Carbonate-platform slope succession in the Upper Devonian at Slichowice, Holy Cross Mountains, central Poland.

Chapter 5 Devonian

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1 Introduction

1.1 Data sources and literature review

Devonian rocks within the basement of the SPB are found primarily along the basin margins and adjacent regions (**Figure 5.1**). They must also occur in the axial part of the basin, but are too deep to have been reached by boreholes. The hydrocarbon potential of the Devonian deposits within the SPB area remains limited even though Devonian successions are locally very thick and include organic-rich sediments as well as carbonate and clastic rocks of good reservoir quality. This is partly because of the high thermal maturation level acquired by Devonian rocks during the Variscan Orogeny in most areas, or because potential reservoirs are exposed on the surface elsewhere. Although oil seepages can therefore be seen locally in some outcrops, for example in the Holy Cross Mountains, no hydrocarbons are currently produced from the Devonian.

This chapter is a compilation of the Devonian geology of the SPB area based on local and regional studies published mainly during the last decade. Additional information from boreholes that reached Devonian rocks has been provided by the six participating Geological Surveys and, to a lesser extent, the oil industry and are included in the geological descriptions and the maps presented in **Figures 5.1** & **5.2**. A recent publication by Bełka & Narkiewicz (2008) provides an overview of the Devonian geology in central Europe, including the entire SPB area. The UK offshore stratigraphic succession was described by Cameron (1993) and Gatliff et al. (1994), whereas there have been no published reports on the onshore Devonian strata of the UK since the work of Butler (1981). The Devonian stratigraphy of Belgium is described in overviews by Bultynck et al. (2000) and Bultynck & Dejonghe (2001). The Devonian geology of the Netherlands was described by Geluk et al. (2007a). Summaries of Devonian depositional and palaeogeographical evolution of the Rheno-Hercynian Shelf in Germany (Rhenish Massif, Harz Mountains) have been published by Wachendorf (1986), Meischner (1996) and Stets & Schäfer (2002), and the geotectonic evolution has been treated comprehensively by Franke (2000) and Oncken et al. (2000). The Devonian geology of the Rügen area (Germany), Pomerania (Poland) and the Baltic region was recently reviewed by Matyja, H. (2006); this compilation includes information from earlier papers by Volkolakov et al. (1977), Dadlez (1978), Matyja (1993), Zagora (1995), and McCann (1999a). The Devonian of south-eastern Poland has been reviewed by Malec et al. (1995), Szulczewski (1995), Narkiewicz et al. (1998), Racki & Turnau (2000), and Narkiewicz (2002). Information on Devonian rocks in various tectonostratigraphic units of the Saxo-Thüringian Zone was published by Franke & Zelazniewicz (2000).

1.2 Tectonic evolution

In terms of palaeogeography and geotectonic evolution, almost the entire SPB area was located on the passive continental margin of Euramerica during Devonian times. This palaeocontinent was separated from Gondwana-derived massifs and terranes by the Rheic Ocean (Chapter 3). Tait et al. (1997) termed these massifs the Armorican Terrane Assemblage, which included the Saxo-Thüringian Zone. The Rheic Suture extends eastwards from south-west England to the south of the Ardennes, Rhenish Massif and Harz Mountains and continues to the north of the Sudetes in south-west Poland (**Figure 5.2**). Magmatic rocks in the Saxo-Thüringian Zone provide evidence for closure of the Rheic Ocean before 410 Ma (Pragian), but no evidence of deformation or metamorphism related to this convergence episode has been observed within the Euramerica continental margin. One scenario that has been put forward is that the opening of a narrow Rheno-Hercynian Ocean may have started before the Rheic Ocean had completely closed (Franke, 2000). A strong pulse of extension had already started during Early Devonian times and led to the formation of a rift basin on the Rheno-Hercynian Shelf filled with a considerable thickness (up to 14 km) of marine Lower Devonian sediments (Oncken et al., 2000). The extensional regime continued during Mid- and Late Devonian times and caused rapid subsidence of the shelf and the local occurrence of basic volcanics. Closure of the Rheno-Hercynian Ocean and the final collision took place during the Carboniferous. Devonian strata throughout the SPB area have consequently been folded and locally metamorphosed within the Saxo-Thüringian Zone. The Devonian rocks are therefore deformed in the basement of the SPB, but there are no angular unconformities within the Devonian successions. The only exceptions can be seen in eastern England and beyond the SPB area in Wales and northern England, where Lower Devonian strata are slightly deformed and unconformably overlain by rocks that are mainly of very Late Devonian (Famennian) age. This regionally important unconformity is related to the Acadian Phase, the final Caledonian deformation episode that took place as the Iapetus Ocean closed (McKerrow, 1988) during the late Emsian or Mid-Devonian interval (Verniers et al., 2002).

Stratigraphic gaps associated with erosional phenomena are quite common in the Devonian successions of the SPB area. One such gap is a global discontinuity and occurs at the top of the Devonian sequence, usually encompassing the uppermost Famennian and lowest Carboniferous strata. In the past, this discontinuity was related to the Bretonian Phase of the Variscan Orogeny in Stille's (1924) concept of tectonic deformations. However, more recent studies have shown that the gap(s) was due to glacially induced eustatic sea-level changes (e.g. Streel et al., 2000; Sandberg et al., 2002).

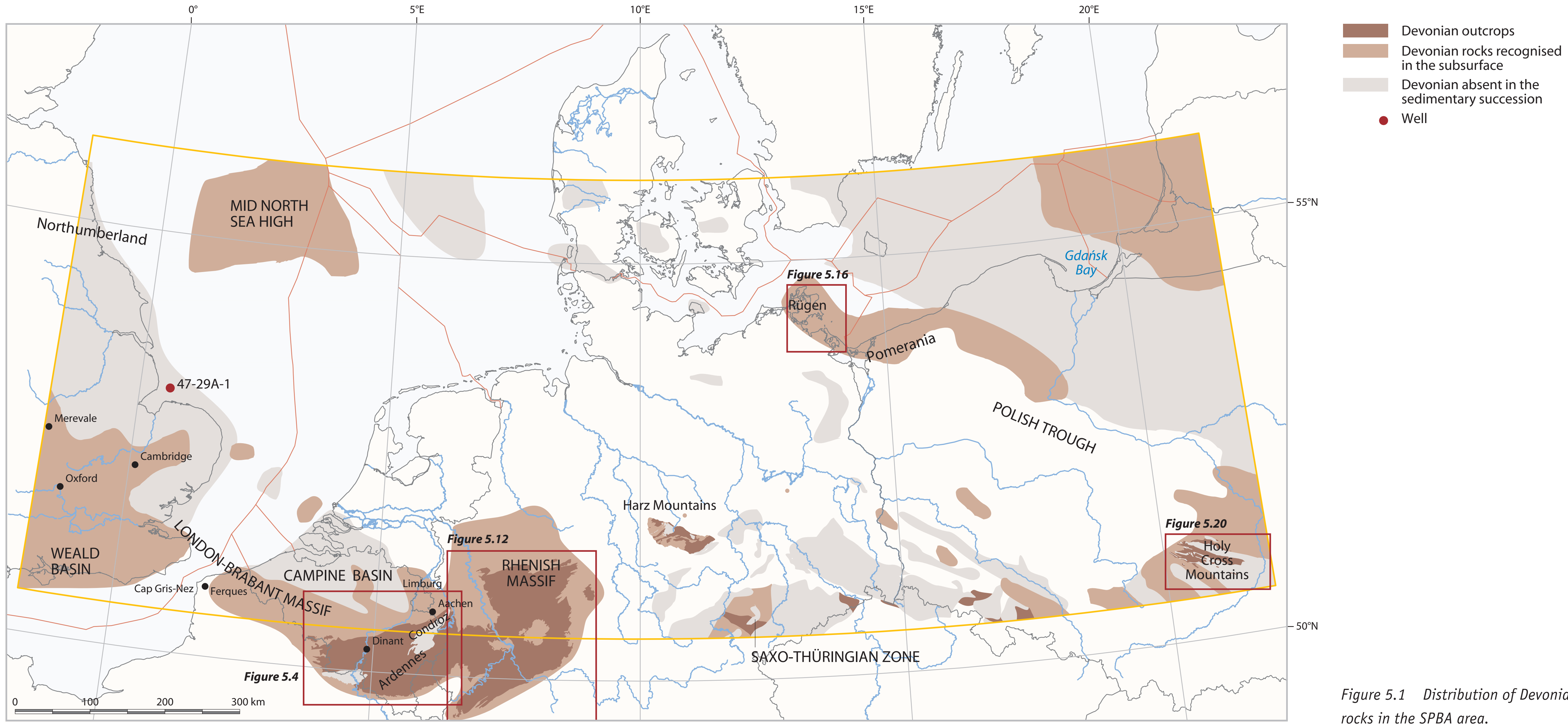

Figure 5.1 Distribution of Devonian rocks in the SPBA area.

1.3 Distribution of Devonian rocks

Devonian outcrops are found mainly along the southern margin of the SPB (**Figure 5.1**). In the UK part of the SPBA area, there is only one outcrop at Merevale, Warwickshire, where Upper Devonian strata lie unconformably on Upper Cambrian and Tremadocian rocks and unconformably beneath Namurian strata (Taylor & Rushton, 1971). In northern France, Devonian rocks are exposed in small outcrops near Ferques in the Boulonnais (Wallace, 1968; Brice, 1988) where the succession is very similar to the Devonian of England south of the Variscan Front. Eastwards, Devonian rocks crop out extensively within the Rheno-Hercynian Zone in the Ardennes and the Rhenish Massif. During Devonian times, these areas were situated on the passive continental margin of the Euramerica Palaeocontinent. A fragment of this palaeocontinent is exposed in the Holy Cross Mountains of Poland, where there are also many Devonian outcrops. Devonian rocks are also exposed along the Saxo-Thüringian Zone, which can be traced within the SPB area from Thüringia to the Sudetes, although here the Devonian consists mainly of metamorphic or plutonic rocks; unmetamorphosed sedimentary rocks are rarely found.

1.3.1 Boreholes in Devonian rocks

Devonian rocks have been encountered in more than 100 boreholes in eastern England within the SPBA area and in the half-graben basins of the Mid North Sea High. The half-graben basins are known only on this high and display thickening of Devonian strata away from the granites (Gatliff et al., 1994). A similar relationship has been suggested in the Netherlands (Geluk et al., 2007a). There are no Devonian rocks in eastern England north of Cambridge and offshore (e.g. 47/29A-1) between the East Anglian coast, where Acadian folding and uplift occurred during Devonian times, and the north-eastern Brabant Massif of Belgium and the Netherlands (**Figure 5.1**). Although more than 40 boreholes have encountered Devonian rocks along the southern flank of the Brabant Massif, only three have done so on the northern flank within the British and Dutch sectors of the southern North Sea. Farther east, only nine deep boreholes have drilled Devonian rocks north of the Rhenish Massif of Germany and two east of the Harz Mountains. Devonian rocks of the Rheno-Hercynian and Saxo-Thüringian zones have been encountered in only a few boreholes north of the Sudetes in south-western Poland (**Figure 5.2**).

The most detailed information on the Devonian subsurface geology is from the eastern part of the SPB area. In south-eastern Poland, more than 300 boreholes have penetrated Devonian rocks, mostly during exploration for mineral deposits or hydrocarbons. To the north of the Holy Cross Mountains, the Devonian probably extends north-westwards beneath the Polish Trough towards Pomerania and farther to the Rügen area of north-east Germany; more than 50 deep boreholes have encountered Devonian rocks in these areas (**Figures 5.1** & **5.2**). North of this zone, from eastern Poland to Sweden, the Devonian succession was removed from the margin of the East European Platform during post-Variscan erosion. Devonian strata are also absent from Denmark and the Danish and northern German sectors of the North Sea (**Figure 5.1**). The extent of Devonian rocks in the Baltic area has been proved by several deep boreholes in Poland, Lithuania,

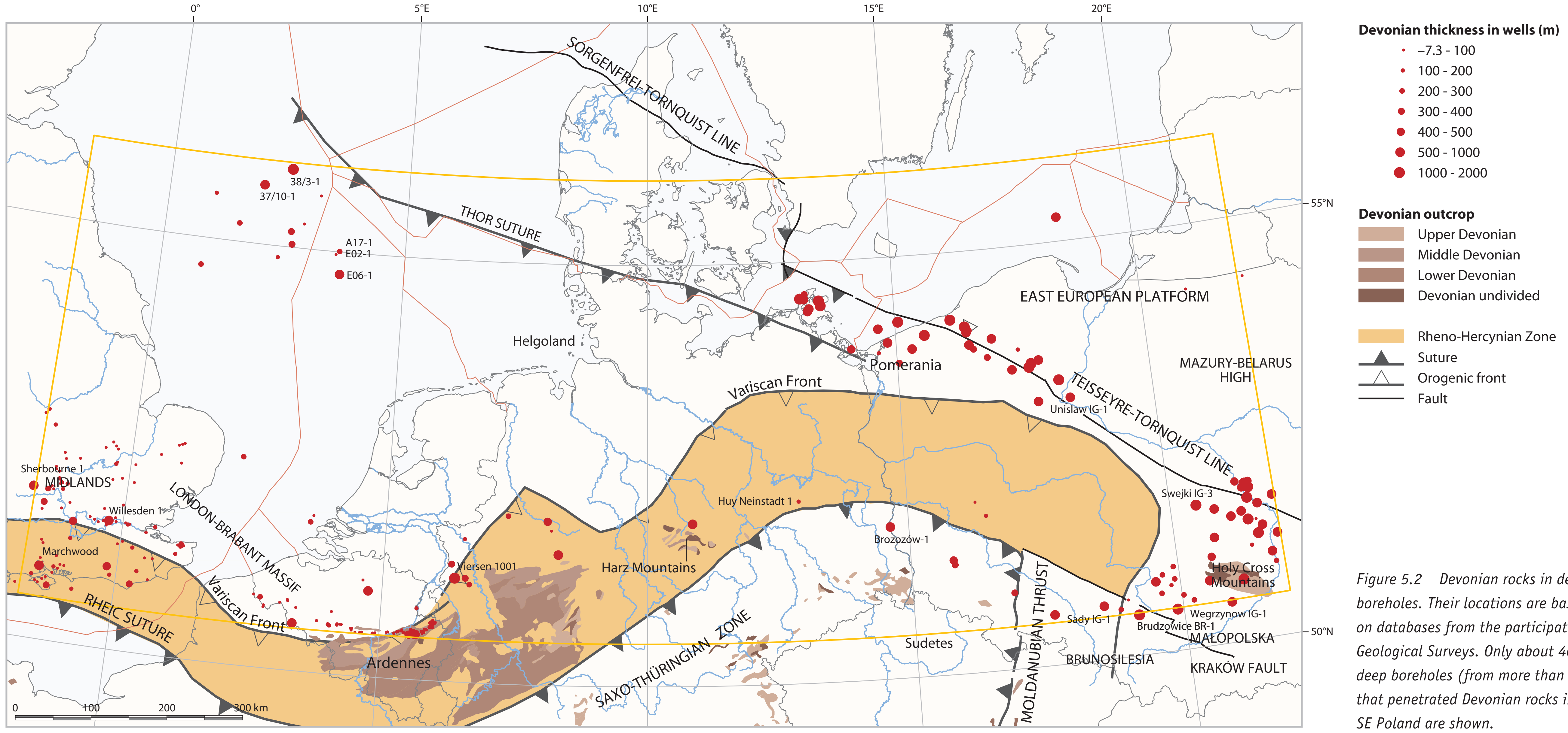

Figure 5.2 Devonian rocks in deep boreholes. Their locations are based on databases from the participating Geological Surveys. Only about 40 of the deep boreholes (from more than 300) that penetrated Devonian rocks in SE Poland are shown.

Russia (Kaliningrad) and their offshore areas. The distribution and lithological facies of Devonian rocks from 15 regions within the SPBA give an appreciation of the lateral and vertical changes throughout the region (**Figure 5.3**).

2 Stratigraphy and lithology

2.1 *Eastern England and offshore*

Lower Devonian

Six boreholes have reached Lower Devonian strata in England, all of them onshore. Lower Devonian rocks lie conformably on Silurian strata, but are usually unconformable with the overlying Upper Devonian succession in the western part of the Variscan Foreland Basin. From about the 0° meridian eastwards, there is evidence of Middle Devonian strata lying above the unconformity, which is also seen at Ferques in northern France (Wallace, 1968; Brice, 1988). The Lower Devonian rocks north of the Variscan Front were deformed during the Acadian Orogeny and so, strictly interpreted, form part of the folded basement and are related to the Caledonian Phase of orogenesis. Uplift and erosion that followed the Acadian Orogeny removed the Lower Devonian succession from the Mid North High Sea and adjacent areas. A typical sequence in the Variscan foreland (e.g. at the Apley Barn borehole in Oxfordshire) comprises interbedded sandstones and mudstones with plant remains (Poole, 1969) and reworked Tremadocian acritarchs (Richardson & Rasul, 1978).

