be seen at outcrop in Leicestershire in central England and in the south-west of the Brabant Massif. They subcrop in East Anglia in England, but are scarcely known in the Netherlands. These marine-shelf to deep-water clastics were deformed during the three-plate convergence of Avalonia, Baltica and Laurentia in two distinct phases of the Caledonian Orogeny. The first phase, the Shelveian or Ardennian as it is known in the UK and Belgium respectively, took place in Late Ordovician times; the second phase, the Acadian (UK) or Brabantian (Belgium) took place during late Silurian to Mid-Devonian times (Verniers et al., 2002).

Based on faunal evidence, Cocks & Fortey (1982) showed that the Avalonian Microplate was attached to Gondwana in a southern high-latitude position during the Cambrian. The microplate separated from Gondwana when the Rheic Ocean opened during the Early Ordovician and then migrated to lower latitudes near Baltica, to which it has similar Late Ordovician fauna. Palaeomagnetic data indicate that Avalonia occupied positions of 60°S during the Tremadocian (Early Ordovician), 40°S in Caradoc (Late Ordovician) time, 20°S during the Silurian and 10°S in Famennian time (Late Devonian) (Torsvik et al., 1996; Cocks, 2002).

2.1.1 Pre-Devonian rocks in eastern England

The first map of the base of the Devonian in the UK was made by Wills (1978). Smith (1987) produced a subcrop map at the base of the Devonian for central England to accompany a discussion of hydrocarbon prospectivity, which was slightly revised by Lee et al. (1991). As the Acadian Unconformity lies between Lower and Upper Devonian strata in England and Wales, the Lower Devonian has been removed for the purpose of the SPBA.

2.1.1.1 Outcrops in England
There are five small outcrop areas at the western margin of the SPB (**Figure 4.2**). The best known, because of their Ediacaran fossil assemblage, are the Upper Proterozoic volcaniclastics, lavas and diorite intrusions that comprise the Charnian Supergroup, which crops out in a number of inliers in the Charnwood Forest area of Leicestershire. The overlying formations are now considered to be Cambrian in age and the relationship between them and the Charnian is either conformable or disconformable (Carney, 1999).

About 5 km to the east of Charnwood Forest, the Mountsorrel Granodiorite also emerges through the overlying Triassic strata. This intrusion coincides with a prominent linear aeromagnetic anomaly that trends in a north-west–south-east direction to the north-east of the Charnian rocks. This trend is related to a line of small batholiths (Carney et al., 2008) that can be traced beneath the East Midlands by borehole and seismic data, and by their aeromagnetic expression (Evans & Allsop, 1987; Lee et al., 1990). To the south of Charnwood, the South Leicestershire Diorites are exposed around Enderby in small, quarried outcrops. These plutonic suites have calc-alkaline chemistry and, together with volcanic rocks, they mark the axis of an Ordovician continental-type magmatic arc that extended eastwards into Belgium (Le Bas, 1972; Pharaoh et al., 1993a).

To the south-west, on the eastern flank of the Warwickshire coalfield syncline (Bridge et al., 1998) is the Nuneaton Anticline where Proterozoic volcaniclastics (Caldecote Volcanic Formation) of Charnian affinity (Pharaoh & Gibbons, 1994) are exposed with minor intrusions. These are unconformably overlain by Lower Cambrian rocks (Hartshill Sandstone Formation) and the succeeding shales of the Stockingford Shale Group, which extend up into the Tremadocian with minor lamprophyric intrusions. The Hartshill

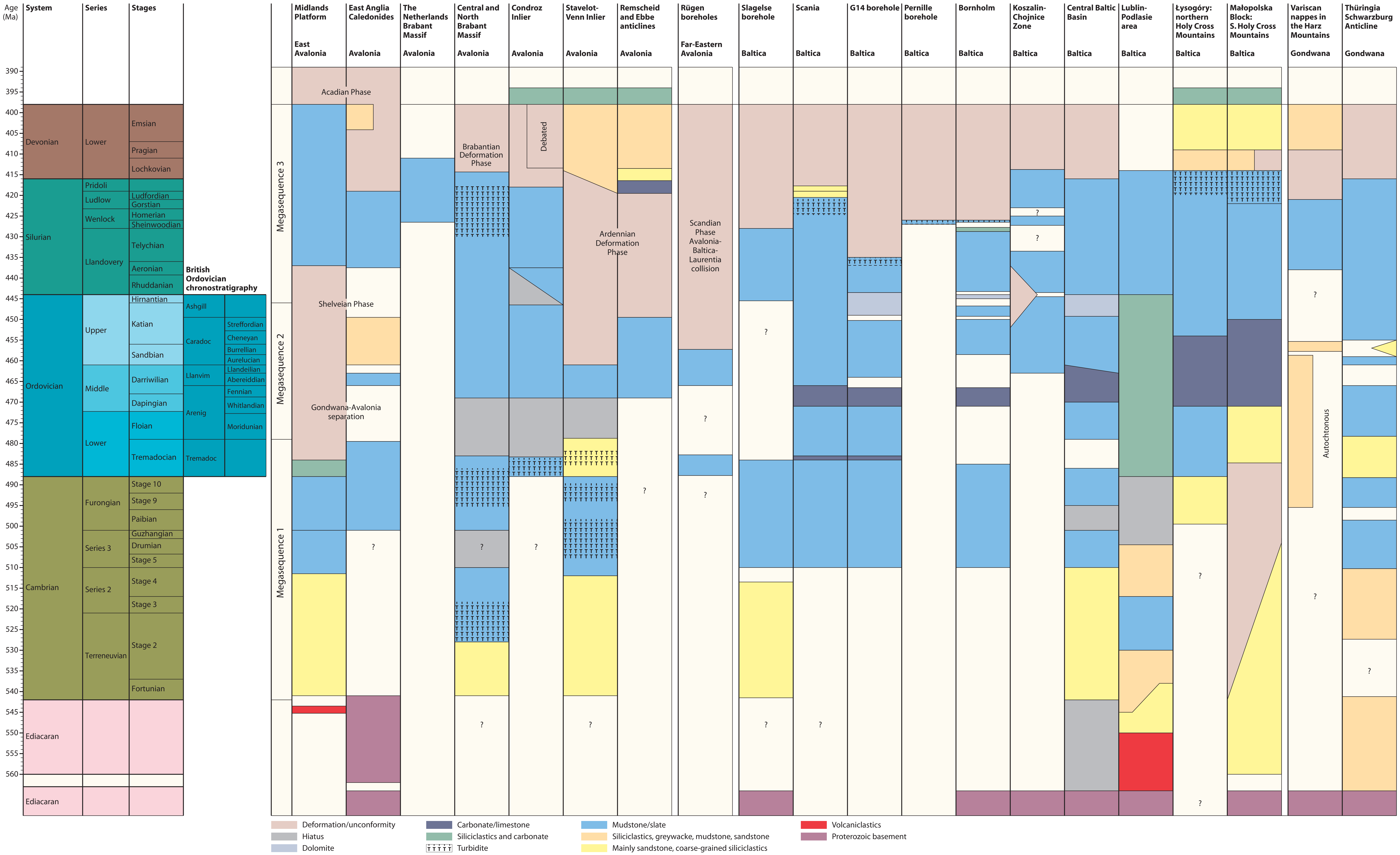

Figure 4.1 Tectonostratigraphic correlation chart for the Ediacaran to Silurian in the SPBA area. See Figure 4.2 for locations of boreholes.

Sandstone Formation represents the initial deposits of a marine transgression that followed a phase of rifting on the western margin of the Gondwana Palaeocontinent. This rifting, which was related to the opening of the Rheic Ocean, continued to affect the Midlands Microcraton at least until Tremadocian times (Smith & Rushton, 1993).

At Dosthill on the north-west flank of the Warwickshire coalfield, there is another small faulted inlier of Cambrian and Tremadocian shales intruded by lamprophyres and unconformably overlain by Namurian rocks (Taylor & Rushton, 1971). The latter two outcrops lie inside the undeformed Midlands Microcraton and so were not deformed by the Acadian Orogeny. No younger Ordovician or Silurian rocks crop out in the SPB area in England, and they are also absent from much of the subsurface (Smith, 1987).

2.1.1.2 Boreholes in the pre-Devonian in the UK

Only two boreholes have reached pre-Devonian strata in the offshore part of the UK within the SPBA area (**Figure 4.2**). In well 47/29A-1, chitinozoans were recovered from a 115 m-thick section of turbidites that were metamorphosed at greenschist facies and dated as probable Llanvirn age (Ordovician). Silurian strata are therefore absent here, as they are from a large part of the adjacent area onshore. Borehole 53/16-1 proved 223 m of steeply dipping pre-Carboniferous (Woodcock & Pharaoh, 1993) grey turbiditic sandstones of comparable facies to those in the nearby O18-1 borehole in the Dutch sector and are probably of latest Silurian age; they are metamorphosed in low anchizone (T.C. Pharaoh, pers. comm., 2008).

There are more than 100 boreholes on land that have reached pre-Devonian rocks in the Anglo-Brabant Deformation Belt, which in general was not (or only thinly) covered by Devonian or Lower Carboniferous strata. About 50% of the boreholes penetrated a short distance into the Cambrian and Tremadocian shales beneath the Warwickshire coalfield near the western margin of the SPB area. Many of the boreholes nearer the North Sea coast have not been dated precisely. However, reliable U-Pb zircon ages from felsic magmatic rocks in the North Creake and Claxby boreholes (Noble et al., 1993) provide evidence for a phase of Late Ordovician calc-alkaline magmatism (Pharaoh et al., 1993). Boreholes from the area around the Upper Proterozoic Charnian inliers have encountered Tremadocian shales.

2.1.1.2.1 Proterozoic and Cambrian

Several boreholes penetrate Proterozoic rocks. The Glinton borehole drilled ash-flow tuffs dated at 612±21 Ma using the U-Pb zircon method (Noble et al., 1993); the Orton and Oxendon Hall boreholes have yielded rocks of similar age. Quartzites in the Wisbech and Spalding boreholes in Lincolnshire are probably Cambrian in age. A Late Cambrian age has been assigned to the predominantly shale succession beneath the Westphalian rocks of the south Midlands (Bridge et al., 1998) and on the Midlands Microcraton. Lower Cambrian sandstones overlie Proterozoic rocks in the Withycombe Farm borehole (Rushton & Molyneux, 1990).

2.1.1.2.2 Ordovician

Possible Ordovician strata include those drilled at Saxthorpe, East Ruston, Bacton, West Somerton and Somerton (Norfolk). Tremadocian shales and siltstones are rarely encountered in boreholes from the Caledonides of eastern England, but are common in those from the Midlands Microcraton (Smith, 1987; Bridge et al., 1998). Where boreholes have reached Tremadocian rocks, seismic-reflection profiles show thicknesses in excess of 1000 m on the microcraton (Smith & Rushton, 1993). Within the Caledonides, the Ironville 5 borehole has cored cleaved black shales containing carbonised acritarchs. Lamprophyric minor intrusions are common in both the Caledonides and the microcraton.

Ordovician rocks younger than Tremadocian age appear to be absent from the Midlands Microcraton (Smith, 1987). However, the Strat A1 borehole near the Variscan Front found cleaved and steeply dipping shales beneath the Variscan Unconformity. Steeply dipping graptolitic mudstones from the Great Paxton borehole have been dated as Llanvirn age (Molyneux, 1991), as have similar rocks in boreholes nearby. An eastward-thickening and deepening facies is suggested by the trilobite assemblage from Great Paxton (Rushton & Hughes, 1981) and by the absence of Llanvirn rocks to the south-west. Ordovician rocks may extend north-eastwards offshore of north Norfolk, where the basal core of well 47/29a-1 (**Figure 4.2**) recovered graded-bedded turbidites with a high sonic velocity. The overlying mudstone sequence with interbedded cleaner sandstones is also likely to be Ordovician in age. The Caledonian unconformity was initially placed at a depth of 1675 m in the well, overlain by Namurian rocks. However, there is a more significant boundary at 1533 m depth, where the overlying lower velocity shales are more definitely Carboniferous. At 1700 m depth and below, acritarchs were dated as probable Llanvirn age. A similar sequence, although sandstone-dominated in the upper part, was drilled onshore to the west at Halton Holegate 1. The Bobbing borehole in north Kent, which is also near the Variscan Front, encountered steeply dipping siltstones and sandstones that yielded Caradoc macrofauna, acritarchs and chitinozoans (Lister et al., 1969).

2.1.1.2.3 Igneous rocks of Caradoc age

There are two belts of similarly aged igneous rocks within the Caledonides of eastern England. To the north-east in Lincolnshire and Norfolk, the Moorby Microgranite was drilled at the Claxby borehole (Pharaoh et al., 1997) and dated using the U-Pb zircon method at 457±20 Ma. Ash-flow tuffs from the North Creake borehole were dated using the same method and gave an age of 449±13 Ma (Noble et al., 1993). This north-eastern belt is associated with a prominent aeromagnetic anomaly that extends to northern England, but which may be concealed by thick Silurian and Devonian strata in Suffolk and Essex. To the south-west, the belt of aeromagnetic anomalies coincides with the Mountsorrel Granodiorite mentioned above and the Rempstone, Kirby Lane, Upwood and Warboys boreholes. The Mountsorrel Granodiorite was dated using the U-Pb zircon method at 463±32 Ma (Noble et al., 1993). A third aeromagnetic anomaly belt (Chapter 2; **Figure 2.24**) lies between these two, but has not been drilled.

The South Leicestershire Diorites crop out, or are close to the surface, south of Charnwood (Le Bas, 1972) and were re-evaluated to give a date of 449±18 Ma (Noble et al., 1993). These calc-alkaline intrusions have been linked to the collision of Avalonia and Baltica by subduction (Pharaoh et al., 1993a, 1995), although the direction of subduction is not established beyond doubt.

2.1.1.2.4 Silurian

Rocks from the Lowestoft, Stutton and Harwich boreholes in Suffolk are probably Silurian in age; the Culford borehole encountered unfossiliferous Silurian rocks. Silurian strata were probably reached to the north of the Kent coalfield in boreholes at the Isle of Grain, Sheerness, Reculver, Beltinge, Herne and Thornden Wood. The Chilham, Brabourne (Kent) and Weeley (Suffolk) boreholes proved Llandovery shales. Boreholes at Ware and Cliffe Marshes reached Wenlock fossiliferous shales and limestones (Molyneux, 1991). The Stowlangtoft borehole (Suffolk) encountered fossiliferous sandstones and mudstones of Ludlow age. Grey shales and sandy limestones at the Little Missenden borehole (north-west of London) were dated by ostracods as Pridolian in age (Siveter, 1989). In Suffolk, the Lakenheath borehole encountered hard fossiliferous siltstones and mudstones. The Soham borehole drilled mostly steeply dipping mudstones with ostracods and the Clare borehole recovered richly fossiliferous mudstones, siltstones and thin sandstones, which also have ostracods.

2.1.2 The Brabant Massif in Belgium and the Netherlands

Several hundred wells reached Lower Paleozoic rocks in the Brabant Massif of Belgium. Southwards, there are outcrops in the Dender, Senne, Dyle, Orneau and Mehaigne basins. Several subcrop maps have been published, which initially relied on lithological and macropalaeontological borehole data (Legrand, 1968), but microfossils and aeromagnetic data were used in later interpretations (De Vos et al., 1993; Mansy et al., 1999). More recently, improved sedimentological, palaeontological and especially structural information (Debacker et al., 2004a; 2004b) have led to a revised subcrop map of the pre-Devonian geology of the Brabant Massif (Piessens et al., 2005). Lower Paleozoic rocks crop out in the south of the Brabant Massif and in the Condroz Inlier near the southern edge of the SPB area (**Figure 4.2**).

In the Netherlands, pre-Devonian rocks have been encountered in two wells: the Kortgene well reached the pre-Devonian at a depth of 1350 m, and offshore well O18-1 at a depth of 2953 m; both recovered sedimentary rocks of Silurian age. As noted above, well O18-1 lies close to 53/16-1 in the UK sector and the turbidite facies in both indicate a Silurian deep-water basin extending from the UK to the Low Countries (Pharaoh, 1999).

2.1.2.1 Sedimentology and basin evolution

In most parts of the Anglo-Brabant Deformation Belt, the Cambrian to Silurian can be subdivided into three megasequences (**Figure 4.1**) (Woodcock, 1991; Vanguestaine, 1992; Verniers et al., 2002) separated by sedimentation hiatuses or unconformities; one in the upper Tremadocian to lower Arenig, and several minor ones in the Upper Ordovician sequence. Each megasequence was deposited in a different tectonic setting. For detailed descriptions of the stratigraphy and sedimentology, reference is made to Verniers & Van Grootel (1991), De Vos et al. (1993), Servais et al. (1993), Verniers et al. (2001), Verniers et al. (2002), Debacker et al. (2003). Most of the Condroz Inlier sediments were deposited in the same basin as the Brabant Massif sediments.

