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# SEQUENCE STRATIGRAPHICAL STUDY OF THE TOURNAISIAN STRATA IN BELGIUM AND SOUTHERN CHINA

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(14 figures, 1 table, 2 plates)

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**ABSTRACT.** Strata of late Devonian and Tournaisian age in Belgium and Southern China were studied sedimentologically. This detailed study integrated into a biostratigraphical framework, based on foraminiferal zonation, allowed the construction of a sequence stratigraphical model for both areas. Based on these models a correlation on the scale of third order sequences between these two widely separated depositional environments can be made. This indicates the eustatic nature of the sea-level changes that caused the sedimentological changes during the Tournaisian.

**KEYWORDS:** Sequence stratigraphy, carbonates, Tournaisian, Late Devonian, Belgium, Southern China

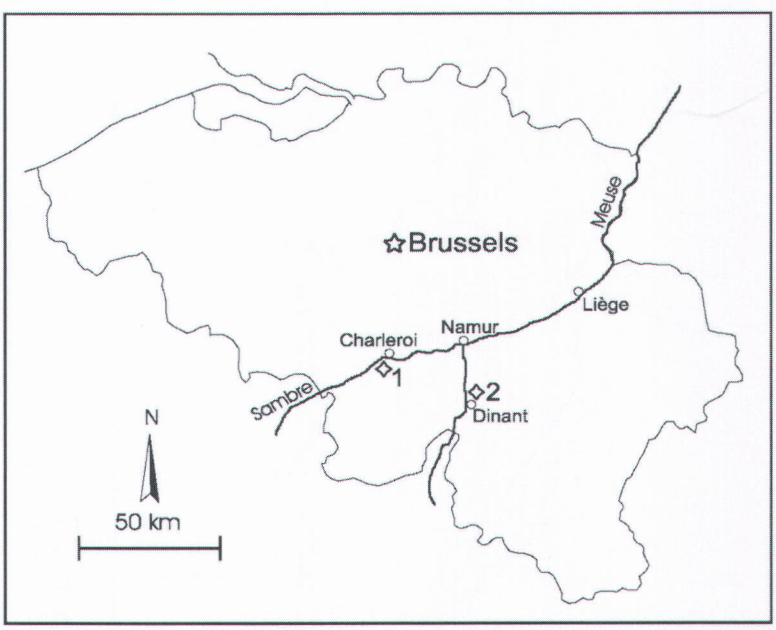


**Figure 1.** Location of the sections studied in Belgium. 1 = Landelies; 2 = Yvoir.

## 1. Introduction

During the past ten years a number of sequence stratigraphical studies on the Lower Carboniferous of Belgium and Southern China have been carried out. They focused primarily on the Devonian-Carboniferous (Van Steenwinkel, 1990, 1993; Hance et al., 1993) and Tournaisian-Visean (Hance et al., 1997) transitional strata. During the Tournaisian both areas were located in a sub-equatorial position, on the northern border of the Tethys realm. In Southern Belgium, sedimentation took place on a south facing ramp (Lees et al., 1985; Van Steenwinkel, 1988) while the depositional area in Southern China was a shelf with several intraplatform basins (Liao & Li, 1996).

The aim of this study is to review the existing data, to combine them with the results of a detailed sedimentological investigation of the Tournaisian strata in Belgium and Southern China, and to construct a sequence stratigraphical model for the Tournaisian in these two areas. Both sequence stratigraphical models will be compared. For this purpose, 7 sections have been studied sedimentologically. These comprise Landelies and Yvoir in Belgium (Fig. 1) and Malanbian, Sujiaping, Shifendong, Jiguangshan and Luojia in Southern China (Fig. 2).

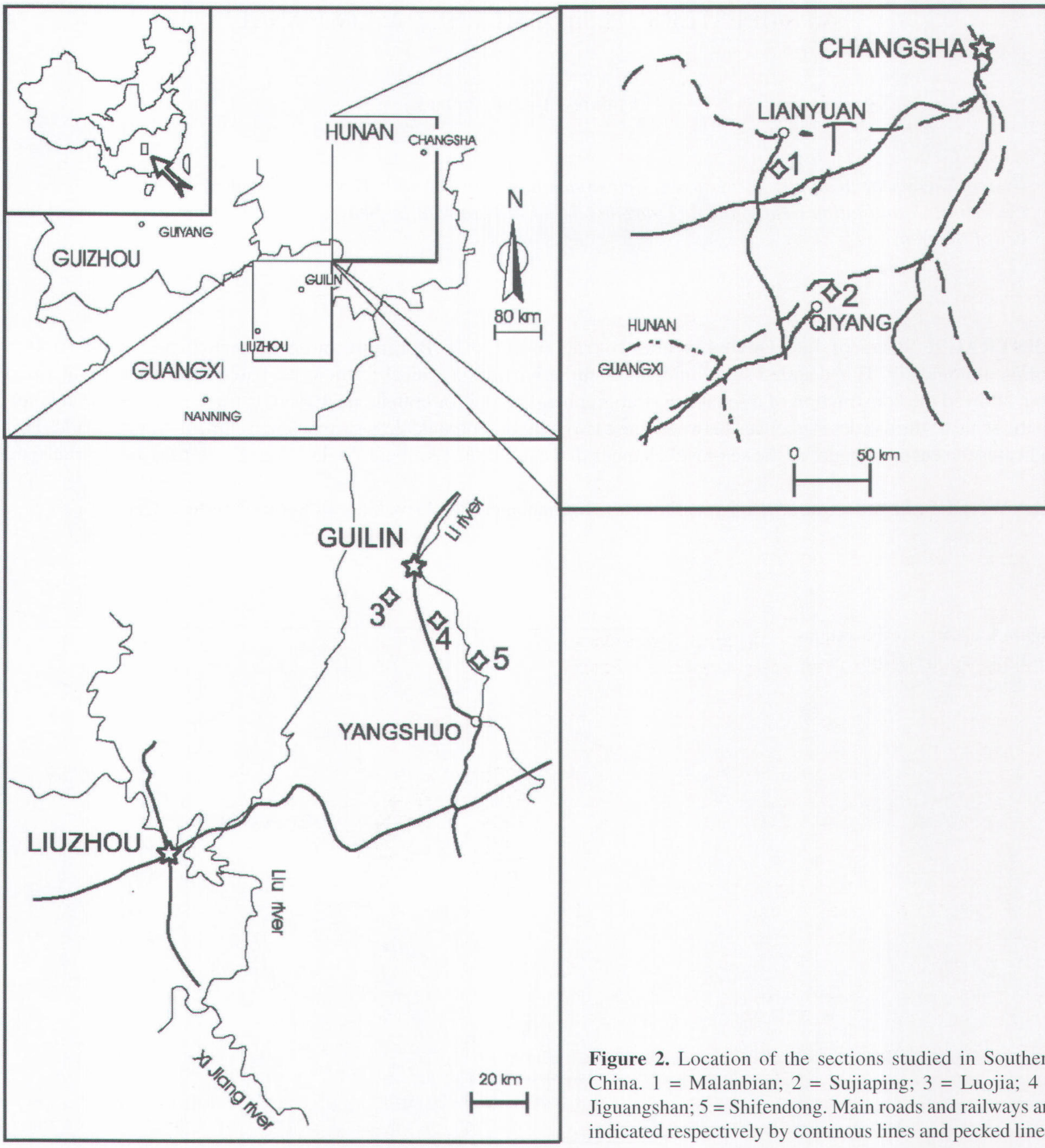


**Figure 2.** Location of the sections studied in Southern China. 1 = Malanbian; 2 = Sujiaping; 3 = Luojia; 4 = Jiguangshan; 5 = Shifendong. Main roads and railways are indicated respectively by continous lines and pecked lines.

## 2. Bio- and lithostratigraphy

The absence or scarcity of index fossils makes a biostratigraphical correlation between the sections and areas studied very difficult. However, a biostratigraphic framework constructed on the basis of foraminiferal zonation allows a large-scale correlation of the different formations investigated. Table 1 gives an overview of this correlation based on studies by Conil et al. (1990), Hance (1996) and Muchez et al. (1998). In this table, also the relative stratigraphic position of the sections is given.

## 3. Sedimentpetrography, facies evolution and sequence stratigraphy

### *3.1. Belgium*

Only the upper part of the Pont d' Arcole Formation, the Landelies Formation and the lower part of the Maurenne/Hun Formation at the Landelies and Yvoir sections were sedimentologically investigated. Data about the sedimentology of other formations that belong to the Tournaisian were taken from previous studies carried out by Bouckaert et al. (1971), Paproth et al. (1983), Van Steenwinkel (1990, 1992, 1993) and Hibo (1993). A schematic lithological evolution of the Etroeungt and Hastière Formations is given in figure 3. Logs of the sections at Landelies and Yvoir can be found in figures 4 and 5 respectively. The lithological evolution of the Yvoir and Encrinite de l'Ourthe Formations is displayed in figure 6.

#### 3.1.1. Etroeungt and Hastière Formations

*Description*

The sedimentological description of these strata was taken from the studies by Van Steenwinkel (1990, 1992, 1993). The uppermost Devonian strata (Fig. 3), which make up the Etroeungt Limestone, are characterised by bioclastic wackestones and bioclastic, peloidal packstones with calcareous shale intercalations. The biota consists mainly of crinoids, bryozoans, ostracods and brachiopods. A slightly progradational sequence towards the top can be seen. The boundary between the Etroeungt Limestone and the Hastière Formation shows an abrupt transition to a lithoclastic bed (10-15 centimetres thick) or a level of non-deposition marked by sub-marine erosion. The lithoclasts are rounded and have a size range from a few millimeters to a few centimeters. They are made up of the bioclastic wackestones and bioclastic, peloidal packstones that are found in the Etroeungt Formation (Van Steenwinkel, 1988). This lithoclastic bed, or the submarine erosional surface, is followed by oolitic and grapestone grain- and mudsupported limestones or the deposition of wackestones with mainly ostracods, calcispheres and algae (mainly Girvanella). The major part of the Hastière Formation consists of coarsening-upward cycles, consisting of shaly limestone intervals (bioclastic wacke- to packstones) at the base and massive crinoidal limestones (peloidal, bioclastic grainstones) at the top. The bioclasts are crinoids, brachiopods, bryozoans, ostracods and calcispheres. The thickness of these cycles ranges from 2 to 5 metres and, depending on the location, 3 to 5 cycles can be identified. The upper 3 cycles can be correlated throughout the area studied. The lower 2 cycles cannot be correlated or are absent in parts of the basin. The massive crinoidal limestones with a progressively thicker and shallower facies towards the upper cycles indicate an overall prograding tendency. Following the thickest grainstone unit near the top of the Hastière Limestone, a transition to bioclastic wackestones intercalated with marls can be identified. A similar biota than in the underlying grainstones can be recognised with the addition of corals, gastropods and foraminifers. These wackestones grade into bioturbated marls and shales of the Pont d'Arcole Formation.

*Interpretation*

The bioclastic wackestones and bioclastic, peloidal packstones of the upper part of the Etroeungt Limestone have been deposited in relatively deep water below to around fairweather wave-base (Van Steenwinkel, 1988). The progradation of the sequence points to a shallowing of the depositional environment towards the top. These strata were interpreted by Van Steenwinkel (1990) as the top of a Highstand Systems Tract (Fig. 7), marked by a slow rise in relative sea-level and a sedimentation rate that could outpace the created accommodation space.