Lower Devonian rocks crop out just beyond the western limit of the SPBA area in the Mendips, south-west England, the Welsh borders, Scotland and northern France, but there are no outcrops in south-east England. There is no evidence of the Acadian Orogeny or unconformity south of the Dinant outer tectonic zone of the Variscides (Smith, 1993), suggesting that a conformable Lower to Upper Devonian succession may be present as seen in south-west England. However within the Dinant Zone in the Mendips, the presence of the Acadian Unconformity suggests that a similar relationship may be expected just south of the Variscan Front to the east, although this has not been proved in the Weald Basin.

In northern France, Lower Devonian rocks at outcrop (Wallace, 1968; Edwards, 2006), and borehole evidence of them resting conformably on Silurian strata (Bouroz, 1960) at subcrop towards the coast between Boulogne and Cap Gris Nez (Wallace, 1968), suggest that a more internal zone of the Variscides is present south of the Grande Faille du Midi Thrust compared to the Ferques Inlier to the north. Narrowing of the Dinant Zone is indicated in this thrust-dominated inlier, which exposes the typical Dinant Zone sequence lacking Lower Devonian rocks (Wallace, 1968; Brice, 1988).

Middle Devonian

Five boreholes have encountered Middle Devonian strata in the UK area of the SPBA. In the North Sea, Cameron (1993) included a sequence of limestones, mudstones and dolomites in the Kyle Group, which lies unconformably on Lower Paleozoic basement in the Auk field. The Kyle Group is known to extend across UK quadrants 29, 30, 37 and 38 and probably farther to the west, but it is not found onshore. The evidence of marine limestones, the thickening and onlapping sequences revealed by seismic-reflection data (Gatliff et al., 1994), and synsedimentary faults, suggest that there was a Mid-Devonian rift. The rift probably extended south-eastwards to the Rheic Ocean, where similar tectonics in the Netherlands have been invoked (Geluk et al., 2007a), and appears to be displaced to the south-west relative to the present North Sea rift. The rift may also have extended northwards to the Orcadian Basin, where Marshall & Hewett (2003) described extensional half-grabens. The north-eastern limit is to the north-east of Embla (Marshall & Hewett, 2003) in Norway, west of borehole P1X in Denmark, east of B4-1 and north of C15-1 in Germany (Geluk et al., 2007a). It is possible that the rift formed by reactivation on the inferred Thor Suture (**Figure 5.2**). The western limit is not yet defined, although work is in progress (Milton-Worssell, pers. comm., 2009). The transgression came from the Rheic Ocean to the south-east (Marshall et al., 1996).

Upper Devonian

Mudstones, sandstones and thin limestones have been found in several boreholes in the Variscan Foreland Basin of south-east England and were assigned to the Holt Farm Formation (Poole, 1977). In the small outcrop at Merevale, Upper Devonian strata lie unconformably on Upper Cambrian and Tremadocian rocks (Taylor & Rushton, 1971). They include a marine to fluvial sandstone and mudstone sequence with lingulids, bivalves, brachiopods, crustaceans and fish.

In the North Sea, Upper Devonian strata were assigned to the Buchan Formation (Cameron, 1993). This formation is comprised mainly of sandstones with thin mudstone and siltstone beds and sandy conglomerates at the base. Clasts include dolomite, phyllite and vein quartz, indicating that basement highs were still being eroded, as phyllite has been found in basement rocks in well 30/16-5. There are possible coalified beds in the lower part of the sequence (Cameron, 1993); however they do not show the normal low gamma and low velocity of Carboniferous coals. Marshall & Hewett (2003) have also questioned the existence of these beds. The Upper Devonian succession is known to extend across UK quadrants 37 and 38, and probably continues to the Northumberland Trough in northern England.

2.2 *The Ardennes and neighbouring areas*

Devonian rocks in the Ardennes are found mainly in the Walloon region of Belgium and adjacent areas of France (Boulonnais and southern Ardennes) and Germany (Aachen area). They occur mainly to the south of the Variscan Front where they are represented by a major overthrust (Midi Overthrust) and its eastern extension, the Aachen Overthrust (**Figure 5.4**). This west-south-west-trending structure has displaced Carboniferous and underlying rocks up to about 30 km towards the north. However, it does not obscure the general palaeogeography of the Devonian, which has been deduced from the overthrusted strata in the south (Ardennes and Vesdre nappes) and autochthonous successions in the north (the Namur Synclinorium along the southern flank of the Brabant Massif). The basement of the Devonian succession is part of the Avalonian Terrane (Verniers et al., 2002).

The main palaeogeographical feature in this region was the elevated Brabant Massif area, which was characterised by an erosional or continental regime. The area to the south of the massif was gradually subsiding to give progressively greater sediment thicknesses and more marine influence in the coeval depositional units. Second-order structures that developed mainly during Early Devonian and Eifelian times partly controlled the sedimentation patterns. These structures include the elevated areas formed by Lower Paleozoic rocks (essentially the Rocroi, Givonne and Stavelot massifs; **Figure 5.4**). Synsedimentary block-tectonics are also thought to have influenced deposition, particularly during the Early and Late Devonian.

Lower Devonian

The Lower Devonian succession can generally be subdivided into two complexes. The lower complex developed as thick siliciclastic units during the Lochkovian and early part of the late Emsian. The upper complex is mostly late Emsian fossiliferous marly carbonates. Lower Devonian rocks are missing in the area of the Brabant Massif due to the prevailing erosional regime.

The basal part of the Devonian succession lies unconformably on the Lower Paleozoic basement and is a transgressive clastic sediment, commonly with a basal conglomerate, that was deposited in an alluvial to nearshore tidal-marine environment (Bultynck & Dejonghe, 2001). Evidence from brachiopods, spores and conodonts suggest that sedimentation started during the Pridolian to early Lochkovian interval in the Dinant and the Neufchâteau synclinoriums to the south. Northwards, the onset of deposition of the basal clastics is seen at a stratigraphically higher interval in the upper Lochkovian. This diachroneity is associated with a thickness decrease, from 4000-5000 m in the area of the Neufchâteau Synclinorium to 1000-2000 m in the northern part of the Dinant Synclinorium (Bultynck et al., 2000).

Lower Devonian deposits of the southern Ardennes are characterised by sediments of mixed continental to shallow-marine facies (**Figure 5.5**). The facies range from shales and carbonate intercalations with diverse marine fauna (Mondrepuis, Levrezy, and Ville formations), through nearshore restricted siliciclastics with a poor marine fauna (Saint-Hubert, Mirwart, La Roche, Pernelle, and Vireux formations), to alluvial mottled sandstones and mudstones (Oignies and Chooz formations). In general, regressive episodes are noted in late Lochkovian and mid-Emsian times (Bultynck et al., 2000). The onset of the important transgressive period that continued into Mid-Devonian times took place during the late Emsian. The transgression is marked by a thin (~20 m) basal sandstone unit, which grades upwards into thick (~300 m) fine-grained clastic deposits (Hierges Formation) with an abundant and diverse marine fauna (**Figure 5.6**).

The sedimentary rocks of the northern Dinant Synclinorium are typically siliciclastics varying from shales and mudstones to sandstones and conglomerates. In places these rocks contain plant remains and fish fauna, but notably lack marine fossils.

The upper carbonate complex has been documented only on the southern flank of the Dinant Synclinorium (**Figure 5.6**) where it is a succession of alternating shales and limestones with abundant brachiopods (Saint Joseph Formation) overlain by predominantly marly carbonates (Eau Noire Formation) with rugose and tabulate corals. Both formations are about 100 to 160 m thick and correspond to a carbonate-shaly ramp of latest Emsian age. The temporal equivalents of these facies in the north and north-east are siliciclastic successions (**Figure 5.5**), which become progressively more continental (Hampteau, Wépion and Burnot formations).

Middle Devonian

In the southern Dinant Synclinorium, the Eifelian Stage constitutes the major part of the transgressive-regressive cycle that commenced in the late Emsian; its total thickness is 650 to 700 m. The Eau Noire Formation is overlain by biostromal (rugose-tabulate-stromatoporoid) limestones up to 380 m thick (Couvin Formation), broadly equivalent to the lower part of the Eifelian. The extent of the carbonate platform is controlled by the basement elevation of the Rocroi Massif (**Figure 5.4**). The Couvin Formation is replaced laterally to the east by shales (Jemelle Formation) with silty-sandy intercalations in the lower part and small biohermal lenses in the upper part. The formation is gradually onlapped by shales and

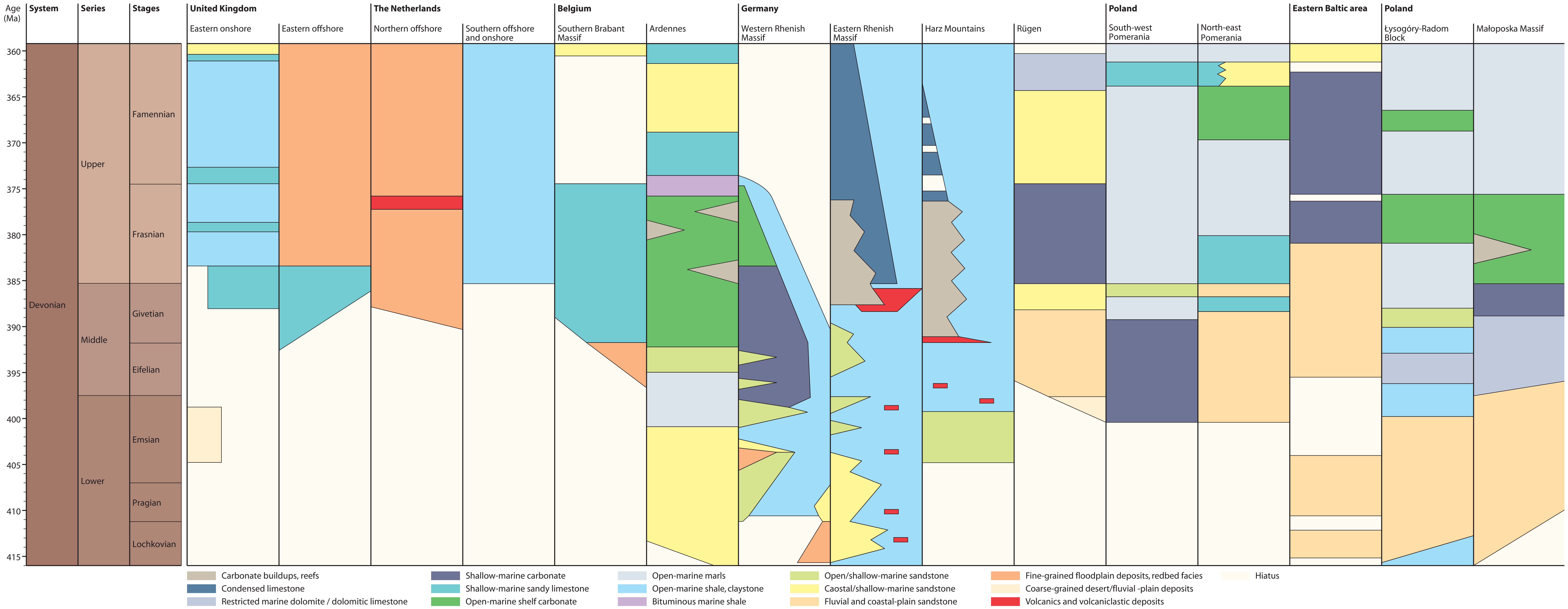

Figure 5.3 Devonian lithostratigraphy in the SPBA area.

sandstones of the Lomme Formation, which are up to 110 m thick and were deposited during a regressive phase that persisted into late Eifelian times (**Figure 5.6**).

The Lomme Formation is overlain by shales and marly nodular limestones (Hanonet Formation) with abundant brachiopods and rugose corals, and biostromal intercalations in the upper part. This unit corresponds to a transgressive regime during Eifelian to Givetian times. The Eifelian-Givetian stage boundary is in the lower part of the Hanonet Formation (30-70 m thick) and passes laterally into the crinoidal, coral and stromatoporoid limestone bodies (~120 m thick) of the Trois-Fontaines Formation (Bultynck et al., 2000). To the south, Givetian rocks are about 450 m thick and formed a shallow-marine carbonate platform constructed mainly by coral-stromatoporoid biostromes with a slightly restricted back-reef facies (Trois-Fontaines, Mont d'Haurs and upper Fromelennes formations). The upper, mostly biostromal, part of the Fromelennes Formation continues upwards close to the Frasnian Stage boundary.

In the north, the Middle Devonian sequence has reduced sediment thicknesses (**Figure 5.6**) and was deposited in a more shallow-marine to continental environment. Eifelian sediments lie unconformably upon Silurian strata along the southern flank of the Namur Synclinorium. The lowermost part of the Eifelian sequence consists of red sandstones and conglomerates with plant-bearing shales (Burnot Formation). This succession is overlain by mixed siliciclastic-carbonate sediments (Riviere Formation) comprising the main part of the Eifelian (50-100 m thick). The Givetian strata are 130 to 160 m-thick shallow-marine carbonates (Névremont Formation) overlain by a succession of shales, sandstones and variable carbonates (Le Roux Formation). Farther north, Givetian rocks directly overlie the Silurian basement in the northern part of the Namur Synclinorium. The succession (Bois de Bordeaux Formation) consists of basal siliciclastic red beds overlain by various limestones, including oolites, bioclastic and biostromal units, and is capped by red sandy-silty shales with rare limestone intercalations (Bultynck & Dejonghe, 2001).

Upper Devonian

The total thickness of the Frasnian succession is about 400 m in the southern Dinant Synclinorium (**Figure 5.7**), gradually thinning northwards to about half this thickness (Boulvain et al., 1999). The base of the succession is the Nismes Formation consisting of greenish shales with subordinate nodular-limestone horizons rich in brachiopods. These sediments are interpreted as being deposited during a global eustatic transgression that gradually moved northwards, where the sediments pass into argillaceous and bioclastic limestones with hematitic oolites of the Presles Formation.

Each of the two succeeding formations (Moulin Liénaux and Grands Breux) marks a separate transgressive-regressive cycle (cf. Gouwy & Bultynck, 2000). They correspond to a basal marly carbonate ramp with local development of large coral-stromatoporoid and stromatactis buildups. The buildups, referred to as the Arche and Lion members (**Figure 5.7**), have thicknesses of up to 120 m and 120-250 m respectively. Their sedimentology, biota and palaeoecological aspects have been the subject of numerous studies (e.g. Lecompte, 1970; Tsien, 1979; Sandberg et al., 1992). The buildups are surrounded by shaly and marly sediments, which partly represent post-buildup sediments with some calcareous-detrital intercalations sourced from the buildups. According to Sandberg et al. (1992), the Lion Member buildups show evidence of karst development as a result of a regressive episode and subsequent or coeval extensional tectonics and volcanism. Towards the north in the Phillippeville area, the two cycles mentioned above are represented by two units of coral-stromatoporoid biostromal carbonates (Pont de la Folle Formation and the Phillippeville Formation, **Figures 5.7** & **5.8**) separated by a marly wedge thinning to the north (upper Pont de la Folle Formation). The southern edge of the biostromal complexes shows pervasive dolomitisation and is probably controlled by a synsedimentary fault (Da Silva & Boulvain, 2002). To the north of the Dinant Synclinorium, both units merge into a single carbonate-platform succession (Lustin Formation) that reaches a thickness of about 100 m (**Figure 5.7**).

A transgressive event at the beginning of the late Frasnian led to the development of a third biohermal level represented by numerous red stromatactis mounds (Petit-Mont Member). These mounds are found within nodular marls (Neuville Formation) and are usually 20 to 80 m high; in places (e.g. the Philippeville area) they protrude into the overlying shales (Les Valisettes Formation). According to Sandberg et al. (1992), the development of the stromatactis mounds was succeeded by a regression that led to deep karstification of the buildups (**Figure 5.7**).

The uppermost Frasnian sediments are black shales (Matagne Formation) with rare limestone intercalations yielding mostly small pelagic fauna. This formation is 50 m thick in the south, but it thins progressively northwards in the Philippeville area. Along the northern margin of the Dinant Synclinorium, the equivalent of the Matagne Formation is a 50 to 100 m-thick succession of silty shales and limestone intercalations including a biostrome and brachiopod coquinas (Lambermont Formation). Da Silva & Boulvain (2002) suggested that the southern limit of these facies was controlled by synsedimentary faulting.

Much of the Famennian was a time of predominantly continental erosion in the Namur area. Only terrestrial red clastics and shallow-marine littoral deposits (Samme Formation) of the uppermost Famennian are preserved (**Figure 5.9**). The relatively simple pattern of increasing subsidence and marine influence to the south was complicated by differential tilting of basement blocks on the shelf (Dreesen et al., 1988). Famennian strata are most completely developed in the Dinant Synclinorium, whereas to the east in the Vesdre Nappe they are considerably reduced both in thickness and in terms of stratigraphy.

