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# HIGH-FREQUENCY CYCLES AND THEIR SEQUENCE STRATIGRAPHIC CONTEXT: ORBITAL FORCING AND TECTONIC CONTROLS ON DEVONIAN CYCLICITY, BELGIUM

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(17 figures, 7 tables)

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**ABSTRACT.** The sequence stratigraphic approach has evolved into an important tool for stratigraphic analysis and does have an element of prediction. Several sequence models have been proposed and are in use, but there have been emotive discussions in the literature over these, as well as systems tracts and key surfaces. Metre-scale cycles (parasequences) are the building blocks of sequences and are an essential component of carbonate successions throughout the stratigraphic record. Their thickness and facies patterns, reflecting the longer-term changes in accommodation that affected deposition, enable the various systems tracts in a sequence to be recognised. There have been many arguments over the origin of parasequences with orbital forcing, tectonic and sedimentary mechanisms all having their proponents. Devonian carbonates of the Ardennes-Eifel-Aachen area are dominated by a suite of parasequence types deposited in ramp and shelf-interior locations. They show thickness patterns and trends in facies, which on a broad scale can be correlated across the region, whereas individual cycles cannot. Some packaging of cycles is seen, which could indicate an orbital-forcing control. However, there is clear evidence for a tectonic control on regional thickness patterns in some parts of the succession, as a result of deposition across syn-sedimentary extensional faults. As with many areas of Earth Science, explanation involves a combination of several hypotheses and here one mechanism does not seem to have been responsible for the Devonian cyclicity.

**KEYWORDS:** Sequence stratigraphy, parasequences, Devonian, Belgium, limestones, orbital forcing, metre-scale cycles, Fischer plots.

## 1. Introduction

Shallow-water limestones are a major component of the stratigraphic record since almost the beginning of time and they contain a wealth of information on the evolution of organisms and their environments, as well as on seawater and atmospheric chemistry, sea-level and climate change, and small- and large-scale tectonic processes. Shelf carbonates exhibit a great range of facies and microfacies, and they have been subject to various diagenetic processes to form the lime*stones* themselves. Porous carbonates are major reservoirs for hydrocarbons and water, so their study is not just academic. At outcrop shelf carbonates are commonly distinguished by their stratification – the beds and cycles which are on the scale of 10s of centimetres to a metre or 2 or more. These high-frequency stratal units are the product of changes in sedimentation on the scale of 100s to 1000s to 10s of 1000s of years. Some of these changes are simply the result of random or quasi-periodic sedimentary processes, like storms, earthquakes and fault movements, or volcanic activity, whereas others are the product of more regular processes, such as sea-level or climate change induced by variations in solar irradiation as a result of orbital forcing and solar forcing.

This paper gives an overview of some aspects of carbonate deposition leading to the formation of the high-frequency stratification. As an example, the metre-scale cyclicity of the Devonian shallow-water carbonates of Belgium is described. These parasequences are well developed in carbonate ramp and shelf interior facies and provide a good case-study of the various factors involved in the formation of cycles.

## 2. The highest-frequency cycles: metre-scale cycles or parasequences

In shallow-water carbonates, as well as many other sedimentary rock-types, there are small-scale cycles, usually composed of beds, which consist of repetitions of facies. These cycles are on the metre-scale, from 0.5 to 5 metres in thickness, in some cases up to 10 metres, rarely more. Metre-scale cycles are a feature of platform carbonates, deposited in a range of environments from the open shelf/ramp to lagoon to tidal flat. High-frequency cycles also occur in lacustrine and pelagic carbonate successions too, and may all be defined by changes in microfacies, as well as by other features such as grain-size, colour, mineralogy and intensity of bioturbation.

The features of metre-scale cycles are an important component of the sequence stratigraphic analysis of a succession and therein these units are referred to as parasequences. In the most commonly-used definition of the term (Van Wagoner et al., 1988), which was derived largely from studies of shoreline to shallow-marine siliciclastic sediments, ‘‘a parasequence is a relatively conformable succession of genetically-related beds or bed-sets bounded by marine flooding surfaces and their correlative surfaces’’, and “parasequences are typically a shoaling-upward succession of facies”. There has been much discussion of the term parasequence in recent years; indeed some authors have found such difficulty with the term they have suggested it be abandoned. However, it is well entrenched in the literature, and in people’s psyche, so that the term will doubtless remain. There are some good arguments for keeping it: if you talk about parasequences people will know you are referring to metre-scale units, and you are thinking in sequence stratigraphic mode. When applied to carbonates, a strict application of the definition can be hard to apply. Carbonate metre-scale cycles may show a deepening up, if the transgressive (or positive) part of the accommodation cycle was sustained. Some carbonate cycles show deepening and then shallowing (T-R, symmetrical cycles); some of these may then have a flooding surface or flooding zone of deepest water facies in the middle of the parasequence. In addition, many carbonate cycles do not ‘shoal-up’, i.e. grade up into shallow-water facies of higher energy, sand-bank (i.e. shoal) facies, but they shallow-up into sediments which are still muddy (like tidal-flat facies), and so are of similar grain-size (i.e. fine) to the somewhat deeper-water, often lagoonal part of the cycle below. To overcome some of the difficulties of the original definition of parasequence, Spence & Tucker (2007) redefined the parasequence, broadening it out somewhat, to: “A regionally significant metre-scale sedimentary package characterised by a succession of facies that may shallow-up, deepen-up then shallow-up, aggrade, or reflect constant water depth. Bounding surfaces between each parasequence are sharp and defined by abrupt changes in genetic relays or assemblages of grains or bioclasts, or in palaeowater depth and/or in facies. Bounding surfaces need not always correspond to flooding surfaces”. They showed that in a complete cycle of accommodation change (i.e. relative sea-level change), the nature of the metre-scale cycles could vary considerably and include all types – simply transgressive and transgressive-regressive, as well as the more typical simple regressive cycle.

Many carbonate cycles of course do not shallow-up to sea level to be terminated by an exposure surface and overlain by the flooding surface of the next cycle, but are entirely subtidal. Many of these terminate in oolitic-bioclastic grainstone facies, in some cases with a firmground or hardground surface. These cycles have commonly shallowed up to fairweather wave-base, above which there was plenty of current/wave activity that kept sediment moving about, rather than being deposited. In these situations, wave-base was acting as base level (rather than sea level which is usually the case); base level is the datum above which sediment is eroded, or rather not deposited (for examples see Calvet & Tucker, 1988; Osleger, 1991; Jennette & Pryor, 1993).

## 3. The sequence stratigraphic context of high-frequency stratal units

### *3.1. Sequence stratigraphy preamble*

Sequence stratigraphy has evolved much since the heady days of the early 1980s when everybody’s appetite was whetted but there were few detailed papers to read apart from the quite broad, classic AAPG Memoir 26, with its emphasis on the seismic scale. There were arguments then over the immense sea-level changes postulated for sequence formation in non-icehouse times, and issues of the supposed global correlation chart. Sequence stratigraphy has now developed into a fundamental approach for describing, understanding and predicting the nature of sedimentary units. Successions are analysed for their stratal packages, their geometric arrangement and their stacking patterns; these are all considered within a temporal framework. The dominant underlying controls on sedimentary successions are accommodation – the space available for sediment, and sediment supply. For sediment supply in the case of shallow-water carbonates, and in contrast to clastics where supply is often related to tectonic movements in a source area (as well as climate and sea-level change), sediment *production* is more often the key, since shelf carbonates are mostly formed and deposited in situ, and this is very much affected by the depositional environment – temperature, energy levels, nutrients, oxia-anoxia, turbulence, climate, state of biotic evolution, etc.

### *3.2. Sequence stratigraphy and standardisation of approach*

Sequence stratigraphy is widely used now in the petroleum industry and academia, but there are still sceptics of its value and criticisms of the burgeoning jargon and models. In the last few years there have been attempts to standardise the sequence stratigraphic approach with working groups set up by the North American Commission on Stratigraphic Nomenclature and the International Sub-Commission on Stratigraphic Classification, but a consensus has yet to emerge. In the meantime an international group of interested persons (the self-styled International Working Group on Sequence Stratigraphy) has gotten together under the leadership and guidance of Octavian Catuneanu (University of Alberta, Edmonton) to try and standardise

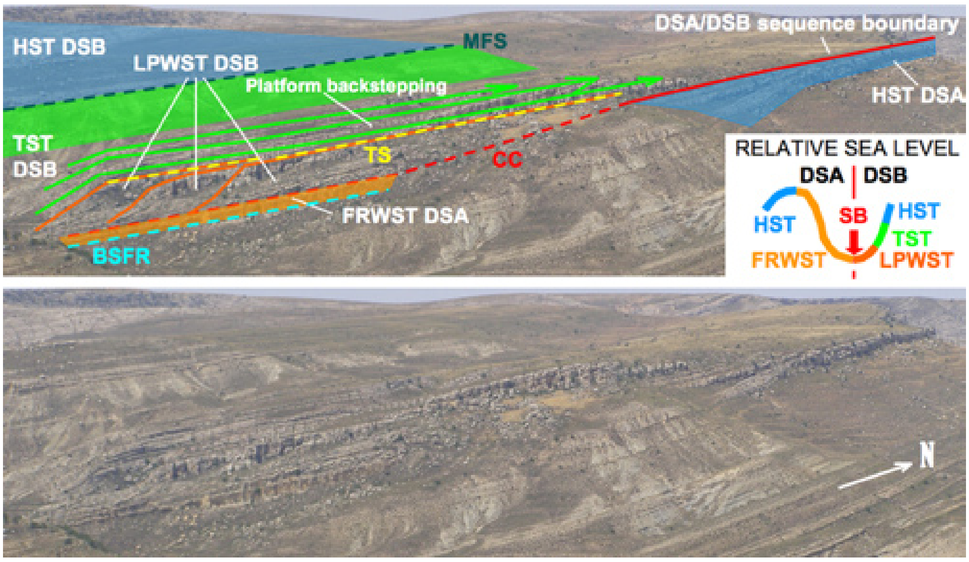


**Figure 1.** Lower Cretaceous sequences in the Maestrat Basin, eastern Spain. Photo courtesy of Telm Bover-Arnal (see Bover-Arnal et al., 2009 for more information).

sequence stratigraphy and find some common ground after 3 decades of development. This has been extremely successful and so far has led to 2 important publications for the geological community (Catuneanu et al., 2009, 2010) and a report (Catuneanu et al. in prep).

Over the past 30 years, 3 types of sequence have been defined, with different surfaces chosen for the bounding surfaces: *depositional sequences*, bounded by subaerial unconformities and their correlative conformities (e.g. Posamentier et al., 1988; Van Wagoner et al., 1988, 1990; Hunt & Tucker, 1992); *genetic sequences* bounded by unconformable maximum flooding surfaces and their correlative conformities (Galloway, 1989), and *transgressive-regressive sequences*, bounded by composite surfaces which include the subaerial unconformity and the marine portion of the maximum regressive surface (Embry & Johannessen, 1992). The reviews of Catuneanu et al. (2009, 2010) have attempted to show that there is no single sequence stratigraphic approach or model that can be applied to all successions in view of the nature of the data available, the depositional and tectonic setting of the succession, and the scale of observation. However, model independent features of sequence stratigraphic significance, namely facies relationships and geometries, stratal stacking patterns, and unit bounding surfaces, can be recognised and described from the data objectively, over which there should be little or no argument. With this information, the stratigrapher can then make model-dependent choices of which surfaces to use to define the sequence stratigraphic units and which model best fits the data.

The definition of sequence by Mitchum (1977) as "a relatively conformable succession of genetically-related strata bounded by unconformities or their correlative conformities" can be broadened out to "the product of a cycle of change in accommodation and sediment supply" (Catuneanu et al., 2009) so that any type of sequence is included. A cycle of accommodation change may involve an increase (positive accommodation) in the space available for sediments and/or a decrease (negative accommodation). The sequence then consists of its systems tracts: "a linkage of contemporaneous depositional systems" (Brown & Fisher, 1977), consisting of a relatively conformable succession of genetically-related strata. In the depositional sequence model of Hunt & Tucker (1992, 1993), devised largely from studies of carbonates, four systems tracts were recognised as the product of a full cycle of accommodation change: falling stage (FSST), lowstand (LST), transgressive (TST) and highstand (HST) systems tracts, although of course in many cases all four are not present in a particular sequence. This model is widely applicable; for an example see the recent study of Bover-Arnal et al. (2009) from the Mid-Cretaceous of the Maestrat Basin, eastern Spain (Fig. 1).

Recognising stratal geometries then is a crucial part of the sequence stratigraphic methodology, and allows the identification of the systems tracts. In essence, stratigraphic units of the shelf-ramp shoreline environment are the result of 3 basic types of shoreline trajectory: forced regression, normal regression and transgression. The first is a response to negative accommodation, the second and third to positive accommodation, with sedimentation outpacing the creation of accommodation space with normal regression, and the opposite situation for transgression. Thus, stratal units show either: 1) progradational-downstepping as a result of forced regression, 2) progradation-aggradation for normal regression, or 3) retrogradation for transgression. Arrangement 1 is typical for falling stage/forced-regressive wedge systems tracts (FSST), or late HST/early LST; arrangement 2 is characteristic of LST (especially late) and HST (especially early), and 3 is the TST.

### *3.3. Position of sequence boundaries*

One issue that has concerned sequence stratigraphers for decades is where to place the sequence boundary in a 'classic' depositional sequence. Where sequences consist of prograding highstand deposits overlain by a clear exposure surface (e.g. palaeokarst/palaeosoil) and/or more proximal facies (e.g. fluvial to shoreline) of the falling stage-lowstand, and then retrogradional, deepening-upward transgressive facies, there should be no argument as to where the unconformity occurs – between the highstand facies and falling-stage-lowstand facies to mark the sequence boundary. There are of course many carbonate platforms where highstand facies (prograding clinoformed shelf-margin facies say) are directly succeeded by transgressive facies, since the platform was fully exposed during the time of negative accommodation and no FS-LS facies were deposited there (but they may well have been deposited on the slope or basin floor, as seen in Fig. 1 for example). However, in some cases, especially seen in shelf-margin and slope environments, sediments were deposited during the time of decreasing accommodation, the forced regressive (or falling stage) deposits, before the decrease in accommodation space reached its low point, and lowstand facies accumulated. With this type of sequence there has been an issue of where to place the sequence boundary. Posamentier et al. (1988, 1994), Kolla et al. (1995) and Coe et al. (2003) suggested it be at the start of decreasing accommodation, that is between the highstand and forced-regressive deposits. Hunt & Tucker (1992, 1995) suggested the boundary should be placed between the forced-regressive deposits and the lowstand deposits.

The neat aspect of Catuneanu et al.'s (2009) philosophy – that the most appropriate sequence stratigraphic model be used for the study in hand – is that all models are 'correct' where they are the best fit for the data. Hence, in retrospect, the arguments over where to place the sequence boundary were academic. However, it might be useful to note again (18 years later!!) the reason that Hunt & Tucker (1992, 1993) placed the sequence boundary *after* the forced regressive deposits: it was because in carbonates (and many clastics!), the forced regressive sediments are commonly derived from reworking of the just-deposited highstand facies. Thus it was argued that the FR sediments actually belong to the same sequence as those highstand facies, and represent the last gasp of that phase of deposition. One classic type of forced regressive deposit in a carbonate system is the megabreccia (Spence & Tucker, 1998), formed from the collapse of the shelf margin during the decrease in accommodation/fall in relative sea level, and deposited on the lower slope. The succeeding lowstand deposits in this carbonate setting are typically primary carbonates, usually prograding basinwards, generated in an often small, 'new' shallow-water platform located below the shelf-margin of the previous sequence (see Fig. 1 again, and Bover-Arnal et al., 2009), hence with freshly-formed sediment, heralding the new sequence, and so placed *above* the sequence boundary.

