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The 'black marble' of Denée, a fossil conservation deposit from the Lower Carboniferous (Viséan) of southern Belgium

BERNARD MOTTEQUIN*

Unité de Paléontologie animale, Université de Liège, Liège, Belgium

The palaeoenvironment of the 'black marble' of Denée [Dinant sedimentation area (DSA), southern Belgium], included in the Molignée Formation of Lower Carboniferous (Viséan) age, is discussed. This fossil conservation deposit ('fossil Lagerstätte') yielded a rare but remarkably preserved macrofauna (including fishes, echinoderms and brachiopods). It developed in a confined intra-platform basin progressively filled by distal calcareous turbidites originating from the southward prograding shelf to the north. This basin was bordered to the south by a discontinuous barrier of Waulsortian mud mounds built against a major synsedimentary fault separating the DSA from the southern Avesnois sedimentation area (ASA). The alternations of laminated ('black marble' facies) and bioturbated ('thick-bedded' facies) lithofacies occurring within the Molignée Formation imply that the palaeoenvironment recorded several anoxic to dysoxic periods alternating with more oxygenated ones due to sea-level fluctuations of low magnitude and was strongly influenced by the basin architecture inherited from the late Tournaisian.

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1. INTRODUCTION

The localities of Tournai and Visé, respectively, the historical type areas of the Tournaisian and Viséan stages, have contributed widely to the fame of the 'Dinantian' of the Namur-Dinant Basin [southern Belgium and northern France (Avesnois)] by the great diversity and the abundance of the macrofauna (Demanet 1958). In addition to both these well-known fossiliferous localities, the quarries located around the village of Denée (Namur province) (Figure 1) have yielded remarkably preserved but rare fossils (including echinoderms and fishes), which have been collected within the 'black marble' of Denée, a black coloured limestone of early Viséan age.

All the fossils, with few exceptions, were collected at the end of the 19th century and at the beginning of the 20th century by quarrymen when the 'black marble' was intensively and manually quarried. Most of the excavations were subterranean and, nowadays, most of them are disused and flooded. If it had not been worked, the 'black marble' of Denée would have been considered probably as azoic due to the rarity of the fossils. The bulk of the material is deposited at the Maredsous abbey ('Centre Grégoire Fournier'), but additional specimens are housed in the Université de Liège (Liège), the Université Catholique de Louvain (Louvain-la-Neuve), the Institut Royal des Sciences Naturelles de Belgique (Brussels) and the Museum of Comparative Zoology (Harvard). A modern systematic revision is urgently needed for most of the invertebrate phyla; the latest comprehensive list of the faunas dates back to Fournier and Kaisin (1929). As is generally the case with old collections, the origin of the specimens is usually not known with precision, except for some fossils which have a mention of the quarried level ('la Veine',

* Correspondence to: B. Mottequin, Department of Geology, Trinity College, Dublin, Ireland. E-mail: mottequb@tcd.ie

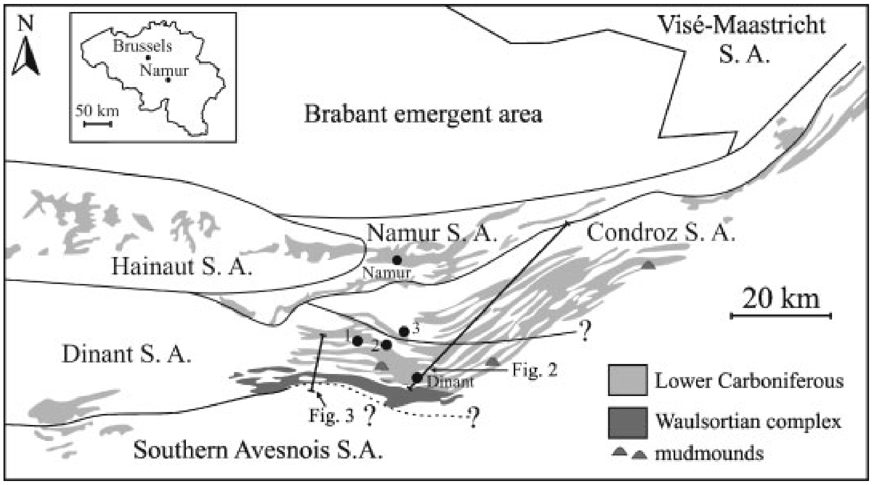

Figure 1. Lower Carboniferous sedimentation areas in the Namur-Dinant Basin (not palinspastic) (modified from Devuyst *et al*. 2005). 1: Denée; 2: Salet; 3: Sovet. S.A = sedimentation area.

'les Drîs') on their label. We can suspect that most of the specimens were collected at Denée, from the exploited levels figured by Fournier (*in* Fournier and Pruvost 1928).

This paper deals mainly with the interpretation of the palaeoenvironment of the 'black marble' of Denée on the basis of recently published sedimentological data.