The Early Cambrian to Tremadocian Megasequence 1 (**Figure 4.1**) is a sequence of coarse-grained quartzites (Blanmont Formation) followed by coarse-grained turbidites (Tubize Formation). The Early Cambrian Tubize Formation is an epimetamorphic turbiditic sequence with decimetre to metre-size, fining-upward layers of greenish arkose, sandstone, siltstone and phyllite. The rocks contain disseminated magnetite, which helps to reveal structures on large and intermediate scales on aeromagnetic maps (Chacksfield et al., 1993; De Vos et al., 1993; Sintubin, 1997, 1999). Fine-grained mudstones were deposited in the basin as it deepened in Mid- to Late Cambrian times, followed by black shales (e.g. Mousty Formation) and finally fine-grained distal turbidites (e.g. the Tremadocian Chevlipont Formation) that marked a return to shallow-water sedimentation. Megasequence 1 deposits are mostly marine and terrigenous siliciclastics derived from the Gondwana Palaeocontinent, as evidenced by the faunal affinity of acritarchs and other fossils (Cocks & Fortey, 1982; Cocks et al., 1997; Servais & Fatka, 1997). The sediments were deposited at a time when Avalonia was still attached to Gondwana in waters that were generally deeper than a shelf environment. The total thickness of this megasequence is estimated to be at least 3700 m in the Brabant Massif (Verniers et al., 2001).

Megasequence 2 consists mainly of fine-grained, shallow-shelf sediments with several sandy beds (Tribotte Formation). The overlying Rigenée Formation (Ordovician Darriwillian Stage) consists of mudstones deposited in a basin in which water depths were temporarily rapidly increasing, possibly caused by a sudden eustatic rise in sea level. Towards the top of the sequence, turbiditic layers appear (Ittre and Bornival Formations in the Brabant Massif) with interstratified volcanic layers in the upper Caradoc and lower Ashgill (fine-grained siliciclastic Huet and Madot Formations). The thickness of Megasequence 2 in the Brabant Massif is estimated to be at least 850 m (Verniers et al., 2001).

The sediments of Megasequence 2 were deposited during a period of rapid, approximately northward, drift of Avalonia, which had rifted away from Gondwana in Early Ordovician times. Only a limited amount of eroded material was derived from Avalonia due to the small size of the microcontinent. The upper Caradoc and Ashgill (Upper Ordovician) sediments at the top of this megasequence have microfauna similar to that of Baltica. During mid-Caradoc times, there were large-scale slumps in the Brabant Massif (Debacker et al., 2001), the existence of the Asquempont detachment (Debacker et al., 2004a) and the onset of turbiditic sedimentation, all of which point to a period of basin instability.

Megasequence 3 sediments (**Figure 4.1**) were deposited from the Late Ordovician through the Silurian. The sediments represent shallow-marine environments during Ashgill to mid-Llandovery times, which evolved to a rapidly subsiding foreland basin in the Brabant Massif and its western prolongation in East Anglia (Woodcock & Pharaoh, 1993; Pharaoh et al., 1995; Van Grootel et al., 1997; Debacker et al., 2005). Sediments consist of deep-water, fine-grained siliciclastics and fine-grained distal turbidites with laminated hemipelagic intercalations. Sedimentation in the foreland basin continued while the Cambrian core of the Brabant Massif was being inverted and compressed.

2.1.2.2 Tectonic framework and deformation

Avalonia joined Baltica in a soft collision or 'terrane docking' event that closed the Tornquist Ocean at the end of the Ordovician (Cocks & Fortey, 1982; Chapter 3). The Iapetus Ocean was subducted beneath Laurentia and Avalonia during Ordovician and Silurian times (with a suture in Scotland and Ireland). In north Wales and the Lake District of northern England, Mid- to Late Ordovician calc-alkaline magmatism is evidence of this subduction. Likewise, Late Ordovician calc-alkaline magmatic rocks in East Anglia and the Brabant Massif (Pharaoh et al., 1993a; Verniers et al., 2002), and inferred granites beneath the volcanic rocks (Everaerts et al., 1996; Mansy et al., 1999), are probably related to this subduction. Deep-seismic profiles in the southern North Sea (Blundell et al., 1991) reveal a south-west-dipping deep reflector in the mantle beneath the Dowsing-South Hewett Fault Zone, which was interpreted as a possible remnant of this Ordovician subduction zone (Lee et al., 1993; Pharaoh et al., 1995) separating a far-Eastern Avalonian Microcontinent from Eastern Avalonia proper (Verniers et al., 2002).

The Brabant Massif was progressively deformed in a long diachronous phase, the Brabantian Deformation Phase (**Figure 4.1**), which started in late Llandovery time and continued until the end of the Early Devonian (Debacker et al., 2005). In England, north of the Variscides, the Acadian Deformation Phase was slightly later from Early to Mid-Devonian times (McKerrow, 1988). Deformation consisted of basin inversion with folding and faulting. This orogenic belt is referred to as the Caledonides of the Anglo-Brabant Massif (Pharaoh et al., 1993b), the Anglo-Brabant Fold Belt (Van Grootel et al., 1997) and the Anglo-Brabant Deformation Belt (Verniers et al., 2002, Winchester et al., 2002). Interestingly, there is no evidence of the Acadian/Brabantian orogeny within the Variscides in England, northern France, Belgium and Germany (i.e. the Rheno-Hercynian Zone).

There is an angular unconformity between upper Silurian and Middle Devonian rocks in the Brabant Massif, where undeformed Givetian strata overlie deformed Lower Paleozoic metasediments (**Figure 4.4**, Ronquières unconformity). The structure of the massif has a west-north-west-oriented Cambrian core curving eastwards to an east–west direction and surrounded on both sides by Ordovician and Silurian rocks (De Vos et al., 1993; Piessens et al., 2005). A series of negative gravity anomalies, mostly interpreted as granitic bodies (Everaerts et al., 1996; Mansy et al., 1999), sometimes as Precambrian horsts (Sintubin & Everaerts, 2002) or simply called low-density competent bodies (Debacker et al., 2005), reflect the shape of the Brabantian structures in the Brabant Massif (De Vos, 1997; Sintubin, 1999; Verniers et al., 2002). An important pre-deformation detachment, the Asquempont detachment system (Debacker et al., 2004a), probably occurred in Late Ordovician time and explains several observed hiatuses between different stratigraphic levels in the Cambrian-Ordovician succession (Herbosch et al., 2008). The most recent subcrop map of the Brabant Massif (Piessens et al., 2005) takes into account the Brabantian folding of the Asquempont detachment system.

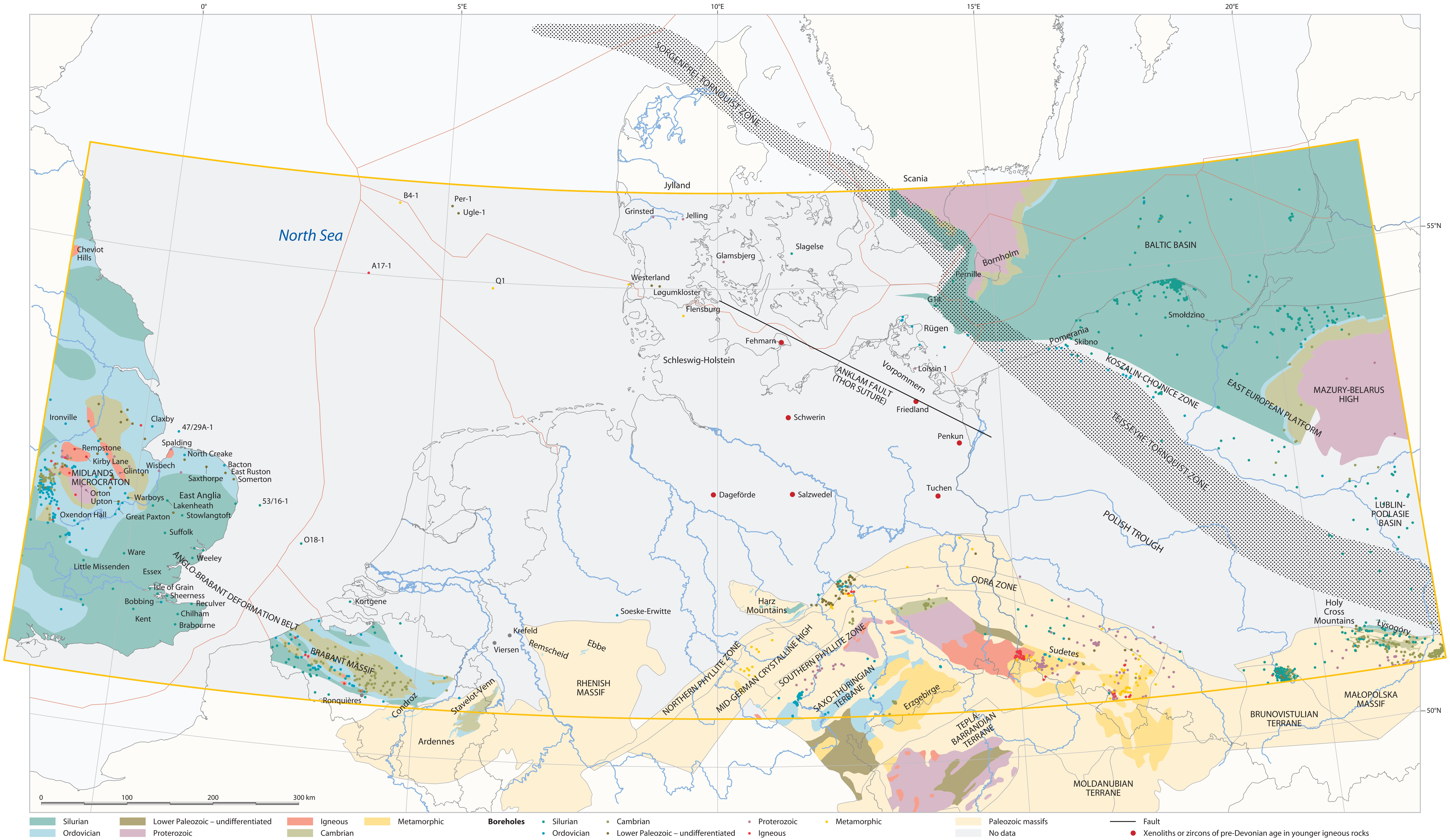

Figure 4.2 Locations of boreholes and pre-Devonian outcrops (with geology and chronostratigraphy). Borehole locations are based on the databases of the participating Geological Surveys. Coloured surfaces represent inferred subcrop occurrences of the horizon just below Devonian or younger rocks in the UK (based on Smith (2007), unpublished report), in Belgium (Piessens et al., 2005), and in the Baltic Basin area in Denmark and Poland (Vejbæk et al., 2000). Variscan massifs and/or crustal basement blocks with crystalline rocks are shown (following Franke, 2000; Franke & Żelaźniewicz, 2000; Mazur et al., 2006; Nawrocki & Poprawa, 2006). Outcrops of pre-Devonian rocks occur in the Midlands (UK), the Brabant Massif (Belgium), the Variscan massifs (Ardennes, Rhenish Massif, Harz Mountains, different parts of the Bohemian Massif, Holy Cross Mountains), in Bornholm (Denmark) and Scania (Sweden). Magmatic rocks are plotted if their crystallisation age is older than Devonian. Rocks plotted as metamorphic have a probable protolith age older than Devonian, but a younger age of metamorphism. The location of the Anklam Fault (representing the Thor Suture) is taken from Hengesbach (2006), who relates it to the SW limit of the Cambrian-Tremadocian Alum Shale Formation at depth.

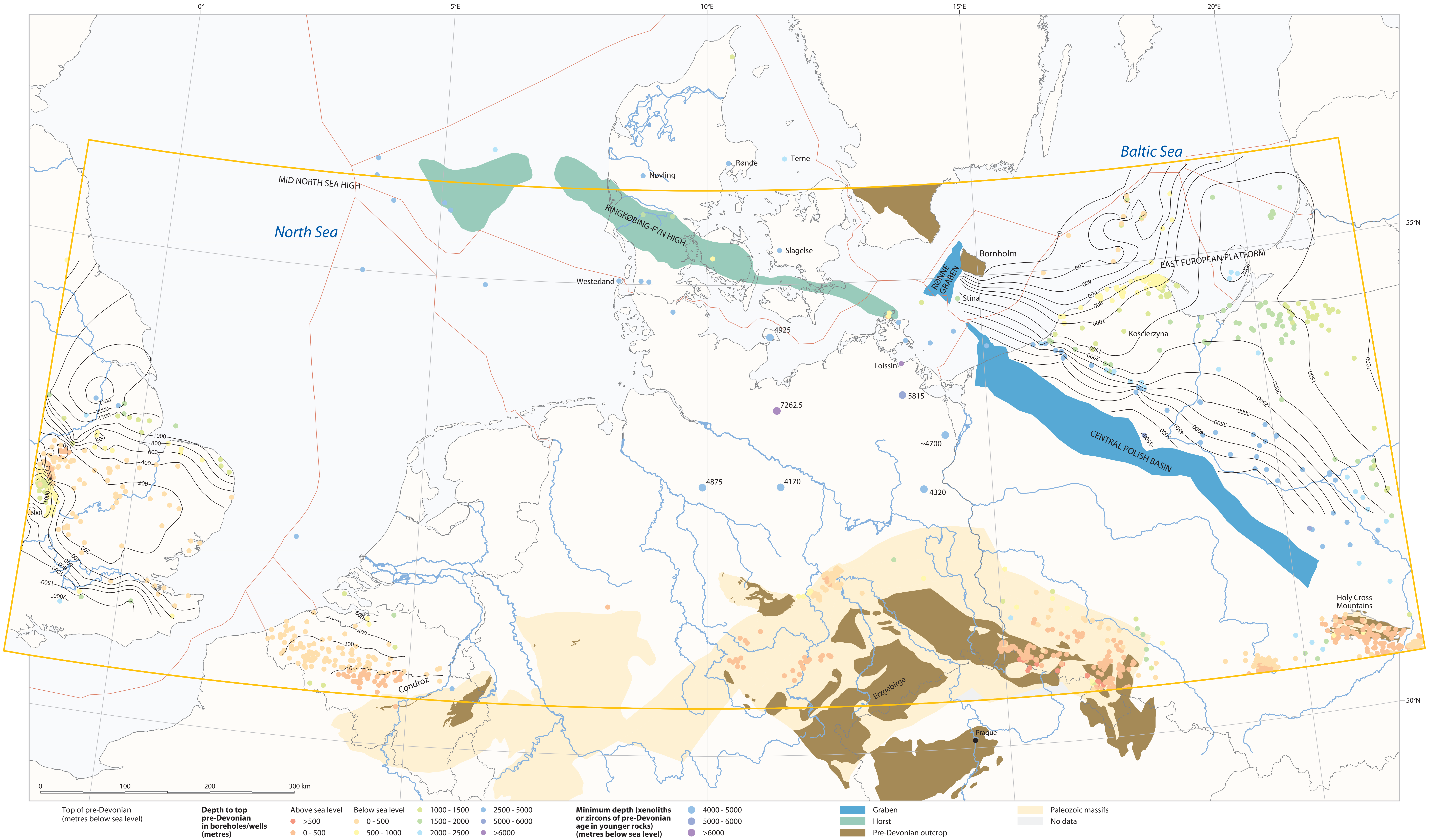

Figure 4.3 Depth to the top of the pre-Devonian basement. Individual borehole locations are shown indicating depth to the top of the pre-Devonian below sea level or above sea level. Outcrop areas of pre-Devonian rocks are also shown. The areas of Paleozoic massifs are either exposed or present in the shallow subsurface. Depth-contour lines are drawn where there is a high borehole density (UK, Belgium, NE Poland and Baltic area), with 200 m interval up to 1000 m depth, and 500 m interval below 1000 m. Boreholes where xenoliths or zircons of pre-Devonian age were found in Permian volcanic rocks are also indicated.