### *3.4. Hierarchy and orders of cyclicity*

Another area of sequence stratigraphy which has frequently come in for criticism is the use of orders of cyclicity and the hierarchy of stratal units. For decades people have spoken of sequences as being of 3$^{rd}$ order, $10^{5\text{-}6}$ years duration (0.5 to 3 million years), and parasequences as being of 4-5$^{th}$ order ($10^{4\text{-}3}$ years duration). Lower-frequency megasequences / supersequences (also called transgressive-regressive cycles) have been referred to as 2$^{nd}$ order, and the continental encroachment cycles as 1$^{st}$ order (Duval et al., 1992). Beds are then 6$^{th}$ or 7$^{th}$ order (few 100-1000 years). However, it has been suggested (Drummond & Wilkinson, 1996) that this is rather contrived and little more than an arbitrary subdivision of an uninterrupted stratigraphic continuum. Schlager (2004) showed that depositional sequences have a similar internal structure at a wide range of scales, so having a fractal nature, and suggested that the orders were subdivisions of convenience rather than an indication of natural structure. The orders of cyclicity and hierarchy of stratal units in one basin need not necessarily correlate with those in another basin of course; except for those stratal units produced by orbital forcing (the Milankovitch rhythms of precession, obliquity and eccentricity), but then with these units, there are often missed beats and local tectonic effects to confuse the stratigraphic record (see later sections). There is a range of generating mechanisms, each with its various timescales, for the stratal units (Miall, 1997), from dominantly tectonic through to orbital and solar forcing to sedimentary processes. The overlap in the timescales of these processes accounts for the continuing arguments, as, for example, over the origin of parasequences – tectonic versus eustatic versus sedimentary (see later section). Nevertheless, it is useful to refer to stratal units in a descriptive and relative sense as being of lower versus higher frequency. It is useful to make reference to the duration of stratal units in a succession (if known or an inspired guess is possible), and this could be used as a basis for the hierarchy, referring to units in terms of their $10^n$-year episodicity; thus a sequence might have a $10^6$-year periodicity (see Catuneanu et al. in prep, for further discussion).

Hierarchies of cyclicity are extremely well developed in some stratigraphic successions, most notably where solar and orbital forcing has been a major control on deposition. Mawson & Tucker (2009) for example identified packaging in Upper Permian (Zechstein) calciturbidites of NE England on millennial, semi-precession, precession (20,000-year), short eccentricity (100,000-year), and long eccentricity (400,000-year) scales; that is five orders of cyclicity within one stratigraphic formation. Durations of cycles were deduced from counting the number of laminae between turbidites making up the cycles (laminae were assumed to be annual), and the cycles themselves were identified on the basis of the stacking patterns of the calciturbidites which show upward changes in bed thickness (thinning-up and thickening-up patterns), turbidite bed percentage and turbidite accumulation rate. Chen & Tucker (2003) found a similar hierarchy of stratal units in Devonian basinal strata close to the Frasnian-Famennian boundary in China, where the basic cycle consists of some 6-8 beds, mostly calciturbidites, showing upward-increasing thickness. These cycles could be correlated with peritidal cycles ('classic' parasequences), deposited on the adjacent carbonate platform (Chen et al., 2001). Both the basinal and platform cycles are bundled into lower-frequency packages, to which the terms cycle-set, meso-cycle set and mega-cycle set were applied in descending order; several of the last then form the sequence itself. Interpretations here were millennial-scale for the beds, and then precession (16-18 kyr), short-eccentricity (100 kyr), mid-eccentricity (200 kyr), and long eccentricity (400 kyr) for the lower frequency, lower order units. There is no valid reason why such terms as cycle-set, meso-cycle-set, etc. should not be used to describe a hierarchy of cyclicity if assumptions and terms are explained at the outset. See Strasser et al. (1999, 2006) for further discussion of these aspects of cyclostratigraphy.

## 4. Mechanisms causing metre-scale cyclicity

Metre-scale cyclicity is a feature of many shallow-water carbonate successions throughout the sedimentary record and there have been numerous reviews of its origin (e.g. Lehrmann & Goldhammer, 1999; Schlager, 2005; Bosence et al., 2009). Three mechanisms have been invoked to explain the repetition of these shallowing-upward cycles: sedimentary, tectonic and eustatic.

Two types of autocyclic sedimentary mechanism are generally invoked: the tidal-flat progradation model, of Ginsburg as described by James (1984) and Lehrmann & Goldhammer (1999), and the tidal-flat island model of Pratt & James (1986). The former allows shallowing-upward cycles to be generated by the progradation of a tidal-flat wedge across a platform under conditions of long-term relative sea-level rise and / or continuous subsidence. The large subtidal area is the major location of carbonate production (the carbonate ‘factory’), and sediments generated there are deposited on the tidal flats through storms, waves and currents. As the tidal-flat area becomes larger and progrades over the platform, the area of carbonate production decreases, and eventually ceases to be active. The continuing subsidence leads to submergence, and after some lag-time, carbonate production resumes. In the second model, low-relief supratidal-intertidal islands and banks surrounded by shallow water migrate and prograde across a platform. Laterally impersistent shallowing-upward cycles are generated against regional subsidence.

Tectonic mechanisms for cycle repetition have invoked periodic syn-sedimentary extensional and strike-slip faulting (e.g. Cisne, 1986; Bosence et al., 2009) to create accommodation space. In-plane stress variations in the lithospheric plates as a result of larger-scale tectonic movements have been suggested by Cloetingh (1988) as leading to subsidence or uplift and thus transgression or regression. Laterally impersistent cycles of variable thickness are the likely product.

Orbital forcing has been a popular explanation for the creation of metre-scale cycles, with the three Milankovitch rhythms of precession (~20 kyr), obliquity (~40 kyr) and eccentricity (short ~100 and long 400 kyr) being responsible for variations in the amount of solar irradiance reaching the Earth. This causes temperature variations which affect sea level through expansion and contraction of ice caps during icehouse times, and of the ocean-water volume during greenhouse times. The magnitude of the sea-level change is higher (10s of metres) during icehouse compared with greenhouse times (metres). It does seem that the various orbital rhythms were more of a control on sea level at different times; in some cases two rhythms may have affected deposition, at other times just one. Over the last 700 kyr for example, short eccentricity and precession have been dominant but before then it was obliquity. Where two rhythms were affecting sea level, that is composite eustasy, then packages or bundles of metre-scale cycles could be the result, the so-called parasequence sets (equivalent to the cycle-sets mentioned above). Goldhammer et al. (1990) described such ‘pentacycles’ from the Triassic of northern Italy, a bundle of around 5 cycles showing upward-decreasing thickness and attributed to the effects of precession superimposed on eccentricity (however, see Zühlke et al., 2003 for an alternative view, namely millennial-scale rhythms superimposed on precession). One feature in addition to the bundling of cycles that should distinguish cycles formed through orbital forcing from both tectonic and autocyclic mechanisms is that cycles will be laterally persistent on a regional, even global scale; this would generally be the broad thickness pattern rather than the individual metre-scale cycle trend (see Grötsch, 1996 for an example). Cycles may also show a regular periodicity and stacking pattern reflecting long-term changes in accommodation; that of course could be entirely tectonically driven, rather than eustatic.

Since all three controlling processes have similar rates of operation, deciphering the over-riding control can be difficult, if not impossible. Statistical analysis of cycle thicknesses and stacking patterns, such as application of runs tests and autocorrelation, is essential to identify ordered successions, likely of orbital-forcing origin, from disordered random stacks of cycles, more likely of tectonic or autocyclic origin (see Sadler et al., 1993; Drummond & Wilkinson, 1993; Lehrmann & Goldhammer, 1999; Burgess, 2006).

## 5. Fischer Plots

Fischer plots are a popular tool in cyclostratigraphy to illustrate graphically deviations from average cycle thickness (Fischer, 1964; Sadler et al., 1993; Bosence et al., 2009). The graph plots ‘cumulative departure from mean thickness’ against ‘cycle number’, so that thicker-than-average cycles show as a plot with a positive slope and thinner-than-average cycles show a negative slope (see later figures). The Fischer plot provides an illustration of cycle-thickness variation that can be useful to bring out longer-term trends and patterns. In particular, bundling of cycles may be revealed, indicating the presence of cycle-sets within the succession. More precise interpretations of the plots are often criticised as being too subjective and speculative. Statistical analysis should be carried out to determine the degree of randomness (Sadler et al., 1993), since patterns may be perception rather than reality.

Ideally only Fischer plots with more than 50 cycles should be considered, but circumstances of development or exposure may mean this is not possible.

Fischer plots have been used successfully for correlation between different localities or across a platform (e.g. Grötsch, 1996), and to show the effects of tectonics, i.e. differential subsidence or faulting, during deposition of a succession of cycles. Where cycles shallow up to base level, filling the available accommodation space each time, then the overall pattern of the Fischer plot has been interpreted as a reflection of the long-term rise or fall of relative sea level, i.e. changes in the accommodation cycle, positive or negative. Thus thickening-upward cycle trends, showing as a rising plot on the diagram, would be indicative of a transgressive systems tract, that is a long-term increase in accommodation (positive), with an overall retrogradational, onlapping pattern of facies; and thinning-upward cycle trends, a falling limb on the diagram, an overall regressive, progradational, offlapping pattern, would indicate a long-term decreasing, i.e. negative, accommodation trend.

Where Fischer plots are useful is when combined with facies analysis of the cycles, and upward changes in facies are examined in the context of upward changes in cycle thickness through an accommodation cycle. Patterns may emerge in the way particular facies relate to the accommodation cycle, that is *facies partitioning*, where certain facies are preferentially developed at specific times in a cycle of accommodation change. For example, in a succession of peritidal parasequences, small reefal or microbial buildups may preferentially develop during times of more positive accommodation; influxes of clastics may occur during times of more negative accommodation. Although some of this is blinding obvious, in some successions of parasequences, subtidal facies are quite different – say oolitic grainstones versus bioclastic grainstones, or all bioclastic but different biotic grains, in those parasequences deposited during times of more positive (transgressive) versus more negative (regressive) accommodation. This is where facies and cycles become very interesting; e.g., what is the difference between the shallow subtidal environments of the transgressive versus the regressive cycles, and why? An element of facies prediction also becomes possible when facies partitioning is apparent.

Fischer plots can contribute to the discussion of the origin of parasequences – one would expect non-random patterns for those produced by orbital forcing, so simple rising (transgressive) and falling (regressive) limbs of a plot reflecting the high-frequency ($10^{4\text{-}5}$ year) sea-level changes superimposed on a longer-term pattern of accommodation change. Where there are two (or even 3) Milankovitch rhythms controlling deposition then the Fischer plot will show a bundling of the cycles, into groups of 5 (pentacyles) if precession and short eccentricity were the cause, as was described by Goldhammer et al. (1990) from the Triassic Latemar complex, Italy and by Satterley (1996) for the Triassic Hauptdolomit Lofer cycles, Austria. Where the cyclicity was produced by sedimentary processes, notably tidal-flat progradation or tidal-island migration (autocyclicity), then the Fischer plot should show a more random pattern of cycle thickness,

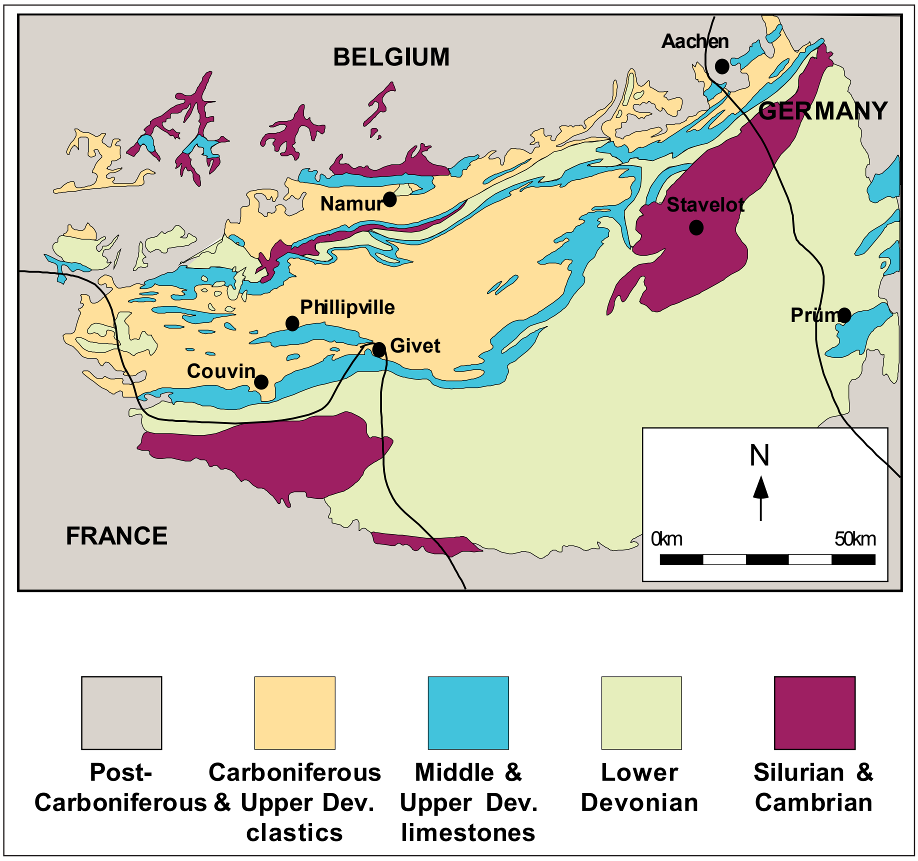


**Figure 2.** Generalised geological map showing the outcrops of Devonian rocks in the Ardennes-Aachen-Eifel area.

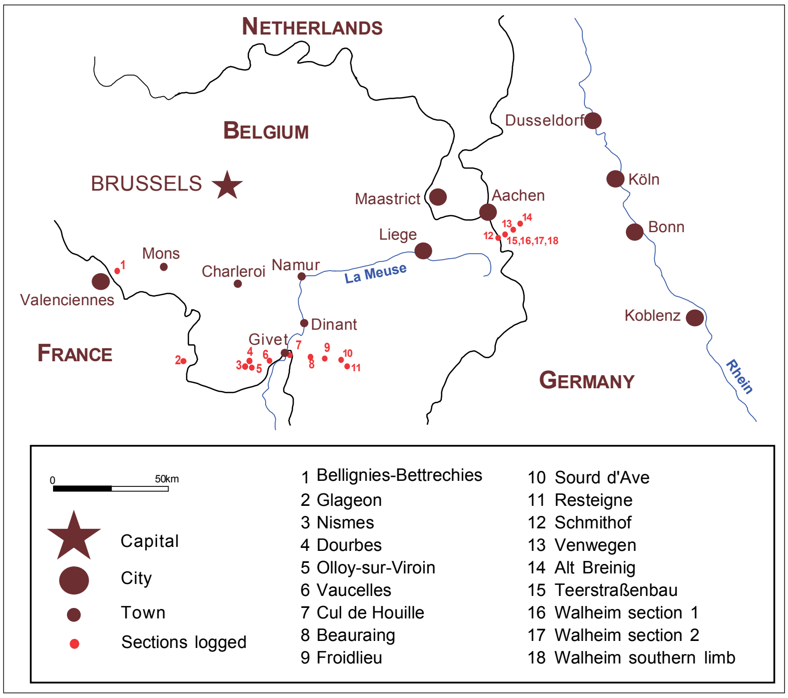


**Figure 3.** Map of NE France, southern Belgium and western Germany showing location of exposures examined for this project.

