TIDE - AND WAVE - INFLUENCED DEPOSITIONAL ENVIRONMENTS IN THE PSAMMITES DU CONDROZ (UPPER FAMENNIAN) IN BELGIUM

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ABSTRACT. The Psammites du Condroz (Upper Famennian, Upper Devonian) in Belgium display a complex interfingering of depositional environments that developed during a rhythmic progradation on the Condroz Platform, south of the London-Brabant Massif. The Lower Famennian Famenne Shales and the Upper Famennian, coarser Psammites du Condroz are sandwiched between two extensive, thick, transgressive carbonate series: the Frasnian below and the Dinantian above. A variety of depositional environments is represented: distal alluvial, alluvio-lagoonal, evaporitic lagoonal, tidal lagoonal, inshore sandy barrier, tidal flats, tempestites, offshore mixed sandy and crinoidal limestone barrier, fluxoturbidites, and outer shelf mud deposits. The regression was controlled by the interplay of paleomorphology of the sedimentary basin, differential subsidence, paleotectonics (block tilting), paleooceanography, and paleoclimate. Tide- and wave-influenced deposits occupied a large area which was limited to the north, in the Dinant Synclinorium, by diachronic sandy barriers (generated by the mutual interference of alluvial discharge, tides and waves), and to the southwest, by an offshore barrier composed of mixed sands and incipient carbonate buildups. The rhythmic pattern of the tide- and wave-influenced deposits is discussed considering the overall paleogeography of the Psammites du Condroz.

INTRODUCTION

The paper focuses on the siliciclastics deposited within the tide- and wave-influenced depositional environments in the Psammites du Condroz (Upper Famennian, Upper Devonian) of the eastern part of the Dinant Synclinorium. Locally, the siliciclastics (arkosic sandstones, siltstones and mudstones) are interbedded with evaporitic dolomites and limestones (Thorez & Dreesen, 1986).

Two decades of intensive studies on the lithostratigraphy, biostratigraphy and sedimentology of this series have resulted in a paleogeograhical reconstruction demonstrating the progradational (regressive) pattern of the Psammites du Condroz on the Condroz Platform, south of the London-Brabant Massif (Fig. 1) (Thorez & Dreesen, 1986). The study has been carried out in the eastern part of the Dinant Synclinorium and in the nearby Vesdre area (Verviers Synclinorium),

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and it has been extrapolated to the Federal Republic of Germany (Paproth et al., 1986).

Detailed stratigraphical and sedimentological analyses show that the various lithologies represent many different depositional environments, rather than only a "tidal lagoon bordered (possibly) by tidal flats and receiving a more or less periodical supply of fluviatile material" (van Straaten, 1954). The lithologies belong to a spectrum of environments comprising, from inshore to offshore: distal alluvial (deltaic in the Vesdre), alluvio-lagoonal, evaporitic lagoonal, tidal lagoonal, inshore (inner) and offshore sandy barriers, tidal flats, tempestites, fluxoturbidites, and outer shelf mud deposits (Thorez, 1969; Thorez et al., 1977; Thorez & Dreesen, 1986) (Table 2, Plates 1, 2).

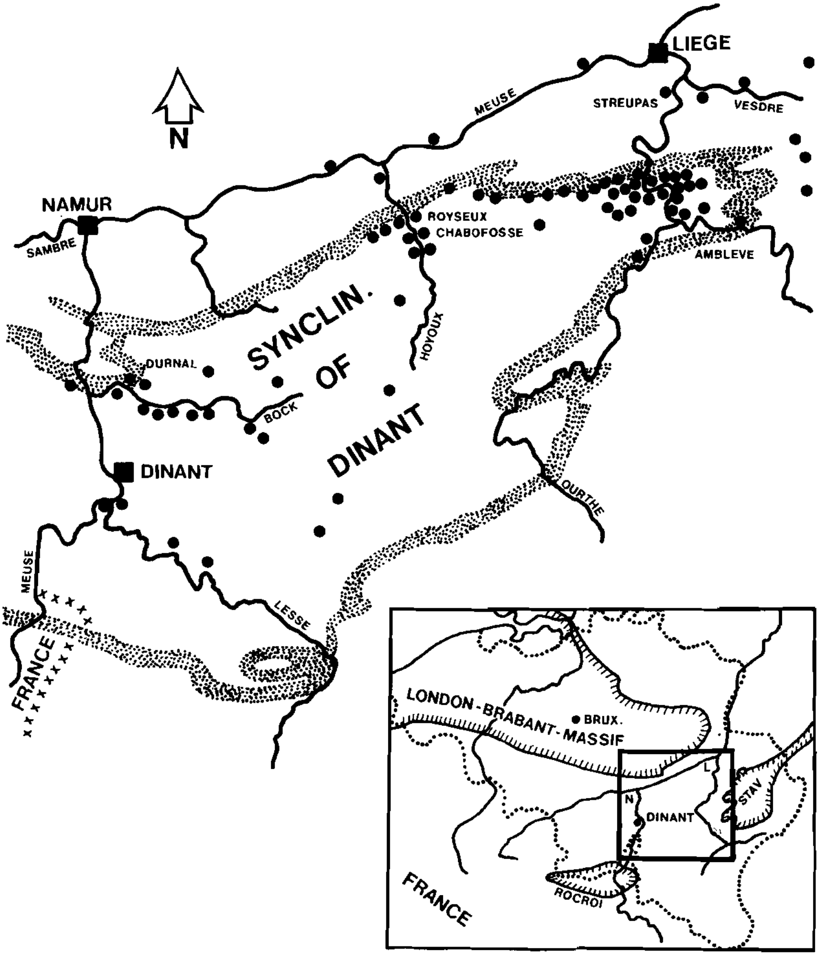


Figure 1. Location map of the outcrops studied and river valleys in the eastern part of the Dinant Synclinorium and the Vesdre (Verviers) Synclinorium. The stippled band represents the limits of exposure of the Famennian.

GEOLOGICAL SETTING

The Psammites du Condroz are well exposed in three main tectonic units in Belgium: in the allochthonous Dinant Synclinorium, and in the autochthonous Namur and Vesdre (Verviers) Synclinoria. The former unit is actually separated from the Namur Synclinorium by the Midi-Eifel-Aachen Overthrust. The main movement along this thrust, which compressed the original sedimentary basin, occurred during the Asturian phase. The precise timing and amount of movement remains a matter of debate.

The width of the Dinant Synclinorium is 20 km - 30 km measured at a right angle to the Midi-Eifel-Aachen Overthrust. The numerous quarries and outcrops discussed in this paper, are concentrated along the main river valleys of the Ourthe, Amblève, Hoyoux, Bocq, Meuse and Lesse. On the plateau (Condroz area) outcrops are far apart and incomplete (Fig. 1).

STRATIGRAPHY

A new lithostratigraphic framework for the Psammites du Condroz in their type locality (Ourthe Valley, south of Liège) and for the neighbouring areas has been proposed by Bouckaert et al. (1968), Thorez (1969), Thorez et al. (1977) (Fig. 2, Table 1). It considers the diachronism of the newly proposed formations within the Dinant Synclinorium, and can be easily extrapolated, with some adaptations, to the Namur and Vesdre Synclinoria. It provides the necessary 'grid' on which the progradation of the Psammites du Condroz can be firmly traced.

The lithostratigraphic grid has been controlled by micropaleontological data based on the study of spores, conodonts and ostracodes (Thorez et al., 1977), requiring the introduction of 'Micropaleontological Guide Marks' (MGM)

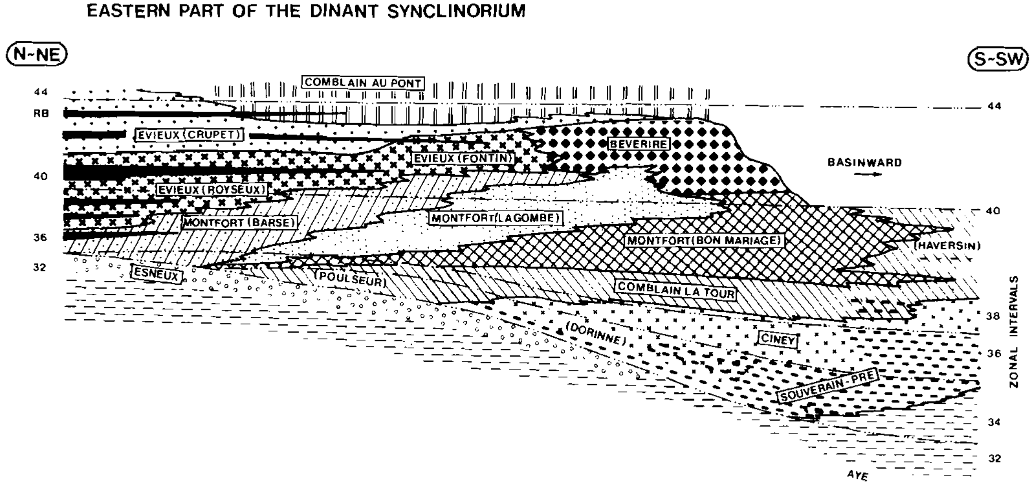


Figure 2. Generalized NNE-SSW section (not to scale) through the Upper Famennian Psammites du Condroz showing the lateral and vertical relations of the formations and members (Thorez, 1969; Thorez et al., 1977). Names of the members are in parentheses.

(Bouckaert & Streel, 1974). The MGM combine the microfossil zonal ranges into a calibration of multiple zonal schemes for both local (in-valley) and intrabasinal (valley-to-valley) correlations. The lithostratigraphic grid was completed by using lithological marker beds (redbeds and continuous levels of ball-and-pillows), and by checking the lateral continuation of rhythmic patterns in the sedimentation (Thorez, 1969; Thorez & Dreesen, 1986).

COMBLAIN-AU-PONT FORMATION
Alternating sandstones, siltstones and mudstones, with minor intercalations of dolomites and micritic limestones. Unidirectional cross stratification, erosive scars, some ripple marks and tracks.

