An Introduction to the Geology of Belgium and Luxembourg

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Frédéric Boulvain and Noël Vandenberghe

Abstract

Belgium and the Grand-Duchy of Luxembourg show surprising geological diversity over their small combined area of 33,114 km^2. Almost all types of sedimentary rocks crop out and are generally preserved along well-described and easily accessible sections or in quarries. Several sections are known worldwide and are visited for stratigraphic or sedimentological purposes. Magmatic rocks are not abundant and metamorphic rocks are restricted to slates. The stratigraphic scale ranges from the Cambrian to the Quaternary, which translates to a half billion years of Earth history. This chapter provides a comprehensive overview of the different stratigraphic units, starting from the oldest and ending with the youngest. Modern stratigraphic schemes highlight formations' geometries and interrelations. Some of the most remarkable units are further detailed. The two orogenic phases that shaped the Lower Paleozoic inliers and the Devonian-Carboniferous faulted and folded belt, i.e. the Caledonian and Variscan orogeny, are also addressed.

Keywords

Caledonian inliers • Variscan fold-and-thrust belt • Brabant massif • Ardenne allochthon • Mesozoic sedimentation in Belgium and Luxembourg • Cenozoic Belgian basin

2.1 Introduction

Despite the limited size of the Belgian and Luxembourgian territories, the cumulative thickness of their geological formations is thought to reach 18 km. Stratigraphically, these formations range from the Lower Cambrian to the Quaternary, with only minor hiatuses. More than a half billion years of Earth history is thus exposed.

Books and papers on the geology of Belgium and Luxembourg are too numerous to be cited here. Still worth being mentioned are the "Prodrome d'une description géologique de la Belgique" (Fourmarier 1954) and the "Manuel de la Géologie du Luxembourg" (Lucius 1952). More recently, the regional geological guidebooks 'Ardenne Luxembourg' (Waterlot et al. 1973) and 'Belgique' (Robaszynski and Dupuis 1983) must be cited. Boulvain and Pingot (2015) have proposed a synthesis of the geology of Wallonia (southern Belgium).

The subsurface of Belgium and Luxembourg is mostly characterized by the presence of sedimentary rocks. Magmatic rocks are subordinate and metamorphism has never reached more than the epizone (green slate facies). The sedimentation periods and subsequent deformation events shaped the Belgian and Luxembourgian substrates into four major sedimentary-structural units, namely (1) the Lower Paleozoic inliers, (2) the Devonian-Carboniferous faulted and folded belt including the former, (3) the homoclinal Triassic-Jurassic series and (4) the subhorizontal

F. Boulvain (✉)
Pétrologie Sédimentaire, Université de Liège,
Sart Tilman, B20, 4000 Liège, Belgium
e-mail: fboulvain@ulg.ac.be

N. Vandenberghe
Department Earth and Environmental Sciences,
Division of Geology, Leuven, KU Leuven,
Celestijnenlaan 200E, 3001 Leuven-Heverlee, Belgium
e-mail: noel.vandenberghe@kuleuven.be

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Cretaceous (4a) Cenozoic (4b) cover (Figs. 2.1 and 2.2). The faulted and folded belt includes three tectonic units, the Brabant parauthochton (BP), the Haine-Sambre-Meuse thrust sheets (HSM) and the Ardenne allochthon (AA), separated by the Midi-Eifel thrust fault (F). The Ardenne allochthon is structured in major anticlines and synclines, from north to south, the Dinant Syncline and its eastern equivalent in the Vesdre-Aachen area, the Ardenne Anticline, the Neufchâteau-Wiltz-Eifel Syncline and the Givonne Anticline.

The following provides a description of the different sedimentary units, from the oldest to the youngest. The two orogenic phases that shaped the Lower Paleozoic inliers and the Devonian-Carboniferous faulted and folded belt will also be briefly addressed.

2.2 The Caledonian Cycle: The Lower Paleozoic Inliers

The sediments that constitute the Lower Paleozoic inliers were deposited during the Caledonian sedimentary-tectonic cycle. In the beginning, Belgium and Luxembourg belonged to the Avalonia microplate, part of the Gondwana super-continent situated around the South Pole (Fig. 2.3). At the Cambrian/Ordovician transition, Avalonia separated from Gondwana and started to drift away. During the Middle and Late Ordovician (Sandbian—Hirnantian), a first continental collision between Avalonia and the Baltica microplate was responsible for the Ardenne phase of the Caledonian orogeny and, throughout the end of the Silurian, the merged Avalonia-Baltica microplates collided with Laurentia

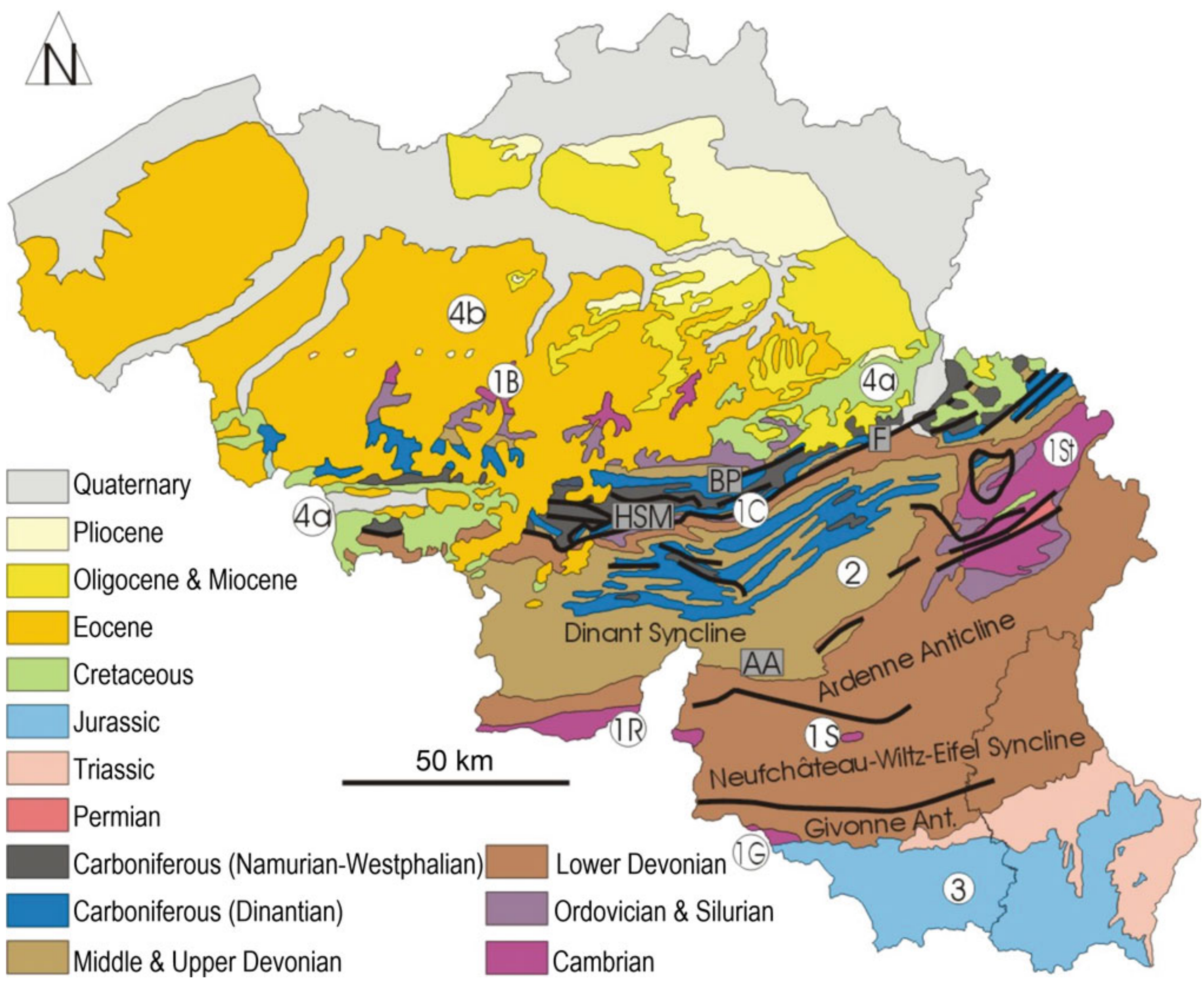

Fig. 2.1 Schematic geological map of Belgium and Luxembourg. *BP* Brabant parautochthon. *AA* Ardenne allochthon. *F* Midi-Eifel Fault. *HSM* Haine-Sambre-Meuse thrust sheets. *1B* Brabant Lower Paleozoic (LP) inlier. *1C* Condroz LP inlier. *1St* Stavelot LP inlier. *1R* Rocroi LP inlier. *1S* Serpont LP inlier. *1G* Givonne LP inlier. *2* Devonian-Carboniferous faulted and folded belt. *3* Homoclinal Triassic-Jurassic series. *4a* Cretaceous subhorizontal cover. *4b* Cenozoic subhorizontal cover. *Thick black lines* denote thrust faults

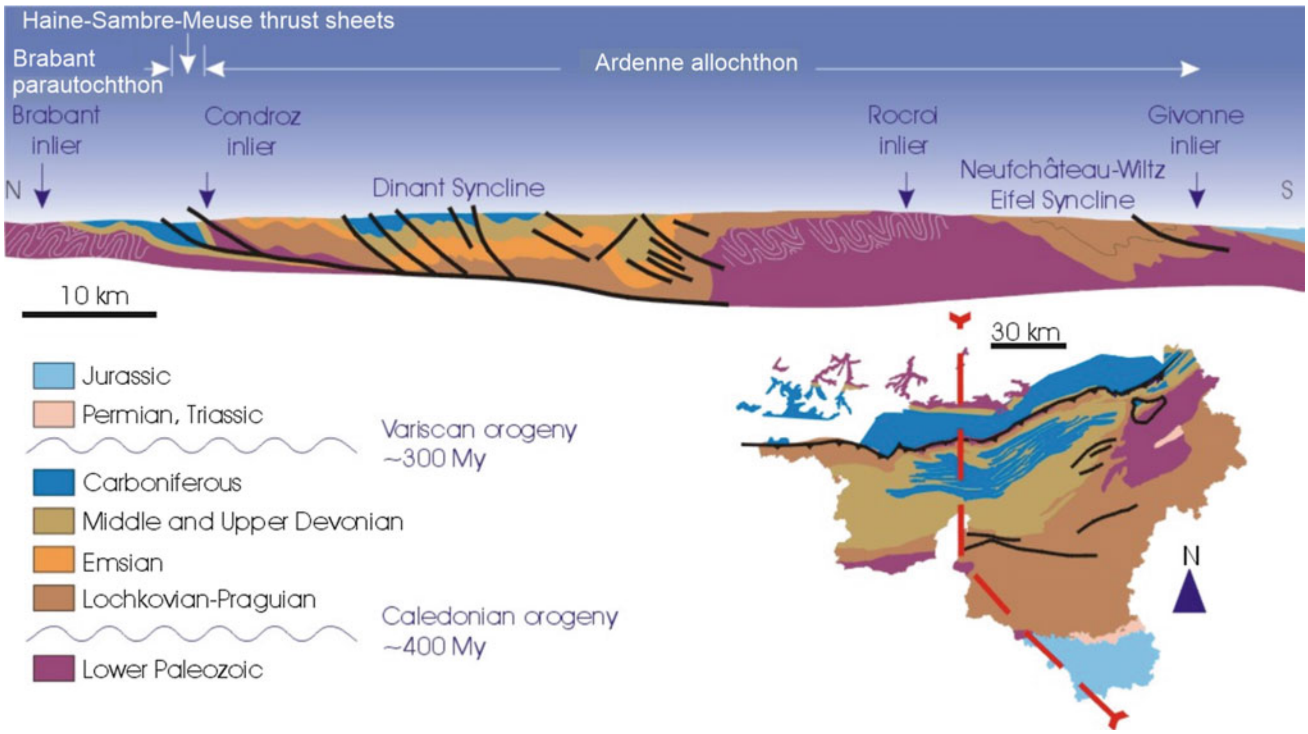

Fig. 2.2 Geological cross-section of South Belgium (Wallonia). *Thick black lines* are for Variscan thrust faults

(another supercontinent, located further north), giving rise to the Brabant phase of the Caledonian orogeny.

Six Paleozoic inliers dating back to this cycle crop out in Belgium. From north to south these are the Brabant, Condroz, Stavelot, Serpont, Rocroi, and Givonne massifs (Fig. 2.4). Sedimentation in the Condroz and Brabant inliers is so similar that Herbosch and Verniers (2014) have proposed a common sedimentary basin. The other inliers are part of the Ardenne basin, located further south.

According to geochemical studies, the Brabant Lower Paleozoic formations were deposited on a crystalline basement dated back 1800 Ma, topped by volcanic material (André 1991). This hypothesis was recently confirmed by the age of detrital zircons from the old basement cropping out in Hunsrück (Wartenstein Gneiss, Germany), related to the Panafrican orogeny (Linnemann et al. 2012).