**Table 1**: Localities examined and their co-ordinates and section thickness..

| Age and facies-types | Location | Topographic map number and co-ordinates | Thickness of log |
|---|---|---|---|
| **Givetian ramp facies** | Glageon quarry | 1:25,000, Sheet 57(5-6), co-ordinates not available. Working quarry S of Glageon, near Trélon | 140.5m |
| | Bellignies-Bettrechies quarry | 1:25,000, Sheet 51(1-2), Roisin-Erquennes 05.5360 55.7555 | 63.1m |
| **Givetian ramp and shelf facies** | Teerstraßenbau quarry | 1:50,000, Map L5302, Aachen r:25.1260 h:56.1825 | 83.5m |
| **Givetian shelf facies** | Alt Breinig quarry | 1:50,000, Map L5302, Aachen r:25.1571 h:56.2100 | 35.4m |
| | Beauraing quarry | 1:25,000, Sheet 58(3-4), Agimont-Beauraing 06.3945 55.5245 | 42.8m |
| | Cul de Houille quarry | 1:25,000, Sheet 58(3-4), Agimont-Beauraing 06.3265 55.5270 | 62.1m |
| | Dourbes quarry | 1:25,000, Sheet 58(5-6), Olloy-sur-Viroin - Treignes. 06.1445 55.4970 | 41.8m |
| | Froidlieu quarry | 1:25,000, Sheet 59(5-6), Pondrôme-Wellin, co-ordinates not available. East of Froidlieu village, set back N of N40 road. | 28.8m |
| | Keldenich quarry | 1:25,000, Map 5405, Mechernich r:25.4200 h:55.9933 | 38.5m |
| | Nismes quarry | 1:25,000, Sheet 58(5-6), Olloy-sur-Viroin - Treignes. 06.1150 55.4845 | 24.9m |
| | Olloy-sur-Viroin quarry | 1:25,000, Sheet 58(5-6), Olloy-sur-Viroin - Treignes. 06.1350 55.4850 | 43.6m |
| | Resteigne quarry | 1:25,000, Sheet 57(5-6), co-ordinates not available. Quarry N of Resteigne near the River Lesse on the road to Belvaux | 88.0m |
| | Sourd d'Ave section | 1;25,000, Sheet 59(5-6), Pondrôme-Wellin, co-ordinates not available. Roadside outcrop on junction between N835 and N94 at Sourd d'Ave | 37.5m |
| | Vaucelles quarry | 1:25,000, Sheet 58(1-2), co-ordinates not available. Overgrown quarry NW of Vaucelles, on road to Doische | 19.6m |
| | Venwegen quarry | 1:50,000, Map L5302, Aachen r:25.1500 h:56.1981 | 11.5m |
| | Walheim southern limb | 1:50,000, Map L5302, Aachen r:25.1315 h:56.1831 | 40.0m |
| **Frasnian shelf facies** | Schmithof quarry | 1:50,000, Map L5302, Aachen r:25.1150 h:56.1750 | 22.4m |
| | Walheim section 1 | 1:50,000, Map L5302, Aachen r:25.1311 h:56.1875 | 15.6m |
| | Walheim section 2 | 1:50,000, Map L5302, Aachen r:25.1320 h:56.1885 | 39.5m |

and one would not expect the plots to correlate over any significant distance. In tectonic explanations for metre-scale cycles (e.g. Bosence et al., 2009 for the Lower Jurassic platform carbonates of the western Mediterranean area, outcrops in Tunisia, Italy, Spain, France), mostly involving fault-controlled subsidence, cycle thickness patterns would again be quite random, with no clear correlation across a region. As with many issues in the Earth Sciences, the explanation in the end is often a compromise, and more than one mechanism actually involved. Orbital forcing has been a process through geological time, but the signal can easily be distorted or masked by tectonic and autocyclic mechanisms to produce a random stack of parasequences.

## 6. The Devonian of Belgium

The Devonian of Belgium is a classic succession for carbonates and there are many interesting developments, notably the coral-stromatoporoid reefal complexes and the mud-mounds, but of particular note here is the occurrence of cyclic peritidal carbonates. These were studied by one of the authors for a PhD (Garland 1997, Durham University) and some of the results are presented here. Many people have studied the cyclic Devonian carbonates in Belgium, notably Alain Préat and colleagues (e.g., Préat & Carliez, 1994; Préat & Kasimi, 1995; Préat & Weis, 1994; Kasimi & Préat, 1996). The Belgian cycles are very interesting in that they show a variety of types; they are similar to others in the geological record, and their interpretation seems to be the result of several processes, but primarily orbital forcing and tectonic processes.

The distribution of the Devonian limestones in the Ardennes, Aachen and Eifel regions is shown in Fig. 2 and the outcrops examined in Fig. 3 and Table 1. Fieldwork was undertaken in old quarries and road sections; successions were logged; the facies and metre-scale cycles documented, and samples were collected for microfacies analysis. The stratigraphic division of the Middle-Upper Devonian succession is displayed in Fig. 4, which also shows the stratigraphic intervals of the various exposures.

### *6.1. Context of Devonian carbonates in Belgium*

The Middle and Upper Devonian (Eifelian-Givetian-Frasnian) shallow-water carbonate facies of western Europe were deposited as a large-scale broadly transgressive succession over continental facies of the Old Red Continent (see reviews of Burchette, 1981; Préat & Mamet, 1989; Da Silva & Boulvain, 2004; Boulvain et al., 2009). The transgression was in a northerly direction, reaching the southern Ardennes by the lower Eifelian and the Aachen area of Germany by the middle Givetian. Carbonate sedimentation continued through to the middle Frasnian, when a major pulse in relative sea-level rise drowned the platform.

The Eifelian of the Dinant basin in Belgium, the Couvin, Jemelle and Hanonet Formations (Fig. 4), consists of crinoidal limestones and interbedded mudrocks with small organic buildups, and to the north some sandstones,

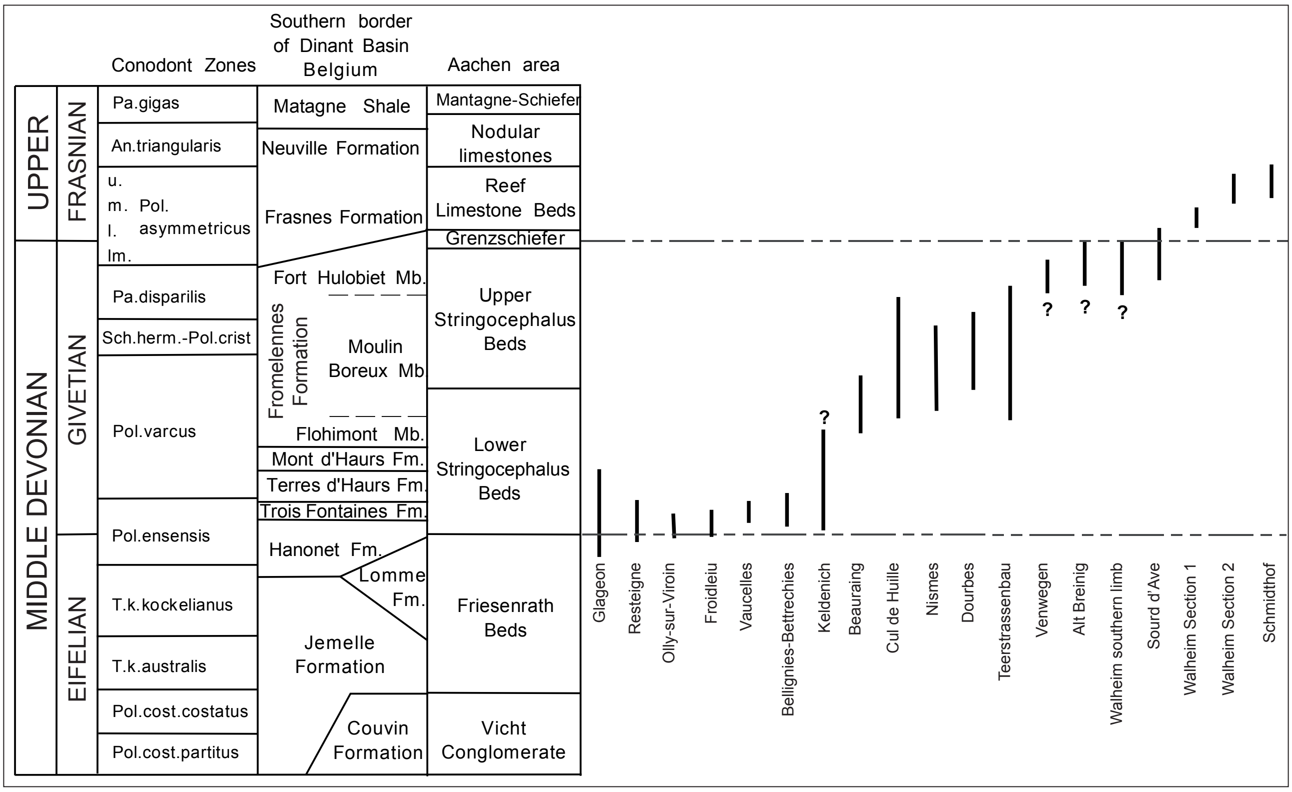


**Figure 4.** Stratigraphic chart showing conodont zones, lithostratigraphic names and ages of the successions examined in the Eifelian-lower Givetian ramp and Givetian-Frasnian shelf lagoonal facies. Data from various sources.

all deposited on a broad storm-influenced homoclinal ramp. Sedimentation was mostly open-marine in nature, with protected back-ramp and tidal-flat areas. Towards the end of the Eifelian and through the Givetian, the Belgian Ardennes and Eifel areas of Germany saw the development of a large shelf lagoon, up to 60 km in width, with stromatoporoid-coral reefs developed along the shelf edge located in the present-day southern Ardennes region, which provided the restriction. The shelf had an ESE-WNW trend and extended from Boulogne (northern France) in the west to Aachen (western Germany) in the east. The northward progradation of these carbonate facies over Lower Devonian clastic facies accounts for the earlier carbonate facies in the Dinant basin compared to the more northerly Namur basin in Belgium.

Late Givetian transgression caused back-stepping of the margin towards the north in the direction of the Old Red Continent. Isolated red-coloured mud-mounds of Frasnian age developed basinwards of the barrier reef at approximately 100 m water depth, well below the photic-zone. Barrier reefs were still present in the lower Frasnian along the shelf-edge rise, now farther north towards Phillipeville, enabling lagoonal sedimentation to continue (Da Silva et al., 2004; Gouwy & Bultynck, 2000). Carbonate sedimentation was succeeded by deposition of the Matagne Formation shales. The broad Middle Devonian shelf was divided into numerous tilted fault blocks, each a few kilometres wide, the result of extensional tectonism in a back-arc setting (Préat, 1984; Préat & Weis, 1994). These affected the deposition of the lagoonal-peritidal parasequences, as explained below.

### 6.2. Devonian carbonate facies and microfacies

In the Ardennes, the Eifelian in the southern Dinant basin is characterised by a carbonate ramp setting. This evolved into a carbonate shelf in the late Eifelian and this continued through Givetian into Frasnian times. Six common ramp facies can be distinguished (Table 2): from the outer ramp - R1) bioturbated wackestones, commonly argillaceous, and R2) bioclastic packstones; from the mid-ramp - R3) stromatoporoid floatstones with high faunal diversity and R4) oolitic, peloidal, bioclastic grainstones, both commonly with indications of storm activity; and from the inner ramp - R5) gastropod-bivalve wackestones, R6) leperditicopid ostracode packstones from highly restricted environments, see Casier et al., 1992, and R7) laminated dolomudstones. The occurrence of these facies on a

| Microfacies | Carbonate ramp microfacies summary | Approximate water depth |
|---|---|---|
| R1 | Bioturbated wackestones. Well preserved open-marine faunas, below storm wave-base. | ~>10-30 m |
| R2 | Bioclastic packstones. Reworked, broken-up fauna, deposited between storm wave-base and fair-weather wave-base. | ~ 5-20 m |
| R3 | Stromatoporoid floatstones. Reworked, broken-up fauna, between storm wave-base and fair-weather wave-base | ~ 5-20 m |
| R4 | Oolitic-peloidal-bioclastic grainstones. Oolitic banks, shallow waters | < 5 m |
| R5 | Gastropod-bivalve wackestones. Well-preserved fauna, restricted circulation, subtidal, bioturbated. | ?< 5 m |
| R6 | Leperditicopid ostracode packstones. Highly restricted assemblages, low-energy, rare storm beds. | shallow subtidal |
| R7 | Laminated dolomudstones. | intertidal to supratidal |

| Microfacies | Shelf interior microfacies summary | Approximate water depth |
|---|---|---|
| S1 | Intraformational breccias. | ? 1-3 m |
| S2 | Stromatoporoid floatstones. Bulbous stromatoporoids, low-energy | ≤ 3 m |
| S3 | Bioclastic wackestones to grainstones. Stachyodes- or Stringocephalus-rich facies, storm derived. | ? 1-10 m |
| S4 | Amphipora floatstones. low-energy, restricted circulation. Lagoonal. | ~ 1 m |
| S5 | Bioclastic wackestones. Restricted faunas, bioturbated. Lagoonal. | ? ~1 m |
| S6 | Macrofossil-poor mudstones. Rich in dasyclads, vertical fenestrae, oncoids. Low-energy, restricted environment. | ~ 1 m |
| S7 | Peloidal grainstones. Relatively high energy, poorly fossiliferous. | < 1m |
| S8 | Fenestral mudstones to grainstones. | intertidal |
| S9 | Bioclastic grainstones with meniscus and microstalactitic cements. | intertidal to supratidal |
| S10 | Microbial fenestral laminites. | intertidal |
| S11 | Intraformational breccias. Reworking of desiccation cracks. | high intertidal to supratidal |
| S12 | Laminites and stromatolites. Cyanobacteria, mud cracks. | high intertidal to supratidal |
| S13 | Unfossiliferous dolomudstones. Pseudomorphs of evaporite minerals. | supratidal |
| S14 | Calcrete. | supratidal to subaerial |

**Tables 2A, 2B**: Microfacies of the Devonian carbonate ramp and shelf interior limestones in Belgium.

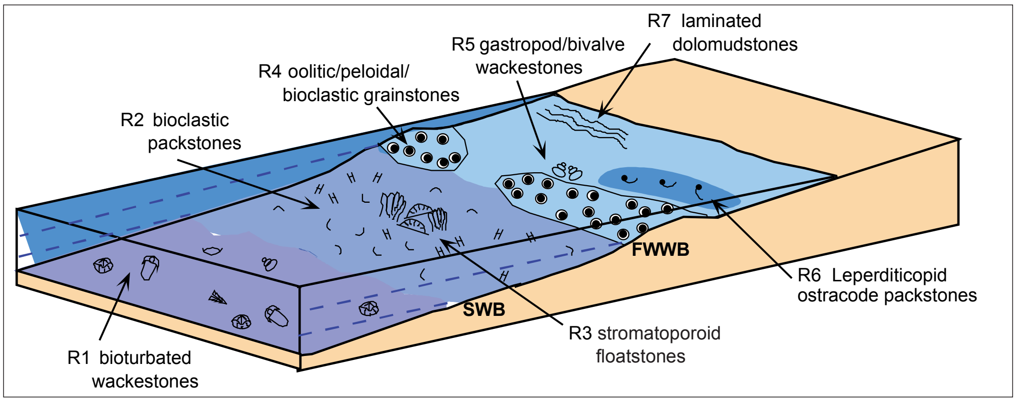


**Figure 5.** Palaeoenvironmental reconstruction of the early Middle Devonian ramp setting in northern France, southern Belgium and western Germany, showing the likely depositional environments of the 7 major microfacies recognised. SWB = storm wave-base; FWWB – fair-weather wave-base.

carbonate ramp model is shown in Fig. 5.