EVIEUX FORMATION; Crupet Member
Thick red beds (sand- and mudstones); intercalated dolomite and paleodolcrete. Alluvial environment.
Royseux Member
Rhythmic alternations of sandstones (some of them red), siltstones, mudstones and dolomites. Local paleodolcretes. Distal alluvial and alluvio-lagoonal environments.
Fontin Member
Rhythmic alternations of sandstones, mudstones and ostracodal limestone. Local tidal channels. Sublagoonal environment.

BEVERIRE FORMATION
Seaward equivalent of Evieux Formation. Rhythmic alternations of sandstones, siltstones, mudstones, with local ostracodal limestone. Many sedimentary structures related to a tide- and storm-influenced depositional environment.

MONTFORT FORMATION
Barse Member
Rhythmic alternations of sandstones, dolomitic sandstones, micaceous dolomites. Sedimentary structures pointing to back-barrier, tidal and evaporitic lagoonal depositional environments.
La Gombe Member
Thick multistorey sandstone beds, with local intercalations of mudstones and micaceous dolomites. Lenticular bedding, some channelling, mud balls, ripple marks. Barrier system.
Bon Mariage Member
Rhythmic alternations of sandstones, siltstones, mudstones, with crinoidal limestones at the base of the rhythms and locally preserved ostracodal limestone at the summit. Abundance of sedimentary structures pointing to tide-and wave-influenced deposition.

COMBLAIN-LA-TOUR FORMATION
Alternating centimetre to decimetre thick sandstones, mudstones and local crinoidal limestones, with many beds of sandstone with scattered Brachiopod shells. Subtidal environment with possible storm influence.
Poulseur Member
Alternating sandstones and mudstones in dm thick beds. Local pockets of crinoidal limestone embedded in sandstones. Unidirectional cross stratification, ripple marks. Subtidal and intertidal environments.

CINEY FORMATION
Thick series of sandstones, in massive or stratified metric beds, with intercalations of siltstones, crinoidal limestones or limestone clasts. Lenticular bedding, megaripples and some channelling. Shell concentrations. Barrier system (subtidal).
Dorinne Member
Cm to dm sequences of massive sandstone grading into laminated sandstone, and ending with a thin mudstone. Lenticular beds and/or crinoidal limestone clasts embedded in the sandstone. Numerous scattered shells. Storm deposits.
Haversin Member
Thick series of sandstones, siltstones, with mudstone and crinoidal limestone intercalations. Several sandstone beds have layers of crinoidal limestone clasts. Subtidal environment, (fluxo)turbidites.

SOUVERAIN-PRE FORMATION
Subangular to subrounded cm thick crinoidal limestone clasts embedded in a calcareous siliciclastic matrix. Interpreted as a subtidal deposit.
Baelen Member (in the Vesdre area)
A reefoid structure composed of algal-sponge-crinoidal massive limestone.

ESNEUX FORMATION
Thick series of cm thick evenly laminated fine sandstones with mica concentrations on bedding planes. Abundant wave ripple marks.

AYE FORMATION
Thick series of silty shales with numerous limestone clasts. Seaward equivalent of the Esneux Formation.

Table 1. Character of the formations of the Psammites du Condroz

RHYTHMS IN THE PSAMMITES DU CONDROZ

A trademark of the sedimentation of the Psammites du Condroz is the existence of rhythms on different scales, varying from within beds (i.e., alternations of sandstone and mica layers) to groups of beds comprising contrasting lithologies (Figs. 4 - 6). Typically, minor rhythms are incorporated into the major rhythms, and these reproduce vertically more or less the same lithological organization and grain size evolution. Moreover, similar major rhythms can be reproduced vertically a number of times, without strong changes, at the scale of the formations (i.e., the Montfort and the Evieux Formations). Thus many depositional environments have remained fairly constant through time and space. Many rhythms were formed under shallow to very shallow water conditions. Occasionally emersion occurred, confirmed by polygonal dessication cracks, eroded beds with small channels or with crescent scour marks produced by deflection of currents at low tide, and by red paleosols and dolcretes with in situ root fragments.

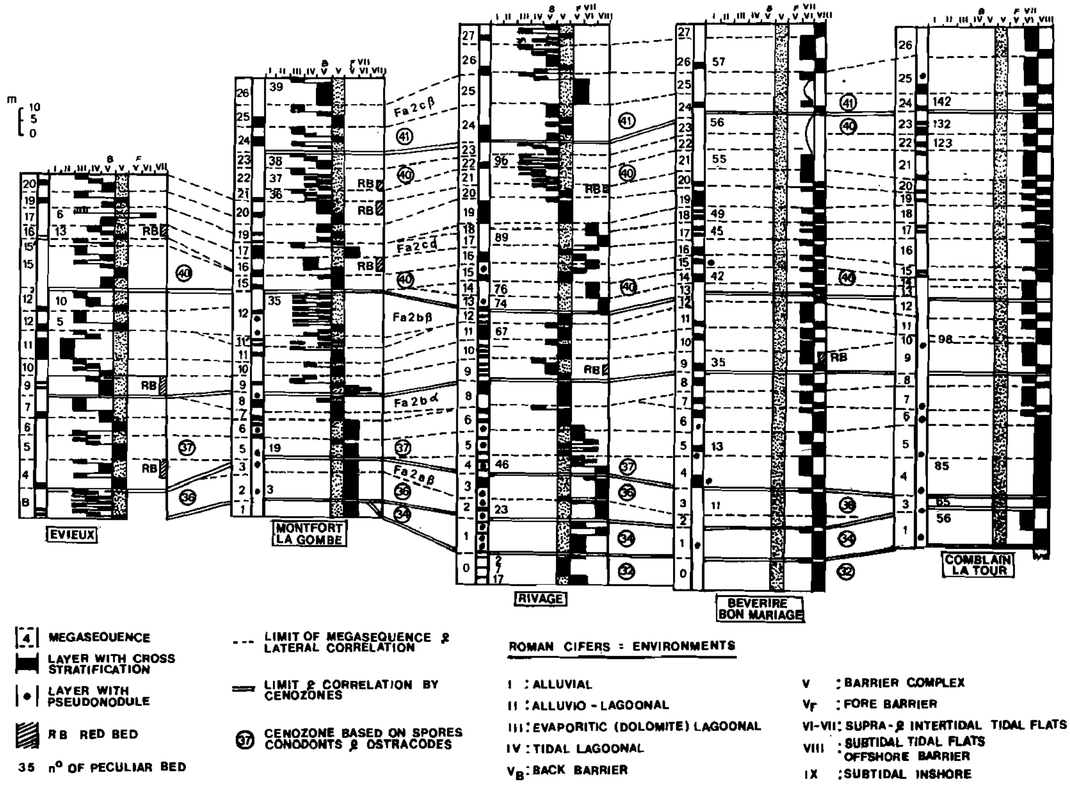
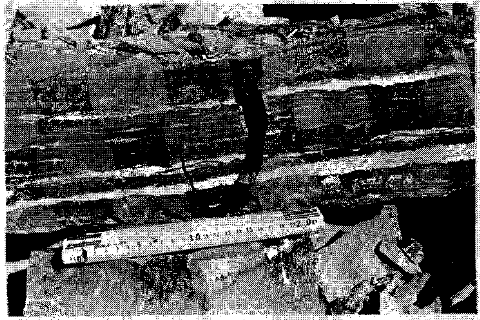


Figure 3. Lateral correlation between outcrops in the Psammites du Condroz of the Ourthe valley, south of Liège (northeastern corner of the Dinant Synclinorium), based on the limits of major rhythms, markerbeds and MGM.

PLATE 1



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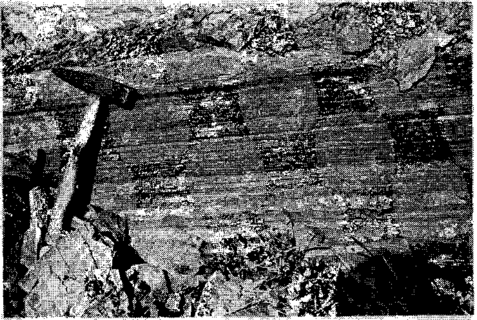

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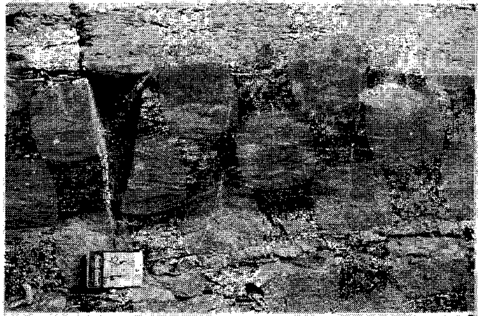

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The vertical succession of many major rhythms, developed under shallow water conditions, implies a continuous balance between the rates of deposition and subsidence. Only in the southwestern part of the area (near Gendron-Celles in the Lesse Valley) has a deeper bathymetry developed, indicated by some fluxoturbidites (Thorez & Dreesen, 1986).

The organisation of rhythms varies according to the combined and superimposed lithologies, grain size evolution, thickness of beds and associations of sedimentary structures. Several models of rhythms have been proposed for the different sedimentary environments (Thorez, 1965, 1969; Thorez & Dreesen, 1986).

PLATE 1 (facing page)

1. Interlaminated silty mudstone, laminated siltstone and sandstone with wavy and lenticular bedding. Halfway up the bed, dessication cracks filled with sandy material occur. Interpretation: intertidal environment at the transition of Poulseur Member (Comblain-la-Tour Fm) and La Gombe Member (Montfort Fm). La Gombe-Montfort quarry (Ourthe valley).

2. Interlaminated sandstone and mudstone with horizontal lamination in the upper part of the bed, and wavy lamination in the less muddy, lower part of the bed. This bed forms the upper part of a typical tidal sequence, well preserved with its subtidal (channelling), intertidal (interlaminated sandstone and mudstone) and supratidal (interlayering of black mudstone and ostracodal micrite) sequences in the quarry of Beverire (Comblain-au-Pont locality, Ourthe valley). The stratigraphical level is the Beverire Formation.