2. GEOLOGICAL SETTING

The Namur-Dinant Basin developed on the SSE margin of the London-Brabant Massif in a back-arc extensional setting (Hance *et al*. 2001), north of the Ligerian Arc (Leeder 1987, 1988). In the course of late Tournaisian and early Viséan time, the ramp setting that has prevailed since the early Tournaisian progressively evolved to a rimmed-shelf and to a broad flat-topped platform of regional extent during the middle and late Viséan (Hance *et al*. 2006). On the basis of their lithostratigraphic character, several sedimentation areas have been defined within the Namur-Dinant Basin by Poty (1997) and Hance *et al*. (2001). These are notably from the NE to the SW (Figures 1 and 2): (1) the Namur sedimentation area (NSA) characterized by the more proximal facies and the less complete lithostratigraphic succession; (2) the Condroz sedimentation area (CSA) with relatively proximal facies and some sedimentary breaks—it displays southward and southwestwards a transition with the Dinant sedimentation area (DSA); (3) the DSA displaying the deeper water facies with the development of Waulsortian mud mounds, as well as an almost complete stratigraphic succession ['Auge dinantaise' of Paproth *et al*. (1983)]; (4) the southern Avesnois sedimentation area (ASA) ['Ride d'Avesnes' *sensu* Conil (1973)] showing a similar situation to that of the CSA, but with a markedly different lithostratigraphy (shallower water facies). In Belgium, the absence of Lower Carboniferous exposures south of the DSA, due to post-Variscan erosion, does not allow the precise delineation of the eastern extension of the ASA. However, according to recent investigations of Pirotte (2006), it seems, at least, that the ASA borders the southern margin of the DSA, south of the Waulsortian complex (Figure 3).

The 'black marble' of Denée was formerly included in the 'black marble' of Dinant ('V1a' of the Belgian authors), but according to Conil (1967), it precedes this latter unit, strictly speaking, on the basis of the foraminifer associations (Figures 2 and 3). Now, both former units are included in the diachronic Molignée Formation [*sensu* Poty *et al*. (2002)] of early Viséan age [regional Moliniacian Substage (Devuyst *et al*. 2006; Hance *et al*. 2006)]. This formation is developed only in the central part of the DSA between the prograding platform and the

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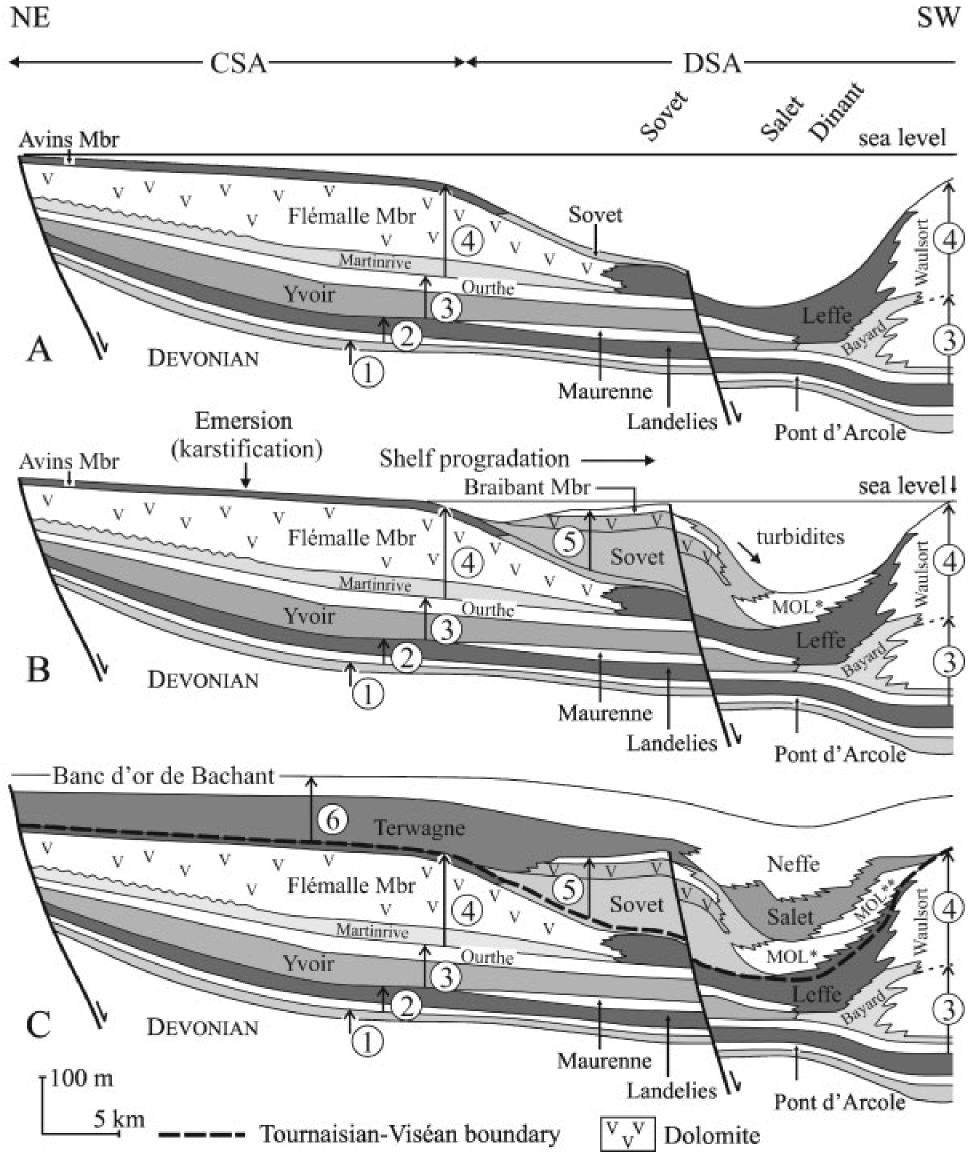