In the carbonate shelf interior, 14 major microfacies can be distinguished landward of the shelf margin (see Table 2), and these can be broadly categorised into four major groups. The semi-restricted subtidal microfacies group (group 1, S1-S3) has a rich faunal assemblage which, although diverse, did not represent fully open-marine deposition. Sedimentation was entirely subtidal in nature. The restricted subtidal microfacies group (2, S4-S7) is either characterised by monospecific fossil assemblages (chiefly molluscs, amphiporoids or leperditicopid ostracods if highly restricted), or by macrofossil-poor facies. These facies represent poorly-circulated, subtidal environments which may have been subjected to fluctuating salinities. The intertidal microfacies group (3, S8-S10) is characterised by fenestral limestones, locally microbialitic, which are commonly poorly fossiliferous. Finally the high intertidal-supratidal

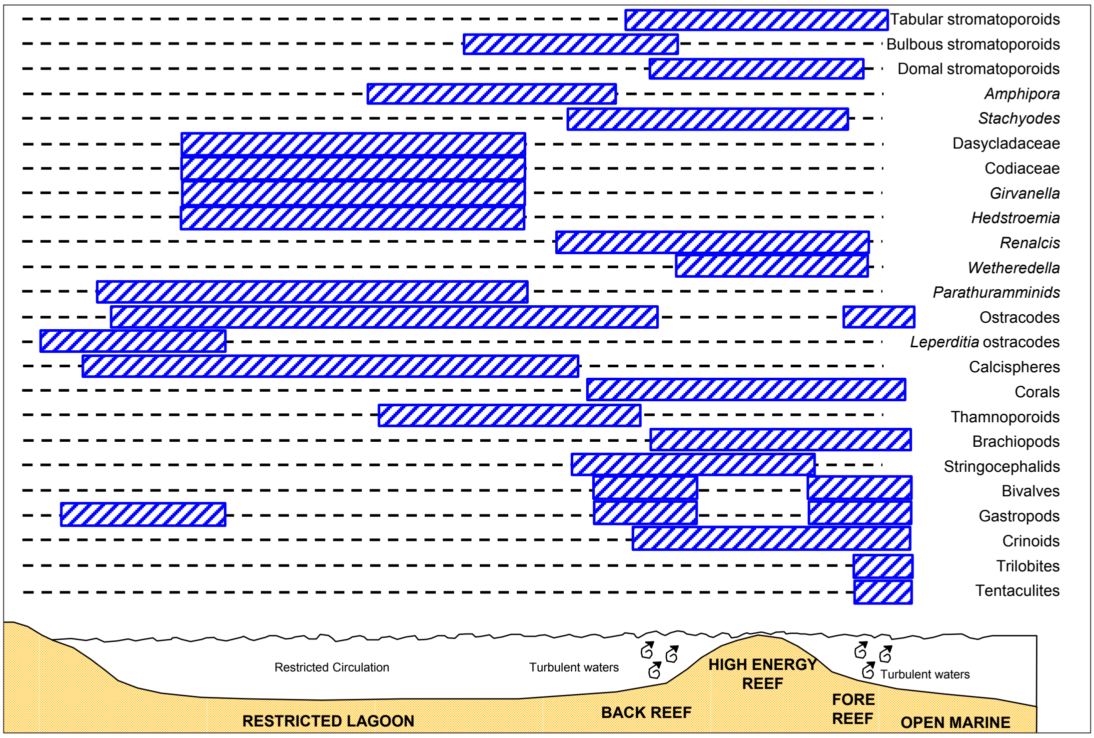


**Figure 6.** Palaeoecological reconstruction of the Middle and Upper Devonian back-reef and lagoonal environments of western Europe.

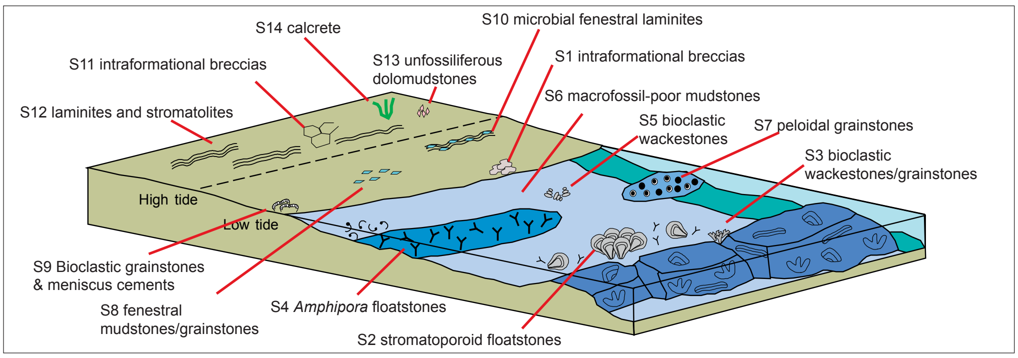


**Figure 7.** Palaeoenvironmental reconstruction of the Middle Devonian shelf lagoon showing the likely depositional environments of the 14 microfacies identified.

microfacies group (4, S11-S14) is typified by dolomudstones, microbial laminites, intraclast breccias and calcretes.

Fossils are abundant in many of the microfacies and these show a variable distribution across the shelf depending the environmental factors controlling their development (Fig. 6). The location of these lagoonal facies on a carbonate shelf model is shown in Fig. 7. Note that detailed examination of the shelf-margin reefs and basinal facies was not part of the present study.

## 7. Cyclicity in the Devonian of Belgium

Cyclicity is well developed in the Devonian of Belgium and some is of the classic shallowing-up to emergence type, overlain by a flooding surface to denote the beginning of the next cycle and conforming to the original definition of parasequence. However, in some dominantly subtidal parts of the succession, the strict definition of cycle is difficult to apply since clear flooding surfaces are not obvious and the interpretation of depth of deposition of the facies is often equivocal; however, various facies are present which show clear differences in terms of biota and texture, and these are a reflection of the varying degrees of restriction of the shelf-lagoon environment. For these subtidal sediments, cycle boundaries are taken where a quite restricted facies is overlain by a more open-water, less-restricted facies. Increased circulation in the shelf lagoon and deposition of more open-marine facies probably reflects an increase in accommodation space and deeper water, but not necessarily so; it could reflect a time of less effective shelf-margin barrier. Using these principles of microfacies successions and boundaries,

| Cycle-type | Characteristics | Occurrence |
|---|---|---|
| A1 | Cycles have semi-restricted subtidal bases and restricted subtidal tops. They show a decrease in circulation-, decrease in diversity of organisms and increase in salinity upwards through the cycle. Cycles are both symmetrical and asymmetrical.<br>Cycle thickness from less than 0.5m to 6.5m; average 1.9m. | Common throughout the Givetian and Frasnian successions. Particularly abundant in the 'lower unit' of the Trois Fontaines Formation (lower Givetian) and in the upper Givetian Fromelennes Formation. |
| A2 | Cyclicity within the restricted subtidal facies. These cycles show a decrease in diversity upwards through the cycle, synonymous with a ?decrease in salinity. Cycles are mostly asymmetric (regressive).<br>Cycle thickness from 0.2m to over 7m; average 1.9m. | Common throughout the Givetian and Frasnian, but especially in the upper Givetian Fromelennes Formation and the middle Givetian of the Eifel area (Keldenich). |
| A3 | Cyclicity within the semi-restricted subtidal facies. These cycles show an increase in energy and decrease in diversity of organisms upwards through the cycle. Cycles are regressive. The cycle is 5.4m thick. | Only seen in one horizon in the lower Givetian of Olloy-sur-Viroin. |
| B1 | Cycles which shallow from a semi-restricted subtidal base to an intertidal cap. Shallowing is accompanied by a decrease in diversity of organisms and increase in fluctuating salinity. Cycles are both transgressive-regressive, and regressive.<br>Cycle thickness from 0.3m to 5.7m; average 2.5m. | Not very common cycle-type. Distributed through all time periods. |
| B2 | Cycles which show shallowing from restricted subtidal facies to intertidal facies. Shallowing is accompanied by a decrease in diversity of organisms and increase in fluctuating salinity. Cycles are mainly regressive, without any transgressive component.<br>Cycle thickness from 0.1m to 6.2m; average 2.1m. | Common cycle-type. Seen mostly in the lower Givetian at Resteigne, Froidlieu Keldenich and at Teerstraßenbau |
| B3 | 'Complete cycles' which fully shallow from a semi-restricted subtidal base through to a supratidal cap. Shallowing is accompanied by a decrease in diversity of organisms and increase in fluctuating salinity. Cycles are regressive (asymmetrical).<br>Cycle thickness from 0.2m to over 9m; average 2.1m. | Common throughout the Givetian and Frasnian shelf successions. |
| B4 | Cycles which shallow from subtidal restricted facies to supratidal facies. Shallowing is accompanied by a decrease in diversity of organisms and increase in fluctuating salinity. Cycles are mostly asymmetric.<br>Cycle thickness from 0.2m to 4.7m; average of 1.2m. | The most common B-type cycle, occurring at all stratigraphic levels in the Ardennes, Aachen and Eifel areas. |
| B5 | Cyclicity within the intertidal to supratidal zone. Cycles are asymmetric (regressive).<br>Cycle thickness is 0.2m. | Only seen in one horizon at upper Givetian Walheim Southern Limb Section. |
| C1 | Cycles which shallow from outer to inner ramp facies. Cycles are regressive, being asymmetrical.<br>Cycle thickness from 0.2m to over 10m; average 2.8m. | Identified in all ramp successions. Most common C-type cycle. |
| C2 | Cycles which shallow from outer to inner ramp. Cycles show an increase in spar matrix, and increase in abrasion. Cycles are asymmetric.<br>Cycle thickness from 0.4m to 5.4m; average 2.5m. | Identified both in the lower Givetian successions at Glageon and Bellignies-Bettrechies. |
| C3 | Cycles which shallow from open marine ramp to restricted ramp facies. Cycles show a decrease in diversity of organisms, and increase in lime-mud. Cycles are asymmetric.<br>Cycle thickness from 0.2m to 7.4m; average 2.5m. | This cycle-type is most prominent in the lower Givetian ramp succession at Bellignies-Bettrechies. |

**Table 3**: Cycle-types in the Eifelian, Givetian and Frasnian strata of the Ardennes-Aachen-Eifel area, NE France, southern Belgium and western Germany.

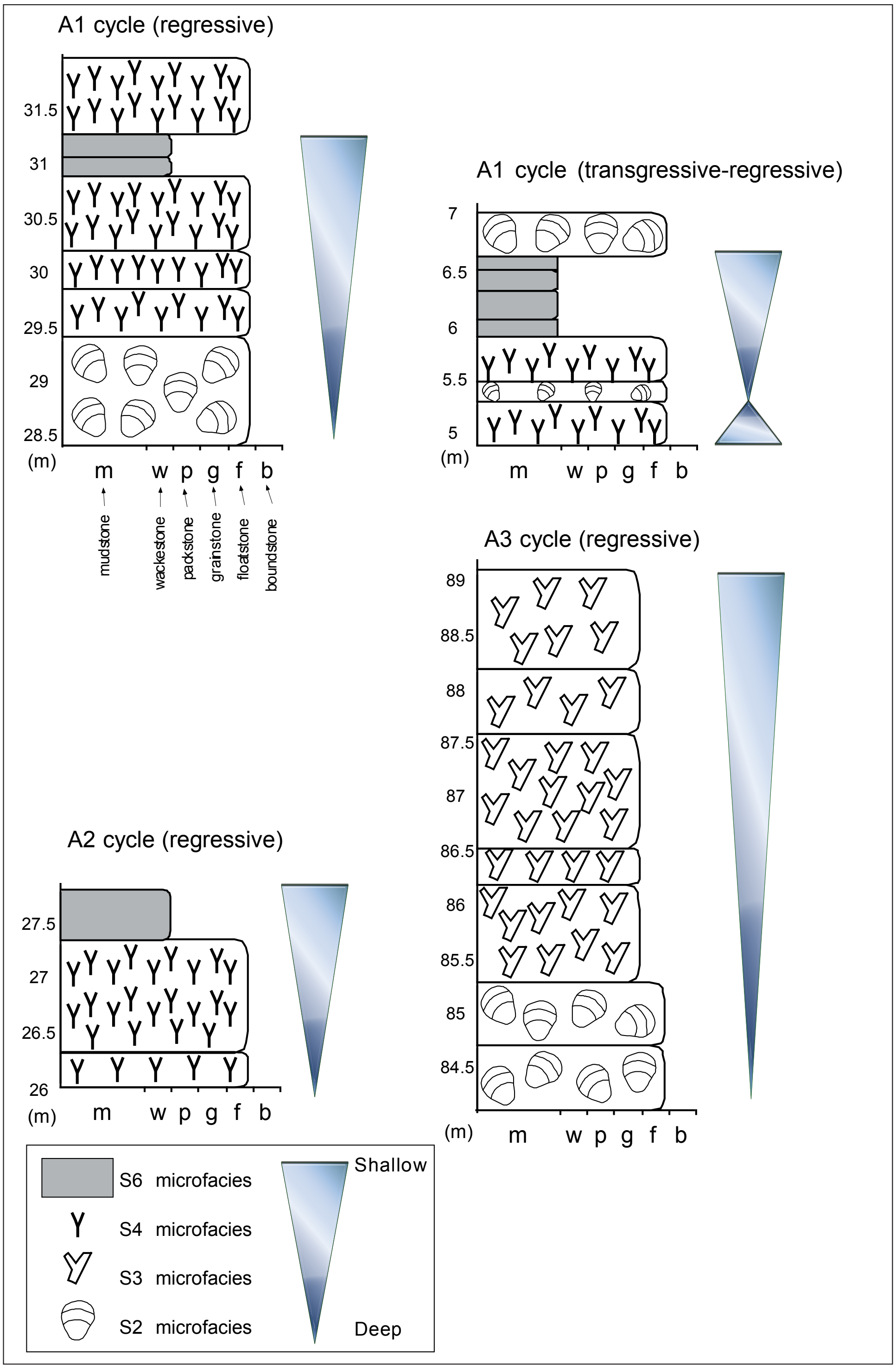


**Figure 8.**
Schematic representations of type-A cycles.

cycles can be designated as either transgressive-regressive, or wholly regressive, and these would have depended upon the rate of accommodation space increase and/or the ability of carbonate production to keep up with that. The longer-term (lower order) relative sea-level history also had a substantial influence on cycle type.

### *7.1. Cycle types in the Devonian of Belgium*

Three major categories of cycle type can be recognised with various subtypes (see Table 3):

a) Type A cycles (e.g. Fig. 8) - wholly subtidal cycles showing evidence of upward decrease in circulation / increase in restriction of the environment, in the form of a decrease in diversity of the biota, occurring in shelf-lagoon successions.

b) Type B cycles (e.g. Fig. 9) - shallowing-upward cycles with a decrease in diversity of organisms and evidence of exposure, occurring in shelf-lagoon successions.

c) Type C cycles (e.g. Fig. 10) - cycles generally with a shallowing-upward trend, an upward increase in fossils and bioclastic debris, and decrease in lime mud, occurring in carbonate-ramp sections.

