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PALEOENVIRONMENTAL RECONSTRUCTION OF THE MIRWART FORMATION (PRAGIAN) IN THE LAMBERT QUARRY (FLAMIERGE, ARDENNE, BELGIUM).

Eric GOEMAERE & Léon DEJONGHE

(3 figures, 2 tables and 3 plates)

Geological Survey of Belgium, Royal Belgian Institute of Natural Sciences, Jenner Street, 13, B-1000 Brussels, Belgium
e-mail: Eric.Goemaere@naturalsciences.be;Leon.Dejonghe@naturalsciences.be

ABSTRACT. This paper describes the palaeoenvironments of the Mirwart Formation in the Belgian Ardenne. A tectonical, petrological and sedimentological study of the Lambert Quarry (Flamierge commune, Bertogne entity) has been carried out. Criteria are discussed that may be used in interpreting ancient sedimentary environments in the central Ardenne area. Distinctive sedimentological structures pointed out that the very fine sands, coarse silts and muds originated in a tidal flat environment. Tidal channels, mud flat, mixed flats and sand flats sub-environments are vertically stacked. Mud/Sand flats represented extended surfaces with very low relief areas without any sandy barrier to protect tidal flat environments from the open sea. These large surfaces are an answer to the transgression over large flood- and delta plain flat environments. In comparison with equivalent present-day environments, the unusual thickness of tidal deposits is related to a continuous subsidence and a regular and constant influx of clastics through a well-developed fluvial system. Clastics derived from the northern Old Red Sandstone Continent, trough alluvial and deltaic environments situated northerly of the studied area. Muddy islands, above the tidal range, occasionally fell dry and allowed the development of paleosoils and plant communities.

KEYWORDS. Mirwart Formation, Pragian, Lower Devonian, tidal flats, sedimentary structures, depositional model, Ardenne.

RÉSUMÉ. **Reconstitution paléo-environnementale de la Formation de Mirwart (Praguien) dans la carrière Lambert (Flamierge, Ardenne, Belgique).** Cet article décrit les environnements de dépôt de la Formation de Mirwart (Ardenne belge) suite à l'étude tectonique, pétrologique et sédimentologique de la carrière Lambert (commune de Flamierge, entité de Bertogne). Les critères utilisés pour interpréter les environnements sédimentaires anciens rencontrés en Ardenne centrale sont discutés. Un ensemble de structures sédimentaires caractéristiques ainsi qu'une lithologie restreinte aux sables fins, aux silts grossiers et aux boues indiquent un milieu soumis à l'influence des marées. Les sous-environnements représentés par les chenaux de marée, les zones tidales sableuses, argileuses et mixtes s'empilent verticalement. Ces milieux, de très faible relief, forment des surfaces très étendues sans barrière sableuse protégeant l'estran des influences de la mer ouverte. La forte extension de la zone tidale est une réponse à la transgression dévonienne sur des surfaces planes constituées de milieux de plaine d'inondation et de plaine deltaïque. En comparaison avec des environnements comparables actuels, ces séries présentent des épaisseurs inhabituelles en relation avec un taux de subsidence élevé et continu et un apport sédimentaire régulier. Le système fluviatile bien développé apporte les sédiments issus du continent des Vieux Grès Rouges à travers les milieux alluviaux et deltaïques développés au nord de la zone d'étude. Des îles argileuses, au-dessus de la zone de battement des marées, s'assèchent occasionnellement en permettant le développement de paléosols et l'installation de communautés végétales.

MOTS-CLÉS. Formation de Mirwart, Praguien, Dévonien inférieur, milieux tidaux, structures sédimentaires, modélisation des environnements, Ardenne.

1. Introduction

During Lower Devonian times, at the end of the Caledonian orogeny, a large open marine basin developed in the Ardenne, south of a continent located in the North, the so-called Old Red Continent. The Ardenne-Rhenish Basin originated from a narrow but elongate rift-like mobile belt, starting its history in the Early Devonian (already at the end of Silurian, Godefroid & Cravatte, 1999). This mobile belt persisted until the end of the Early Carboniferous and was subsequently incorporated in the Rhenohercynian fold and thrust belt during the Variscan orogeny. Recent studies (Paquet & Goemaere, 1996; Paquet *et al.*, 1998) show that the depositional setting changed from continental to shelf marine environments including fluvial, deltaic, foreshore, shoreface and offshore depositional environments. All the sediments are clastic and very similar to the Rhenish facies. Stets & Schäfer (2002) analysed, interpreted and reconstructed the depositional palaeoenvironments of the Lower Devonian siliciclastics within the Rhenohercynian Basin. This major synthesis is useful for comparing the Northern Facies belt and the Belgian

Ardenne Basin. Up to now, no extensive sedimentological studies were undertaken on these rocks of Lower Devonian age in Belgium. This is due to the partial absence of a detailed biostratigraphic control in the Anticlinorium of the Ardenne and in the Synclinorium of Neuchâteau (effect of metamorphism and/or inappropriate facies) and to the intense folding and the scarcity of good sections.

The purpose of this paper is to contribute to a better understanding of the depositional model of the Belgian Lower Devonian series. Physical and biogenic sedimentary structures are described from a large outcrop resulting from a sandstone exploitation (Lambert Quarry): here the upper part of the Mirwart Formation is well exposed. The quarry is located (Fig. 1) (IGN: 60/6, Belgium Lambert coordinates 1972, X: 240.450; Y: 86.190, Z: 375m, NE of the Amberloup-Flamierge geological map n°196), 1.2km NNW of the small village of Gives (Flamierge commune, Bertogne entity, Province of Luxembourg). This quarry is reported in the archives of the Geological Survey of Belgium as observation point n°196E263. The sandstone quarry is owned by the Lambert Company of Bertogne (work of civil engineering). Quarrying is intermittent, production encompasses aggregates as well as decorative stones. Geological surveys (see further) were carried out along two working faces, a larger one, oriented N320°E (SSE-NNW) (Plate 1, photo A) and a smaller one oriented N60°E (SW-NE). All together, they provide a geological cross-section of 130 m long, perpendicular to the strike of the beds.

2. Geological setting

The Flamierge area is located on the northern limb of the tectonic structure connecting the Ardenne Anticlinorium to the Neufchâteau – Eifel Synclinorium. Detailed mapping at the scale of 1:10.000 reveals that the rocks are folded with axial planes trending from N60°E to N75°E. The Lambert Quarry corresponds to the NW limb of a rather large syncline with a local wavelength of 700 m. This locality has suffered very moderate tectonic disturbance and the cleavage is only slightly expressed in a few places (Table 1). In the Lambert Quarry, the layers are gently dipping to the SE with an average of 25°. Measurements of the bedding planes are given in Table 1.

Locally, beds can be slightly deformed as mullions (Kenis *et al.*, 2002) which are very well displayed on a height of approximately 1 m below the top of Unit VI made of 10.5 m of sandstone - siltstone. The corresponding undulations disappear progressively downwards. In the inter-mullion planes, cm- to dm-thick milky quartz vein are sometimes located in the competent unit. They are quickly thinning downwards.

Other milky quartz veins are also particularly common within the sandy units II, IV & VI (Plate 1, photo B). They are distributed from bottom to top of the competent units and always disappear in the surrounding shaly rocks. Most veins are roughly perpendicular or slightly oblique to the bedding. Cm- to dm-thick quartz veins and en-échelon tension gash veins (sometimes displayed in conjugate arrays) indicate respectively extensional and shear regimes during their formation. Fanning veins occur as well, coinciding with gently buckled layers.

Field observations do not reveal peculiar mineralogical associations and no mineralogical or fluid inclusions studies were performed on the quartz veins of the Lambert quarry.

The rocks exposed in the eastern part of the geological map Amberloup-Flamierge (Stainier, 1900), enclosing the Lambert Quarry, belong to the former "Grès d'Anor et de Bastogne" (Cb1a). The latter is composed of siliceous slates, phyllites, banded quartz-phyllites, and banded sandstones. The name "Anor" was now abandoned and replaced by "Mirwart" for two reasons: 1) the lack of a good section in the Anor area and 2) the name Mirwart had already been used in the past for the upper part of the formation (Hebert, 1855; Stainier, 1994). Asselberghs & Leblanc (1934) have published a map of the Champlon – La Roche - Houffalize area on which the Lambert Quarry would belong to the Middle Siegenian - Sg2 (see also their comments for the Wigny area pp. 23-26). Strictly, this corresponds to the Villé Formation. Detailed mapping of this area does not confirm this interpretation: the rocks belong indeed to the Mirwart Formation (Dejonghe, in preparation). A possible explanation is that due to the presence of rare fossils in the upper part of the Mirwart Formation, it was also attributed to the Midde Siegenian – Sg2 by Asselberghs & Leblanc (1934) or to the Midde Siegenian - S2 by Asselberghs (1946).