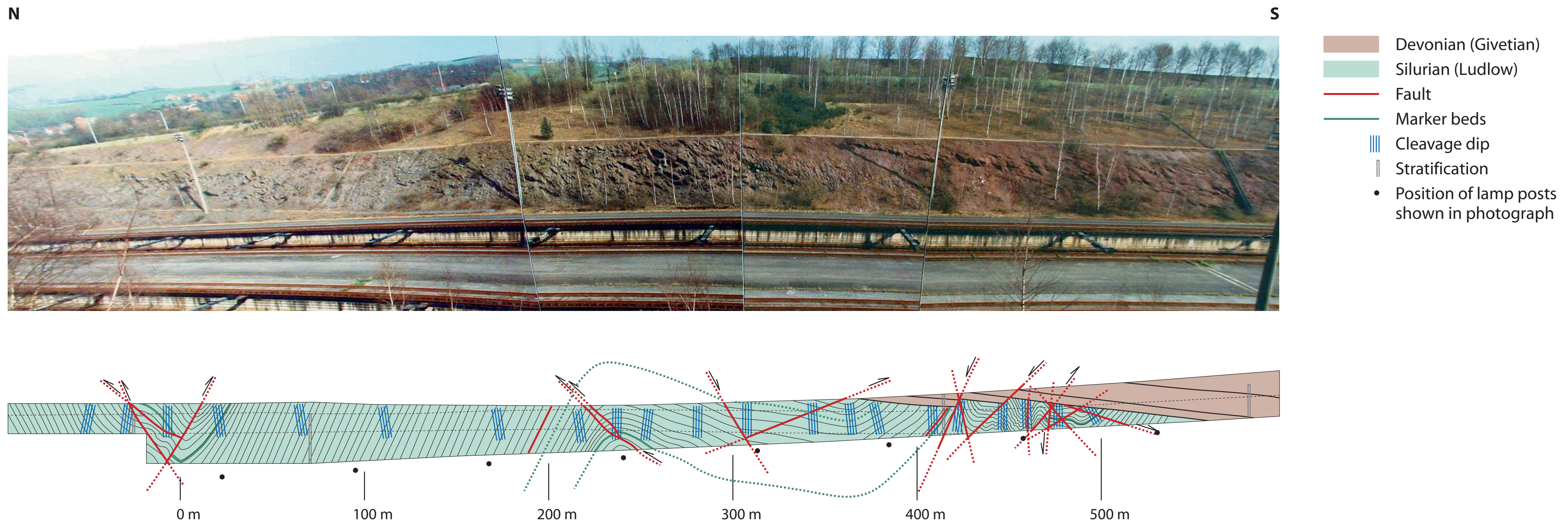

Figure 4.4 Ronquières unconformity. Unfolded sediments of Givetian age (Devonian) overlie a deformed sequence of Ludlow age, Silurian. Photograph of outcrop courtesy of J. Verniers, and line drawing of geology by T. Debacker (Coenen et al., 2007).

Low-grade epizonal metamorphism affects the Brabant Massif with the exception of its south-western part. There is no systematic difference in metamorphic grade between Cambrian, Ordovician and Silurian rocks, but this grade diminishes to the north and south (Van Grootel et al., 1997) regardless of the ages of the rocks involved; the decrease is sharper in the south. Debacker et al. (2005) explained the metamorphic pattern in the framework of the progressive deformation mentioned above.

The name London-Brabant Massif is used in the literature for the post-Caledonian structural high that includes both the Proterozoic Midlands Microcraton and overlying undeformed Paleozoic rocks, and the folded Anglo-Brabant Deformation Belt to the north and north-east. The massif represents the stable area against which the Variscan Orogeny abutted. The area remained a structural high during Mesozoic and Cenozoic times, although it was periodically transgressed by shelf seas.

2.2 The Rheno-Hercynian Zone

The Rheno-Hercynian Zone was part of Avalonia in terms of palaeofauna, until the collision with Baltica in the late Ordovician. Within the Rheno-Hercynian Zone, Lower Paleozoic rocks are known in southern England, in the Stavelot-Venn Inlier of the Ardennes, the Ebbe and Remscheid anticlines of the Rhenish Slate Mountains, in the Harz Mountains and in the Northern Phyllite Zone (**Figure 4.2**). For more detailed descriptions of German pre-Devonian stratigraphy and facies, reference is made to monographs edited by the Stratigraphic Commission, for example Hoth & Leonhardt (2001) for Riphean to Ordovician strata and Heuse & Leonhardt (2006) for the Silurian.

In England, south of the Variscan Front, Tremadocian shales are the oldest strata found in boreholes in areas where Upper Paleozoic rocks have been removed (comparable to parts of the Ardennes inliers). Younger Ordovician and Silurian strata are found in boreholes at, or north of, the Variscan Front, indicating more steady subsidence with no uplift and erosion compared to areas to the north. This zone was subsiding on the northern margin of the Rheic Ocean, which was probably still opening while Avalonia drifted into collision with Baltica and Laurentia (Cocks & Fortey, 1990).

There are four inliers (formerly massifs) in the Ardennes (Verniers et al., 2002) that have pre-Devonian rocks: Stavelot-Venn, Rocroi, Serpont and Givonne (see **Figure 5.4**). Only the Stavelot-Venn Inlier is within the SPB area in Belgium and Germany, where the oldest rocks are quartz-arenite and mudstone of the Lower Cambrian Deville Group. The sediments were deposited on a shallow shelf that subsequently deepened and have a minimum thickness of 300 m. These are overlain by about 1400 m-thick, Middle to Upper Cambrian (Revin Group) coarse-grained turbidites alternating with fine-grained siliciclastics, mudstone and siltstone, capped by a black slate (Geukens, 1999; Verniers et al., 2001), which were deposited on the slope of a submarine fan-valley (Von Hoegen et al., 1985). The third sediment group is the Ordovician Salm Group, which starts with the Tremadocian Jalhay Formation (Geukens, 1999) with Bouma-type turbidites, followed by low-density turbidites and platform-deposited mudstone and sandstone with a total thickness locally exceeding 400 m. There is a small sedimentation gap at the Tremadocian-Arenigian transition, which corresponds in age to the gap between Megasequences 1 and 2 of the Anglo-Brabant Deformation Belt (**Figure 4.1**) (Verniers et al., 2002). The overlying Ottré Formation is probably Arenig in age and consists of fine-grained siliciclastics that were deposited in a deep-water environment. The formation has interstratified layers of coticule, a hard manganese-garnet-bearing rock. The top of the Salm Group is marked by deep-water deposits represented by the black silty slate of the Bihain Formation. The minimum thickness of Megasequence 2 is 330 m (Verniers et al., 2002).

These rocks were folded during the Ardennian Deformation Phase between Mid-Ordovician Llanvirn and late Silurian times (Mansy et al., 1999; Verniers et al., 2002). This phase is almost contemporaneous with the Shelveian Phase of Caradoc-Ashgill age in England and Wales (Pharaoh et al., 1995; McKerrow et al., 2000). In the Stavelot-Venn Inlier, sedimentation recommenced with a basal conglomerate and a highly fossiliferous marine sandstone of latest Silurian to earliest Devonian age.

In the concealed Devonian north of the Rhenish Massif, coarse-grained clastic schist debris of Lower Ordovician age, and with a pre-Variscan tectonic imprint, was found in the Middle Devonian nearshore conglomerates of the Viersen 1001 well (Ahrendt et al., 2001). This indicates an eastern outlier of Brabant-like pre-Devonian rocks known as the Krefeld High.

In the northern Rhenish Massif, a succession of Ordovician shales (Herscheid Group) is exposed in the core of the Ebbe Anticline, with a thickness of about 750 m. Recorded sedimentation starts during earliest Llanvirn times with shales and thin layers of siltstone and fine-grained sandstone followed by shales and greywackes. The youngest sediments are late Caradoc (Alum) laminated shales. There are Ordovician rocks of similar composition in four isolated outcrops in the Remscheid Anticline about 50 km to the west. The graptolite-bearing pre-Devonian rocks of the Soeste-Erwitte well (Clausen & Leuteritz, 1982) about 60 km to the north-east of the Ebbe Anticline remain doubtful. It is not clear whether or not the stratigraphic gap between Ordovician 'deeper' water deposits and the late Silurian sediments of flat-water shelf origin is a sedimentary gap or a tectonically induced gap such as that found at the Stavelot-Venn Anticline.

After a sedimentation gap in latest Ordovician and most of Silurian times, deposition started again during Pridoli times and continued into the Devonian. Late Silurian shales, marlstones and carbonates are known from the Ebbe, Remscheid and Müsen anticlines. During the Variscan Orogeny, the Early Paleozoic Ebbe Anticline complex was strongly folded and thrusted together with the overlying Devonian strata. The slightly rotated fold axes of the Early Paleozoic core complexes might indicate pre-Variscan (Caledonian) deformation of these older rocks.

The Harz Mountains are part of the Rheno-Hercynian Zone in terms of Variscan tectonic development, but most of their pre-Devonian rocks, with the exception of the Wippraer Zone in the south-east, have a Gondwana affinity and were not part of Avalonia. These rocks are described in Section 2.8 under 'Rocks of Gondwana affinity'.

The 10 to 50 km-wide Northern Phyllite Zone forms the south-easternmost part of the Rheno-Hercynian Zone in Germany. The extent of the zone is known mainly from boreholes as the only outcrops are found in the Wippraer Zone in the south-eastern Harz Mountains (Wachendorf et al., 1995). The Northern Phyllite Zone consists of Cambrian to Ordovician (and partly Silurian) phyllitic shales with quartzitic intercalations, phyllites, meta-greywackes and meta-diabases, micaschists and gneisses, which were intensely deformed and metamorphosed (anchizonal to greenschist facies) during the Variscan Orogeny.

2.3 Intrusive and metamorphic rocks of the North Sea and southern Denmark

Only one borehole has encountered igneous rocks within the SPB area of the North Sea. Well A17-1 in the Elbow Spit High reached a strongly altered biotite monzogranite at a depth of 2985 m (**Figure 4.5**); U-Pb zircon ages indicate emplacement at 410±7 Ma in the Early Devonian (A Gerdes, pers. comm., 2008; Pharaoh et al., 2006). The Ar-Ar age of 346±7 Ma given by Frost et al. (1981) probably reflects the thermal influence of subsequent earliest Carboniferous volcanism. A series of gravity lows extending westwards from borehole A17-1 (Chapter 2; Figures 2.19 & 2.20) suggest that there are more granitic rocks in the basement of this region (Donato et al., 1983), and indeed underpin the Mid North Sea High. Just beyond the SPB area in north-east England, the Cheviot Granite was emplaced in Early Devonian time, like many other granites in northern England.

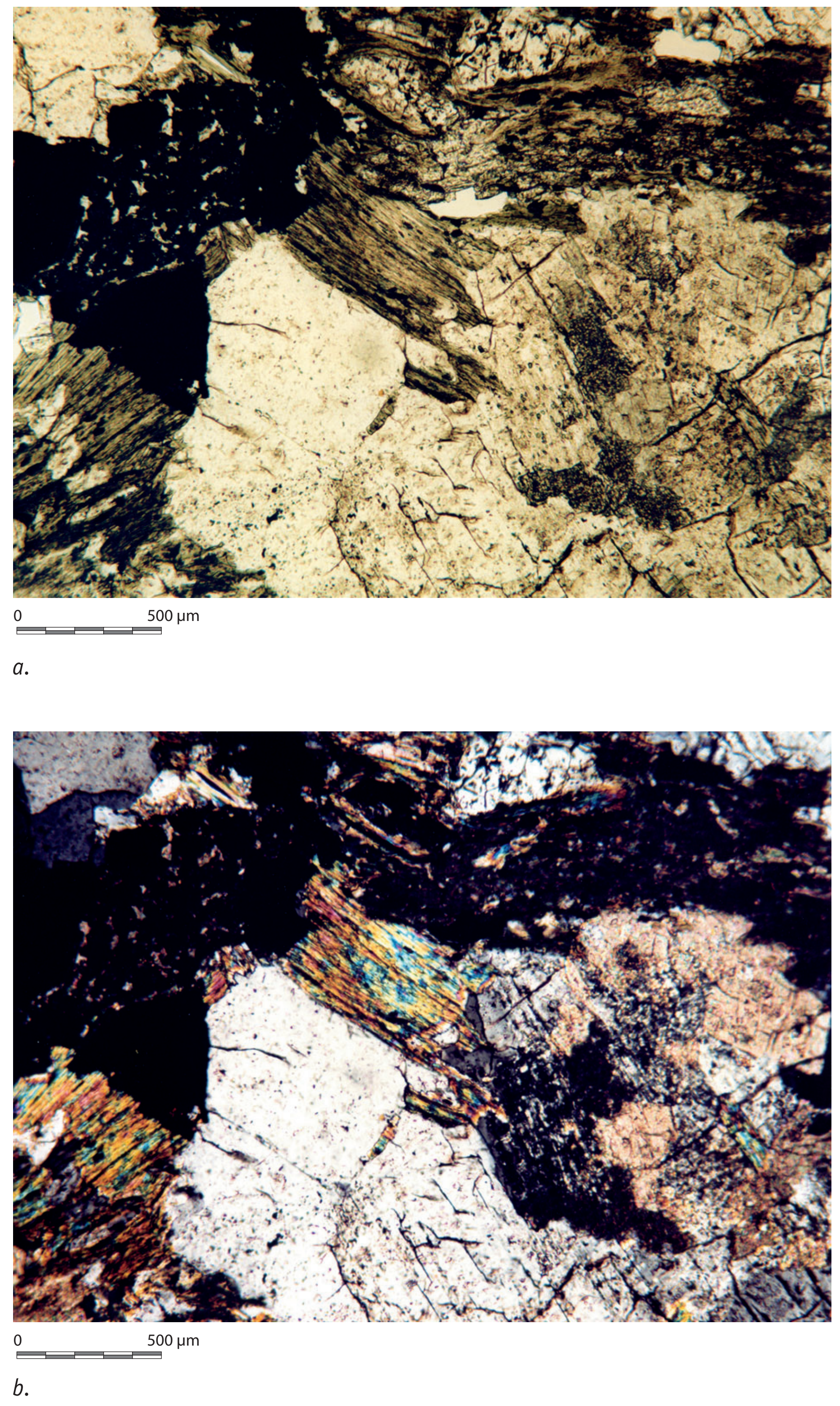

Figure 4.5 Borehole A17-1, Dutch offshore sector. Photomicrographs of altered biotite granite: (a) plane polarised light, (b) crossed polars. Copyright NERC (British Geological Survey). Photomicrographs of borehole core samples studied by Frost et al. (1981), kindly supplied by Dr R.T.C. Frost (Conoco) and Dr J.A. Miller (University of Cambridge). See Figure 4.2 for location of borehole.

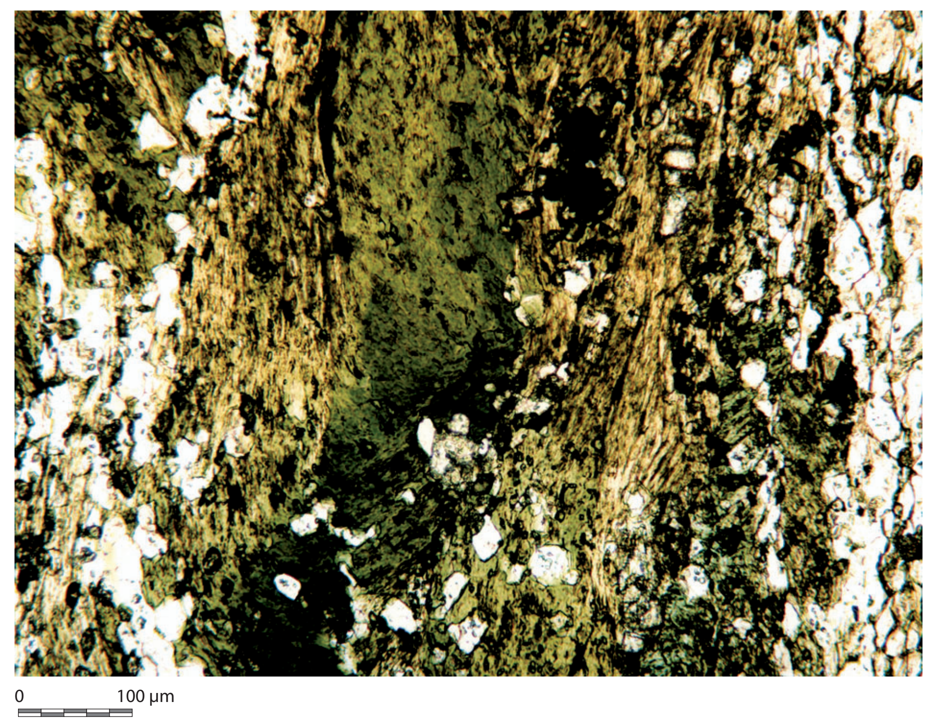

Figure 4.6 Borehole B4-1, German offshore sector. Photomicrograph of retrograded biotite-chlorite schist (plane polarised light). Copyright NERC (British Geological Survey). Photomicrograph of borehole core sample studied by Frost et al. (1981), kindly supplied by Dr R.T.C. Frost (Conoco) and Dr J.A. Miller (University of Cambridge). See Figure 4.2 for location of borehole.