The Lower Paleozoic sedimentation is organized in three supersequences, starting with littoral or platform sandstones and ending with deep hemipelagic or turbiditic deposits. These large-scale sequences (10–50 My) recorded major paleogeographic changes due to plate movements (Cocks and Torsvik 2002). The first supersequence spreads from the Lower Cambrian to the Lower Ordovician and corresponds to the separation of Avalonia from Gondwana, associated with the opening of the new marine domain of the Rheic Ocean. The second supersequence ends during the Late Ordovician and is likely related with the Ardenne Caledonian orogenic phase. The third supersequence is only observed in the Brabant and Condroz inliers (Table 2.1) because it developed during the Late Ordovician and Silurian, when the Ardenne was undergoing the Caledonian orogeny.

The first supersequence (Lower Cambrian-Lower Ordovician), observed in all but the Condroz inliers, is described hereafter as a representative example (Fig. 2.5, Table 2.1). Within the Ardenne massifs, the quartzitic sandstones of the Deville Group characterize the Lower Cambrian. These light-coloured, massive sandstones are believed to have been deposited on a shallow detrital platform. The Middle and Upper Cambrian correspond to the Revin Group, which are dark-coloured formations dominated by slates. Turbidites are widespread and the youngest Cambrian formation even contains black shale, suggesting a deep and anoxic sedimentation basin. The supersequence ends in the Stavelot massif with the lower part of the Salm Group, which exposes alternating green sandstone and slate strata corresponding to distal and Bouma-type turbidites (Lamens 1985).

A significant magmatic episode occurred during the Ordovician-Silurian. This episode is well documented in the Brabant massif, with lava flows, volcano-sedimentary deposits, and volcanic pipes such as the 2-km-wide Quenast pipe made of a quartz-rich microdiorite. This event is now interpreted as intracontinental calcalcaline magmatism

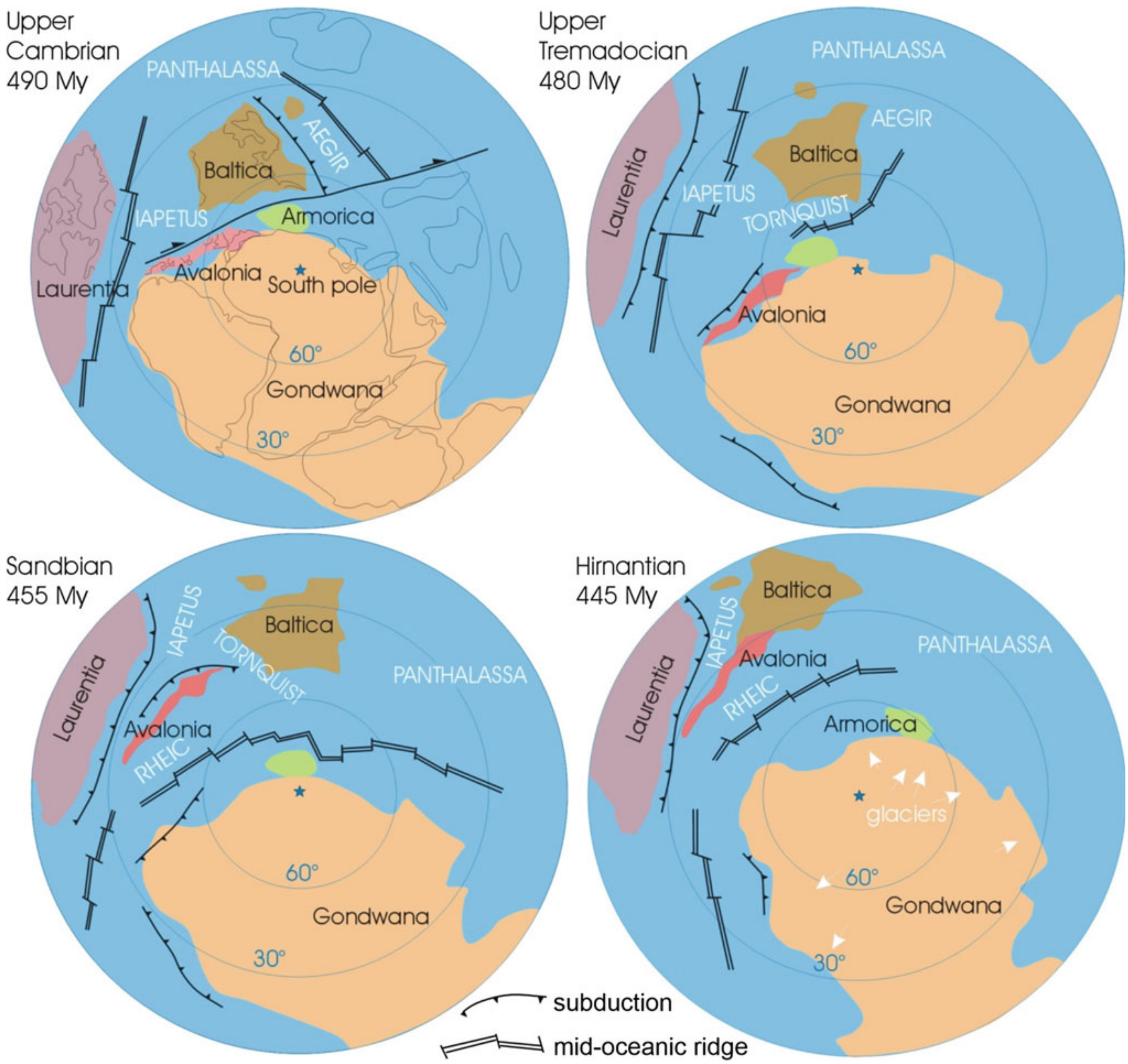

Fig. 2.3 Paleogeography of the Lower Paleozoic. *White arrows* indicate ice movements. Simplified after Cocks and Torsvik (2002)

related to the Avalonia-Baltica docking phase (Linnemann et al. 2012). It probably ended with the main compressive phase of the Caledonian orogeny.

As a consequence of the diachronism of the Caledonian orogeny mentioned above, the first post-Caledonian sediments are also diachronic, attributed to the lowermost Lochkovian in the Ardenne and to the Givetian around the Brabant massif. Another major difference is that the Variscan orogeny affected the Ardenne and Condroz inliers but not the Brabant massif, located north of the Variscan deformation front. As a result, the Ardenne and Condroz inliers were affected by two orogenic phases while the Brabant massif underwent only the Caledonian orogeny.

In the Ardenne inliers, the Caledonian orogeny is largely characterized by thrust sheets and tight north-verging folds. The presence of many slumps often obscures the structural interpretation (Meilliez and Lacquement 2006). The Condroz inlier shows south-verging folds associated with a north-dipping schistosity. With regard to the Brabant massif, Sintubin and Everaerts (2002) and Debacker (2012) have proposed a detachment mechanism between the Cambrian core and the Ordovician-Silurian border (see Fig. 2.4).

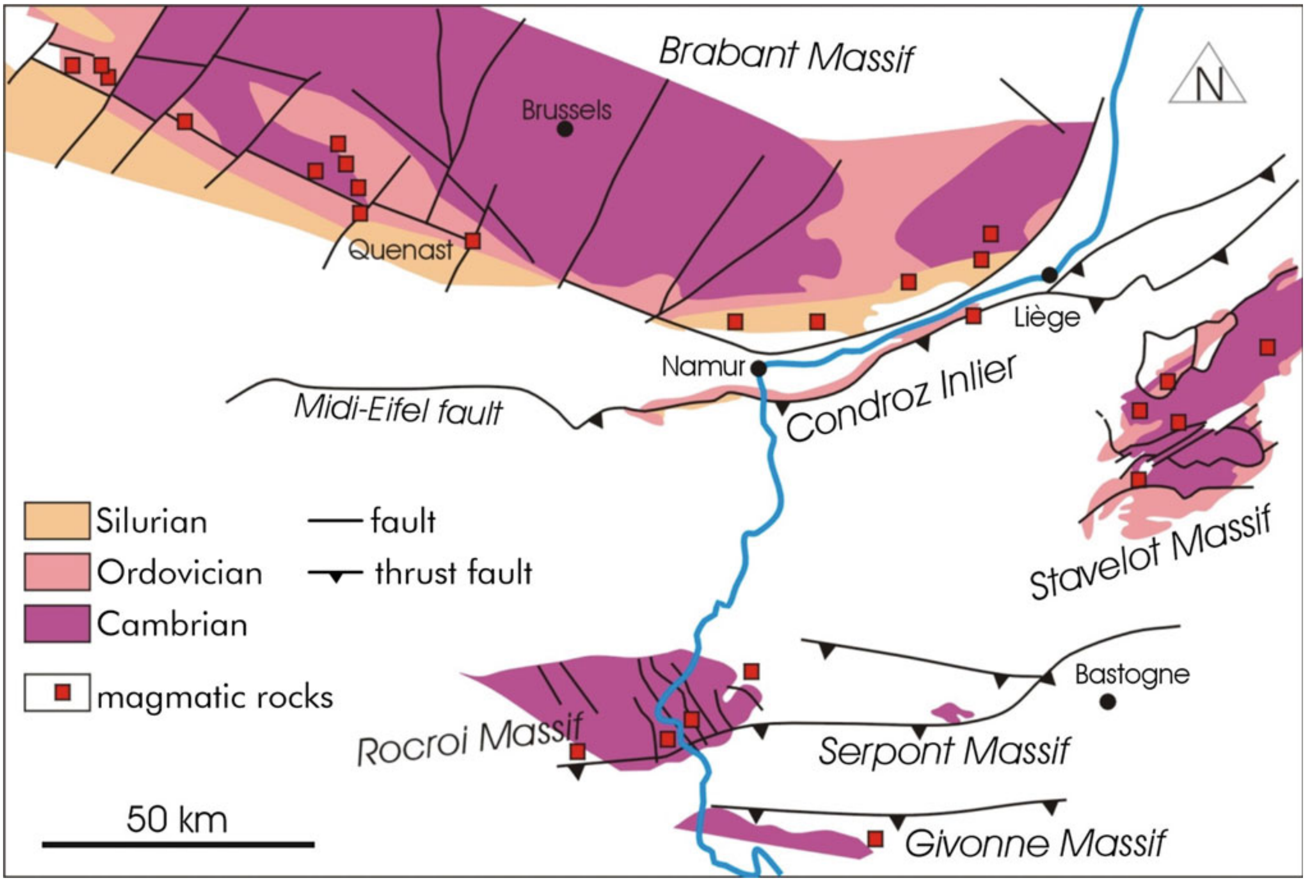

Fig. 2.4 Simplified geological map of the Belgian Lower Paleozoic inliers (below the Meso-Cenozoic sedimentary cover, compare with Fig. 2.1) (modified after De Vos et al. 1993)

Table 2.1 Age and thickness of formations in the different Lower Paleozoic inliers

Inliers	Stratigraphy	Thickness
Brabant	Lower Cambrian-Upper Silurian	>13 km
Condroz	Middle Ordovician-Upper Silurian	>1.5 km
Stavelot	Lower Cambrian-Middle Ordovician	>3 km
Serpont	Cambrian	>0.8 km
Rocroi	Lower Cambrian-Middle Ordovician?	>2.5 km
Givonne	Cambrian	>1.5 km

Indeed, the core displays steeply plunging folds associated with a subvertical schistosity whereas the borders show moderately plunging folds with a north-dipping schistosity (Debacker et al. 2005). The centripetal character of the deformation is markedly diachronic (by ~30 My) throughout the Brabant massif (Debacker et al. 2005).

2.3 The Variscan Cycle

The Variscan sedimentary-tectonic cycle took place in Belgium and Luxembourg during the Late Paleozoic. It began in the Early Devonian with renewed detrital sedimentation on the shores of the Old Red Sandstone Continent and ended with the Variscan orogeny in the Late Carboniferous. We review hereafter the successive series that make this sedimentary cycle, ending in an orogenic period responsible for the formation of the Pangea supercontinent.

2.3.1 The Lower Devonian Detrital Formations

The Lower Devonian crops out in large areas of the Ardenne Anticline, continued into the Luxembourgian Eisleck, and in the Neufchâteau-Wiltz-Eifel Syncline. Sediments mainly consist of sandstones, siltstones, slates, and shales. The

Fig. 2.5 **a** Quartzitic sandstones from the Deville Group, Rocher des Quatre Fils Aymon. **b** Black slate from the Revin Group, Saint-Nicolas. Rocroi inlier

regional seascape followed the east-west trending southern coast of the Old Red Continent, bordered by the northern Rheic Ocean (Fig. 2.6). In this passive margin setting, sediment thickness increases rapidly southward. The Lower Devonian totals 1.3 km along the northern border of the Dinant Syncline, 3.1 km along its southern border and 4.5 km in the Neufchâteau-Wiltz-Eifel Syncline (Fig. 2.7). There is no Lower Devonian sedimentation north of the Midi-Eifel Fault (Fig. 2.1). The sediment supply originated from the Old Red Sandstone Continent.

The first Lower Devonian sediments deposited on the Caledonian basement are conglomerates interpreted as continental alluvial fans (Meilliez 2006) (Fig. 2.8a). They rapidly pass upwards to versicoloured shales and siltstones including sandstone lenses (Fig. 2.8b), in patterns typical of alluvial plain and channel systems. The first marine sediments are littoral and platform sandstones/quartzites or shales/slates (Goemaere and Dejonghe 2005). They are younger along the northern border of the Dinant Syncline (Pragian) than along its southern border (Lochkovian), reflecting the progression of the Lower Devonian marine transgression. The transgression peak was reached during the Pragian, with external platform shales and slates in the south (La Roche Formation) and fluvio-littoral sandstones in the north (Acoz Formation). The Emsian shows a marked regressive trend, with fluvio-littoral environments prograding southward at the expense of the marine facies. The most spectacular unit is the deltaic Burnot Formation, which includes several hundred metres of red conglomerates, sandstones, and siltstones (Corteel and De Paepe 2003).