The lithoclastic bed or sub-marine erosion surface at the base of the Hastière Limestone formed as the result of an important lowering of relative sea-level which resulted in non-deposition and submarine erosion (Van Steenwinkel, 1988, 1990, 1992). In sequence stratigraphical terms this event will mark the position of a Sequence Boundary. The exact position of the sediments formed during sea-level fall and consequently the position of the Sequence Boundary can be determined using the sequence stratigraphical scheme of Hunt & Tucker (1993). These authors pointed out that the sediments formed during relative sea-level fall should be placed below the Sequence Boundary since in this case, the Sequence Boundary truly coincides with the lowest point of relative sea-level. These sediments form a Forced Regressive Wedge Systems Tract, constitute the top of the sequence and are capped by the Sequence Boundary. So, in this model the Sequence Boundary is positioned above the lithoclastic bed in the lower part of the Hastière Limestone in areas where this bed can be found. In areas where the only evidence of the sea-level fall is a surface of submarine erosion, the position of the Sequence Boundary coincides with this erosional surface. The presence of a Sequence Boundary at this level can also be concluded from the transition from below-fairweather wave base

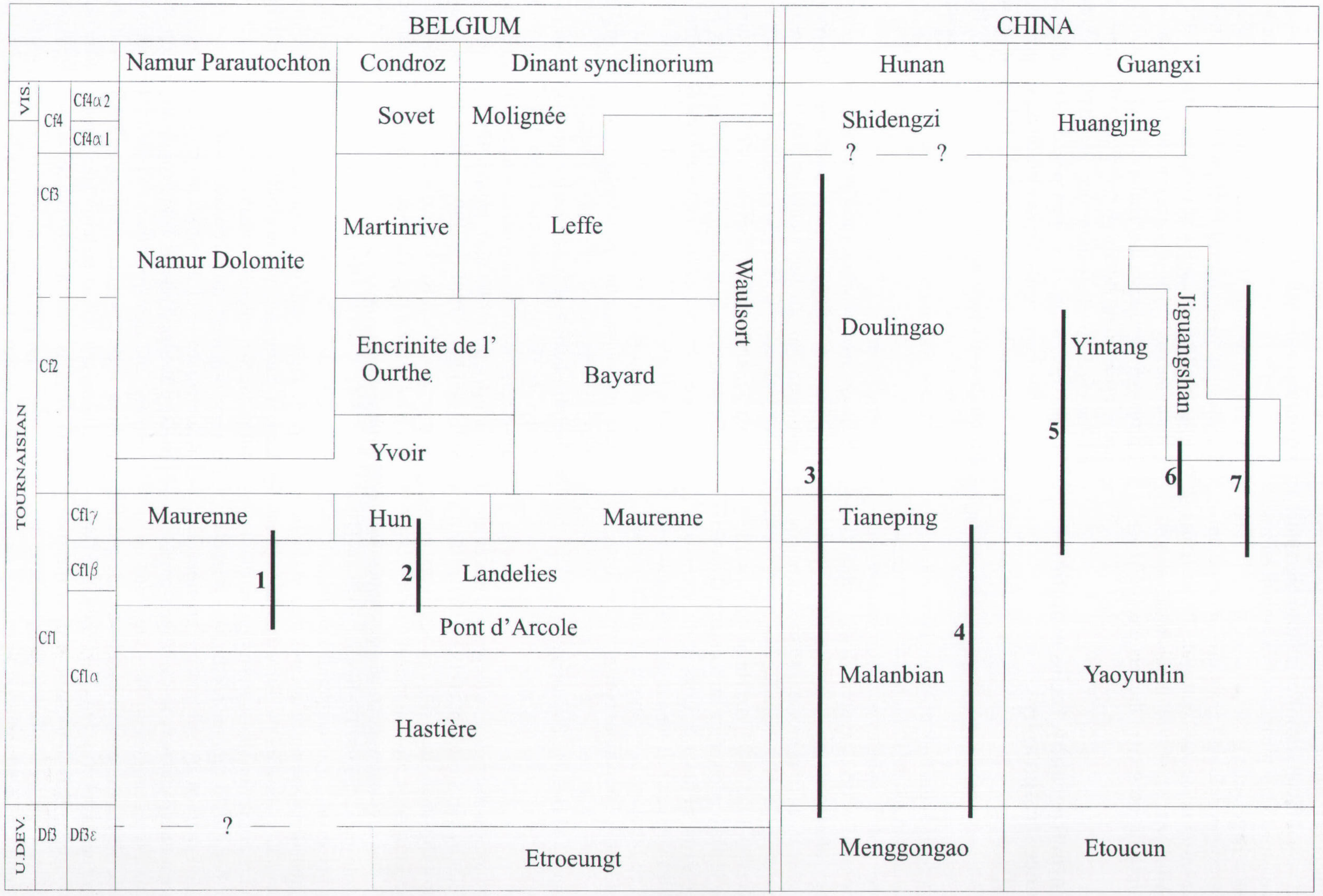


**Table 1.** Bio- and lithostratigraphy of Belgium and Southern China. Lithostratigraphic position of the sections studied is indicated. 1 = Landelies; 2 = Yvoir; 3 = Malanbian; 4 = Sujiaping; 5 = Luojia; 6 = Jiguangshan; 7 = Shifendong. Biostratigraphy based on foraminiferal zonation constructed by Conil et al., 1990, Hance, 1996 and Muchez et al., 1998. Cf = 'Carboniferous foraminiferal zonations'.