The Famennian succession has a characteristic tripartite development, with basal (Famenne Group) and top (Strunian Group) units of predominantly fine-grained clastic and carbonate lithologies, whereas the middle part consists of coarse-grained siliciclastics, commonly arkosic sandstones, with subordinate

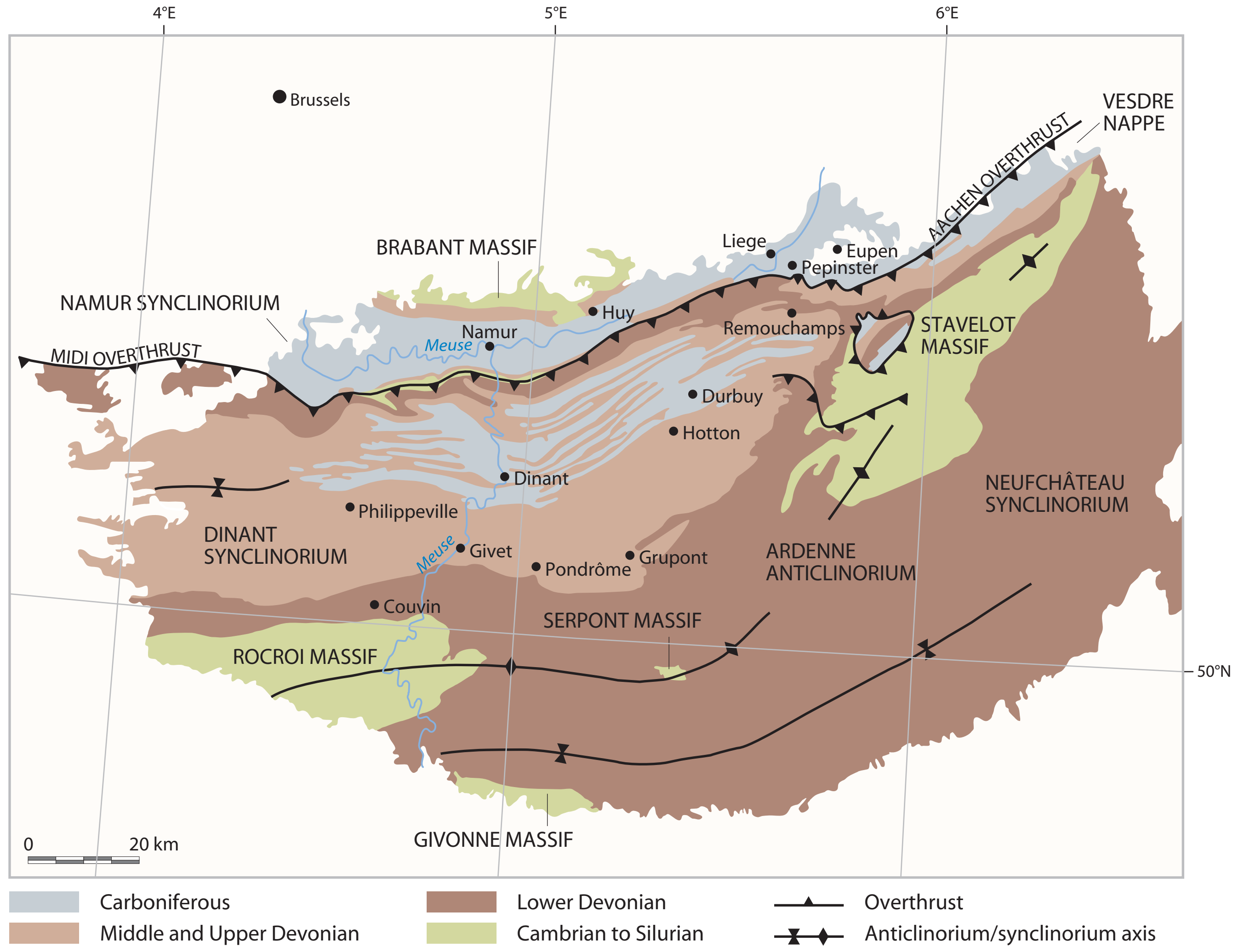

Figure 5.4 Simplified geology of the Ardennes (after Bultynck & Dejonghe, 2001). See Figure 5.1 for location.

carbonates (Condroz Group, Psammites du Condroz) (**Figure 5.9**). The Famenne Group uniformly developed as open-marine shales with siltstone intercalations, which become more common upwards in the succession. Subordinate constituents include carbonate nodules, sandy-calcareous beds with crinoids and rhynchonellid brachiopods, and several Fe-oolitic horizons. The thickness increases from 50 to 60 m south of Namur to more than 400 m towards the southern Dinant Synclinorium.

The Condroz Group is up to 800 m thick in the Dinant Synclinorium and wedges out northwards. The lowest deposits are shaly (Aye Formation), passing northwards into more proximal sandy-silty facies (Esneux Formation) corresponding to a shallow subtidal environment. A eustatic transgressive event (Baelen Event; Dreesen et al., 1988) resulted in more open-marine nodular limestones with reworked skeletal material (Souverain-Pré Formation) and local development of crinoidal-stromatactoid mud-mounds (e.g. the 20 to 150 m-thick Baelen Member). In more proximal locations, the nodular limestones intercalate with sandstones and siltstones (Ciney Formation). The overlying sediments are mostly sandstones (Montfort

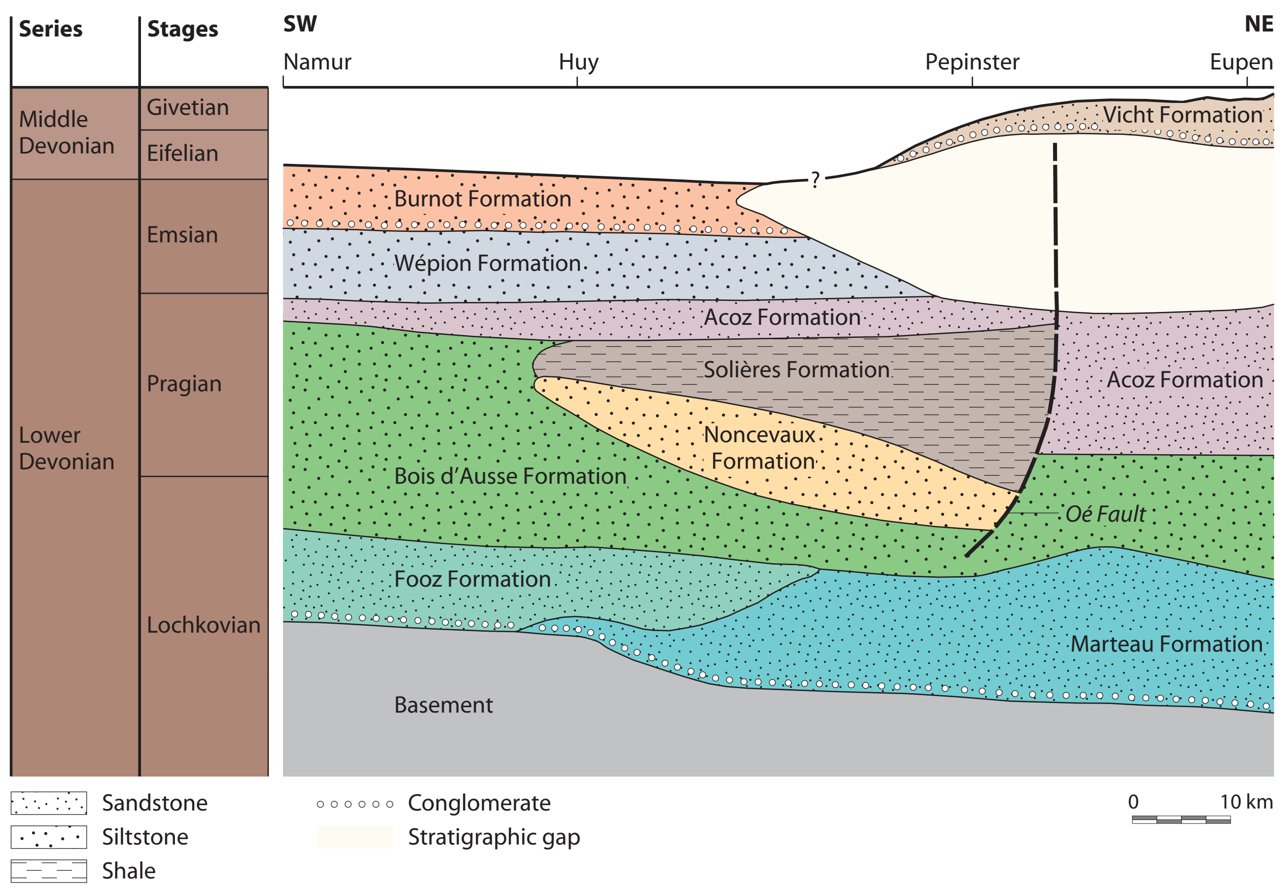

Figure 5.5 Lower Devonian lithostratigraphy in the NE Ardennes. See Figure 5.4 for locations.

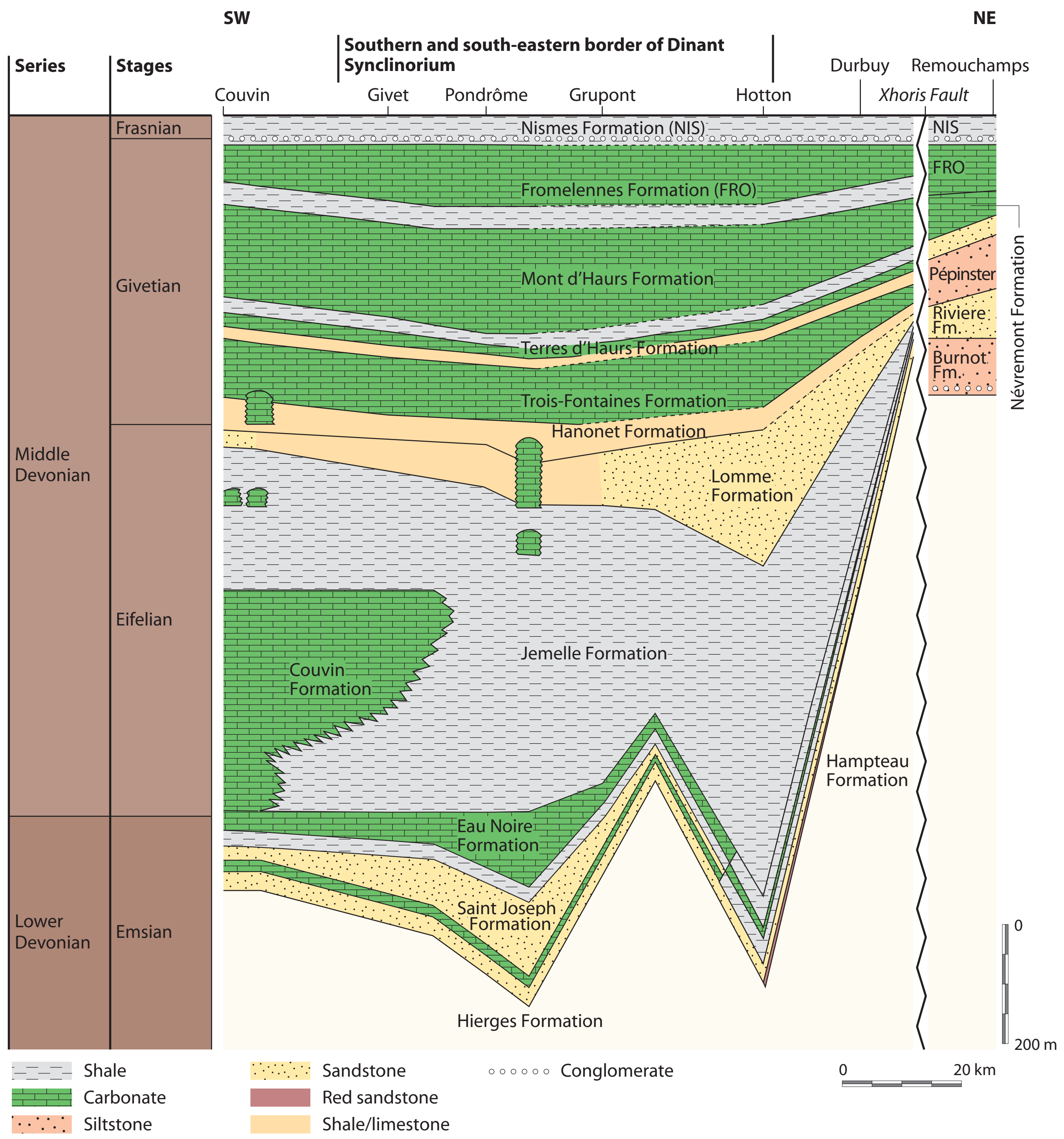

Figure 5.6 Middle Devonian lithostratigraphy in the southern part of the Dinant Synclinorium. See Figure 5.4 for locations.

Formation), which are interpreted as deposits of a sand-barrier complex with facies ranging from subtidal fore-barrier to barrier and lagoonal-evaporitic back-barrier environments (**Figure 5.10**). The uppermost Condroz Group sediments represent a regressive interval with continental clastic red beds and lagoonal dolomites (Evieux Formation) grading laterally to marginal-marine peritidal limestones (Beverire Formation).

Late Famennian time was characterised by a transgressive regime that led to the deposition of marine shales with siltstones in the lower part, common sandy interbeds in the middle part, and crinoidal limestones in the upper part of the succession. These lithologies (Etroeungt Formation) are 120 to 200 m thick and pass laterally into 30 to 40 m-thick coral-stromatoporoid biostromes of the Dolhain Formation. The buildups are mostly known from the Vesdre Nappe area (**Figure 5.9**). Devonian sedimentation ended with significant regression during latest Famennian times, which was responsible for the deposition of extremely shallow-water carbonates and/or stratigraphic gaps in the Devonian-Carboniferous transition.

The Devonian rocks of the Boulonnais (France) crop out in the Paleozoic massif of Ferques (**Figure 5.1**). The succession starts with clastic lithologies of the Caffiers Formation (lower Givetian?) and limestones with reefal mounds in the Blacourt Formation (middle to upper Givetian). The Frasnian formations (Beaulieu, Ferques and Hydrequent) have alternating clastic (claystones and siltstones) and carbonate lithologies with a total thickness of 365 m. The overlying Sainte-Godeleine Formation (lower Famennian) comprises 50-m thick fine-grained sandstones.

2.3 *The Netherlands*

Devonian rocks in the Netherlands have been encountered in a few deep wells, most of them offshore. The Lower Devonian is absent. In the western part of the Dutch offshore sector on the flanks of the Brabant Massif, wells S02-2, S05-1 and 018-1 have penetrated the marine, dark-coloured shaly mudstone and intercalated white to greenish-grey, fine-grained sandstones of the Banjaard Group (**Figure 5.11**). Directly east of the Brabant Massif, well Kastanjelaan-2 in Limburg has also penetrated some 120 m of

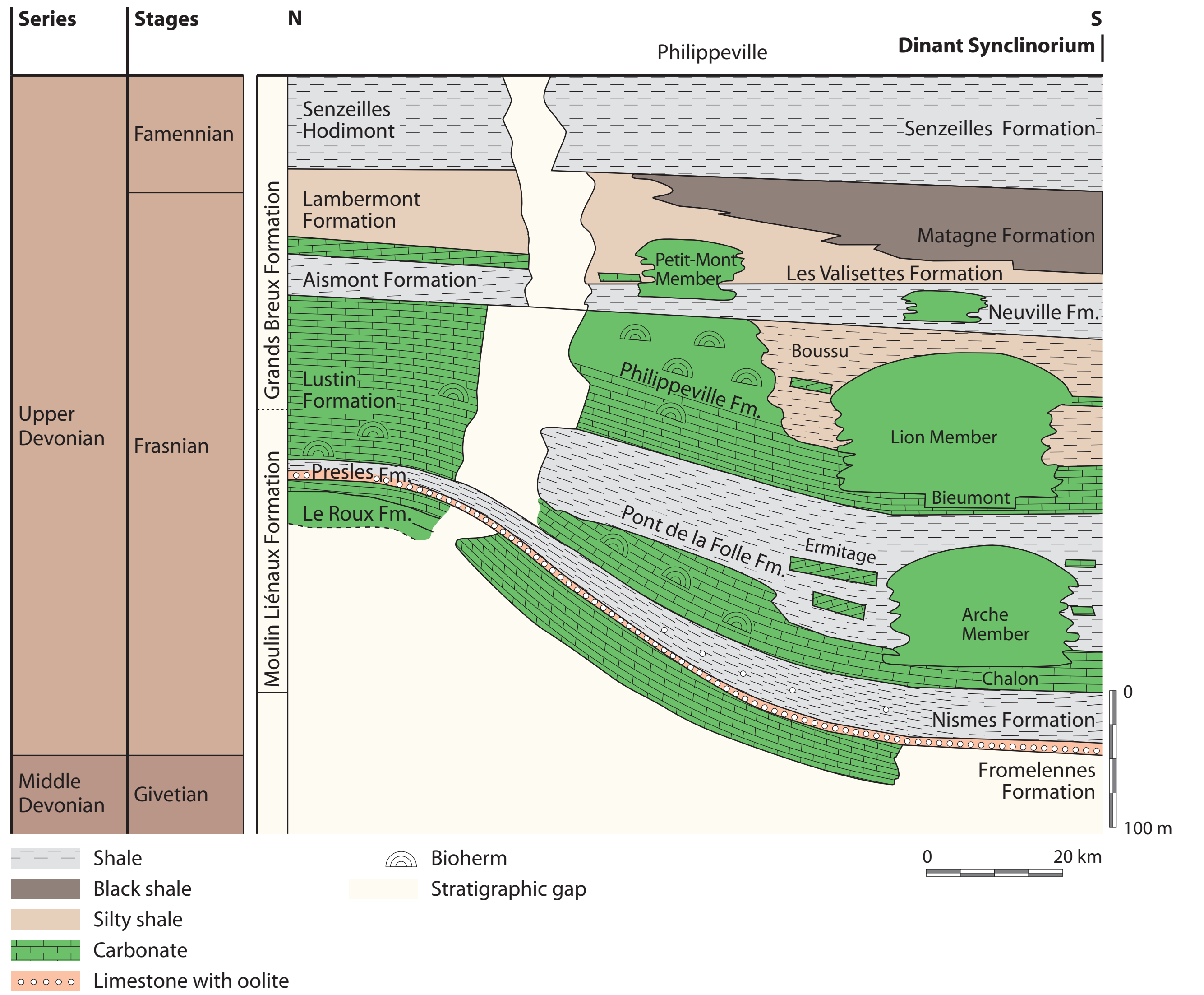

Figure 5.7 Stratigraphy of the Frasnian succession in the Dinant Synclinorium (from Bultynck & Dejonghe, 2001). See Figure 5.4 for locations.