There are two common types of cycle A: type A1 with semi-restricted facies, commonly stromatoporoid

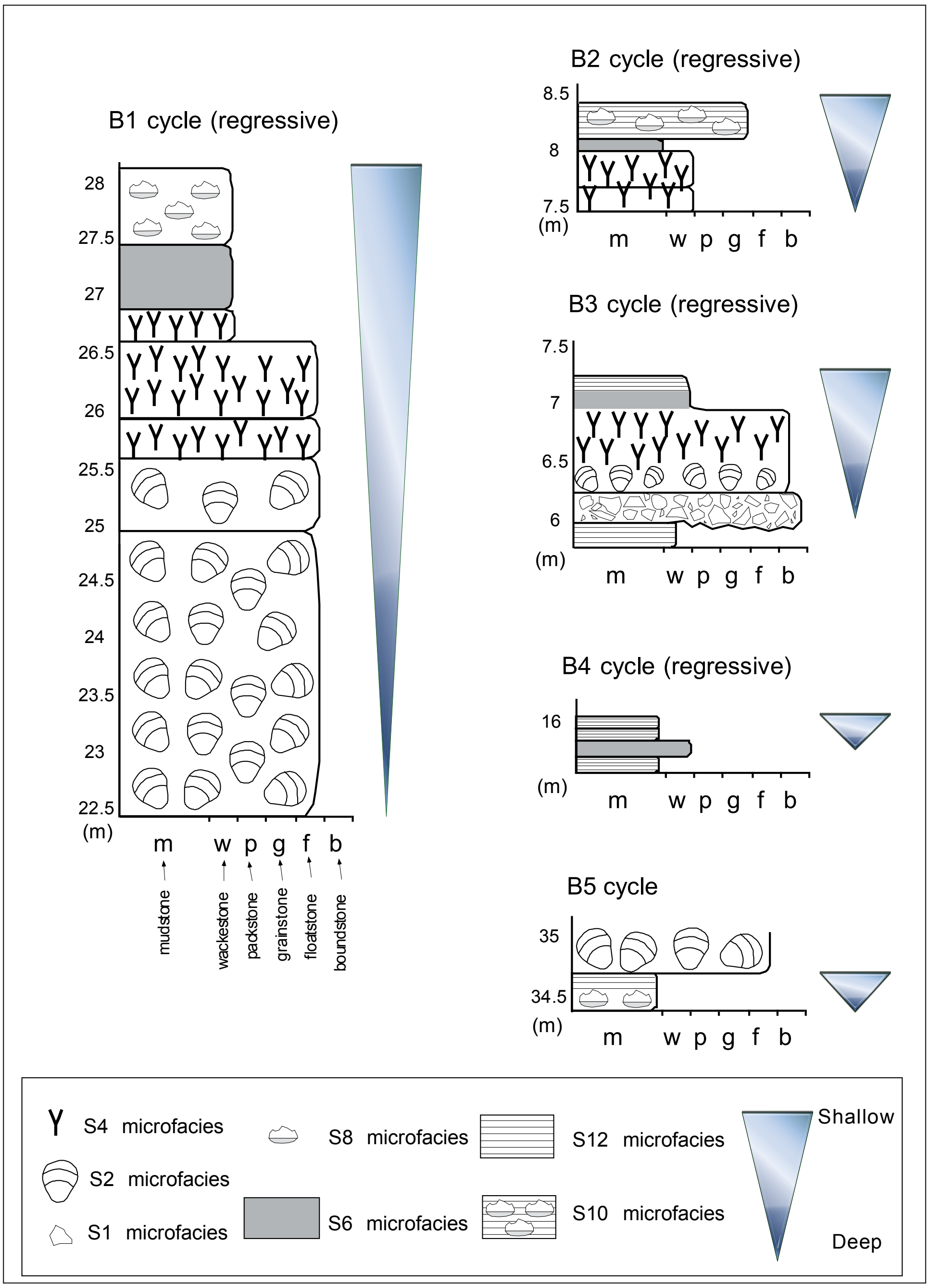


**Figure 9.**
Schematic representations of type-B cycles.

floatstone, succeeded by more restricted facies (especially *Amphipora*-rich floatstone-mudstone) then fossil-poor mudstone; and type A2 with more restricted facies (e.g. *Amphipora*-rich mudstone) succeeded by fossil-poor mudstone (Fig. 8). These increasing restriction-upward cycles are broadly regressive in nature but the cycles did not aggrade or prograde into intertidal-supratidal facies. In this sense they are similar to keep-up cycles of Soreghan & Dickinson (1994). The facies variations reflect a progressive restriction of the shelf lagoon, with decreasing circulation and fluctuating salinities. Some of these cycles are symmetrical, i.e. transgressive-regressive, with a basal fossil-poor mudstone below the floatstone. A total of 124 A1-type cycles and 81 A2-type cycles (both average thickness 1.9 m) were recorded in Givetian-Frasnian strata. A third type of subtidal cycle (A3), only seen in one locality, occurs in the semi-restricted facies, is regressive, and shows an increase in energy but decrease in diversity of organisms upwards through the cycle. The various permutations of facies succession in the type-A cycles are shown in Table 4.

Type B cycles typically shallow-up from semi-restricted (type B1) or restricted (type B2) facies (Fig. 9), through fossil-poor mudstones to intertidal fenestral carbonates. Some type B cycles (type B3, Fig. 11) show a complete shallowing up to a high intertidal-supratidal microbial laminite or dolomudstone. Yet another type (B4) is thinner (average 1.3 m) and begins with fossil-poor mudstone which is capped by microbial laminite, dolomudstone and/or calcrete. Rarely, a transgressive lag or clear erosional surface is present at the base of these cycles. A rare fifth type (B5) shows intertidal facies passing up into supratidal facies. Type B cycles are mostly regressive, likely formed by tidal-flat progradation, but

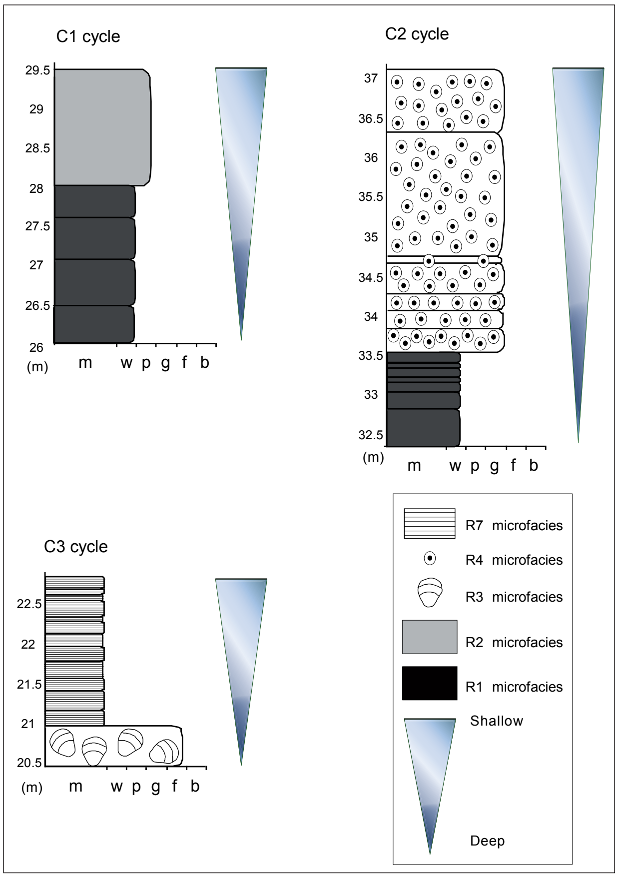


**Figure 10**. Schematic representations of type-C cycles.

transgressive-regressive B-type cycles are not uncommon too, with restricted or fossil-poor facies in the basal part before the semi-restricted facies. These type B cycles would be the equivalent to the catch-up cycles of Soreghan & Dickinson (1994), in which sedimentation initially lags behind the creation of accommodation space, but progressively overtakes sea level at highstand.

Rarely with these shallowing-upward type B cycles, the intertidal facies rests directly on the semi-restricted stromatoporoid floatstone. Where a facies belt is omitted (here no restricted facies) then a forced regression is indicated; this would typify the catch-down (truncated) cycles of Soreghan & Dickinson (1994). With only 22 examples recorded, type B1 cycles (average thickness 2.5 m) are not as common as type B2 (44 cycles, average thickness 2.1 m) and type B3 (41 cycles, average thickness 2.1 m). The various permutations of facies succession in the type-B cycles are shown in Table 5.

The most common cycle-type (C1, Fig. 10) in the Eifelian-Givetian ramp successions are mostly regressive (rarely transgressive-regressive) and shallow up from outer-ramp (bioturbated mudstone) to mid-ramp (storm-influenced bioclastic packstones or high-diversity stromatoporoid floatstones) facies.

Average thickness is 2.8 m. They show evidence for shallowing only up to fair-weather wave-base. Other, quite rare, ramp cycles are argillaceous mudstones passing up to inner-ramp oolitic grainstones (also terminating at FWWB; type C2), and open-marine facies passing up to

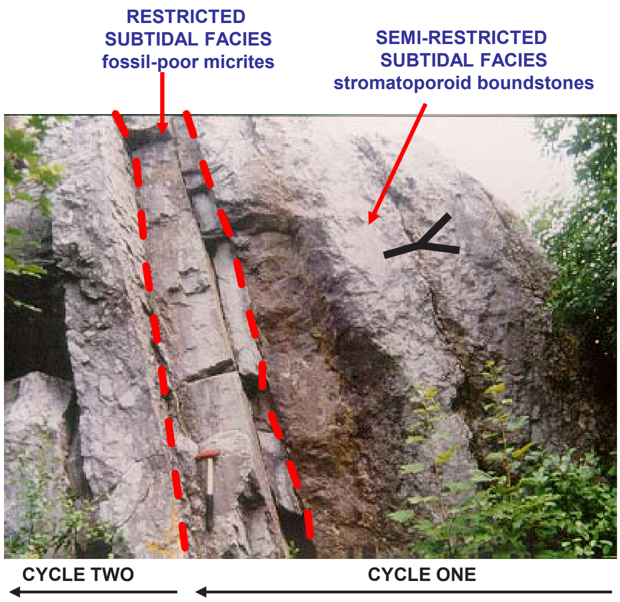


**Figure 11.** Cycles of type B3 with semi-restricted subtidal base, followed by restricted subtidal horizon. Walheim Section 1, Aachen, Germany. Hammer 42 cm long.

| A1 cycle, facies permutations (base ⇨ top of cycle) | | A2 cycle, facies permutations (base ⇨ top of cycle) | A3, cycle facies permutations (base ⇨ top of cycle) |
|---|---|---|---|
| S2-S4 | S4-S2-S6 | S4-S5 | S2-S3 |
| S2-S5 | S4-S3-S4 | S4-S6 | S3-S2-S3 |
| S2-S6 | S4-S2-S6 | S4-S7 | |
| S2-S7 | S6-S2-S6 | S5-S6 | |
| S3-S4 | S6-S3-S6 | S5-S7 | |
| S3-S5 | S3-S2-S3-S4 | S6-S7 | |
| S3-S6 | S4-S2-S4-S6 | S4-S5-S6 | |
| S2-S3-S4 | S4-S2-S4-S7 | S4-S6-S7 | |
| S2-S4-S6 | S5-S4-S3-S6 | S5-S4-S6 | |
| S2-S4-S7 | S6-S2-S6-S7 | S5-S6-S7 | |
| S2-S5-S6 | S6-S4-S2-S4 | S6-S4-S6 | |
| S2-S6-S7 | S6-S4-S2-S6 | S6-S4-S7 | |
| S3-S2-S4 | S6-S4-S2-S7 | S6-S5-S6 | |
| S3-S2-S6 | S4-S3-S2-S3-S7 | S6-S4-S6-S7 | |
| S3-S6-S3 | S6-S4-S2-S6-S7 | S6-S4-S5-S6 | |
| S4-S2-S4 | | S6-S5-S4-S6 | |

**Table 4**: Microfacies permutations in type-A cycles, which are either transgressive-regressive or wholly regressive in character.

| B1 cycle, facies permutations (base ⇨ top of cycle) | B2 cycle, facies permutations (base ⇨ top of cycle) | B3 cycle, facies permutations (base ⇨ top of cycle) | B4 cycle, facies permutations (base ⇨ top of cycle) | B5 cycle, facies permutations (base ⇨ top of cycle) |
|---|---|---|---|---|
| S2-S8 | S4-S8 | S2-S12 | S4-S12 | S8-S11-S12 |
| S3-S8 | S6-S8 | S3-S12 | S5-S13 | |
| S2-S4-S8 | S6-S10 | S2-S6-S12 | S6-S11 | |
| S2-S6-S8 | S7-S8 | S2-S8-S11 | S6-S12 | |
| S2-S6-S10 | S7-S10 | S2-S8-S12 | S6-S14 | |
| S3-S5-S8 | S4-S6-S8 | S2-S10-S11 | S4-S6-S12 | |
| S4-S2-S8 | S4-S6-S10 | S3-S6-S12 | S6-S4-S12 | |
| S6-S2-S8 | S4-S8-S10 | S4-S2-S12 | S6-S7-S12 | |
| S1-S2-S3-S9 | S5-S6-S8 | S6-S2-S12 | S6-S7-S14 | |
| S2-S3-S8-S10 | S5-S6-S10 | S6-S2-S13 | S6-S8-S12 | |
| S2-S4-S6-S8 | S6-S4-S8 | S2-S4-S6-S12 | S8-S6-S12 | |
| S4-S2-S4-S8 | S7-S6-S8 | S2-S4-S6-S13 | S12-S4-S12 | |
| S4-S2-S6-S8 | S8-S4-S8 | S2-S6-S7-S12 | S4-S5-S8-S13 | |
| S8-S4-S2-S8 | S8-S6-S8 | S2-S6-S8-S11 | S5-S4-S6-S12 | |
| | S4-S5-S6-S8 | S2-S6-S11-S12 | S6-S4-S6-S12 | |
| | S6-S4-S6-S8 | S4-S3-S6-S12 | S6-S8-S10-S12 | |
| | S6-S5-S6-S8 | S6-S2-S6-S12 | S8-S4-S6-S12 | |
| | S6-S4-S7-S10 | S6-S3-S6-S12 | S6-S4-S5-S6-S8-S11 | |
| | | S1-S2-S4-S6-S12 | S6-S10-S12-S11-S12 | |
| | | S6-S3-S4-S6-S8-S12 | | |

**Table 5:** Microfacies permutations in type-B cycles.

restricted ramp facies (type C3). The various permutations of facies succession in the type-C cycles are shown in Table 6.

### *7.2. Cyclicity in the Eifelian successions*

Type C1 cycles are most common in the upper Eifelian ramp succession (Hanonent Formation), as seen in Glageon quarry for example. The succession is characterised mainly by regressive, outer to mid-ramp facies cycles, with shallowing into the inner ramp environment, represented by oolite banks and C2-type cycles, only occurring in a few cases. Average cycle thickness for the upper Eifelian is 3.5 m (range 1-7 m), somewhat thicker than those in the younger lagoonal sediments. The thickness plot for the upper Eifelian shows a subdued cycle-thinning followed by a more pronounced pattern of cycle-thickening (Fig. 12). Broadly, the shallowest facies (i.e., the oolitic grainstone) occurs just before the development of the thicker cycles. The overall pattern would indicate a long-term regression followed by a transgression. This plot mimics those of Kasimi & Préat (1996) for other upper Eifelian successions in France and Belgium, suggesting regional or eustatic rather than local mechanisms were causing these depositional trends.

Ramp cycles in the Eifelian rarely show full regression into intertidal environments. The cycles build up to either storm wave-base or fair-weather wave-base. An explanation for this may be that the pulses of relative sea-level fluctuation may have been of short duration such that sediments were unable to build up to sea level before the next deepening event. Alternatively, and more likely, sediments were unable to aggrade to intertidal facies because turbulent high-energy waters above fair-weather wave-base were constantly reworking and re-depositing sediments to other environments (offshore to the mid-ramp or onshore to the shoreline), such that this depositional environment, the shoreface, did not actually record sedimentation. Thus, wave-base here effectively controlled cyclicity.