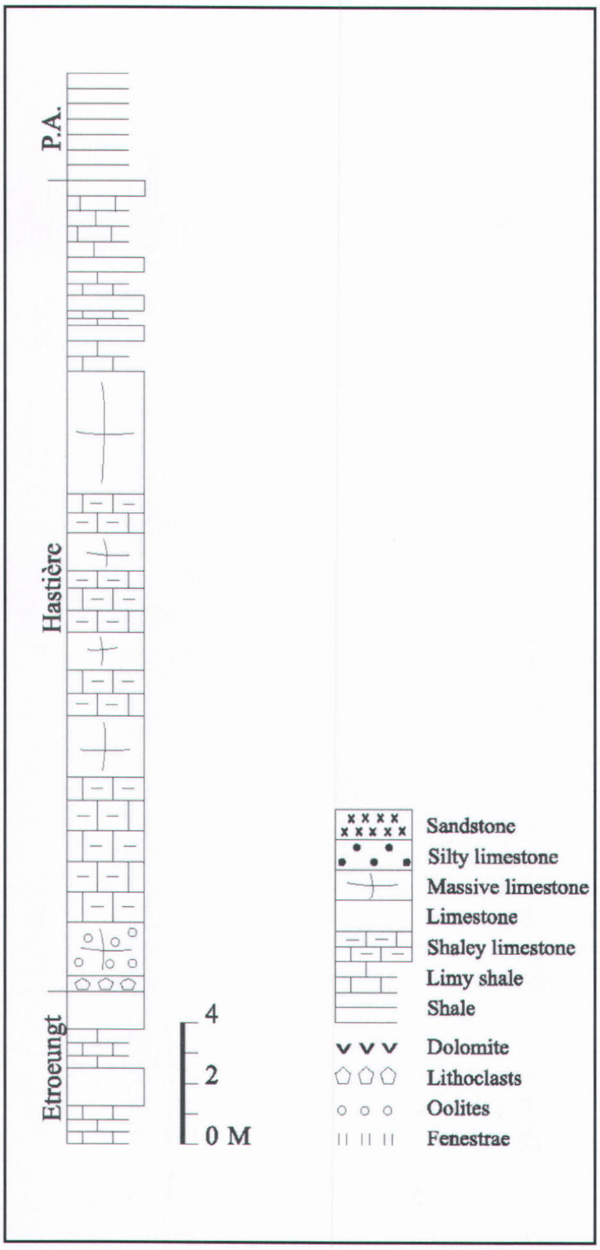


**Figure 3.** Schematic lithological evolution of the Etroeungt, Hastière and Pont d' Arcole (P.A.) Formations.

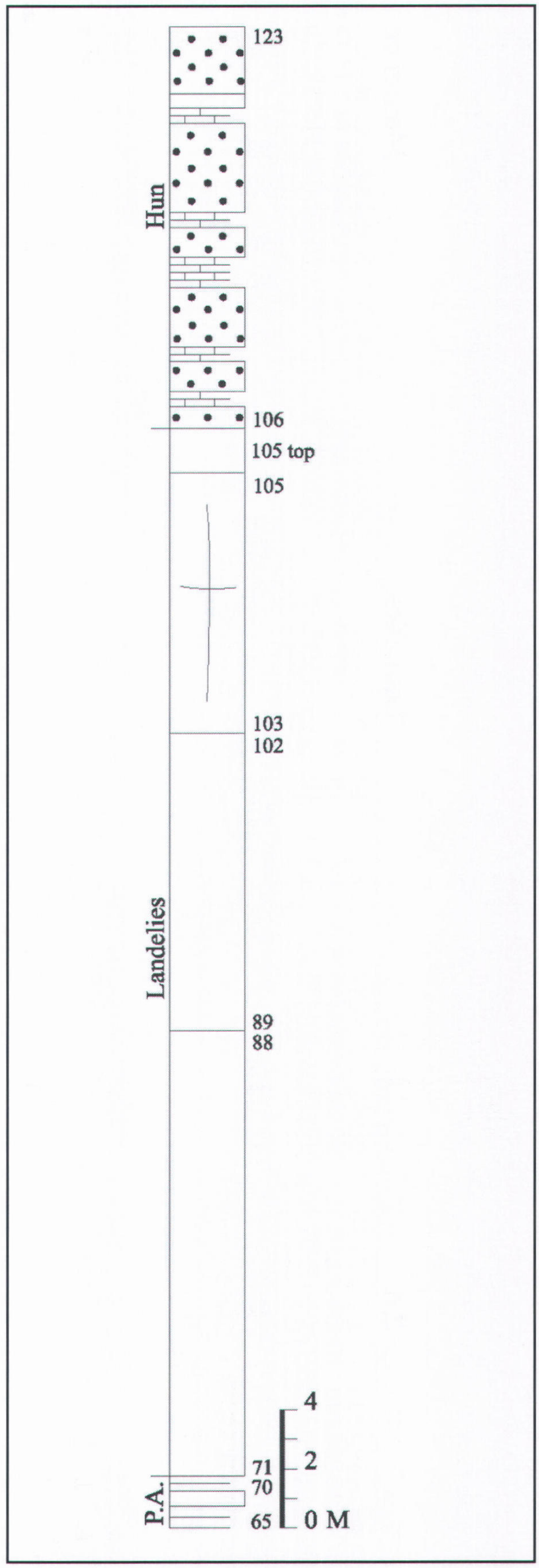


**Figure 4.** Log of the section at Yvoir. P.A. = Pont d'Arcole.

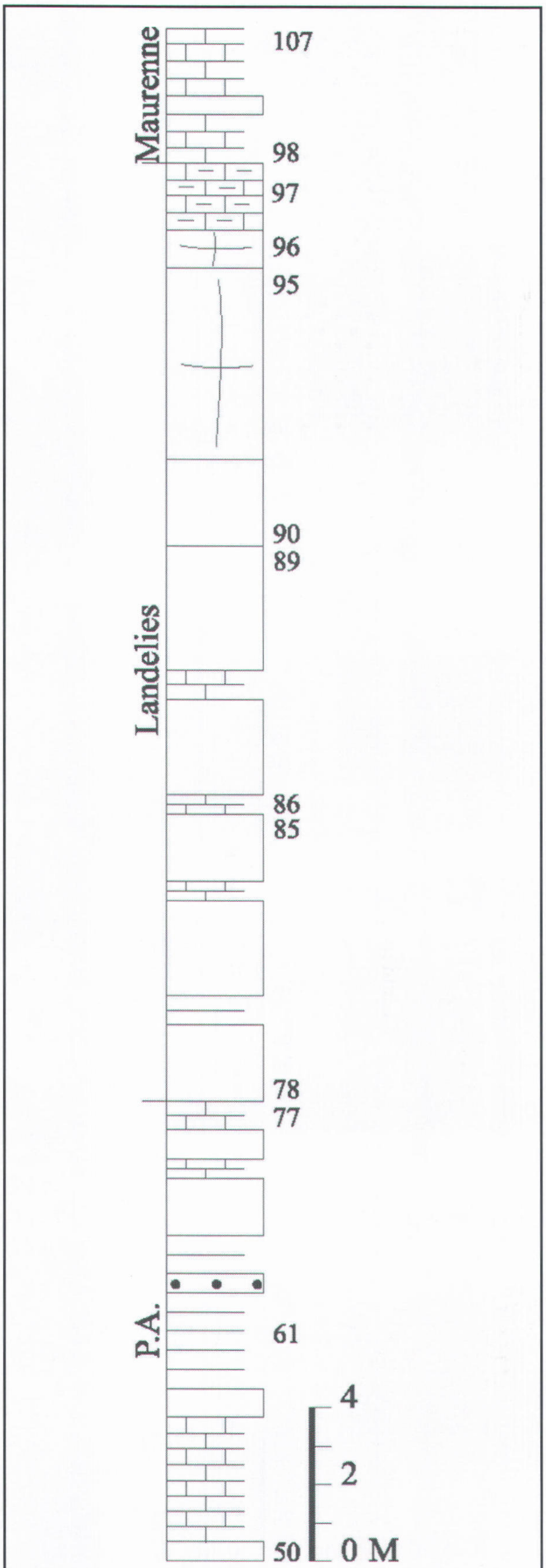


**Figure 5.** Log of the section at Landelies. P.A. = Pont d'Arcole.

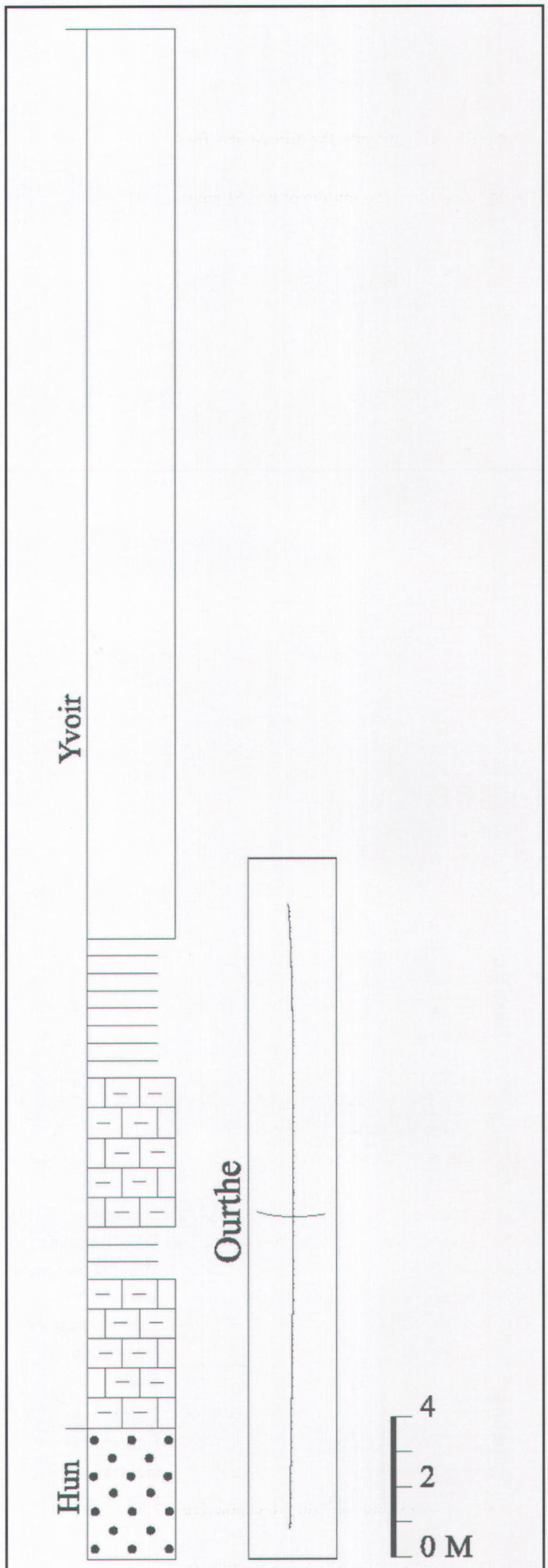


**Figure 6.** Schematic log of the Yvoir and Encrinite de l' Ourthe Formations.

deposits in the Etroeungt Formation to oolite and grapestone grain- and mud-supported limestones in the lower part of the Hastière Formation. These oolite and grapestone grain- and mud-supported limestones were deposited in a lagoonal setting where sporadic water agitation made the formation of grapestones possible. The oolites originate from a nearby oolite shoal and are carried into the lagoon by storms or currents (Van Steenwinkel, 1988). The wackestones with restricted biota formed in a protected lagoonal setting with little water agitation.

The oolitic and grapestone grain- and mud-supported limestones and the wackestones with the restricted biota of ostracods, calcisphers and algae, deposited above the lithoclastic bed, are interpreted by Van Steenwinkel (1988) as the result of a rise of relative sea-level and the creation of accommodation. This rise continues at a slightly increased rate throughout almost the entire Hastière Limestone. This is reflected in the deposition of several shallowing upward cycles. These cycles are interpreted as parasequences in which the shaly limestone intervals mark the periods in the rise where sedimentation cannot keep up with the rate of accommodation creation. The deposition of massive peloidal, bioclastic grainstones at the top of every cycle, however, shows that after a certain period, sedimentation is capable to fill up the available space.The progradational way in which the parasequences are stacked, combined with the observation that the uppermost grainstone unit is the most massive, points to an overall shallowing of the sedimentation environment. The major part of the Hastière Limestone, from the top of the lithoclastic bed to the top of the most massive grainstone unit is interpreted as a Lowstand Systems Tract marked by a slow rise in relative sea-level.

The transition towards bioclastic wackestones, marls and shales above the massive grainstone unit marks the beginning of a rapid rise in relative sea-level which sedimentation cannot outpace. It results in an overall drowning. The base of these sediments, deposited in markedly deeper water, is a Transgressive Surface and marks the start of a Transgressive Systems Tract which continues into the Pont d' Arcole Formation.

3.1.2. Pont d'Arcole, Landelies and Maurenne/Hun Formations

*Description*

The data for this part of the Tournaisian in Belgium were obtained from a petrographical study of the limestones at the sections in Yvoir (Fig. 4) and Landelies (Fig. 5). In both sections the upper part of the Pont d'Arcole Formation (at Landelies: beds 50 to 77; at Yvoir: beds 65 to 70) consists of black to dark grey shales and calcareous shales with intercalations of wackestones with a large siliciclastic component (mainly clay and silt-sized quartz) and a relatively small amount of bioclasts (Pl. 1\A) as well as silty micrites (Pl. 1\B). The biota consists of crinoids, brachiopods, ostracods, bryozoans and foraminifers. Towards the top of the formation, the number of limestone intercalations increases. In the section at Landelies, the middle of bed 61 consists of a distinctive black, organic-rich shale level.

The Landelies Formation is characterised by a dominantly limestone sedimentation. The lower 15 m of the section at Yvoir (beds 71 to 88) are composed of bioclastic wacke- to packstones with crinoids, brachiopods, algae, bryozoans, foraminifers, ostracods and moravamminids (Pl. 1\C). This is followed by 10 m of bioclastic, peloidal packstones and pack- to grainstones with an identical, fully open marine biota (beds 89 to 102) (Pl. 1\D). From bed 103 to the middle of bed 105, massive, peloidal, bioclastic grainstones with heavily micritised clasts, micritised grains and peloids and a similar biota as in the underlying strata are present (Pl. 1\ E, F). The top of the formation (upper part bed 105) is a poorly sorted, bioclastic, peloidal pack- to grainstone also with an open marine biota. In the section at Landelies, a very similar sequence can be observed with 7.5 m of bioclastic wacke- to packstones (beds 78 to 85) with crinoids, brachiopods, algae, bryozoans, foraminifers and moravaminids intercalated with calcareous shales. This is followed by 7 m of bioclastic, peloidal pack- and grainstones (beds 86 to 89) with a similar biota (Pl. 1\G) and with calcareous shale intercalations. Towards the top of the Landelies Formation (beds 90 to 95), peloidal, bioclastic pack- to grainstones with clasts and an open marine biota occur. The clasts range from 200 to 500 μm in size, are moderately well-sorted and have an irregular outline. Traces of internal structure, mainly bioclasts, can be distinguished but a detailed identification is impossible due to the very intense micritisation. Bed 96 is a well-sorted peloidal, bioclastic grainstone with micritic clasts, micritised grains, peloids and an open marine biota. The top of the Landelies Limestone (bed 97) is a bioclastic, peloidal packstone with ostracods, crinoids, algae, foraminifers, moravamminids and bryozoans. This limestone appears shaly in the field.

The start of the Maurenne Formation at Landelies (base bed 98) is marked by a transition to calcareous shales with macroscopically visible branched bryozoans and some intercalated limestone units of bioclastic, clay-rich wackestones with a small amount of algae, ostracods, crinoids, brachiopods and foraminifers. At Yvoir, the equivalent strata (starting from the base of bed 106) are called the Hun Formation and are characterised by silty micrites and silty, bioclastic wackestones (Pl. 1\H) with calcareous shale intercalations. These units contain a large amount of siliciclastic material, mostly quartz, in a micritic carbonate matrix with sporadic fragments of crinoids and brachiopods.