Figure 2. Evolution of the CSA and the DSA during the third-order sequences 4 (**A**), 5 (**B**) and 6 (**C**) (numbered black arrows) [Tournaisian (Ivorian) to Lower Viséan (Moliniacian)] (modified from Hance *et al*. 2001); see also Figure 1. The Banc d'Or de Bachant is a bentonite, locally transformed into a palaeosol (Poty *et al*. 2002). The Longpré Formation includes, from base to top, the Flémalle and the Avins members; the Braibant Member corresponds to the top of the Sovet Formation (Poty *et al*. 2002). Mbr = Member; MOL* = Molignée Formation ('black marble' of Denée); MOL** = Molignée Formation ('black marble' of Dinant).

Waulsortian complex (Hance *et al*. 2001) running along the border between the DSA and the ASA (Figures 1–3). The Molignée Formation consists of a succession of thin-bedded (less than 1 m to several metres thick), commonly laminated black limestones which alternate with thick-bedded, dark-grey limestones ('thick beds') (Figure 4). These alternations correspond to the 'polysequences' and 'monosequences' of Mamet (1964). The contacts between both lithotypes are always clear-cut.

The range of the 'black marble' of Denée, in terms of Mississippian Foraminifer Zone (MFZ), spans the interval of the MFZ 9 (upper part) to the MFZ10 according to Devuyst and Hance (*in* Poty *et al*. 2006), that is the upper part

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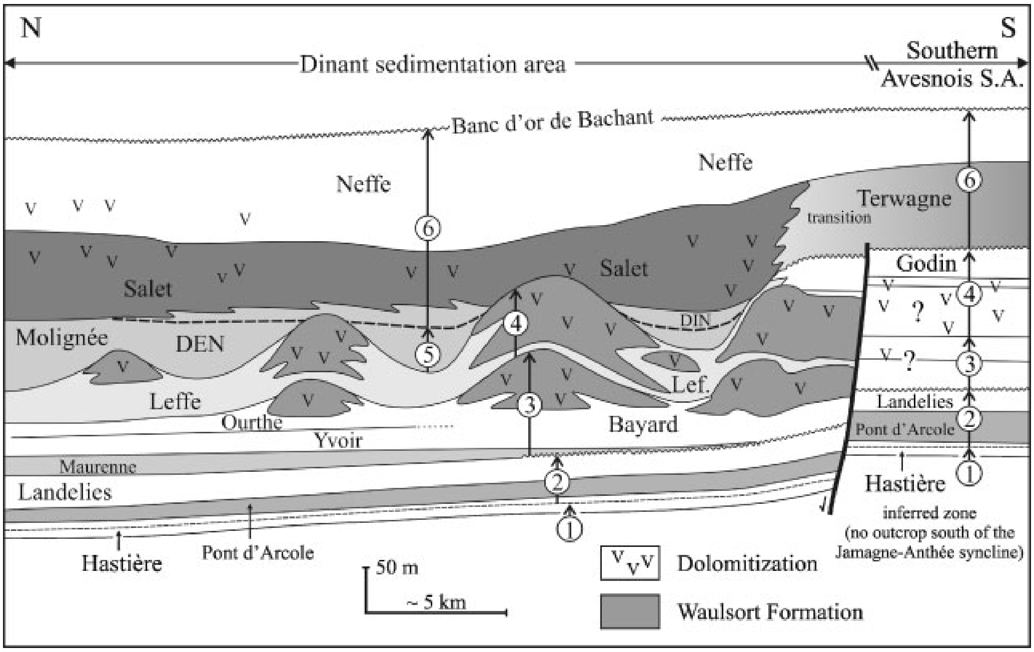

Figure 3. Pirotte's (2006) modified model of stacking of the third-order sequences (numbered black arrows) in the southern part of the DSA and in the southern ASA, from the Lower Tournaisian to Lower Viséan; see also Figure 1. DEN = 'black marble' of Denée; DIN = 'black marble' of Dinant; Lef. = Leffe.