Banjaard Group sediments where they developed in a facies with sporadic carbonate streaks. The succession at Kastanjelaan-2 has been dated using microspores (Bless et al., 1981). The informal Banjaard Group consists of the late Frasnian to early Famennian Bollen Claystone (in Kastanjelaan-2), and the Famennian Bosscheveld Formation (in S05-1 and S02-2) comprising claystones and siltstones with sandstone and shallow-water limestone intercalations. The group reaches thicknesses of 300 to 700 m in the southern Netherlands, but is thinner in the eastern Netherlands where it is up to 500 m thick (NITG, 1999).

Figure 5.8 The 'Rocher de la Falize', also known as the Durbuy Anticline, is located in the village of Durbuy (see Figure 5.4 for location). It consists of grey to black limestones of Frasnian age (Philippeville Formation).

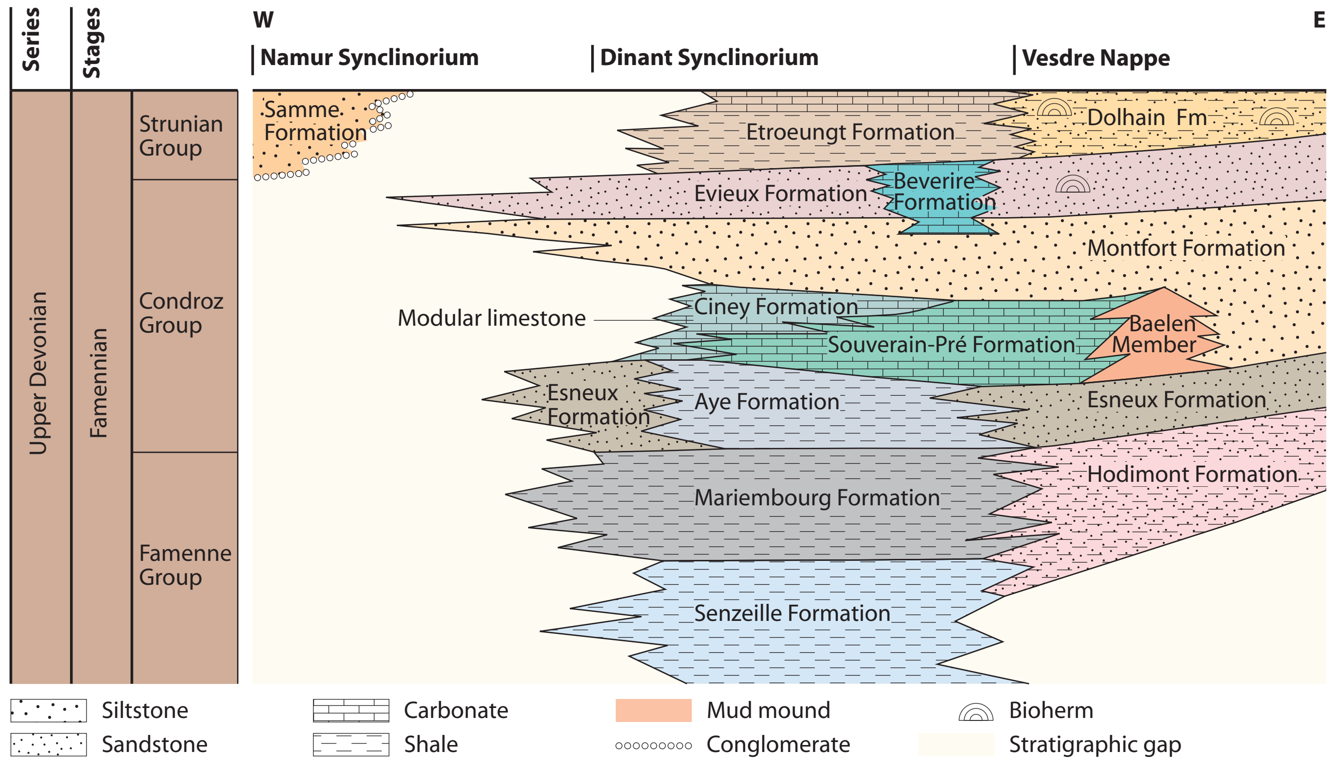

Figure 5.9 Lithostratigraphy of the Famennian succession in Belgium (from Bultynck & Dejonghe, 2001).

In the northern Dutch offshore sector, three wells (A17-1, E06-1 and E02-1) (**Figure 5.2**) have penetrated parts of the Old Red Group (**Figure 5.11**), a succession of white to reddish sandstones and red to red-brown claystones and siltstones with disseminated anhydrite. The sandstones were deposited in a fluvial setting as stacked channel sediments in a braided-river system. The Devonian Old Red Group includes the Patch, Buchan and Tayport formations (Van Adrichem Boogaert et al., 1993). A Givetian to Famennian age is assumed, although no key fossils have yet been recognised. The Patch Formation consists of silty claystones of lacustrine or floodplain origin, which are up to 300 m thick. The Buchan Formation is a 600 m-thick succession of fluvial sandstones, conglomerates, claystones and siltstones. Acid volcanics (rhyolite) are found in the formation in the eastern Mid North Sea High (well A17-1). A radiometric age of 341±30 Ma (Early Carboniferous) is given for the volcanics, although it is not certain that this is reliable (Sissingh, 2004). The Tayport Formation is a sequence of claystones and siltstones with fluvial sandstone intercalations. Its total thickness is not known due to limited well control, but it is at least 500 m thick in the Dutch offshore sector.

2.4 Rhenish Massif and Harz Mountains

The Rhenish Massif has the most complete palaeogeographical record of the Rheno-Hercynian Zone. Traditionally, it has been subdivided into a western part, including the Eifel and Hunsrück Mountains, and an eastern area that includes the Bergisches Land, Sauerland-Siegerland, and Taunus; the boundary corresponds broadly to the Rhine River (**Figure 5.12**). Moreover, this subdivision reflects a major difference in terms of the general development of Devonian sedimentation. The boundary may have been controlled by a deep-crustal discontinuity (cf. Engel et al., 1983); for example, the faults bordering the elongated structural feature termed the Zandvoort-Krefeld High (Bless et al., 1976) or a transform fault named the Lower Rhine Lineament by Franke (1995b). The latter reaches as far as the North Sea and possibly continues in the Loki Shear according to Berthelsen (1992b), although Marshall et al. (1996) did not see evidence for continuation so far to the north.

The Devonian rocks of the Rhenish Massif and Harz Mountains can be subdivided into several south-west–north-east-trending structural-sedimentary belts that developed from the sedimentary prism of a passive

Figure 5.10 An active quarry exploiting the coloured sandstones of the Montfort Formation (upper Famennian; see Figure 5.9). The geological structure corresponds to a perched syncline.

continental margin of Euramerica. Early Devonian rifting led to the formation of an intracontinental rift basin (the Rhenish Trough) and a marginal plateau at the transition to the ocean to the south (Oncken et al., 2000). According to the palinspastic reconstruction by Franke (2000) (see also Franke (1995b) for a review, and Jansen et al. (2001) for alternative views), the allochthonous units recognised in the south-east Rhenish Massif and Harz Mountains constitute fragments of the two south-easternmost belts of the Rheno-Hercynian Zone (**Figures 5.12** & **5.13**). The belts are:

1. Distal continental margin/slope with rifted basement composed of a Silurian / Early Devonian magmatic arc and adjoining Armorican crust. The Devonian deposits, mostly ascribed to the so-called Hercynian Complex, are Eifelian to upper Famennian condensed pelagic limestones, Famennian quartz arenites intercalated with pelagic shales and radiolarites, Middle to Upper Devonian limestone turbidites and shales overlain by greywackes, and Lower Devonian sandstones topped by Middle to Upper Devonian hemipelagic shales and limestones.
2. The oceanic Rheno-Hercynian crust overlain by Emsian to Upper Devonian condensed shales and radiolarian cherts, succeeded by Frasnian greywackes with metamorphic material derived from the Mid-German Crystalline High. The latter deposits record the first stages of compressional deformation related to the development of the active south-east margin of the Rheno-Hercynian Basin.

Devonian rocks have also been encountered in several research boreholes (up to 5766 m deep) beneath thick Mesozoic and Cenozoic strata to the north of the Rhenish Massif. In the Middle Devonian succession of the Viersen 1001 well (**Figure 5.2**), the existence of an eastern outlier of the Brabant Massif could be suggested by Ordovician marine, nearshore coarse-grained clastic debris (Neumann-Mahlkau & Ribbert, 1998; Ahrendt et al., 2001). The predicted 'Krefeld High' (Bless et al., 1976) could therefore be proved (see Section 2.2 in Chapter 4). Upper Givetian to lowest Frasnian Massenkalk was found in the Münsterland-01 well some 70 km north of the Rhenish Massif (Wolburg, 1963). The Famennian Condroz shelf facies could be recognised as far as the Münsterland-01 well and with increasing thickness and possible basinal trend somewhat farther to the east (Wolburg, 1963; Ribbert, 1998).

2.4.1 Western Rhenish Massif

The Devonian west of the Rhine differs from the eastern succession mainly in terms of its negligible volcanism and earlier development of a carbonate platform (Franke, 1995b, 2000). The development of the carbonate platform began in the early Eifelian following a period of Early Devonian siliciclastic shelf sedimentation. In the Eifel area, the succession is mainly Lower Devonian marginal-marine to shallow-marine clastics and Middle Devonian carbonates (**Figure 5.14**).

Lower Devonian

The oldest Lower Devonian deposits are lower Emsian clastics with continental red beds, which are overlain by thick, shallow-water marine and continental clastics with impoverished fauna and locally abundant plant remains. In the north, these sediments represent a terrestrial environment dominated by large deltas (Stets & Schäfer, 2002). There was an open-marine prodelta depositional system to the south, where sediments had a partly calcareous admixture and more diverse fauna. The fauna includes exceptionally

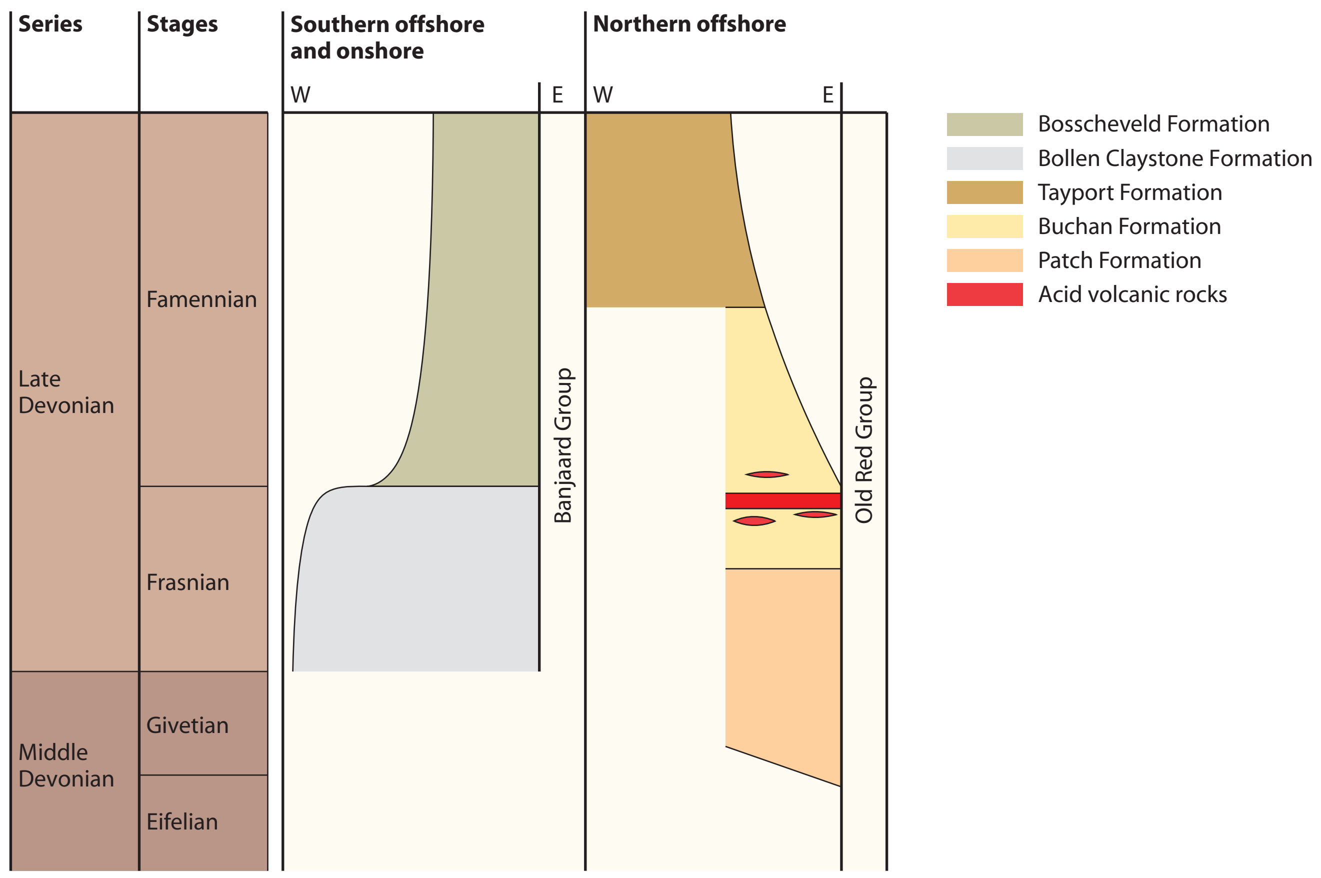

Figure 5.11 Chronostratigraphy of the Devonian rocks of the Netherlands (from Van Adrichem Boogaert & Kouwe, 1993).