### *7.3. Cyclicity in the Givetian of the Ardennes-Aachen-Eifel area*

#### *7.3.1 Cyclicity in Lower Givetian strata*

Six successions in lower Givetian strata (Trois Fontaines and Terres d'Haurs Formations) were examined in the Ardennes (at Glageon, Resteigne, Olloy-sur-Viroin, Froidlieu, Vaucelles and Bellignies-Bettrechies) and one in the Eifel (Kelderich) (Fig. 3). The strata can be informally divided into two parts: a lower unit denoted by a lack of laminite horizons, and an upper unit characterised by the development of several laminite horizons. The cycle-types seen in the lower Givetian were not only

| C1 cycle, facies permutations (base ⇨ top of cycle) | C2 cycle, facies permutations (base ⇨ top of cycle) | C3, cycle facies permutations (base ⇨ top of cycle) | |
|---|---|---|---|
| R1-R2 | R1-R4 | R1-R7 | R1-R4-R7 |
| R1-R3 | R5-R1-R4 | R3-R7 | R2-R1-R6 |
| R1-R2-R3 | | R4-R6 | R3-R4-R6 |
| R2-R1-R2 | | R5-R6 | R6-R5-R7 |
| R2-R1-R3 | | R5-R7 | R1-R2-R4-R7 |
| | | R6-R7 | R5-R3-R2-R7 |

**Table 6:** Microfacies permutations in type-C cycles.

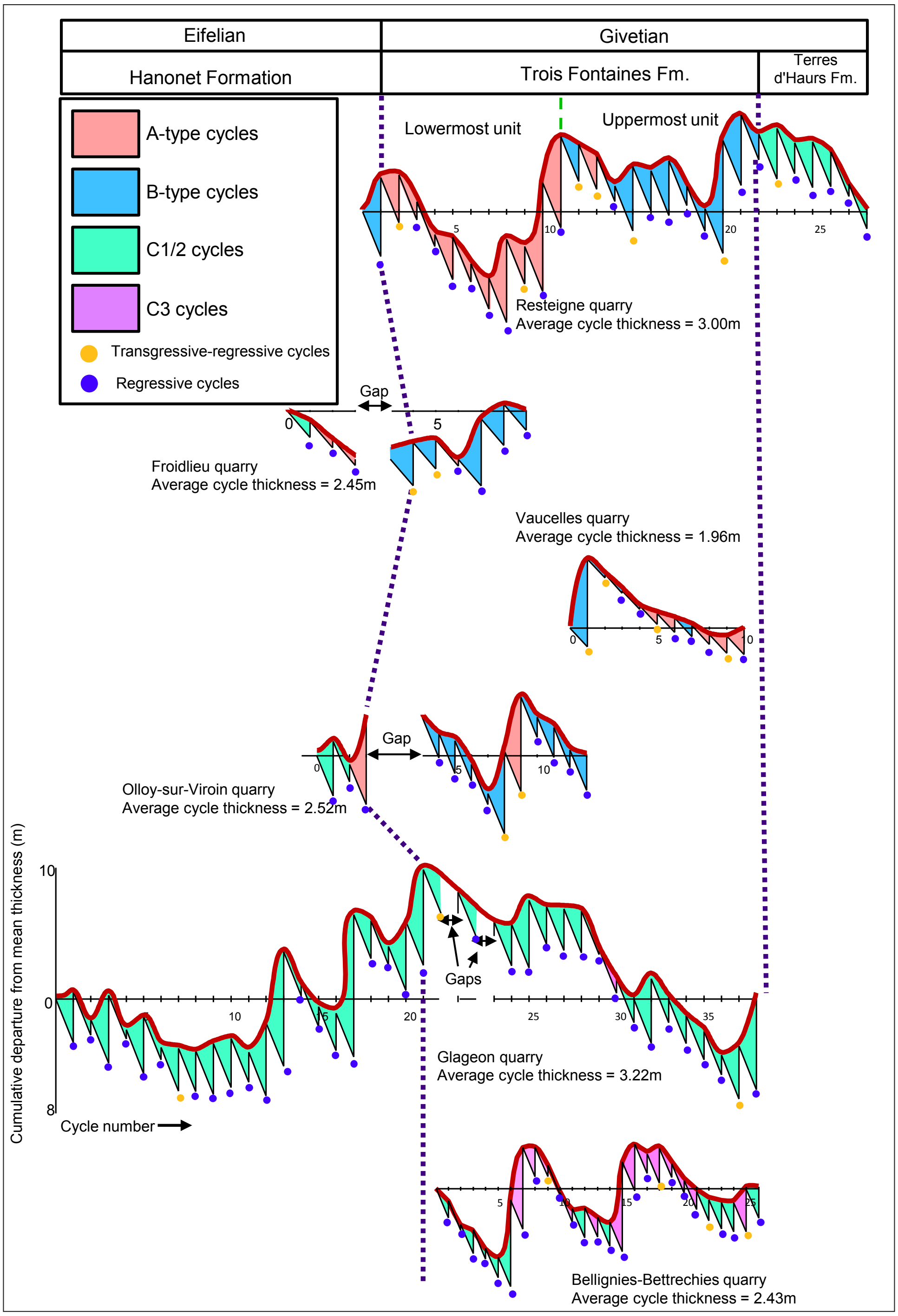


**Figure 12.** Fischer plots for the upper Eifelian and lower Givetian successions in the Belgian and French Ardennes.

influenced by these long-term styles of sedimentation (as a result of longer-term trends in accommodation space), but also by the location of outcrops relative to individual tilted fault-blocks several km in width within the shelf area (Préat, 1984; Préat & Weis, 1994)(see Fig. 13).

Figure 12 presents a correlation panel for Fischer plots of the lower Givetian succession. It can be seen that although individual cycles may not be traceable from succession to succession, there is a suggestion that trends in cycle thickness are regional and broadly correlatable. There are many cycle-types represented in the lower Givetian. Cycles range from subtidal dominated (type A cycles) to fully regressive cycles with a subtidal base

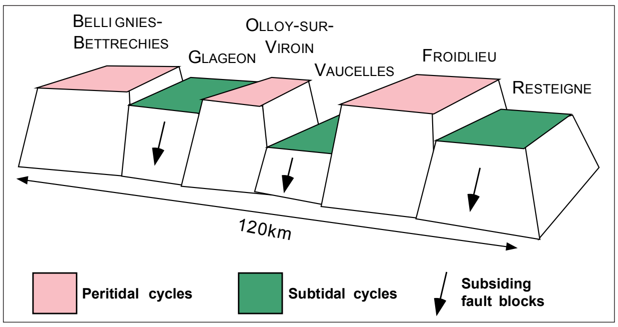


**Figure 13.** Highly simplified and idealised cartoon of relative elevations of fault blocks in the lower Trois Fontaines Formation in the Ardennes. Vertical scale exaggerated.

through to supratidal cap (B3 type cycles). Many cycles, however, are either type A or type B1/B2 where cycles are capped by fenestral horizons rather than supratidal facies. Fully regressive cycles (B3) are rare in the lower Givetian. Trends in cycle-type are somewhat difficult to pick out since the cycle-type depends not only on the ability of carbonate production to pace any change in relative sea level, but also on the subsidence or consequent uplift of the respective fault blocks. For example the lowermost part of the lower Givetian sees a negative slope followed by a positive slope on the Fischer plot, a trend which can be seen in all successions. However, the cycle-types are different in each succession. For example, at Resteigne quarry the lowermost part of the Trois Fontaines Formation is dominated by low-energy subtidal deposition (and consequently type A cycles), yet at Froidlieu and Olloy-sur-Viroin types B1 and B2 cycles are present, as cycles shallow into the intertidal zone. This would suggest that the Resteigne area was a more rapidly subsiding fault block during the lowermost Givetian, whereas the Froidlieu and Olloy-sur-Viroin blocks were relatively higher / less subsident (Fig. 13).

Farther to the west, where an elongate barrier reef did not develop, the carbonate platform still had a ramp geometry. A similar trend can be seen in the Fischer plots, of an initial negative slope (indicating decreasing accommodation space) followed by a positive slope (thicker cycles, increasing accommodation space). Naturally, facies and hence cyclicity differ from that seen in the shelf successions. Yet, it is suggested that Glageon quarry was situated on a subsiding fault block since sedimentation was entirely open-marine in nature (cycle-types C1 and C2); whereas the Bellignies-Bettrechies area (50 km to the northwest) was situated on a palaeo-high or nearer to the shoreline, since restricted and even intertidal facies are recorded (and consequently C3 cycle types).

There is a suggestion that in some cases the relative subsidence of the fault blocks comprising the Givetian shelf is recorded in the average cycle thickness. For the lowermost Givetian at Resteigne quarry the average is 3.3 m, an area of supposedly greater subsidence, whereas the cycles at Bellignies-Bettrechies, a less subsident area, average 2.3 m.

In the lower Trois Fontaines Formation, cycles are both transgressive-regressive and wholly regressive in nature (Fig. 12). Regressive cycles are most common, and are distributed mostly on the falling limbs (negative slopes) of the Fischer plots. The rare cycles which do show transgressive deposits at the base of the cycle (i.e. initial and maximum flooding surfaces can be differentiated) tend to be distributed on the rising limbs of the Fischer plots, for example at Resteigne and Olloy-sur-Viroin successions. This would suggest that transgressive facies were only recorded during the small-scale deepening events when accommodation space was at its maximum (i.e., where there are thicker cycles), and thus this indicates that the rises in relative sea level were magnified during these times.

The uppermost part of the Trois Fontaines Formation, in both shelf (Resteigne) and ramp situations (Glageon and Bellignies-Bettrechies sections) shows two thinning-thickening cycle packages (parasequence sets) which are superimposed upon a longer-term negative slope (Fig. 12). It is during this package of sediments that evidence for periodic emergence into the supratidal zone is recorded by the presence of several laminite horizons. At Resteigne quarry, cycle-types B2, B3 and B4 dominate the upper Trois Fontaines Formation. Cycle thickness is extremely variable, with some B3-type cycles reaching 7.5 m thick. This would suggest that the carbonate production rate was only slowly outpacing creation of accommodation space, so that thick, 'facies complete' (*sensu* Soreghan and Dickinson, 1994) cycles developed.

A similar Fischer plot trend can be seen both at Glageon and Bellignies-Bettrechies quarries. Sedimentation remained open-marine in the Glageon quarry section, and hence cycle-type is either C1 or C2. However, there was emergence into the intertidal zone at one stage in Glageon's depositional history (cycle number 30; see Fig. 12), which is recorded as a type C3 cycle. Sediments in the Bellignies-Bettrechies quarry become increasingly restricted during the upper Trois Fontaines Formation, where cycles are capped by intertidal or highly restricted subtidal facies and are of type C3.

The succession at Vaucelles quarry (near Givet) records the long-term negative slope in its Fischer plot, yet the superimposed thinning-thickening trends are not apparent. The succession at Vaucelles is likely to be condensed, since cycle thickness is substantially thinner than in other successions (1.96 m average) and the overall succession is thinner. Both subtidal-dominated cycles (type A) and cycles with a supratidal cap (type B3 and B4) are recorded, with type A cycles more common towards the top of the succession (Fig. 12). The fault block upon which Vaucelles was located was likely to have been relatively elevated during the initial parts of the middle Trois Fontaines Formation, so that accommodation space was reduced and relative sea level was low. However, during the latest middle Trois Fontaines times subsidence of the fault block may have played a more important role so that subtidal sedimentation was the norm.

For the upper part of the Trois Fontaines Formation, cycles are mostly regressive. Transgressive-regressive cycles are present, locally occurring in a regular pattern where two to four regressive cycles are followed by one transgressive-regressive cycle (see for example Resteigne and Vaucelles succession, Fig. 12). This pattern is not seen basin-wide, however. Cycles which have a transgressive base commonly form when the rate of creation of accommodation space is slow, and therefore carbonate production is able to pace the deepening event. The distribution of these transgressive deposits may therefore be related to the long-term accommodation potential of the system and hence long-term relative sea-level fluctuations.

It is interesting to point out that the classic relationship between sediment type and cycle thickness trend (i.e., negative slopes of the Fischer plots showing increasing proportions of intertidal-supratidal cycles, positive slopes showing increased proportions of subtidal cycles) is not seen in the lower Givetian strata. Progradational, regressive (thinning-upwards) stacking patterns can be dominated by both subtidal cycles and peritidal cycles, as can retrogradational, transgressive (thickening-upwards) stacking patterns (Fig. 12). This may suggest that the longer-term trend in the Fischer plot does not truly represent lower order eustatic sea-level fluctuations, and that there must have been local interference by tectonic movement or autocyclic processes. Cycle thickness for the lower Givetian averages 2.7 m, substantially thicker than that recorded in the upper Givetian Fromelennes Formation (see below), suggesting some change in the controlling parameters.

*7.3.2 Cyclicity in the upper Givetian succession*

Upper Givetian successions outcrop at Sourd d'Ave, Beauraing, Cul de Houille, Dourbes and Nismes in the Belgian Ardennes and also at Walheim, Teerstraßenbau, Venwegen and Alt Breinig in the Aachen region of Germany (see Fig. 3). The upper Givetian Fromelennes Formation can be divided into three members in the

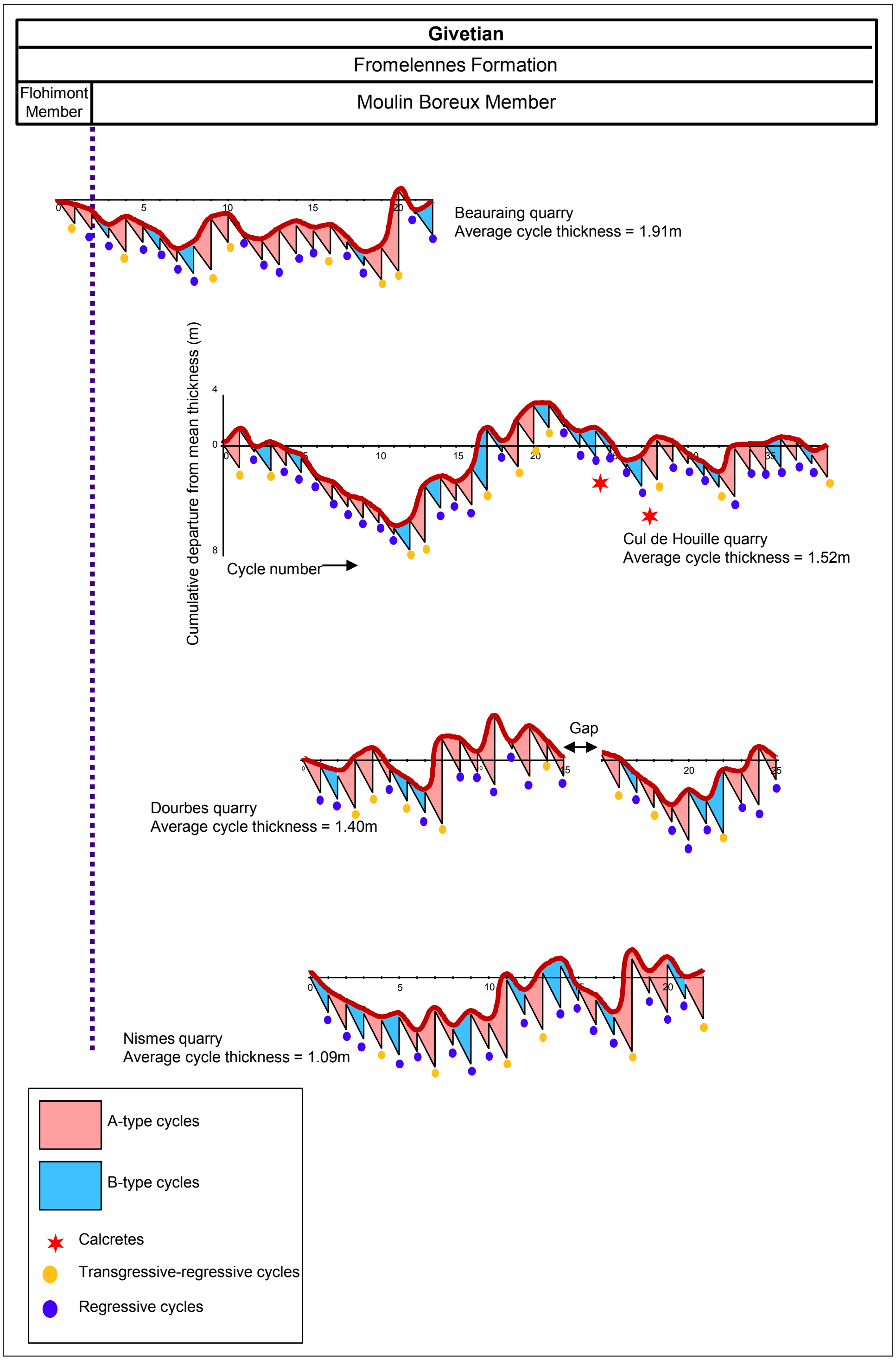


**Figure 14.** Correlation of Fischer plots for the lower and middle Fromelennes Formation in the Ardennes.

Ardennes area, of which Beauraing exposes the Flohimont Member and Moulin Boreux Member; Cul de Houille, Dourbes and Nismes expose the Moulin Boreux Member, and at Sourd d'Ave the Fort Hulobiet Member crops out. The successions at Aachen broadly correlate with the Fort Hulobiet Member.