To the east, a metamorphic zone extends from the Mid North Sea High to the Ringkøbing-Fyn High in southern Denmark. In the German sector of the North Sea, borehole B4-1 reached an amphibolite facies schist at a depth of 3077 m (**Figure 4.6**). It contains mainly albite, chlorite, biotite, epidote and hornblende, with minor quartz, pyrite and hematite; a mineralogical composition that is typical of a metabasic rock in transition between greenschist and amphibolite facies (Frost et al., 1981). The age of the metamorphism was determined by Frost et al. (1981) at 448±6 Ma.

Borehole Q1 in the German sector of the North Sea was drilled to a depth of 3804 m in a muscovite-biotite schist that is probably a high-grade augengneiss showing retrograde metamorphism in the greenschist facies (Frost et al., 1981). The absolute age of 415±8 Ma measured on muscovite with K-Ar is probably the age of greenschist-facies metamorphism.

Precambrian basement was reached in the area of the Ringkøbing-Fyn High in Denmark at Glamsbjerg (depth 834 m), Grinsted (depth 1567 m) and Jelling (1911 m). The rocks encountered include hornblende gneiss at Glamsbjerg and biotite gneiss at Grinsted, yielding K-Ar ages of 825±15 Ma and 880±15 Ma respectively; they show no retrograde metamorphism (Frost et al., 1981). Similar Sveconorwegian gneisses probably formed the protolith of the mylonites proved by boreholes P-1, Per-1 and Ugle-1 (**Figure 4.2**) in the footwall of the Central Graben. These cataclastic tectonites yielded an Ar-Ar age of about 435 Ma, interpreted as greenschist-facies retrogression (Frost et al., 1981), as well as a younger (Permian) thermal event. This zone of intense deformation is very likely to be part of the fabric of the Thor Suture.

2.4 The Danish-North German-Polish Caledonides

2.4.1 General geological setting

The remains of the Danish-North German-Polish Caledonides, an Early Paleozoic thrust-and-fold belt, are buried beneath Cenozoic to Devonian deposits at the south-west margin of the East European Craton (EEC). The thrust-and-fold belt developed during the collision of the Avalonian Microcraton with the Baltica Palaeocontinent in Early Paleozoic times and was subsequently thrusted onto the south-west margin of Baltica (Berthelsen, 1992a). The belt extends from the North Sea and Denmark in the north-west to the Holy Cross Mountains in south-east Poland; the Thor Suture represents its northern boundary. The area to the north of this suture represents the foreland of the Caledonian thrust belt with Neoproterozoic and Lower Paleozoic cover sequences of the EEC. The Lower Paleozoic foreland basin accompanying the Caledonian deformation developed from the Late Ordovician to the latest Silurian / earliest Devonian (Poprawa et al., 1999; Beier et al., 2000). The Anklam Fault (**Figure 4.2**) marks the southern extent of the geophysical signal of the conductive Alum Shale Formation (see below) deposited on the EEC (Hengesbach, 2006). It therefore represents the most likely location of the Thor Suture.

The mid-European Caledonian Orogen is recorded in about 50 boreholes (Katzung, 2001). Its extension to the south and south-west is not known precisely because of the overprint of the Variscan Orogeny and the following Permo-Silesian extensional phase, which caused the formation of the Central European Basin system. However, electrical conductivity data and Ar-Ar investigations of sediments from the borehole Loissin 1 (**Figure 4.7**) (Dallmeyer et al., 1999) indicate that the basement of the EEC, and accordingly the overthrusted orogenic belt, reaches at least to the Anklam Fault in north-east Germany (Hoffmann et al., 1998; Katzung, 2004). This has been confirmed by Hengesbach (2006) on the basis of a new interpretation of electrical conductivity of the Alum Shale Formation at depth (**Figure 4.2**). The Cambro-Ordovician Alum Shale Formation of the EEC, which dips gently from the foreland towards the Caledonian Deformation Front and farther south beneath the thrust-and-fold belt, mark the basal décollement upon which the orogenic wedge was thrusted onto Baltica (Hoffmann et al., 1998; Hengesbach, 2006). The Alum Shale Formation is found at a depth of about 7000 m beneath northern Rügen and at about 11 km depth close to the Anklam Fault.

2.4.2 Stratigraphy and lithology of the Caledonian Orogen

Caledonian deformed sedimentary rocks are known from boreholes in southern Denmark, northern Germany and the Koszalin-Chojnice Zone of north-west Poland (**Figure 4.2**).

2.4.2.1 The Rügen area

The boreholes on Rügen Island and the adjacent areas both offshore and onshore in north-east Germany penetrate Neoproterozoic and Ordovician successions that represent different depositional settings (Beier & Katzung, 2001). The successions were intensely disturbed due to the Caledonian thrust tectonics. There are no Cambrian and Silurian rocks south of the Thor Suture.

Neoproterozoic rocks were encountered in the deepest parts of boreholes Rügen 5 (Schwarbe Buntschiefer Formation) and Loissin 1 (Lubmin Sandstone Formation) at depths of 3850 m and 6876 m respectively (**Figure 4.7**). The rocks are variegated shales with intercalated sandstones in parts. The composition and

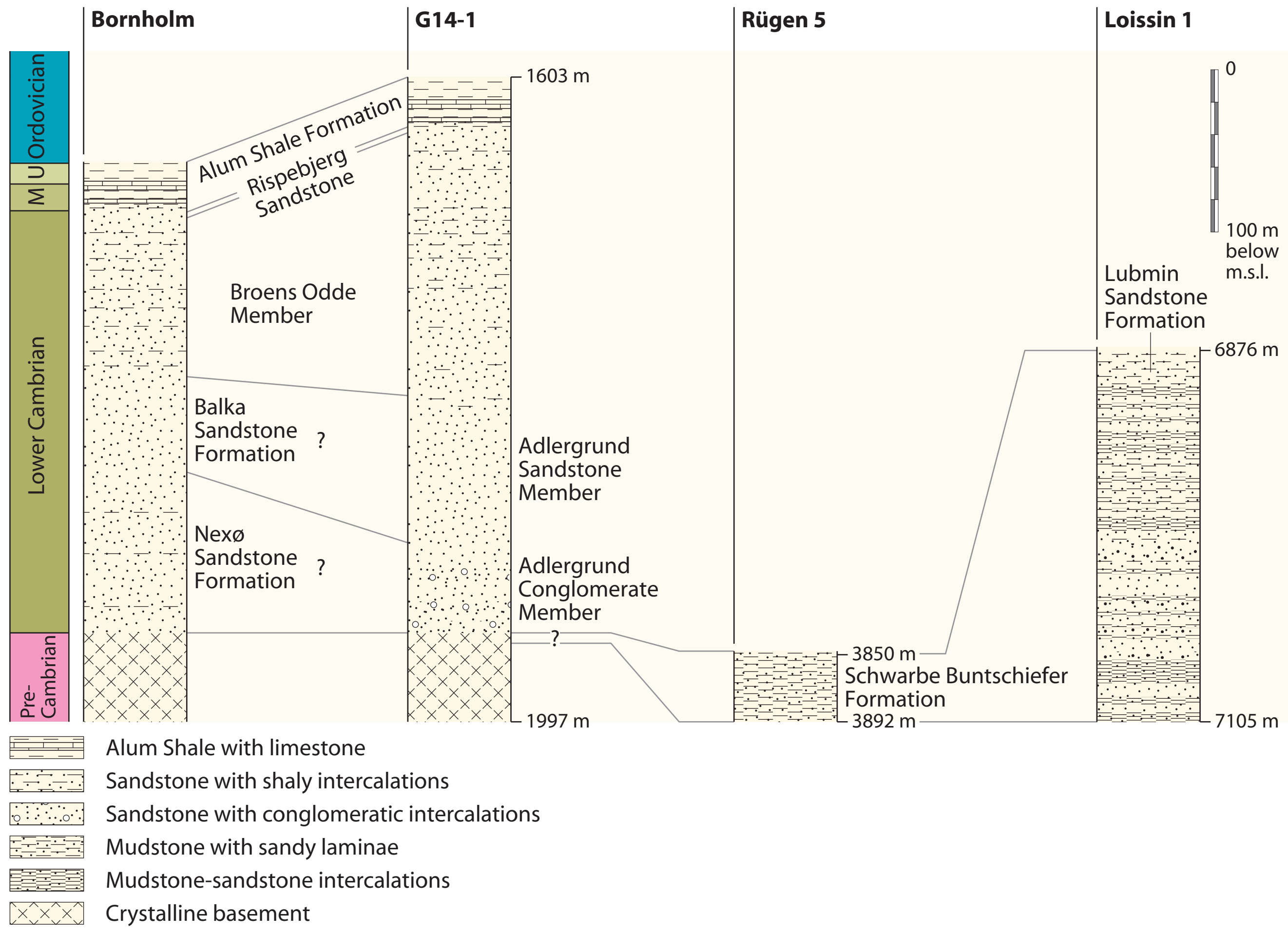

Figure 4.7 Lithostratigraphy of the Neoproterozoic and Cambrian successions in the Danish-North German Caledonides area at Bornholm and boreholes G14-1, Rügen 5 and Loissin 1. See Figure 4.2 for locations. After Feldrappe et al. (2005), modified, www.schweizerbart.de.

sedimentary features of the sandstone intercalations suggest deposition on the unstable shelf of a passive continental margin, which was probably affected by rifting processes (Giese et al., 1994). Rift volcanism is inferred from rare fragments of lapilli and ash-size particles within the variegated shales (Feldrappe et al., 2005). The U-Pb isotope pattern of zircons, Ar-Ar plateau ages of detrital muscovites, as well as fluid inclusions and cathodo-luminescence investigations, are evidence of a Baltic provenance for the detritus and therefore for deposition at the south-west margin of Baltica (Dallmeyer et al., 1999; Boose et al., 2001; Giese et al., 2001a; Giese & Köppen, 2001).

Ordovician rocks of the Caledonian Orogen found in deep boreholes on Rügen and the adjacent offshore area can be assigned to three formations: the Tremadocian Varnkevitz Sandstone Formation, the Llanvirn Arkona Black Shale Formation and the Llanvirn to Caradoc Nobbin Greywacke Formation. The fossil record of these formations and isotope investigations suggest deposition in the peri-Gondwanan Avalonian realm (Servais & Katzung, 1993; Maletz, 1998; Samuelsson, 1999; Dallmeyer et al., 1999). The Varnkevitz Sandstone Formation is more than 250 m thick and consists of interbedded fine-grained sandstones, siltstones and mudstones, which were deposited in a turbiditic environment. Sandstones dominate the lower sequence, whereas the upper part has thicker and more common siltstone and mudstone intercalations (Giese et al., 1994; Beier & Katzung, 2001). The Arkona Black Shale Formation is more than 1000 m thick and consists of dark grey to black mudstones and intercalated thin siltstone layers with very rare fine-grained greywackes and thin tuff horizons. Fine-graded bedding indicates deposition

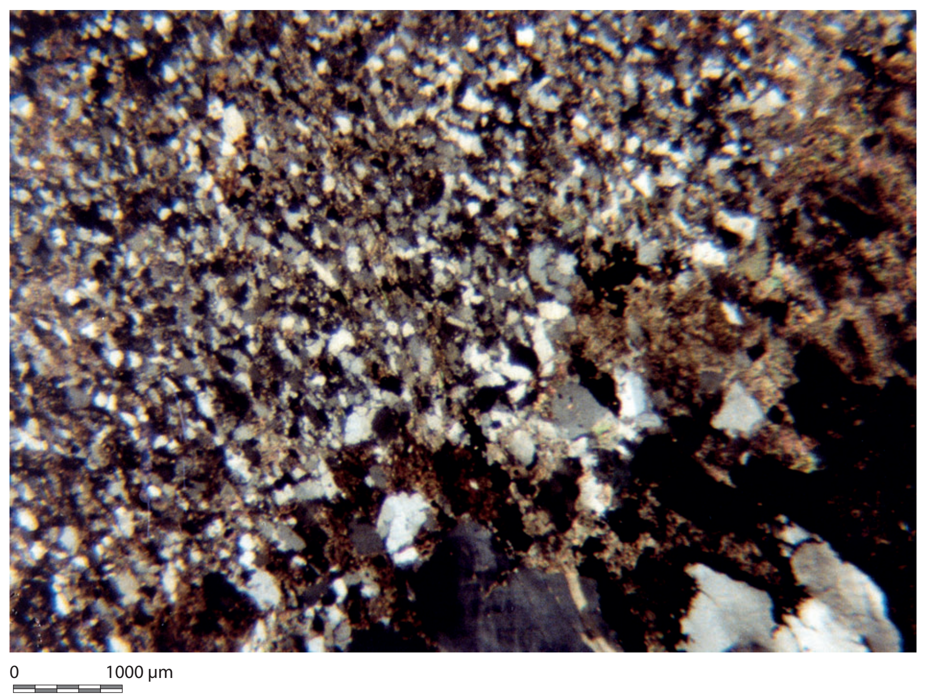

Figure 4.8 Borehole Flensburg Z1, northern onshore Germany. Photomicrograph of grey-green psammite (crossed polars). Copyright NERC (British Geological Survey). Photomicrograph of borehole core sample studied by Frost et al. (1981), kindly supplied by Dr R.T.C. Frost (Conoco) and Dr J.A. Miller (University of Cambridge). See Figure 4.2 for location of borehole.

as distal turbidites. The Nobbin Greywacke Formation is more than 2100 m thick and is composed of greywacke beds up to 6 m thick with siltstone and mudstone intercalations, and siltstone layers that can be more than 100 m thick. Based on their detrital composition, the greywackes are thought to be the debris of a complex continental arc, which were deposited in a deep-marine basin (Giese et al., 1994).

2.4.2.2 Danish-German border area

Deformed and weakly metamorphosed pre-Devonian sedimentary rocks are found on both sides of the Danish-German border in southern Jylland and northern Schleswig-Holstein (**Figure 4.2**). The German boreholes Westerland Z1 (3843.4 to 3945.5 m) and Flensburg Z1 (4926 to 5194 m; **Figure 4.8**) encountered alternating phyllitic slates and graded laminae of siltstone and sandstone (Schenck, 2001). These rocks have been folded and faulted and different cleavage generations have been observed. The deformation was associated with metamorphism of lowermost to lower greenschist facies. The age of the main metamorphism, based on Ar-Ar whole rock dating, is 453±2 Ma (Westerland Z1) and 482±5 Ma (Flensburg Z1) with later overprint by the folding and recrystallisation events at 419±15 Ma and 414±4 Ma respectively (Frost et al., 1981). Lithological similarities with the Loissin 1 sequence and the deepest part of the Rügen 5 succession point to a late Neoproterozoic age for the Flensburg Z1 succession (Beier & Katzung, 2001). Detrital micas of 922±13 Ma (Grenvillian) age in Flensburg Z1 (Frost et al., 1981) indicate a Baltic provenance, similar to the Loissin 1 succession (Katzung, 2001).

The Danish boreholes Åbenrå-1, Borg-1, Brøns-1, Kværs-1, Løgumkloster-1 and Varnæs-1 penetrated 8 to 51 m-thick successions of deformed pre-Devonian rocks that are discordantly overlain by Devonian, Rotliegend or Zechstein formations. The barren successions are fine-grained sandstones to sandy siltstones, quartzites, phyllitic rocks or graded greywackes alternating with shales (Katzung, 2001). At Løgumkloster, the rocks have graded bedding with Bouma sequences. The basement rocks encountered at Åbenrå-1 are more argillaceous; the phyllites found by borehole Varnæs-1 are lithologically comparable to the phyllites at Westerland Z1 and Flensburg Z1. These rocks were all affected by Caledonian deformation as shown by different generations of cleavages and foliations, and by slickensides and shear zones. A general stratigraphic assignment to the Ordovician is made only for the greywackes in boreholes Løgumkloster-1 and Borg-1, based on lithological similarities to those of the Nobbin Greywacke Formation in the Rügen area. Whole-rock Ar-Ar investigations show similar ages of a prograde metamorphism with 454±2 Ma (Løgumkloster-1) and 461±4 Ma (Varnæs-1) and possible overprinting ages of about 420 Ma (Borg-1) (Frost et al., 1981; Katzung, 2001).

2.4.2.3 The East European Platform and the Baltic Basin

The successions north of the Thor Suture show the stratigraphic development on the south-west margin of the East European Platform. The Mesoproterozoic crystalline basement is discordantly overlain by Neoproterozoic and Lower Paleozoic sedimentary successions, which are known from outcrops on Bornholm and Scania, and from several boreholes in Denmark, Sweden, northern Germany and Poland. The successions always have a threefold subdivision: basal sandstones and siltstones of the Lower Cambrian with a thickness of about 300 m, followed by about 30 m-thick Middle Cambrian to Arenig black shales and alum shales with calcareous intercalations, overlain by several hundred to thousand metre-thick Caradoc to Pridoli shales.