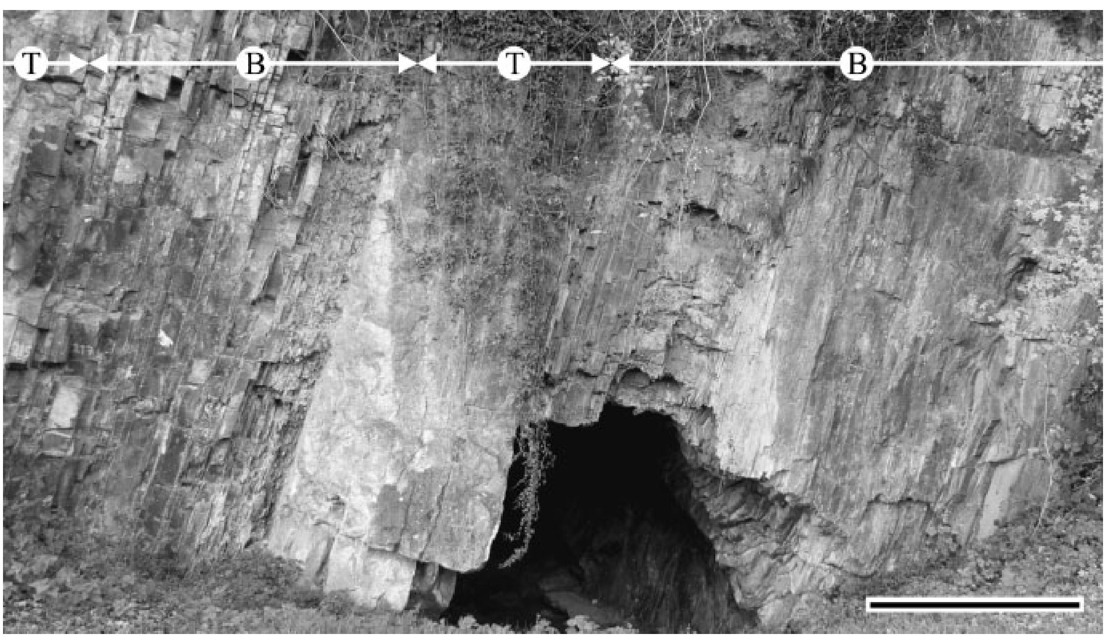

Figure 4. Molignée Formation in its stratotype, that is Salet road section, showing the alternating thicker bedded and thinner bedded units. B = 'black marble' facies; T = 'thick beds' facies.

of the Cf4α2 Subzone and the lower half of the Cf4β Subzone of Conil *et al*. (1991). In the Salet road section (stratotype of the Molignée Formation) (Figure 1), the ‘black marble’ of Denée begins at bed 191 and ends at bed 273; 39 m thick [see Hance 1988; Devuyst *et al*. 2006; Poty *et al*. 2006 for detailed logs of this section]. Thus, it does not correspond completely to the Molignée Formation (from bed 169 to the top of bed 294; 57.6 m thick) as redefined by Poty *et al*. (2002).

3. THE ‘BLACK MARBLE’ OF DENÉE, A FOSSIL CONSERVATION DEPOSIT

The ‘black marble’ of Denée has yielded the following biota: echinoids (Fraipont 1904; Jackson 1929; Kier 1962), crinoids (Fraipont 1904), ophiuroids (Fraipont 1904), holothuroids (?), dendroid graptolites (Renier 1925; Ubaghs 1941), bivalves (Demanet 1929), gastropods, goniatites (Delépine 1940), nautiloids, bryozoans, brachiopods (Delépine 1928), rugose and tabulate corals, sponges, conulariids, phyllocarids, trilobites, chondrostean and elasmobranch fishes (Van Beneden 1871; Traquair *in* de Koninck 1878; Fraipont 1890; Boulenger 1899, 1902; Pruvost *in* Fournier and Pruvost 1922, 1928; Woodward 1924; Ivanov and Derycke 2005) and floated plant remains. Most of the fossils belong to the autochthonous epibenthos (Mottequin 2004). The echinoid fauna, including the largest and most remarkable Palaeozoic specimens, as well as the fishes, have contributed largely to its fame. Nowadays, it is not possible to sample all the fauna anymore because of the poor exposures of the Molignée Formation. Fossils such as productid brachiopods, bryozoans, rugose corals, echinoids, bivalves and goniatites have been collected during recent field work (1999–2000). However, the collections are quite insufficient for reconstructing the biocoenose on a reliable basis; Mottequin (2004) provided some information related to the palaeoecology.

During the Moliniacian, the colonization of the sea floor of the central part of the DSA by benthos and the diversity of the latter were strongly influenced by oxygen concentration. Only some organisms were able to develop in this particular environment. Most of the bivalves belong to the ‘paper pecten’ morphotype which is diagnostic of dysaerobic environments according to Allison *et al*. (1995). Echinoderms, especially the echinoids, seem to have been well adapted to face this poorly oxygenated environment, as indicated by their relative abundance in the collection and their preservation *in situ* (complete tests with spines in anatomical connection). This is not surprising because these organisms are known in upper dysaerobic facies of modern oxygen deficient basins; Savrda *et al*. (1984) reported also ophiuroids, holothuroids, polychaetes, crabs and gastropods in their lower dysaerobic facies. Among brachiopods, representatives of the suborder Productidina predominate in the collection. Some of them have spines of much greater length than the shell bearing them (Delépine 1928). These long spines were most probably for support (Brunton and Mundy 1988) and acted as a stabilizing snowshoe to prevent shells from sinking in the muddy substrate (Bowen *et al*. 1974). Their preservation attests to the absence of or only minor transport. Productidina would indicate better oxygenated conditions than those prevailing during the colonization by bivalves and echinoids. Chonetidina, Orthotetida, Spiriferida, Athyridida, Orthida, Rhynchonellida and Terebratulida (?) are present in the collections, but most of them occur as fragments within shelly limestones. After additional cleaning and sectioning by E. Poty, it turned out that the fossil identified as an echinoid by Mottequin (2004: pl. 4, figure C) is in fact a sponge with long spicules, close to representatives of the genus *Belemnospongia* (personal communication, Poty E, 2007) from the Carboniferous of the United States (cf. Rigby *et al*. 1979; Rigby and Ausich 1981).