In the absence of reliable characteristic biological markers, only sedimentological studies can contribute to unravel paleoclimatic conditions during deposition of the Mirwart formation. The Mirwart formation is part of the Lochkovian-Pragian fining-upward transgressive clastic wedge that developed at about 15 to 20° southern latitude during

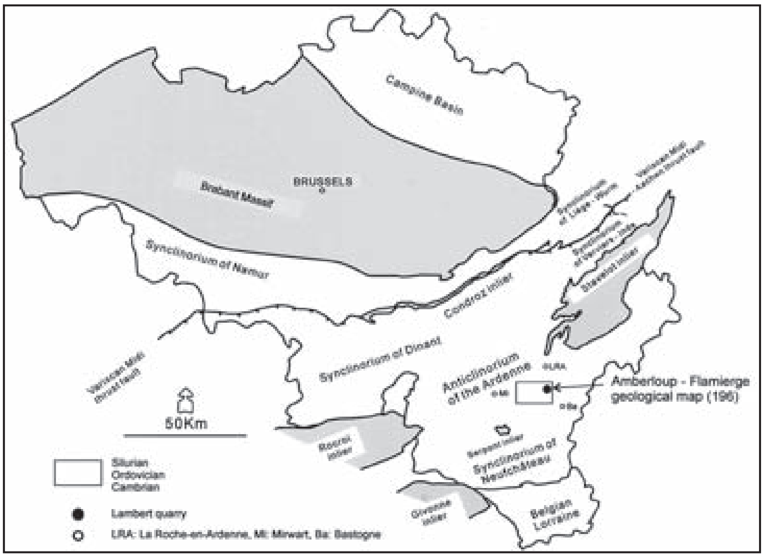

Figure 1. Location of the studied Lambert Quarry on a simplified geological map of the Belgium. The grey background highlights the Lower Palaeozoic basement.

Lower Pragian times (Golonka *et al*., 1994). Due to the Caledonian collision, the Laurussian Old Red Continent formed an orographic mountain barrier in the north favouring perennial rainfall at its flanks. As a consequence, presumably tropical wet environments existed on the Old Red Continent all over the year with a mean annual temperature of about 25°C (Stets & Schäfer, 2002).

The Mirwart Formation is diachronous from the west to the east, with ages ranging from Lochkovian to Pragian (Bultynck & Dejonghe, 2001). According to Godefroid *et al*. (1994), its thickness varies from 300 to 700 m along the southern flank of the Dinant Synclinorium. The Mirwart Fm corresponds also to the Mohret Formation of Beugnies (1985) with thicknesses ranging from 700 to 900 m in the Bertogne area (the so-called Opont tectonic unit), whereas its thickness does not exceed 400 m thick in the north (the so-called St-Hubert tectonic unit).

At its base, the Mirwart Formation begins with greyish green shales (eventually, slates if a cleavage is visible, which is not always the case in the Bertogne area) overlying the quartzites of the St-Hubert Formation. At its top, green quartzites occur, underlying carbonate and fossiliferous beds of the succeeding Villé Formation. In between, thick lenses of green, light blue, greenish blue, or even white or cream-coloured quartzites and sandstones occur, interbedded with green grey or dark shales (or slates) and siltstones. Sandstones often contain pebbles of dark shale. Towards the top of the formation, the dark shales contain plant remains. In the 100 uppermost meters, the sandstone layers may also contain rare shells (Bultynck & Dejonghe, 2001). Due to its fossil content (many plant debris, rare shells – see below), the Lambert Quarry most probably exposes rocks belonging to the upper part of the Mirwart Fm.

3. Description of the succeeding lithofacies in the Lambert Quarry

The survey is made in a stratigraphical order, from older rocks (at the NNW) to younger ones (at the SSE). Different lithofacies were defined according to the field observations. In this paper, a complete 60-meter thick section is described (Fig. 2). Nine different lithological units have been distinguished (Table 1). Units 3 to 9 (exhibited on the main working face) are identified on Plate 1, photo A.

3.1 Lithological unit 1: The siltstone-sandstone unit

This unit is observed along the N60°E oriented working face; its base is not visible. Decimetre-thick beds of bluish grey siltstones alternate with cm-thick beds of fine-grained greyish sandstones (superficial weathering produces beige to brownish colours). The sandstone beds frequently show wavy-bedding and simple flaser-bedding, while the siltstone beds exhibit lenticular bedding (single lenticular bedding with flat and thin lenses until connected bedding with thick lenses). Oblique lamination and cross-lamination are usually observed within the current ripples. Ripples of fine sand occur interbedded with shales either as isolated or starved ripples, or single or multiple layers, or lenticular layers intimately mixed with shales (commonly called “flaser bedding”). The current direction is from the NE to the SW. The current ripples have wavelengths varying between 5 to 20 cm and amplitudes between 1 to 3 cm. The same orientation is shown by numerous tool marks preserved at the base of the sandy layers and printed in the underlying muddy sediment. Some linear drags are continuous over 50 centimetres. The mud was just right - soft, yet firm enough – so that tracks and sole marks were remarkably well preserved. Millimetre–thick and repetitive alternations of both sand and clay bedding (= tidal bedding) sometimes show alternatively opposite dipping foreset laminae, related to tidal currents. Both weakly bioturbated and non-bioturbated silty and sandy layers occur. Layers of sandstones and siltstones alternate in a changing and quick succession. Metric-thick sequences are observed with a decreasing sand content from bottom to top, and with a gradual shift of the tidal structures: from connected flaser bedding, over lenticular bedding to tidal bedding (Plate 3, photo A). The latter succession is called a ‘fining-upward sequence’ here. The top of each sequence (flat-bedded or with current ripples) shows vertical and oblique burrows, linguoid ripple marks (Plate 1, photo F; Plate 2, photo A), tracks, tool marks and groove marks. Antiripplets, foam marks, crescent marks (Plate 2, photo D) and shallow gullies are less frequent. Small flute casts are frequent at the interface between the mud and sandstone layers (Plate 2, photo D). Together with rare crescent marks, these

Lithological unit	Thickness (m)	Dip direction of bedding (°)	Dip direction of cleavage (S1) and undifferentiated joints (J)
1	< 5.5 to 7.90	25-135 to 15-140	
2	3.9 to 6.3		
3	8.5 to 9	25-142	S1: 40-135 weakly developed
4	11.5	25 to 30-132	J: 83-221 to 70-315
5	1.55 to 3	30-145	
6	10.5	30-143	J: 74-155.
7	9	25-158	S1: 45-138 (weakly expressed); J: 74-203
8	2.2	25-132 to 35-138	J 75-223
9	> 2 m		

Table 1. Overview of thickness and structural data of the lithological units.

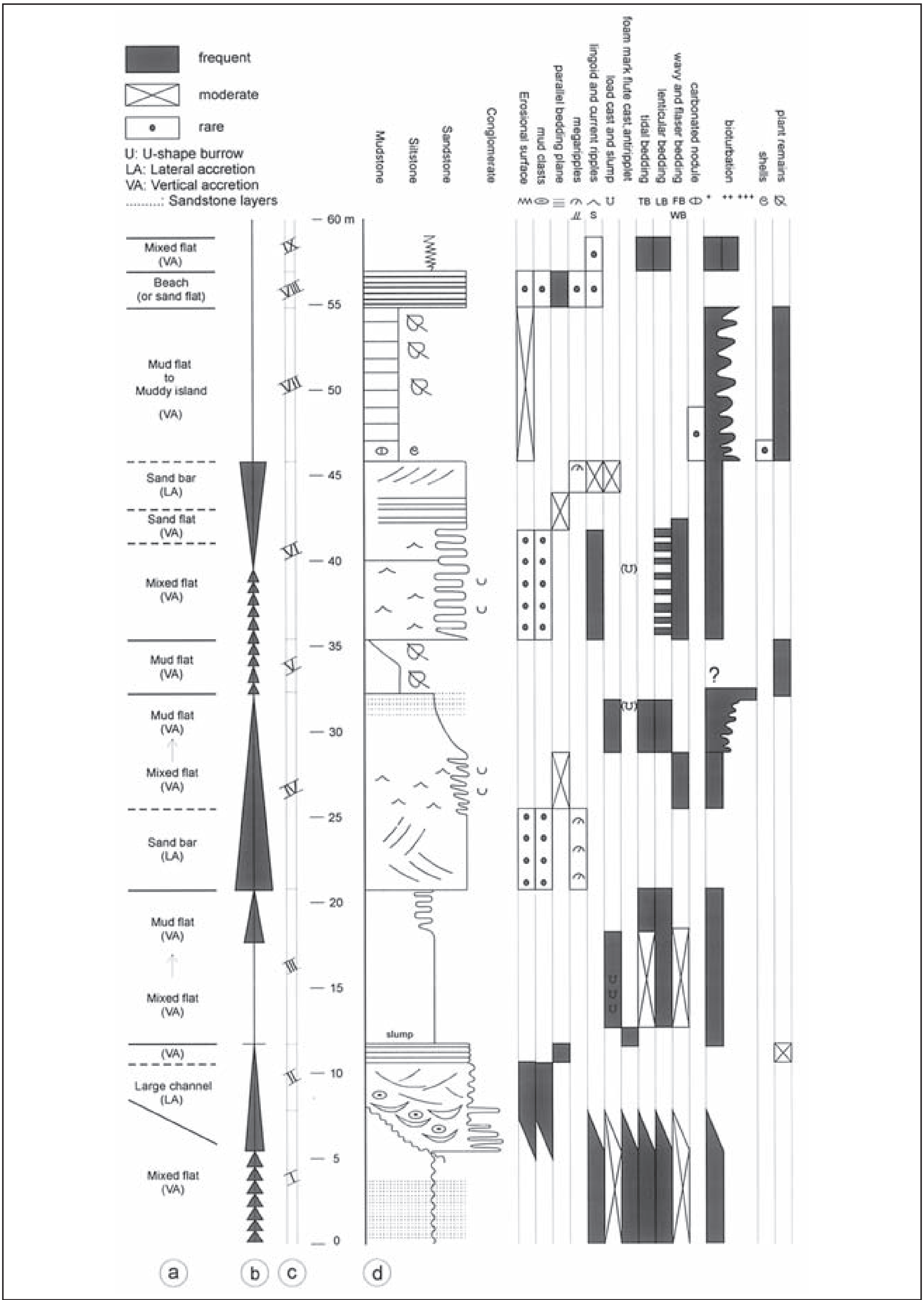

Figure 2. Sedimentological log of the Lambert quarry (Upper Pragian). a: interpretation of the paleoenvironments, b: vertical evolution of grain size, c: succession of lithological units, d: columnar lithological section, vertical distribution and abundance of sedimentological features.

sedimentary structures are good criteria for measuring the orientation and the strength of the current. Figures interpreted as foam marks could even be an evidence of emersion of this part of the section. Occasionally, traces of escaping animals are encountered, pointing to a high sedimentation rate. This unit is truncated at its top by an erosional unconformity.