On Bornholm, the oldest Neoproterozoic/Paleozoic succession is the fluviatile-aeolian Nexø Sandstone Formation, consisting of more than 100 m-thick feldspar-bearing sandstones and thin siltstone layers (**Figure 4.7**) (Clemmensen & Dam, 1993). The Nexø Sandstone Formation passes into the 60 m-thick shallow-marine Balka Sandstone Formation, a quartz arenite with siltstone layers, which is overlain by the Broens Odde Member, about 100 m-thick glauconite-rich siltstones and sandstones of subtidal facies. The 3 m-thick carbonaceous Rispebjerg Sandstone completes the Lower Cambrian sedimentary cycle on Bornholm. Borehole G14-1 between Rügen and Bornholm encountered Mesoproterozoic crystalline basement between depths of 1942 m and 1997 m (Tschernoster, 2001). The microcline-rich biotite granite (Obst et al., 2004) is discordantly overlain by a Lower Cambrian succession similar to that of Bornholm, starting with the 55 m-thick Adlergrund Conglomerate Member, followed by the ~90 m-thick Adlergrund Sandstone Member, which is in turn overlain by the Broens Odde Member (170 m), an alternation of fine-grained quartzitic sandstones, siltstones and mudstones; the top of the succession is the 1 m-thick Rispebjerg Sandstone (**Figure 4.7**).

From Mid-Cambrian to Tremadocian times, fine-grained clastic sediments were deposited on the south-west margin of Baltica. These constitute the Scandinavian Alum Shale Formation, a black shale with pyrite, phosphate and intercalated limestone beds commonly containing anthraconite concretions. In Pomerania (north-west Poland) the sequence is known as the Piaśnicy Shale Formation. The Alum Shale Formation is followed by the Bjørkåsholmen Formation, a thin limestone found only locally in Scania and in borehole G14-1, overlain by the Toyen Shale and Sluchowo Shale formations (Pomerania). Above these lie the Arenig Komstad Limestone and Kopalino Limestone formations, and Llanvirn to Caradoc black shales known as the *Dicellograptus* Shale. In Pomerania, alternating mudstone and claystone in this interval is called the Sasino Shale Formation (Podhalańska & Modliński, 2006). There are several gaps in the succession, especially between the Komstad Limestone Formation and the shale formations below and above (**Figure 4.9**).

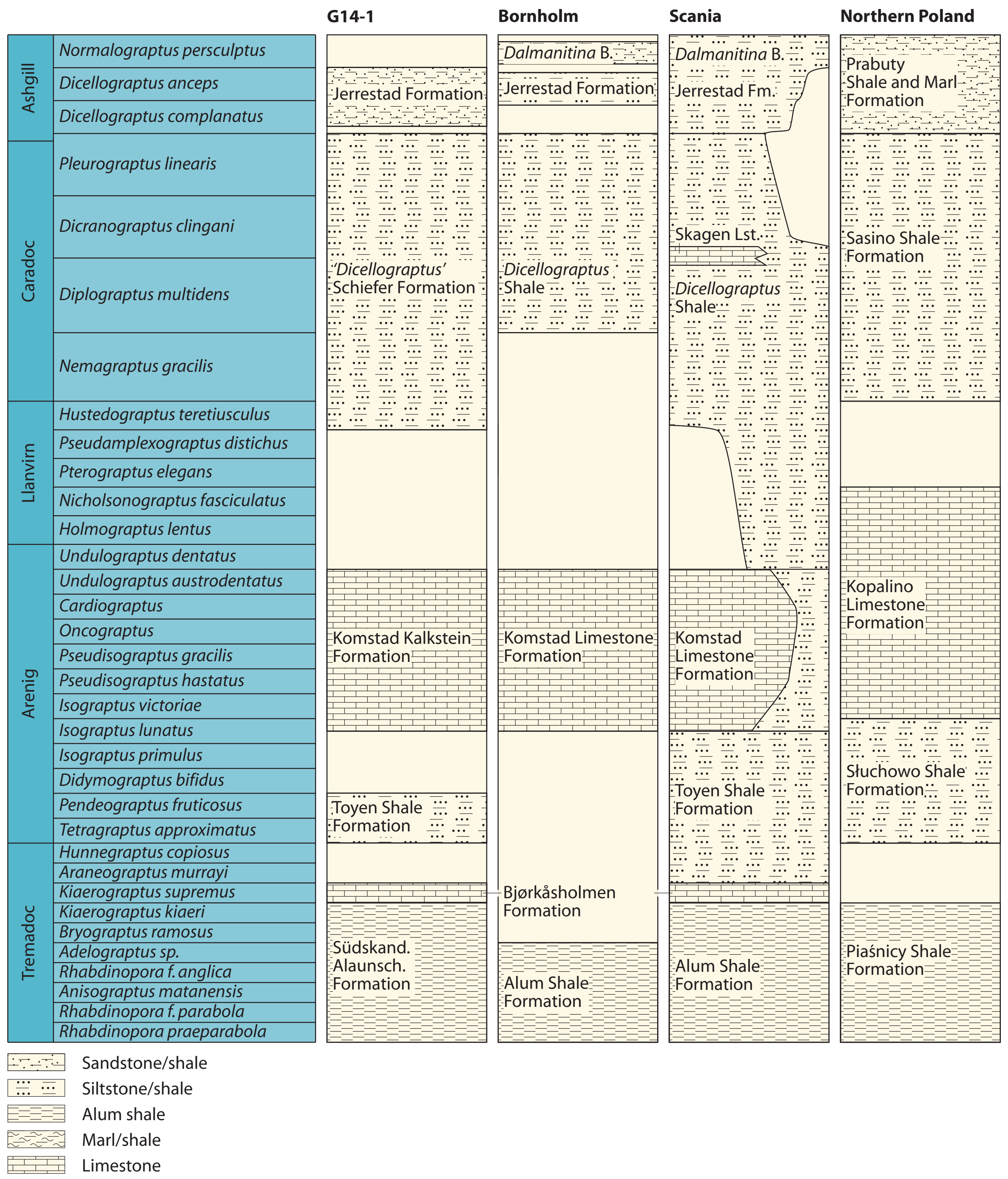

Figure 4.9 Lithostratigraphic comparison and biozones of the Ordovician successions of borehole G14-1, Bornholm, Scania and northern Poland, modified after Beier et al. (2000). Stratigraphy after Modlinski & Szymanski (1997), Bergström et al. (1982), Gravesen & Bjerreskov (1984), Lindholm (1985), Franke et al. (1994), Vejbæk et al. (1994), Maletz (1997), Samuelsson et al. (2001), Stouge (2001). See Figure 4.2 for locations.

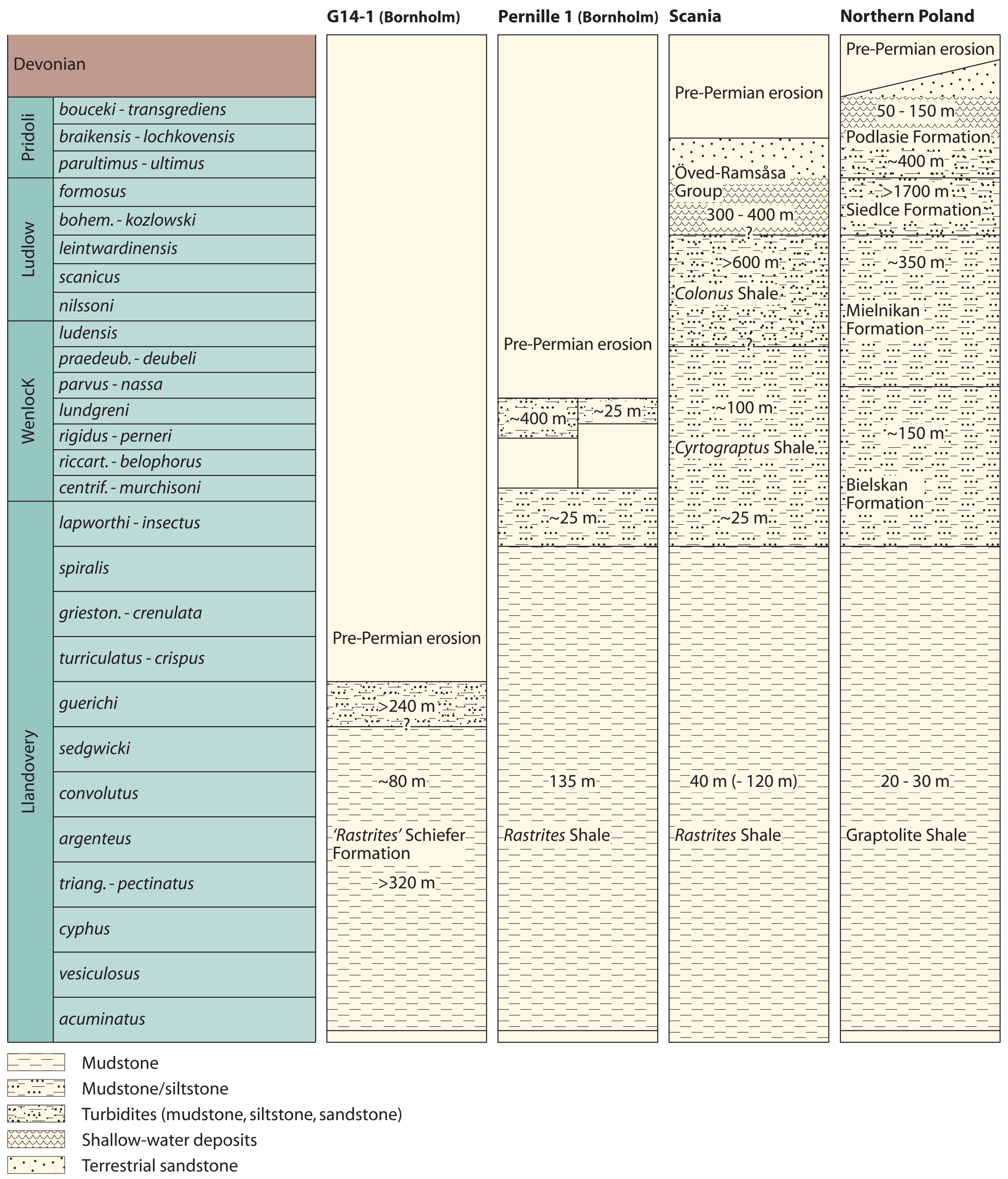

Figure 4.10 Lithostratigraphic comparison and biozones of the Silurian successions of boreholes G14-1 and Pernille 1 (Bornholm), Scania and northern Poland, modified after Beier et al. (2000). Stratigraphy and thicknesses after Tomczyk (1968), Tomczykowa & Tomczyk (1979), Gravesen & Bjerreskov (1984), Lindholm (1985), Franke et al. (1994), Vejbæk et al. (1994), Lindh & Bergman (1995), Maletz (1997), Beier & Katzung (2001). See Figure 4.2 for locations.

The Ordovician succession ends with the shales and marlstones of the Ashgill Jerrestad Formation and the Prabuty Shale and Marl Formation; thin sandstone beds are intercalated in borehole G14-1.

The oldest Silurian rocks are the Llandovery *Rastrites* Shales, known as the Graptolite Shale in north-west Poland (**Figure 4.10**). The shales are overlain by the more silty *Cyrtograptus* Shale and the Wenlock to Ludlow *Colonus* Shale and their stratigraphic equivalents, the Bielskan and Mielnikan formations of Pomerania. The Silurian succession ends with the shallow-marine and terrigenous sedimentary rocks of the Ludlow/Pridoli Öved-Ramsåsa Group in Scania and their slightly younger equivalents, the Siedlce and Podlasie formations of Pomerania (Jeppson & Laufeld, 1986; Modliński et al., 1994). A remarkable feature of the development of Silurian deposition at the south-west margin of Baltica is the thick turbiditic sequences in stratigraphically successive formations from the south-west to north-east. The G14-1 borehole proved turbidites more than 240 m-thick that were deposited in a very short time interval during the late Llandovery (Maletz, 1997). Turbidites with intercalated tuff horizons are found on Bornholm (Obst et al., 2002) and in Wenlock rocks from the Pernille 1 borehole. They are also found in Scania in the Ludlow *Colonus* Shale and in the upper Ludlow Siedlce Formation of Pomerania (**Figure 4.10**). This suggests that the depocentre of the foreland basin was migrating in front of the north-eastward moving orogen (Beier et al., 2000).

Subsidence curves show a typical pattern from Mid-Cambrian to Mid-Ordovician times, representing post-rift subsidence of the newly formed passive continental margin of Baltica (Nawrocki & Poprawa, 2006). The subsidence rate increases later from Late Ordovician to late Silurian times, especially during the Ludlow and Pridoli, with the subsidence curve showing a convex shape typical of foreland-basin development. Folding and uplift of the Caledonides in the south caused tectonic loading of the foreland and resultant rapid sedimentation in the foreland basin (Vejbæk et al., 1994; Nawrocki & Poprawa, 2006). **Figure 4.11** shows two profiles through Lower Paleozoic rocks in the southern Baltic Sea: (A) a west–east profile from south of Bornholm to the Lithuanian coast, and (B) a north-west–south-east profile from Sweden to Kaliningrad. The profiles show that Cambrian and Ordovician sedimentary successions are moderately thick throughout the Baltic area. However, the Silurian sediments of the Caledonian foredeep are very well developed, with increasing thickness towards the south-west of the foredeep basin, especially in the syntectonic Rønne Graben.

In Denmark, north of the Ringkøbing-Fyn High, Silurian strata were reached in four boreholes at Nøvling, Rønde, Terne and Slagelse (**Figure 4.2**), in which the sedimentary rocks are undeformed and unmetamorphosed. This area is the western prolongation of the Early Paleozoic Baltic Basin; only Slagelse and Terne lie within the SPB area. Silurian rocks were reached at a depth of 2594 m, and are unconformably overlain by Permian (Rotliegend) sediments. At Pernille, Silurian strata were encountered at 3212 m, and in Stina at 2075 m; Silurian rocks were reached at 1198 m in the G14 well.

2.4.2.4 The Koszalin-Chojnice Zone and East European Platform area of Pomerania, north-west Poland

The oldest rocks documented in the Koszalin-Chojnice Zone are Ordovician strata of Llanvirn and Caradoc age, which represent four graptolite biozones from the *teretiusculus* to the *clingani* biozone (**Figure 4.9**) (Podhalańska & Modliński, 2006). As found in Rügen, the rocks in boreholes at depths between 2000 and 6000 m have steep and variable stratal dip and other deformational structures. They consist of fine-grained, mainly hemipelagic siliciclastics, with poorly laminated mudstones and claystones that gradually increase in silt and sand content upwards in the Caradoc succession. There are local carbonates, mostly dolomites and siderites. The Pomeranian basin was probably very distant from the source area of the detrital material. The great thickness of sediments is due to a high subsidence rate compensated by a high sedimentation rate; ichnofossils point to a deep-marine facies.