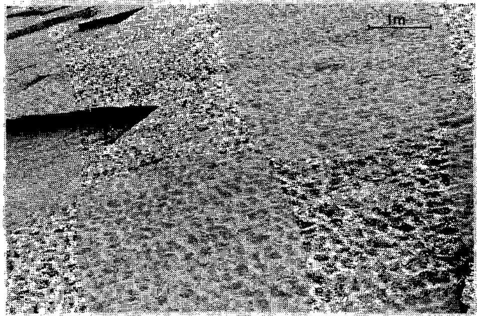
3. Flaser bedding and small-scale ripple bedding in a micaceous fine-grained arkosic sandstone. The bed is surmounted by a more muddy siltstone with micro-cross-stratification and is underlain by a coarser sandstone with widely spaced inclined stratification. Interpretation: upper part of a shallow tidal channel in the Evieux quarry (Fontin Member of the Evieux Formation, Ourthe valley).

4. Hummocky cross-stratification and interference ripple marks in the middle of a complex sequence bearing evidence of subtidal, intertidal and supratidal environments of deposition (cf. Fig. 6). Interpretation: transition between subtidal and intertidal environments. Bon Mariage Member (Montfort Formation) at the Bon Mariage quarry (Ourthe valley).

5. A sandstone with low-angle cross-stratification and mud-draped reactivation surfaces, intercalated between two sandstone beds with horizontal and wavy bedding. Note the erosional contact at the base of the cross-stratification. Interpretation: subtidal environment. Lowermost part of the barrier system at La Gombe quarry (La Gombe Member of the Montfort Formation, Ourthe valley).

6. Cross-stratified sandstone with characteristic clay drapes, reactivation surfaces and flattened mud clasts, directly overlying a strongly bioturbated (originally interlaminated) mudstone and a siltstone. Interpretation: subtidal to intertidal. Beverire quarry (Beverire Formation, Ourthe valley).

PLATE 2



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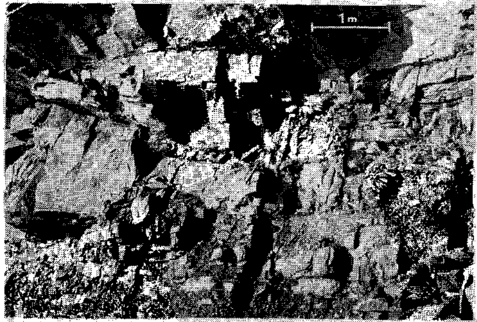

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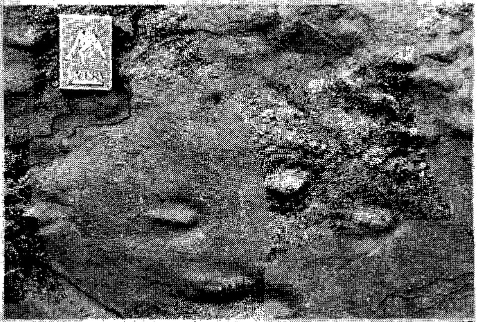

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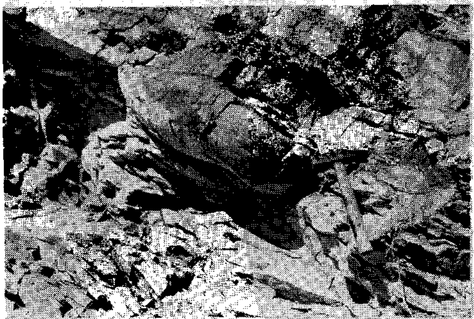

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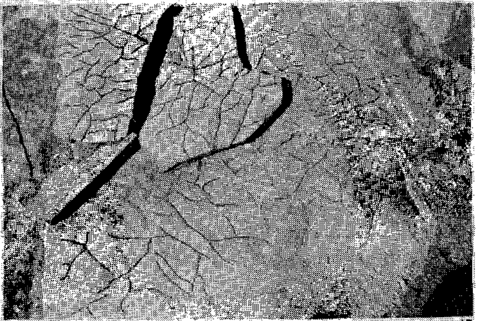

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Alluvio-lagoonal rhythms

In the Royseux Member (Evieux Formation) in the Hoyoux valley (Fig. 4) the rhythms display a typical fining- and thinning-upwards trend and comprise three distinct lithologies: arkosic sandstones, mudstones and dolomites. The latter is the result of physico-chemical precipitation in a lagoonal system (Thorez, 1969). Mudstones and dolomites increase in number and bed thickness towards the top of the rhythm, and the mean grain size fines upwards.

Backbarrier-lagoonal rhythms

In the same area, the Barse Member (Montfort Formation) is characterized by minor and major rhythms, composed of lithological 'doublets'. Such doublets consist of decimetre to metre thick, well sorted sandstones (more or less contaminated by dolomite) capped by micaceous dolomites, usually in thinner beds (Fig. 5). Each doublet exhibits a typical coarsening-upwards trend (a trend which delimits the minor rhythms) whereas the major rhythms (which incorporate a certain number of minor rhythms) may exhibit a cyclic grain size trend.

PLATE 2 (facing page)

7. Interference ripple marks. Barrier shoreface and subtidal environment. La Gombe quarry, transition between Poulseur Member (Comblain-la-Tour Formation) and La Gombe Member (Montfort Formation, Ourthe valley).

8. Dense vertical burrowing within a mud-capped arkosic sandstone. Interpretation: lower intertidal to subtidal environment. Bon Mariage quarry. Stratigraphical level: Bon Mariage Member (Montfort Formation, Ourthe valley).

9. Cross-section of a tidal channel filling a depression within the coarsening-upwards barrier sandstones of the La Gombe Member (Montfort Formation) at la Gombe quarry. The sandstone overlies highly bioturbated mudstones and siltstones corresponding to a mixed tidal flat deposit (intertidal environment).

10. Crescent scour marks developed around mud pebbles. The level passes laterally to a micaceous dolomite bed with mud cracks, and to a series of eroded mounds (remains of a former sandstone bed partially eroded by the activity of the currents). Interpretation: supratidal La Hazotte (HAZ) (Exneux area). Stratigraphical level: Barse Member (Montfort Formation).

11. Ball-and-pillow (Macar's 1948 "pseudo-nodules") structure composed of a sandy material which is embedded in a muddy siltstone. Locality: Comblain-au-Pont, Beverire quarry. Stratigraphical level: transition between Bon Mariage Member (Montfort Formation) and Beverire Formation (Ourthe valley).

12. Irregular mud cracks covering a thin (order of centimetres thick) evaporitic dolomite bed. The latter overlies a massive dolomitic sandstone showing a characteristic coarsening-upwards. Stratigraphical level: Barse Member (Montfort Formation). Locality: Royseux, Hoyoux valley.

Nature	Formations and Members							
	EVIEUX	BEVERIRE	MONTFORT(BM)	MONTFORT(LG)	MONTFORT(B)	COMBL.TOUR	CINEY(D)	ESNEUX
Parallel laminations	X	X	X	(x)	X	(x)	(x)	X
Undulating laminations	-	(x)	X	-	-	X	(x)	(x)
Lenticular bedding	X	(x)	(x)	X	(x)	(x)	X	-
Massive bedding	(x)	-	(x)	X	X	(x)	X	-
Flaser bedding	(x)	(x)	X	-	-	-	-	-
Inclined stratifications	X	X	X	X	(x)	(x)	X	-
Ripple drift	X	X	(x)	-	-	-	(x)	-
Wave ripple marks	-	X	X	(x)	(x)	(x)	(x)	X
Oscillation ripple marks	-	X	X	(x)	X	X	(x)	(x)
Interference ripple marks	-	(x)	(x)	(x)	(x)	(x)	-	-
Through cross-stratification	X	X	X	(x)	-	-	-	-
Megaripples	-	X	X	(x)	-	-	-	-
Alluvial channels	X	-	-	-	-	-	-	-
Tidal channels	-	X	X	(x)	-	-	-	-
Mud balls	X	(x)	(x)	-	X	-	-	-
Mud cracks	X	(x)	(x)	-	X	-	-	-
Burrows	(x)	X	X	-	X	-	X	(x)
Drifted plant remains	X	X	(x)	(x)	(x)	-	-	-
Concentration of shells	-	-	X	-	-	X	X	-
Ball-and-pillows	(x)	(x)	X	X	(x)	(x)	(x)	-

Legend: (BM) = Bon Mariage Member; (LG) = La Gombe Member; (B) = Barse Member; (D) = Dorinne Member

X = abundant; (x) = occasional; - = none

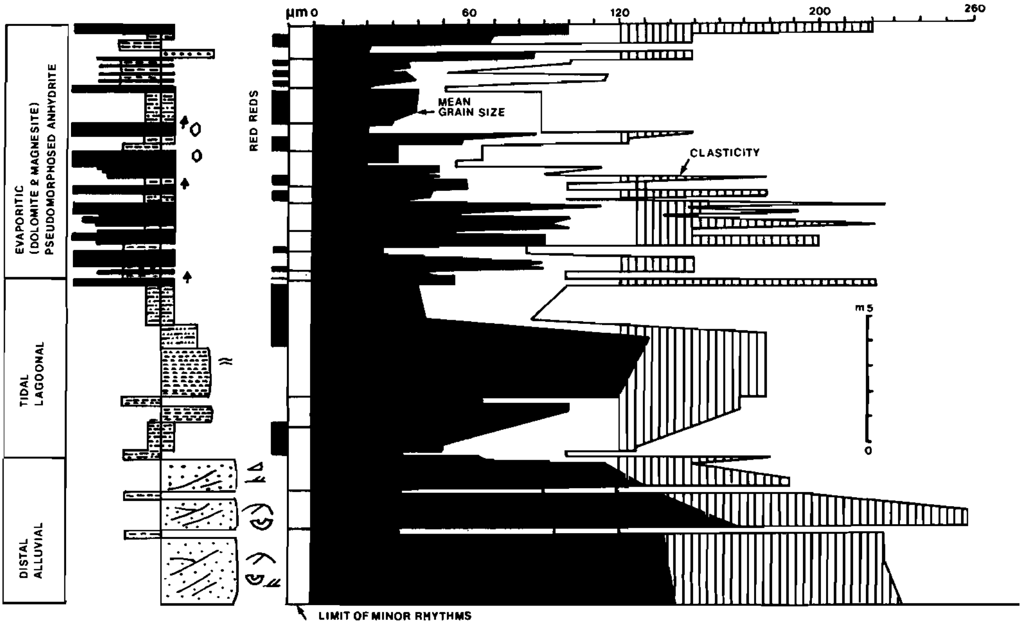


Figure 4. An example of a rhythmic (major and minor) structure in the basal Evieux Formation (Royseux Member) in the Hoyoux valley. This rhythm comprises different lithologies (sandstone - dotted, mudstones - striped, and dolomites - black). Redbeds are interlayered with grey to beige layers. The overall grainsize from the base to the top of the major rhythms fines upwards (based on the mean grain size and the clasticity or maximum 1% coarsest fraction). In the minor rhythms, the grainsize either coarsens or fines upwards. The environment is interpretated as a distal alluvial or tidal delta, grading into a tidal lagoon and finally into an evaporitic lagoon.