2.3.2 The Middle Devonian Mixed Carbonate-Detrital Formations

The Middle Devonian formations crop out along the borders of the Dinant Syncline and its eastern equivalents. They are also present in the Haine-Sambre-Meuse thrust sheets and the Brabant parautochthon.

The Middle Devonian was marked by a more drastic transgressive regime. The rising sea level was responsible for an extension of the ocean north of the future Midi-Eifel Fault, up to the Brabant parautochthon. Simultaneously, the Lower Devonian detrital facies gave way to argillaceous limestone and to first carbonated platforms (Fig. 2.6b). The Eifelian marks the transition between the old detrital and the new carbonate world. Facies are still mixed and carbonate platforms, laterally restricted, were still surrounded by shale. However, at the onset of the Givetian, a huge carbonate platform was established over southern Belgium. The contemporaneous coast was located near the Brabant massif. This spectacular development of carbonates was probably related to a warmer climate in an area that was then situated between the Equator and the Southern Tropic, combined with a dramatic decrease in detrital supply coming from the Old Red Sandstone Continent.

Along the southern border of the Dinant Syncline, the well-developed Givetian platform shows 450 m of limestone including fore-reef, reef, and lagoon environments (Boulvain et al. 2009) (Figs. 2.9 and 2.10). This thickness decreases northerly to ~100 m of typical littoral carbonates.

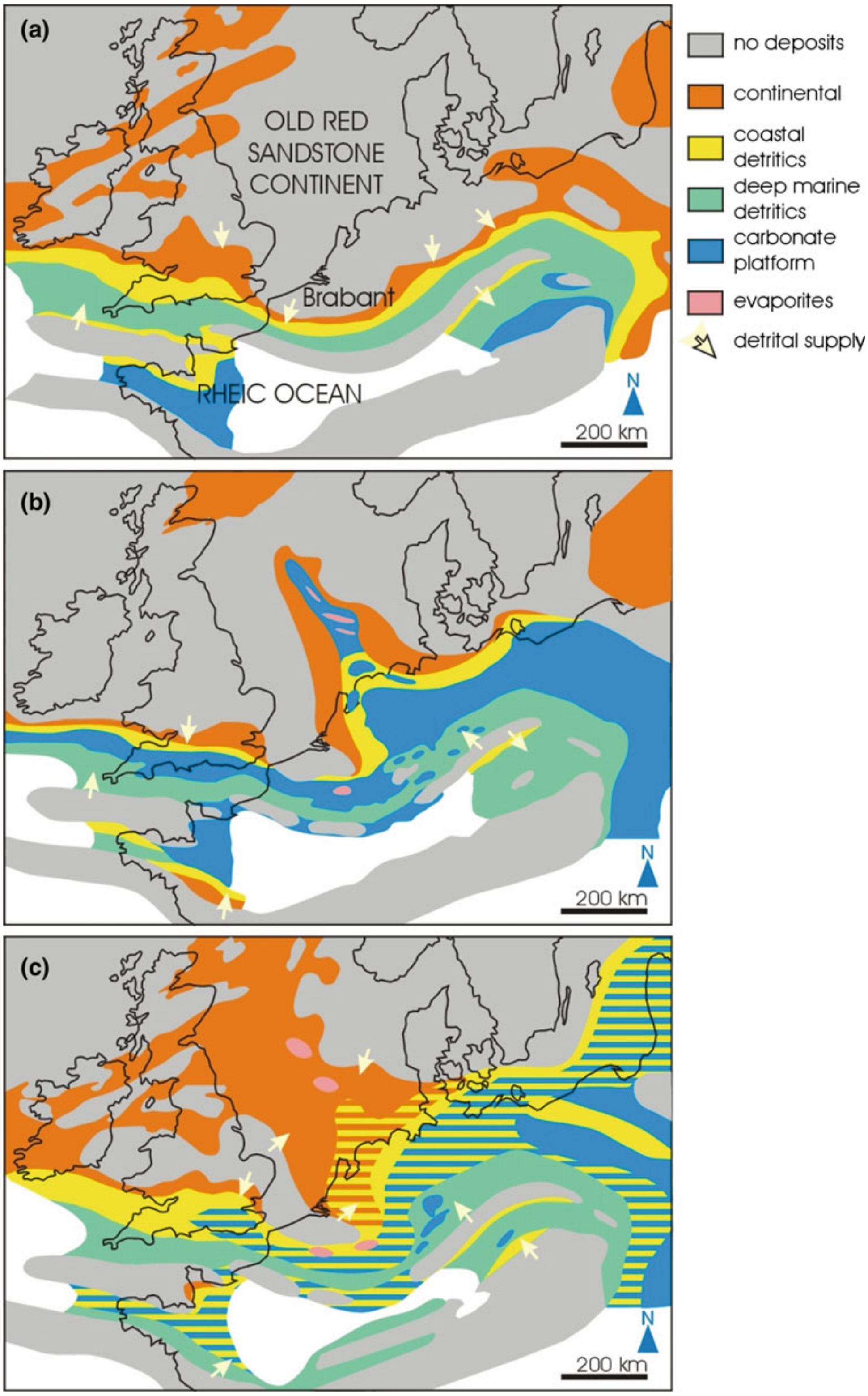

Fig. 2.6 Schematic paleogeographical maps of northwestern Europe during the Devonian. **a** Lower Devonian, **b** middle Devonian and **c** upper Devonian (simplified after Ziegler 1982)

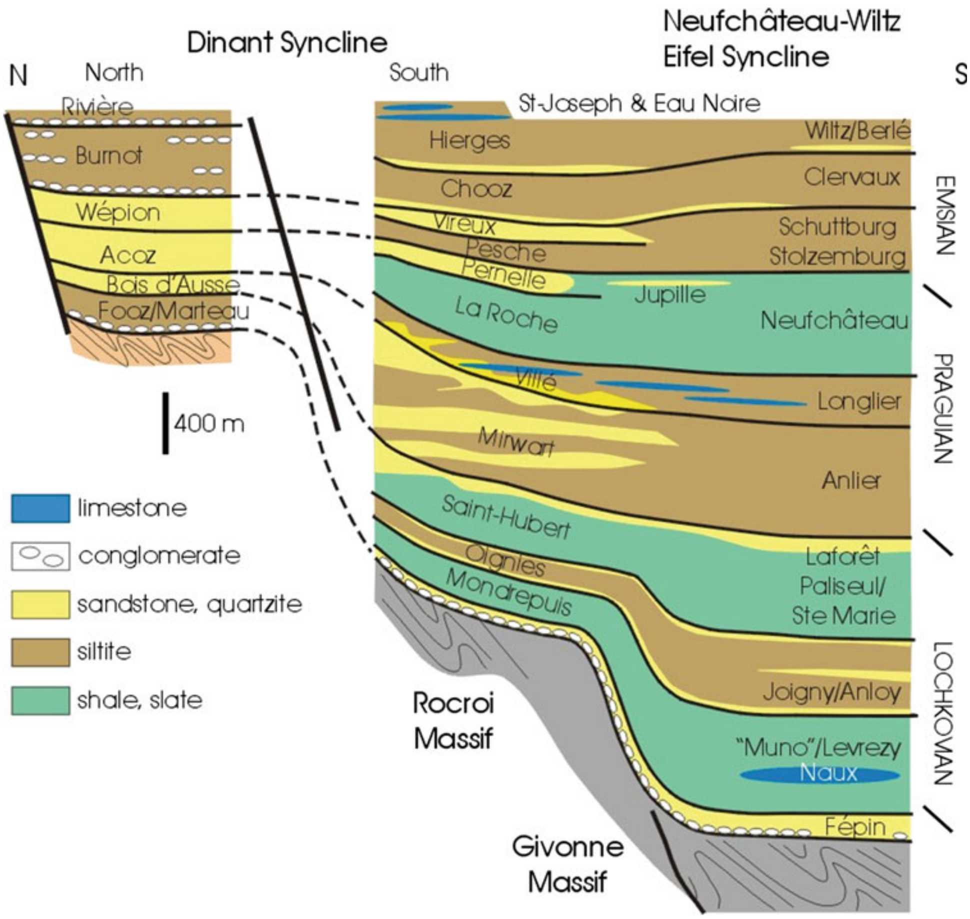

Fig. 2.7 Synthetic north-south transect through the Dinant and Neufchâteau-Wiltz-Eifel synclines before Variscan tectonism, showing the Lower Devonian formations. Lateral thickness variations are attributed to syn-sedimentary normal faults

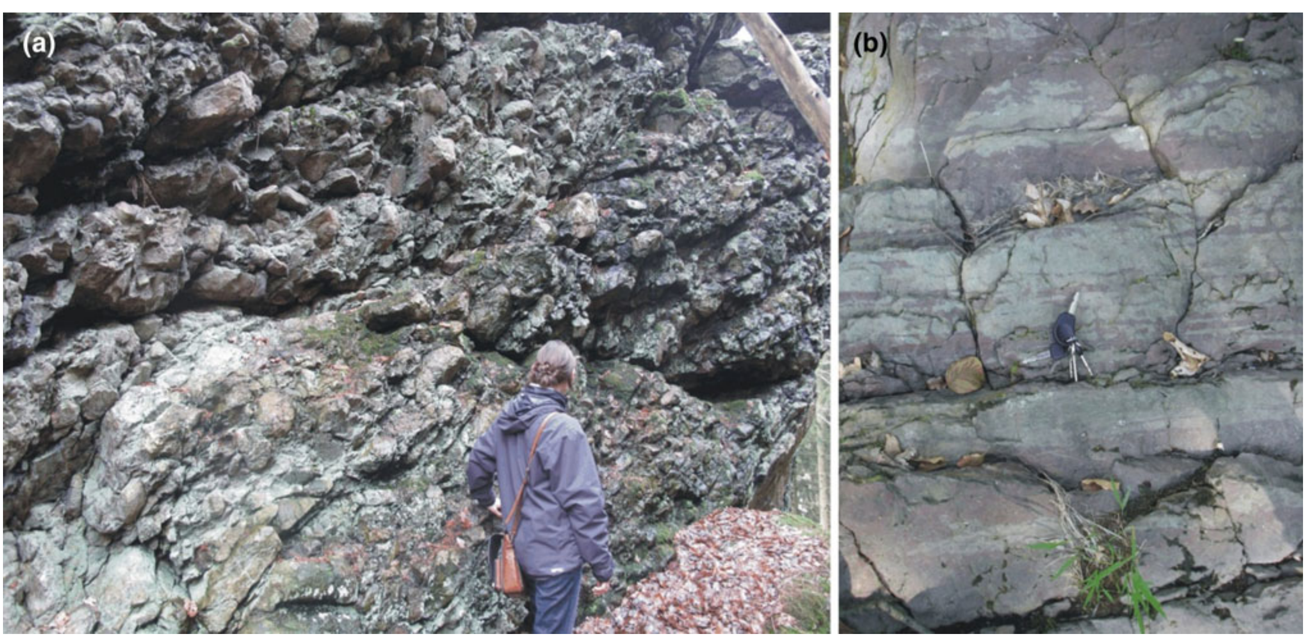

Fig. 2.8 Lower Devonian sediments. **a** Conglomerate, Ninglinspo and **b** versicoloured shale and siltstone, Helle valley. Marteau Formation, Lochkovian

Fig. 2.9 Givetian limestone. **a** Coral colonies, Resteigne and **b** coquina bed (storm deposit), Couvin

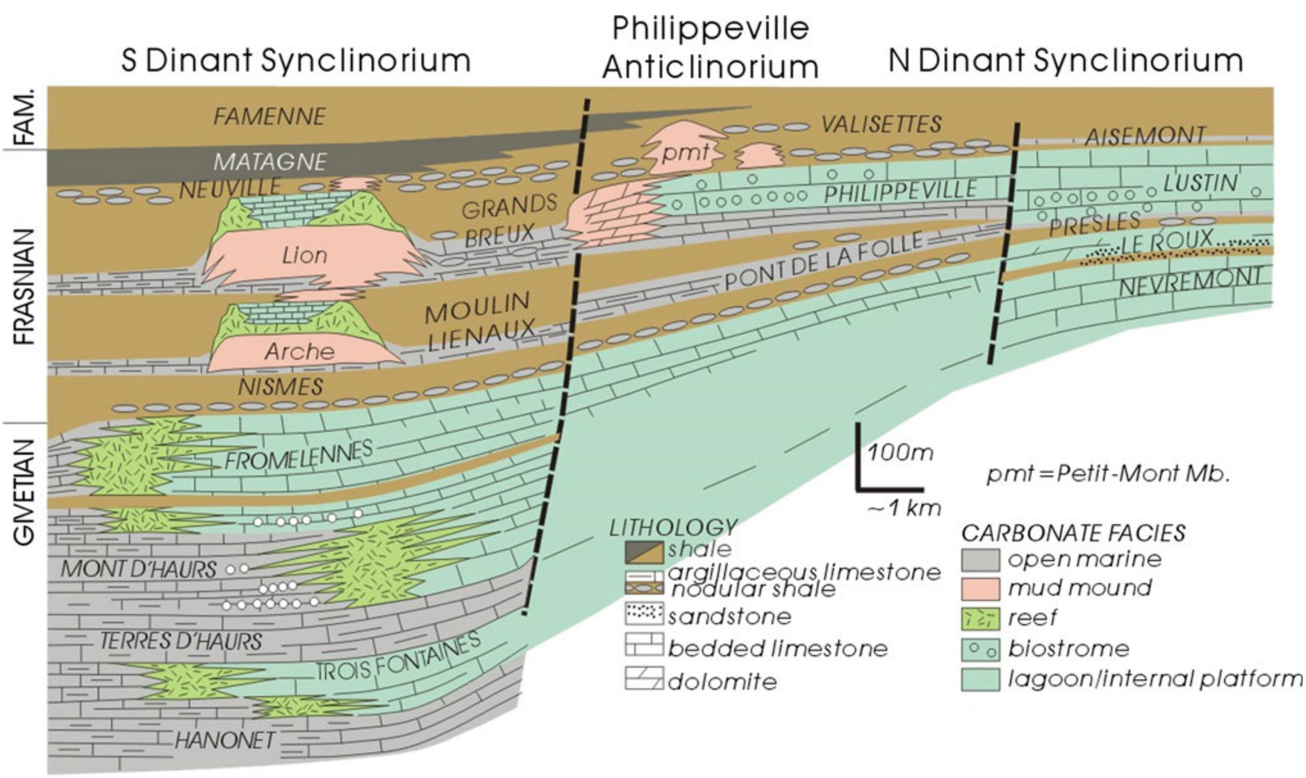

Fig. 2.10 Synthetic north-south transect through the Dinant Syncline before Variscan tectonism showing the Givetian and Frasnian formations