3.2 Lithological unit 2: The sandstone and conglomerate unit

The next 2 metres of the section show dm-thick, strongly lenticular beds of grey-blue conglomeratic sandstones separated by numerous erosional unconformities. Sandstones contain numerous well rounded (clay balls) as well as angular (clay galls) mud clasts (dark blue and micaceous shale and fine-grained siltstone) (Plate 1, photo C). The mud clast size ranges from 1 to 30 cm. The clay galls and ovoid mud balls generally have their long axes preferentially oriented parallel to bedding plane. In general, the size of the mud balls decreases and the roundness increases from base to top of the beds and from the base to the top of the unit. Many lenses of conglomerate are composed of up to 80% of angular mud clasts. In the latter clasts, structures such as microtidal bedding and isolated lenticular bedding with flat lenses are clearly recognised: they are resembling the sedimentary structures observed in unit 1.

In the succeeding part of this lithological unit, grey-blue sandstones are subdivided into lenticular dm-thick beds enclosing rare and small mud balls. The channel fill is composed of finer-grained bluish sandstone with irregular internal stratification grading into a parallel planar stratification (sometimes underlined by small mica flakes). Furthermore, both cross-stratification and oblique stratification (lateral accretion) occur in the sandstone bodies. Bioturbated structures are absent, probably because the intensity of reworking is too high. The large size of the mud balls and the high frequency of the erosional gullies (dm to m-wide), support the idea of a high level of energy for the lower part of this unit (Plate1, photo E). Lenticular micaceous bluish-grey sandstone beds contain unidentified plant remains, these are deposited along the bedding plane. Their axes generally are preferentially oriented and strongly deformed and oxidised in outcrop (gold colour).

The upper 4.5m-thick body of sandstone presents a fining-upward sequence topped with lenticular sandy siltstone (containing bioturbated sandstone lenses). This unit continues with lenticular sandstone bodies, cut by lenses of conglomerates and internal erosion surfaces. Smooth current ripples cover the top of some beds.

A fractured zone is pointed out by an alteration that confers a brown-chocolate colour and a friable texture to the sandstones. Mud chips are more sensible to this alteration than the sandstone, especially when aggregates of pyrite are present.

3.3 Lithological unit 3: The siltstone-mudstone unit

Unit 3 starts with a strongly slumped lenticular siltstone bed (with sandy streaks) of 6 to 80 cm thick (Plate 1, photo G). This horizon was not observed laterally. In the upper part, the slump structures are bounded by an even plane and are followed by the usual, undisturbed tidal -, wavy - and lenticular bedding types.

The overlying succession is made up of m-thick fining-upward sequences displaying the following structures from bottom to top: (wavy) flaser bedding, wavy bedding and lenticular bedding (connected with thick lenses to isolated thin and flat lenses) (Plate 3, photo B). Bioturbation is generally weak but overall present. Short vertical burrows, feeding and reptation tracks are present at each top of bed or sandstone layer. Subordinate flaser and wavy bedding structures show linguoidal-rippled surfaces. Furthermore, small load casts are locally observed at the base of thin sandstone beds.

3.4 Lithological unit 4: The sandstone unit

This sandy unit was quarried for building stones and aggregates: it is essentially composed of lenticular dm-thick beds of grey to beige fine-grained sandstones. Mud is very subordinate. Locally, discontinuous and eroded mm to cm-thick (vertical and oblique short simple burrows) layers of dark fine siltstone are burrowed. In rare cases, they are laterally reworked as mud clasts or occur in the overlying sandy sediments. Exceptionally, inconspicuous widened U-shaped burrows were observed in the laminated sandstones.

The lower part of the unit essentially shows moderate erosion surfaces, lenticular beds and sometimes isolated centimetric clasts of blue shale (mostly near the base of the beds). Rippled megaripples are present showing lateral migration.

In the middle part of this unit, wavy bedding and wavy flaser bedding (separated by mud drapes of dark blue clay) often alternate in the sandstone beds (Plate 3, Photos C & D). The ripples are present in the form of current ripples and linguoid ripples. Thin burrowed layers of dark blue micaceous siltstone (sometimes with sand streaks) are intercalated. Horizontal bedding and cross-bedding are common. Cross-bedding and unidirectional tangential oblique bedding is mainly related to the presence of megaripples or relics of sandbars. The upper surface of megaripples expose small current ripples. Generally the ripple crests have been partially eroded before deposition of a new sandstone bed. Load cast, flute marks and tool marks are present on the bottom of the sandy layers.

The top of unit 4 contains dark, burrowed siltstones with isolated flat sandstones lenses (lenticular bedding) or tidal bedding in alternation with cm-thick rippled beds of sandstone. The lithological change from sand to clay and clay to sand is always abrupt and resulted from decreasing current velocities. The uppermost bed is a strongly bioturbated fine-grained sandstone interlayered with dark blue burrowed siltstone (Plate 2, photo F). Unit 4 exhibits a general fining-upward tendency.

Potential plane-parallel micro-stylolithes affect the impure sandstones.

3.5 Lithological unit 5: The mudstone unit

This unit is lenticular and mud is predominant. The blue shale becomes gradually darker upwards and contains thin discontinuous sandstone layers at the base. Black shales (locally carbonaceous), without any lamination, are rich in plant remains. Nude plant axes reach up to 25 cm long, and are often dichotomous; spines and fertile organs were not observed. Each bedding plane contains abundant plant debris, probably related to Zosterophylls (personal communication of P. Gerrienne – macroscopic investigation).

A shear zone parallel to the bedding plane, producing a shiny graphiteous aspect in the black shales, overprints the basal part of the unit.

3.6 Lithological unit 6: The sandstone-siltstone unit

The first 6.4 m are characterised by an alternation of bluish-grey fine-grained siltstones and greyish-beige sandstones. Siltstones systematically display lenticular (all types) and tidal bedding. Bioturbation is weak, with vertical and oblique burrows (mm-sized). Large, simple burrows of centimetric diameter and widened U-shaped burrows locally occur. The sandstones are composed of ripple bedded sediments. Simple flaser bedding and wavy flaser bedding are remarkably well exposed. Isolated small clasts (angular to rounded) of (blue to black) shale are present at the base of sandstone beds, pointing to regular reworking of muddy layers. The stratification surfaces show linguoid ripples with smooth crests, weak amplitude (1 to 3 cm) and a variable wavelength (10 to 30 cm). Superposed ripples occasionally show alternatively opposite dipping foreset laminae, as a result of the tidal currents. The overlying 2 metres of the profile are mainly composed of sandy beds. Massive sandstones, with plane-parallel stratification, rippled (linguoid) upper surfaces, are the main sedimentary structures in this unit. The upper part of this sub-unit is composed of megaripples (laterally prograding to the south) made up of lenticular sandstones showing flaser-bedding and linguoid ripples upward (very low amplitude and high wavelength). The top surface shows undulations, burrowing and mud balls. Near the top of the unit, the coarsening-upward sequence grades into a fining-upward sequence. Here, it is muddy with streaks of moderately bioturbated sands. Upwards, laminae of sand decrease both in number and width. A clastic dyke of 50 cm long cuts the overlying shales.

3.7 Lithological unit 7: The mudstone unit

Clayey and silty sediments dominate within this unit. Near its base rare moulds of small brachiopods, gastropod and molluscs (unjoined valves) occur, dispersed in a 5 cm-thick layer of bioturbated muddy sandstone. Above this level and higher, rare bivalves occur in dark blue micaceous and finely bioturbated siltstone. No molluscs have been found in living position: all shells have been reworked from adjacent biotopes, most probably by storms. Subsequently their shells have been dissolved. No crinoïd ossicle, particularly frequent in the overlying Villé Formation, was found. Only polished sections through fossiliferous shales could highlight the internal erosional surfaces, allowing to interpret this level as a washed surface after a storm event. Later on, only moderate bioturbation could have disturbed the sediment.

The unit is made up of deep blue shale, very rich in plant debris (Plate 2, photo G) and pyrite. However, all the organic matter has been replaced by micro-flakes of a green chlorite with preservation of the external morphology of the plant remains (pseudomorphism). A conchoidal pattern appears when breaking the rock with the hammer: this phenomenon reveals the homogeneity of the sediment and the absence of vertical variation in the grain-size. Bedding is underlined by the concentration and alignment of plant axes. This alignment varies from one level to another. The plant axes are nude, sometimes dichotomous. When weathered, we observe a whitish-grey rim around the plant fragments. Occasionally, one can find rounded carbonate nodules (4-10 cm in size) (Plate 2, photo E); a paleopedogenetic origin is suspected here. Polished sections show the intense internal perturbation and root imprints.

The middle part of the unit (0.80 m) is composed of coarsening-upward siltstones displaying regular and parallel laminae of sand (tidal bedding). It grades into burrowed sandstones with bi-directional μcross-stratification, ending with planar stratification and then undulating beds of bioturbated clayey sandstone. A 3.70 m-thick bed of siltstone (displaying sand laminae) is very rich in plant debris and forms the top of the unit 7. Alteration shows limonitic spots (after pyrite) and minor coatings of limonite on the bedding plane.