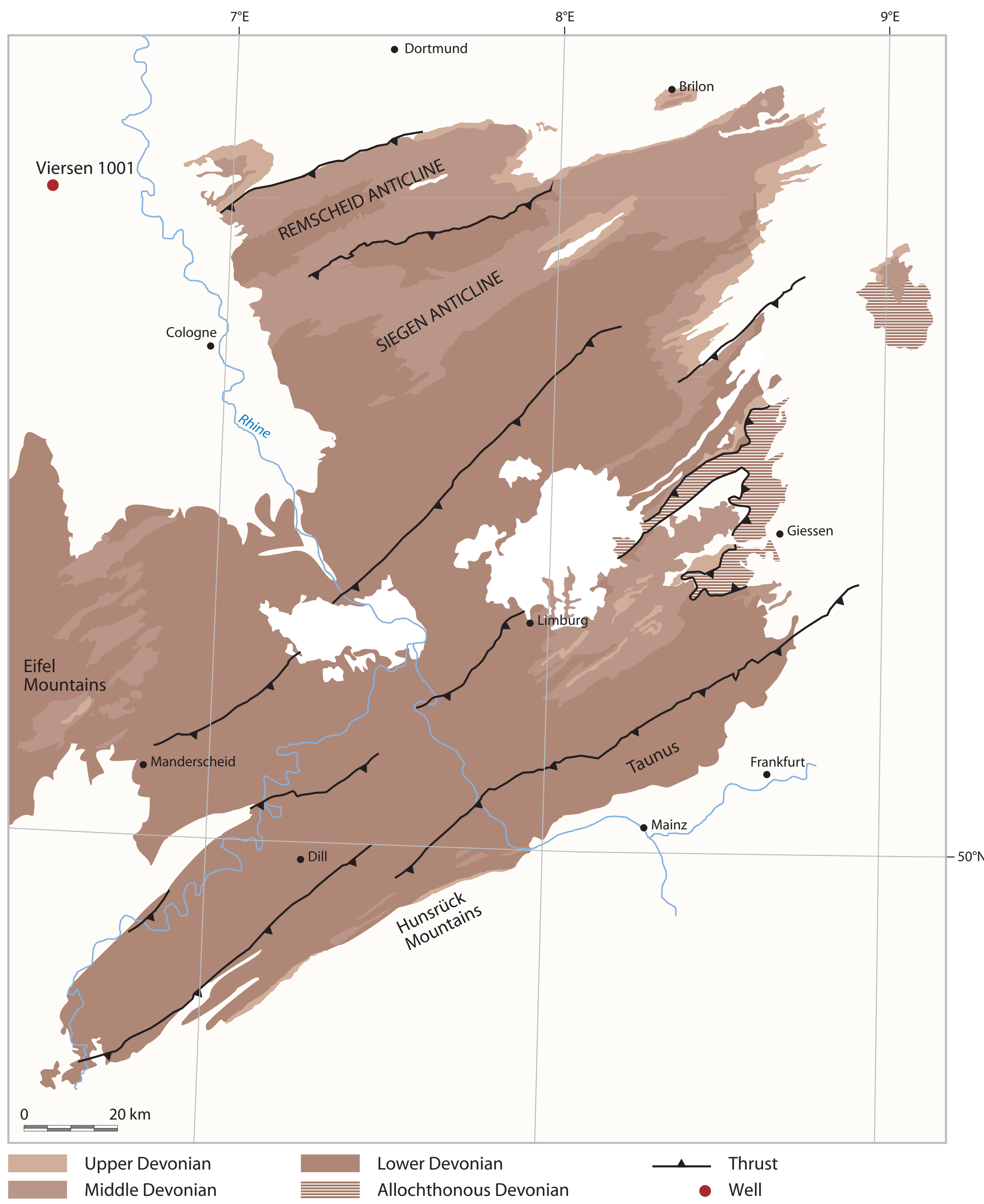

Figure 5.12 The distribution of the Devonian rocks in the Rhenish Massif (adapted from Oncken et al., 2000). See Figure 5.1 for location.

well-preserved arthropods and crinoids, and is particularly well-known from the Hunsrück Shale, a sequence of black shales with turbiditic silty and sandy intercalations deposited in a deep-basinal setting (Krebs, 1979). The upper Emsian sediments record regressive conditions with red-bed sedimentation (Klerf Formation) succeeded by sandstones deposited in a tide-dominated setting (Ems Quartzite). The late Emsian was a time of considerable retrogradation of the nearshore-facies belt towards the north-west, paralleled by the encroachment of more open-marine systems on continental and restricted-marine facies. Geometric analysis and palinspastic restoration show that the Lower Devonian siliciclastic basin infill is up to 14 km thick in the Mosel Synclinorium, which represents the central rift zone (Oncken et al., 2000). In contrast, the clastic sediments deposited on the marginal plateau to the south-east, which are now mainly exposed in the Taunus area, are no more than 5000 m thick.

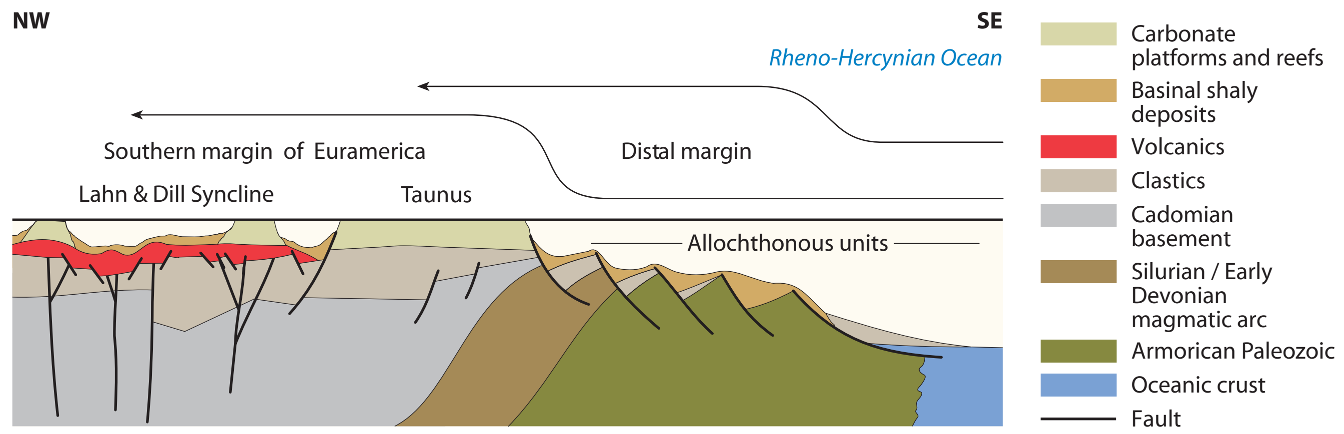

Figure 5.13 Palinspastic restoration of allochthonous units in the Rhenish Massif (from Franke, 2000).

Middle and Upper Devonian

In the Eifel Mountains, the type area for the Eifelian Stage, the base of the stage is established in the upper part of a mudstone and siltstone succession (Heisdorf Formation), which also contains some rare argillaceous limestone or calcareous sandstone beds (**Figure 5.14**). The Middle Devonian succession is shallow-marine, mostly carbonate units, with marly horizons marking the relatively deeper-water intervals. Siliciclastic input extending into the present-day Aachen region from the north was derived from the basement of the London-Brabant Massif. According to Faber (1980), there was cyclic development of a carbonate coral-stromatoporoid platform in early Eifelian times, whereas during the late Eifelian and early Givetian the environment was mainly a shelf-lagoon. The upper Givetian to lower Frasnian (Bolsdorf Schichten, Wallersheim Dolomit) is represented by a partly dolomitised biostromal platform. The whole Middle Devonian to lower Frasnian carbonate succession is up to 1000 m thick. Variable subsidence created a platform-to-basin pattern in the shelf bathymetry during mid-Frasnian times (Krebs, 1969). Fossiliferous turbiditic limestones (Oos Formation) were deposited in the basinal area. However, the upper Frasnian again shows more uniform facies development; it is represented by fossiliferous, especially goniatite-bearing, black shales that have two anoxic carbonate levels (Kellwasser Limestones) in the upper part of the succession (**Figure 5.15**). The Devonian strata are terminated by lower Famennian ostracod-bearing shales passing laterally into black marls (Neu-Oos Formation).

2.4.2 Eastern Rhenish Massif

Lower Devonian

In the Rhenish Trough, it is generally assumed that the clastic deposition that developed and reached its maximum during Early Devonian times was sourced from the Caledonian basement exposed to the north-west. Only the southernmost clastic units, such as the Pragian to Emsian Taunus Quartzite, can be related to sources within the Mid-German Crystalline High (**Figure 5.15**). It has been estimated that Lower to Middle Devonian shelf clastics representing rift deposits may have reached a maximum thickness of more than 10 km (Oncken et al., 2000). The biostratigraphy of these deposits is mostly based on brachiopods and, to a lesser extent, bivalves and fish remains. East of the Rhine River, facies development in the north-west Rhenish Massif (Bergisches Land) is somewhat different from that of the Eifel area. Marginal-marine and continental deposits alternate several times, resulting in a quite complex lithostratigraphic scheme.

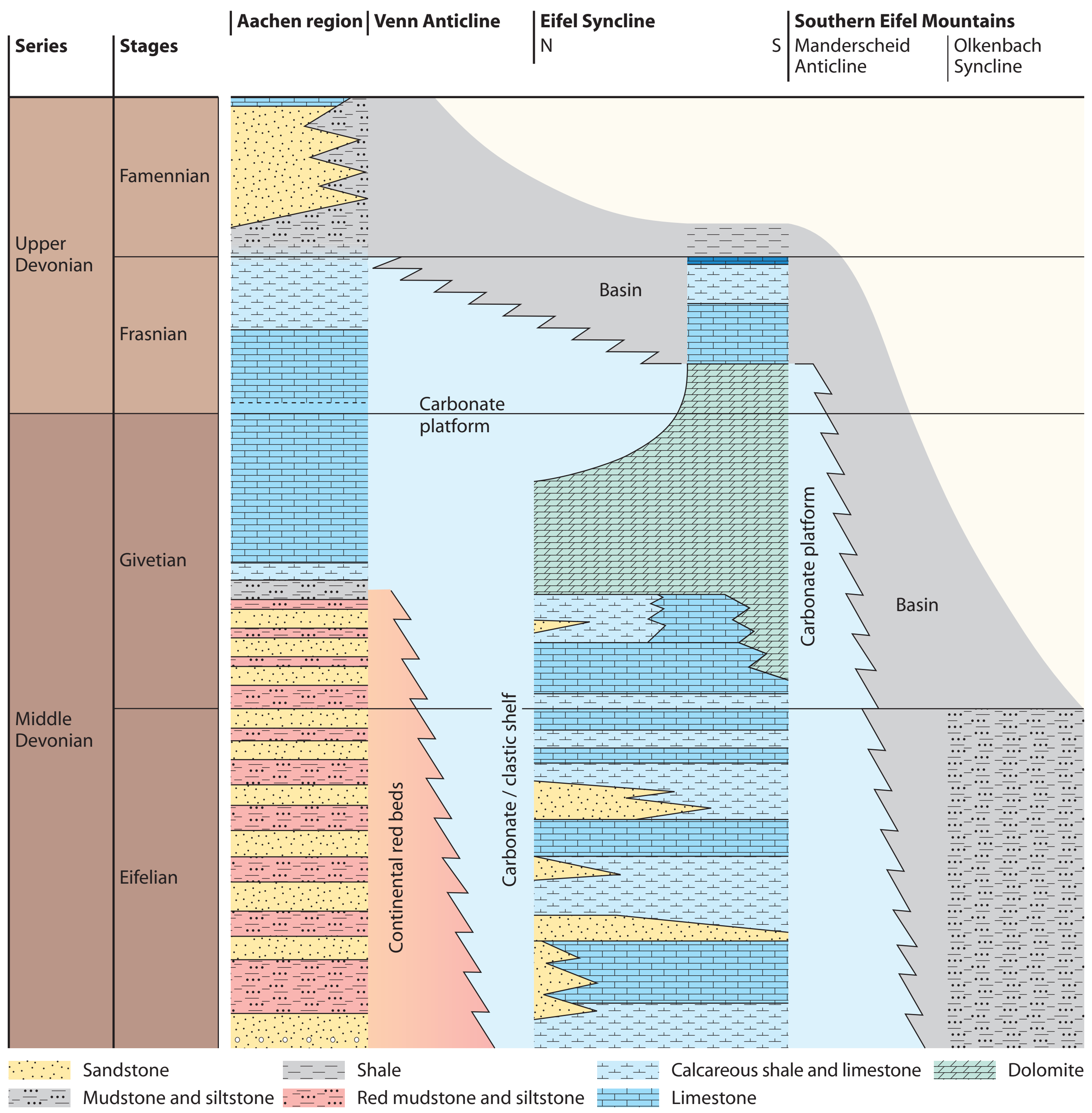

Figure 5.14 Middle and Upper Devonian lithostratigraphy and facies in the western part of the Rhenish Massif (Eifel area).

The upper Silurian to lowest Devonian fully marine succession (Köbbinghausen Formation) of the Remscheid Anticline was gradually replaced by deltaic clastics. This development led to fully continental environments during the deposition of the Bunte-Ebbe Formation. The main depocentre of deltaic strata lies in the Siegen Anticline, where they are about 6000 m thick (Oncken et al., 2000). Sedimentation of fossiliferous shales (Remscheid Formation) during the late Emsian marks the first phase of marine transgression, which was coincident with the culmination of the felsic volcanism (Hauptkeratophyr) that had been developing since the Lochkovian, mostly in the north-western part of the eastern Rhenish Massif (**Figure 5.15**). The local depocentres and volcanism were presumably related to synsedimentary faulting (Engel et al., 1983) under an extensional regime, which also led to the onset of rifting along the southern margin of Avalonia where the Rheno-Hercynian Ocean had started to open (Franke, 2000).

Middle Devonian

Three main depositional realms were established in latest Emsian and early Eifelian times (**Figure 5.15**). In the north-west, the inner-shelf environments were polarised into more proximal nearshore-marine facies with continental red beds and rare coarse-grained intercalations, whereas there were more open-marine environments to the south-east (e.g. Lenneschiefer). The biota of the inner-shelf areas include fish, eurypterids, bivalves, ostracods, rare brachiopods and abundant plants. The outer-shelf environment accumulated fine-grained sandstones with limestone intercalations and a diverse open-marine fauna with common bioturbation (Goldring & Langenstrassen, 1979). These facies graded to the south-east into a much thinner black-shale succession known as the Wissenbach Shale, with siltstone-sandstone turbiditic intercalations and a mainly pelagic fauna of cephalopods and dacryoconarids deposited in a deep-marine setting. In the Lahn-Dill area, a typical trough-high (schwellen-becken) topography began to develop due to the development of volcanic basaltic highs (**Figure 5.13**). Condensed cephalopod limestones occur on the tops of the highs, which are surrounded by shale-dominated basins. During the late Eifelian, the shelf-edge was positioned along a line running from the south-west (Siegen Anticline) to the north-east (Ostsauerland Syncline) probably controlled by a basement fault.

The Eifelian-Givetian boundary is marked by a transgressive event recorded as a tongue of basinal shales (Odershausen Beds) within the coarse-grained clastic shelf sequence. Lower Givetian deposits are similar to the underlying, mainly siliciclastic, shelf sediments. During mid-Givetian times, the sources of clastic material were less productive due to progressive levelling of the Caledonian hinterland and concomitant sea-level rise (Engel et al., 1983). The reduction in clastic input created suitable conditions for the establishment of carbonate platforms on the former clastic shelf, with the development of a widespread coral-stromatoporoid facies (Schwelm Limestone) that was succeeded by areally restricted reef complexes (Dorp Limestone). The so-called Massenkalk was widely deposited from the former inner-shelf areas to the shelf margin and upon volcanic elevations, such as in the Lahn-Dill area. The total thickness of the reef carbonates varies widely from 100 to 2000 m (Bender et al., 1977; Meischner, 1996). Dark-coloured, marly, well-bedded limestones and shales (Flinz facies) were deposited between the buildups, often with turbidites of reef-derived detrital material. In the deeper basinal areas to the south-east, continuous deposition of black shales (Wissenbach Shale) and turbiditic sandstones (Styliolina Sandstone) led to the accumulation of fine-grained siliciclastics up to 1500 m thick during the Eifelian and Givetian.

The Givetian was a time of intense submarine basaltic volcanism; in the Sauerland area, the volcanics are up to 250 m thick (Bender et al., 1977) and in the Lahn-Dill area they reach a thickness of hundreds of metres (Franke, 1995b). The volcanism has a geochemical signature that suggests a within-plate setting (Nesbor, 2004), and it contributed to the persistence of the established high-to-basin topography and the development of characteristic deep-marine volcaniclastics (Schalstein). Volcanic ridges became sites of reef growth (e.g. Dill Syncline) and consequently sources of the bioclastic detritus transported into the adjoining basinal depressions (**Figure 5.13**). Iron ores are associated with sites of submarine volcanism (e.g. the Roteisenstein-Grenzlager in the Lahn-Dill and Brilon areas; **Figure 5.12**).

Upper Devonian

The general facies distribution of the Upper Devonian succession follows the pattern of the former Givetian Massenkalk highs and the adjacent basinal areas. The stage of reef growth and the corresponding pattern of depositional systems affected by synsedimentary block faulting (Krebs & Wachendorf, 1979) persisted into mid-Frasnian times. Reefs attained a high diversity, including tabulate corals and stromatoporoids as the main frame-builders, and contained a complex array of sub-environments including fully developed back-reef and fore-reef areas with transitions to more off-reef areas (for review, see Krebs, 1974; Burchette, 1981; Machel & Hunter, 1994). In the basinal areas of eastern Sauerland, the deposition of pale- to dark-coloured banded shales (Bänderschiefer) continued throughout the entire Frasnian interval (Piecha, 1993). During mid-Frasnian times, widespread reef growth ceased for reasons that are not yet fully understood, but probably due to a combination of both global and regional factors (Eder & Franke, 1982; Narkiewicz & Hoffman, 1989). In places, the termination of reef growth broadly coincides with the appearance of the lower Kellwasser horizon (Buggisch, 1991), characteristic black, organic-rich limestones and shales, which are well known from many localities including the Rhenish area. Following the end of widespread reef growth, dark-coloured shales with calcareous nodules or cephalopod limestones were deposited in the formerly elevated areas, whereas the Bänderschiefer continued to be deposited in the deeper basins. The submarine topography was still largely controlled by inactive reef complexes and by volcanic-reef highs in the Lahn-Dill area. The topographic highs were sites of nondeposition and/or accumulation of condensed crinoidal and cephalopod limestones. During the latest Frasnian, anoxic conditions developed once again on the sea floor, and the upper Kellwasser horizon was deposited on much of the shelf. However, this event did not change the overall pattern of sedimentation that continued into the Famennian. There is evidence for a decrease in carbonate production in the more elevated and relatively shallower-marine areas during earliest Famennian times (e.g. Buggisch, 1972).