The ‘black marble’ of Denée is a fossil conservation deposit [see discussion in Shields (1998)], that is the skeletons and the tests of organisms are preserved in their entirety. However, soft parts have not really been highlighted with certainty although Van Straelen (1926) described an enigmatic fossil under the name of *Medusina boulengeri* that he interpreted as the mould of the exumbrella of a jellyfish. It has been assigned to the Medusae *incertae sedis* by Harrington and Moore (1956), but Mottequin (2004) reinterpreted it as a probable burrow. This hypothesis must be confirmed by X-ray analysis. Exceptional burrows have been recognized within the ‘black marble’ facies such as *Zoophycos* (Mottequin 2004). Rapid burial is considered here as one of the major factor of preservation [‘obrution deposits’ of Seilacher *et al*. (1985)]. It is well exemplified by the excellent preservation of

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most of the echinoderms. Low oxygen concentrations prevailing within the substrate slowed down the disarticulation of the tests and excluded the eventual predators.

Carpentier (1913) and Jackson (1929) have compared the 'black marble' of Dinant with the lithographic limestone of Portlandian age from the Solnhofen area in Germany which is the type of the 'taphofacies IF: dysoxic/anoxic basin' of Brett *et al*. (1997) based on echinoderm taphonomy. However, in the case of Denée, the organisms are essentially benthic and generally autochthonous, contrary to the lagoon of Solnhofen, where the benthos was imported during storms and only survived for some days before the re-establishment of hypersaline conditions. The black marble is close also to the obrution deposit typified by the Hunsrück Slate of Emsian age (Brett and Seilacher 1991) and more especially by the locality of Budenbach. Although the faunas of the 'black marble' of Denée are not pyritized, the burial of the organisms in the Belgian conservation fossil deposit is approximately the same as in the German locality (Sutcliffe *et al*. 1999). Nevertheless, the environment in Denée may have been less oxygenated as indicated by the presence of bivalves of the 'paper pecten' morphotype and the very rare to absent trilobites.

4. SEDIMENTATION IN THE CENTRAL PART OF THE DSA DURING THE LOWER PART OF THE MOLINIACIAN

4.1. General context

An important factor that influenced the sedimentation and the palaeoenvironment of the Molignée Formation was the topographic context inherited from the upper part of the Tournaisian. During the Ivorian (Tournaisian), the DSA was characterized by the build-up of large Waulsortian mudmounds whose maximal development gave rise to a discontinuous barrier in its southwestern part (Waulsortian complex) (Lees 1997). At the same time, the ASA recorded a subsidence rate lower than the one of the DSA, from which it was separated by a synsedimentary fault (Pirotte 2006). The end of the Tournaisian, that is at the end of the third-order sequence 4 of Hance *et al*. (2001), is marked by a major sea-level drop which induced the emersion of the shallower areas of the Namur-Dinant Basin (karstification of the top of the Avins Member) and the southward progradation of the shelf during the next sequence (sequence 5) (Figure 2B). In the early Viséan (sequence 5) that corresponds to the period of deposition of the Molignée Formation, the central part of the DSA evolved as a residual intra-platform basin bounded by the prograding shelf to the north and the Waulsortian complex built against a major synsedimentary fault to the south. The eustatic magnitude of this sequence was probably low, because, in the Namur-Dinant Basin, it is only recorded in the DSA. In the ASA, the Terwagne Formation (sequence 6) lies directly on the Godin Formation (sequence 4) whereas in the CSA and the NSA, the former caps the Avins Member of the Longpré Formation (Hance *et al*. 2001) that indicates clearly a sedimentary gap (Figure 3). According to Devuyst (2006), it is probable that the top of the Waulsortian complex emerged also, because it was growing in very shallow water at the end of the Tournaisian (Lees 1997), although no trace of such emersion has, however, yet been found. According to Devuyst (2006), this may be the result of the monotonous facies which hinder the recognition of facies variations. Sequence 5 is rarely recorded at a global scale (personal communication, Hance L, 2007); it has been recognized in the Pengchong section in South China (Guangxi) where it consists of a turbiditic sequence with shale intercalations (Devuyst *et al*. 2003).

