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Sequence stratigraphy of the Frasnian–Famennian transitional strata: a comparison between South China and southern Belgium

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Abstract

The sedimentological evolution of the Frasnian–Famennian transitional strata in South China and southern Belgium has been investigated. A similar trend in the deepening and shallowing of the sedimentation environment occurs in the two palaeogeographically distinct areas. The stratigraphic succession has been subdivided into depositional sequences. A general deepening occurs in the *Palmatolepis rhenana* conodont zone. During the most rapid rise in sea level, a transgressive systems tract formed. This transgressive systems tract is followed by a highstand systems tract in the late *P. rhenana* zone. A major sequence boundary within the latter zone is indicated by an unconformity in intraplatform and platform areas and by a conformity in the basinal area. The uppermost sediments within the late *rhenana* zone correspond to a lowstand systems tract. A rapid flooding took place near the base of the *Palmatolepis linguiformis* zone and dark shales and limestones formed. A second sequence boundary coincides with or is very close to the Frasnian–Famennian boundary (base *P. triangularis* zone). The global extinction event at the Frasnian–Famennian boundary coincides with an important eustatic fall in sea level. The proposed stratigraphic subdivision should allow worldwide correlations of shallow and deep water deposits.

1. Introduction

The Frasnian–Famennian (F/F) boundary is one of the five major "bio-events" known in Phanerozoic times (Raup and Sepkoski, 1982). It has been identified as the latest Frasnian "Kellwasser event" (Sandberg et al., 1988; Walliser et al., 1989). At a few localities, geochemical anomalies have been found in the Frasnian and Famennian strata. Ir anomalies have been recorded from the Canning basin, Western Australia (*crepida* zone; Playford et al., 1984) and from South China (Wang et al., 1991). Positive $\delta^{13}C$ anomalies occur in Poland (Halas et al., 1992), Germany, France and Austria (Buggisch, 1991; Joachimski and Buggisch, 1993) and a negative $\delta^{13}C$ anomaly in South China (Yan et al., 1993). Glass spherules, similar to microtektites, have been found near the F/F boundary in southern Belgium (Claeys et al., 1992; Claeys and Casier, 1994). These anomalies and occurrences have been related to an asteroidal impact which also caused the Late Devonian worldwide benthic mass extinction (Wang et al., 1991; Claeys et al., 1992). However, the major problem is to demonstrate successfully the link between impact and extinction (e.g. Claeys and

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Casier, 1994). The biostratigraphic resolution available for the Upper Devonian may not permit such a correlation, especially in shallow water environments where the characteristic conodonts are absent. The sea-level curve (Johnson et al., 1985) and especially the event stratigraphy reconstructed for this period (Sandberg et al., 1992) partly resolve this problem. Detailed worldwide correlations can be obtained from sequence stratigraphy (Haq et al., 1987, 1988). Sequence stratigraphy allows the subdivision of transgressive–regressive cycles in the record into systems tracts that are genetically related to a particular rate of relative sea-level rise or fall. In the Palaeozoic, lateral correlations have been made for the Devonian–Carboniferous boundary between Belgium, Germany and south China (Van Steenwinkel, 1992; Hance et al., 1993).

The aim of this study is to propose a sequence stratigraphic framework for the F/F transitional strata which permits detailed correlation, essential to test the proposed relationship between mass biotic extinction and asteroidal impact in further studies. We have investigated the Upper Devonian in South China and southern Belgium (Fig. 1).

2. Geological setting

Late Devonian sedimentation in South China took place in an epicontinental sea on the southern margin of the south China plate, whereas the northern part was a landmass that provided siliciclastics. Mixed siliciclastic-carbonate sediments were deposited in intraplatform depressions, limestones on shallow platforms and siliceous carbonates and shales in intraplatform basins. Three sections have been studied: the Laojiangchong (intraplatform facies), the Lijiaping (platform facies) and the Luoxiu section (basinal facies). In the Luoxiu section, the F/F boundary is biostratigraphically well-defined (Ji, 1989) and is marked by a 20-cm thick mudstone (bed *E* in Fig. 2). Due to the scarcity of standard zonal conodonts in the intraplatform and platform facies, the exact position of the boundary is difficult to determine at Laojiangchong and Lijiaping. Based on the available litho- and biostratigraphic criteria, Hou et al. (in press) placed the boundary at the top of black shales and limestones (Fig. 3), which separate strata with Frasnian megafossils from strata with possibly Famennian shallow water conodonts.