3.8 Lithological unit 8: The sandstone unit

This part of the section consists of fine-grained beige (slightly micaceous) sandstones. Mud becomes very subordinate and is limited to rare mud clasts and discontinuous thin layers of fine blue siltstone. Sometimes, beds of beige finely laminated sandstones are cut by erosive surfaces. Reworked material is trapped in small gullies. Beside horizontal stratification, parting lineation (traction transport of sand in the "flat bed" mode), low planar cross-bedding and wide low amplitude basal scours are present, reflecting the high velocity of the current. Rarely, beds show undulating top surfaces covered with smooth current ripples (wavelength > 20 cm and amplitude < 2 cm).

3.9 Lithological unit 9: The siltstone unit

This unit is very badly exposed. Its base and its top cannot be observed. The lithological content of this unit (lithology and sedimentary structures) is quite similar to that of unit 6. The main sedimentary structures observed are flaser bedding, (micro)-lenticular bedding, bioturbation and vertical burrowing.

4. Petrography

Twenty-eight rock samples were studied under the optical microscope. Selective coloration of feldspars was performed on 4 of the sandstone samples. The rocks comprise sandstones, quartzitic sandstones and shales (grading into fine-grained siltstones). Shales rarely contain sand except where they are affected by bioturbation. Primary sedimentary features can still be observed, because of the weak development of the slaty cleavage.

Petrologically, the sandstones and quartzitic sandstones from the Lambert Quarry consist of very fine- to fine-grained quartz arenites or sublitharenites. Subarkoses are absent. The sandstones are mature. Quartz grains generally represent more than 80% of the bulk of the grains. Sorting is good to very good. Quartz overgrowths and clay minerals represent the characteristic cements.

The coarse silt-size quartz grains in the claystones with matrix-supported fabric, are sub-angular with a low sphericity. These quartz grains sometimes show mineral inclusions (micas, rutile) and fluid inclusions. The mean grain size of the sandstone fluctuates according to the paleoenvironment. In the channel sands, the mean size of sand grains lies between 140 and 180 μm (clasticity up to 400 μm), whereas in sand flat and mixed flat environments, the mean grain size lies between 70 and 140 μm (clasticity up to 300 μm). In coarse siltstones, both the silt-graded quartz and the feldspar grains are angular. Quartz (with undulatory extinction) and feldspar grains occur throughout all of the studied rocks. In the Mirwart and Maboge sections, the mean quartz grain sizes range respectively between 140 to 160μm and between 120 to 160 μm, whereas their clasticity ranges respectively between 240 to 370 μm and 150 to 370 μm (Paquet *et al.*, 1996, 1998). The mean grain size of the sandstones deposited in channels is quite similar for the sections of Maboge, Mirwart and Flamierge. However, the mean grain size of the sandstones from sand flat and mixed flat environments are slightly thinner in the Lambert Quarry.

Sandstones show the effects of pressure dissolution, resulting in sutured grain contacts. The initial morphology of the grains and the primary grain size distribution are slightly modified by the quartz overgrowths. The quartz grains then appear angular and tightly interlocking. Dust lines around grains are rarely visible. During burial (low-grade metamorphism and slaty cleavage) the clay minerals recrystallised into sericite and oriented iron-bearing chlorite flakes.

The feldspar content in the sandstones averages between 1 and 4%. The average grain size of feldspar is always lower than that of quartz. Feldspars generally have a dusty/dirty looking compared with quartz grains. In fresh sandstones, feldspars vary from fresh to altered, which is interpreted here as the result of rapid erosion in a relatively humid climate. Incipient replacement by sericite and the presence of unweathered plagioclases are characteristic features. Potash feldspar is rare, while plagioclase is common. Perthites are rarely present and zoned plagioclases are absent. Rare myrmekites were identified in some thin sections. In weathered sandstones, feldspars are subject to partial dissolution, mainly along the cleavage planes: iron oxides and hydroxides frequently occur within the cleavage planes or as films around the grains. Grain-sized pores appear where feldspars are entirely dissolved. Strong alteration of feldspars, iron-bearing chlorites and Fe-Ti minerals lead so a distinct red-brown colouring of the rock. Locally, total replacement of the feldspars produces clay mineral pseudomorphs.

Sand-sized lithic grains are uncommon, all of which are sedimentary in origin, i.e.: laminated and silty shales or laminated and sandy siltstones. Polycrystalline quartz grains are subsidiary, some of which exhibiting sutured contacts and fine sericite flake inclusions. Mud drapes and chips of siltstone or shale show the effect of compaction, with a tight-fitting arrangement of clasts and minor interpenetration or squashing of the grains. This texture is accentuated by the development of a slaty cleavage. Soft sand-sized grains, including lithic grains (siltstone, shale), have lost their identity and evolved into a pseudomatrix.

Rare muscovite, iron chlorite, and (infrequent) muscovite-chlorite stacks occur as rare distorted detrital flakes (up to 400 μm long and 10 to 200 μm wide) in the sandstones. The flakes are never concentrated along the bedding plane in the sandstones. In silty and shaly rocks, abundant thin flexuous (until 200 μm long and between 5 and 15 μm wide) flakes of muscovite and chlorite occur. The latter are concentrated along partings, laminae and bedding planes. Exceptionally, hematite crystals are aligned along the cleavage plane; in this case, flakes have a rugby ball shape. Plurimicrometric crystallites of micas, generally included in the overgrowth cement, result from diagenesis of the clay-sized minerals. In the finest pelitic rocks, a reorientation of the long axis of the crystallites in the cleavage plane has been observed.

Carbonate cement is normally absent, but in 7 samples taken from all units, scattered zoned ferroan dolomite rhombs were identified. Dolomite is diagenetic in origin and represents less than 5% of the total rock. However, micritic calcite is the main component in the ovoid nodules (5-12 cm), with diagenetic iron-bearing chlorite. Petrologically, the chlorite seems to progressively have replaced the calcite. Weathering of this material produces a typical yellow brownish pigmentation. Moreover, Beugnies (1986b) reported the presence of carbonate cemented nodules near the top and at the base of the Formation of Mohret: these carbonate nodules are transformed into quartz-amphibolitic nodules in the internal metamorphic area, south of the Flamierge area.

In the sandstones, heavy minerals are frequent (until 5%) and they often underline the stratification (horizontal planar- and cross-stratification). This reveals an important hydraulic sorting. The more common, translucent heavy minerals comprise rounded zircon (60-100 μm) (rarely zoned or subidiomorphic) and green tourmaline. Detrital grains of rutile, blue tourmaline and apatite are less common. Ilmenite and its weathered products are the most common accessory heavy minerals and represent about 60% of the population. This is a common feature of beaches and other locations where continuous winnowing takes place. No concentrations of heavy minerals were recognised in the tidal channel environments. The study of heavy minerals can give useful information on provenance and geological events in the source area. Rutile, apatite and tourmaline point to metamorphic and igneous source rocks, whereas ilmenites are characteristic of basic igneous and metamorphic source rocks. As a result of their high specific gravities, the heavy-mineral grains in sandstones always display grain sizes below or near 100 μm.

Beside detrital ilmenite grains in the sandstones, ilmenite crystals of metamorphic origin have also been identified in the fine-grained siltstones. The size of the porphyroblasts lies between 100 and 300 μm. The elongated axis of the porphyroblasts show isotropic distribution without relation with the bedding plane nor with the penetrative Variscan cleavage. The ilmenite porphyroblasts are considered as prekinematic minerals. Residues obtained after hydrofluoric acid attack of plant-rich samples of shales contain, beside thin idiomorphic crystals of blue tourmaline, also numerous grains of ilmenite s.l. This HF treatment highlights the leucoxene "treillis" engaged in the (111) network of titanomagnetite. Ilmenite is well-known in the metamorphic zone of Bastogne and its NE-extension zone (Grand Duchy of Luxembourg) as small grains in quartz veins and as needles of 1 to 2-mm size in slates and phyllites (Antun, 1971, Hatert *et al.*, 2002) as well as in stream sediments (Sondag & Duchesne, 1987). Ilmenite lamellae can reach 1 cm of length in the quartz veins of Bertrix and Bastogne. Ilmenite is also present in many rocks of the Rocroi Massif. Ilmenite porphyroblasts (tabular to elongated "rugby balloons") observed in the Lambert Quarry are associated with the finest rock types: they correspond to the northern border of the "préexterne" metamorphism zone of Beugnies (1986a). Illite crystallinity measurements, reported by Fielitz & Mansy (1999), point to epizonal metamorphic conditions for the Pragian rocks of the Bastogne area up to the connection within the southern Stavelot Massif. Paragenetic minerals typical of the greenschist facies (such as magnetite, plagioclases, andalousite, garnets, chloritoïds, biotite, amphiboles, epidotes and titanite) were not identified in the studied section. Calcite porphyroblasts and pyrrhotite are absent as well iron-bearing chlorite replacing plant debris. The mechanism and conditions of occurrence of that iron-chlorite (chamosite) is of particular interest in the study of the regional metamorphism conditions.

Thanks to this study, the area of occurrence of ilmenite-bearing rocks (macroscopic identification), on the 1/40,000 geological map of Amberloup-Famierge of Stainier (1900), can now be extended at least 3 kilometres towards the north (of the small village of Ruette). North of the studied area, ilmenite porphyroblasts are absent in the La Roche, Maboge and Mirwart sections.

5. Sedimentological structures

Sedimentary features are present within the whole lithological range of fine-grained sandstones to fine-grained siltstones. The observed sedimentary facies were compared with those occurring in modern sedimentary environments and in comparable ancient deposits, in order to interpret their depositional environmental conditions (Table 2).