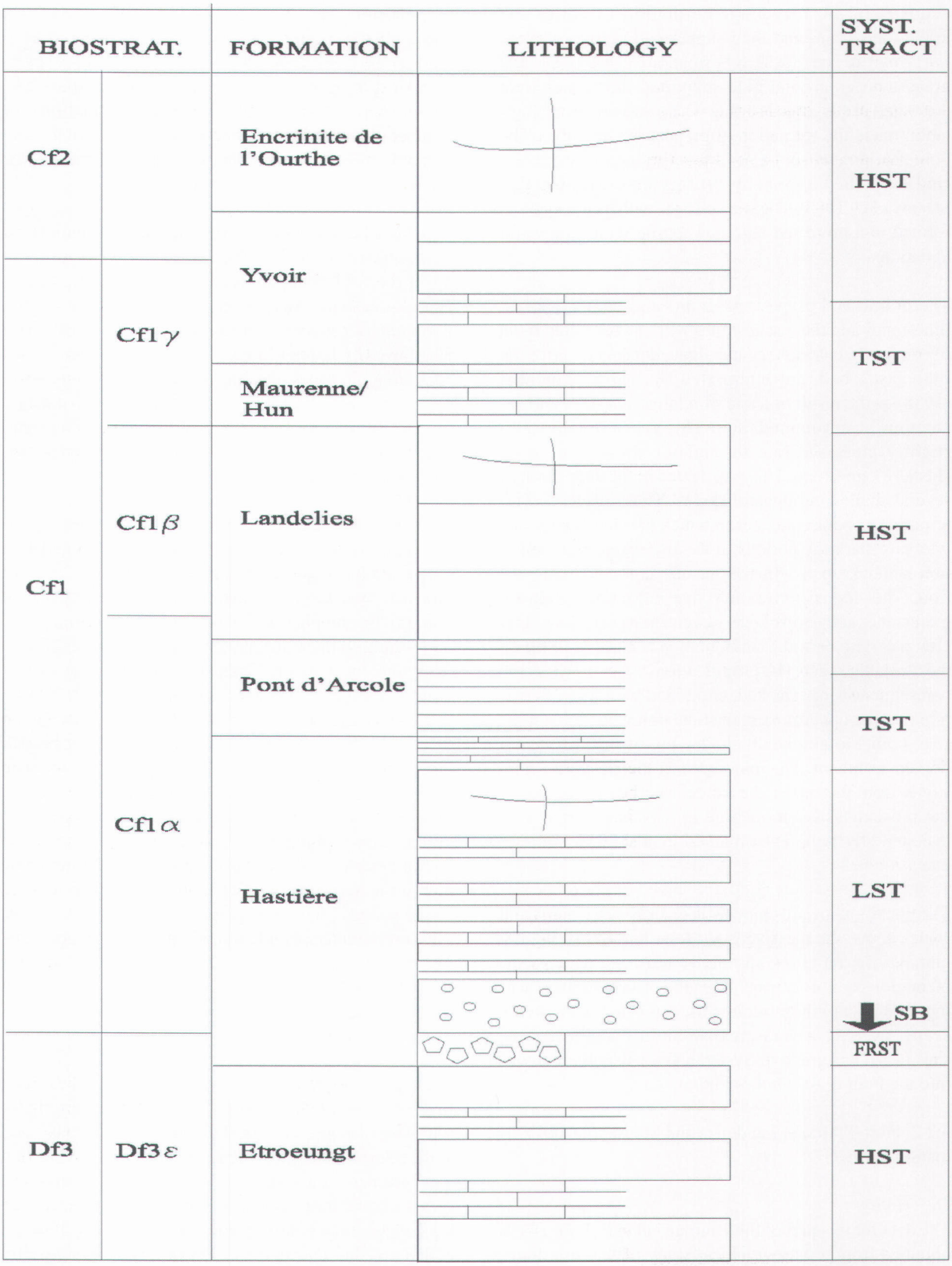


**Figure 7.** Sequence stratigraphical model for Belgium. SB = Sequence Boundary, LST = Lowstand Systems Tract, TST = Transgressive Systems Tract, HST = Highstand Systems Tract, FRST = Forced Regressive Systems Tract. Not to scale.

*Interpretation*

The sediments that make up the Pont d'Arcole Formation are interpreted to have been deposited well below wave base in a quiet environment with a mostly siliciclastic sedimentation. The more calcareous sediments originated in shallower water and were transported down slope into the basin. In the Landelies section, the deepest deposits are present in level 61, i.e. the organic-rich shale. This level is interpreted as the Main Flooding Surface of the Transgressive Systems Tract (Fig. 7) that started near the top of the Hastière Formation (see 3.1.1). From this surface upwards, the amount of limestone beds increases in the Pont d'Arcole Formation and finally culminates in the limestone sedimentation of the Landelies Formation.

At Yvoir and Landelies, the upward transition from bioclastic wacke- and packstones to bioclastic, peloidal pack- to grainstones and finally massive peloidal, bioclastic grainstones in the major part of the Landelies Formation is interpreted to indicate a progressive shallowing of the sedimentation environment as a result of the slowing down of the relative sea-level rise. This allowed the sedimentation to catch up with the rise and to fill up the accommodation space formed during the previous rapid sea-level rise. The whole unit, starting from the Main Flooding Surface identified at level 61 at Landelies, up to the top of the massive limestones (middle of bed 105 at Yvoir; top of bed 96 at Landelies) is interpreted as a Highstand Systems Tract.

The poorly sorted, bioclastic peloidal pack- to grainstone at the top of bed 105 at Yvoir and the bioclastic peloidal packstone in bed 97 at Landelies have been deposited in a deeper environment than the underlying massive grainstones. This interpretation is based on the poorer sorting, the presence of more micrite, the dominance of bioclasts over peloids and the shaly appearance at Landelies of these upper packstones and grainstones. The deepening becomes even more pronounced in the Maurenne and Hun Formations with a transition to a mixed siliciclastic-carbonate sedimentation that results in the deposition of calcareous shales in the Maurenne Formation and silty micrites in the Hun Formation. This rise in relative sea-level marks the start of a Transgressive Systems Tract that begins with the Transgressive surface near the top of the Landelies Formation (base of bed 97 at Landelies; middle of bed 105 at Yvoir).

3.1.3. Yvoir and Encrinite de l'Ourthe Formations.

*Description*

The sedimentology of the Yvoir Formation is based on the publications of Bouckaert et al. (1971), Paproth et al. (1983) and Hibo (1993). All these autors note the existence of an important shale unit in the lower part of the Yvoir Formation (Fig. 6). Below this level, the sediments are clay-rich limestones, with a sparse biota of crinoids, brachiopods and branched bryozoans, alternating with shale intercalations. The latter increase towards the thickest shale level. The overlying sediments consist of pure limestones without siliciclastic material. The facies of these pure limestones is a peloidal wacke- or packstone with crinoids, brachiopods, bryozoans, moravamminids and foraminifers (Hibo, 1993). The Encrinite de l' Ourthe Formation consists of massive crinoidal pack- to grainstones (Hibo, 1993). No sedimentary features can be observed in these monotonous deposits.

*Interpretation*

The lower part of the Yvoir Limestone consists of shaly limestones with a sparse open marine biota, and are interpreted to have been deposited in a quiet, fairly deep water environment. A further deepening towards the pure shale unit is indicated by the thickening of the intercalated shale levels. These deeper water sediments are considered as being the upper part of the Transgressive Systems Tract (Fig. 7) that started near the top of the Landelies Formation and contains the entire Maurenne/Hun Formations (see 3.1.2). This systems tract ends at the Main Flooding Surface within the shale unit.

The upper part of the Yvoir Formation, consisting of wacke- and packstones with an open marine biota, is supposedly deposited in a quiet water environment below fairweather wave base. The Encrinite de l'Ourthe Formation, made up of massive crinoidal pack- to grainstone, was deposited in a shallow sedimentation environment above fairweather wave base where wave action could winnow away the micrite. The transition from deeper water limestones in the Yvoir Formation to the shallower water sediments of the Encrinite de l'Ourthe shows a gradual shallowing of the sedimentation environment. This is a result of the slowing down of the relative sea-level rise and the filling of the available space by the sediments and is interpreted as a Highstand Systems Tract.

3.1.4. Discussion

Recently, Hance et al. (submitted) proposed an alternative interpretation for the Devonian-Carboniferous transitional beds in Belgium. They interprete the Etroeungt Limestone and the lower member of the Hastière Limestone as being part of the same Transgressive Systems Tract. The lithoclastic bed or submarine erosion surface that occurs at the transition between these formations is considered as an event horizon (Hangenberg event) that reflects an important sea-level drop but is not interpreted as a Sequence Boundary. This interpretation differs from the one given in this article mainly by the significance given to the fall in relative sea-level near the Devonian-Carboniferous Boundary. Hance et al. (submitted) consider this fall as being a short term 'event' superimposed on a gradual rise in sea-level that starts in the Late Devonian and continues into the Early Carboniferous. In this article, we consider this, and other, major drops in relative sea-level to be a Sequence Boundary based on the definition of such a surface in the theory of sequence stratigraphy (see for example Vail et al., 1977; Van Wagoner et al., 1988; Sarg, 1988).

Evidence for a sea-level drop can also be found in the Rhenish Slate Mountains in Germany in the form of an erosional channel (Van Steenwinkel, 1992) and in Poland expressed by a non-depositional surface and a major biostratigraphical hiatus (Matyja & Stempien-Salek, 1993). Johnson et al. (1986) indicate in their sea-level curve for the Devonian an important regression starting in the latest Devonian (Middle praesulcata zone). A correlation of this global sea-level curve with sections in Germany (Sauerland) and France (La Serre section) was worked out by Bless et al. (1992). The fact that this drop in relative sea-level can be demonstrated at several locations, favours the interpretation of a Sequence Boundary.

### *3.2. China*

The sections at Malanbian (Fig. 8), Sujiaping (Fig. 9), Luojia (Fig. 10), Shifendong (Fig. 11) and Jiguangshan (Fig. 12) were studied.

#### 3.2.1. Menggongao Formation

*Description*

The sedimentology of these strata has previously been described by Muchez (1996). At the section at Malanbian (Fig. 8), the Menggongao Formation contains bioclastic mudstones, wackestones and packstones (beds 99 to 101) (Pl. 2\A). The biota is very similar in all the limestones and consists of crinoids, brachiopods, bryozoans, foraminifers, ostracods, moravamminids, echinoid spines and bivalves. The top of the formation is marked by a siliciclastic unit with shales that contain a larg amount of pollen (Steemans et al., 1996) and massive sandstone beds (beds 102 and 103) (Pl. 2\B). At Sujiaping (Fig. 9), the time equivalent strata (beds 51 and 53) are made up of bioclastic packstones with crinoids, foraminifers, bryozoans, brachiopods, moravamminids and echinoid spines intercalated with bioclastic, peloidal wacke- to packstones with a similar biota in addition to peloids, clasts and micritised grains. At this section, the top of the Menggongao Formation (unit 54) is a mudstone with very small amounts of ostracods, calcispheres, algae and gastropods. Irregular and tubular fenestrae can be observed.