Tidal flat rhythms

In the Bon Mariage Member (Montfort Formation) in the Ourthe valley (Fig. 6) the rhythms comprise from base to top: crinoidal packstones (usually developed as lenticular beds or as lag deposits at the base of channels), sandstones with numerous brachiopod shells, black (organic-rich) siltstones and mudstones and, at the top of certain rhythms, a thin ostracodal biomicrite. The internal grain size evolution is generally fining-upwards or, sometimes, a short coarsening-upwards followed by a more important fining-upwards trend. Sedimentary structures include a variety of cross-stratifications, bimodal inclined stratification, megaripples (some including tree debris), flaser bedding, micro-crossstratification, (wavy) lamination, numerous burrows and tracks, some local intraformational conglomerates (mudstone clasts), escape structures, mud drapes, etc.

The rhythms are not always evident in the field. In the Comblain-la-Tour Formation, the depositional conditions merely led to thin (mm to dm thick) alternating sandstones, siltstones and mudstones with sharp or erosional contacts between the superposed lithologies, and with local lenticular crinoidal limestone beds.

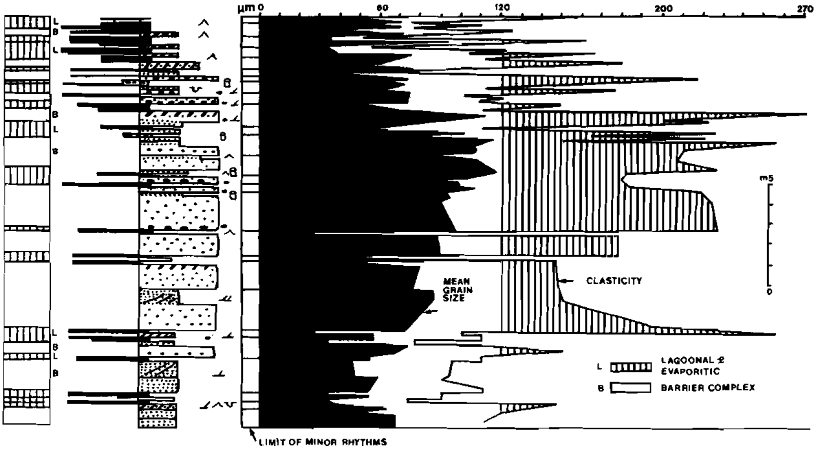


Figure 5. An example of a major rhythm (with similarly organized minor features) in the Barse Member of the Montfort Formation (Hoyoux valley). Characteristically the rhythms are built up of alternating sandstone (dotted), dolomitic sandstone (oblique black stripes), and mostly micaceous dolomite layers (black). The sandstone beds display a basal thickening-upwards followed by a thinning trend in the upper part of the major feature; here, the dolomitic layers become thicker but less contaminated with micas than the basal dolomites. The grain size similarly shows a coarsening-upwards trend in the base of the feature, followed by a fining-upwards in the upper part. The interpretation is an alternating sandy barrier (with reverse graded bedding) and tidal lagoon.

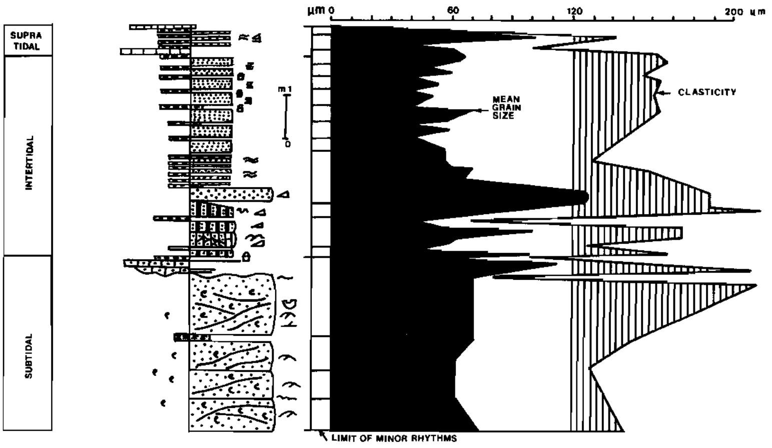


Figure 6. An example of a complete tidal sequence in the Bon Mariage Member of the Montfort Formation (Ourthe valley, Quarry Bon Mariage). Three sub-environments are displayed: subtidal, intertidal and supratidal. The first is characterized by thick, relatively massive sandstones with scattered brachiopod shells, locally hummocky cross-stratification and coarsening-upwards trends (shown by the clasticity). They are capped by a lenticular crinoidal limestone bed constituting a lag deposit at the base of a tidal channel. The intertidal interval is subdivided into two parts. The lower part is composed of thin sandstone beds with calcitic cement (vertical black bands), generally pinching out over a short distance. The upper part is composed of alternating micaceous grey to black siltstones and mudstones which are strongly bioturbated. (marked in figure by a crossed Z). The supratidal environment is represented by dark shales with local flaser bedding and thin ostracodal micrites. The grain-size generally fines upwards in the intertidal and supratidal environments.

Tempestites

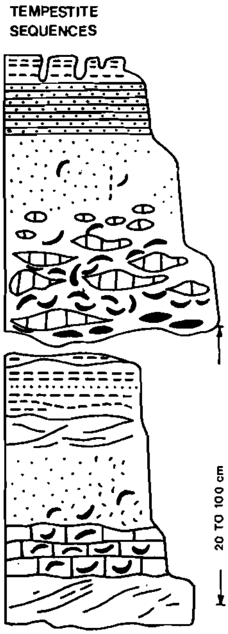
Another kind of rhythmic deposit is developed in the Dorinne Member (Ciney Formation) (Fig. 7). Each feature is made of a massive unsorted sandstone (with 'pockets' of crinoidal limestone) grading into a thin laminated sandstone and ending with a (seldom entirely preserved) thin black mudstone (Fig. 7). The lateral extension of these decimetre thick rhythms is typically very short, not exceeding a few tens of metres. Some rhythms in the Evieux Formation, with a typical fining- and thinning-upwards trend, end with red hydromorphic paleosols and dolcretes (dolomitic equivalent of calcretes).

A genetic sequential model is presented in figures 8 - 10. It corresponds to a NNE-SSW section through the area. The model depicts the lateral succession of depositional environments developed within a minor rhythm. The environments are numbered in roman numerals. Each rhythm, with its contrasting and varying lithologies, grain size evolution and association of sedimentary structures, matches a different environment. The environments are also reproduced on the scale of the major rhythms with a similar internal organization.

MEGAENVIRONMENTS OF THE PSAMMITES DU CONDROZ

The grouping of depositional environments resulting from the study of minor and major rhythms (sequences) and the association of similar models in time and space, when supported by the biostratigraphical grid, give rise to the reconstruction of the megaenvironments of the Psammites du Condroz over the paleobasin (Figs. 10, 11) (Thorez et al, 1977; Thorez & Dreesen, 1986). The latter paper gives separate paleogeographic maps, corresponding to eleven superposed sedimentary phases, and encompassing a stratigraphical range from the top of the Esneux Formation (MGM 32) to the base of the Strunian (MGM 44).

A synthetic two-dimensional paleogeographical model is proposed (Fig. 12) in which the various environments are depicted, from inshore to offshore, emphasizing an area where the tide-influenced deposits are confined between two barrier systems. Such a paleogeographic reconstruction results from the superposition of the eleven separate paleogeographic maps and, hence, proposes a strongly condensed paleogeographic model for the Psammites du Condroz, between the top of the Esneux Formation and the base of the Strunian (Fig. 13).



LITHOLOGY	SEDIMENTARY STRUCTURES	FLOW REGIME	SEDIMENTATION RATE
DARK MUDSTONE	BURROWS	LAMINAR FLOW	VERY LOW
WELL-SORTED SANDSTONE	PARALLEL LAMINATIONS	UPPER FLOW REGIME	HIGH
ILL-SORTED SANDSTONE	MASSIVE TO NEBULOUS STRUCTURE	REDEPOSITION OF SILICICLASTICS AND OF SUSPENDED CLASTS	
NODULAR (CLASTS) & LENTICULAR CRINOIDAL LIMESTONE IN SANDSTONE	CLASTS & BRACHIOPOD SHELLS IN ALL ORIENTATION		VERY HIGH
MUD CLASTS	EROSION SCAR	STORM EROSION	
EROSIONAL CONTACT			
DARK MUDSTONE	RIPPLE MARKS	LAMINAR FLOW	VERY LOW
INTERLAMINATED MUDSTONE AND SILTSTONE	ONDULOUS LAMINATION	LOWER REGIME	LOW TO MODERATE
CALCAREOUS SANDSTONE	HUMMOCKY CROSS-STRATIFICATION	HIGH REGIME	HIGH
WELL SORTED SANDSTONE	MASSIVE STRUCTURE	VERY HIGH REGIME	
SANDY CRINOIDAL LIMESTONE	MASSIVE STRUCTURE WITH SHELLS CROSS STRATIFICATION		VERY HIGH
WELL SORTED SANDSTONE			
EROSIONAL CONTACT	EROSION SCAR		

Figure 7. Typical tempestite (storm deposit) sequences in the Dorinne Member of the Ciney Formation (Bocq valley) (Goemaere, 1984). These deposits have a mean thickness of 20 cm - 100 cm and are each formed by a single phase of deposition on top of an erosion scar, starting with a sandstone, usually with brachiopod shells, a lenticular crinoidal limestone bed or clasts and, locally, mud clasts. The sorting of the detrital grains (quartz, feldspars) improves upwards. The deposit ends with either a laminated but slightly bioturbated fine sandstone or with a mud layer.