2.3.3 The Upper Devonian Mixed Carbonate-Detrital Formations

During the Frasnian, a transgressive phase brought the coastline farther north, perhaps flooding the entire Brabant massif. A shale unit, several tens of metres thick (Nismes Formation), concealed the entire drowned Givetian platform. After this episode, a new carbonate platform developed, shifted northward relative to the Givetian one (Fig. 2.10). The southern border of the Dinant Syncline shows three stratigraphic levels bearing Frasnian carbonate mounds (Boulvain 2007). These are, in stratigraphic order, the Arche, the Lion and the Petit-Mont members (Fig. 2.10). In the Philippeville Anticline, only the upper level contains mounds (Petit-Mont Member), the other carbonate mound levels being replaced laterally by bedded limestone, with local back-reef character. At the northern border of the Dinant Syncline and in the Brabant parautochton, the entire Frasnian consists of bedded limestone and argillaceous strata (Da Silva and Boulvain 2004).

The Frasnian Petit-Mont carbonate mounds of Belgium are probably the earliest studied among Palaeozoic carbonate mounds worldwide. This remarkable interest shown by generations of geologists derives from the outcrop number and quality, with 69 known carbonate mounds, the majority of which were actively quarried for 'marble' (this word being not used here in a strict petrographic meaning). Consequently, several hundred square metres of sawn sections are accessible for studies (Fig. 2.11). Embedded in shale and nodular shale, the Petit-Mont mounds are 30–80 m thick and 100–150 m in diameter. The initial carbonate mound facies consists of red limestone with sponges, becoming progressively enriched in crinoids and corals, then in stromatopores (calcified sponges) and cyanobacteria. The red pigment was produced by microaerophilic iron bacteria.

After the drowning of the Frasnian carbonate platform and its burial under transgressive shale, the Famennian Stage marked a seascape's complete renewal (Fig. 2.6c). A clear regressive trend brought the coastline back to the south of the Brabant massif and carbonates were replaced by detrital sediments (Thorez et al. 2006). Clastic sedimentation began with the Famenne shale, deposited below the storm wave base, followed by the Esneux Formation, rhythmically alternating shale and sandstone in the storm wave zone, and, finally, after a minor carbonate episode, the Montfort and Evieux formations, consisting in littoral and fluvio-littoral sandstones. These so-called Condroz sandstones are still used in many public and private buildings.

2.3.4 The Dinantian Carbonates

The Carboniferous in Belgium is traditionally subdivided into three series, the Dinantian, the Namurian, and the Westphalian. Carbonates, detrital sediments, and mixed detrital sediments and coal dominate these series, respectively (Fig. 2.12). During the Carboniferous, the Rheic Ocean, located near the Equator, was closing, as evidenced by the forthcoming collision of Gondwana and Laurussia (i.e., the Old Red Sandstone Continent). This major tectonic event gave rise to the Variscan mountain belt and to the formation of the supercontinent Pangea.

Following the fluvio-littoral environment of the Upper Famennian, the Dinantian sedimentation marks a return to pure marine conditions. A dramatic decrease of detrital supply favoured the resumption of a carbonate factory, and a

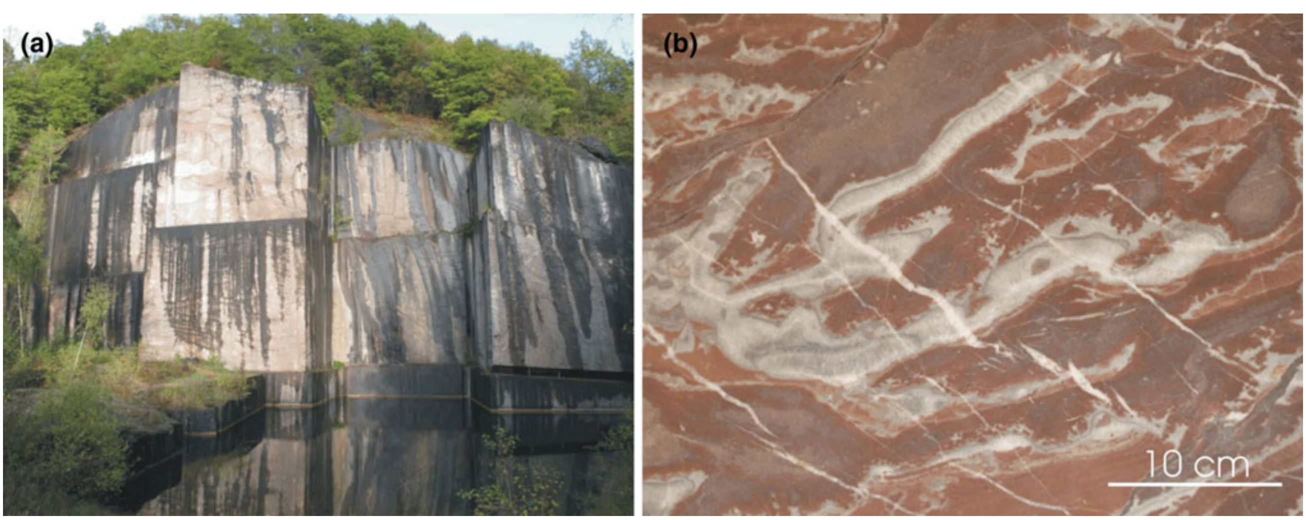

Fig. 2.11 Frasnian carbonate mounds (Petit-Mont Member). **a** The Beauchâteau mound is 30 m high and is in nearly *horizontal position*. Philippeville Anticline and **b** *red* "marble" with sponges

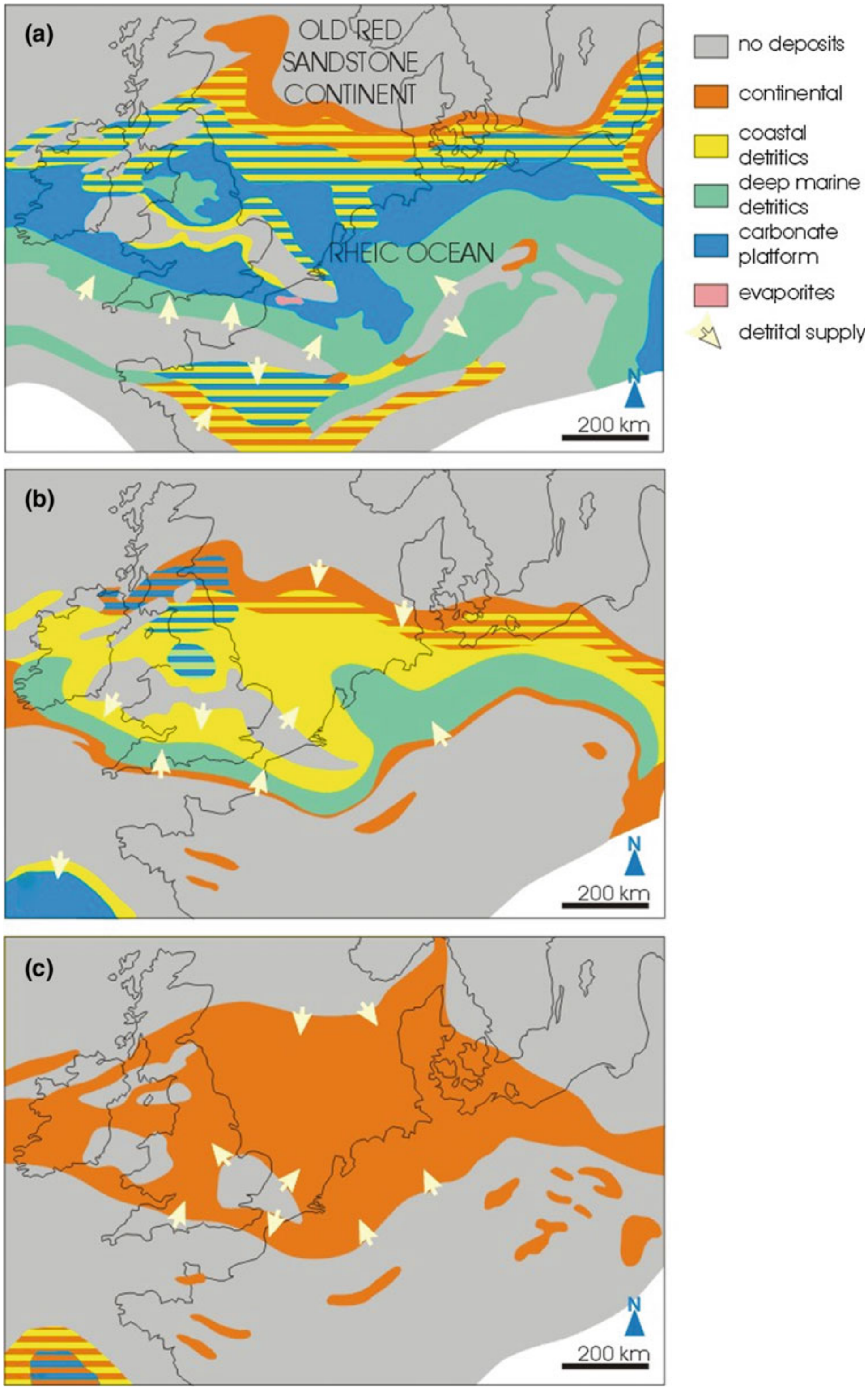

Fig. 2.12 Schematic paleogeographical maps of northwestern Europe during the Carboniferous. **a** Dinantian, **b** Namurian and **c** Westphalian. (simplified after Ziegler 1982)

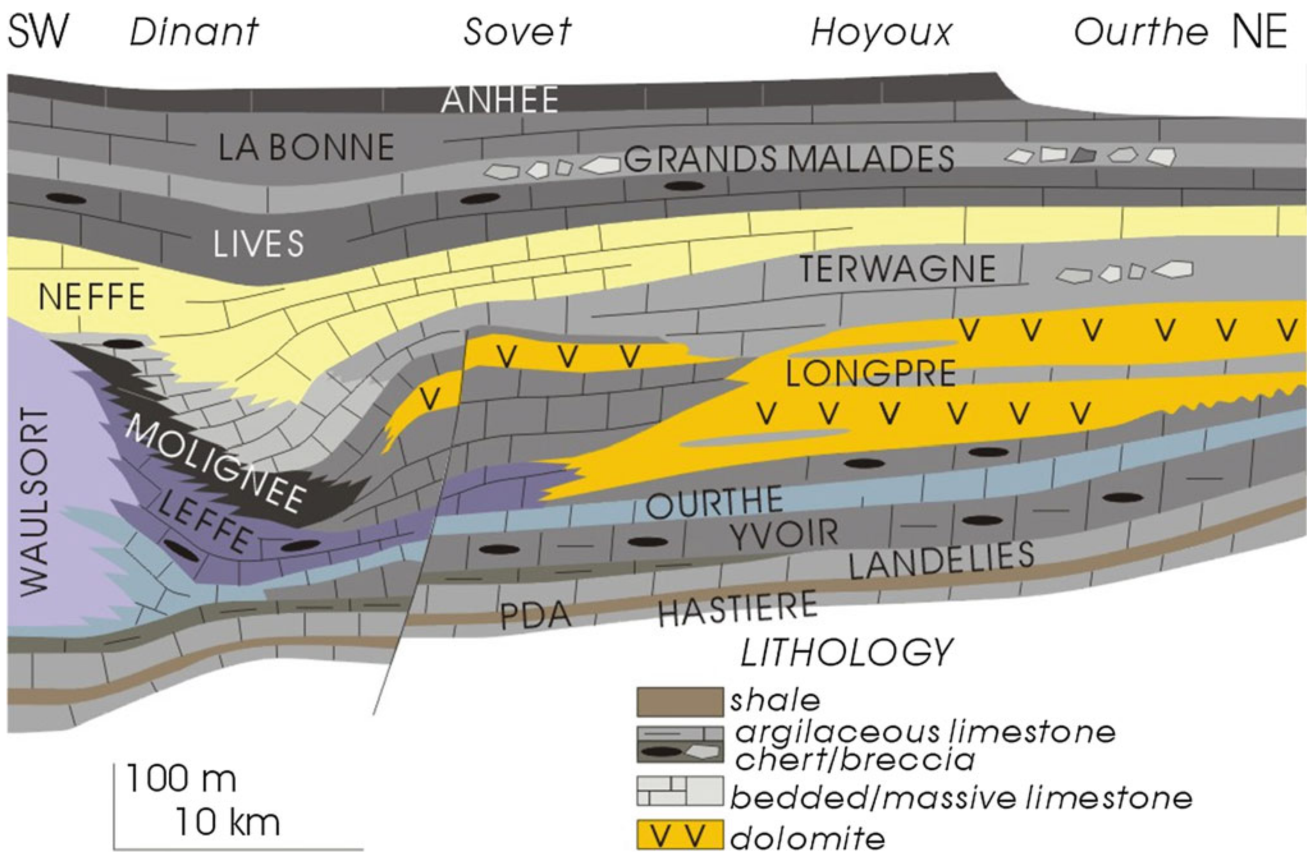

Fig. 2.13 Synthetic north-south transect through the Dinant Syncline before Variscan tectonism showing the Dinantian formations. *PDA* Pont d'Arcole. See text for explanation

large carbonate platform subsequently developed south of the Brabant massif (Fig. 2.12a). This platform was divided into several sedimentary areas with different types of limestones in variable accommodation spaces (Hance et al. 2001). The maximum thickness of the Dinantian reaches 2.5 km in the Hainaut area. Several Dinantian formations from the Dinant-Condroz areas are briefly described, because of their economic significance or international status (Fig. 2.13).