During the Famennian, the shelf margin retreated to the north-west of the Rhenish Massif near the present-day Rhine (Bergisches Land). Sedimentation was characterised by sporadic ostracod-rich shales with the intermittent influx of well-sorted sandy material that formed individual turbidites in shale successions or predominantly sandy units (e.g. middle Famennian Nehden Sandstone, or upper Famennian Dasberg Beds). The source of sandy material was the Condroz Shelf that rimmed the Brabant Massif. Red shales intercalated with nodular limestones were deposited locally in a deep-water environment (e.g. middle Famennian Hemberg Beds). The thickness of Famennian rocks decreases from about 500 m in the north-west to 150-300 m in the Lahn-Dill area. The Devonian-Carboniferous boundary occurs just above the base of the poorly fossiliferous Hangenberg Shale (Meischner, 1996).

2.4.3 Harz Mountains

The structural equivalents of the central and south-eastern part of the Rhenish Massif are exposed in the Harz Mountains (**Figure 5.1**). Whereas the north-western Harz area may be broadly considered as an extension of the Dill Syncline, the rest is mainly composed of complex, thrusted and chaotic units comparable to the allochthonous units of the south-east Rhenish Massif (Franke, 2000). The boundary runs along the north-west border of the Acker-Bruchberg Zone, which comprises the Lower Carboniferous Hörre-Gommern Quartzite. South of this line, the autochthonous basement crops out in the Elbingerode Window.

In the north-west Harz area, the autochthonous Devonian succession starts with sandstones deposited in a clastic-shelf environment (Franke, 1995b). The 600 m-thick, deep-water basinal Wissenbach Shales were

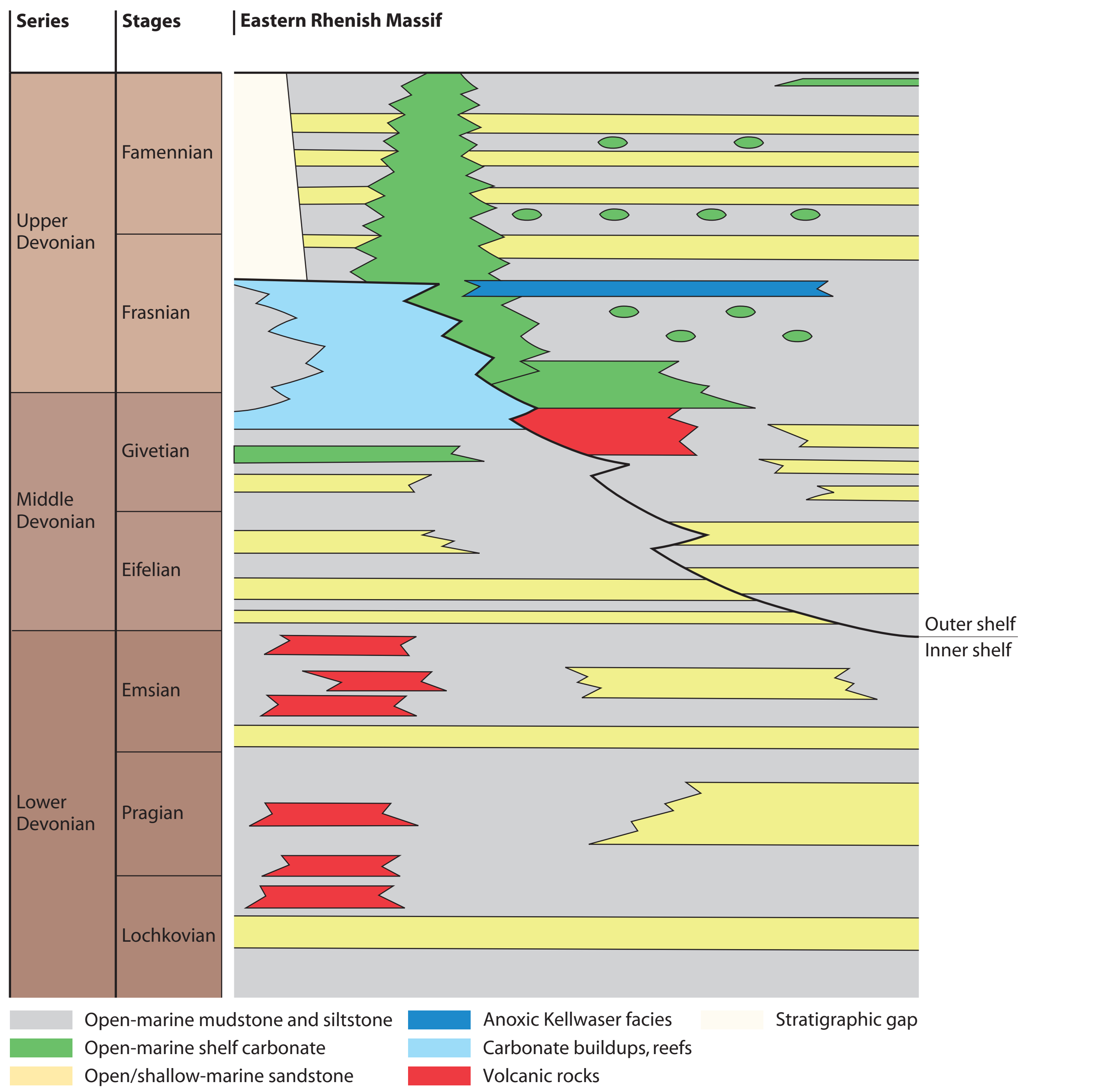

Figure 5.15 Lithostratigraphy of the Devonian in the north-eastern part of the Rhenish Massif.

deposited during the latest Emsian (Kulke, 1997). The area was subsequently influenced by the development of basaltic volcanism that continued into the early Givetian. Volcanic activity led to the development of a series of submarine volcanic complexes more than 100 m thick with pillow-lavas and volcaniclastic sediments (Alberti & Walliser, 1977). During the early Givetian, the volcanic highs became sites of reef growth as seen at Iberg (Franke, 1973) and Elbingerode. Reef development ended before the late Frasnian. In the western Harz Mountains, in a deeper-marine setting, two Kellwasser limestone levels can be observed in the upper Frasnian succession. During Famennian times, the former reefs and non-active volcanic highs (such as the Oberharzer Diabaszug) were covered by condensed cephalopod limestones, while shales with variable calcareous admixtures accumulated in the adjoining troughs (Wachendorf, 1986).

Several allochthonous units (South Harz / Selke Nappe, Blankenburg Zone, Harzgerode Zone) contain isolated tectonic slices of ocean-floor rocks (MORB-type metabasalts) overlain by Emsian to Upper Devonian shales, radiolarian cherts and limestones (Hünecke, 1995). Large isolated blocks of these strongly condensed deposits are embedded in thick flysch-type successions (greywacke turbidites and shales) that started to accumulate during the early Famennian and continued into Early Carboniferous times.

2.5 North-east Germany (Rügen area)

The Devonian succession in north-east Germany is up to 3000 m thick and was deposited in a local north-west-trending fault-bounded basin (Rügen Depression) subcropping between the Arkona and Stralsund uplifts (**Figures 5.16** & **5.17**). It lies unconformably on Ordovician rocks and is overlain either conformably by Lower Carboniferous or unconformably by Upper Carboniferous rocks. In each case, there is a significant stratigraphic gap between the Devonian and Carboniferous successions. The base of the Devonian is locally marked by terrigenous fine- to coarse-grained sediments up to 10 m thick containing late Emsian spores and plant remains (Zagora, 1995); elsewhere, deposition commenced in the Eifelian. The Middle Devonian succession is biostratigraphically documented by palynomorphs and ostracods whereas Upper Devonian sediments contain marine fauna, including stratigraphically important brachiopods and ostracods.

Eifelian strata are up to 800 m thick and are mostly nonmarine mudstones, quartz siltstones and sandstones with subordinate calcareous marine horizons. The transitional Eifelian to Givetian interval shows a lateral change from more sandy and thinner (~200 m) deposits in the north-west to finer-grained, muddier and thicker (up to 430 m) sediments in the south-east. Givetian strata are up to 700 m thick and are mainly siliciclastic rocks varying from quartz sandstones to mudstones, although the ~100 m-thick upper succession (Zagora, 1995) is grey to dark grey mudstones, siltstones and sandstones with marly intercalations and marine fossils, including brachiopods indicative of a late Givetian age (Schmidt & Franke, 1977). The total thickness of Middle Devonian strata locally reaches 1800 m (**Figure 5.16**).

The Frasnian deposits are mostly fossiliferous, commonly biostromal, limestones, which are locally dolomitised. Thicknesses decrease from 900 m in the north to about 200 m towards the south. The fossil assemblages may be diverse and include locally abundant corals, stromatoporoids, brachiopods, molluscs, crinoids and bryozoans. Terrigenous intercalations are rare and found mainly in the north-western Rügen area. Seismic data suggest that there has been synsedimentary fault activity with sediments prograding basinward from local highs of footwall blocks. McCann (1999a) took this as evidence for an extensional regime. The Famennian strata are nearly 200 m thick, and have bipartite development. The lower part is lithologically similar to the Frasnian, overlain by mixed shallow-marine carbonates (including oolites) and terrigenous brown claystones to sandstones. The total maximum thickness of Upper Devonian rocks is about 1100 m.

Devonian strata have been encountered in two wells to the south of the Rügen area, Buchholz 6 and Huy Neinstedt 1, to the south-west and west of Berlin respectively. However, only the ~500 m-thick succession in Huy Neinstedt (**Figure 5.2**) has been biostratigraphically dated as upper Givetian to Famennian deep-water mudstones and siltstones with rare limestone and greywacke intercalations (Franke, 1990).

2.6 Pomerania

The Devonian rocks of Pomerania form a north-west-trending wedge-shaped subcrop area along the Teisseyre-Tornquist Zone (**Figures 5.1** & **5.2**). Unpublished data from petroleum exploration wells in the Polish offshore sector suggest that the Devonian continues at depth between Rügen and the offshore area. The north-east limit of the Devonian is clearly erosional; towards the south-west, the Devonian strata dip progressively beneath the Permian to Mesozoic rocks of the Mid-Polish Trough and are too deep to be reached by boreholes. Devonian rocks lie unconformably on Lower Paleozoic strata of the Helgoland-Pomerania Deformation Belt (Winchester et al., 2002). The Devonian succession of Pomerania has been encountered in tens of deep wells and these data have been used by Dadlez (1978) and Matyja (1993, 1998) to establish the stratigraphic framework.

Figure 5.16 Thickness of Devonian rocks in boreholes in the Rügen region (from Zagora & Zagora, 2004). See Figure 5.1 for location.

Devonian deposition started after a period of erosion that lasted throughout much of Early Devonian times (**Figure 5.18**). The lowermost deposits are most likely early to mid-Eifelian in age (Turnau & Matyja, 2001). The sediments are siliciclastic coastal and marginal-marine facies in the north-east (Jamno and Studnica formations) grading south and south-westwards to nearshore clastic-carbonate facies (Tuchola Formation). In the middle to upper Givetian, the predominant sediments are nearshore-marine clastic and clastic-carbonate environments of the Silno and Chojnice formations (south-west) and the Miastko and Sianów formations (north-east). The uppermost Middle Devonian succession is represented by regressive nearshore-marine and coastal-clastic deposits (Wyszebórz Formation). The overall thickness of the Middle Devonian strata ranges from about 800 m in the south-east to 1360 m in the north-west (Matyja, H., 2006).

Frasnian rocks show evidence of typical transgressive development (Matyja, H., 2006). The nearshore-clastic sediments are replaced in some sections by mixed carbonate-siliciclastic, alluvial-deltaic to open-marine (outer platform) cyclically-arranged facies (Dadlez & Dadlez, 1986) succeeded by a coral-stromatoporoid biostromal platform. The total thickness of these shallow-marine sediments (i.e. Koczała Formation) ranges from about 130 to 350 m (Matyja, H., 1993, 2006). Towards the south-west they grade into more open-marine, dark-coloured marly facies (Człuchów Formation). The lower part of this unit is dark-coloured marly limestones with silty-sandy intercalations. The lower Frasnian succession is overlain

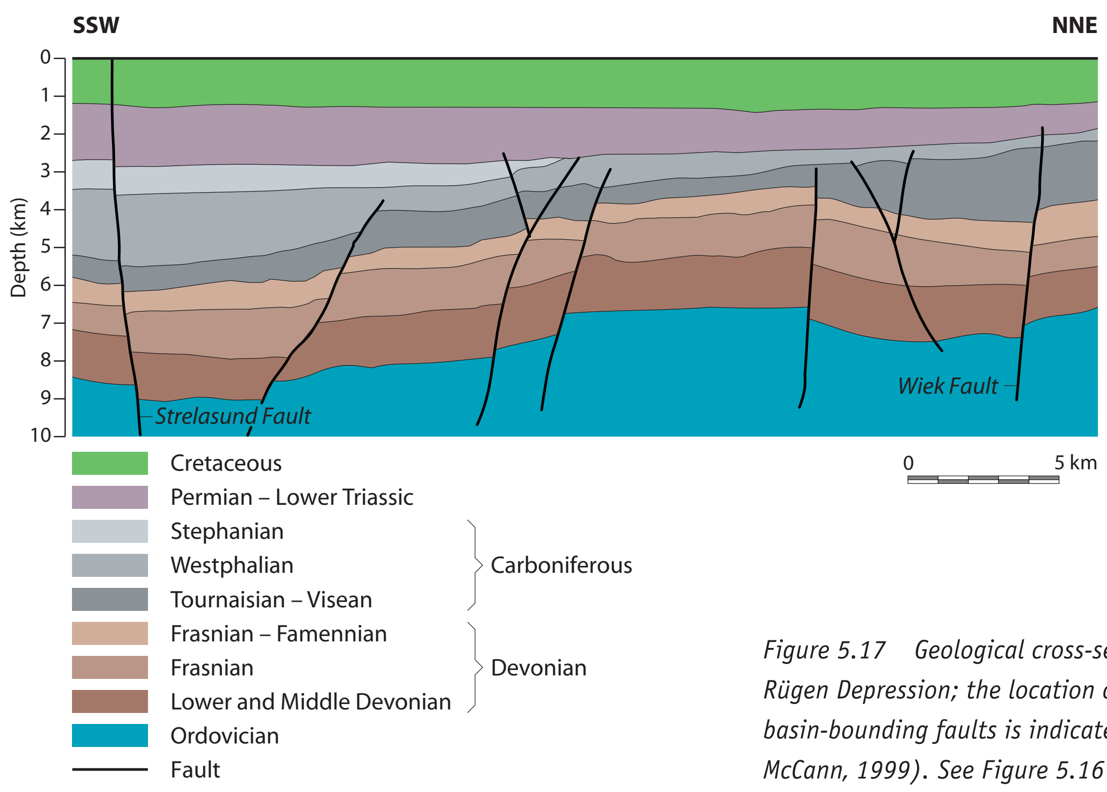

Figure 5.17 Geological cross-section across the Rügen Depression; the location of the two main basin-bounding faults is indicated (modified after McCann, 1999). See Figure 5.16 for location.

by dark-coloured, pyrite-rich, laminated mudstones up to 800 m thick, with a pelagic fauna. These mudstones have local intercalations of platform-derived debris flows. Carbonate-platform development ended with a short-lived regression during mid-Frasnian times, recorded by fine-grained sandstones up to 50 m thick with redeposited platform-derived skeletal material and intercalations of bioturbated mudstones. This unit is overlain by marly-carbonate fossiliferous deposits of an open subtidal shelf.

Following a short period of black-shale deposition, fossiliferous marls and marly limestones (up to 840 m thick) became widespread across the area during the Famennian (Matyja, H., 2006). Global sea-level rise during mid-Famennian times led to the development of stromatoporoid-coral mud mounds (60 to 220 m thick); inter-mound facies are represented by nodular bioclastic limestones. At the beginning of the late Famennian, 150 to 380 m-thick peritidal siliciclastic-carbonates with local evaporites (Kłanino Formation) were deposited in the north. These deposits grade southwards into a ~500 m-thick sequence of more open-marine carbonates (Krojanty Formation). The end of shallow-marine sedimentation is marked by the onlap of deeper-shelf marly deposits (Sapolno Formation) with an open-marine fauna (**Figure 5.18**).