The dominant sedimentological structures in the studied section (lithological units 1, 3, 4, 6 & 9) are tidal bedding, lenticular bedding, wavy bedding and flaser bedding (Plate 3). The classification used is that of Reineck & Wunderlich (1968) and Reineck & Singh (1973). All transitional types were observed. Tidal rhythmites, defined as tidal bedding displaying a vertical record of tidal cyclicities, such as the semi-diurnal, diurnal and neap-spring cycles, are well understood in vertically accreted deposits (Tessier, 1995). Tidal signatures in modern and ancient sediments are now well documented (Flemming & Bartholomä, 1995;

11. Features	Flow model	Environment
Bimodal frequency distribution of dip angles of cross-strata	Tidal currents	Tidal flats
Bipolar current ripples	Tidal currents	Intertidal zone
Tidal bedding	Tidal influence	Tidal flats – Mud flats
Lenticular bedding	Alternation of tidal current minor bedload transport with suspension deposition during slack water	Tidal flats – Mud flats
Wavy bedding	Alternation of tidal current bedload transport with suspension deposition during slack water	Tidal flats –Mixed flats
Flaser bedding	Alternation of tidal current bedload transport with minor suspension deposition during slack water	Tidal flats –Sand flats
μ-load casts	Differential compaction and loading due to rapid deposition – shock event	No specific
Drag casts, small gullies	Erosion by high-velocity flow	Fluvial to high subtidal
Flute casts	Erosion by high-velocity flow	**12. Flysch sediments, shallow marine and non-marine**
Foam marks, antiripplets	Temporary emerged zone	High intertidal to supratidal
Oblique and vertical burrows	Burrowing	Intertidal until subtidal
Tracks and trails	Burrowing	No specific
U-shaped burrow	Suspension feeder	High subtidal to intertidal
Megaripple (sand wave)	High stream power	Tidal flats
Mud chips conglomerate	Erosion and deposit near	Subtidal, base of washouts and channel
Parallel laminae in sandstones and low-angle cross-bedding	High-velocity flow	Upper intertidal zone -beach, sand flats
Concentration of fossils	Tempest, scour surfaces	Subtidal to high intertidal
Oriented debris of plants	Tempest accumulation and currents	Continental to marine
Carbonated nodules	paleopedogenesis / diagenesis	Supratidal, fluvial plain / any relation

Table 2. Sedimentary structures related to a flow model and the correlated depositional sedimentary environments.

Ginsburg, 1975; Singh & Singh, 1995). Wavy bedding (or lenticular bedding with thick connected lenses) was already described by Asselberghs & Leblanc (1934, reported by Asselberghs, 1946, Fig. 11, p.128) : "Près de Givry affleure du quartzite quartzophylladeux présentant une texture très curieuse: les strates très régulières sont brusquement ravinées par le dépôt suivant qui se calme peu à peu pour reprendre une allure régulière et recommencer une nouvelle période; la hauteur correspondant à une période atteint de 4 à 8 cm". Reineck & Wunderlich (1968) show a continuum of rippled sand-shale mixtures ranging from starved ripples to lenticular and wavy bedding, with flaser bedding as the end member. As in modern tidal rhythmites, the Lambert quarry rhythmites are characterised by the vertical evolution from flaser to wavy bedding and lenticular bedding, when the tidal range decreases from spring to neap. These changes in bedform character reflect a decrease in tidal current velocities during neap tides, associated with weaker (in comparison with spring tides) movement of sand-sized particles. Flaser bedding develops when mud fills in the ripple troughs and is then covered by successive ripples. The muds interbedded with rippled fine sands result from intermittent slack water conditions, during which clays settle out of suspension. Ripple crest and micro-cross-lamination orientation were used in deducing paleocurrent and dispersal pattern. The main current direction is from NE to SW and is underlined by the dipping of the foreset laminae and the asymmetry of the current ripples (Plate 1, photo D). The wave lengths vary between 5 to 20 cm, the amplitudes vary between 1 to 3 cm. Lenticular-bedding is dominant within lithological units 1, 3 and 9, while flaser- and wavy-bedding are dominant in the lithological units 4 and 6. Tidal bedding is a repeatedly rhythmic bedding produced by tidal changes: it is a characteristic feature of lithological unit 3 and it is present within lithological unit 1. It is essentially composed of thinly interlayered sand/mud bedding, made up of fine sand layers (1 to 5 millimetre thick), alternating with mud layers (fine silt) (1 to 5 millimetre thick). Laminated sands and muds show small-scale planar horizontal bedding forming tidal couplets. Sets of couplets can be included in 10 to 20 cm-thick beds of some mud. Tidal bedding is characteristically ungraded and the contact between sand and mud is rather sharp. Laterally, some layers show microlenticular bedding (isolated asymmetric lenses of sand) and weak bioturbation (sand-filled burrows). The preferred environments of deposition for these structures are, therefore, areas where a change takes place between slack water and turbulent water and where the needed sediment exists: these are subtidal zones and intertidal zones. Thick cosets of lenticular and flaser bedding are characteristic of tidal sea deposits (Reineck & Singh, 1986).

Beside the above previous sedimentological structures, other inorganic and organic primary sedimentary structures are produced and contain: clay clasts, flute casts, load casts (Plate 1, photos D & F; Plate 2, photo B), tool marks (Plate 2, photo D), crescent marks (Plate 2, photo D), current ripples, megaripples, cross-stratification, erosional surfaces, channels and gullies (Plate 1, photo E), clastic dyke, foam marks, antiripplets, bioturbation, trails and burrows, carbonate nodules (Plate 2, photo E), plants debris and invertebrate fossils. Some of them are described above, while plates illustrate others. All structures are listed on Figure 2.

The frequency of clay clasts (coarse sand- to boulder-size) (Plate 1, photos C & E) in sandstone bodies (lithological units 2, 4 & 6) is one of the criteria to recognise the Mirwart Formation. These clasts also occur within sandstone beds interbedded with shales. Sedimentary structures, observed inside the biggest clasts (field observations and polished slabs), are tidal bedding, micro-lenticular bedding, burrowing and μ-load casts. Morphology, size and abundance of the clay clasts (clay galls and clay balls) are related to the distance of transport from the source area. Moreover this confirms the proximal source of the material as the tidal environment of deposit of the clays. Clay clasts derived from the hydraulic erosion of cohesive mud laminae or beds by the erosional shift of the channel trough the intertidal plain. Clay galls derived from the eroded parts of the channel with a minor transport, while rounded clay balls have been transported over longer distances from the catchment area of the channel (several hundreds of metres). Very typically, angular fragments are enclosed both as single clast dispersed in a sandy matrix (lithological units 4 and 6) and as framework constituents in conglomeratic lenses (lower part of the lithological unit 2). The mud-size particles, resulting from the shaping of the clay clasts, are not present as matrix in the sandstones, inferring a high energy level. In the absence of desiccation cracks, the cohesiveness of the mud substrate is the major critical factor in producing mud clasts, because if it is too soft, mud is simply re-suspended by turbidity current flow. The abundance of markings (tool marks) on the sediment surface demonstrate the cohesiveness of the substrate. On the opposite, a too firm substrate can not be sculpted. It is likely that this requested cohesiveness requires intermittent sedimentation where the mud substrate is exposed for a sufficient long period of time without deposition. Furthermore, a firm mud surface allowed the migration of sand (mega)ripples (Plate 3, photo A). In some cases, load structures (Plate 1, photos D & F), centimetre in size, are also present on the lower side of the sand layer overlying the mud layer. Rarely, we can observe ripples crests tending to sink down in the underlying plastic mud layer. Load structures are not restricted to any particular environment. They are known from channels of muddy intertidal flats, where a rapid mud sedimentation is interrupted by occasional sand deposition.

Flute marks are present in lithological units 1 and 3, as elongate-symmetrical flute moulds on the lower surface of the sand layers (Plate 2, photo D). They are a few millimetres up to 2 centimetres deep in their deepest part and a few centimetres to twenty centimetres long. The observed flute marks are arranged in groups in parallel rows and more rarely in an en-echelon fashion. Although characteristic for flysch sediments, flute marks are abundant as well in shallow-water marine and even in non-marine environments (Reineck & Singh, 1980). They result from erosion on a muddy surface by vortices and need vigorous currents.

A clastic dyke is observed in lithological unit 7. The latter results from liquefaction and fluidisation phenomena. The pressure needed for such an injection can be produced by the load of overlying sediments, accumulated gas pressure or even by hydrostatic pressure. The high sedimentation rate of water-loaded sediment and eventually the gas produced by the decay of organic matter from abundant debris of plants can be suggested here as triggering mechanisms. Jankowsky (1955, reported by Stets & Schäfer, 2002) described several V-shaped, so-called "Grauwackengänge" (sand dykes) within the silt/sandstones successions of the tidal environments from the Upper Siegenian Herdorf-Schichten (Northern Facies Belt of the Rheinisches Schiefergebierge, W-Germany).

In the lithological unit 3, a slumped lenticular bed of siltstone with sandy streaks (Plate 1, photo G) has been observed. The shock of an earthquake at low tide might have been the main trigger. This hypothesis is supported by the fact that in the upper part, slumping structures are bounded by an even plane and are followed by undisturbed tidal, wavy and lenticular bedding.

Rich ichnofossils (vertical – *Skolithos*-like - and oblique burrows) (Plate 2, photo F), U-shaped burrows (Plate 2, photo H)– *Diplocraterion*-like - , surface tracks, locomotion and feeding tracks) recorded in the Lambert quarry are quite similar to those observed in a modern tidal environment. In general, the sediments of the rhythmites show sporadic bioturbation or they are only weakly bioturbated, but they may exhibit abundant surficial biogenic structures as well, without disrupting the sedimentary fabric. The bedding plane is never totally reworked. According to the abundance of organic traces, we can assume that suitable conditions for living were mostly present. Bioturbation is absent from the sandy lithological units 2 and 8. It is also suggested that a muddy environment, the high sedimentation rate and frequent reworking were limiting factors. Only two muddy sandstones show a strong bioturbation, resulting in a disappearance of the primary sedimentary structures. This points to a longer period of still stand in the process of reworking and deposition. Biogenic traces left on the surface of the sediment are more frequent than those within the sediment and this also points to a high accumulation rate.