4.2. Microfacies of the Molignée Formation

Among the thin beds ('black marble' facies), the dominant microfacies consists of well-sorted and laminar packstones to grainstones composed of calcispherids, peloids, moravamminids, plurilocular foraminifers, algal fragments and other allochems of similar size (Figure 5A, B). By their characteristics (flat parallel laminations, allochems of small dimensions), they have been interpreted previously as distal turbidites by Overlau (1966), which poured out on the marine floor and were intercalated with mudstones with calcispherids and radiolarians

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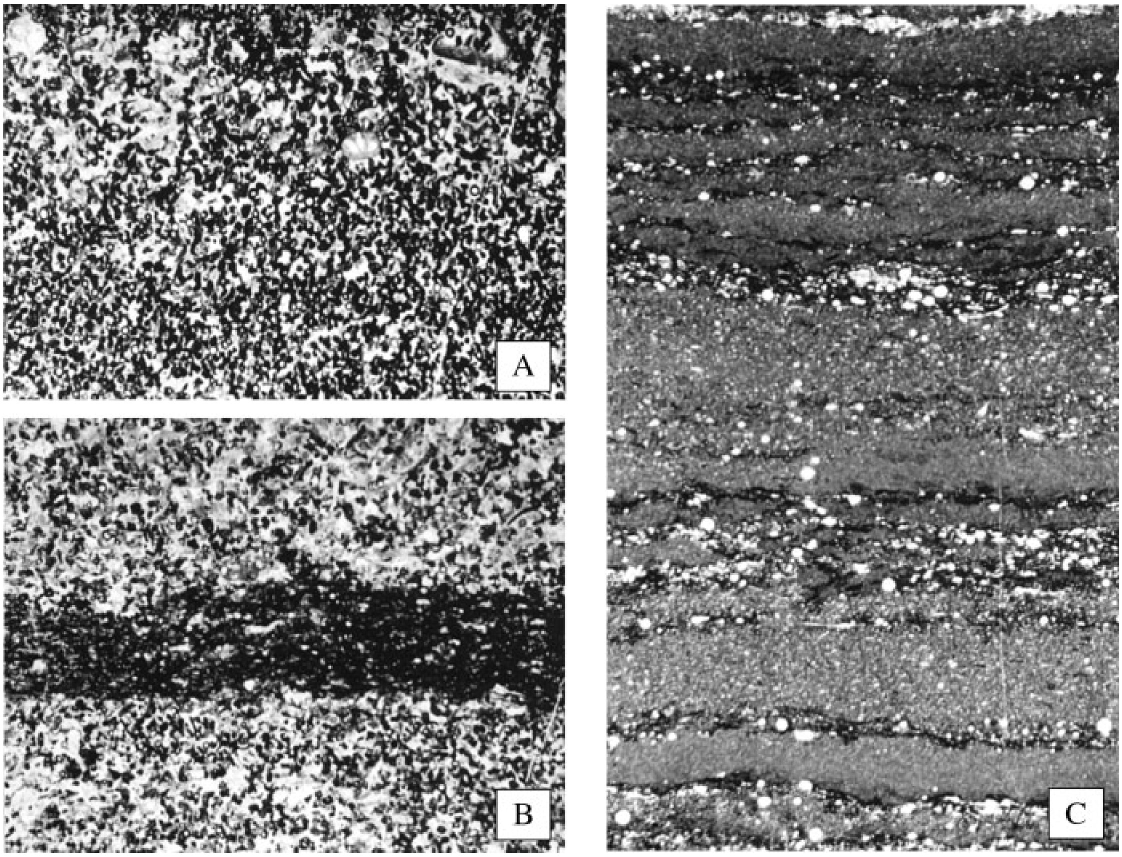

Figure 5. Microfacies of the Molignée Formation (‘black marble’ facies) in the Denée area (all figures × 10); the bed numbers are those of Mottequin (2004). (**A**) Well-sorted, laminated grainstone with peloids and calcispherids, Debras quarry in Salet (bed 49). (**B**) Grainstone with peloids and calcispherids, and packstone with bioclasts, Debras quarry in Salet (bed 2e). (**C**) Alternation of mudstone, wackestone and packstone with radiolarians, En Gilotia locality in Maredret (bed 8a).

(Figure 5C). The packstones–grainstones shift laterally to wackestones–packstones due to the progressive decrease of the turbidity currents. Moreover, the rugose and tabulate corals recovered in the ‘black marble’ are always reworked fragments which are transported into the basin via the turbidity currents. Numerous skip marks produced by broken shells of gastropods and cephalopods also confirm the existence of bottom currents. The burrows are exceptional (*Zoophycos* sp.; see also Section 3). The ‘thick beds’ are mainly composed of bioturbated wackestones to packstones with a high diversity of allochems, among which include major components: bryozoans, echinoderms, gastropods, ostracods, trilobites and foraminifers (especially *Tetrataxis*) (Figure 6B–D). Sponge spicules, algae, *Rectangulina*, *Globochaete*, cephalopods, solitary rugose corals (*Cyathaxonia* sp.), brachiopods and calcispherids have been also recognized (see Subsection 4.3 for their interpretation). Rudstones (Figure 6A) and grainstones occur at the base of some beds. The microfacies of the ‘thick beds’ occurring in the Molignée Formation are reminiscent of those of the underlying Leffe Formation (Noël *in* Groessens and Noël 1975), though coated clasts and oncoids are less abundant. According to Lees *et al*. (1977), the carbonate mud of the Leffe Formation is probably derived from the Waulsortian mounds developed in the DSA. However, the Leffe facies has never been identified with certainty in other areas with Waulsortian mud mounds (Lees 1997). Devuyst (2006) suggested that a large part of the lime mud of the upper part of the Leffe Formation was exported from the mud mounds when they reached depths at which the accommodation space for aggradation was reduced.