A metre-scale cyclicity is pervasive throughout the upper Givetian successions and is commonly very easy to identify in the field. Cyclicity is recorded as both type A and type B cycles, with their distribution not only related to long-term trends in accommodation space, but also to influences of local fault-block movements, as with the lower Givetian. Figure 14 presents a Fischer plot correlation panel for the Flohimont and Moulin Boreux Members of the Fromelennes Formation in the Ardennes. Correlation of individual cycles is difficult; yet, broad correlation of trends in cycle-thickness can be made. The lower part of the Moulin Boreux Member is characterised by a large-scale thinner-than-average cycle package followed by a thicker-than-average cycle package. This can be seen at Beauraing, Cul de Houille, Dourbes and Nismes quarries (Fig. 14). Cycles are of both type A and type B. Type A cycles are the most common, typically having a stromatoporoid floatstone unit at the base and capped by a poorly fossiliferous horizon. Where type B cycles are present, shallowing is often incompletely recorded, as locally supratidal laminite horizons rest directly on semi-restricted biostromal facies (e.g. at Cul

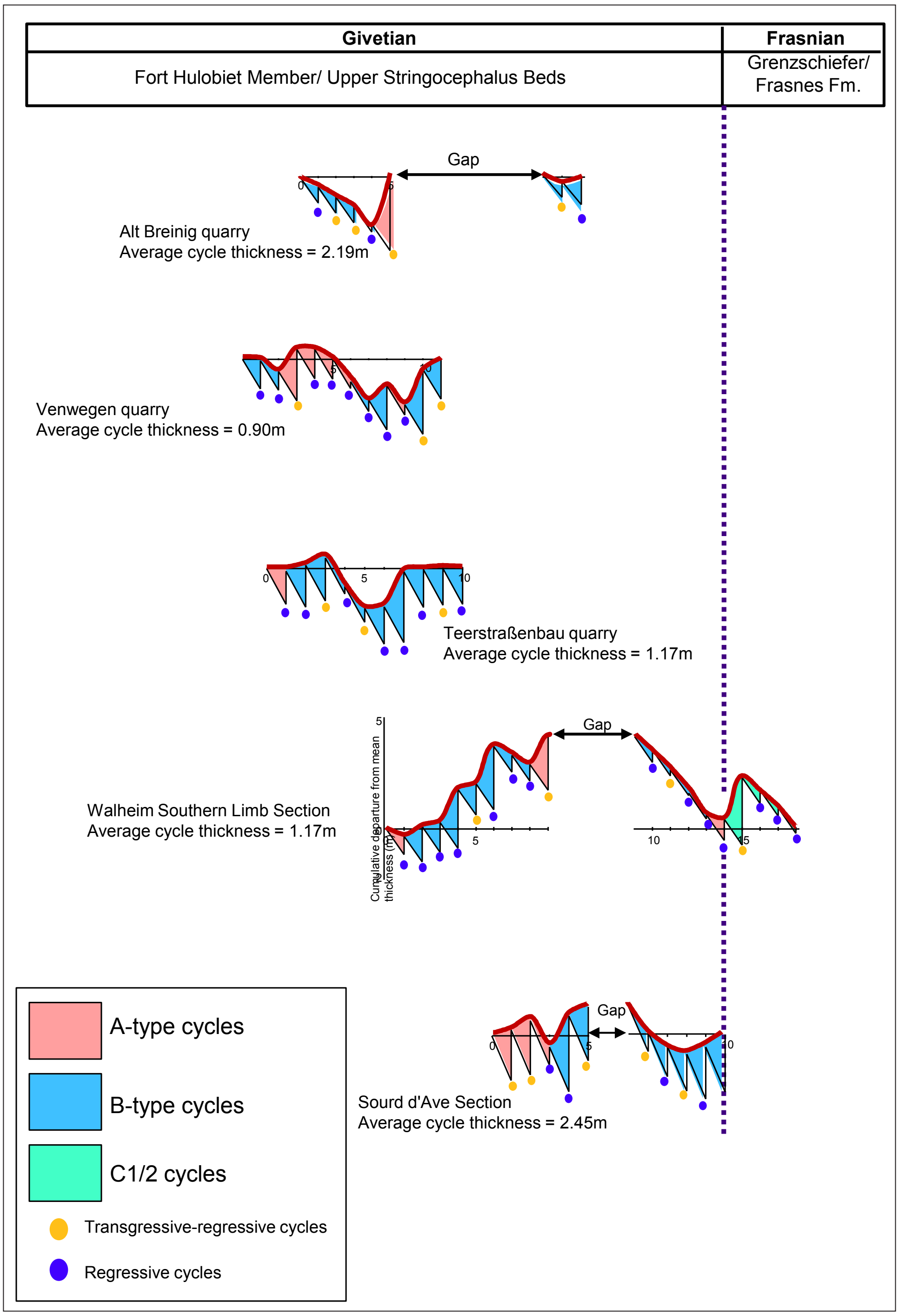


**Figure 15.** Correlation of Fischer plots for the uppermost Givetian successions in the Ardennes and Aachen area. Approximate distance between Alt Breinig and Sourd d'Ave is 100 km.

de Houille). This would suggest a relatively rapid decrease in accommodation, i.e. a forced regression, such that restricted subtidal and intertidal facies were not deposited. Cycles during this time period are mostly asymmetric, with only periodic transgressive facies deposited (Fig. 14). This implies that for most of the time increases in accommodation were swift enough for sedimentation to severely lag behind and hence not record the deepening events. The transgressive-regressive cycles do have a vague pattern in their distribution, where commonly two to five regressive cycles were deposited which were then interrupted by one (or locally two) transgressive-regressive cycles. This pattern may relate to a longer-term trend in accommodation, which is discussed in Section 6.7.

The distribution of cycle-types does not appear to follow any specific pattern, although cycles which have intertidal or supratidal caps (type B) do tend to be distributed on the falling limb of the slopes (Fig. 14). If Fischer plots were interpreted to represent long-term trends in accommodation, then this pattern is what one might expect; there would have been a reduction in accommodation space and therefore sedimentation would have been more likely to build up to, and above, sea level. Type B cycles are, however, also recorded on the rising limbs of the Fischer plot, particularly at Cul de Houille. Here, type B cycles are especially thick as they record full shallowing from semi-restricted stromatoporoid boundstone bases through *Amphipora*-rich facies and poorly-fossiliferous facies to supratidal laminites. These B3 cycles show catch-up characteristics and are both facies and thickness complete. B4 cycles are also present, where semi-restricted facies are not developed and shallowing is recorded from the restricted subtidal zone through intertidal to the supratidal zone. The initial thinning-thickening trend in Fischer plots is then repeated in the upper part of the Moulin Boreux Member. This trend can be seen at Cul de Houille, Dourbes and Nismes. The falling limb at Cul de Houille is characterised by B-type cycles, with two of the cycles capped by calcretes (see Fig. 14). The development of these calcrete horizons would suggest there was exposure of the local area for a sustained period of time. However, these calcretes do not appear to have a regional extent, although outcrops of this formation are poor. Laminites, which are interpreted as forming in the high intertidal to supratidal zone, are well developed in the other successions at this time and may represent the lateral equivalents of the calcretes. It is interpreted that this period represents either a lowstand in relative sea level, or one where the decrease in accommodation was at its greatest.

The rising limb of the Fischer plot shows a complex array of cycle-types. At Cul de Houille the package takes on a more aggradational rather than thickening trend, and is dominated mainly by subtidal cycles. At Dourbes, on the other hand, the rising limb has two B-type cycles at the base, and is then followed by subtidal (type A) cycles. Nismes displays a very abrupt thickening package which is the result of just one unusually thick cycle (i.e., number 18 is 2.92 m thick, almost three times as thick as the average cycle thickness), and is then followed by an aggradational trend (i.e., cycles are more or less of average thickness). Cycles are mostly subtidal in nature, as with Cul de Houille. These differing patterns may reflect the differing structural character of the areas, where Nismes was situated on a more rapidly subsiding fault block, producing periodic thick cycles, yet the Cul de Houille/ Dourbes areas were on relatively stable fault blocks. The upper part of the Moulin Boreux Member has a similar pattern in distribution of regressive and transgressive-regressive cycles to that seen in the lower part. The successions are mostly characterised by regressive cycles, yet this is punctuated after approximately three to five cycles, by a transgressive-regressive cycle. The Fort Hulobiet Member in the Ardennes broadly correlates to successions in the Upper *Stringocephalus* Beds of the Aachen area. It is difficult to assess how much of the stratigraphy is omitted between the Moulin Boreux and Fort Hulobiet Members, since successions are incomplete. Yet it is likely to be approximately 50 m. These uppermost Givetian successions in both the Ardennes and Aachen areas show a positive-negative-positive-negative trend on Fischer plots (Fig. 15).

Teerstraßenbau and Venwegen quarries show the initial rising limb, where cycles are thicker than average. Cycles are mostly of type B, having a subtidal base and either a fenestral or microbial laminite cap, indicating intertidal to supratidal depositional environments. The falling limb is short, and characterised by thinner-than-average B-type cycles. The following rising limb can be seen in all successions and is again typified by supratidal-capped type B cycles. This indicates that the long-term pattern of accommodation change may have been at a lowstand during this time, or that the successions were positioned close to the palaeotidal-flat area, as a result of lower subsidence rates in the area. Most cycles are regressive.

The latest Givetian is characterised by a negative slope on the Fischer plot which can be seen at Sourd d'Ave and Walheim Southern Limb (Fig. 15). Both successions show type-B cycles which thin towards the Givetian/Frasnian boundary. The base of the Frasnian represents a dramatic deepening, when open-marine interbedded nodular limestones and marly shales were deposited. Cycles are of type C1.

Overall cycle thickness in the upper Givetian is much thinner than that seen in the lower Givetian, at 1.56 m (compared to 2.7 m). Type B cycles are more abundant also, suggesting that the long-term pattern was one of decreasing accommodation through the Givetian.

*7.3.3 Cyclicity in the Frasnian succession*

Frasnian and upper Givetian successions in the Aachen area have been extensively studied in the past two decades, in terms of palaeontology and cyclicity, with Kasig (1980) identifying an 'ideal cycle' as having an *Amphipora*-rich base, followed by a unit of bulbous stromatoporoids, and capped by laminated and structureless lime mudstone. It was suggested that all stromatoporoids were preserved in life position and the cycles represented a 'growth cycle'. However, little evidence was found to support these ideas. Horizons of bulbous stromatoporoids only locally have an *Amphipora* layer beneath them, and the bulbous stromatoporoids themselves are commonly overturned and abraded. Indeed, *Amphipora* commonly overlies the bulbous stromatoporoids, rather than being underneath them. Therefore, an 'ideal' shallowing-upward cycle would have a lower bulbous stromatoporoid base, overlain by an *Amphipora*-rich horizon, followed by a fine-grained poorly fossiliferous lime mudstone, finally capped by a microbial laminite (see Figs 8 & 9).

Frasnian strata were examined at three short successions in the Aachen area: Walheim Sections 1 and 2 and Schmithof. The complete cycle-thickness pattern through the Frasnian is impossible to determine, since successions are incomplete and do not cover the whole of the stratigraphy. However, correlation between two successions is possible, using relative thickness below overlying nodular shales and also Fischer plots (Fig. 16). Lower parts of the Reef Limestone Beds are exposed at Walheim Section 1. Cycles are mainly type B, and Walheim Section 1 exposes the only record of a transgressive lag-deposit. The lag is composed of ripped-up intraclasts of laminite facies and fenestral facies (facies S1) and occurs at the base of a B3, 'complete' cycle. Overlying the lag is a horizon of bulbous stromatoporoids, which then fully shallowed into subtidal restricted facies, and was capped by a thin microbial laminite. The cycle is thin, at only 1.3m, and cycle thickness on the whole for this lower package of Frasnian sediments averages only 1.7m. The presence of this transgressive lag would suggest that the increase in relative sea level was prolonged enough so that underlying sediments were reworked and subsequently redeposited on the ravinement surface (Arnott, 1995). Cycles in this package of sediments are, on the whole, regressive, indicating that the rises in relative sea level were too quick for sedimentation to pace.

## 8. Cyclicity in the Devonian of Belgium : Discussion

### *8.1. Magnitude and duration of small-scale relative sea-level fluctuations*

The shelf-lagoon microfacies are all shallow-subtidal to inter/supratidal, and the magnitudes of the changes in accommodation / relative sea level to generate the metre-scale cycles are thus likely to be in the range of 1-3 m. The duration of the cycles is more difficult to determine accurately since successions are likely to be incomplete, as a result of missed beats and deposition in mostly shallow water, and absolute dating is not of a sufficiently high resolution. The best exposed and most complete succession is at Cul de Houille where almost the whole of the Moulin Boreux Member of the upper Givetian Fromelennes Formation is exposed. This member encompasses the top of the Middle *varcus* to Upper *disparilis* conodont zones (Préat & Weis, 1994; Préat & Bultynck, 2006), and from estimations of conodont zone duration (e.g. House, 1995), the Moulin Boreux Member is likely to be approximately 1.9 Myr in duration. The Cul de Houille succession starts 10m from the base of the Moulin Boreux Member, which equates to ~7 cycles (average cycle thickness = 1.5 m); these, with the 38 cycles identified in the logged succession, gives an estimate of cycle duration as 42 kyr. This gives an average carbonate accumulation rate of 0.037 m 1000 $yr^{-1}$, which is similar to figures for other ancient carbonate platforms

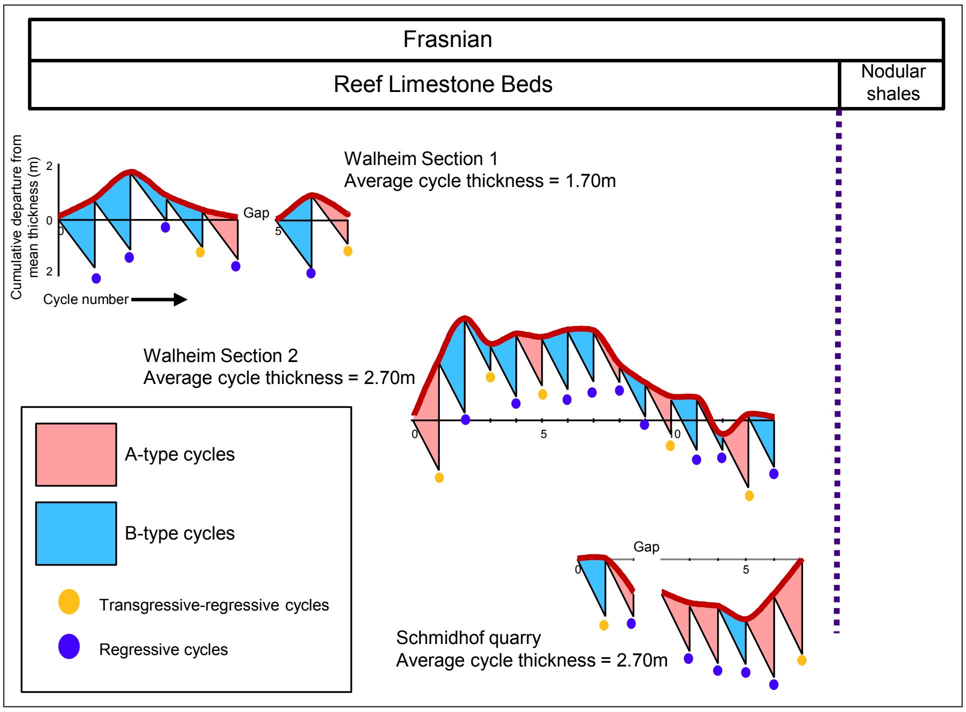


**Figure 16.** Correlation of Fischer plots for the Frasnian in the Aachen area.

(e.g., 0.04 m 1000 $yr^{-1}$ for the Upper Cretaceous Bahama platform; 0.05m 1000 $yr^{-1}$ for the Upper Permian of Texas; 0.05 m 1000 $yr^{-1}$ for the Barremian-Aptian platform carbonates of France; from Tucker & Wright, 1992). For the Eifelian ramp carbonates, Kasimi & Préat (1996) suggested that cycles were between 17,000 and 53,000 years duration, with an average of 35,000 years.