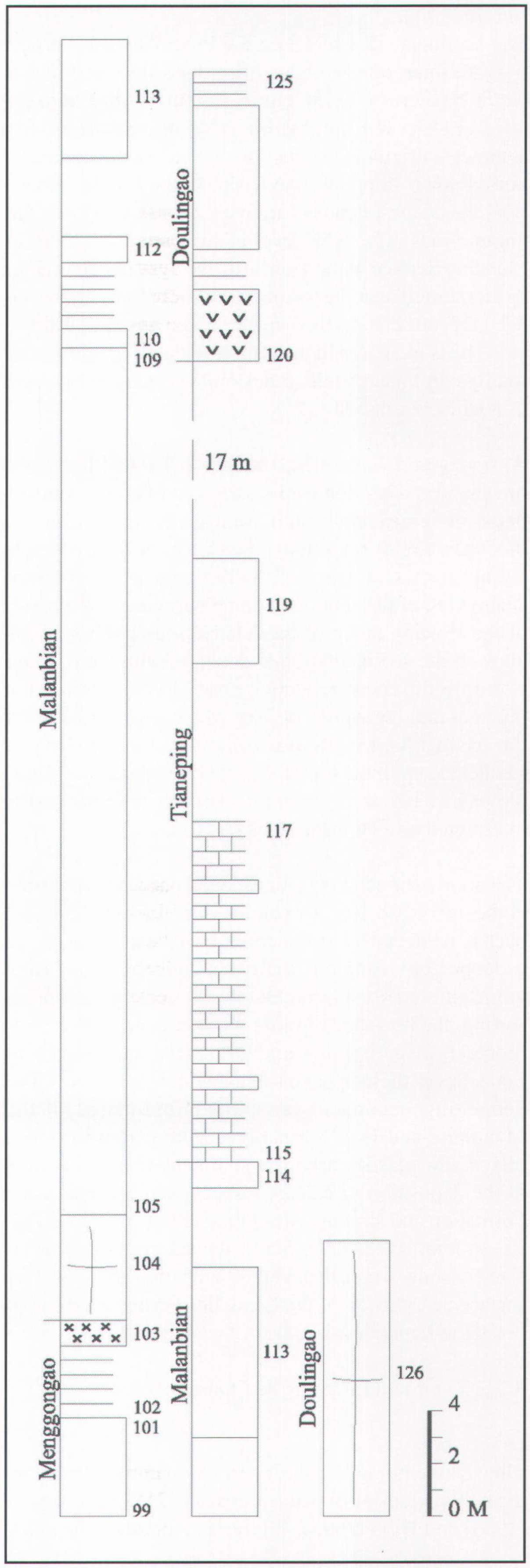


**Figure 8.** Log of the section at Malanbian.

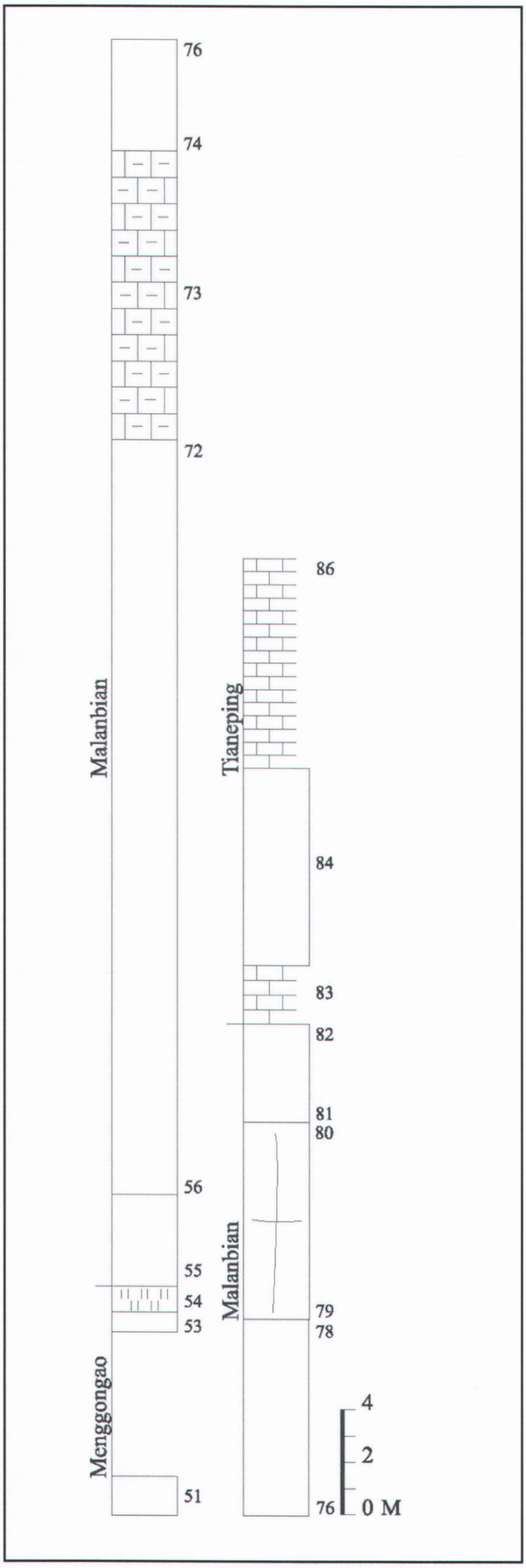


Figure 9. Log of the section at Sujiaping.

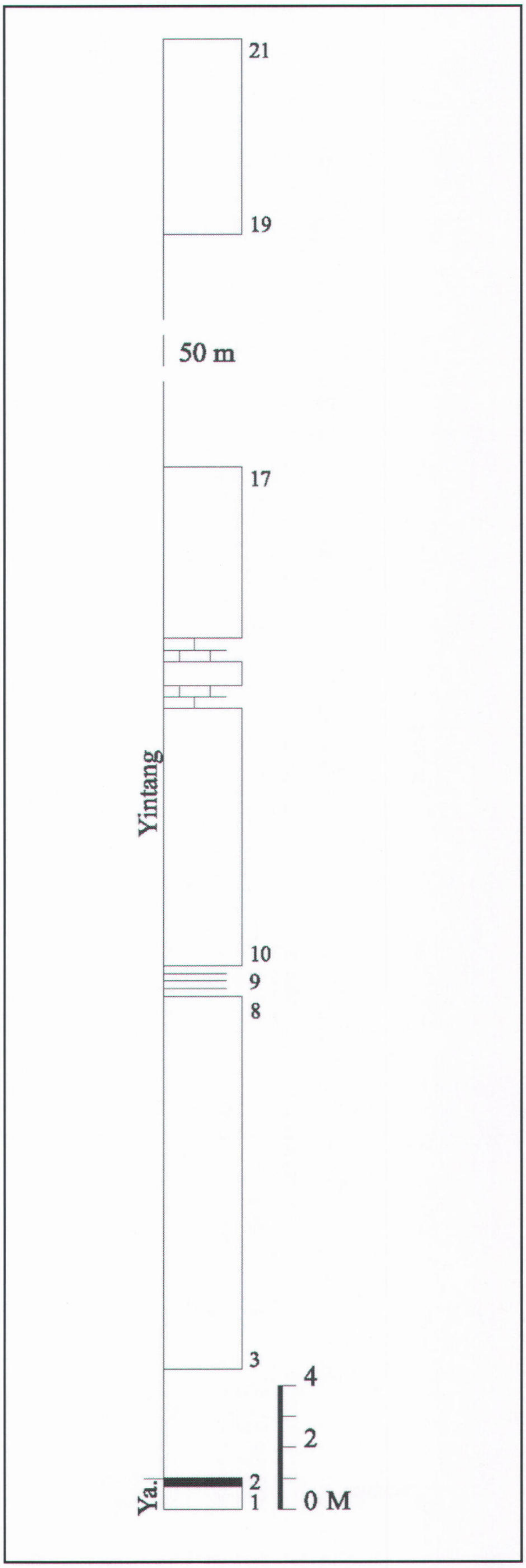


**Figure 10.** Log of the section at Luojia. Ya. = Yaoyunlin.

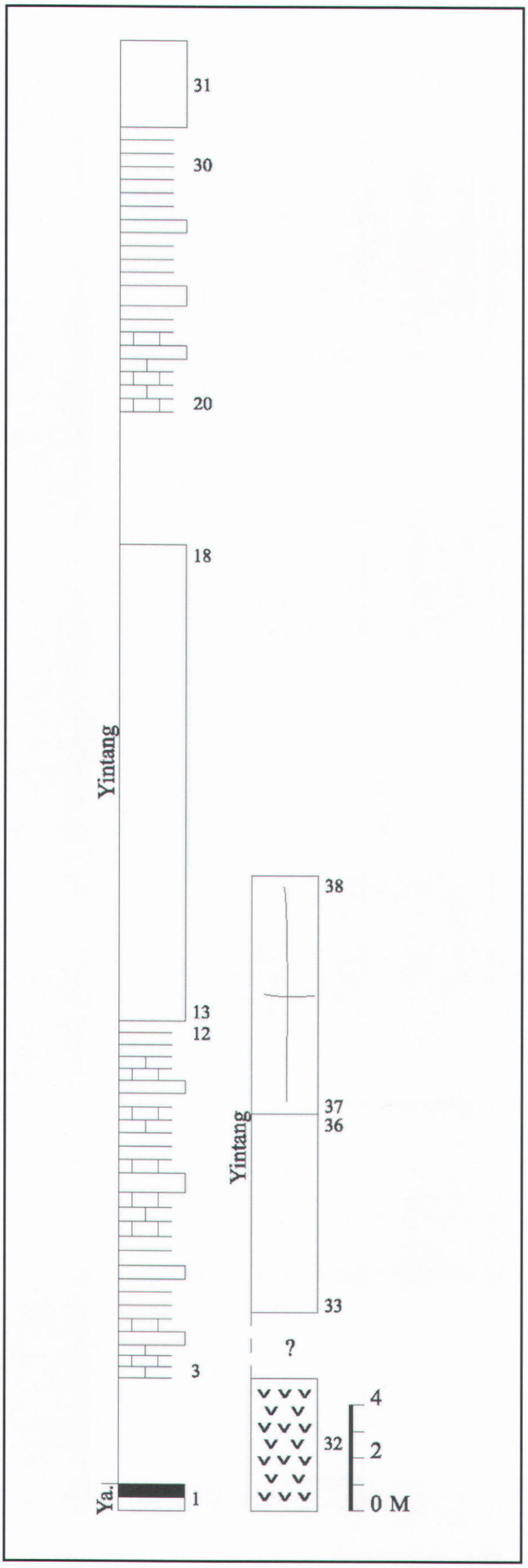


**Figure 11.** Log of the section at Shifendong. Ya. = Yaoyunlin.

*Interpretation*

The fossiliferous mud-, wacke- and packstones of the Menggongao Formation at Malanbian were deposited below to near wave-base. The bioclastic, peloidal wacke- to packstones of the Sujiaping section also indicate a sedimentation environment near fairweather wave-base where sporadic water agitation can carry away part of the accumulated mud. The biota points to an open marine setting. These deposits are interpreted as a Highstand Systems Tract (Hance et al., 1993).

The siliciclastic sediments at Malanbian as well as the fenestral limestones at Sujiaping have been deposited in response to a significant lowering of relative sea-level in a nearshore, shallow water environment. They are interpreted as a Forced Regressive Wedge Systems Tract that is capped at the top by the Sequence Boundary that marks the lowest position of relative sea-level (Hance et al., 1993).