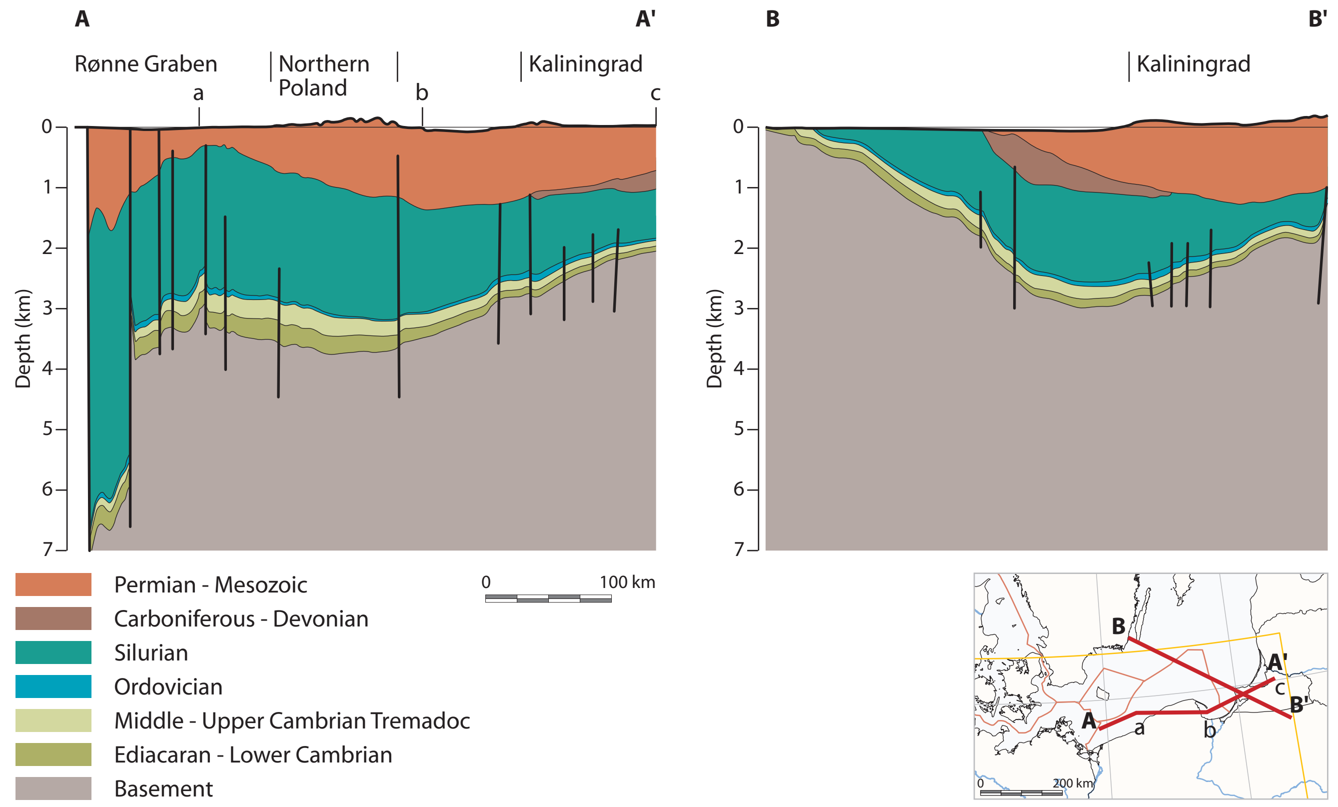

Figure 4.11 Profiles across the Baltic Basin showing the thickness of Ediacaran and Paleozoic deposits. Note the thick Silurian basin. Hydrocarbons are present in the Upper Cambrian to Tremadocian strata. Modified after Vejbæk et al. (2000), with reference to Bednarczyk (1968), Tomczyk (1976), Floden (1980), Ulmishek (1990), Grigelis (1991), Vejbæk et al. (1994), Vejbæk & Britze (1995), Schlüter et al. (1997), Vejbæk (1997), Zaivecs et al. (1997) and Brangulis & Seredenko (1998).

To the north-east of the Koszalin-Chojnice Zone, an almost complete Ordovician succession has been documented from the East European Platform in boreholes at Kościerzyna, Żarnowiec, Smołdzino, and offshore in boreholes B16 and A8 (**Figure 4.2**) (Podhalańska & Modliński, 2006). The sediments here were deposited in a predominantly shelf environment and are much thinner than in the Koszalin-Chojnice Zone. The main lithology is claystone, starting with the Piaśnicy Shale Formation (Tremadocian), overlain by the Słuchowo Shale Formation, the Kopalino Limestone Formation (Arenig to Llanvirn) and the Sasino Shale Formation (Caradoc) (**Figure 4.9**). Mudstone and marl intercalations are common in the Ashgill Prabuty Shale and Marl Formation. The sediments contain more graptolites than in the Koszalin-Chojnice Zone due to the neritic facies. The middle Caradoc succession has intercalated pyroclastic beds of acidic affinity, both in the East European Platform and the Koszalin-Chojnice Zone. No correlation has been made between each borehole, but a common source area is tentatively placed to the west (Podhalańska & Modliński, 2006).

2.4.3 Basement of north-east Germany and Denmark

Several very deep boreholes provide important information about the composition of the deep-crystalline basement of northern Germany. Permian basalts with xenoliths of anorthosite, gabbro and ilmenite ore are found between depths of 7262.5 m and 7343 m in the Schwerin 1/87 borehole (**Figure 4.2**) (Kämpf et al., 1994; Kämpf, 2001). The xenoliths most probably represent an anorthosite massif in the deeper crust, which might be part of the so-called East Elbian Massif that has been defined by gravity and magnetic highs (Conrad, 1996; Katzung, 2004). Precambrian anorthosite massifs with a comparable xenolith association are known from southern Norway and north-east Poland (Kämpf, 2001).

Zircons in Permian basalts from boreholes at Friedland 1/71 (5815 m depth), Penkun 1/71 (~4700 m and 5940 m), Fehmarn Z1 (4925 m), Dageförde Z1a (4875 m), Salzwedel 2/64 (4170 m) and Tuchen 1/74 (4320 m) indicate Neoproterozoic to Neoarchean rocks in the deeper crust (Breitkreuz & Kennedy, 1999; Breitkreuz et al., 2007) (**Figure 4.2**).

2.4.4 Baltica-Avalonia collision

The Baltica – far-Eastern Avalonia collision in the Early Paleozoic gave rise to an orogen that has been variously called the North German-Polish Caledonides (Ziegler, 2002a), the English-North German-Polish Caledonides (Berthelsen, 1992a), the Pomeranian Caledonides (Dadlez, 2000), the Danish-North German-Polish Caledonides (Katzung, 2001) and, by the same author, the Schleswig Caledonides, Rügen Caledonides, Pomeranian Caledonides and the Caledonian orogenic belt of northern central Europe, and the Helgoland-Pomerania Deformation Belt (Winchester et al., 2002). This orogeny is called the Scandian Phase in Scandinavia (McKerrow et al., 2000), including Scania (southern Sweden) within the SPB area.

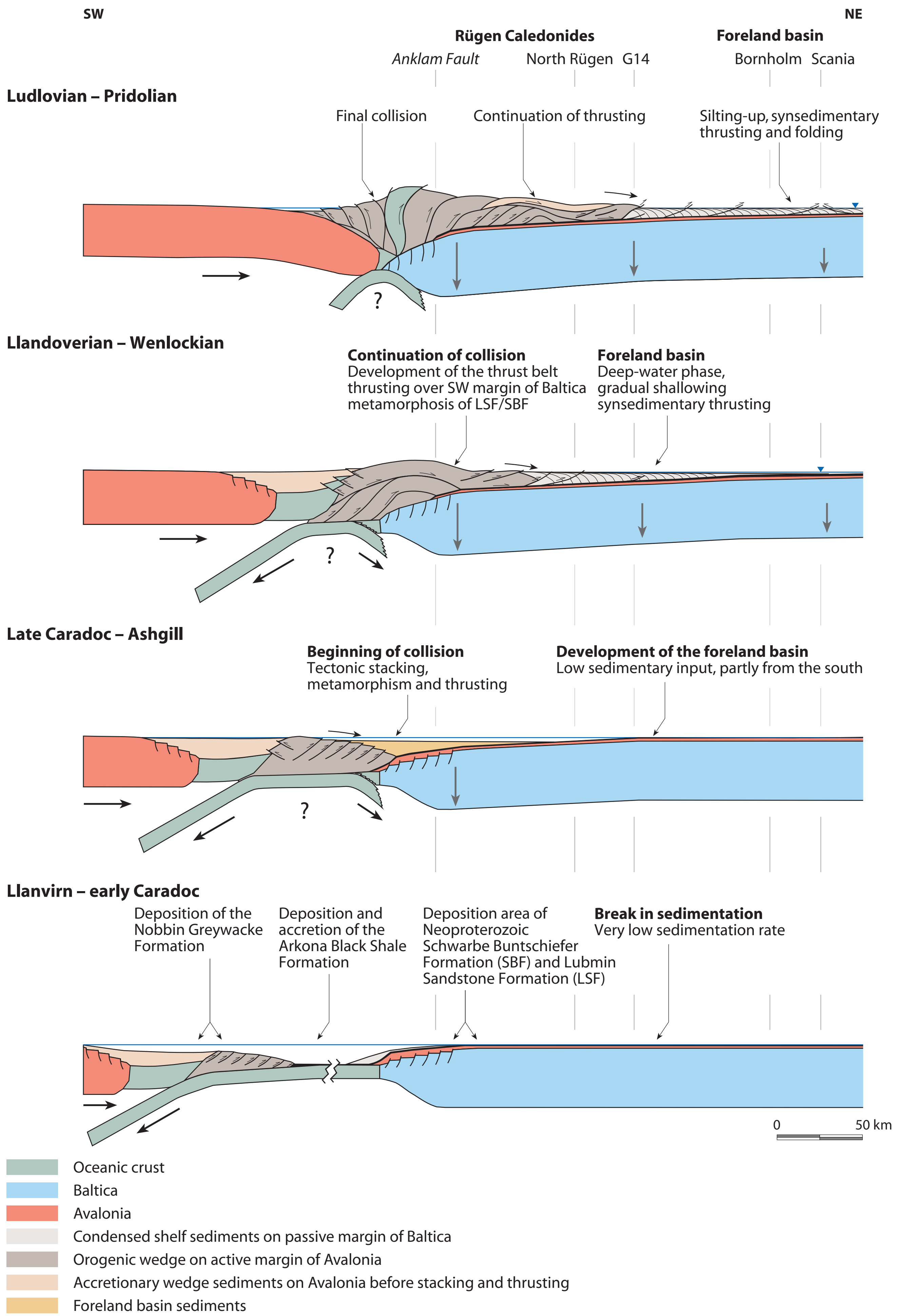

Figure 4.12 Schematic cross-sections showing the collision of Avalonia and Baltica: the tectonic evolution of the Rügen Caledonides and their northern foreland during the Ordovician and Silurian. The scale refers only to horizontal distances. The thickness of the sediments and of the orogenic wedge are exaggerated. Modified after Beier (2001).

The development of these Danish-North German-Polish Caledonides and the foreland basin situated to the north is depicted in a series of cross-sections based on geological data from north-east Germany across the southern Baltic Sea to Bornholm and Scania (**Figure 4.12**).

Avalonia separated from the Gondwana Palaeocontinent during the Early Ordovician (Prigmore et al., 1997; Cocks, 2002). At that time, the south-west margin of Baltica was situated between 40° and 50°S and was separated by the Tornquist Ocean from Avalonia, which was in a position closer to the South Pole (Torsvik et al., 1996; Cocks & Torsvik, 2005). The two continents subsequently drifted northwards during Mid-Ordovician times. Evidence of the subduction of oceanic crust of the Iapetus/Tornquist ocean beneath Avalonia is shown by the Middle to Upper Ordovician calc-alkaline volcanic rocks found in England and Belgium (Pharaoh, 1999). During Llanvirn to early Caradoc times, the sediments of the Arkona Black Shale and Nobbin Greywacke formations (see Section 2.4.2.1) were deposited on the apron of the active margin of Avalonia; sedimentary structures suggest that they were deformed shortly after their deposition, probably in an accretionary wedge (Beier & Katzung, 2001). At the same time, condensed shelf-sediment formations with prevalent stratigraphic gaps were accumulating at the passive margin of Baltica (**Figure 4.12**). The timing of the Avalonia-Baltica plate convergence is constrained by palaeogeographic and stratigraphic data from chitinozoan assemblages (Samuelsson et al., 2002). In the Rügen area south of the Thor Suture, the youngest preserved sediments in the deformed Ordovician are of mid-Caradoc to Ashgill age. Reworked acritarchs of Llanvirn age and Avalonian affinity in the Ashgill successions of Baltica (G14 borehole) show that erosion of the Caledonides collision zone had started before Ashgill times. Chitinozoans from lower Caradoc sediments in the Skibno borehole in Pomerania (**Figure 4.2**) have an Avalonian affinity, evidence that the Koszalin-Chojnice Zone was part of the Avalonian Microplate before the collision.

The collision between Baltica and Avalonia probably started during late Caradoc to early Ashgill times (**Figure 4.12**) based on evidence from palynomorph studies in borehole G14-1, which show low sedimentary input derived from Avalonia during earliest Ashgill time (Samuelsson et al., 2001). The continuing convergence of Avalonia and Baltica caused tectonic stacking and metamorphism of the sediments in the accretionary wedge in the apron of Avalonia and subsequent thrusting onto the south-west margin of Baltica. The collision of the palaeocontinents, and the incipient thrusting, caused the development of a foreland basin at the south-west margin of Baltica. Evidence for this is provided by the thick sequence of Upper Ordovician to Silurian rocks found in boreholes and outcrops at the south-west margin of the East European Platform (Beier et al., 2000; Beier, 2001). Subsidence increased from Caradoc times (Poprawa et al., 1999) and the proximal parts of the basin are now deeply buried beneath the orogen. Deposits from the distal parts of the basin are typically dark-coloured mudstones with carbonaceous intercalations from the Caradoc succession, and of alternating carbonaceous sandstones, marls and muddy siltstones (Lindholm, 1985; Franke et al., 1994; Beier & Katzung, 1999).

Figure 4.13 Photograph of an overturned fold in the upper Alum Shale Formation of Bornholm, Denmark. Outcrop in the embankment at the river Læså, about 500 m north of Våsegard (courtesy of H. Feldrappe).

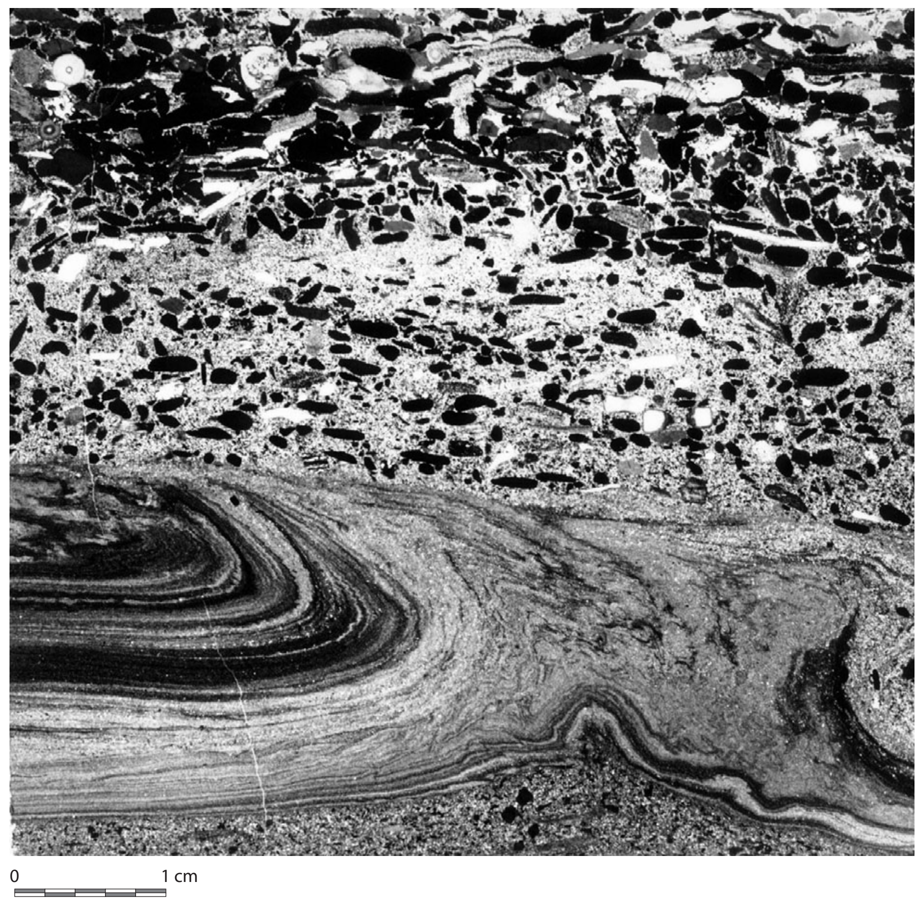

Figure 4.14 Borehole G14-1, 1310.2 m depth. Photomicrograph of Silurian Rastrites *shale with a microconglomerate layer over a laminated mudstone. The microconglomerate contains well-rounded prolate mudstone clasts, delivered from the orogen, and fossil detritus. The slumping structures in the mudstone layer indicate the unstable depositional regime in the foreland of the orogen during the Silurian (courtesy of H. Feldrappe).*

Continued continental convergence during Silurian times led to the complete closure of the Tornquist Ocean. The development of a thrust-and-fold belt and its successive movement over the south-west margin of Baltica can be deduced from evidence of further subsidence (Poprawa et al., 1999), synsedimentary compressive tectonics in the foreland (Beier et al., 2000), thrusts and faults in the underlying successions (e.g. Alum Shale Formation in Bornholm, **Figure 4.13**), and from the age of low-grade metamorphism of the Lubmin Sandstone Formation in borehole Loissin 1 (427 Ma – Dallmeyer et al., 1999). The Neoproterozoic formations of boreholes Rügen 5 and Loissin 1 were overridden, metamorphosed and subsequently incorporated into the thrust belt and transported to the north (Beier, 2001). The foreland of the thrust belt was affected by major subsidence during Llandovery and Wenlock times (**Figure 4.12**). A deep-water basin developed, where dark-coloured mudstones of the *Rastrites* Shale and the *Cyrtograptus* Shale were deposited (**Figure 4.10**). The composition of the sediments, tuff layers and enrichment of chromite grains (Böhnke & Katzung, 2001) imply that sedimentary input was mainly from the approaching orogen to the south (**Figure 4.14**, *Rastrites* Shale). This phase of basin development can be correlated with the deep-water phase of a foreland basin (Beier, 2001). Depending on the distance to the orogenic wedge, the deep-water phase lasted until latest Llandovery (at borehole G14-1) and late Wenlock (at Bornholm) times. In the northern Polish area, the deep-water phase probably continued during Ludlow times (Jaworowski, 1971; Dadlez, 1978; Modliński et al., 1994).