The first Dinantian formations, up to the Ourthe Formation, show only moderate lateral variation. The Ourthe Formation is extensively quarried for its crinoid-rich limestone, misleadingly known as 'Petit granit', as are several equivalent units from the Hainaut area (Fig. 2.14a). Following this formation, a significant differentiation occurred between a shallow, locally dolomitic platform (Condroz and Namur areas) and a more subsiding area where increased accommodation space allowed for carbonate-mound building (Fig. 2.13). These mounds, called Waulsortian reefs, are nearly 400 m high and are rich in bryozoans and sponges (Lees et al. 1985). They are surrounded by chert-rich flank sediments (Fig. 2.14b). The final filling of the Dinant trough included restricted fine-grained black limestone (the world-famous 'black marble' of the Molignée Formation). The subsequent Neffe Formation, consisting of bioclastic shoals, is a very pure light grey limestone intensely quarried for chemical purposes. Dissolution of evaporite beds in the overlying Grands Malades Formation was responsible for the formation of the Grande Brèche, which is a decametres-thick collapse breccia. Finally, the Anhée Formation registered a gradual decrease in carbonate production, progressively replaced by fine-grained detrital sediments.

2.3.5 The Namurian Detrital Formations

The Namurian series, corresponding to the Serpukhovian and the base of the Bashkirian, is essentially characterized by several hundred metres of black shale with subordinate marine limestone (Nyhuis et al. 2014), followed by shale and coarse-grained sandstones or conglomerates. Small beds of coal announce the future development of the great equatorial coal forest (Fig. 2.12b).

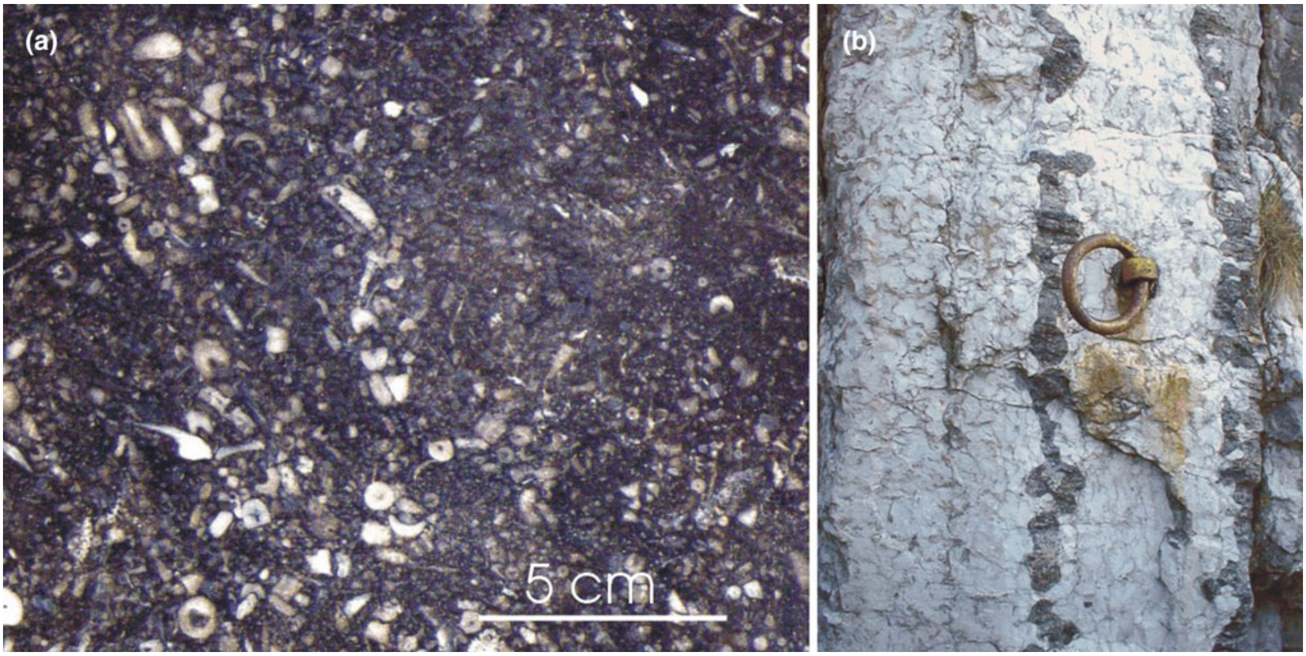

Fig. 2.14 Dinantian carbonates. **a** Polished crinoid-rich limestone (*Petit-granit*) from the Ourthe Formation and **b** chert-rich flank sediments of the Waulsortian buildups. Rocher Bayard, Dinant

2.3.6 The Westphalian Coal Measures

The Westphalian (Bashkirian-Moscovian) includes the bulk of the coal measures in Belgium. The uplift of the Variscan mountain belt led to a general retreat of the seas, giving way to extended lagoon and marsh environments (Fig. 2.12c). Huge amounts of detrital sediments coming from the Variscan mountains mixed with plant remains and accumulated in subsiding areas, now locally forming over 2-km-thick formations. Even the Brabant massif was covered by kilometres of sediment. The Westphalian sedimentation shows a characteristic cyclicity, each cycle starting with a sandstone bed, followed by a coal seam and topped by shale. The sandstone corresponds to coastal and fluvial sediments affected by soil formation and topped by organic matter from plants of the equatorial forest accumulated in a reducing swamp environment, itself overlain by floodplain and lacustrine shale. The ocean was confined to the Netherlands and made only episodic incursions, depositing marine sediments whose fossils are stratigraphically very useful.

2.3.7 The Variscan Orogeny

The remains of the Variscan mountain belt crop out from Spain to Bohemia, going through the Vosges, Massif Central, Ardenne, and Cornwall. Variscan tectonics is responsible for the general structure of Belgium, with the major Midi-Eifel thrust fault separating the Brabant parautochthon in the north from the Ardenne allochthon in the south. The Ardenne allochthon itself is structured in large-scale anticlines and synclines that extend eastward into Luxembourg (Figs. 2.1 and 2.2). The currently accepted model involves closing of the Rheic Ocean during the Late Carboniferous and continental collision between Laurussia and Gondwana (Matte 1986). Belgium and Luxembourg are part of the Rheno-hercynian fold-and-thrust belt (Ardenne allochthon) and of the Variscan foreland (Brabant parautochthon), which show the following characteristics in our region (see Fig. 2.1):

– The southern limb of the Ardenne Anticline and the Neufchâteau-Wiltz-Eifel Syncline are affected by large-scale thrust faults (Schavemaker et al. 2012). North-verging overturned folds are predominant with an axial planar cleavage.
– The Caledonian massifs (Stavelot, Rocroi, Serpont, Givonne) are polycyclic domains that were affected by both the Caledonian and Variscan orogenies. The respective influence of the two deformations is still a matter of discussion. In the Rocroi massif, for example, the similarity of major folds between the Lower Paleozoic and the Lochkovian cover, together with a cleavage affecting both units (Fig. 2.15), argues in favour of the prevalence of the Variscan structuration.
– The Dinant Syncline's southern border is characterized by north-verging overturned folds, whose inverted limbs are frequently affected by subhorizontal inverse faults. The cleavage dips south.

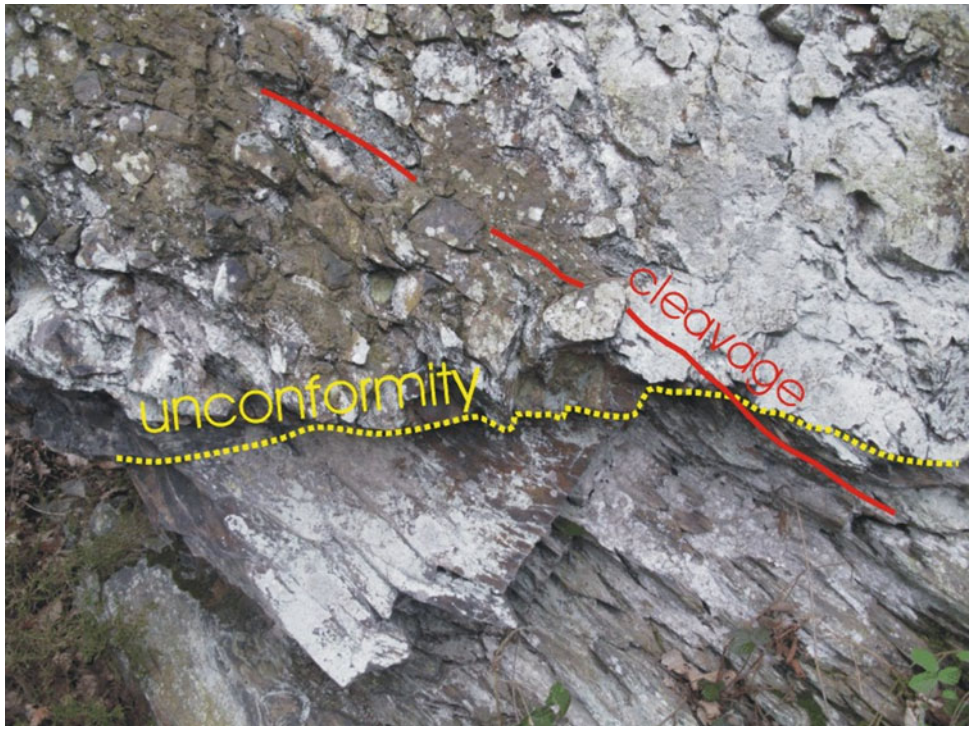

Fig. 2.15 The Lower Devonian Fépin conglomerate forms an unconformity over the Cambrian Revin Group, Fépin. Note the throughgoing Variscan cleavage

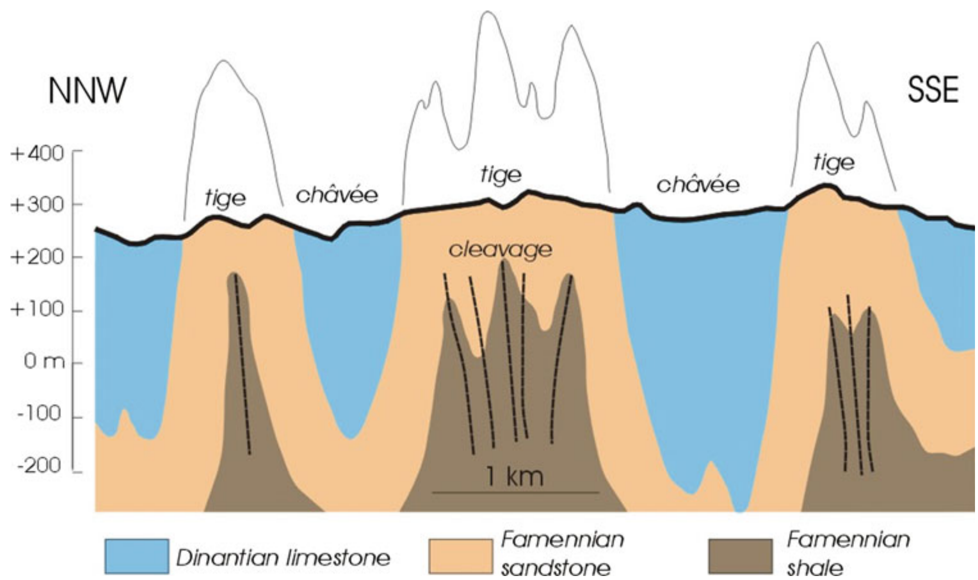

Fig. 2.16 Schematic cross-section in the Condroz area (Achêne) showing the relation between geological structure, lithology, and topography. 'Tige' and 'châvée' are the local names given to ridges and troughs, respectively. Height exaggeration 4×

– In the Dinant Syncline, folds are generally upright with a planar axial cleavage. The presence of folded sandstone and limestone formations is responsible for the development of the well-known condruzian morphology, with elongated hills following the axis of hard sandstone anticlines and troughs being cut in the soluble limestone that outcrops in the synclines (Fig. 2.16).
– North of the Midi-Eifel thrust fault, several complex tectonic units form the 'Haine-Sambre-Meuse thrust sheets' area as a consequence of the thrusting of the Ardenne allochthon onto the Brabant parauthochton (Belanger et al. 2012) (Fig. 2.17). Beds are vertical or overturned and longitudinal faults are common.
– North of the Haine-Sambre-Meuse thrust sheets, folds, and faults are weakly developed and the beds of the Middle Devonian-Carboniferous Brabant parautochthon cover the Brabant massif with a dip of 10°–20° to the south. Theoretically, the Variscan front is located north of the last deformational structure observed in the Brabant parautochthon.