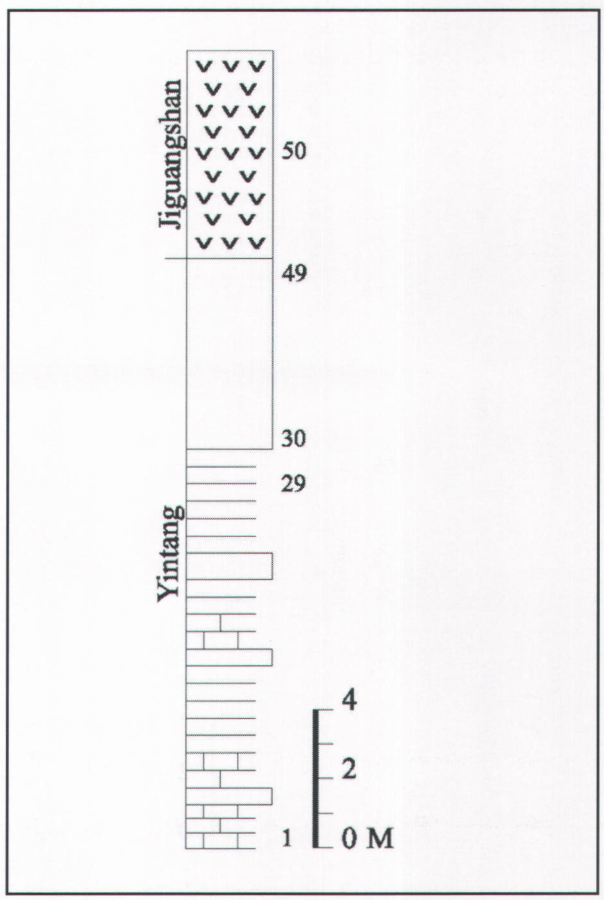


**Figure 12.** Log of the section at Jiguangshan.

3.2.2. Malanbian / Yaoyunlin Formation

*Description*

The lower part of the Malanbian Formation at Malanbian (bed 104; fig. 8) is a pack-to grainstone unit with peloids, clasts and micritised grains. The clasts are irregular in shape, 200 µm to 1 mm large and contain relicts of bioclasts. The very intense micritisation prohibits a more detailed identification. The biota is not very diverse and contains crinoids, bivalves, calcispheres and echinoid spines. From bed 105 to bed 109, the limestones are made up of wacke- to packstones with an open marine biota of crinoids, bryozoans, bivalves, ostracods, foraminifers, echinoid spines and brachiopods as well as peloids, clasts, micritised grains and sporadically aggregate grains (Pl. 2\C). The upper part of bed 109 is again a peloidal, bioclastic grainstone (Pl. 2\D). In the field, several shallowing upward sequences evolving from bioclastic wackestones to peloidal, bioclastic grainstones can be recognised (Muchez, 1996). However, the exact number of sequences has not been determined. Beds 110-112 are made up of bioclastic, clay-rich wackestones with an open marine biota (Pl. 2\E) and shaly intercalations. These beds are followed by a hiatus. Above the hiatus, bed 113 shows a mudstone with a few ostracods, crinoids, sponge spicules and bryozoans at the base grading upwards into more massive pack- to grainstones with a more diverse open marine biota. Again, the section is interrupted by a hiatus. Above this, a limestone bed with a packstone texture and a biota of crinoids, bivalves, ostracods, foraminifers, calcispheres and sponge spicules is present (bed 114). At Sujiaping (fig. 9), the lower part of the Malanbian Formation (bed 55) consists of a bioclastic wackestone with ostracods, calcispheres, algae and gastropods. From bed 56 to bed 72 a transition from bioclastic wackestones with crinoids, bivalves, bryozoans, brachiopods, echinoid spines, ostracods and foraminifers to bioclastic, peloidal grainstones with a similar biota and peloids, clasts and micritised grains can be observed. The intensely micritised clasts contain relicts of bioclasts and are moderately well-sorted. Similar to the Malanbian section, several shallowing upward sequences can be distinguished in the field (Muchez, 1996). These sequences are made up of bioclastic wackestones with an open marine biota at the base and bioclastic, peloidal grainstones with a similar biota at the top. Bed 73 is made up of clay-rich wackestones with an open marine biota and devoid of other allochems. From bed 74 to bed 80, an evolution from bioclastic wacke- to packstones to massive peloidal, bioclastic grainstones can be seen. All these beds contain the same open marine biota of crinoids, bivalves, bryozoans, brachiopods and foraminifers. Beds 81 and 82 are also characterised by an open marine biota but show only a packstone texture. At Luojia (Fig. 10) and Shifendong (Fig. 11), the first beds of both sections (beds 1 and 2 at Loujia; bed 1 at Shifendong) are made up of a peloidal, bioclastic grainstone with a biota of mainly calcispheres and bivalves and small amounts of crinoids and echinoid spines. At both sections these beds are intensely impregnated with iron oxides and hydroxides (Muchez et al., 1998) and followed by an important hiatus. These beds are located near the top of the Yaoyunlin Formation which is time equivalent with the Malanbian Formation (Table 1).

*Interpretation*

The first limestones of the Malanbian Formation in both sections (bed 104 at Malanbian; bed 55 at Sujiaping) have been deposited in a very shallow sedimentation environment. The low diversity of the biota points towards a certain restriction of the marine environment. Yet, these limestones have been deposited in a deeper environment than the sediments that form the top of the Mengonggao Formation (see 3.1.1). They are the result of the first slow rise in relative sea-level following the formation of the Sequence Boundary at the top of the Menggongao Formation (Fig. 13). The creation of accommodation space continues in the following strata (beds 105 to 109 at Malanbian; beds 56 to 72 at Sujiaping) and is reflected by the deposition of a thick sequence of bioclastic wacke- and packstones and peloidal, bioclastic grainstone with an open marine biota. These beds show shallowing upward sequences and an overalll shallowing trend towards the top. The entire sequence of strata from the base of the Malanbian Formation to the top of bed 109 at Malanbian, respectively bed 72 at Sujiaping is interpreted as a Lowstand Systems Tract that formed in response to a slow rise in relative sea-level combined with a sedimentation that could generally keep up with the creation of sedimentation space.

The base of bed 110 at Malanbian and the base of bed 73 at Sujiaping both reflect an important change in water depth. The transition to clay-rich wackestones with an open marine biota, at both locations, combined with the occurrence of true shale levels at Malanbian, point to an important increase in water depth as a result of a sea-level rise that was to rapid for sedimentation to keep up with. The base of these beds is therefore a Transgressive Surface that marks the start of a Transgressive Systems Tract. The exact position of the deepest deposits can not be determined on the bases of the available data but is most likely located in the upper part of bed 73 at Sujiaping where wackestones with a high clay content are encountered.

Above the hiatus at Malanbian (bed 113) and starting from bed 74 to bed 80 at Sujiaping a shallowing upward trend can be observed starting with bioclastic wacke- or mudstones, deposited below wave base, and ending with massive bioclastic, peloidal grainstones, deposited in shallow water above normal wave base. This sequence is the result of the slowing of the relative sea-level rise so that the sedimentation can catch up and progressively fill the available space. Therefore, these beds form a

Highstand Systems Tract. The first beds of the sections at Luojia and Shifendong are most likely also part of this Highstand Systems Tract although the scarce data do not allow more than a tentative correlation.

The base of bed 81 at Sujiaping reflects a renewed deepening of the environment with the transition to bioclastic packstones deposited around wave base. This level is interpreted as the start of the next Transgressive Systems Tract. At Malanbian, equivalent strata are not entirely exposed but the packstone that forms the top of the Malanbian Formation was probably also deposited in deeper water than the massive bed below the hiatus. This makes the position of a Transgressive Surface within the hiatus feasible. At Luojia and Shifendong the presence of iron-impregnated grainstones likely reflects the development of a hardground and an important break in the sedimentation (Flügel, 1982). Such a break in the sedimentation can be related to a rapid rise in sea-level where a so called lag-time is observed before sedimentation starts again (Kendall & Schlager, 1981; Emery, 1996). This indicates that in these sections a Transgressive Surface is situated near the top of the Yaoyunlin Formation.

3.2.3. Tianeping / Lower Yintang Formation

*Description*
At both Malanbian and Sujiaping, the lower part of the Tianeping formation (beds 115 to 117 at Malanbian; beds 83 to 86 at Sujiaping) is made up of dominantly calcareous shales with intercalations of bioclastic wackestones with a biota containing crinoids, bivalves, ostracods, bryozoans and foraminifers. The section at Sujiaping ends with these deposits. At Malanbian they are followed by a hiatus of approximately 6 metres followed by a wacke- to packstone unit (bed 119) with crinoids, bivalves, ostracods, bryozoans, echinoid spines and moravamminids. Above this unit a major hiatus of 17 metres occurs. At Luojia the time equivalent Yintang Formation starts above bed 2, i.e. the iron-impregnated grainstones which form the top of the Yaoyunlin Formation. A hiatus is followed by 12 metres of bioclastic wacke- and packstones with an open marine biota of crinoids, bryozoans, bivalves, brachiopods, foraminifers, echinoid spines and moravaminids (beds 3 to 8). Bed 9 is a 1 metre thick shale unit. The following strata (beds 10 to 17) are again made up of wacke- to packstones with a similar biota as below the shale unit. Some limy shale intercalations can also be recognised. Above these strata a hiatus of at least 50 metres appears in the section. At Shifendong, a similar sequence as at Malanbian and Sujiaping can be observed. The Yintang Formation starts in the hiatus above bed 1. The lower part (beds 3 to 12) consists of mainly shales and calcareous shales with intercalated thin limestone beds that have a wackestone texture and contain an open marine biota. This is followed by a unit of wackestones without shale intercalations (beds 13 to 18). Above a 5 metre hiatus, mostly shaly and calcareous shaly sediments with a number of intercalated packstones (beds 20 to 31) that contain a similar biota as in the lower part and peloids occur. At the section at Jiguangshan (Fig. 12) only the upper part of the time equivalent strata is exposed. These consist of shales and calcareous shales together with thin mudstones containing ostracods, crinoids, sponge spicules and bryozoans (beds 1 to 29) (Pl. 2\F). The beds 30 to 49 contain a more diverse open marine biota together with peloids and have a pack- to grainstone texture (Pl. 2\G).

*Interpretation*
The sediments of the Tianeping and the lower part of the Yintang Formations were deposited below to around wave base (shales, calcareous shales, mudstones and wacke- to packstones respectively). This is the result of a continued rapid sea-level rise that started near the top of the Malanbian and Yaoyunlin Formations (see 3.2.2). During a certain period of time, the sea-level rise appears to have slowed down which led to the deposition of limestone units (bed 119 at Malanbian; beds 10 to 17 at Luojia; beds 13 to 18 at Shifendong). However, the wacke – and packstone textures of these limestones, the open marine biota and the shale and limy shale intercalations still indicate a relatively deep environment. These units do not reflect a true filling up of the accommodation due to an important slowing down of the sea-level rise. Therefore, the largest part of the Tianeping/Yintang Formation is interpreted as being part of the Transgressive Systems Tract that started at the last beds of the Malanbian/ Yaoyunlin Formation (Fig. 13). The Main Flooding Surface capping the deepest deposits, can not be located exactly in the sections. At Shifendong and Jiguangshan, the Main Flooding Surface is placed within the most pronounced shale level before a more limestone dominated sedimentation reappears. This is bed 30 at Shifendong and bed 29 at Jiguangshan. At Malanbian it is probably situated in the hiatus above bed 119 and at Loujia it is most likely located somewhere within the hiatus above bed 17. This Main Flooding Surface marks the start of a Highstand Systems Tract, that formed during a slowing down of the relative sea-level rise. The first strata of this systems tract are only exposed at Jiguangshan (beds 30 to 49) and Shifendong (bed 31).

3.2.4. Doulingao Formation and middle part of the Yintang Formation with the Jiguangshan Dolomite

*Description*
At Malanbian, the Doulingao Formation starts with bed 120 above the major hiatus. The first unit (beds 120 to 122) is made up of dolomites and shales. This is followed by wackestones with crinoids, bivalves, ostracods, foraminifers, sponge spicules and peloids and a shale unit (beds 123 to 125). Bed 126 is a massive limestone with a packstone texture and a similar open marine biota.