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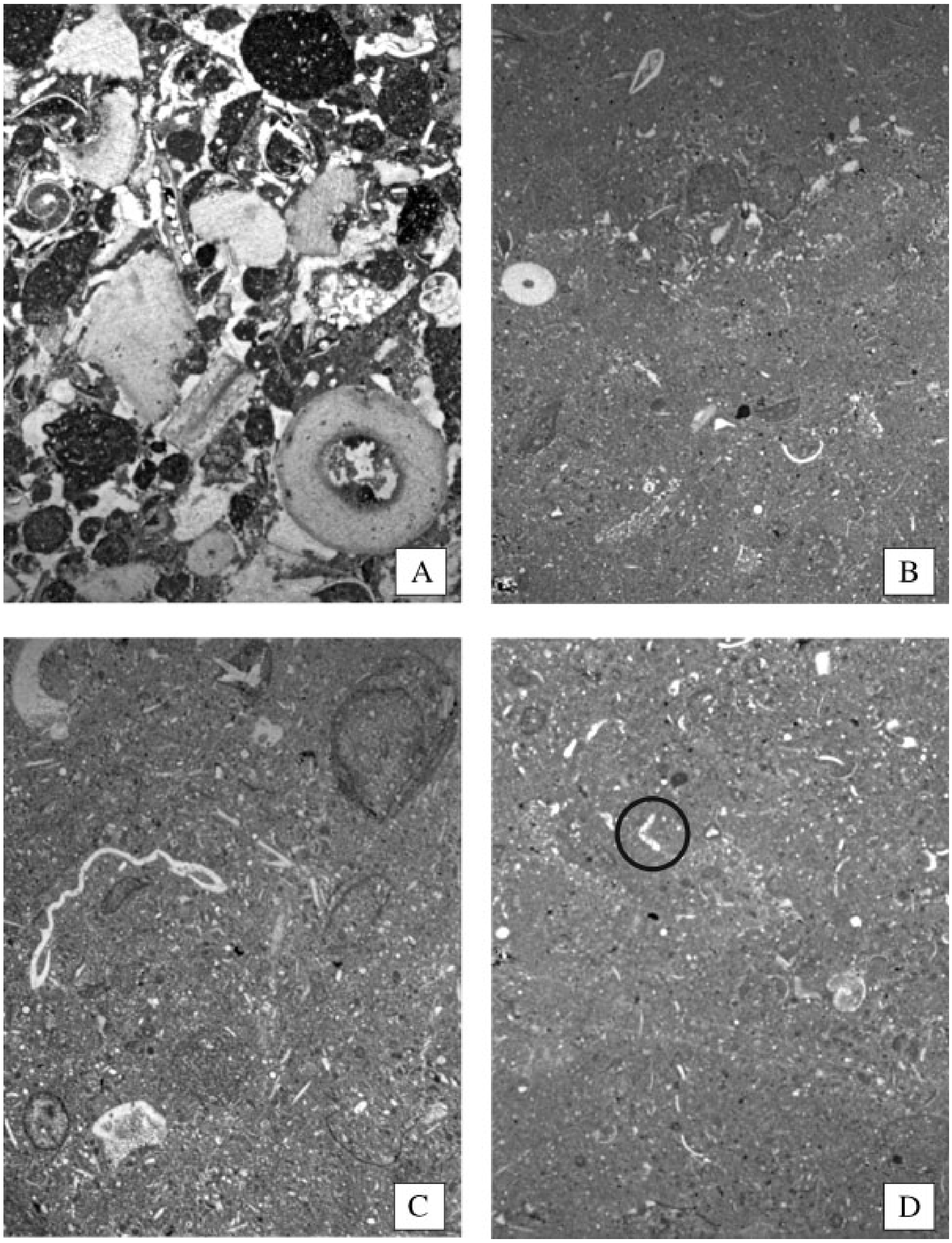

Figure 6. Microfacies of the Molignée Formation (‘thick beds’ facies) in the Denée area (all figures × 10, except D × 15); the bed numbers are those of Mottequin (2004). (**A**) Rudstone with lithoclasts, crinoids, bryozoans and peloids, Debras quarry in Salet (bed 27a). (**B**) Wackestone with peloids, ostracods and crinoids, Debras quarry (bed 27b). (**C**) Wackestone with peloids, trilobites, crinoids, bryozoans and mud balls, En Gilotia locality in Maredret (bed 24). (**D**) Wackestone with peloids, ostracods, *Tetrataxis* sp. (ringed) and gastropods, Debras quarry (bed 27c).