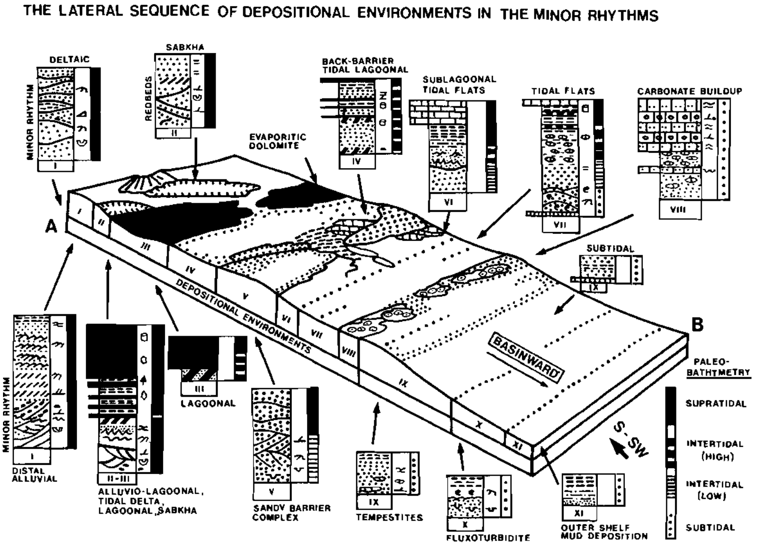


Figure 8. Diagram showing the lateral sequence of depositional environments reconstructed to the scale of a minor rhythm over the entire study area. This reconstruction concerns essentially the depositional characteristics of the Psammites du Condroz Formations overlying the Souverain-Pre Formation.

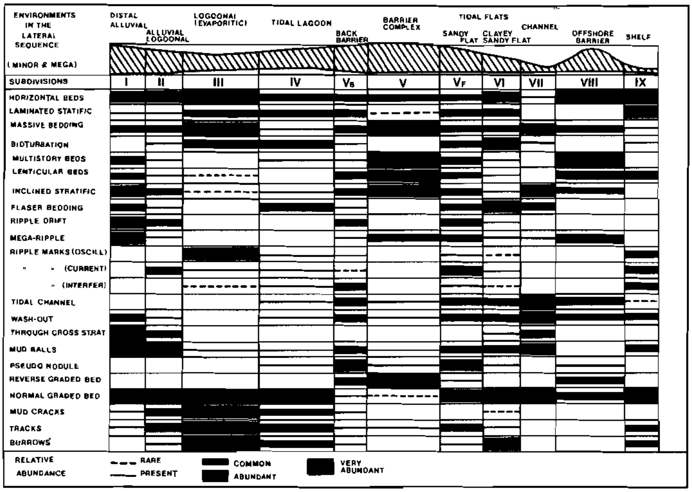


Figure 9. Cross section (with the main depositional environments) at the level of a minor lateral sequence, showing the relative abundance and distribution of sedimentary structures (Becker et al., 1974).

All megaenvironments and the corresponding lithostratigraphic units (formations) are incorporated in the model, except those related to the nodular limestone Souverain-Pré Formation. The representation of these in the paleogeographic model (Fig. 12) would have confused the reconstruction. From this synthetic and general reconstruction, it can be shown that the various environments (from distal alluvial to subtidal, including the tidal flats) were developed on a shallow shelf. Tide-influenced sequences were always confined between an inshore barrier complex (developed along a NNE-SSW trend on the northern flank of the Dinant Synclinorium) and an offshore mixed barrier trending NNW-SSE. This latter trend corresponds to a tectonic lineament (limit between two tectonic tilting blocks) (Fig. 14; Thorez & Dreesen, 1986), on which carbonate buildups developed but did not assume the importance of a reef-type structure like the the Baelen reef in the Vesdre area (Dreesen et al., 1985). Seaward from the second barrier, the shallow platform sloped gently, and formed the setting of successive fluxoturbidite deposits (Gendron-Celles area).

The paleogeographic model (Fig. 12) depicts in particular the spatial distribution of the tidal flat deposits. These occupied a large part of the shallow marine platform between the two barrier systems. The intertidal and supratidal subenvironments (zebra legend, Fig. 12) mostly fringe the seaward side of the inner barrier, whereas the lower intertidal and the subtidal subenvironments

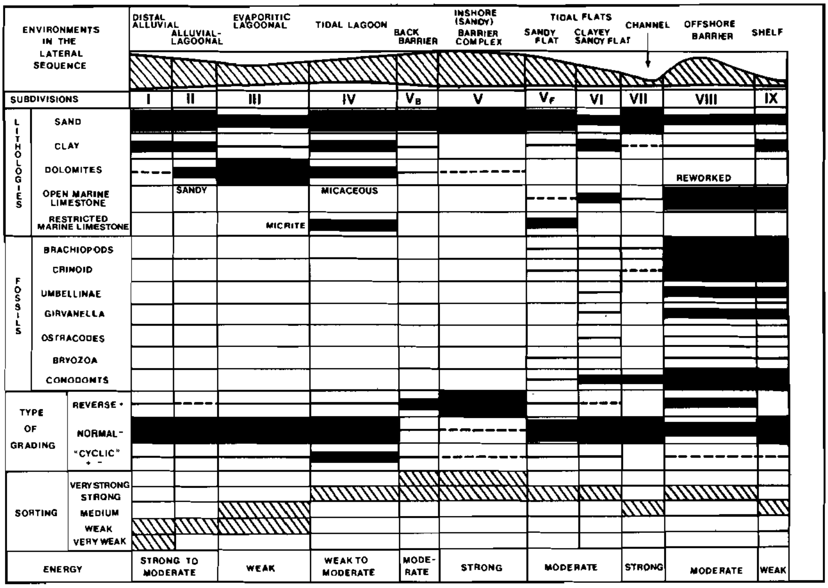


Figure 10. Cross-section (with the main depositional environments) at the level of the minor lateral sequence, showing the relative abundance and distribution of sediments, fossils, types of graded bedding, sorting of the coarser (quartz, feldspars) siliciclastics and the inferred energy for the alluvial, tidal and longshore currents and waves (Becker et al., 1974).

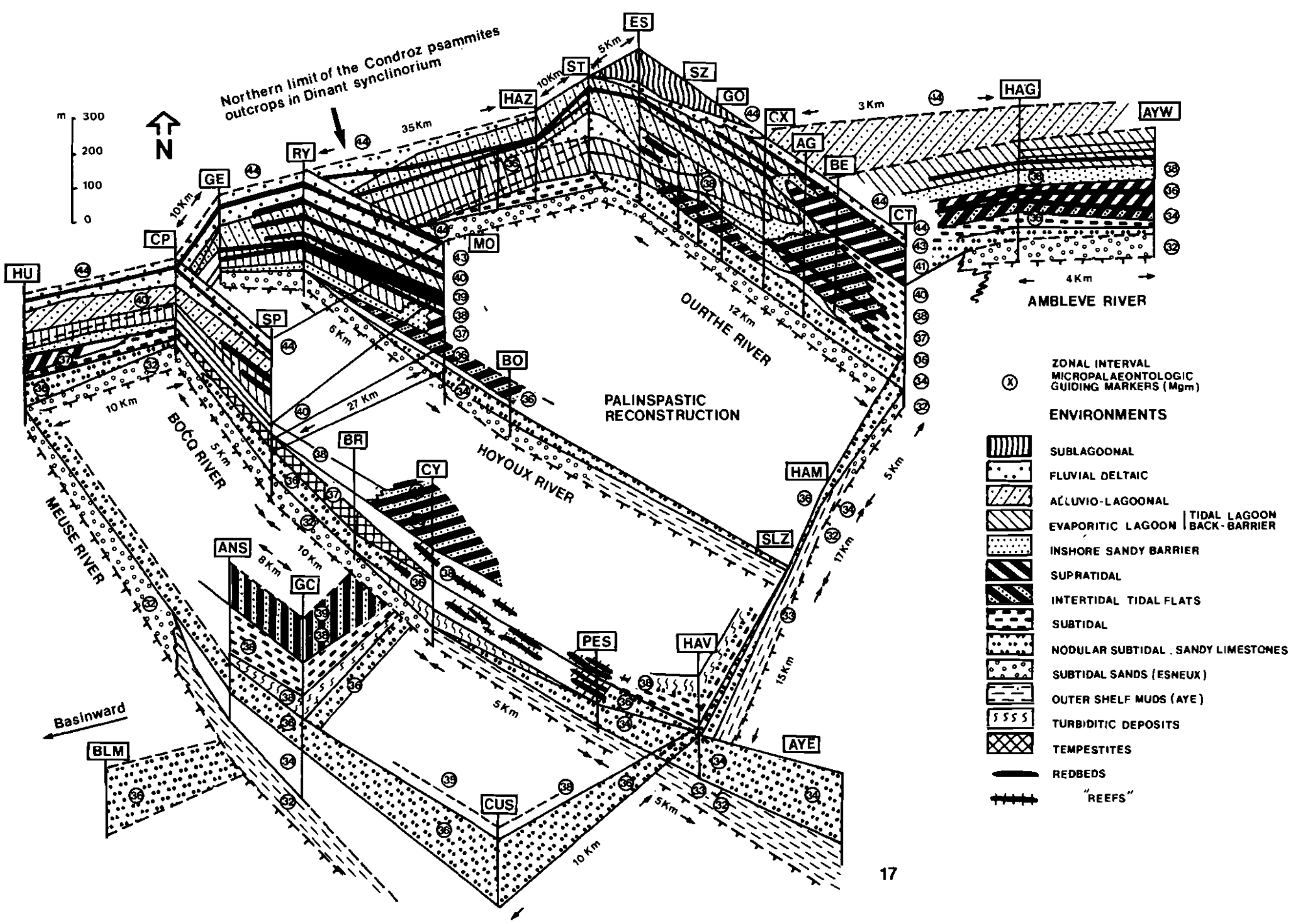


Figure 11. Diagram showing the lateral and vertical succession and interlayering of the megaenvironments of the Psammites du Condroz in the eastern part of the Dinant Synclinorium (Thorez, 1969; Thorez et al., 1977; Thorez & Dreesen, 1986).