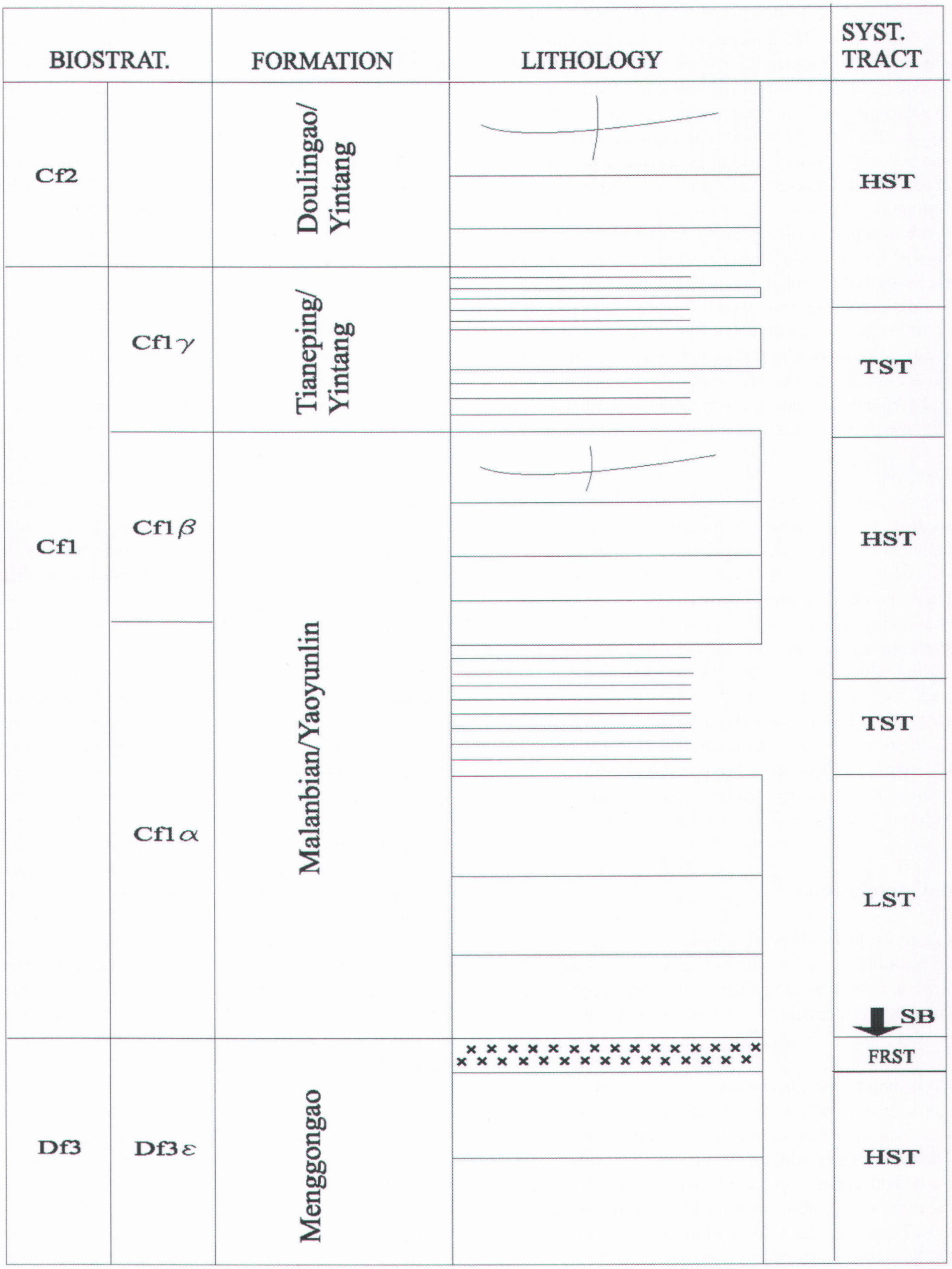


**Figure 13.** Sequence stratigraphical model for Southern China. Not to scale.

Time equivalent strata are partly exposed in the Luojia, Jiguangshan and Shifendong section and form the middle part of the Yintang Formation. At Luojia beds 19 to 21 belong to this formation and are composed of wacke- to packstones with an open marine biota and peloids. At Jiguangshan, a sedimentological study of these strata is hampered by a pervasive dolomitisation. These dolomites are called the Jiguangshan Dolomite. At Shifendong, the formation starts at level 32 with a massive dolomite unit that is also part of the Jiguangshan Dolomite. The thickness of this unit could not be determined precisely but the strata that appear above it are still part of the Yintang Formation. These strata (beds 33 to 38) show a gradual change from bioclastic wackestones with crinoids, bivalves, bryozoans, moravamminids and echinoid spines to packstones that contain a similar biota as well as peloids and eventually grainstones with peloids, micritised grains and intensely micritised clasts.

*Interpretation*
The exposure of the strata is not optimal in the sections studied and the presence of intensely dolomitised strata hampers a detailed interpretation of the facies evolution. However, the overall trend in the lower part of the Doulingao Formation is characterised by a progressive shallowing upward of the sedimentation environment starting with the deposition of bioclastic wackestones and ending with more massive units of peloidal, bioclastic pack- to grainstones (beds 123 to 126 at Malanbian; beds 19 to 21 at Luojia; beds 33 to 38 at Shifendong). This shallowing upward is the continuation of the trend that started near the top of the Tianeping/Lower Yintang Formations and is interpreted to be part of that Highstand Systems Tract (see 3.2.3) (Fig. 13).

## 4. Correlation

Figure 14 shows, together with the biostratigraphy based on foraminifers, a comparison between the Tournaisian strata in Belgium and Southern China. An important similarity in the sedimentary evolution of the two areas can be observed.

According to Van Steenwinkel (1988, 1990, 1993) and Hance et al. (1993) the Devonian wacke- and packstones were deposited during a highstand in relative sea-level. The top of the Devonian is a sediment unit that was deposited during an important lowering of sea-level and is therefore interpreted as a Forced Regressive Wedge Systems Tract. The top of this systems tract, coinciding with the Devonian-Carboniferous boundary, is the Sequence Boundary that reflects the lowest position of relative sea-level. Three types of Sequence Boundaries can be distinguished. A Type 1 Boundary develops in response to relative sea-level fall and is associated with an abrupt basinward shift of coastal onlap characterized by forced regressions and in some cases fluvial incision (Posamentier & Vail, 1988). Type 2 Boundaries develop in response to decelerating and accelerating relative sea-level rise. In this case no relative sea-level fall occurs because the maximum rate of eustatic fall never quite attains the rate of subsidence. This Boundary is characterized by an abrupt basinward shift of coastal onlap without forced regressions and significant fluvial incision. (Posamentier & Vail, 1988). Schlager (1999) recently defined a Type 3 Boundary as the combination of a Highstand Systems Tract immediately followed by a Transgressive Systems Tract without a recognizable sea-level fall or lowstand deposits in between. In general, the distinction between Type 1 and Type 2 Boundaries is difficult when sedimentation occurred on a ramp as is the case here (Tucker et al., 1993). However, the Forced Regressive Systems Tract that was identified below the Devonian-Carboniferous boundary indicates that the Sequence Boundary at this level is, most likely, of Type 1. The slow rise of relative sea-level that follows the formation of the Sequence Boundary creates accommodation for the deposition of the Hastière Formation in Belgium and the lower part of the Malanbian/Yaoyunlin Formations in Southern China. In both areas, a number of shallowing upwards cycles can be distinguished. These parasequences are superimposed on the overalll shallowing trend. The strata are interpreted as a Lowstand Systems Tract that is located in the Cf1$\alpha$-biozone. This systems tract is succeeded by an important deepening in the sedimentation environment, reflected in the Pont d'Arcole Shale and the middle, shaly part of the Malanbian/Yaoyunlin Formations. This Transgressive Systems Tract is also of Cf1$\alpha$-age. The limestones of the Landelies Formation and the upper part of the Malanbian/ Yaoyunlin Formations are interpreted as a Highstand Systems Tract that spans the upper part of the Cf1$\alpha$- and the largest part of the Cf1$\beta$ -biozone. Near the top of these formations, just below the base of the Cf1$\gamma$-biozone, a deepening occurs that marks the start of a new Transgressive Systems Tract that contains the Maurenne/Hun Formations and the major part of the Tianeping/Lower Yintang Formations and reaches its maximum in the lower part of the Yvoir Formation and near the top of the Tianeping/Lower Yintang Formations in the Cf1$\gamma$-biozone. The base of this Transgressive Systems Tract is interpreted as a Sequence Boundary. This Sequence Boundary shows no evidence of a drop in relative sea-level and is therefore a Type 3 Boundary (Schlager, 1999).The upper part of the Yvoir Formation and the Encrinite de l' Ourthe in Belgium and the upper Tianeping/Lower Yintang and the lower part of the Doulingao/Middle Yintang Formations in Southern China form a Highstand Systems Tract that starts in the Cf1$\gamma$-biozone and spans the entire Cf2-biozone.

The duration of the sequences in the Tournaisian can be calculated taking into account the time span of the