Palaeogeographically, southern Belgium was situated at the northern margin of the Cornwall–Rhenish Basin. During the Late Devonian, the latter was characterized by back-arc extension and rapid subsidence (Leeder, 1987). In the Frasnian type region mudmounds occur. These are overlain by the black Matagne Shale, an anoxic facies, comparable to the Upper Kellwasser Limestone of Germany, and by the Famenne Shale. The F/F boundary occurs approximately between the Matagne and Famenne Shale.

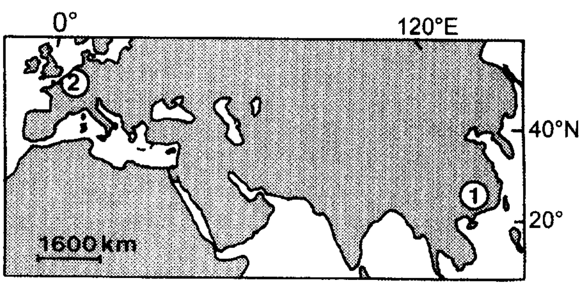

Fig. 1. Location of the studied area in South China (*1*) and Belgium (*2*).

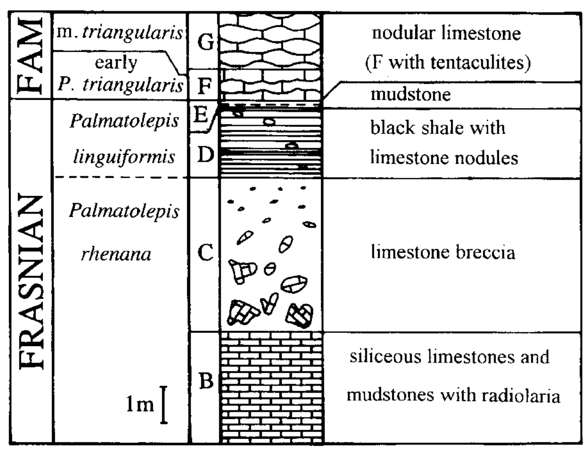

Fig. 2. Lithological log of the Frasnian–Famennian transitional strata in the Luoxiu section (partly after Wang et al., 1991 and Hou et al., 1992).

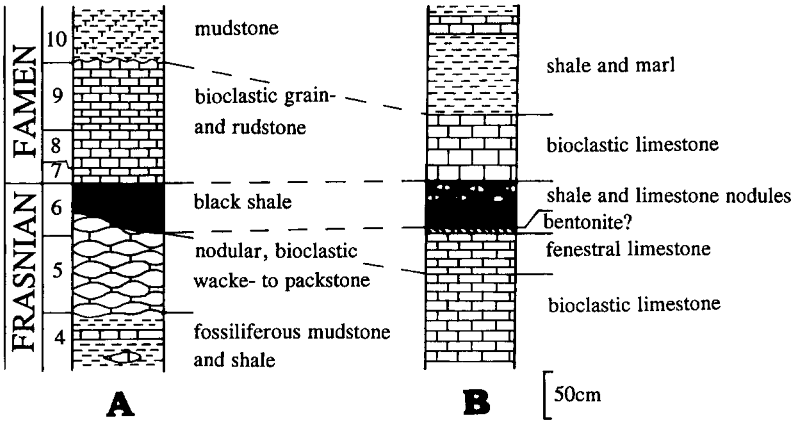

Fig. 3. Lithological log of the Frasnian–Famennian transitional strata in the Laojiangchong (A) and Lijiaping (B) section (partly after Hou et al., in press).

3. Sedimentological evolution

3.1. South China

During the *Palmatolepis rhenana* zone, an alternation of siliceous limestones and mudstones with radiolaria and ostracods were deposited in the intraplatform basin in South China (Fig. 2). These basinal limestones (bed B) are followed by limestone breccias (bed C). The fragments of this breccia are boundstones partly composed of *Renalcis* and *Epiphyton*, which were derived from the nearby carbonate platform as debris flows (Wang et al., 1991). Similar boundstones form shallow water buildups at the shelf margin (James and Gravestock, 1990). During the *Palmatolepis linguiformis* zone, organic-rich black shales and limestone nodules with bivalves and radiolaria (bed D) developed. Bed E is a brown mudstone with silt-size quartz crystals and micas. In the early *Palmatolepis triangularis* zone, pseudonodular limestones with tentaculites and bivalves (bed F) were deposited in an open marine neritic environment. The tentaculites only occur in the lower part of bed F. The middle *triangularis* zone consists of nodular limestones intercalated with lenticular bioclastic limestones (Hou et al., 1992; Yan et al., 1993).