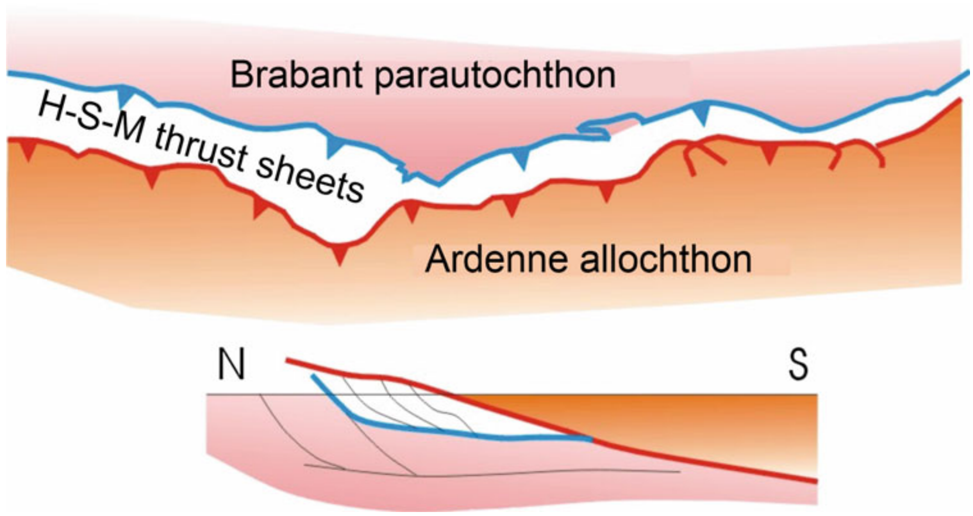

Fig. 2.17 Tectonic relations between the Haine-Sambre-Meuse (H-S-M) thrust sheets and the Ardenne allochthon, in map view and cross-section

A well-developed, though low-grade, metamorphic phase (anchizone-epizone, around 400 °C) is recorded in the Ardenne (Fielitz and Mansy 1999). Geographically, this narrow, ~120-km-long metamorphic area extends from SW Ardenne to N Luxembourg. The Variscan metamorphism was responsible for the transformation of shale into fine slate, used locally for roof tiles. The age of the Variscan metamorphism is pre-orogenic, probably related to burial.

2.4 The Post-orogenic Times

Since the Variscan orogeny, no tectonic phase has affected the Belgian and Luxembourgian regions other than through far-field epeirogenic effects and limited brittle deformation (Vandycke 2002; Havron et al. 2007; Demoulin and Hallot 2009). However, limited subsidence has made further sedimentation possible. Homoclinal or horizontal unfolded formations have been locally accumulating from the Permian to the present.

During the Permian, the Pangea supercontinent moved into an arid climate, due to generalized continental conditions induced by its huge surface. Permian formations are uncommon in Belgium and Luxembourg, cropping out only in the Malmédy graben of NE Ardenne (alluvial fan conglomerate) and determined in the deep subsurface in the Campine basin (Dusar et al. 2001).

2.5 The Homoclinal Triassic-Jurassic Series

The geodynamic context of the Mesozoic series is that of the break-up of Pangea. Epicontinental seas, connected with either the Paris basin or Germany and the Netherlands, episodically covered our countries. Climate was still warm due to low latitude, and the erosion of the Variscan mountains brought large amounts of detrital material into the seas. It was not until the Middle Jurassic (Bajocian) that a carbonate factory started up again (Fig. 2.18a, b).

The Triassic-Jurassic series are confined to the Belgian Lorraine in SE Belgium and Guttland in Luxembourg. Together with a very low dip angle to the south, alternating weak and hard strata have been responsible for the development of cuestas (Lucius 1952; Maubeuge 1954; see also Chap. 23). The earliest formation covering the Ardenne-Eisleck basement corresponds to alluvial systems (clay and gravels of the Habay Formation in Belgium, red sandstones from the Buntsandstein in Luxembourg, Fig. 2.19). Their age is gradually younger westward because the Triassic coastlines progressed from east to west (Fig. 2.19). The first marine influence is recorded by the Muschelkalk formations in Luxembourg, with sandstone and marls with evaporites and encrinites. In Belgium, the first marine unit is the Attert Formation with clay and dolomitic marls including evaporitic pseudomorphs. The Mortinsart Formation ends the Triassic marine transgressive cycle with littoral sandstone and marls, topped by alluvial clay.

The Jurassic marine transgression was more important and deposited several tens of metres of alternating calcareous marls and sand or sandstones. The prominent Luxembourg Formation consists of alternating littoral sand and sandstone reaching nearly 100 m in thickness (Van den Bril and Swennen 2009) (Figs. 2.19 and 2.20). The upper part of this diachronic formation, still actively exploited for building stone, grades laterally eastwards into the marls of the Arlon Formation. Pliensbachian and Toarcian formations then correspond to fine-grained dark marls, locally rich in organic matter, indicating quiet sedimentation conditions on an anoxic sea floor. In Luxembourg, the top of the Toarcian is sandier with ironstone beds (the '*Minette*'), which fully

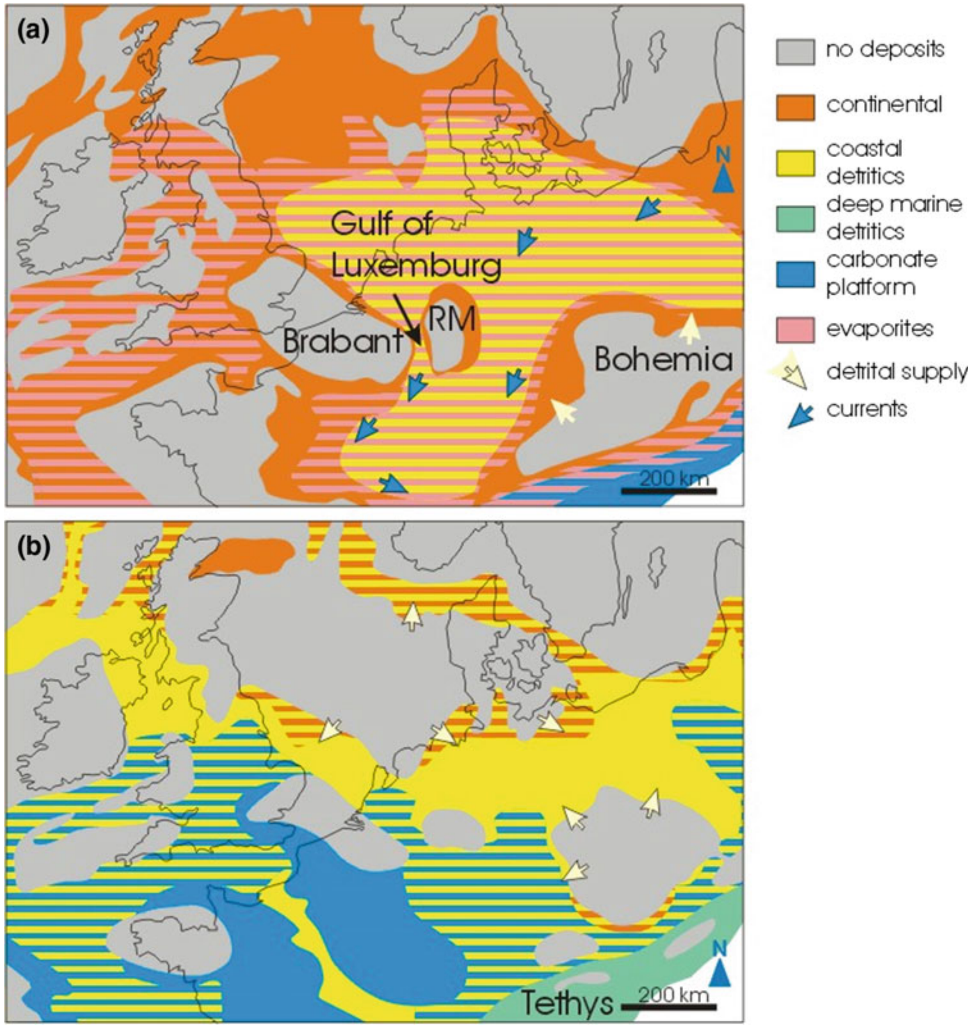

Fig. 2.18 Schematic paleogeographical maps of northwestern Europe during the Triassic and the Jurassic. **a** Keuper and **b** Sinemurian-Aalenian. *RM* Rhenish massif (simplified after Ziegler 1982)

developed through the Aalenian (Bintz and Storoni 2009). In Belgium, the contemporaneous beds were largely eroded during an episode of emersion. The end of the Jurassic sedimentary record occurred during the Bajocian in both countries. This stage is characterized by the development of a carbonate platform. In Luxembourg, the Audun-le-Tiche Limestone includes spectacular 20-m-thick, 200-m-wide coral reefs.

2.6 The Cretaceous Cover

During the Cretaceous, Pangea was fully broken up. The newly formed Atlantic Ocean started to influence our regions, and Belgium and Luxembourg reached latitudes between 40° and 60°N. The Late Cretaceous was remarkable for its very high sea levels, turning Europe into an archipelago (Fig. 2.21). In Belgium, Cretaceous units crop out in the Mons basin and in the Tournai, Hesbaye, and Herve regions (Fig. 2.1). Though largely dominated by chalk that accumulated from the Coniacian (Mons basin) or the Campanian (Hesbaye and Herve areas) to the Maastrichtian, other types of sediments are also represented.

As an example, the Mons series is briefly described (Fig. 2.22). During the Early Cretaceous, continental facies corresponded to Wealdian alluvial gravels, sands, clay, and lignite. In the north of the basin, Wealdian sediments filled sinkholes where the famous iguanodons of Bernissart were notably trapped (Bultynck 1989). Then, the Albian Sea, coming from the Paris basin, flooded the Mons gulf and deposited littoral gravels, glauconitic sand and sponge-rich marls. The Cenomanian and Turonian stages are characterized by glauconitic marls and silicified limestone (e.g., Baele 2003). From the Coniacian onwards, the detrital supply vanished and the chalk sea was installed in the Mons region. Some Maastrichtian chalk units are sufficiently rich in phosphate debris to justify underground mining. In the Hesbaye-Herve region, the chalk sea was established only in the Campanian, probably in parallel with the complete flooding of the Brabant massif (Felder 1975).