2.7 Central Baltic area

The Devonian rocks of the eastern Baltic area are part of the main Devonian field, the largest continuous area of Devonian shallow subcrops and outcrops in Europe. The field extends from northern Lithuania to Latvia, southern Estonia and the adjacent Baltic Sea in the west, to Russia in the east (**Figure 5.1**). Structurally, the area is part of the Baltic Basin with an axis/depocentre that trends north-eastwards from Gdańsk Bay. The syneclise is situated between the elevated areas of the East European Platform, the Mazury-Belarus High in the south, and the Baltic High in the north and north-west.

The Devonian succession is part of the flat-lying Paleozoic cover of the East European Craton. In the axial part of the syneclise, there was continuous deposition from the Silurian to Devonian within a sequence of shallow-marine sediments. The Devonian rocks are up to 1000 m thick, for example offshore of Kaliningrad and in western Latvia. Towards the basin margins, the succession becomes thinner, and less complete, and lies unconformably on different Lower Paleozoic units and locally on the crystalline Precambrian basement. Away from the basin axis, the upper part of the Devonian succession is progressively truncated by erosion.

The Lower Devonian rocks are a regionally discontinuous unit of mostly fine-grained siliciclastic sediments, which are overall up to 300 m thick (Volkolakov et al., 1977). They are mainly alluvial to lacustrine with two levels showing a marine influence in the Pragian to lower Emsian and the upper Emsian. The younger marine bands mark the onset of the major transgression that culminated in the widespread deposition of the middle Eifelian Narva Group. These are mainly marine sediments, with thicknesses of 70 to 180 m, and consist of mudstones and marly-sandy carbonates with open-marine fossils. The upper part of the Middle Devonian succession is siliciclastic and continental with some marginal-marine influence in the presumed Givetian rocks found in Lithuania. The total thickness of the Middle Devonian strata varies between 50 and 460 m (Volkolakov et al., 1977).

The lower Frasnian succession is mainly alluvial mudstones and sandstones with red terrigenous siliciclastics in parts. They are overlain by a middle Frasnian carbonate complex, which includes fossiliferous limestones and secondary dolostones with a marine fauna, as well as beds of more restricted evaporitic facies containing dolomicrites and sulphates. The top of the carbonate succession is marked by an erosional surface, which is overlain by continental reddish mudstones and sandstones assigned to the lower part of the upper Frasnian. The upper Frasnian sediments have distinct lateral variability with continental red-bed deposits in Latvia grading northwards into open- to restricted-marine carbonates and clastics with sulphates.

The lower Famennian succession is mostly marine carbonates with an open-marine fauna and rare evaporitic-mudstone intercalations indicative of more restricted-marine environments. Upper Famennian rocks are alternating, relatively thin, siliciclastic horizons and more calcareous-dolomitic units, which represent several transgressive-regressive cycles. Restricted-marine and continental sandstones and mudstones are more common in the north, whereas to the south and west these grade into carbonates with an open-marine fauna. The total thickness of the Famennian sequence in Lithuania is about 200 m (Paskevicius, 1993), whereas the entire Upper Devonian succession is up to 500 m thick (Volkolakov et al., 1977).

2.8 South-eastern Poland

There are Devonian rocks in several regions of south-eastern Poland, which vary both in their subsidence history and depositional development. The areas largely correspond to sub-Devonian basement blocks with different Early Paleozoic accretion histories.These include from the south-west to the north-east: (1) Upper Silesian Block (outside the SPB area), (2) Małopolska Block, (3) Łysogóry-Radom Block and (4) the margin of the East European Platform in the Lublin-Lviv area. These crustal units were broadly situated in their present-day positions during Devonian times (Bełka et al., 2000). Devonian rocks are

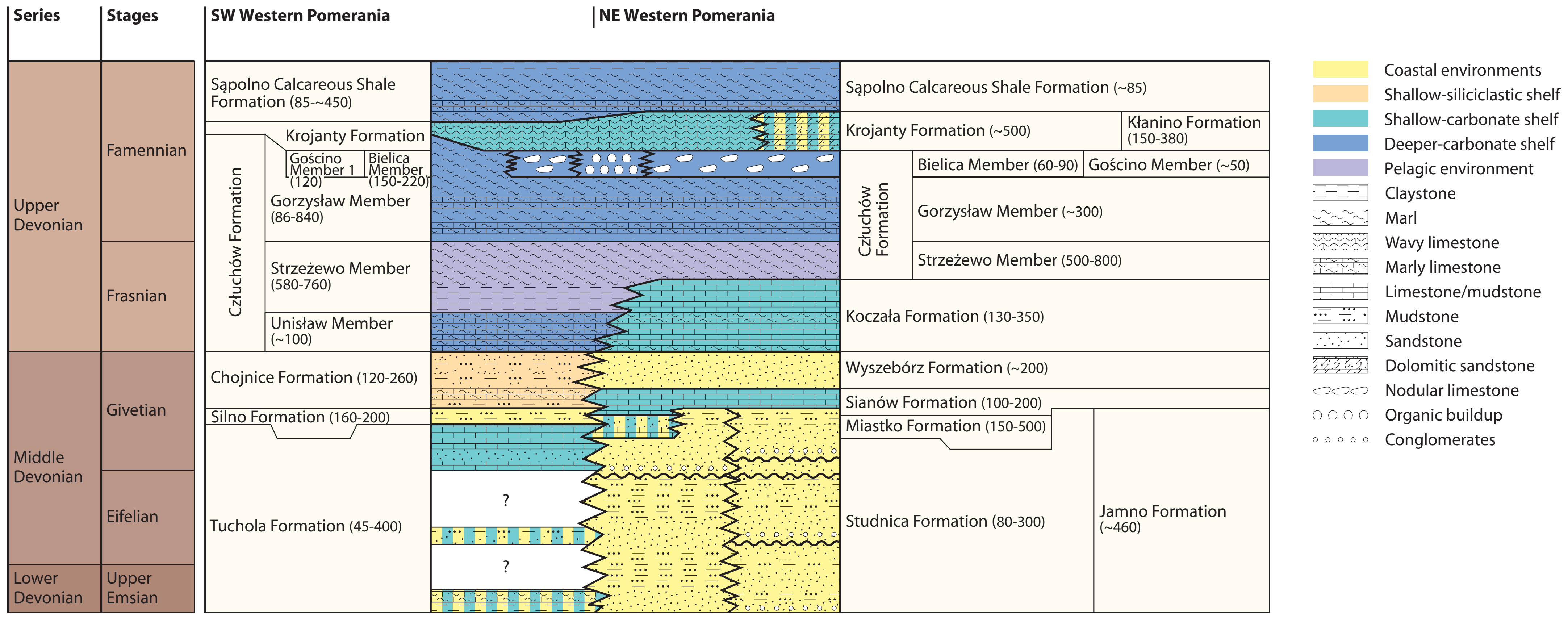

Figure 5.18 Lithostratigraphy and sedimentary environments of the Devonian of Pomerania (modified after Matyja, H., 2006). The numbers in brackets indicate thicknesses.

exposed in the Holy Cross Mountains on the Łysogóry-Radom and Małopolska blocks (**Figures 5.2** & **5.20**). Elsewhere, Devonian rocks have been encountered in numerous deep wells.

Lower Devonian

Continuous deposition across the Silurian-Devonian boundary is observed only in the Łysogóry-Radom Block and over a large part of the Lublin-Lviv area. In the former area, the Lochkovian deposits are mainly fine-grained marine clastics with thicknesses between 170 and 700 m (Miłaczewski, 1981). In Łysogóry, the lower Lochkovian deposits are mudstones (Bostów Beds) with trilobites and miospores (**Figure 5.19**) (Racki & Turnau, 2000). These sediments grade both upwards and laterally into alluvial and marginal-marine clastics (Klonów Beds) of variable thickness (up to 200 m) (Szulczewski, 1995; Kowalczewski et al., 1998). This latter unit is also found in the Małopolska Block where it includes fine- to coarse-grained clastic sediments, mainly greywackes and lithic and quartz arenites, which were deposited in alluvial fan, braidplain and braid-delta settings.

Pragian and Emsian rocks are found across most of the Holy Cross Mountains area (Kowalczewski et al., 1998). The succession, which is usually several hundred metres thick, is mainly sandy deposits of alluvial and marginal-marine facies (Barcza Beds) overlain by sandstones with clayey-silty intercalations (Zagórze Formation) that were deposited in a shallow-marine, nearshore, storm-dominated setting (**Figure 5.19**) (Szulczewski, 1995). North of the Holy Cross area, the equivalents of the Barcza Beds are the 1300 m-thick clastic deposits of the Zwoleń Formation. These sediments are mostly quartz sandstones and siltstones with horizons of pedogenic dolomitic concretions, as well as plants, fish and *Agnatha*, eurypterids and lingulids that were deposited in an alluvial environment under arid climatic conditions (Miłaczewski, 1981).

Elsewhere in southern Poland, clastic sediments ascribed to different Lower Devonian stratigraphic levels lie unconformably on an uneven pre-Devonian basement surface (**Figure 5.19**). In the southern Holy Cross Mountains these deposits, previously named the 'placoderm sandstone', may be more than 200 m thick in places. They are subdivided into lower mottled mudstones with tuffites (Haliszka Formation) assigned to the Pragian Stage, and two sandy units separated by mottled tuffites (Winna Formation), regarded as Emsian in age (Tarnowska, 1976). Depositional environments were predominantly alluvial with some marginal-marine influence along the northern margin of the area.

In contrast to previous suggestions that the provenance of the clastic material was local Lower Paleozoic rocks (Miłaczewski, 1981; Tarnowska, 1988), new isotopic data (K-Ar cooling ages of detrital mica) indicate that there are two widespread mica populations in the Lower Devonian clastics of southern Poland (Bełka et al., 2000). Both the older population, with ~470 to 460 Ma ages, and the younger, with ~430 to 420 Ma ages, are interpreted as having been derived from northerly sources dominated by upper Silurian metamorphic rocks, most probably from the Scandinavian Caledonides.

Middle Devonian

Towards the end of the Early Devonian, the overall sedimentary regime changed from siliciclastic to predominantly shaly and carbonate (**Figure 5.19**). Only in basin-marginal settings (as seen in southern Upper Silesia and the eastern Lublin area) did clastic deposition continue into Mid-Devonian times.

In the Łysogóry region, Emsian marine clastics grade upwards into a mainly marly uppermost Emsian to lower Eifelian sequence (Grzegorzowice Formation), which is fossiliferous and up to 150 m thick. This sequence is overlain by thick (up to 550 m), mainly nonfossiliferous, peritidal-lagoonal dolomites (**Figure 5.21**) that pass upwards into peritidal cycles with *Amphipora* biostromes (Wojciechowice Formation). A deepening phase, which began during the late Eifelian, is manifested by a 260 m-thick unit of fossiliferous shales (Skały Formation) that include an exceptionally well-preserved brachiopod fauna (Malec & Turnau, 1997). Deepening was interrupted by a fall in sea level during mid-Givetian times and is marked by the deposition of shallow-marine clastics (Świętomarz Formation) that reached a thickness of up to 100 m. A renewed mid-Givetian transgression led to local growth of coral-stromatoporoid buildups followed by deep-water marly deposits (Nieczulice Formation, ~350 m thick) with rare brachiopods and cephalopods (Malec & Turnau, 1997).

The highest subsidence rate took place on the shelf in the present-day Radom area north of Łysogóry, where the Eifelian sediments are mainly shaly deposits that are up to 1300 m thick (Malec et al., 1996; Narkiewicz, 2002). In this pelagic setting, the sandy equivalents of the Świętomarz Formation are only 12 m thick and were deposited during the short mid-Givetian regressive phase. The overlying shale sequence is lithologically similar to the upper Givetian equivalents in Łysogóry, but is less calcareous and contains more abundant ostracod assemblages and plant remains.

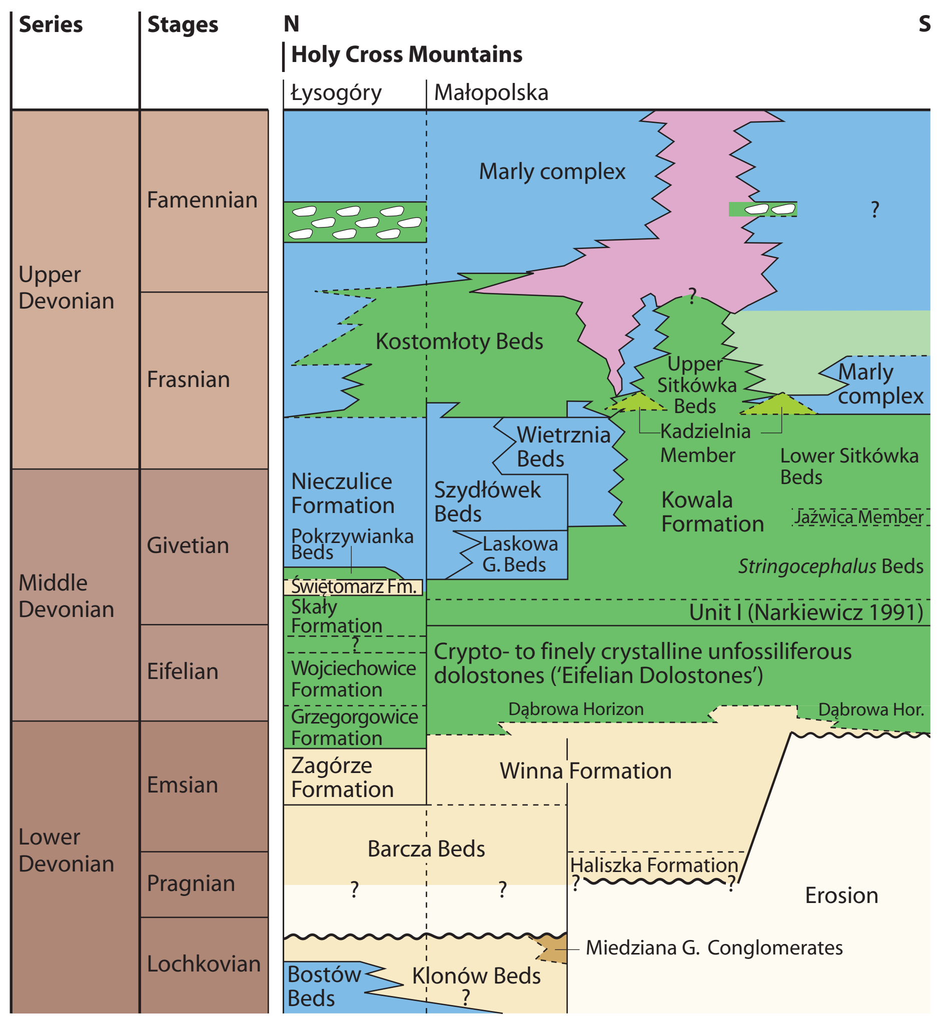

Figure 5.19 Devonian lithostratigraphy in the Holy Cross Mountains (adapted from Racki & Turnau (2000) and Racki & Narkiewicz (2000)).

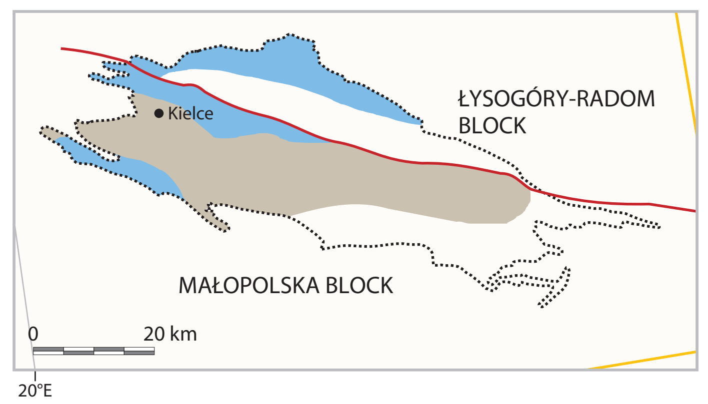

Figure 5.20 Facies distribution in the Holy Cross Mountains during Frasnian times (modified after Racki, 1993). See Figure 5.1 for loaction.

In the southern Holy Cross Mountains, which forms the northern margin of the Małopolska Block, the basal Middle Devonian succession is considered to be latest Emsian to early Eifelian in age. The deposits are open-marine fossiliferous carbonates and black shales (Dąbrowa Unit), which are up to several tens of metres thick. These sediments are succeeded by peritidal-lagoonal, usually laminated, dolomicrites. Despite the absence of biostratigraphic evidence, it is generally assumed that a shallow-marine carbonate platform dominated by coral-stromatoporoid facies (Kowala Formation) developed across the entire Małopolska area at the time of the Eifelian-Givetian transition (Narkiewicz et al., 1990; Racki, 1993). The platform's internal architecture and stratigraphy remain unknown in many places due to extensive secondary dolomitisation (Narkiewicz, 1991). The Givetian section of the carbonate-platform system is at least 500 m thick. Its basal part is formed by peritidal cycles with solution-collapse breccias marking primary supratidal evaporitic levels. These are overlain by sediments of more open-marine facies (**Figure 5.22**) comprising rhythmically bedded coral-stromatoporoid biostromes and various peritidal limestones. The late Givetian transgression led to the development of marly and detrital limestones (Jaźwica Member) with a rich

Figure 5.21 Middle Devonian dolomitic stromatolites in the Zagnańsk Quarry to the north of Kielce (Holy Cross Mountains).