(striped area, Fig. 12) extend to the south and southwest on the inner shelf, towards the outer (offshore) barrier. Some tidal channels, generally less than one metre deep, cross-cut the inner barrier, delivering either micas (the detrital constituent of the micaceous dolomite as in the Barse Member of the Montfort Formation) or pelites (mudstones) (La Gombe Member of the same Formation) to the tidal lagoon and the evaporitic lagoon. Scattered channels are also recognized throughout the Ciney Formation series, in which sandstones display the characteristic coarsening-upwards trend. These channels also intermittently favoured the transport of crinoidal limestone debris towards the front and the back of the barrier (storm activity) and largely contributed to the lag deposits as in the subtidal sandstones of the Bon Mariage Member (Montfort Formation) and Comblain-la-Tour Formation.

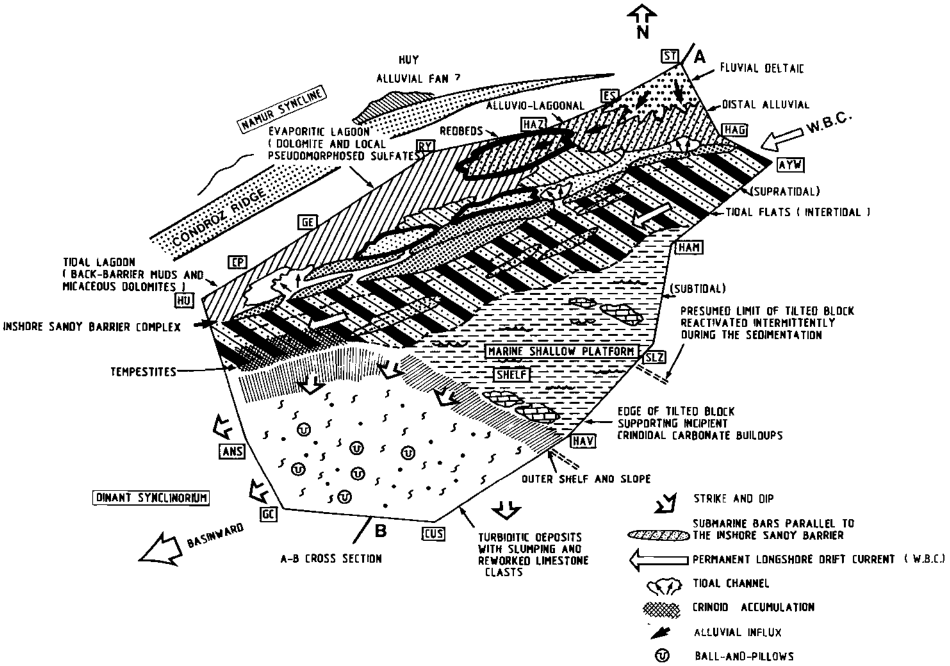


Figure 12. Idealized relation of the depositional environments in the Psammites du Condroz in the eastern part of the Dinant Synclinorium, based on the compilation of eleven successive sedimentary phases. This paleogeographic reconstruction shows all the depositional environments encountered during the general progradation (regression) of the series. The sedimentological events related to the Souverain-Pre Formation (nodular limestone extending over the whole area) have been excluded.

Source of the siliciclastics

Thorez (1969), Thorez & Dreesen (1985) and Paproth et al. (1986) showed that the Condroz shelf (in particular the inshore barrier complex and the associated tidal flats) was fed by siliciclastic influxes from the Western Boundary Current (WBC) entering the paleobasin from the NNE (between Hagoheid and Aywaille, Ourthe Valley) after passing through the Vesdre corridor (Fig 18). The siliciclastics were then reworked by local tides, waves, and storms, redistributing the material along a SSW-NNE trend as shown by the measurements of transport direction (van Straaten, 1954; Thorez 1969). Tidal currents and waves were, indeed, acting from the SSW to the NNE as indicated by the inclined laminations within the sandstones, by the orientation of the flat-topped crests of both symmetrical and asymmetrical ripple marks, and by the direction of flows running through the small gullies cross-cutting the subtidal sandstones and the barrier sandstones. The successive gullies kept their position, becoming superimposed without showing any important lateral migration. Note that most of the alluvial channels in the back-barrier environment trend either NNE-SSW or more about W-E.

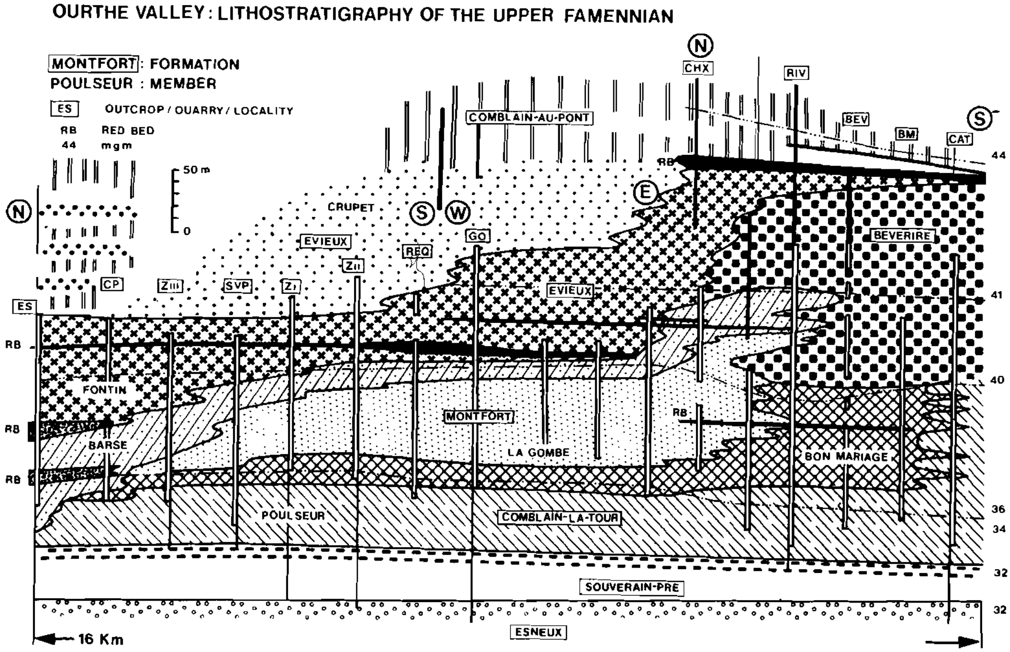


Figure 13. Lithostratigraphical scheme for the Upper Famennian Psammites du Condroz in the Ourthe valley. Biostratigraphic intervals (MGM) 32 to 44. The formation names are in capitals, their related Members are in capitals between parentheses (Thorez & Dreesen, 1986).

THE TIDAL SIGNATURE OF SOME RHYTHMIC DEPOSITIONAL ENVIRONMENTS

Minor and major rhythms displaying a tidal signature are encountered at several stratigraphical intervals (the Fontin Member of the Evieux Formation, the Bon Mariage Member of the Montfort Formation, the Beverire Formation, all in the Ourthe valley, Fig. 13). In other stratigraphical intervals, the tidal flat deposits also occur, but they alternate with other environments on the scale of the rhythms themselves. Such a character is difficult to depict in the paleogeographic reconstruction.

Tidal sequences

Some typical examples of tide-influenced sequences are shown in selected sections from several outcrops (Figs. 16 to 19). In the Fontin Member of the Evieux Formation (area of Esneux, Ourthe valley) (Figs. 11, 13), several sequences display the characteristic depositional features of a tidal flat environment (Fig. 16). Similar sequences can also be found in the Beverire Formation, in the southern part of the Ourthe valley and in the Bocq valley. At Esneux, some of the sequences lack the subtidal deposits whereas the intertidal and supratidal ones are well developed. In other sequences, the subtidal environment is represented by relatively thick, and massive or roughly stratified, sandstones with inclined stratification (sometimes bimodal in a NNE-SSW direction); the upper intertidal subenvironment is thinner (a few decimetres) and the supratidal one (usually represented by an ostracodal biomicrite) is lacking. The intertidal deposits are composed of finely laminated sandstones grading transitionally into siltstones and

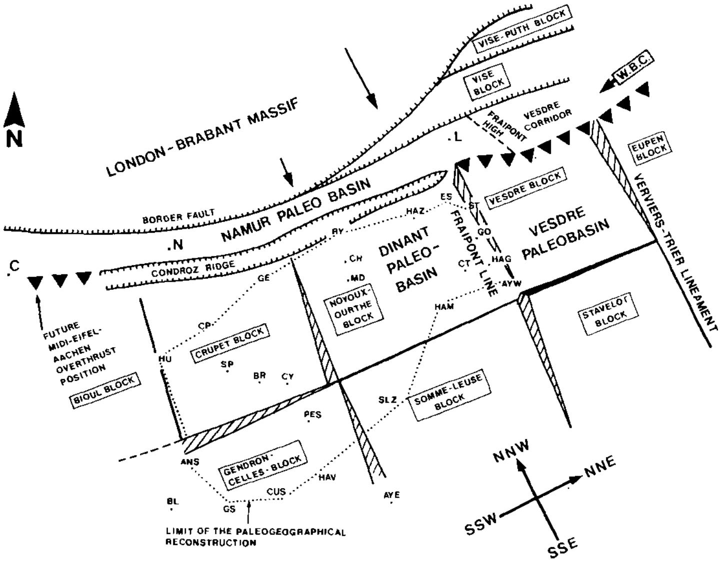


Figure 14. Inferred tectonic blocks within the eastern part of the Dinant Synclinorium. The irregular reactivation of these blocks by a tilting process has greatly influenced the paleogeographic evolution of the Psammites du Condroz during their S-SW progradation.

mudstones; the latter bear characteristic sedimentary structures e.g., small tabular cross-stratification (with some reactivation surfaces and drapes of mud clasts), ripple-drift cross-lamination, flaser bedding. The high intertidal deposits are composed of order of centimetres thick beds of finely interlaminated siltstones and black (organic-rich) mudstones. Locally, bioturbation has obliterated all the original laminations. As quoted above, the supratidal deposits are represented by a thin black (marsh?) mudstone and/or by an ostracodal or oncoidal micrite enclosing thin-shelled dwarf ostracodes and stromatolites. The microfauna points to sub-lagoonal conditions. Some dessication cracks are present on the surface of the uppermost black mudstone or limestone.