Further growth of the orogen can only be reconstructed from evidence of the development of the northern and eastern foreland. Late Silurian compressive tectonics (Lindström, 1960) suggest continuing collision and ongoing thrusting of the orogenic belt. Thick sedimentary successions in the foreland (**Figure 4.11**) imply that the orogen was uplifted above sea level and that the subsequent intensive erosion led to high rates of sediment supply (**Figure 4.12**).

The sedimentation regime in the foreland changed during mid- to late Silurian times as there was a transition from deep- to shallow-water sedimentation. The continuing obduction of the orogenic belt over the south-west margin of Baltica caused a south-west–north-east-prograding basin fill with an enormous amount of sediments shed into the basin in a fairly short time (**Figure 4.11**). The sedimentation rate exceeded the subsidence rate, which in time caused the basin to shallow. The maximum thickness of the sediments, the depocentre of the basin, gradually migrated from the south-west to the north-east (**Figure 4.9**) (Beier et al., 2000). The final fill of the foreland basin began in latest Ludlow times. The Öved-Ramsåsa Group, a succession of shallow-marine sediments and overlying terrestrial deposits, is exposed in Scania and is found in the Nøvling 1 borehole in Denmark (Jeppson & Laufeld, 1986; Christensen, 1971). The shallow-water phase started later in the east, where high sedimentation rates are documented for the Ludlow and Pridoli successions of Poland (Tomczyk, 1968; Tomczykowa & Tomczyk, 1979; Nehring-Lehfeld, 1988; Modliński et al., 1999). The major subsidence during the Ludlow had reduced significantly by Pridoli times (Modliński et al., 1999; Poprawa et al., 1999); evidence of the first shallow-water deposits is found in latest Pridoli sediments from northern Poland.

The convergence of Avalonia and Baltica ceased during the Early Devonian. A last compressive phase caused synsedimentary thrusts in the Lochkovian sediments of Lithuania (Poprawa et al., 1999). The orogen experienced gravitational collapse and horizontal spreading of the nappe pile. The numerous small- to medium-scale extensional structures, which are typical of the successions seen in the Rügen boreholes (Beier & Katzung, 2001), might be attributed to this late event. The foreland of the orogen was also affected by Early Devonian uplift and erosion (Vejbæk et al., 1994). Sedimentation continued until the end of the Lochkovian only in the easternmost part of the basin. Lochkovian terrigenous deposits found both onshore and offshore of Lithuania and Latvia mark the final sediment fill of the foreland basin (Modliński et al., 1999; Poprawa et al., 1999).

2.5 The Lublin-Podlasie Basin

The Baltic Basin is delimited in the south-east by the Mazury-Belarus High, where the crystalline basement of the East European Craton is overlain by Mesozoic and younger sedimentary rocks only (**Figure 4.15**). South of the Mazury-Belarus High is the Lublin-Podlasie Basin with Proterozoic and Paleozoic sediments that thicken south-westwards (Poprawa & Pacześna, 2002; Nawrocki & Poprawa, 2006). The basin was situated on the passive margin of Baltica during Early Paleozoic times. There is an almost continuous Neoproterozoic to Silurian sedimentary sequence with an erosional gap only in the Middle and Upper Cambrian succession, probably related to the soft collision of the Małopolska Block. During Early Cambrian to Ordovician times, sedimentation took place in a passive continental margin setting similar to the Baltic Basin; subsidence rates decreased with time, reflecting progressive cooling and contraction of the lithosphere (Nawrocki & Poprawa, 2006).

2.6 The Łysogóry Unit and the Małopolska Massif

There are two structural units with outcrops of Lower Paleozoic rocks in the Holy Cross Mountains of south-eastern Poland. The northern Łysogóry Unit is separated from the southern Małopolska Massif by the Holy Cross Fault. Recent discussions of the Holy Cross Mountains can be found in Bełka (2000), Bełka et al. (2000, 2002), Cocks (2002) and Nawrocki & Poprawa (2006).

The oldest rocks of the Łysogóry Unit are Middle Cambrian to Tremadocian clastics, which were deposited in a shallow-water shelf environment. The sequence is up to 1800 m thick and the basal sediments are quartzitic sandstones with thin siltstone and claystone intercalations of the Wiśniówka Sandstone Formation; trace fossils are very abundant. Most of the Ordovician and Silurian sedimentary rocks are deep-water graptolite shales, although there are limestones in the Middle Ordovician succession. Coarser-grained clastics, partly greywackes with volcaniclastic interbeds, were deposited from late Silurian to Devonian times. Sedimentation was continuous from Cambrian to Carboniferous times and there are no angular unconformities in the Łysogóry Unit. The exact boundaries of the Łysogóry Unit are not known to the north and east, but from Mid-Ordovician times sedimentation was similar to that of the East European Platform. The crystalline basement of the Łysogóry Unit is also unknown, but geophysical data indicate that it must occur at depths between 6000 and 7000 m.

The Małopolska Massif is known from outcrops in the southern Holy Cross Mountains (the Kielce Unit), but also from numerous deep boreholes to the south and west. The crystalline basement is unknown. From Late Proterozoic (Ediacaran, formerly 'Vendian') to Mid-Cambrian times, thick coarse-grained clastic sediments were deposited in a probable forearc-trench system (Bełka et al., 2000); the rocks are weakly metamorphosed. The lithologies include shale, siltstone, greywacke, conglomerate, arkose, fragments of acid and basic magmatic rocks, and fragments of metamorphic rocks; sedimentation is partly turbiditic. The entire Proterozoic to Middle Cambrian succession is folded (Sandomierz Deformation Phase) and discordantly overlain by Lower Ordovician sediments. The rocks below the unconformity are older and more strongly metamorphosed towards the south-west, suggesting that the Małopolska Block was tilted and eroded before deposition of the Ordovician sediments. This unconformity is the main difference to the Łysogóry Unit, which has a continuous sedimentary sequence. A relatively thin transgressive sequence was deposited during the Ordovician, starting with marine sands followed by open-marine carbonates and graptolitic shale. Graptolitic shale was also deposited during Silurian times, with thicknesses increasing to the north-east. There was a deformation phase at the end of the Silurian and an unconformity separates the Lower Paleozoic from Lower Devonian sedimentary successions.

The plate-tectonic position of the Łysogóry Unit and the Małopolska Massif prior to the Ordovician is not clearly resolved. They could have been two separate terranes before their accretion to Baltica: sediment provenance and biogeographical affinity studies of Cambrian rocks seem to indicate that both are exotic terranes derived from the margin of Gondwana, but already situated close to Baltica during Cambrian times (Bełka et al., 2000; 2002). In this interpretation, it was only from the Ordovician onwards that they were influenced by Baltica. However, the Gondwanan provenance of both terranes is disputed on the basis of geochemical and palaeomagnetic data (Nawrocki & Poprawa, 2006) and the facies similarity with Cambrian rocks of the East European Platform (Jaworowski & Sikorska, 2006); in this scenario, the terranes were initially situated near the southern margin of Baltica, with sedimentation on a stable craton in a passive-margin setting. The Łysogóry Unit would correspond to the proximal part, and the Kielce Unit to the distal part, of the Cambrian passive margin (Jaworowski & Sikorska, 2006). Large strike-slip displacements would have brought the different units together. There is general agreement that, from Mid-Ordovician times, sedimentation in Małopolska and Łysogóry was very similar and of Baltica affinity. Palaeomagnetic data (Nawrocki, 1999) and the facies pattern of Silurian strata seem to indicate that final amalgamation between the two blocks took place during late Silurian times (Bełka et al., 2002).

2.7 The Brunovistulian Terrane

The Brunovistulian Terrane (**Figure 4.2**) (Bełka et al., 2002; Nawrocki & Poprawa, 2006) is separated from the Małopolska Massif by the Kraków Fault. In the west, the terrane is bordered by the Moldanubian and Saxo-Thüringian terranes and to the south it extends beneath the Carpathian Overthrust. The crystalline basement is formed by Cadomian (580 to 610 Ma) igneous rocks and deformed metamorphic rocks of Gondwana derivation (Dudek, 1995), and for this reason its exotic nature with respect to Baltica is generally well accepted. The basement is unconformably overlain by a thick sequence of undeformed Lower to Middle Cambrian clastic rocks with trace fossils and structures that indicate deposition in a shallow-shelf environment. Cambrian sedimentation is very similar to that of the Małopolska Massif, both in lithology (sandstone) and fauna. The fauna is of Baltica affinity, so the Brunovistulian Terrane probably migrated from a peri-Gondwana position to a peri-Baltica position before the Cambrian (see discussion in Nawrocki & Poprawa, 2006). There is a large stratigraphic gap with no clear unconformity between Cambrian and Devonian rocks, except for a wedge of marine Ordovician sediments (limestone and sandstone) in the north.

2.8 Rocks of Gondwana affinity in the Mid-German Crystalline High, Saxo-Thüringian Terrane and the Harz Mountains

The south-east German part of the SPB area, south of the Rheno-Hercynian Zone, is composed of several tectonic units (terranes) with a pre-Devonian basement. The Mid-German Crystalline High (MGCH) consists of Cadomian fragments (terranes) of Gondwana, relics of a Cambro-Ordovician rift, a Silurian island arc and Variscan intrusions. These structural units form a melange accreted to the edge of the Saxo-Thüringian Microplate due to Variscan collision (Bankwitz et al., 2001a, 2001b). The MGCH has a south-west–north-east orientation between the rivers Rhine and Elbe and continues eastwards in an east–west direction into the Odra Zone in Poland (**Figure 4.2**). The pre-Devonian rocks are buried beneath thick Upper Carboniferous to Triassic successions and are known mostly from boreholes and local outcrops, for example in the Kyffhäuser and Ruhla crystalline complexes (Thüringia). The MGCH is bordered by a several kilometre-wide zone of metamorphic rocks to the south, the Southern Phyllite Zone.

The Saxo-Thüringian Terrane (*sensu strictu*) is situated south of the MGCH and the Southern Phyllite Zone. It was part of a peri-Gondwana microcontinent and was deformed during the Variscan collisional processes. A comprehensive review of the central European Variscides is given by Franke (2000). The Cadomian basement is overlain by Neoproterozoic and Lower Paleozoic sedimentary complexes. All successions are more-or-less strongly folded, mostly cleaved, and in some regions strongly metamorphosed. Important regional units with outcropping Saxo-Thüringian rock complexes are the Thüringisch-Fränkisch-Vogtländisches Schiefergebirge, Schwarzburg Anticline, Erzgebirge, Granulitgebirge, Elbtalschiefergebirge, Nossen-Wilsdruffer Schiefergebirge, Meissen Massif and Lausitz Massif. The Sudetes in Poland include several metamorphic units belonging to the same Variscan Orogen with protoliths of Proterozoic or Early Paleozoic age (Franke & Żelaźniewicz, 2000; Mazur et al., 2006). To the south of the Saxo-Thüringian Terrane and the Sudetes are the Teplá-Barrandian and Moldanubian terranes, which were also accreted during the Variscan Orogeny (**Figure 4.2**) (see Franke, 2000).

The Harz Mountains are a southward-dipping horst structure that expose part of the Variscan basement of the Rheno-Hercynian Zone (Wachendorf et al., 1995). Apart from the Wippraer Zone in the south-east, most pre-Devonian rocks in the Harz Mountains are found in isolated outcrops as olistholites in Devonian and Carboniferous nappes and thrust slices. The oldest rocks are Middle Ordovician shales, quartzites and greywackes. The oldest part of the Silurian succession is Llandovery and Wenlock pelites with partly intercalated sandstone layers and greywackes overlain by Ludlow shales, marly shales and limestones. Alum shales of Pridoli age terminate the Silurian succession. The rocks were deposited in a peri-Gondwana basin and were later transported north-westwards over Rheno-Hercynian basement by Variscan nappe movement (Linnemann et al., 2004). The highly metamorphosed Ecker Gneiss in the north-west Harz Mountains, which was originally considered to be an exotic flake of Proterozoic age (Baumann et al., 1991), has been reinterpreted as an erosional relic of a tectonic nappe of Saxo-Thüringian affinity, with a protolith of Early Devonian age (Geißler et al., 2005).

3 Petroleum geology

The Baltic Basin is the only region of the SPB area where petroleum or gas has been found in pre-Devonian formations. Some exploration has taken place in the UK. No hydrocarbons are suspected elsewhere as the rocks are thermally too mature.

3.1 Hydrocarbon exploration in the western SPB

In England, there has been some exploration within Lower Paleozoic strata to the west of the SPB area (see Chapter 13). Tremadocian shales are very thick, but lean. Thinner Cambrian shales have higher total organic carbon (TOC) contents (Parnell, 1983). Conodont (Bergström, 1980; Aldridge, 1986) and graptolite reflectance data (Oliver, 1987) from an area near the Church Stretton Fault system, which forms the boundary between the Welsh Caledonides and the Midlands Microcraton, shows that the fold belt is overmature, although the shelf sediments lie within the hydrocarbon window. Within the SPB area, a similar relationship may exist with illite crystallinity values (Pharaoh et al., 1987) showing that most of the pre-Silurian rocks forming the Eastern Caledonides as far west as Charnwood are overmature. Generally, Cambrian and Tremadocian shales are also overmature, but in a maturity-depth plot the Silurian shales should theoretically lie within the hydrocarbon window (Smith & Rushton, 1993); however these are lacking in the subsurface. Although traces of migrated hydrocarbons were also found in Cambrian sandstones (Parnell, 1987), porosities and permeabilities are very low. Fractured reservoirs are probably the only realistic target. In the offshore area of the SPB, Lower Paleozoic rocks are overlain by thick Carboniferous successions and are overmature; maturities may be lower on the Mid North Sea High to the north. In the Belgian part of the SPB area, the Lower Paleozoic rocks are all overmature, and show deep anchizonal to greenschist metamorphism (Van Grootel et al., 1997; Debacker et al., 2005).

3.2 Hydrocarbon systems of the Baltic Basin

A system of genetically linked sedimentary basins developed on the western slope of the East European Platform during Proterozoic to Early Paleozoic times. The subsequent evolution of this area, particularly the Variscan differential uplift and erosion, caused a separation of the Baltic and Lublin-Podlasie basins by the Mazury-Belarus High (**Figure 4.15**). The thickness of Lower Paleozoic rocks increases westwards along the western margin of the East European Platform to the Trans-European Suture Zone. The tectonic structure of the Baltic Basin is relatively simple; uplift of the basin margins gave rise to a broad regional syncline referred to as the Baltic Syneclise. In contrast, the Lublin-Podlasie Basin consists of several tectonic blocks divided by fault zones, presumably of transpressional origin.

A similar facies development across the area of the Baltic Basin (**Figure 4.16**) led to general similarities in hydrocarbon-systems development. The main hydrocarbon play of the Baltic Basin involves Middle Cambrian sandstones as the reservoir, sealed by thick upper Silesian shales and charged from Upper Cambrian or Tremadocian organic-rich black shales (see Section 2.1.1 in Chapter 13).

The Middle Cambrian sandstones were deposited mainly as shallow-marine sand bars (Kanev et al., 1994; Jaworowski, 1997). These sandstones are the reservoirs for oil and gas in the Polish offshore, as well as for oil in the Russian Kaliningrad district, and in both onshore and offshore Lithuania (**Figure 4.17**). Although there are similar formations in the Lublin-Podlasie Basin, only gas and oil shows have been observed there, and no economic hydrocarbon accumulations have been discovered so far. The key parameter controlling porosity of the Middle Cambrian reservoir is porosity reduction by quartz cementation (Sikorska, 1998; Molenaar et al., 2007.), which increases with depth of burial.

In the north-eastern part of the Baltic Basin (Lithuania, Latvia, and Gotland Island in Sweden), additional reservoirs for small oilfields are the Ordovician and Silurian limestones, mainly carbonate buildups, developed in marginal zones of the basin (**Figure 4.17**) (Brangulis et al., 1992; Kanev at al., 1994). In Estonia, oil is extracted from Lower Paleozoic shale (the Tremadocian *Dictyonema* Shale) in open-pit mines.