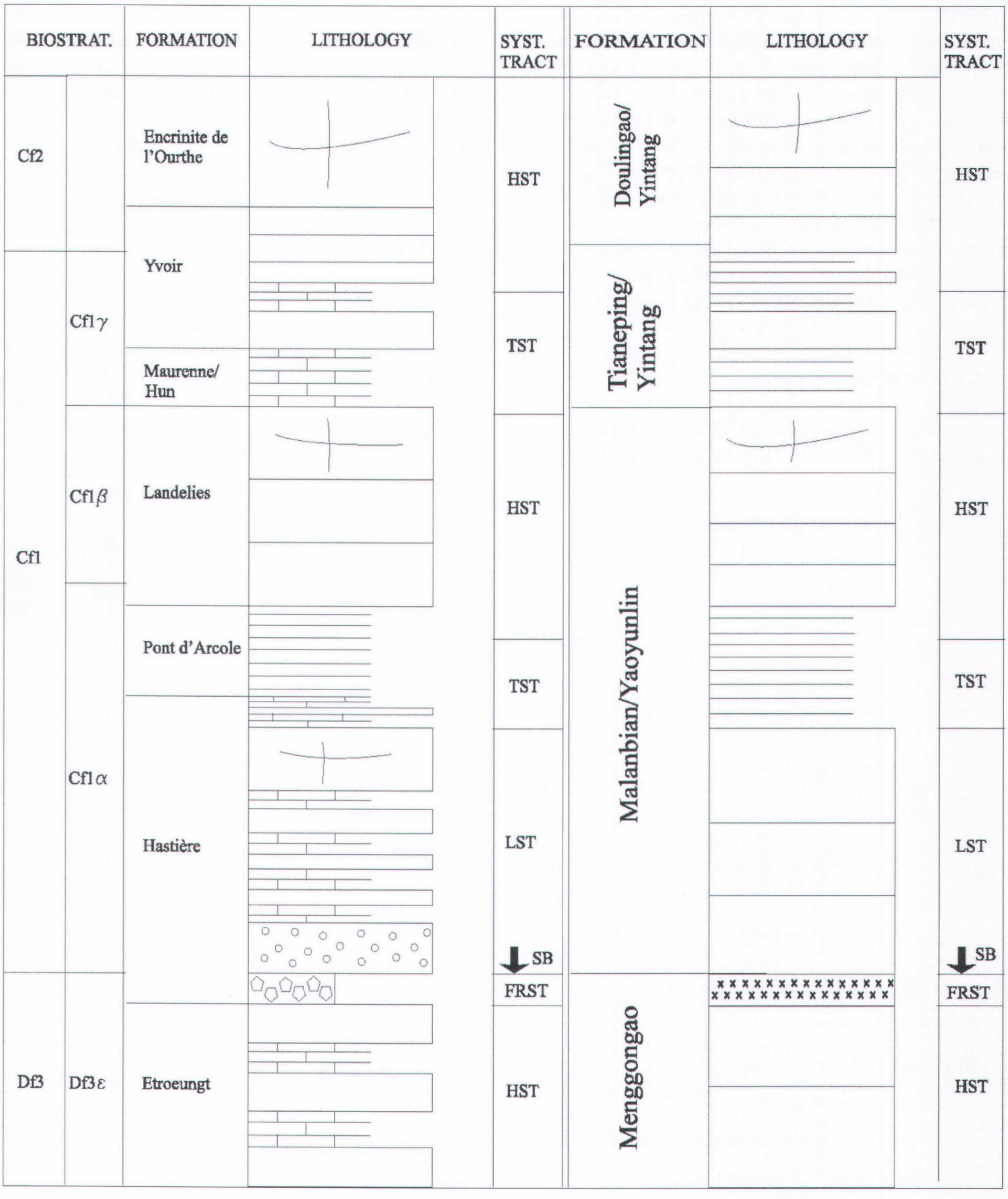


**Figure 14.** Correlation of the areas studied based on the sequence stratigraphical models. Not to scale.

biozones based on Ross & Ross (1987). The first sequence, starting at the Devonian-Carboniferous boundary and ending near the top of the Landelies Formation in Belgium and the Malanbian/Yaoyunlin Formations in Southern China spans the entire Cf1α-zone and the largest part of the Cf1β-zone. The duration of the Cf1α-zone is approximately 1 Ma, that of the Cf1β-zone approximately 500 ka. Taken this into account, the duration of the first Tournaisian sequence is estimated to be 1.5 Ma. The next sequence starts at the top of the Landelies Formation in Belgium and the Malanbian/Yaoyunlin Formations in Southern China and ends at the top of the Encrinite de l'Ourthe in Belgium and within the Doulingao/Yintang Formations in Southern China. It covers the entire Cf1$\gamma$- and Cf2-zones. The duration of these zones is 400 ka and 3.6 Ma respectively. The duration of the entire cycle is approximately 4 Ma. These time periods indicate that the sequences are third order sequences (0.5 to 5 m.y.). Vail et al. (1977) interpreted thirth order sequences to be the result of waxing and waning of continental ice sheets. However, Tucker & Wright (1990) pointed out that they can also be the result of a combination of tectonic extension and the consequent thermal subsidence. Based on the information obtained in this study, it is impossible to determine which process was the cause of the interpreted sea-level changes.

## 5. Conclusion

In this study, a sedimentological investigation of the Tournaisian strata in Belgium and Southern China was carried out and a sequence stratigraphical model for both areas was constructed. A correlation of these two models, based on third order sequences, reveals a striking similarity between the sedimentological evolution in these two widely separated areas. This indicates a strong eustatic control on the sea-level changes that caused these changes in the sedimentology during the Tournaisian.

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## Plate 1.

Microfacies types of the Tournaisian strata at the Yvoir (Y) and Landelies (L) sections (Southern Belgium). Scale bars are 167 μm.

A) Bioclastic, clay-rich wackestone – Y 71

B) Silty micrite – L 62

C) Bioclastic packstone – Y 75

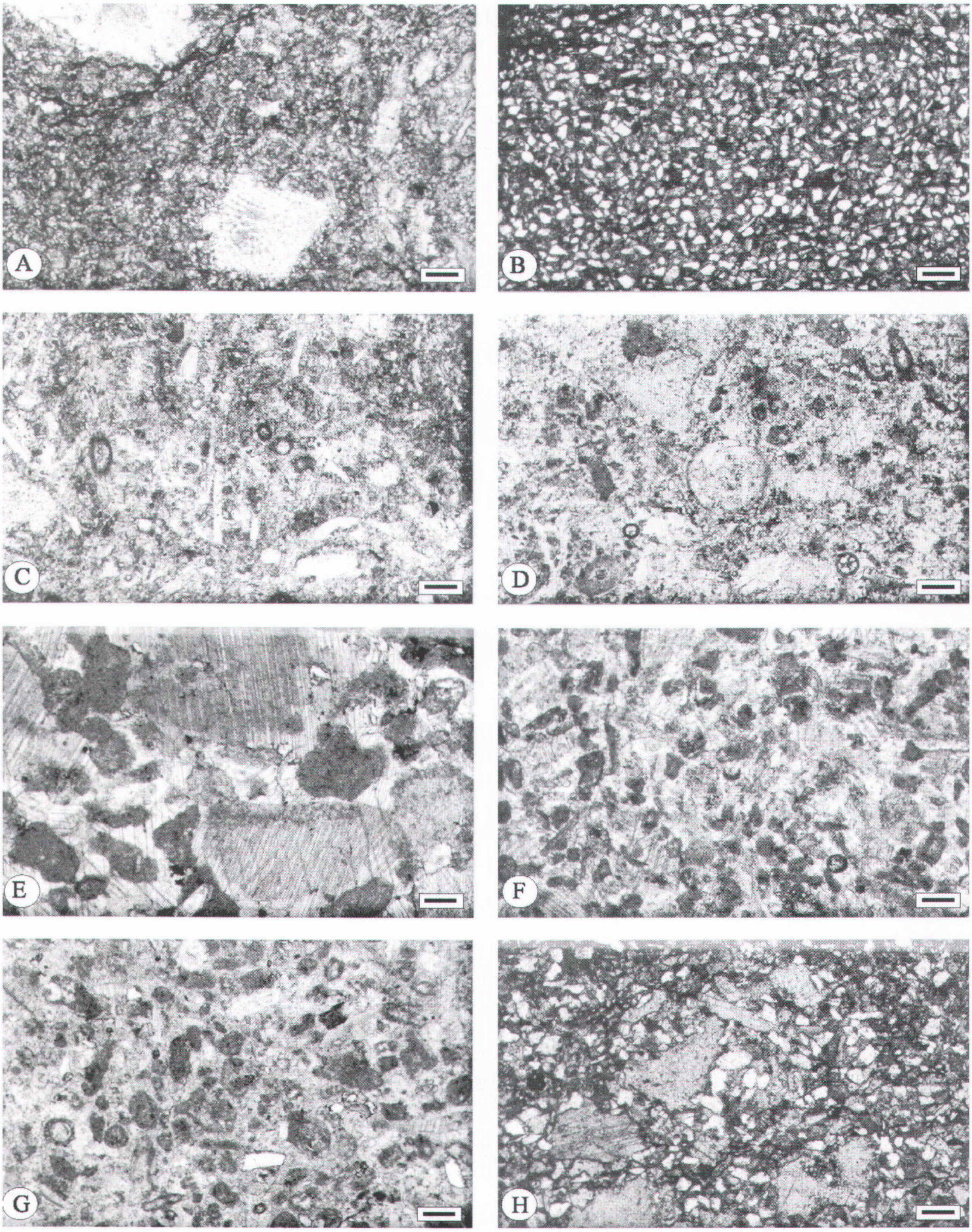
D) Bioclastic, peloidal packstone – Y 88c

E) Poorly sorted, crinoidal grainstone with intensely micritised clasts – L 91

F) Well sorted, peloidal, crinoidal grainstone - Y 104a

G) Bioclastic, peloidal packstone – L 87

H) Silty, crinoidal packstone – Y 121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# Plate 2.

Microfacies types of the Tournaisian strata at the Malanbian (M) and Jiguangshan (J) sections (Southern China). Scale bars are 167 µm.

A) Bioclastic packstone – M 100

B) Sandstone – M 103

C) Bioclastic, peloidal wackestone – M 108b

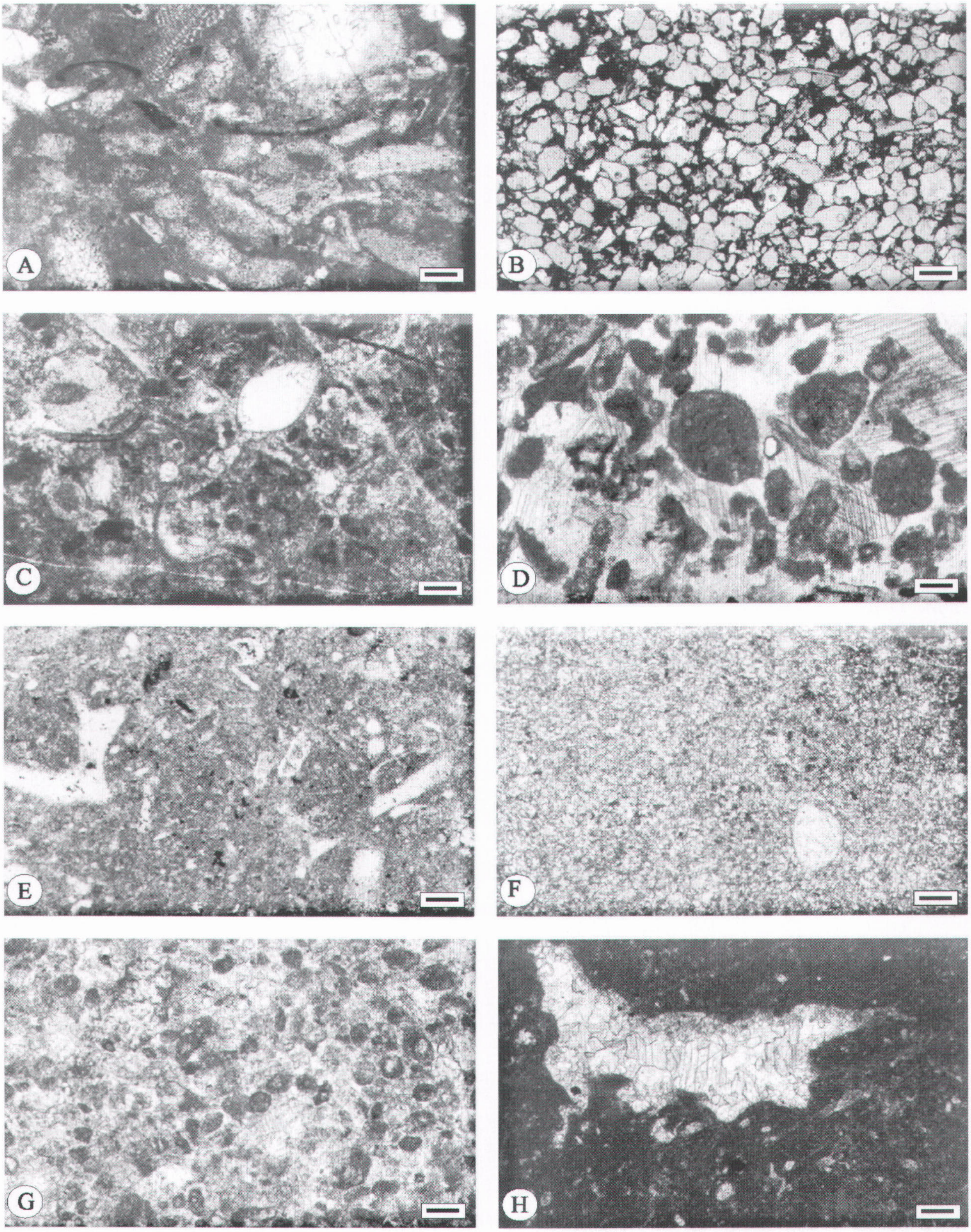
D) Peloidal, bioclastic grainstone – M 109b

E) Bioclastic wackestone – M 111b

F) Mudstone – J 5

G) Bioclastic, peloidal packstone – J 38

H) Fenestral mudstone– M 140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