Macrofaunas are rather exceptional in the Mirwart Formation and they are normally restricted to the top of the Mirwart Formation. Furthermore, former palaeontological work was mostly focused on taxonomic and stratigraphic topics and on listings of fossils (Mailleux, 1936, 1937). These studies are only of a relatively limited paleoecological value (Stets & Schäfer, 2001). Only macrofaunal prints were observed at many places in the upper part of the formation (Bultynck & Dejonghe, 2001). In the studied section, only one level (lithological unit 5) contains some brachiopod and mollusc (bivalve and gastropod) shells associated with rounded clasts. Only one bryozoan stem has been discovered so far. Internal erosion surfaces of the sediments, unjoined mollusc shells and absence of molluscs in living position are indicative for reworking from adjacent biotopes, probably by storm wave activity.

If shell concentrations are well known in modern sediments of tidal environment, there still exist large areas, even in the vicinity of densely populated biotopes, where shells are totally lacking. The amount of fossils is rather low compared with the amount of siliciclastics deposited, although well-oxygenated conditions must be assumed in the channels and on the flats. On the tidal flats, a high accumulation rate and repeated reworking did not allow larvae to develop. They were washed off the sediment or were buried by rapidly accreting further deposits (Wunderlich, 1970; Stets & Schäfer, 2002). Most of the molluscs require several years for their growth. If the reworking process is too frequent and with a regular input and deposit of sediments, larvae do not have any possibility of development. Intensive reworking processes that were common and active during the deposition of the Lambert Quarry beds is another decisive factor.

Three occurrences including two levels very rich in debris of plants (one of 9 m thick – lithological unit 7) were observed in this section. Similar occurrences were reported by geologists in many places throughout the Neufchâteau Synclinorium and the Ardenne Anticlinorium. Unfortunately, detailed description of sections and associated sedimentological features are lacking. Furthermore, numerous plants debris (flat and ribbon-like axes) of the Mirwart Formation were often reported in the old archives of the geological map as "Taeniocrada". Macroscopic observations of newly collected material allowed P. Gerrienne (University of Liège) their attribution to the Zosterophylls. These plants belong to an extinct group of tracheophyte plants and occupy a key place in the evolution of land plants: several fossils show characteristics that are otherwise very typical of the Lycophytes. In spite of the high content in plants remains (Plate 2, photo G), a more detailed identification is impossible because of the disappearance of the organic matter and the pseudomorphic replacement by chlorite flakes (identified as a chamosite by XRD). Furthermore, four representative samples of dark blue plant-rich shales from lithological units 5 and 7 were selected and bulk macerated in hydrofluoric acid (Laboratory of Paleobotany of Liège University) for palynomorphs and to identify additional small minor organic components. Unfortunately, all the organic matter appeared to be destroyed by metamorphism. Only some macroscopic aspect of plant debris is conserved. If understanding the sedimentological context of plant and associated facies is crucial to the reconstruction of living plant environment, paleoenvironmental studies of specific land plant assemblages of the Lower Devonian have been rarely conducted (Hotton *et al*., 2001). Lower Devonian plants (like Zosterophylls) are believed to have occupied sites in rare sexual reproductive events and then formed monospecific stands through extensive vegetative growth. Many Zosterophylls preferentially occupy fine-grained, dysaerobic facies, characteristic of low-energy, water-saturated habitats such as marshes and backswamps. To occupy the muddy, shifting surfaces of tidal flats and backswamps, plants must have been able to tolerate salinity fluctuations (Hotton *et al*., 2001). Collected specimen generally show dichotomous branching but their sporangia were not observed. The first level corresponds to drifted fragmented plants remains deposited on the high energy planar horizontal beds of sandstones, located at the top of a channel filling (lithological unit 2). In the other occurrences (lithological units 5 & 7), plants remains are associated with fine-grained dark blue to black mudstones. Here, plants are preserved in parallel alignments along the bedding plane. Edwards (1979, reported by Hotton *et al.*, 2001) explained that plants were rooted or anchored at one end in the process of burial by the enclosing sediment. Observation of axes undulating in parallel suggests that they were anchored (presumably rooted) at one end, leaving the other ends free to become aligned to water currents. If the observed carbonate nodules are pedogenetic in origin and the presumed root-like structures (?) in one level would corroborate this idea, the other plant-bearing levels do not show any diagnostic feature so that the exact origin of these accumulations can be unraveled. Good subaerial exposure evidences such as mud cracks are lacking. However, both the absence of lamination and other marine influenced sedimentary features (like burrows), together with the overall bioturbation, allow to suggest supratidal conditions like marshes, temporary emerged mud flats or muddy peritidal islands vegetated by plants. These subenvironments were regularly flooded by strong tides. Although the degree of resistance to fragmentation and degradation that these plants may have displayed is unknown, the length of the plant remains (up to 25 cm) and the thinness of the axes cannot be explained by a long transport. In the upper part of the Mirwart Formation, numerous levels of plants were described in the archives of the Belgian geological map, indicating their large distribution area and favourable environment.

6. Paleogeographic reconstruction

Steemans (1989) proposed a general view of the Ardenne basin paleogeography during Lower Devonian time, strictly based on biostratigraphical criteria (reworked Cambro-Silurian acritarchs and Lower Devonian spores). Occurrence of reworked Cambro-Silurian acritarchs shows that the Brabant Massif, the “Mitteldeutsche Schwelle” and (for a short period) the Rocroi inlier were emerged during the Eodevonian. Unfortunately, his study was restricted to the north and the NW of the Ardenne, because of the effect of metamorphism in the southern Ardenne area. Steemans (1989) demonstrated the diachronism of the facies, until the middle part of the Pragian. He showed that the Eodevonian transgression was directed from the SE to the NW and suggested a regression in the NE Ardenne starting in the upper part of the Lochkovian.

The development of the Rhenohercynian basin during the Early Devonian evolved in a tensional setting, with the post-orogenic collapse of the Mid-European and North German-Polish Caledonides (Ziegler, 1990). The thickness of the Early Devonian deposits and their evolution from continental (fluvial, deltaic), over coastal to shallow-marine environments suggest the activity of extensional synsedimentary faults. We assume that the deposition of the La Roche Formation (Upper Pragian) corresponded to a maximum of the extensional stage, coinciding with the maximum deepening of the basin. Younger deposits (Upper Pragian and Emsian) show rather regressive facies and the return of more littoral and even continental environments.

The studied area lies in the prolongation of the South Eifel and the Westerwald area (Germay). The latter two regions correspond to the so-called Siegenian Normal Facies of the Northern Facies belt. This facies belt (Late Lochkovian to Lower Emsian stages) formed with the siliciclastic sediments delivered to the basin from the northern areas and displays a whole spectrum of fluvial and deltaic to tidal and coastal marine sedimentary environments. The sedimentological features and paleoenvironmental interpretation of our study area show many similarities with those of the Middle Siegenian Rauhflaser Schichten, the Upper Siegenian Herdorf-Schichten from the Northern Facies Belt (Stets & Schäfer, 2002), the Lower Emsian NellenKöpfchenschichten from Germany (Wunderlich, 1970), the Bon Mariage Member (Montfort Formation, Upper Famennian, Thorez *et al.*, 1988) and with many modern tidal flat sequences.

The Mirwart Formation is thus a siliciclastic system deposited in a tidal environment in a shallow epeiric sea. Fine-grained muds to fine-grained sands exhibiting wrinkle marks, common current ripples and rare wave ripples as well as bioturbation, are abundant in the studied section. The delicate fauna, the bioturbation features, the ripple-, tidal-, wavy- and flaser-bedded muddy sands to sandy muds, all point to a tidal environment. Vertically, we observe a succession of alternating mixed flat to mud flat or sand flat sediments. Relatively deep major channels and smaller shallow channels or gullies were cutting the tidal flats. Sand and mud sediments were reworked and redeposited as channel lags, through meandering.

Channels, mud flat, mixed flat and sand flat subenvironments are all characterised by rapid rates of vertical accretion. The vertical and horizontal successions of sub-environments are respectively synthesised in Figures 2 and 3. Flats represented extended surfaces with very low relief areas without any proven sand barrier to protect tidal flat environments from the open sea. Only one stratigraphical level contains delicate bivalves, brachiopods and gastropods indicating marine conditions (open marine incursion), but the overall scarcity of faunas in the Mirwart Formation as well as the absence of crinoïd ossicles indicates the lack of direct influence of an open sea. Furthermore, the single occurrence of a sandy mudstone with fauna is interpreted as a (spring) storm deposit with a sea level well above the mean high-level tidal level.

In the studied section, foam marks, antiripplets and small gullies prove short episodic exposure, probably between two successive tides. However, rain-drop impressions and desiccation cracks are lacking. Although significant periods of exposure are absent, evidences for a supratidal environment can be proposed for lithological units 5 and 7 due to the rare occurrences of carbonate nodules (pedogenetic in origin?), the richness in fine and long plants debris and root-like structures. Muddy islands rising above the tidal range, occasionally fell dry and allowed the development of paleosoils and plants communities. Major tidal channels with small tributary channels and gullies developed on these mud flats without splay activities. They normally cut down below the low tide level (subtidal conditions). The lateral migration of tidal channel induces erosion of the muddy banks and correlative incorporation of mud balls like channel lags.