4.3. Palaeoenvironmental interpretation of the Molignée Formation in the Denée-Salet area

The origin of the alternations of ‘black marble’ and ‘thick beds’ facies has been previously interpreted by Mottequin (2004) as shallowing-upwards parasequences with the ‘thick beds’ at their base and the ‘black marble’ facies at their top (Figure 4); their origin would have been linked to the periodic confinement of the DSA due to

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sea-level fluctuations. Low oxygen concentrations are suggested by the remarkable preservation of the fauna and the existence of dysaerobic organisms such as the bivalves of the 'paper pecten' morphotype. Because of the required depth conditions for the expansion of anoxia in recent confined basins (Murray *et al*. 1989), Mottequin (2004) suggested that the 'black marble' facies would have been developed between 100 and 150 m water depth, whereas the 'thick beds' would have been deposited between 150 and 200 m depth. This last estimation used the presence of the plurilocular foraminifer *Tetrataxis* (Figure 6D) within the 'thick beds' which would indicate a depth less than 200 m, according to Lees (1997), as well as the reconstruction of the Namur-Dinant Basin by Hance *et al*. (2001).

The sea-level fluctuations may have been partly induced by glacio-eustasy. According to González-Bonorino and Eyles (1995), ice existed on Gondwana from the Tournaisian up to about mid-early Permian. Bruckschen *et al*. (1999) reported short-term oscillations in $\delta^{18}O$ and $\delta^{13}C$ in the Tournaisian and Viséan that may be reflections of several regional and short-lived glaciations. Mii *et al*. (1999) suggested that the onset of Carboniferous glaciation would have taken place in the course of the early Tournaisian on the basis of $\delta^{18}O$ records and that the temperatures were cool to cold during the early-middle Viséan. However, these isotopic shifts have been considered as poorly known at a global scale by Saltzman *et al*. (2000); Smith and Pickering (2003) reported that the extent of the Tournaisian and Viséan glaciations was limited to isolated and relatively small ice centres. Despite these divergent opinions, we can reasonably admit that the confinement of the central part of the DSA would have probably required only minimal sea-level fluctuations.

'Spasmodic' synsedimentary tectonics of the basin may have also influenced the palaeoenvironment. Indeed, two major synsedimentary faults have been inferred previously on the basis of thickness variations of some formations, as well as on sudden facies changes. The first one would have been located in the Sovet area (Figure 2B), but it is believed to have been active at least after the sedimentation of the Braibant Member forming the cap beds of the Sovet Formation (Hance 1988; Hance *et al*. 2001; Devuyst 2006; Poty *et al*. 2006). The second fault delimited the southern part of the DSA and the northern part of the ASA (Pirotte 2006; Figure 3); it appeared probably at the end of the Hastarian when the ASA began to differentiate from the DSA with the appearance of shallower water facies in the former. If both were active during the deposition of the Molignée Formation, the DSA would have thus evolved as a subsiding zone.

Devuyst (2006) recognized three large-scale shallowing-upwards cycles in the stratotype of the Sovet Formation (the lateral equivalent of the Molignée Formation) which he interpreted as reflecting the southwards progradation of the platform margin as successive mega-clinoforms. Thus, most of the turbidites occurring within the 'black marble' facies would originate from the northern part of the DSA, as previously suggested by Hance *et al*. (2001), on the basis of the allochems present in the packstones–grainstones. The turbidites would result from violent storms, earthquakes or clinoform instability due to an oversteepened slope.

The persistence within the Molignée Formation of facies similar to those observed in the Leffe Formation can be partly explained by the fact that the abrasion of the Waulsortian mounds continued after their decay—they stopped growing in the late Tournaisian—and also by the fact that the topography inherited from these buildups remained for a while. Waulsortian mud mounds are recognized in the Denée-Salet area (Demanet 1923; Delcambre and Pingot 2004).

Because of the random mode of dispersion of the turbidites, it is very difficult to correlate the various sections exposing the Molignée Formation in the Denée-Salet area. The microfacies recognized in Denée and Salet are different because Salet occupied a more proximal position. Hence, the wackestones–packstones occurring mainly in Denée have been interpreted as the distal equivalents of the packstones–grainstones that dominated in Salet.

5. CONCLUSIONS

The 'black marble' of Denée, included within the Molignée Formation of Moliniacian age and developed in the central part of the DSA (corresponding to an intra-platform basin), is a fossil conservation deposit and belongs more particularly to the 'obrution deposits' of Seilacher *et al*. (1985). The turbiditic sedimentation with smothering effect

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combined with deficient oxygenation of the bottom waters favoured the exceptional preservation of the faunas (e.g. echinoderms, fishes) by inhibiting the development of the necrophagous and saprophagous organisms during the deposition of the 'black marble' facies *sensu stricto*. The periodic confinement of the central part of the DSA was induced by sea-level fluctuations of low magnitude and took place during a third-order sequence characterized by a low sea level, namely the sequence 5 of Hance *et al*. (2001).

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