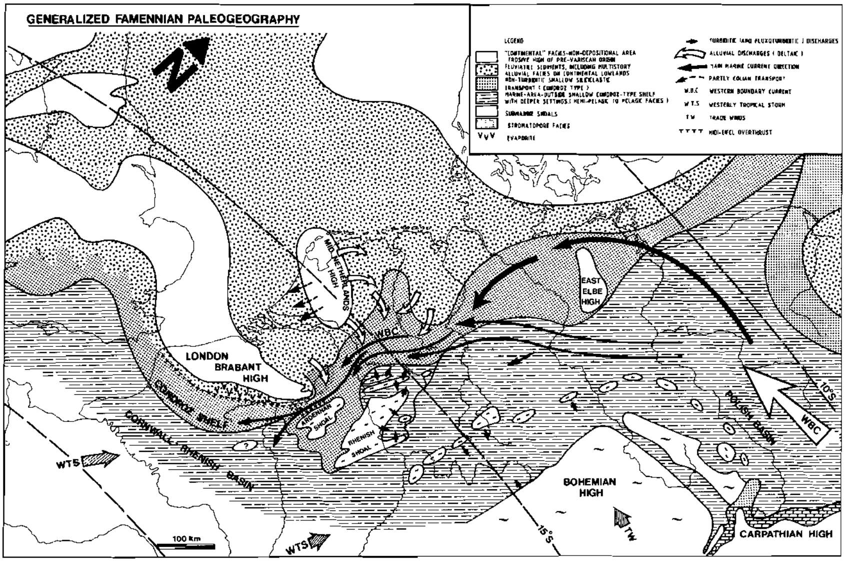


Figure 15. Generalized paleogeography during the Famennian.

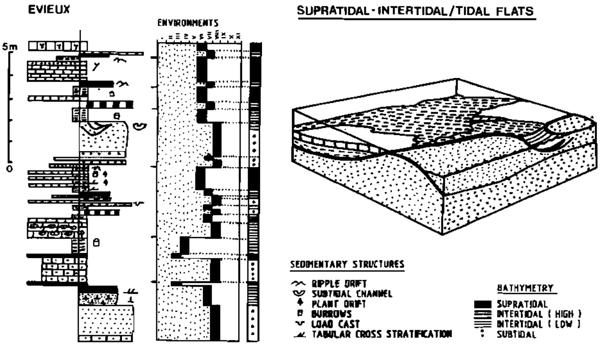


Figure 16. Supratidal and intertidal flats within a series of minor sequences (Evieux Formation, Fontin Member, at Evieux quarry).

Another rhythmic sequence bearing a tidal signature is exposed in the Bon Mariage Member of the Montfort Formation (Ourthe valley). Here, the supratidal and high intertidal deposits are generally lacking (Fig. 17). Subtidal deposits are represented by order of metres thick sandstone beds with inclined bedding and undulating laminations, and covered by ripple marks. Locally, the sandstones contain many dispersed brachiopod shells, 'pockets' of crinoidal limestone or lag

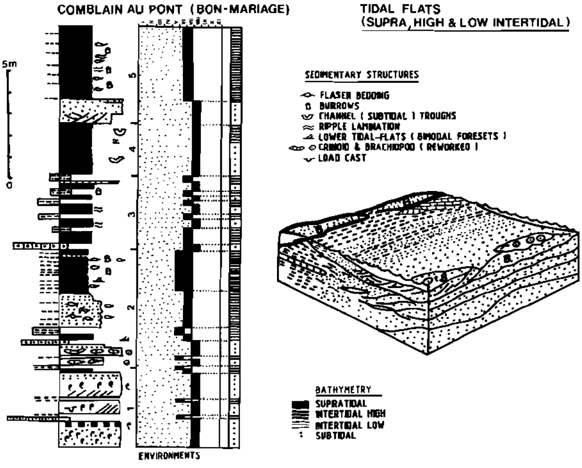


Figure 17. A series of minor rhythms (with a typical shallowing-upwards trend) as seen in the Bon Mariage Member of the Montfort Formation at Comblain-au-Pont (Bon Mariage, Ourthe valley).

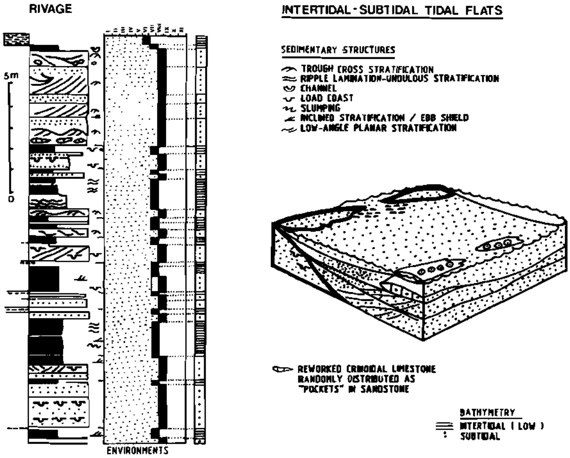


Figure 18. Several rhythmic features within a general intertidal-subtidal environment. Bon Mariage Member of the Montfort Formation near Rivage.

deposits at the base of gullies. North towards the Rivage area, at the same stratigraphical level or within the same interval, the occurrence of brachiopod shells, as well as that of limestone 'pockets' diminishes greatly (Fig. 18). Here the sandstones display characteristic megaripples with numerous levels of ball-and-pillows. The origin of the latter has been related by Thorez & Dreesen (1986) to the passage of seismic waves probably resulting from tectonic movements along deep-seated faults cross-cutting the Ardenno-Rhenish Massif.

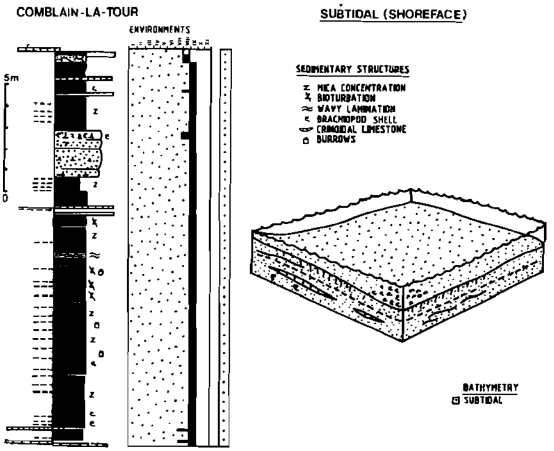


Figure 19. Subtidal series of deposits represented by finely laminated and thin bedded sandstones (black) alternating with thin (cm to mm) layers of a more muddy material (Comblain-la-Tour Formation).

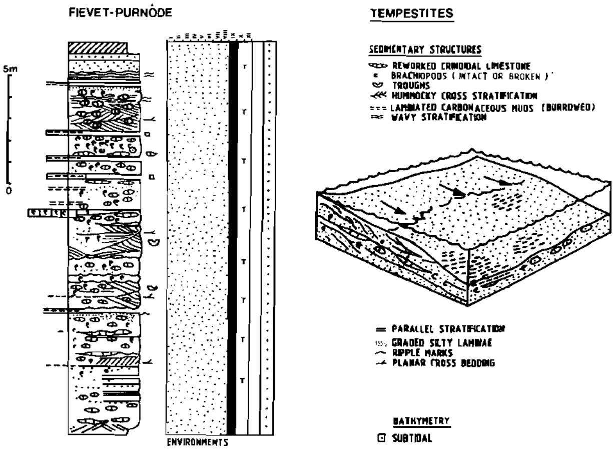


Figure 20. Tempestites (storm deposits) as seen in the Dorinne Member of the Ciney Formation.

Variation in the tidal signature of the deposits

In the Ourthe valley, near Comblain-au-Pont, quarries expose the tidal sequence of the Bon Mariage Member (Montfort Formation) and the Beverire Formation. Tidal sequences are fairly complete (with their subtidal-intertidal and supratidal subenvironments (Fig. 6). The environmental units represented vary in thickness and in the organization of the sequences. In the Bon Mariage Member, the subtidal sand comprises lenticular, crinoidal limestones. The latter contain microfossils indicating a protected marine environment: encrusted girvanellids (algae), umbellinaceans, bryozoans, thick-shelled ostracodes and conodonts. The conodonts typically display a mixed assemblage representing both inshore and more offshore paleoecological conditions. Their mixing may be due to storm activity. Similar associations of conodonts enclosed in a crinoidal limestone occur occasionally behind the sandstones of the inner barrier complex. In the Bon Mariage sequences, the ostracodal limestone capping is rarely represented. When it does occur, it is only a few centimetres thick.

In the Beverire Formation, the tidal sequences typically lack the sandstones with brachiopod shells and the 'pockets' or lenticular, crinoidal limestone beds. On the contrary, the supratidal subenvironment is systematically reaching the ostracodal limestone within beds more than a meter thick. The intertidal sediments are also well represented here by alternating siltstones and mudstones, exhibiting many sedimentary structures related to this subenvironment.