Figure 5.22 Middle Devonian source rocks in the Jozefka Quarry (Holy Cross Mountains). There are numerous oil seeps in the black organic-rich marls and limestones (right). Note the contact of marls with dolomites (left) and the irregular character of the dolomitisation front.

open-marine fauna, including brachiopods, corals, dacryoconarids and conodonts. These carbonates were covered by thick coral-stromatoporoids (Sitkówka Beds) that continued into the Frasnian (**Figure 5.19**).

The Middle Devonian succession in the central Małopolska Block is similar in both lithology and thickness to that of the southern Holy Cross Mountains (Jurkiewicz 1975). However, the lower Eifelian fossiliferous Dąbrowa Unit is absent farther south in the basement of the Carpathian foredeep. Clastic deposition continued into Eifelian times and these deposits are overlain by thick coral-stromatoporoids (Kicuła & Żakowa, 1972).

The Middle Devonian sequence in the Lublin area is characterised by distinct vertical variations related to cyclic facies changes, from open-marine shelf, carbonate-platform, lagoonal facies with evaporites, nearshore clastics and an alluvial system (Narkiewicz et al., 1998). The thickness of the Middle Devonian sediments generally increases south-eastwards, reaching a maximum of 250 m. Three transgressive-regressive cycles can be distinguished, most probably controlled by global eustatic transgressions (Narkiewicz & Narkiewicz, 1992; Narkiewicz et al., 1998). In the area towards the north-east, where the East European Craton is elevated, the Middle Devonian succession consists mainly of clastic sediments that are nearshore-marine and probably alluvial in their basal part. Carbonate deposition may have commenced as late as the late Givetian or even during the early Frasnian.

Upper Devonian

Upper Devonian rocks are rather poorly documented in the northern part of the Holy Cross Mountains even though they reach thicknesses of several hundred metres. The basal Frasnian sediments are a monotonous marly sequence (Nieczulice Formation) deposited in a deep-water basinal environment, which also characterised late Givetian sedimentation (Malec et al., 1995). The overlying well-bedded carbonate mudstones and wackestones with cherts (Kostomłoty Beds) are typical of almost the entire Frasnian succession. This type of sedimentation continued into early Famennian times when the carbonates were replaced by a thick, monotonous, shaly and marly succession that partly includes nodular limestone beds, lithologies that suggest deposition in a deep-water basin.

In contrast to the Łysogóry region, the Upper Devonian rocks in the southern Holy Cross Mountains are well-documented and have considerable facies and stratigraphic variations. The lower Frasnian succession is a coral-stromatoporoid facies of a shallow-water carbonate platform (Lower Sitkówka Beds), which was bordered by intracratonic basins to the north and south (**Figure 5.19**). The internal architecture of the carbonate platform is poorly constrained by its biostratigraphy. Following the global sea-level rise during the early Frasnian, the widespread carbonate platform was reduced in size to form only isolated reef complexes (Narkiewicz, 1988). A typical example is the Dyminy Reef, which developed close to present-day Kielce, where it reaches thicknesses of 200 to 300 m (**Figure 5.2**). Within all reef complexes, a clear facies difference can be seen between the biostromal facies, similar in its lithological development to the Givetian equivalents, and the detrital fore-reef (slope) facies rimming the buildups.

Early in the late Frasnian, the reef complexes were drowned during a strong transgressive pulse preceded by forced regression; shallow-water carbonate sedimentation continued only in the central Dyminy Reef area until early Famennian times (Narkiewicz, 1988; Narkiewicz & Hoffman, 1989). The Frasnian-Famennian transition is generally associated with stratigraphic gaps (Szulczewski, 1971) separating the Frasnian buildups from the overlying Famennian pelagic sediments. These sediments are mainly condensed cephalopod wackestones with abundant nektonic (cephalopods, conodonts) and/or benthic (brachiopods, crinoids) fauna. On the flanks of the buildups, or in proximal basinal settings where the sedimentary record is more complete, there are debris-flow intercalations in sediments deposited about the time of the Frasnian-Famennian transition. These reflect episodes of erosion and re-sedimentation related to a global sea-level fall during the latest Frasnian; in places, the transition is also marked by geochemical anomalies (Racki et al., 2002). Although the growth of coral-stromatoporoid buildups ended during the late Frasnian, these structures still had a significant influence on the bathymetry of the shelf during the early Famennian. Regional extension in the Famennian caused submergence of the submarine highs and a basinal depression developed in the area of the southern Holy Cross Mountains. Consequently, the middle and upper Famennian succession consists mainly of marly sequences with numerous interbeds of nodular mudstones and wackestones. Distinct sedimentary and subsidence evolution, including deposition of condensed pelagic sediments, took place on only a small fragment of the former carbonate platform, but not before late Famennian times (Szulczewski et al., 1996).

In the Radom area north of the Holy Cross Mountains, the base of the Upper Devonian succession generally coincided with the development of a widespread carbonate platform that extended far to the east (Malec et al., 1996); however, post-Variscan erosion has removed most of the Upper Devonian rocks in this area.

In the Lublin region, the lower Frasnian succession (~100 m thick) is a carbonate-platform system overlain by a 300 m-thick carbonate ramp locally containing stromatoporoid-algal buildups. The onset of ramp development coincided with increased tectonic subsidence related to the formation of the Lublin Graben (Narkiewicz et al., 1998; Narkiewicz, 2003); in places, the Famennian succession consequently reached a thickness of about 2000 m. The base of the succession is a poorly fossiliferous sequence of marl-limestone cycles often disturbed by slumping (Bychawa Formation). These are overlain by nodular wackestones (Firlej Formation) that grade upwards into carbonate-siliciclastic sediments (Hulcza Formation) deposited in marginal-marine and continental environments along the active north-eastern basin margin. South-westwards, the succession interfingers with open-marine marls (Niedrzwica Formation) containing cephalopod fauna and plant detritus.

2.9 *Saxo-Thüringian Zone*

In the Saxo-Thüringian Zone of the Variscan Orogen, Devonian rocks are isolated in small areas within various tectonostratigraphic units (**Figure 5.23**). They are both sedimentary and metasedimentary rocks and all are situated south of the SPB margin. The Devonian rocks in East Thüringia and Vogtland are considered autochthonous. Elsewhere, Devonian strata occur in different allochthonous units in which the palinspastically reconstructed palaeogeographical arrangement is not well understood.

East Thüringia and Vogtland

The largest outcrop of Devonian rocks within the Saxo-Thüringian Zone is found in the East Thüringia-Vogtland area, where the complete Devonian succession is part of the autochthon structural level of the belt. The succession consists of pelagic sediments up to 400 m thick and volcanics deposited in a deep-water, distal outer shelf within the Saxo-Thüringian Zone (Franke, 2000). The oldest part of the succession is Lochkovian graptolitic shales. The Pragian to Givetian interval includes pelagic carbonates (wackestones) and shales, both with a very rich tentaculite fauna. During the Eifelian, the tentaculite shales passed upwards into a monotonous black-shale succession. Pelagic sedimentation was dominated by mud suspension and was interrupted in the early Frasnian by intense marine volcanism related to a pulse of crustal extension (Franke, 1993). The volcanism gave rise to 150-m thick metabasalts and tuffs that accumulated on the sea floor to form submarine highs. Coarse-grained greywackes were deposited around the highs. During the late Frasnian and the Famennian, marls accumulated on the highs, while mainly shaly sediments were deposited in the deep waters between. In the uppermost Famennian succession, there are several clastic interbeds representing turbidites derived from the active margin of the Bohemian Terrane (equivalent to the Teplá-Barrandian Terrane).

Münchberg, Wildenfels, and Frankenberg nappes

The tectonic klippes of Münchberg, Wildenfels and Frankenberg represent the allochthon structural level of the Saxo-Thüringian Zone (**Figure 5.23**). They have lithologies that were derived from the southern continental slope of the Saxo-Thüringian Zone (Franke, 2000) and are usually termed the 'Bavarian facies'. The Paleozoic volcanics and fossiliferous sediments are of very low metamorphic grade and are mainly found in the basal parts of the nappes. Devonian rocks are intraplate bimodal volcanics associated with pelites and sandstones (Wirth, 1978), but the most typical are radiolarian cherts, which were deposited on the deepest slope areas, presumably below the Calcium Carbonate Compensation Depth level. Nodular carbonate wackestones and mudstones are the subordinate lithology in the Münchberg Nappe; however, carbonates are predominant in the Devonian succession of the Wildenfels and Frankenberg units.

Elbe Valley

The Devonian rocks exposed in the Elbe Valley are mudstones, which are usually rich in tentaculites in the Lower and Middle Devonian sequence. During early Frasnian times, there was a phase of volcanic activity that subsequently controlled facies distribution in the area. The volcanic complex consists of intraplate basalts accompanied by tuffs. Local uplift supplied siliciclastic material to deeper parts of the slope. The Famennian succession includes basinal siliceous shales with cherts.

Sudetic Ophiolite

The Sudetic Ophiolite, a tectonostratigraphic unit bordering the Sowie Góry Block in the West Sudetes, is a unique part of the Variscan belt where Devonian sediments deposited directly on the oceanic crust are preserved. These rocks have never been exposed to temperatures higher than ~100°C (Dopieralska et al., 2006). The succession consists of about 60 m of Famennian carbonates overlying upper Silurian to Lower Devonian gabbros (Franke & Zelazniewicz, 2000). The sequence is easily accessible in the abandoned quarry at Dzikowiec. The base is a breccia of gabbro clasts overgrown by stromatoporoids and calcareous algae, overlain by ~50 m-thick fine-grained bioclastic wackestones to packstones (Main Limestone) typical of shallow-water deposition (Berkowski, 2002). At the top, there is a small stratigraphic gap separating the Main Limestone from the overlying Wocklumeria Limestone (Dopieralska et al., 2006). The latter is a condensed (~2.5 m thick) sequence of red, cephalopod wackestone and mudstone with a typical nodular appearance. The unit was deposited during a period of pelagic, deep-water deposition.

Świebodzice Depression

The Świebodzice Depression is a small synorogenic basin that developed adjacent to the Sowie Góry Block (**Figure 5.23**) during the Late Devonian and underwent major subsidence at that time. It contains

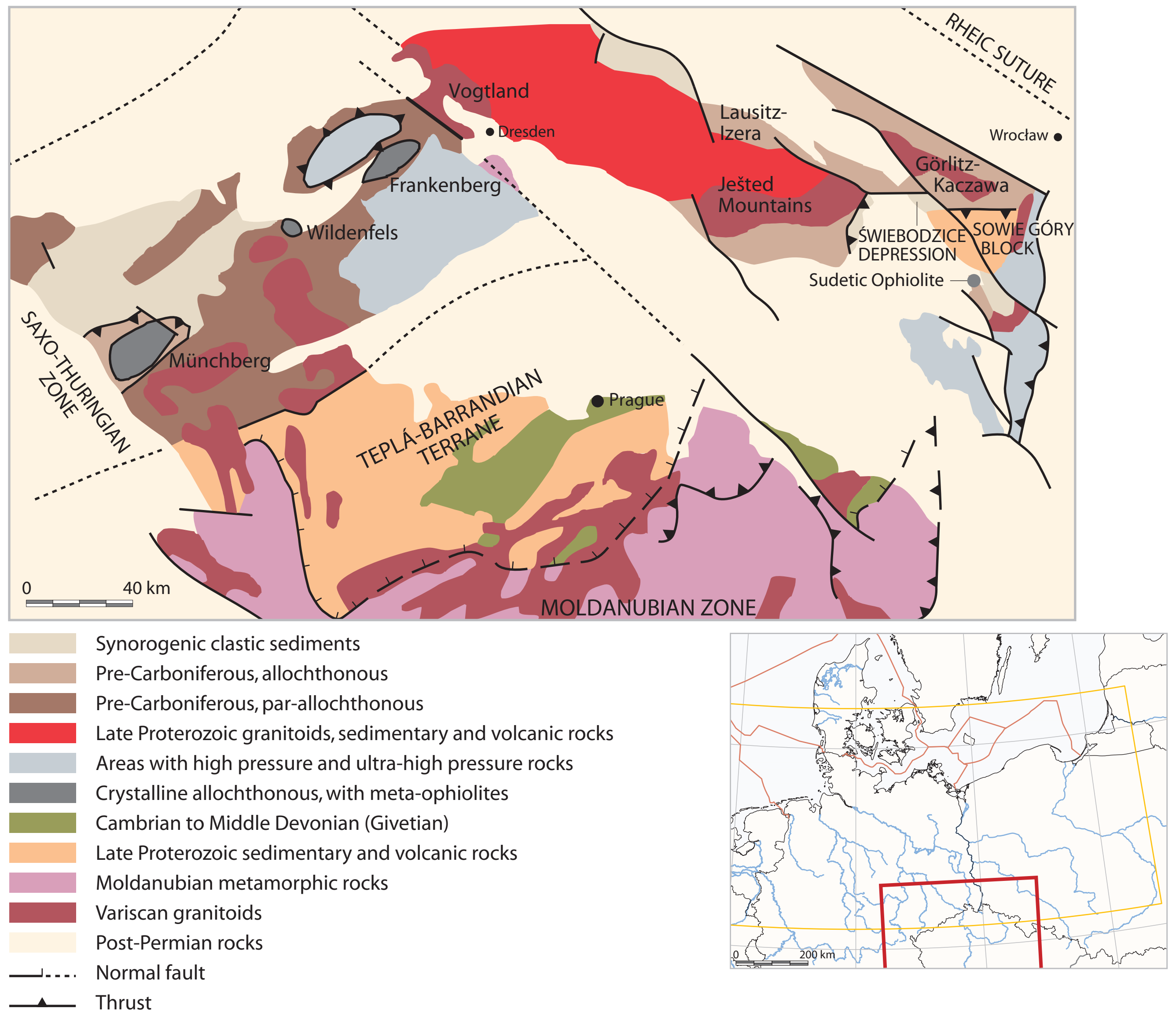

Figure 5.23 Simplified geology of the northern part of the Bohemian Massif (adapted from Franke & Zelazniewicz, 2000) showing the tectonostratigraphic units with Devonian rocks.

a 2500 m-thick succession of late Frasnian to late Famennian, coarse-grained, immature clastics that accumulated on the slope of a fan-delta and in a basin-plain depositional system (Porebski, 1981). An active fault zone separated the delta from the source area. Clastic material was deposited in alluvial fans, which then prograded into a marine environment resulting in a trend from terrestrial deposits in the south to marine sediments in the north. Conglomerates, coarse-grained sandstones and detrital limestones were deposited in the southern (proximal) area, whereas mainly mudstones and siltstones accumulated in the northern, more distal part of the basin. The coarse-grained clastic material was supplied to the fan-delta slope by sediment gravity flows. Sedimentation in the deepest parts of the depositional lobes was controlled by low-density turbidity currents, whereas in the interlobe areas it was dominated by mud suspension (Porebski, 1990). The lithologies of the clastic material suggest a provenance in the Sowie Góry Block and from another massif presumably situated beneath the Intra-Sudetic Basin, and now overlain by Mesozoic sediments.

Görlitz-Kaczawa Unit

Fragments of the Devonian succession are found within various thrust sheets of the Görlitz-Kaczawa Unit. They were all metamorphosed under greenschist facies conditions and are now a monotonous sequence of siliceous shales with rare chert or polymictic clastic interbeds (Baranowski et al., 1990). The sequence was deposited in a very deep-water basinal environment; however, it is not known if the basin was formed on continental or oceanic crust. Dateable microfossils are rare because of metamorphic overprinting, and consequently the Devonian sections are biostratigraphically poorly constrained. The Lochkovian section has been documented in a sequence of graptolite shales exposed in the western part of the Görlitz-Kaczawa Unit (Jäger, 1964). The most complete succession, which is about 100 m thick, has been recognised in the central part of the unit comprising Emsian to late Famennian siliceous shales and cherts.

Lausitz-Izera Unit

Devonian rocks are found only in a small area of the Ješted Mountains in the Bohemian part of the West Sudetes. The slightly metamorphosed succession begins with a thick volcanic complex of metabasalts and tuffs covered by phyllitic shales with intercalations of metaclastics. These are overlain by coral-stromatoporoid limestones up to 100 m thick, most probably of Givetian and Frasnian age (Chlupáč et al., 2000). The Famennian succession is a condensed sequence of nodular limestones (Zikmundová, 1964). Carbonate deposition ended during latest Famennian time and was followed by the accumulation of shales and, later in the Early Carboniferous, by greywackes (Chlupáč, 1993). The Devonian succession of the Lausitz-Izera Unit marks a progressive stepwise lowering of the sediment surface through time from a carbonate platform to a deep-water basin.