In Belgium, the southern part of the Ardenno-Rhenohercynian basin is now buried beneath more than 300 to 600 metres of Permian-Triassic-Jurassic rocks, outcropping along the north border of the Basin of Paris. The reconstruction of the Lower Devonian paleogeography still contains major uncertainties, because it is based largely on long-range extrapolation. Further studies need to be carried in the southern area of Ardenne (Basin of Neufchâteau) in order to propose a complete depositional model for the Belgian Lower Devonian rock sequence. However, the metamorphism and the scarcity of good sections in the southern tectonic units are important limiting factors. Future investigations will have to focus on the transitional areas between alluvial-fluvial-deltaic environments and tidal-open marine environments.

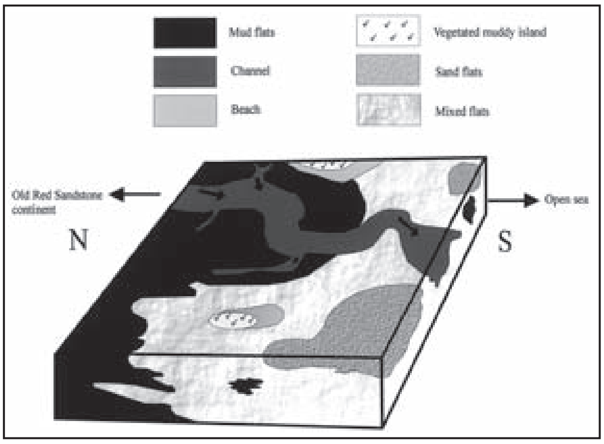

Figure 3. Block diagram illustrating the facies model of the different depositional subenvironments of the Formation of Mirwart in the Flamierge area.

7. Conclusions

The Lambert quarry section exposes Pragian shallow-water silicoclastics deposits corresponding to the Mirwart Formation. The sedimentological study allows to divide the section in ten sedimentological units, all deposited in a tidal environment. Vertically, we observe a succession of alternating mixed flat to mud flat or sand flat sediments. Channels were cutting the tidal flats where sand and mud sediments were reworked and redeposited as channel lags. Channels, mud flat, mixed flat and sand flat subenvironments are all characterised by rapid rates of vertical accretion. Although significant periods of exposure are absent, evidences for a supratidal environment (muddy islands rising above the tidal range) can be proposed as the development of paleosoils, the abundant rests of plants and root-like structures.

It was during the Lower Devonian transgression that many large flat areas (alluvial plains and delta plains – corresponding to the Oignies and Saint-Hubert formations) developed south of the Old Red Sandstone Continent with possible embayments around emerged Caledonian massifs. Wide tidal flat areas developed on clastic sediments derived from northern source areas fed by a well-developed fluvial system. Normally, the chance for preservation of tidal flat sequences (prone to erosion), is rather limited. In modern environments, the thickness and extension of tidal flat deposits are weak. The vertical stacking of hundreds of meters of sediments within the Mirwart Formation, displaying the same architecture needs further explanation. Indeed, the 60 m–thick sequence observed in the Lambert quarry suggests an important and continuous basin subsidence, combined with a high accumulation rate of siliciclastic sediments. The opening of the basin during Pragian times induced possible accommodation space and a subsequent invasion of marine waters resulted in the filling of the basin with mud, silt and sand.

It is suggested here that the source area of the fine quartz sand and mud in the Mirwart Formation of the Bertogne area, was the remote large fluvial system and adjacent deltaic environments bordering the Old Red Sandstone Continent. The fluvial system nourishing this flat environment with fine clastics was located more than 100 km (in a palynspastic reconstruction) north of the studied area. Fluvial influence from a hypothetically emergent Lower Paleozoic Stavelot Massif is still unproved.

8. Collections

All of the collected samples (50 whole rock samples, 35 polished slabs) and 28 thin sections are stored in the collections of the Geological Survey of Belgium (Brussels). Reference: 196E263.

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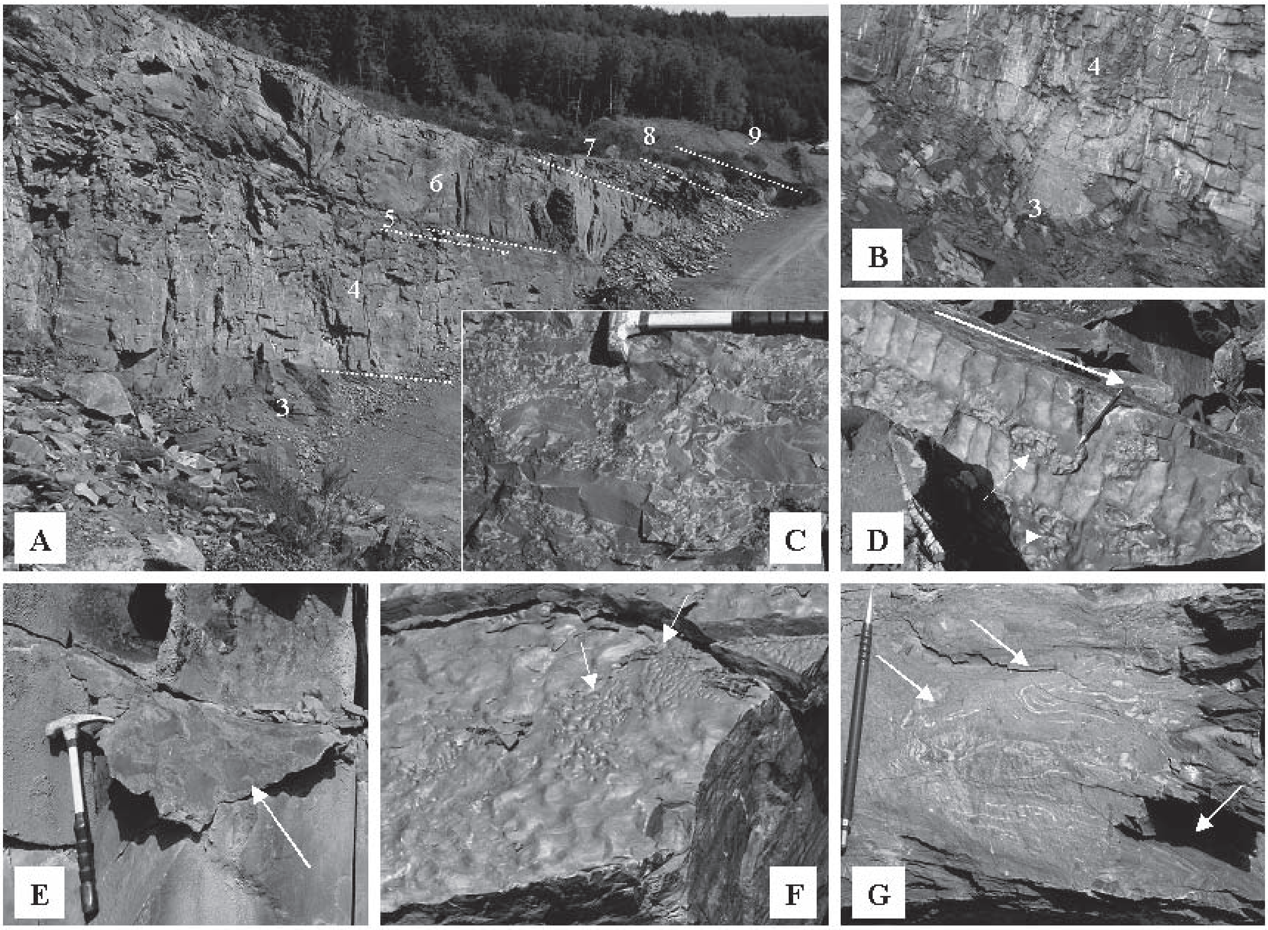

Plate 1. Formation of Mirwart, Lambert Quarry. General view and sedimentological features.

A : SSE-NNW section of 130 m long, perpendicular to the strike of the exposed rocks and showing the top of the lithological unit 3 (siltstone), the quarried sandy lithological units 4, 6 & 8 and the shaly lithological units 5 & 7.

B : Close-up of the previous photograph. Quartz veins (“en-échelon” tension gashes) perpendicularly cutting the quartzite beds of the lithological unit 4. These veins disappear in the slaty rocks of the lithological unit 3.

C : Conglomerate composed of angular blue mud chips in a fine sandy matrix. Lenticular bed at the base of the lithological unit 2.

D : Top of a sandstone bed showing a ripple train with undulatory asymmetrical small-current ripples. Ripple wave length: 8-10 cm. The long white arrow indicates the flow direction whereas the short white arrows point to external load casts moulds. Lithological unit 1.

E : Gully filled by angular mud clasts. Top of the lithological unit 2.

F : Linguoid small-current ripples. The flow direction is from right to left. The white arrows indicate external moulds of superimposed load casts. Lithological unit 1.

G : Small-scale slump structure. The contorted bedding (plastic deformation) is shown by the fine sand/mud interlayering (white arrows). Sand layers are white. Top of the lithological unit 2.