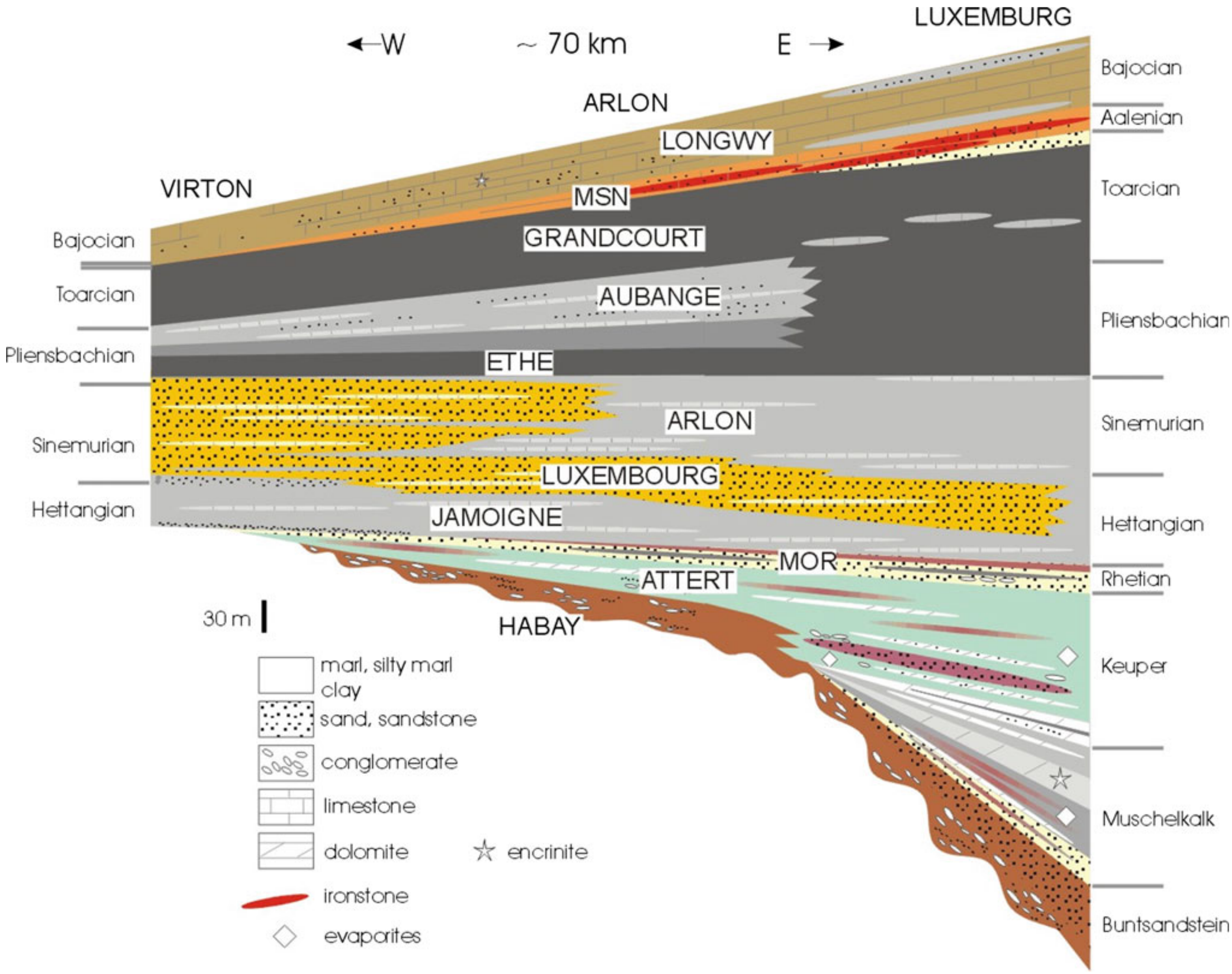

Fig. 2.19 Synthetic east-west transect through the Triassic-Jurassic cover of Belgian Lorraine and Luxembourgian Guttland. *MOR* Mortinsart Formation. *MSN* Mont-Saint-Martin Formation (modified after Boulvain et al. 2001)

2.7 The Cenozoic

Cenozoic sedimentary deposits cover most of the area north of the Sambre-Meuse drainage line and only smaller outliers occur over the Condroz and Ardenne (Fig. 2.1).

The Cenozoic strata in Belgium (Borremans 2015) have formed at the southern rim of the North Sea basin. At the turn of the Meso- to Cenozoic, the North Sea was a shallow dish-shaped area subsiding due to thermal cooling over a failed Mid-Mesozoic rift. At the beginning of the Cenozoic, the southern North Sea extended into the Paris basin (Fig. 2.23) and Alpine tectonic forces caused vertical uplift pulses in the area resulting in hiatuses in the Danian chalk deposition.

During the Selandian (61.6–59.2 Ma), chalk was eroded at a large scale along the margins of the North Sea basin, and redeposited. In Belgium, the resulting Gelinden marls contain subtropical Thetyan-type tree leaves (Steurbaut 1998) (Fig. 2.24).

At the Paleocene/Eocene transition (56 Ma), the North Atlantic Ocean opened further, preceded by a broad thermal uplift that started already in the Middle Paleocene. The earliest indirect indication of related volcanic activity in the Franco-Belgian basin is the middle Thanetian 'tuffeau', a calcareous fine sandstone in the Hannut Formation (Fig. 2.24), which owes its light weight to the voids left by the numerous, now dissolved sponge spiculae, the abundance of which is associated with the excess ash in the sea water at that time. Thin bentonite beds and dispersed glass shards appear only locally in the Belgian basin at the very beginning of the Eocene. At the same time, the dissolved silica from the Middle Thanetian beds allowed for groundwater silcrete formation, notably silicifying the overlying Hoegaarden swamp cypress forest (Fairon-Demaret et al. 2003) (Fig. 2.25). This very early Eocene was a turbulent time with marked climatic changes and vertical uplift of the Bray-Artois and Brabant blocks, resulting in a variety of

Fig. 2.20 View of the interdigitation of the Luxembourg and Arlon formations in the Tontelange quarry, 5 km north of Arlon, southeast Belgium

continental and coastal deposits overlying a major erosive unconformity and grouped in the Tienen Formation (Fig. 2.24) with a duration of only ~0.5 million year. At Dormaal, the basal Tienen Formation deposits have yielded the earliest modern mammal fauna in Europe.

Drifting away from the spreading North Atlantic led to a thermal subsidence in the North Sea basin, which was collecting clay-dominated sediments during most of the Ypresian (56–47.8 Ma) (Steurbaut 2006). Fine sand deposits only formed in the coastal realm. The clay mineralogy in these deposits is mostly smectite, interpreted as the weathering product on land or in the sea of basalts and basaltic pyroclastics. Vertical trends in the clay-to-silt ratio of these Ieper Group sediments (Fig. 2.24) are related to global sea-level variations.

The final Ypresian and the transition to Lutetian time are characterized by the reappearance of dominant sandy deposits, erosive bases of successive sequences and hiatuses. All these features reflect uplift of the Artois-Brabant area, resulting in the separation of the Paris basin and the southern North Sea from the Lutetian onwards. The most prominent, decametres-deep erosive contact occurs at the base of the Brussels sand Formation in Brabant, with an associated erosive channel located offshore Oostende. These approximately north- to northeast-trending channels are supposed to represent the last connection between the Paris and Belgian basins, cut during a global low sea level (Vandenberghe et al. 2004). During the Lutetian, Bartonian, and Priabonian, (47.8–33.9 Ma), a few transgressive pulses, the most extensive of which caused deposition of the Asse-Ursel clay members (Fig. 2.24), did not cover more than northwestern Belgium, while the area to the east remained uplifted above sea level. This major tectonic rearrangement was a response to the Pyrenean deformation pulse at the end of the Eocene. Since the Late Ypresian, also the Hainaut area has remained above sea level and the Brabant block became drowned only sporadically, while subsidence of the Campine Basin, restarted in the latest Cretaceous, continued uninterruptedly (Fig. 2.24).

A renewed transgression over eastern Belgium and even over the Ardenne occurred in the earliest Oligocene and deposited fine sands in a shallow sea. The Sint-Huibrechts-Hern sand Formation (Fig. 2.24) of the Tongeren Group is part of this transgression, as are the sands preserved in large karstic depressions in the Condroz. Since the Early Eocene, the climate was gradually cooling but a sharper cooling occurred worldwide at the end of the short-lived earliest Oligocene marine incursion (De Man et al. 2004). At the same time, in parallel with the sea withdrawal, a short period of widespread soil formation occurred in the newly emerged landscape. In the swampy coastal plain of the subsequent major Rupelian transgression lived a rich tetrapod fauna among which were the

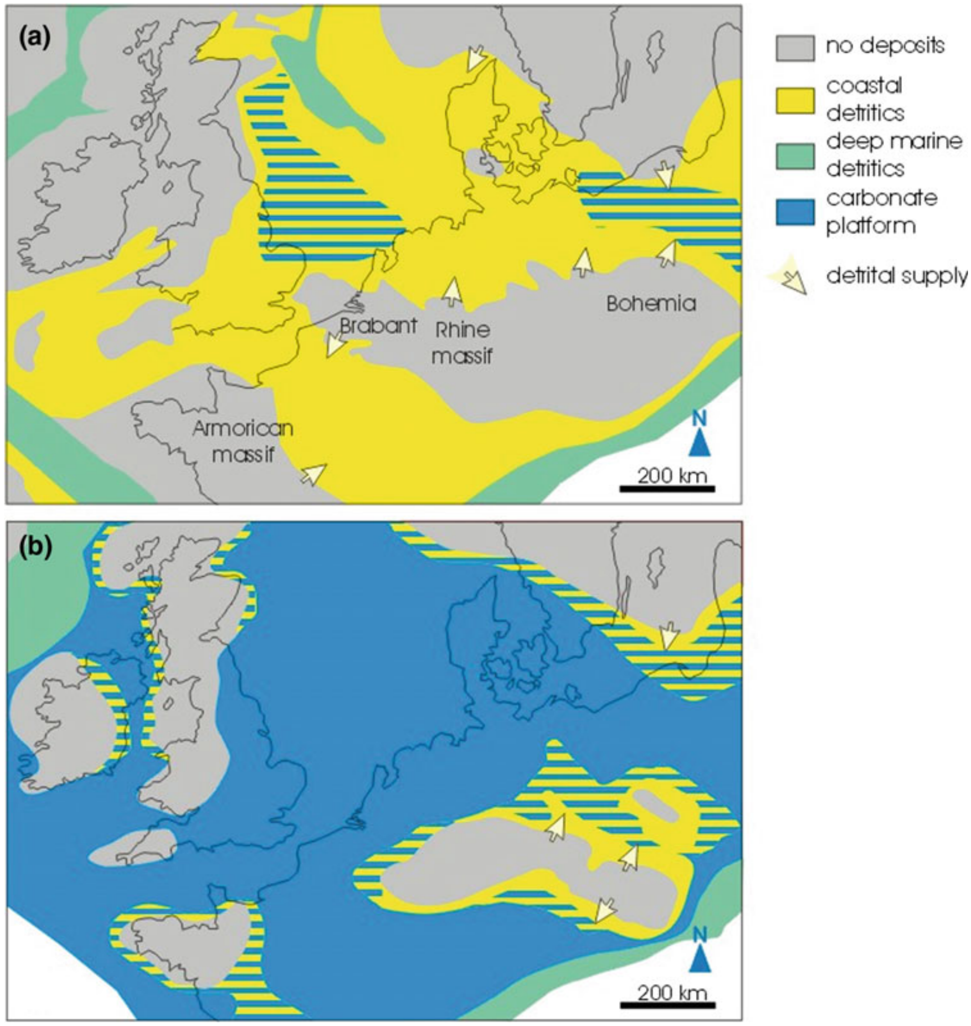

Fig. 2.21 Schematic paleogeographical maps of northwestern Europe during the Cretaceous. **a** Lower Cretaceous and **b** upper Cretaceous (simplified after Ziegler 1982)

first mammals of Asian origin resulting from the faunal turnover known as the Grande Coupure.

During the Rupelian (33.9–28.1 Ma), a large part of north Belgium subsided and became inundated, and the Boom clay Formation (Fig. 2.24) was deposited (Fig. 2.26). Since the Pyrenean tectonic rearrangement in the area, the clay mineralogy had changed to dominantly illitic with associated kaolinite. The Boom Clay displays a banded lithology that reflects water depth changes at a pace controlled mainly by obliquity oscillations and explained by the waxing and waning of a major ice cap that had developed on Antarctica since the abrupt cooling in the very early Rupelian (Vandenberghe et al. 2014a).

By the end of the Rupelian, differential vertical tectonics affected again north Belgium, resulting in uplift of the Antwerp area and erosion of a considerable thickness of previously deposited Boom Clay while in Limburg, in the east, the Upper Rupelian deposits turned from deeper water clay into fine sands of the Eigenbilzen Formation. Such shallowed waters resulted from the broad regional uplift preceding the subsidence of the Roer Valley Graben (RVG) that affected northeast Limburg during the Chattian (28.1–23 Ma). Mainly sandy Upper Oligocene deposits are preserved almost exclusively inside the graben, up to a few hundred metres thick in the very northeast. The northwest-southeast trending RVG boundary faults in eastern Belgium are reactivations of earlier faults that have their origin in the deeper Paleozoic faults. The main boundary fault east of which thick Chattian deposits are preserved is known as the Mol-Rauw Fault (see Fig. 12.1 of Chap. 12).