In both sequences - in the Bon Mariage Member as well as in the Beverire Formation - the grain size generally fines upwards. However, some (basal parts of) sandstones exhibit a short coarsening-upwards trend, particularly at the level of the subtidal depositional subenvironment. This character is due to wave/storm activity and is closely related to sudden influxes of crinoidal limestone with mixed conodont assemblages (Fig. 6).

In the Barse Member of the Montfort Formation (Fig. 5), the characteristic sandstone-micaceous dolomite doublets bear some supratidal characters. The coarsening-upwards sandstones are interpreted as the inshore barrier system whereas the micaceous dolomites and the dolomitic beds accumulated in evaporitic lagoons, under supratidal conditions. The micas were brought in during storms or through small gullies cross-cutting the sand bar (cf. Chabofosse quarry, Hoyoux valley). To the south, near Modave, the same doublets display more lenticular beds of crinoidal limestones in which the conodont assemblages again point to a storm-induced mixing.

Combination of the effects of river input and tidal and longshore currents

Van Straaten (1954), discussing the tidal origin of the Psammites du Condroz (mainly in the stratigraphical interval corresponding to the Montfort Formation), correctly pointed to the many discrepancies between the latter and the Wadden Sea tidal flats in The Netherlands. He further stressed the better comparison of the Psammites du Condroz with the tidal lagoon and bay deposits of Texas and Louisiana. Indeed, our paleogeographic model for the Psammites du Condroz (Fig. 12) fits better with the Gulf Coast lagoons (Krumbein, 1939; Shepard, 1953). In both cases, part of the sediments brought into the depositional area is of alluvial origin (cf. the sediments of the Evieux Formation), whereas the other (main) influx is due to the activity of longshore currents (in our case the Western Boundary Current). The siliciclastics brought in by an intermittent (rhythmic) river system (cf. the alluvial character of the series and sequences in the Evieux Formation) were partly reworked by tidal currents, waves and storms, and mixed with the siliciclastics brought into the depositional area by the longshore currents (Thorez & Dreesen, 1986; Paproth et al., 1986). The combined effect of rivers, local currents (longshore and tidal), waves and storms contributed to the building up of the inner sand barrier complex which, through time and space during the regression, separated the lagoonal environments from the tidal flats. Due mainly to the activity of the Western Boundary Current, the inner sand barrier prograded along a NNE-SSW trend as longshore bars. Behind this inner barrier system, the alluvial and evaporitic lagoons were permanently separated from the tidal flats during the whole progradation. A second, mixed barrier system (comprising sandstones and incipient carbonate buildups) was erected along a tectonic lineament to the southwest of the investigated area. Consequently, tidal flats were sandwiched between this double system of barriers; hence the 'abnormal' character of the tidal flat accumulations in the Psammites du Condroz.

LITHOSTRATIGRAPHY		DEPOSITIONAL ENVIRONMENTS	STYLE OF THE RHYTHMS
Formations	Members		
Comblain-au-Pont		Open marine, mainly subtidal with local sublagoonal to lagoonal intercalations	Fining-upward and coarsening upward sequences (metre scale)
Evieux (members not arranged in stratigraphic position)	Crupet	Distal alluvial with redbeds, evaporitic lagoonal and paleosol (calcrete) intercalations	Fining-upward sequences (metre scale)
	Royseux	Distal alluvial and alluvio-lagoonal with paleosols and sabkhas intercalated (redbeds and anhydrite)	Fining- and thinning upward sequences (metre scale)
	Fontin	Sublagoonal, interlayered with (tidal) delta and distal alluvial to alluvio-lagoonal	Fining- and thinning upward sequences (scale less than a metre)
Beverire (seaward equivalent of Evieux)		Tidal flats with some influence of storm activity, interlayered with subtidal megaripples and local tidal channels	Fining- and thinning upward sequences (less than metre to metres)
Montfort (members grade into each other)	Barse	Back barrier, barrier, tidal lagoonal (with micaceous dolomites) and evaporitic lagoonal	Minor rhythms: coarsening upward (siliciclastics, one to several metres) Major rhythms: thickening and thinning upward with parallel coarsening and fining-upward (several metres)
	La Gombe grades into Pouleur M.	Barrier (inner system) with some intertidal to subtidal influence. Some shallow tidal channels and tidal lagoonal (micaceous dolomites) intercalations.	Coasening-upward in the multistorey set beds; Fining- and thinning-upward in channel-, and sub- to intertidal deposits (less than metre)
grades laterally into:	Bon Marriage	Tidal flats (mainly sub- and intertidal preserved) with wave and storm activity superimposed.	Fining- and thinning-upward sequences (usually less than m, locally several m)
Comblain-la-Tour		Subtidal with some influence of strom activity	Thin (cm to dm) sequences
	Pouleur	Sub- and lower intertidal	Thinning-upward sequences (less than m)
Ciney		Subtidal barrier with some intertidal influence and incipient carbonate buildups (outer barrier)	Coarsening- and thickening sequences (up to several metres)
	Dorinne	Tempestites	f.u. sequences, without breaks between lithologies (dm scale)
	Haversin	Fluxoturbidites (ill-sorted siltstones and mudstones with crinoidal limestone clasts)	Fining-upward sequences and slumped set (less than metre)
Souverain-Pre		Subtidal inshore to offshore; subrounded to subangular crinoidal clasts embedded in the siliciclastics	Some fining-upward trends
Esneux		Subtidal, wave dominated	centimetre scale sequences
Aye		Subtidal, offshore, with fluxoturbidite intercalations	centimetre to decimetre thick sequences

Table 3. Relation between lithostratigraphical units (formations and members) and the depositional environments in the Psammites du Condroz in the eastern part of the Dinant Synclinorium, Belgium.

Van Straaten (1954) also pointed out the absence of marsh deposits and the relative scarcity of channels and larger gullies in the Psammites du Condroz. Marshes could not have developed during the Famennian times because of differences in vegetation. Many black (organic-rich) mudstones in the tidal sequences are composed of decayed algal mats and are typically poor in spores belonging to plant vegetation. However, in the Evieux Formation Lejeune (1986) has found red (hydromorphic) alluvial paleosoils and dolcrete developed on levees in the alluvial system. Tree roots are preserved in these paleosoils.

WAVE AND STORM INFLUENCE IN THE PSAMMITES DU CONDROZ

There are many clues that storms interfered during the development of the tidal sequences. We have pointed out some pertinent criteria, in particular the occurrence of mixed assemblages of conodonts in crinoidal limestone beds, in the tidal environments and behind the inner barrier complex, in the lagoons.

Wave activity was a major mechanical process in the accumulation of parts of the Psammites du Condroz.

For instance, the Esneux Sandstones are widely distributed in the Dinant Synclinorium, in the Namur and Verviers Synclinoria and as far as Aachen (Federal Republic of Germany) (Paproth, Dreesen & Thorez, 1986). The formation is more than 200 m thick in northern parts of the Dinant Synclinorium, with very uniformly-distributed thin sequences (order of cms to dms thick). These are composed of well-sorted, fine-grained, even laminated sandstones. Other lithologies such as crinoidal limestone are scarcely represented and, here, only as thin, lenticular beds of concentrated crinoid debris. Again, these limestones have a mixed conodont assemblage. The Esneux Sandstones grade seawards to the south and southwest into the coeval Aye Shales, composed of silty and sandy mudstones, with lenticular or nodular limestones made of reworked crinoid debris. Brachiopod shells occur either scattered within the siliciclastic matrix or concentrated as coquinas. Slumps and ball-and-pillow structures occur too.

Though the Esneux Formation has not been investigated in the same detail as the underlying and overlying formations, some genetic conclusions can be drawn to explain the widespread and uniform distribution of the siliciclastics. The siliciclastics were brought into the depositional area by the Western Boundary Current (Paproth et al., 1986). Afterwards, the material was subject to wave activity. Waves winnowed the finest (mud) fraction out of the fine sands (less than 40 microns in grain size); mud was laid down to the south and southwest within the Aye Shales, whereas the sands and micas were accumulated into thin rhythms. The Esneux Sandstones are typically poor in sedimentary structures. They are, however, characterized by abundant flat-topped wave and current ripple marks, and by occasional microcross-laminations.

Above the Esneux Sandstones, the Souverain-Pre Formation (in the Dinant Synclinorium) also shows storm and wave features. Characteristically, the Souverain-Pre Formation consists of subrounded limestone clasts embedded in a sandy to muddy matrix. The limestone clasts contain the same microfossil assemblages as the lenticular beds or 'pockets' of crinoidal limestone found occasionally in the overlying Montfort (Bon Mariage Member), Comblain-la-Tour and Ciney Formations. The microfossils imply an open to partly protected, marine environment.

Storm deposits also formed thick series in the Dorinne Member of the Ciney

Formation as exposed in the Bocq valley quarries. The superimposed sequences bear the features of recent storm deposits (Aigner, 1982) (Fig. 20).

Two depositional models have been proposed by Goemaere (1984). Figure 20 depicts a columnar section for part of the tempestite sequences of the Bocq area. More than a hundred successive tempestite sequences have been observed, and their limestone layers also contain mixed conodont assemblages. These tempestites suggest a depositional environment below the normal wave base, subjected to episodic high-energy storm activity. Possibly, these deposits originated from hurricanes (Heckel & Witzke, 1979; Paproth et al., 1986). Indeed, the tempestites as well as the hummocky cross-stratification could be related, in the Psammites du Condroz, to the occurrence of Paleozoic hurricanes: these could be expected in latitudes between 10° and 45°, which fits the paleogeographical model (Fig. 18) (Paproth et al., 1986). This reconstruction shows the position of the Condroz Platform on the shelf south of the London-Brabant Massif. The latter was fully emerged during the deposition of the Psammites du Condroz whereas the Ardennan and Rhenish shoals, to the southeast, were episodically submerged, with the Vesdre Corridor between the Massif and the shoals permitting the passage of the Western Boundary Current. The tropical storms reached the Condroz area from the southwest, the direction also deduced from the wave and current ripple marks and the tidal gullies.

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