### *8.2. Origin of Devonian parasequences in Belgium*

Differentiating between the three mechanisms for producing the metre-scale cycles of the Middle Devonian of the Ardennes and Eifel is not straightforward, as many researchers have found for these cycles and others elsewhere in the stratigraphic record (e.g. Lehrmann & Goldhammer, 1999; Bosence et al., 2009). Although the sedimentary mechanisms provide good explanations for the development of some regressive type B cycles in the Ardennes, the inability to account for many other features makes the mechanism doubtful as a panacea. For example, a large percentage of the cycles are entirely subtidal (162 out of a total of 287 cycles recorded, i.e. 56%), and this is not easily explained by the autocyclic mechanism of tidal-flat progradation and termination of deposition in the intertidal zone. Another strong argument against is that many cycles show transgressive facies at the base, which would not normally be expected to develop in a dominantly progradational system. Cyclicity is also present in contemporaneous reef-core (e.g. at Bleiwäsche isolated reef complex; Städter & Koch, 1987) and deep-water facies (i.e., Givetian rhythmic pelagic micrite/marl beds of the Montagne Noire, House, 1995; Upper Devonian banded shales of the Rhenish Slate Mountains, Piecha, 1993), indicating an external driving force.

A direct tectonic mechanism involving movement on extensional faults is unlikely to account for all cycles in view of the fairly regular amounts of accommodation required for each cycle, and the thinning-thickening upward cycle patterns. However, there is much evidence to suggest that tectonic movements modified cyclic signatures (Mamet & Préat, 2005; Mamet & Préat, 2009, Préat et al., 2007). During the lower Givetian, for example, there is clear evidence that differential subsidence on fault blocks gave rise to condensed successions (e.g. Vaucelles), and it was also interpreted above that some fault blocks were relatively elevated compared to others (compare for example the lower Trois Fontaines Formation at Resteigne and Froidlieu). Although tectonism clearly influenced Middle and Upper Devonian platform development, it is doubtful that it was the major mechanism producing the pulses of increased accommodation space.

Orbital-forcing can explain many of the cycle features and the cycle variety. The common subtidal and peritidal cycles can both develop through sea-level induced accommodation increases. There is no necessity for cycles to aggrade to sea-level, as in the autocylic model, since carbonate production can be terminated by a rapid flooding event. The sedimentary environments were generally shallow enough to record the 1-3 m relative sea-level fluctuations and so produce the commonly-developed peritidal (type B) cycles. However, where sedimentary environments were deeper (such as on the Eifelian outer-mid ramp), these metre-scale sea-level fluctuations may not have been of a large enough magnitude to alter the sedimentary environment substantially. This may explain why many of subtidal ramp cycles are thicker than the lagoonal cycles, since they represent longer-term, higher magnitude, sea-level fluctuations rather than metre-scale changes. Orbital forcing can also account for transgressive deposits at the base of cycles, related to rates of rise and carbonate productivity, and for the packaging of cycles into bundles; although they not very common, some of these can be correlated over the region.

If orbital forcing - eustasy was the only mechanism influencing cycle development, one might expect an idealised distribution of cycle types, where thicker subtidal-cycles showing retrogradational thickness trends were dominant in the transgressive parts of the succession and truncated peritidal cycles were more common in regressive parts. However, this pattern is not seen, suggesting that subsidence may have been variable through time and/or that autocyclic processes were overprinting the eustatic signature, as suggested by Mamet & Préat (2005, 2007). Although packages of cycles can be traced across the platform, it is impossible to trace individual cycles. Indeed, where cycle packages could be followed, some successions contained more cycles than others. This could be the result of local autocyclic processes, the effect of 'missed beats', where sedimentation was either too deep to record the small-scale sea-level fluctuations or the area was exposed, or again, the effect of local tectonic movements.

Although orbital forcing is an attractive explanation for cycle development, the tectonic influences of variable subsidence and movement on faults clearly did affect deposition; indeed in some or even many cases it may well have been the main process creating the accommodation space. It is highly likely that autocyclic processes were operating too. One would expect some degree of order in the cycle stacking pattern if orbital forcing was the dominant mechanism. To test for this, the

| | No. of cycles | Av thickness (m) | n1> | n2< | r-runs | Z score |
|---|---|---|---|---|---|---|
| Beauraing | 22 | 1.91 | 10 | 12 | 12 | 0.04 |
| Bellignies | 26 | 2.43 | 8 | 18 | 11 | -0.5 |
| Cul de Huille | 39 | 1.52 | 17 | 22 | 19 | -0.39 |
| Dourbes | 25 | 1.4 | 8 | 17 | 15 | 1.47 |
| Glageon | 38 | 3.22 | 14 | 24 | 19 | 0.11 |
| Nismes | 22 | 1.09 | 9 | 13 | 16 | 1.97 |
| Resteigne | 28 | 3 | 11 | 17 | 16 | 0.66 |
| Wilheim S | 18 | 1.17 | 7 | 11 | 7 | -1.3 |

**Table 7**: Z-scores for the longer sections of metre-scale cycles in the Ardennes-Aachen-Eifel.

z-values were calculated for the longer successions of cycles (Table 7). In the analyses of Sadler et al. (1993), the z-value is a statistic indicating the level of order in the stack of parasequences. It is a runs test whereby a run (r) is one or more cycles that are thicker, n1 (or thinner, n2) than the average thickness. The z-value expresses the number of runs in a section as the number of standard deviations from the value expected from a random distribution. Where the z-value is more negative than -2, there is less than a 2.3% chance that random stacking could produce fewer runs. The z-values for the Belgian sections are all low negative to low positive; that is falling within the random field. The z-values then would support a strong random process being a dominant or over-riding control on the development of the metre-scale cyclicity in the Middle Devonian of Belgium, supporting the interpretation above that probably tectonics and orbital forcing were the main controls, along with autocyclicity too.

The bundling of metre-scale cycles into packages, which is seen in some sections, could well be a reflection of composite eustasy, such as precession/obliquity, or more likely precession/short eccentricity, since obliquity has more of an effect at higher latitudes, compared to the other two rhythms. An effect of orbital forcing in conjunction with pulsed subsidence, or autocyclicity against an eccentricity sea-level fluctuation could also produce a packaging of cycles.

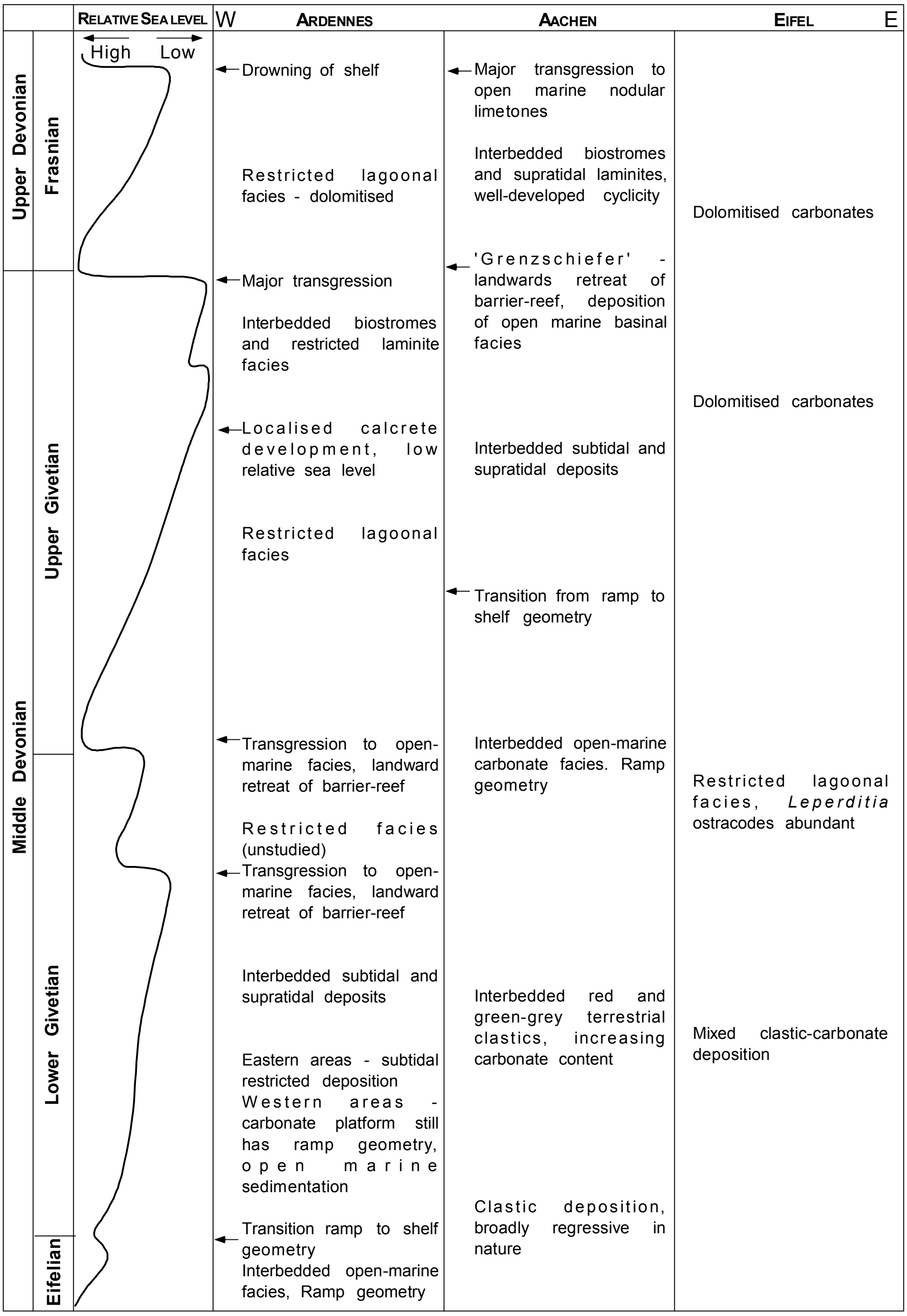


**Figure 17.** Long-term relative sea-level, platform geometry and key facies trends though the Devonian in the Ardennes, Aachen and Eifel areas.

Earlier interpretations of the Devonian cyclicity in the Ardennes, notably Préat & Carliez (1994), Weis & Préat (1994), Préat & Weis (1994), Kasimi & Préat (1996) and Mamet & Préat (2005, 2007), have suggested formation through low-amplitude relative sea-level oscillations, essentially controlled by subsidence, and in some cases related to orbital forcing, especially where bundling of cycles was recognised. Orbital forcing has been invoked to explain the metre-scale cyclicity in the middle Givetian of the Bergisch Gladbach isolated platform (Hering, 1994), and the Balve reef complex (Schudack, 1996) in Germany.

High-frequency cyclicity in the Devonian is apparent worldwide. Outside the Ardennes, it occurs not only in shallow-water carbonates (e.g., USA - Elrick, 1995; Yang et al., 1995; Canada - Fejer & Narbonne, 1992; McLean & Mountjoy, 1994; China - Chen et al., 2001; Poland - Préat & Racki, 1993; Australia – Playford et al., 2009), but also in marine clastic systems (USA - Brett & Baird, 1996), alluvial settings (Ireland - Kelly & Sadler, 1995), lacustrine facies (Scotland - Astin, 1990, Stephenson et al., 2006) and deep-water successions (France - House, 1995). In many cases the cyclicity is attributed to orbital perturbations, but Wong & Oldershaw (1980) and Morrow & Labonte (1988) suggested autocyclic mechanisms, whereas Préat & Racki (1993) suggested local fault-block movement.

### *8.3. Longer-term accommodation changes ('3rd order') of the Givetian and Frasnian strata*

Looking at the Belgian Devonian succession from the point of view of the longer-term pattern of accommodation change ('3$^{rd}$-order'), four major transgressive events can be recognised in the middle Givetian through middle Frasnian strata: 1) at the base of the Terres d'Haurs Formation, 2) at the base of the Fromelennes Formation, 3) at the base of the Frasnian and 4) at the base of the nodular limestones/Matagne Shale (Fig. 17). The transgressive facies are characterised by open-marine sediments, with rich faunal diversities (argillaceous shales, marly shales, storm beds). The transgressive events (episodicity of 10$^6$yrs, 3-4 Myr) are correlatable worldwide and fit in well with published sea-level curves (e.g. Johnson et al., 1985; Haq & Schutter, 2005). The longer duration regressive phases, highstand-falling stage-lowstand, are characterised by the cyclic lagoonal facies described in this paper.

### *8.4. Devonian cycles in Belgium: Summary*

In summary, two major types of metre-scale cycle have been identified in the shelf-lagoonal successions in Belgium: subtidal cycles (type A) which show an upwards decrease in circulation, decrease in diversity of organisms and increase in fluctuation of salinity, through the cycle, and peritidal cycles (Type B) which shallow upwards from a subtidal base through to an intertidal or supratidal cap. The distribution of these cycle-types is related to the amount of accommodation space available, which in turn is controlled by subsidence and small-scale sea-level fluctuations. Cycles are mainly regressive in character; however, transgressive-regressive cycles are not uncommon. Their distribution does not produce a clear pattern, and deposition of the transgressive deposits could either be attributed to the rise in relative sea level being slow enough so that carbonate production was able to pace it, or that the lag time was variable for carbonate production to restart after the initial transgression.

Although the general trends in cycle thickness and cycle packaging within the succession can be correlated across the platform; tracing individual cycles is not possible. It is concluded that the metre-scale cyclicity was most likely to have been controlled by the high-frequency, precession (20,000 year) orbital rhythm, giving a regular sea-level change in the order of 1-3 m, along with the effects of differential subsidence and movement of fault blocks. The latter was of great importance as it had a strong influence on cycle-type distribution, with subtidal cycles more common in areas of rapidly subsiding fault blocks, and peritidal cycles more common in stable elevated blocks. Overprinting the orbital-forcing – tectonic signature were the effects of autocyclic processes (tidal-flat progradation). In some cases, there is a bundling of the metre-scale cycles (5$^{th}$ order) into cycle- sets (4$^{th}$-order, 100,000-400,000 years), but this is not ubiquitous, and could also be a manifestation of orbital-forcing - tectonics. The cycles generally are organised into sequences (3$^{rd}$ -order, 3-4 Myr in duration), delineated by major marine transgressions, which can be correlated worldwide.

## 9. Overall conclusions

Beds and metre-scale cycles are the fundamental building blocks of sedimentary sequences and occur in all facies and in all parts of the stratigraphic record. Their origin is clearly complex and in the majority of cases it is likely that there is not one overriding control. They are formed by normal depositional processes of tidal-flat progradation and lagoonal sediment aggradation; they are also produced by climatic and other changes of the environment, as well as sea-level, on millennial to 10s of 1000s of years, brought about by orbital forcing, and they are also the result of changes in accommodation space brought about by tectonics, notably movements on faults in extensional regimes. The well-developed cyclicity in the Devonian of the Ardennes, Aachen and Eifel regions described here shows all the variety of development that is characteristic of parasequences, and all the issues of interpretation which have dogged stratigraphers for many decades now. And as with many controversies in the Earth Sciences, at the end of the day, the explanation is a combination of the several hypotheses that are available.

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