In the Laojiangchong section, open marine to lagoonal shales and limestones are present in the upper part of the Frasnian (Hou et al., in press). The top of unit 5 (Fig. 3) is truncated and followed by black organic-rich shales (unit 6), indicating anoxic conditions. These anoxic sediments contrast with the overlying grainstones and rudstones (units 7–9) containing a fully open marine biota (e.g. bryozoa, brachiopods, crinoids). This shallow water limestone succession, deposited above wave base, was subsequently drowned, causing the development of a thick mudstone unit (unit 10). A similar evolution can be recognized in the sediments of the Lijiaping section. However, intertidal, fenestral and algal limestones and a possible bentonite layer occur between the shallow open marine limestones and the anoxic shales (Fig. 3).

3.2. Southern Belgium

During the *Palmatolepis rhenana* zone, mudmounds developed during a general rise of relative sea level (Boulvain, 1993). In the mudmounds (type "Les Bulants"), deep red limestones with mainly sponge spicules as macrofossils evolve to light red limestones dominated by platy corals and stromatoporoids, grey coral–algal packstones and grainstones and grey cryptalgal bindstones (Boulvain and Coen-Aubert, 1991; Bourque and Boulvain, 1993). This evolution reflects a shallowing of the environment during a minor drop of relative sea level (Boulvain, 1993). The "Les Bulants" type mudmounds are overlain by shales indicating the drowning of the mounds and the continuation of the major rise of relative sea level (Fig. 4). Subsequently, another type of mudmound developed, i.e. "Les Wayons-Hautmont". The same evolution as in the "Les Bulants" type has been recognized, reflecting again a fall of relative sea level. However, this drop was more important than the first one because it caused an important increase in the diameter of the mudmound and the deposition of oncolitic shoals in the internal parts of the ramp (upper part of the Aisemont Formation, Fig. 4). According to Sandberg et al. (1992), the top of the "Beauchâteau" mudmound (a "Les Wayons-Hautmont" type mudmound) has been karstified. Debris flow deposits, including large boulders and cobbles with a facies similar to that of the mudmounds, have been observed in the intermound facies around Beauchâteau and Hautmont. These boulders and cobbles formed during a fall of relative sea level. The grey cryptalgal bindstones at Hautmont (Fig. 4) were followed by red limestones, firstly with platy corals and stromatoporoids and secondly with sponge spicules (Boulvain and Coen-Aubert, 1991). The mudmound was drowned and shales were deposited. Near the top of the *linguiformis* zone two changes in the conodont biofacies pattern are present: a decrease of the percentage of *Palmatolepis* taxa and a simultaneous increase of the percentage of *Icriodus* taxa and subsequently the almost complete disappearance of the Palmatolepids (Sandberg et al., 1988). These conodont-biofacies changes have been interpreted to reflect a major eustatic fall, immediately preceding the Frasnian mass extinction (Sandberg et al., 1988). The level at which the *Palmatolepis* conodonts almost completely disappear forms also the boundary between bioclastic limestones and shales with coquina layers. The coquina layers have been interpreted as storm deposits and are a characteristic feature of the earliest Famennian deposits (Sandberg et al.,