The main source rocks for the hydrocarbons accumulated in the Cambrian reservoirs are the Upper Cambrian and/or Tremadocian black shales (**Figure 4.16**), which are the equivalents of the Alum Shale Formation (including the upper part of the Alum Shale and the *Dictyonema* Shale). The formation has a relatively limited thickness, generally decreasing eastwards (**Figure 4.18**) from a few tens of metres in the western Baltic Sea to a few metres in the Baltic Basin onshore Poland. This black-shale source rock is relatively rich in marine organic matter, with up to 12% TOC in the central part of the Baltic Basin (Kanev et al., 1994). The thermal maturity of the source rock decreases from west to east: it is in the gas window in the western Baltic Sea and in the oil window in Poland and Kaliningrad, whereas farther east and north the source rock is generally immature. There are no Upper Cambrian and/or Tremadocian source rocks in the Lublin-Podlasie Basin, where this time span is represented by a hiatus (**Figure 4.14**). Geochemical data classify the kerogen of this source rock as oil-prone type II (Kanev et al., 1994).

Another potential source rock is the Upper Ordovician (mainly Caradoc) and Silurian (mainly Llandovery and Wenlock) black graptolitic shale. This relatively homogeneous shale formation is found in both the Baltic and Lublin-Podlasie basins. Apart from being a source rock for conventional hydrocarbons, the

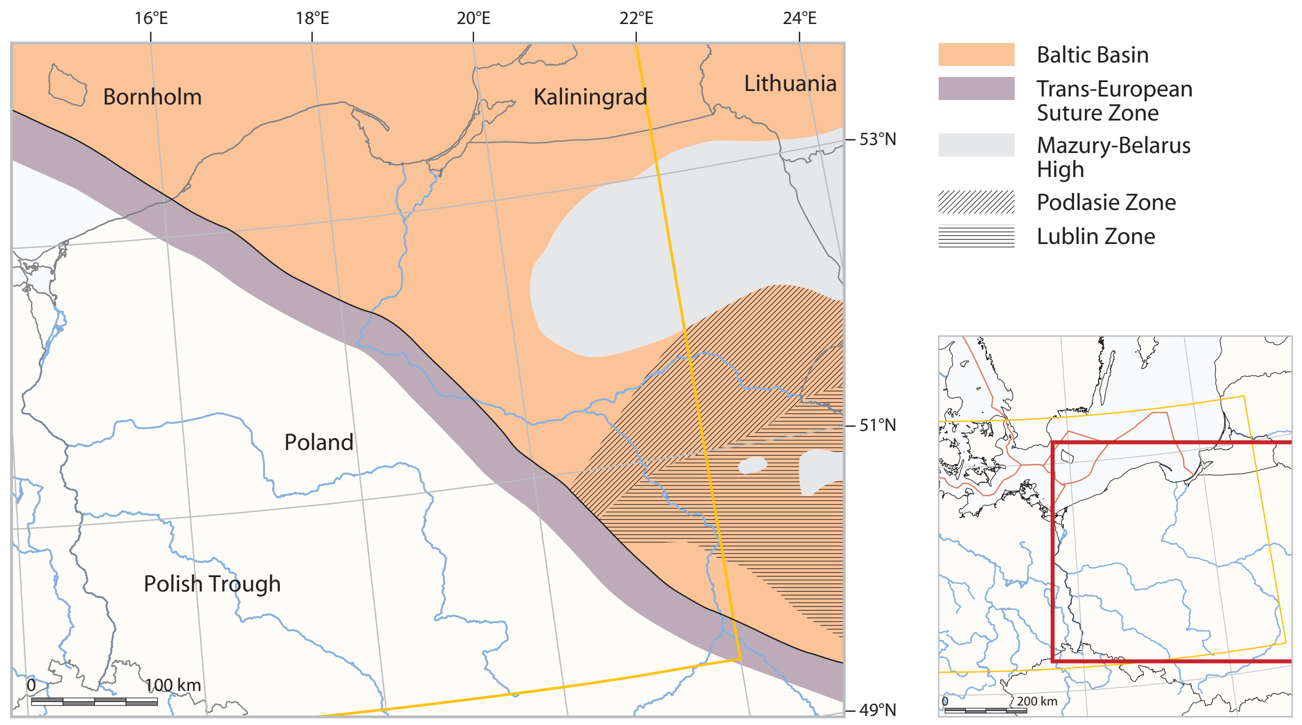

Figure 4.15 Proterozoic to Lower Paleozoic sub-basins and tectonic units on the western slope of the East European Craton (based on Pacześna & Poprawa, 2005).

Upper Ordovician to lower Silurian succession is also a potential target for shale gas. This source rock contains type II organic matter originating mainly from marine algae and zooclasts. Total organic carbon contents in the Upper Ordovician to lower Silurian source rocks vary across the Baltic and Lublin-Podlasie basins; however they are often in the range of a few per cent. Thermal maturity of the Upper Ordovician and lower Silurian rocks in the Baltic and Lublin-Podlasie basins is generally high enough to generate hydrocarbons. In the western part of the basins, the source rock is in the gas window, whereas in the eastern part of both basins it is in the oil window.

The main regional seal for hydrocarbons in Lower Paleozoic strata is the upper Silurian succession. In the Polish part of the Baltic Basin, the upper Silurian rocks are almost entirely shales, mudstones and marls with thicknesses up to a few thousand metres. Traps for conventional hydrocarbon accumulation in the Baltic Basin are usually structural or stratigraphic. Hydrocarbon generation, expulsion and migration from the Lower Paleozoic source rocks presumably began during late Silurian and/or Devonian burial, depending on their location within the basin (e.g. Karnkowski, 2003b): the farther to the west, the earlier hydrocarbon generation started. However, it is difficult to exclude the possibility that another phase of hydrocarbon generation and expulsion took place during Mesozoic burial and the associated positive thermal event (Poprawa & Grotek, 2005).

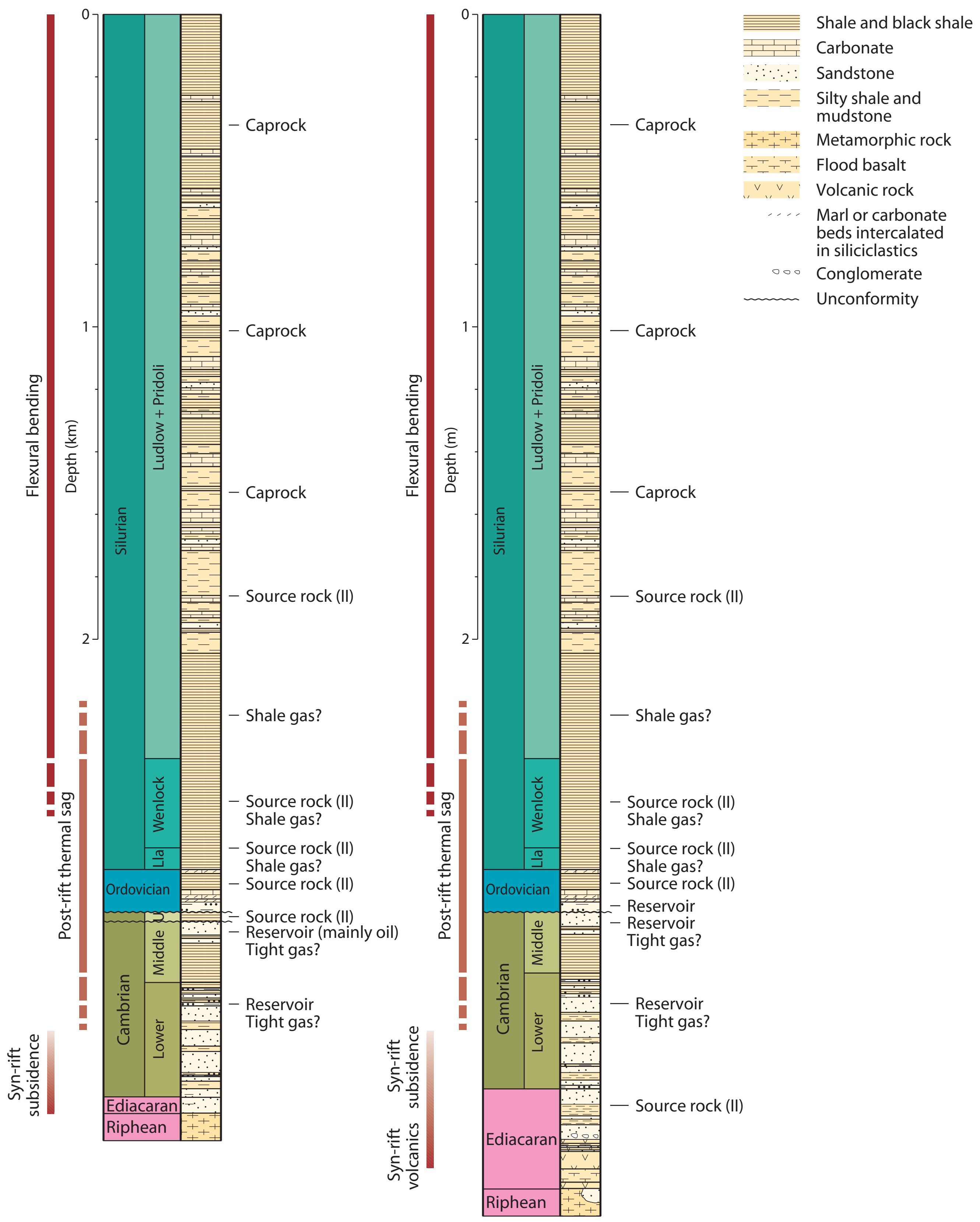

Figure 4.16 General stratigraphic section of the Baltic Basin and the Lublin-Podlasie Basin with elements of the petroleum systems. The figures after the source rock indicate the genetic types of kerogen (i.e. kerogen types I, II and III).

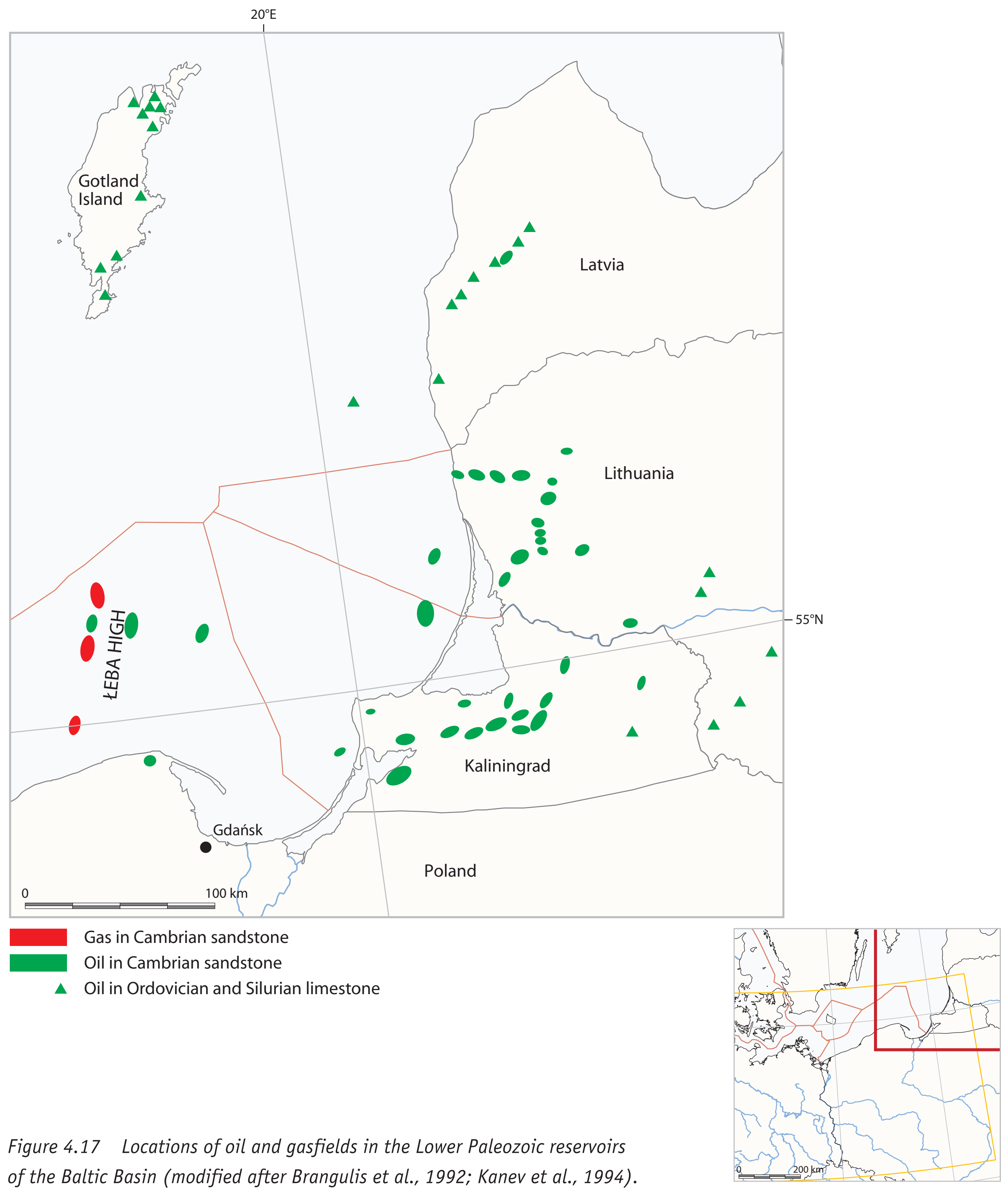

Figure 4.17 Locations of oil and gasfields in the Lower Paleozoic reservoirs of the Baltic Basin (modified after Brangulis et al., 1992; Kanev et al., 1994).

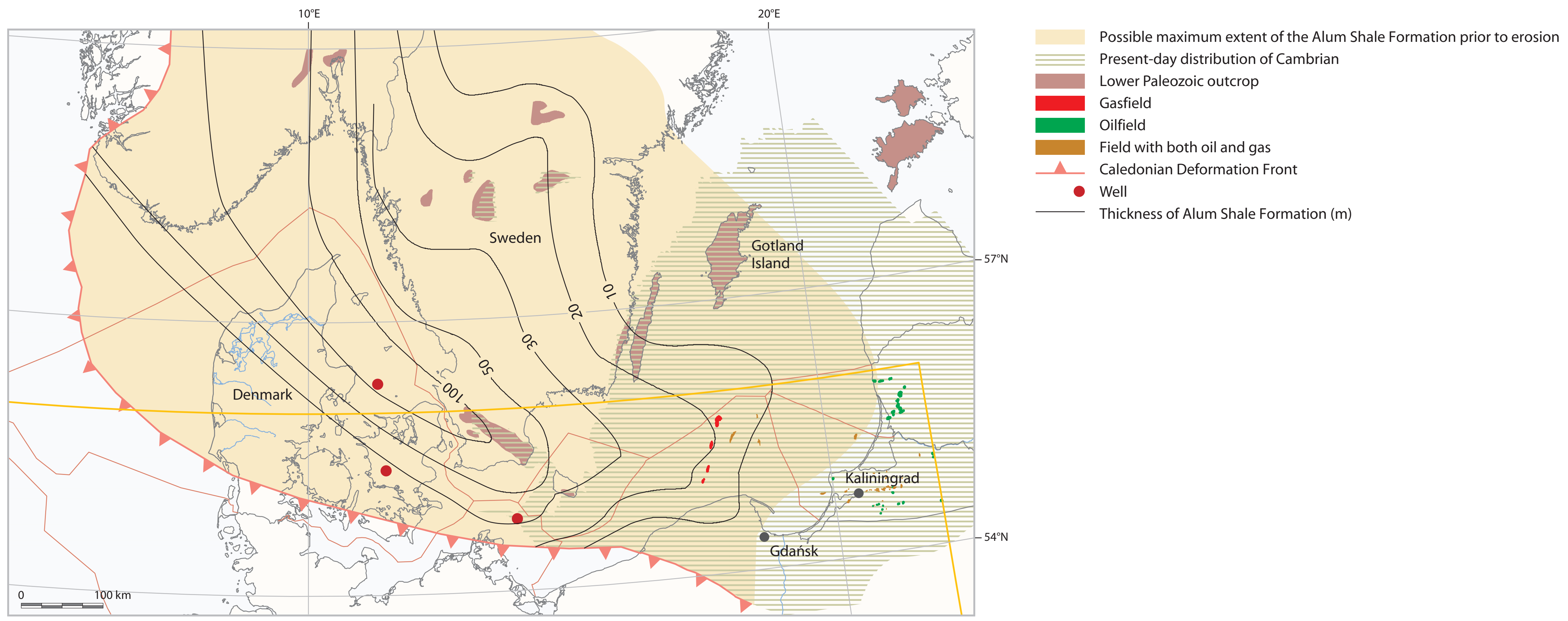

Figure 4.18 Possible maximum extent of the Upper Cambrian 'Upper Alum Shale' and the Tremadocian 'Dictyonema Shale' source rocks prior to erosion, and generalised thickness of the source rock (after Vejbæk et al., 1994). Fields with pre-Devonian reservoir.