Outside the graben to the west, sedimentation resumed after a long hiatus spanning most of the Chattian and the Aquitanian. Resulting from a combination of global low sea level and uplift induced by Alpine tectonics (known as the Savian pulse), this hiatus is widespread in the North Sea basin. The latest Aquitanian and Burdigalian deposits in

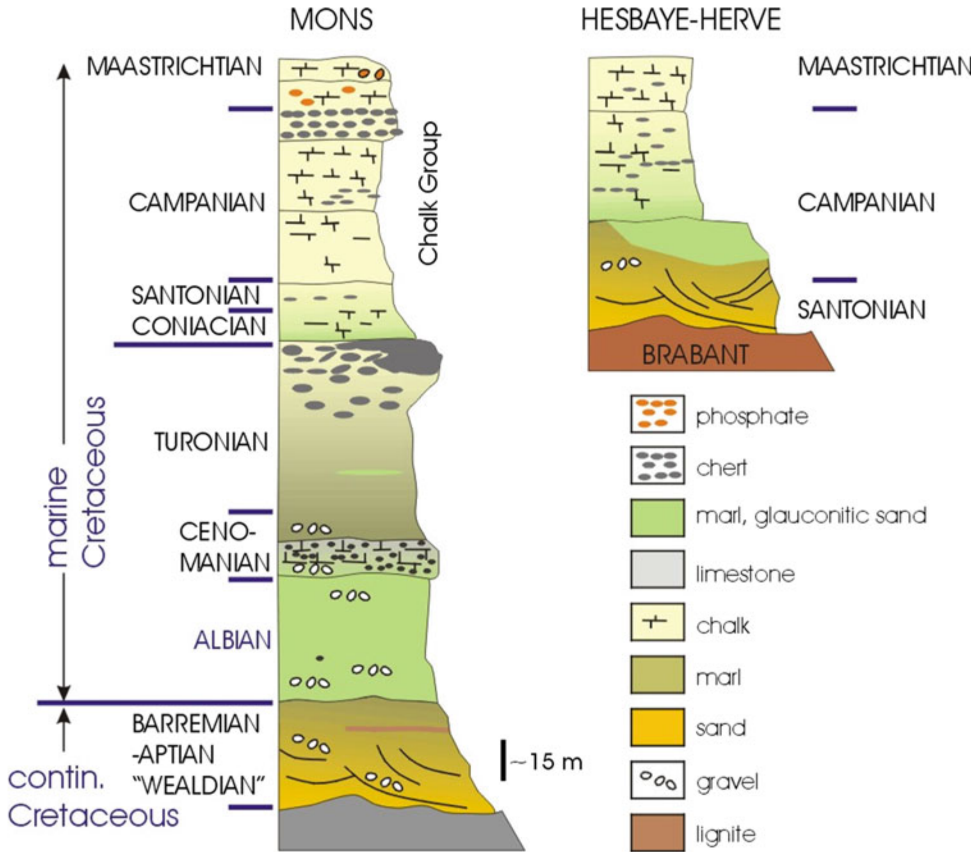

Fig. 2.22 Schematic logs of the Cretaceous cover in the Mons basin and the Hesbaye-Herve region, showing the time lag between the two chalk series

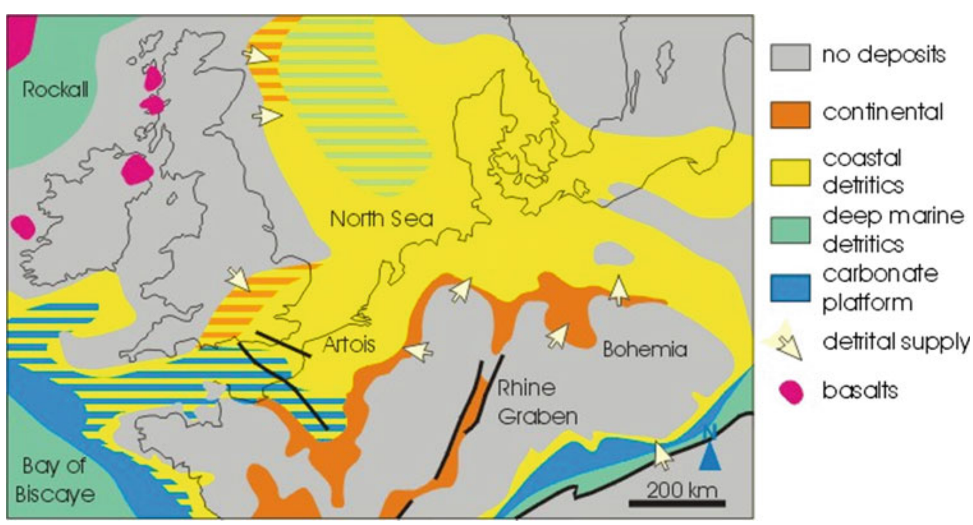

Fig. 2.23 Schematic paleogeographical map of northwestern Europe during the Paleogene (simplified after Ziegler 1982)

north Belgium are shallow-water, glauconite-rich sands of the Berchem and Bolderberg formations (Louwye and Laga 2008) (Fig. 2.24). Several sedimentation pulses can be recognized, possibly continuing into the Middle Miocene. During the Middle Miocene (16.0–11.6 Ma), a quartz-rich continental sand developed in NE Belgium, including the pure quartz Opgrimbie sand facies (Fig. 2.27) and lignite tentatively correlated with the Frimmersdorf seam of the main Lower Rhine brown coal area. Also during the Middle Miocene, important vertical tectonic activity rearranged the Rhine river system and created the major Mid-Miocene Unconformity in the North Sea. In north Belgium, an erosional hiatus occurred at that time between the Berchem-Bolderberg formations and the Upper Miocene deposits of the Diest and Kasterlee formations, representing the remains of an end Serravallian fluvial system draining

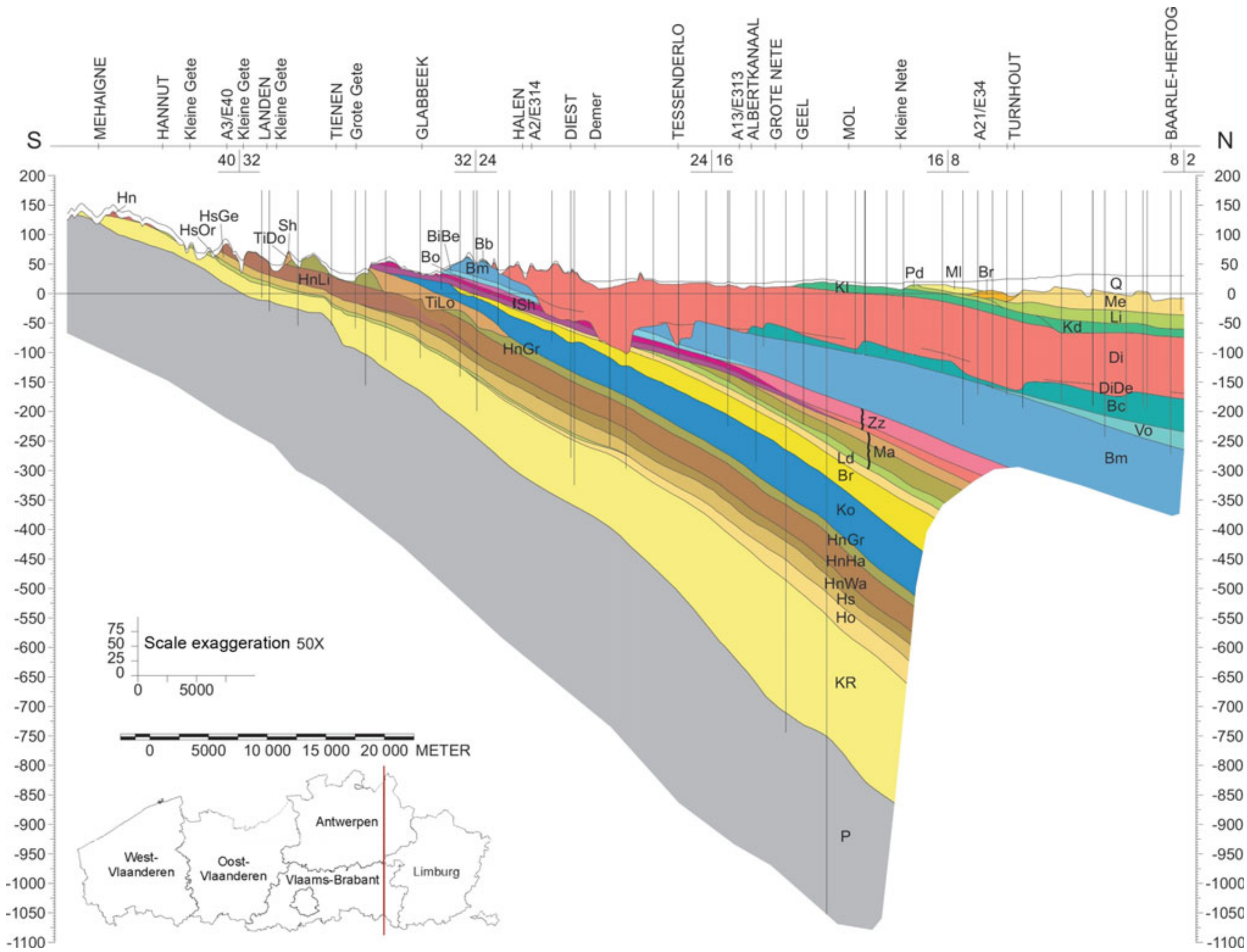

Fig. 2.24 Synthetic geological cross-section between Hannut in the south and Baarle Hertog in the north (location is shown by the *red* line in the *inset*). *P* Paleozoic. *KR* Cretaceous. *Ho* Houthem Formation (Fm) (Danian). *Hs* Heers Fm (Selandian), with HsO Orp Member (Mbr) and HsGe Gelinden Mbr. HnHa Halen Mbr, HnWa Waterschei Mbr, and HnGr Grandglise Mbr of the Hannut Fm (Thanetian). TiDo Dormaal Mbr, and TiLo Loksbergen Mbr of the Tienen Fm. *Ko* Kortrijk Fm of the Ieper Group (Ypresian). *Br* Brussels Fm. *Ld* Lede Fm. *Ma* Maldegem Fm, including the Asse and Ursel Mbrs. *Zz* Zelzate Fm. *Sh* Sint-Huibrechts-Hern *Fm* BiBe Berg Mbr of the Bilzen Fm. *Bm* Boom Fm (Rupelian). *Vo* Voort Fm (Chattian). *Bc* Berchem Fm (Lower to Middle Miocene). *DiDe* Dessel Mbr of the Di Diest Fm (Tortonian to Messinian). *Kd—Kl* Kattendijk and Kasterlee Fms (Messinian). *Li* Lillo Fm (Pliocene). *Me* Merksplas Fm (Pliocene). *Pd* Poederlee Fm (Pliocene). *Ml* Mol Fm (Pliocene). *Br* Brasschaat Fm (Quaternary). *Q* Quaternary (modified after D.O.V. (http://www.dov.vlaanderen.be) and Borremans 2015). *Vertical lines* locate boreholes. *Numbers* refer to geological map sheet numbering

towards the RVG depression. The present geometry of this fluvial system was reshaped during its subsequent transgressive inundation. The Diest Formation deposits in this northeast-trending valley system in the Hageland probably represent a slightly earlier sedimentation pulse than the westward prograding Campine Diest Formation extending from the Rhine delta mouth in the east to the Antwerp area in the west (Vandenberghe et al. 2014b). The classical identification of the Diest Formation in the iron-sandstone-capped hills of southwest Flanders and northern France is debatable (see Chap. 14).

During the Late Miocene and Pliocene (5.3–2.6 Ma), the influence of the prograding Rhine delta became gradually more visible in the sediments of north Belgium. The marine glauconitic fine sands of the Kasterlee Formation in Campine and the suite of Pliocene glauconitic coastal marine deposits in the Antwerp area became progressively replaced by the westward shifting quartz-rich estuarine sands of the Mol Formation, which is part of the Kiezeloolite Formation occurring typically in the RVG in the east. Also the oldest gravels of the Meuse, known as the *Traînée mosane*, are considered Pliocene in age.

Fig. 2.25 **a** Loose white quartz sand of the earliest Eocene Tienen Formation showing a sedimentary silcrete layer of regional extension in central to east Middle Belgium. **b** Top of the same formation including tree stumps (*arrows*) of the silicified Hoegaarden swamp cypress forest in the white sand. The overlying *darker* sand is the glauconitic cross bedded Mid-Eocene Brussels Formation

The Quaternary deposits in Belgium are relatively thin. Coastal plain deposits occur only in the Early Pleistocene formations in north Belgium and in the later Pleistocene series along the present Belgian coast (see Chap. 19). Other Quaternary layers are mainly fluviatile sediments and aeolian loam and coversands, displaying periglacial structures acquired during glacial periods (see Chap. 18). The interplay between tectonic uplift and river erosion and deposition during glacial–i-nterglacial cycles has resulted in the common occurrence of river terraces (see Chap. 10). The Campine Plateau consists of Middle Pleistocene Rhine and Meuse deposits bordered to the west by the Mol-Rauw Fault. It now stands in relief because of deeper erosion of the more erodible Pliocene sand outcropping to the west of the plateau (see Chap. 12). Holocene deposits show significant thickness only along the present coast and in the river valleys (see Chaps. 16 and 18).

Fig. 2.26 The Rupelian Boom clay Formation in the Argex clay pit at Kruibeke-Burcht, near Antwerp. The layering in the clay represents obliquity-driven cycles of varying water depth. The *upper darker clays* contain more land-derived organic particles than the paler lower clays. *Thin white horizons* are septaria layers, which have given the name 'Septarien Ton' to this clay in Germany. The *inset* shows a vertical and a horizontal sections across a septaria

Fig. 2.27 Mid-Miocene Opgrimbie quartz sand facies in the Sigrano exploitation pit near Heerlen, The Netherlands, ~15 km east of the Dutch-Belgian border at Maastricht. Shallow-water sedimentary current structures are cross-cut by subvertical fractures caused by the activity of a nearby fault of the Roer Valley Graben. The *top* cover consists of Pleistocene loam and gravel

2.8 Conclusions

Belgium and Luxembourg are countries where stones have always played a significant role. The history of people and of their underground is intertwined. The immemorial mining of diverse resources, from chert through coal and ironstone to limestone has shaped the landscapes and societies. Sedimentary rocks largely characterize the Belgian and Luxembourgian substrate. The alternation of sedimentation periods and deformation events has shaped the underground into several major sedimentary-structural units, from the Lower Paleozoic inliers through the Devonian-Carboniferous faulted and folded belt, and the homoclinal Triassic-Jurassic series to the subhorizontal Cretaceous and Cenozoic covers. The Variscan fold-and-thrust belt includes two major tectonic units, namely the Brabant parauthochton and the Ardenne allochthon, separated by the Midi-Eifel thrust fault and the Haine-Sambre-Meuse thrust sheets. The Ardenne allochthon is itself formed into major anticlines and synclines.

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