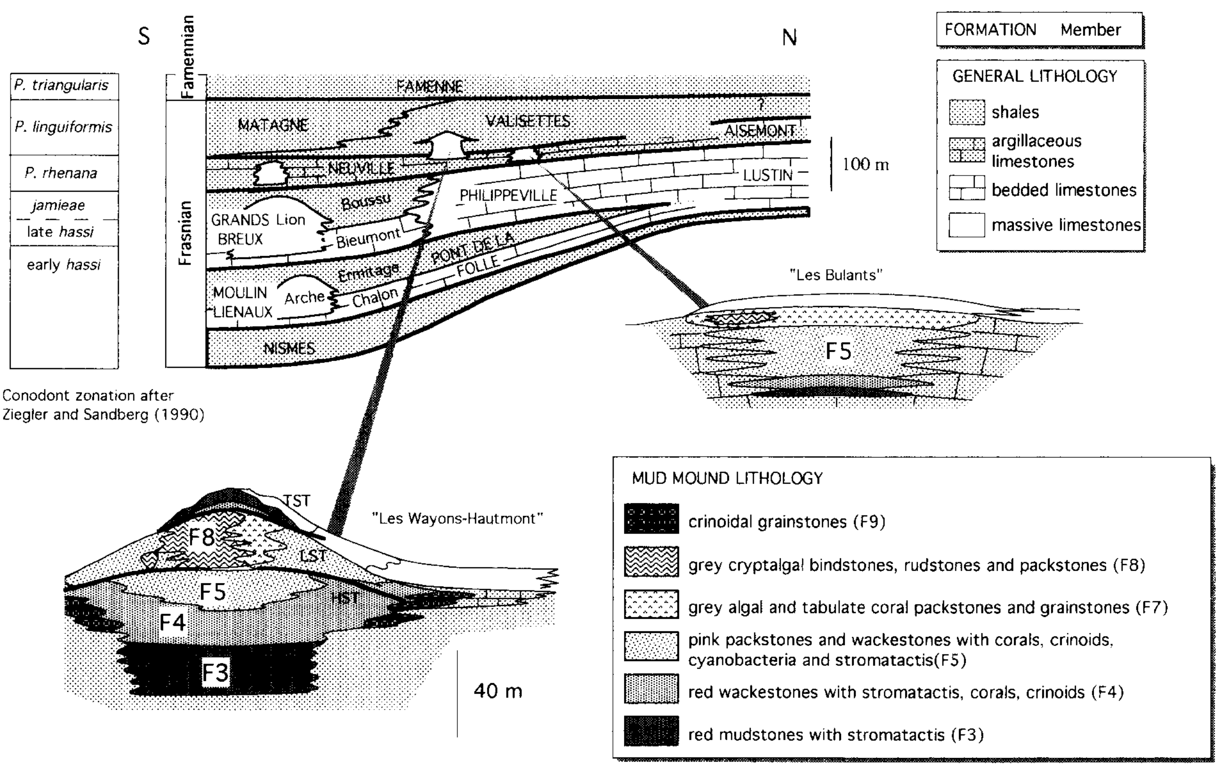

Fig. 4. Cross-section through the Frasnian–Famennian transitional strata of southern Belgium and detail of the facies evolution in the Frasnian mudmounds ($F=$ facies).

1988). In southwest Belgium, an unconformity, occurring at the top of an Upper Frasnian mudmound at Rance, is followed by *P. triangularis* nodular shales (Biron et al., 1983).

4. Sequence stratigraphy

4.1. South China

A similar trend in the deepening and shallowing of the sedimentation occurs in the Frasnian–Famennian transitional strata, deposited in the intraplatform basin and on the platform. The most prominent changes in the succession are the result of the highest rate of relative sea level rise or fall. They are represented in the rock record as key surfaces, which allow a subdivision into depositional sequences.

A first major change in the succession is indicated by the unconformity between unit 5 and 6 at Laojiangchong and by the conformity between the basinal limestones (unit B) and the debris flow deposits (unit C) at Luoxiu. The unconformity and the conformity in the basinal sediments represent a sequence boundary. In the Lijiaping section this sequence boundary has been recognized between the open marine limestones and the intertidal, fenestral and algal limestones. The second key surface is interpreted to occur between the debris flow deposits and the intertidal limestones on the one hand and the black shales with limestone nodules on the other hand. In the Laojiangchong section, the transition from limestones to black shales corresponds with the unconformity. In the three sections, this surface forms a transgressive surface (e.g. Van Wagoner et al., 1988) over which final flooding occurred. A third major change in the succession occurs between the black shales and the shallow water limestone deposits at Laojiangchong and Lijiaping. It is also present between the black shale with limestone nodules and the quartz-rich mudstone with micas at Luoxiu. The surface across which the sudden shallowing took place is interpreted as a sequence boundary. A fourth key surface occurs between the shallow water limestone succession of units 7–9 and the deeper water mudstones of unit 10. It is a transgressive surface formed by the drowning of the platform.

The bioclastic limestones (unit 5) and the siliceous basinal limestones and mudstones (unit B) below the sequence boundary represent a highstand systems tract (HST). The intertidal fenestral and algal limestones (Lijiaping) and the debris flow deposits (Luoxiu) above the sequence boundary could have formed during a lowstand of relative sea level (lowstand systems tract, LST). Schlager et al. (1994) suggested that major gravity flow deposits form during a highstand, when carbonate productivity on the platform was high. However, no high productivity was needed to form the thin debris flow deposits at Luoxiu. The organic-rich shales and limestones above the transgressive surface formed as a result of the drowning of the platform during a transgressive systems tract (TST). In this succession of siliciclastic sediments and limestones, no maximum flooding surface has been recognized between the transgressive surface at its base and the sequence boundary at its top. However, it is often very difficult to recognize this surface in isolated outcrops. Therefore, it is possible that part of the organic-rich shales and limestones represent a highstand systems tract. During the lowstand of relative sea level succeeding the sequence boundary at or near the top of the *linguiformis* zone, the shallow open marine limestones of units 7–9 at Laojiangchong and Lijiaping and likely the mudstone with quartz and micas at Luoxiu have been deposited. On the platform, the limestone succession was subsequently drowned and shales and marls sedimented above the transgressive surface.