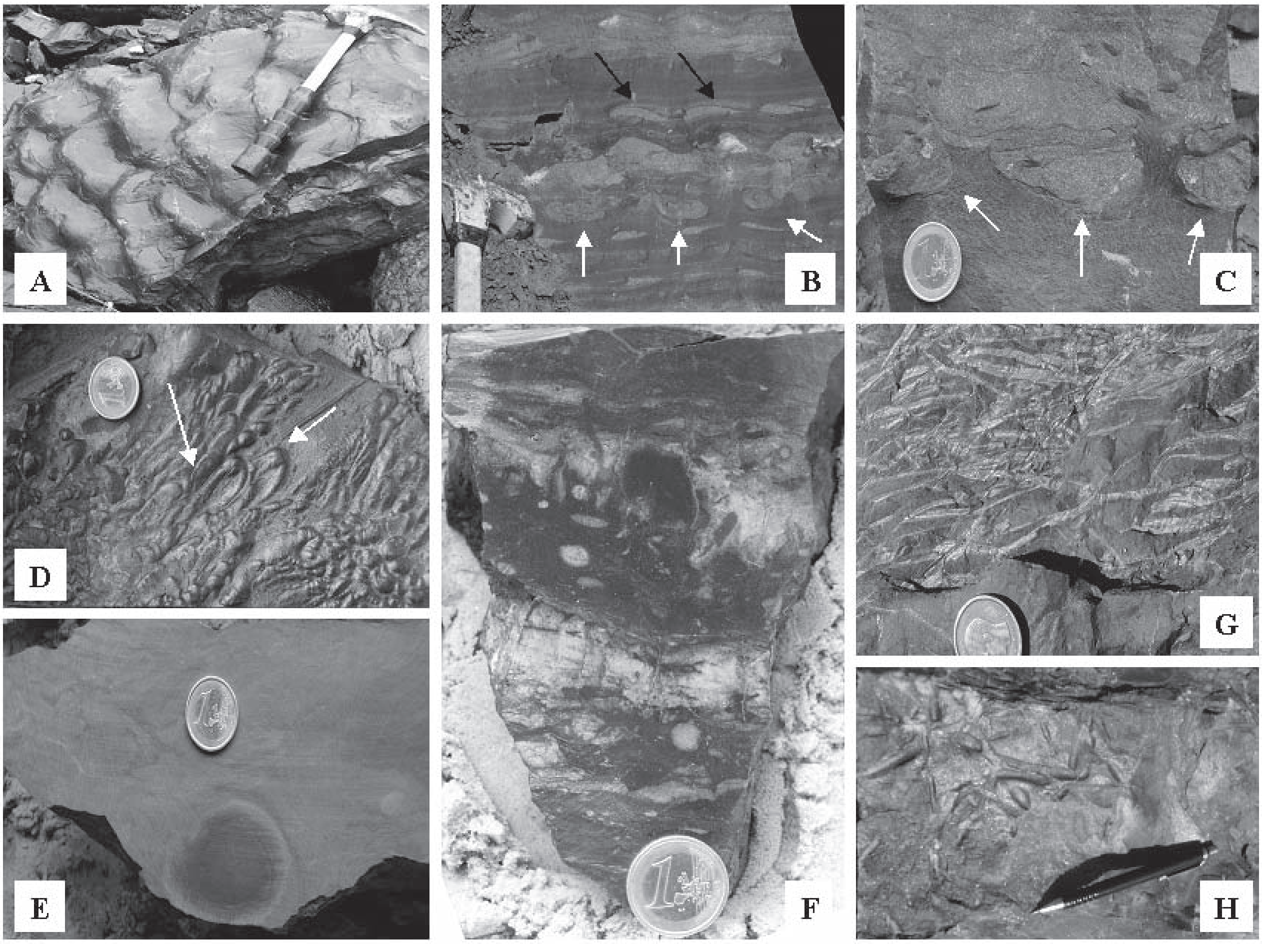

Plate 2. Main sedimentological structures of the Formation of Mirwart, Lambert Quarry.

A : A ripple train showing linguoid-shaped current ripples. The direction of flow is from right to left. Isolated block.

B : Vertical section (lithological unit 1) showing the stacking of some tidal structures. Single lenticular bedding with asymmetrical flat lenses of sandstone (black arrows) represents the main tidal structure. The middle part and the top of the photo show connected lenticular bedding with flat sandstone lenses. The white arrow points to three small load cast.

C : Load cast and associated flame structure (grey blue) at the base of a sandstone bed (grey).

D : Short, shallow and bulbous flute marks preserved as flute moulds (sometimes chevron-shaped) on the lower surface of a sandstone bed. Associated are moulds of tool marks (straight mould on the upper right corner) and supposed crescent marks (white arrows). The current is from the lower left to the upper right. Lithological unit 1.

E : Carbonate concretion in a grey-blue sandy siltstone. The perturbation of the sediment and the internal zonation of the nodule are highlighted by weathering (yellow-brown colour). Lithological unit 5.

F : Moderate bioturbation highlighted by both vertical and oblique burrowing. Burrows are filled with sand.

G : Preferentially oriented plants remains on a bedding plane. Weathering provides a golden colour to these mineralised remains. Lithological unit 5.

H : Open U-shaped burrows preserved as moulds on the lower surface of a sandstone bed. Lithological unit 6.

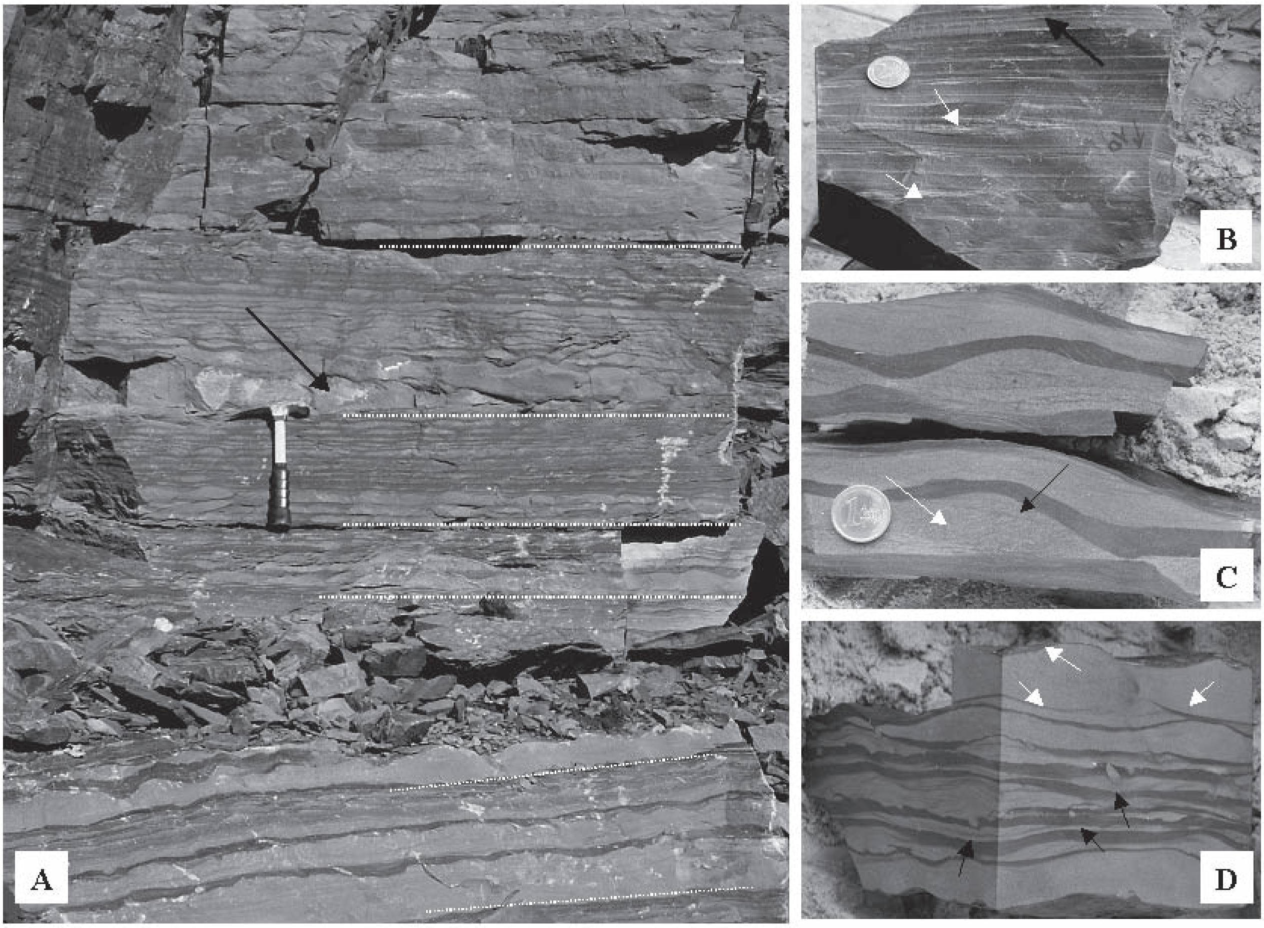

Plate 3. Main sedimentological structures of the Formation of Mirwart, Lambert Quarry.

A : Vertical section (upper part of the unit 1) showing the succession of tidal sequences (white dotted lines) and various bedding types. Each sequence represents a vertical evolution from wavy bedding, flaser bedding to lenticular bedding (thick connected lenses to isolated flat lenses). Sandstones show a brownish colour whereas siltstones show greyish blue colours. The black arrow highlights the lateral displacement of a megaripple. The top of the megaripple is covered with irregular and asymmetrical ripples.

B : Thinly interlayered bedding (tidal bedding) composed of flat layers (black arrows) and flat lenses (white arrows) of sand embedded in mud. Some of the sand layers are only 1mm thick or less. Top of the unit 3.

C : Polished sample. Wavy bedding. White and black arrows show opposite dipping (with a reactivation surface) of internal sand laminae in a ripple.

D : Polished sample (on two perpendicular surfaces - 20 cm high) showing various bedding types: wavy bedding (at the base), connected lenticular bedding – asymmetrical current ripples - with thick lenses (in the middle) and wavy to simple flaser bedding (at the top). Ripple-bedded sequences show two current directions and short burrows (dark arrows).