4.2. Southern Belgium

Here too, several key surfaces have been recognized in the stratigraphic succession, which allow its subdivision into depositional sequences. The surface between the shales, overlying the "Les Bulants" type mudmounds, and the "Les Wayons-Hautmont" mudmounds could represent a maximum flooding surface. However, this interpretation remains speculative. The karstified top of the Beauchâteau mudmound forms a sequence boundary. This boundary also occurs between the light red limestones dominated by platy corals and stromatoporoids and the grey cryptalgal bindstones in the upper part of other "Les Wayons-Hautmont" type mudmounds (Fig. 4) and between the flank of these mudmounds and the debris flow deposits. A second key surface is present between the sudden transition from grey cryptalgal bindstones to red limestones (Fig. 4). This level, above which a significant deepening of the sedimentation environment occurred, is a transgressive surface. The level at which the *Palmatolepis* taxa almost completely disappear and which is the boundary between bioclastic limestones and shales is interpreted as a sequence boundary (see also Sandberg et al., 1988).

If the surface between the shales and the "Les Wayons-Hautmont" mudmound is a maximum flooding surface, then the shales were deposited during a TST and the mudmound represents a HST. The shallow water grey cryptalgal bindstones above the sequence boundary at Hautmont and the debris flow deposits at Beauchâteau formed during a lowstand. The transgressive surface is followed by a TST consisting of red limestones with platy corals and stromatoporoids, of red limestones with sponge spicules and of shales. The evolution in the facies reflects a gradual deepening of the sedimentation environment in the lower part of the *linguiformis* zone. Finally, a sequence boundary occurs near or at the top of the *linguiformis* zone. The storm deposits above this sequence boundary are interpreted as lowstand deposits. At this sequence boundary, the late Frasnian mass extinction occurred (Sandberg et al., 1988). A relation between extinction and a sequence boundary has also been recognized at the Devonian–Carboniferous boundary (Van Steenwinkel, 1993).

4.3. Correlation between South China and southern Belgium

To apply a sequence stratigraphical correlation between the investigated areas, the contemporaneity of the key surfaces has to be demonstrated. In South China, a sequence boundary has been identified at the base of intertidal limestones (Lijiaping) and of debris flow deposits (Luoxiu), which formed during the late *rhenana* zone (Hou et al. 1988, 1992; Ji, 1988, 1989). A sequence boundary within the late *rhenana* zone is also present in Belgium. The karst at the top of the Beauchâteau mudmound developed in the late *rhenana* conodont zone (Sandberg et al., 1992). Other "Les Wayons-Hautmont" type mudmounds in which this sequence boundary also has been determined, occur in the late *rhenana* zone (F2j mudmounds, Boulvain and Coen-Aubert, 1991; Sandberg et al., 1992). The transgressive surface at the base of the black shales with limestone nodules in the Luoxiu, Laojiangchong and Lijiaping sections has been dated at the base of the *linguiformis* zone (Hou et al., 1988; Ji, 1988, 1989). The late Frasnian transgressive surface present near the top of the "Les Wayons-Hautmont" mudmounds also occurs at the base of the *linguiformis* zone (Sandberg et al., 1992). The second sequence boundary recognized in southern China, present at the top of the black shales with limestone nodules, has been dated at the top of the *linguiformis* zone (Hou et al., in press; Ji, 1989; Wang et al., 1991). In Belgium, the sequence boundary identified by the sudden change in the facies and in the conodont population, occurs at or near the top of the *linguiformis* zone (Sandberg et al., 1988).

Detailed biostratigraphic data clearly indicate that the identified sequence boundaries and the transgressive surfaces in South China and southern Belgium developed contemporaneously. They formed as a response to a eustatic sea level fall or rise. The sequence stratigraphy constructed for both areas is identical (Fig. 5). The interpretation of a eustatic sea-level fall at the Frasnian–Famennian boundary is supported by independent evidence of a worldwide drop in relative sea level (Sandberg et al., 1988; Buggisch, 1991; Kennard et al., 1992; Girard, 1995).

5. Conclusion

The sedimentological evolution of the Frasnian–Famennian transitional strata in South China and southern Belgium has been investigated. This resulted in a subdivision of the stratigraphic succession into depositional sequences. The sequence stratigraphical framework has a higher resolution

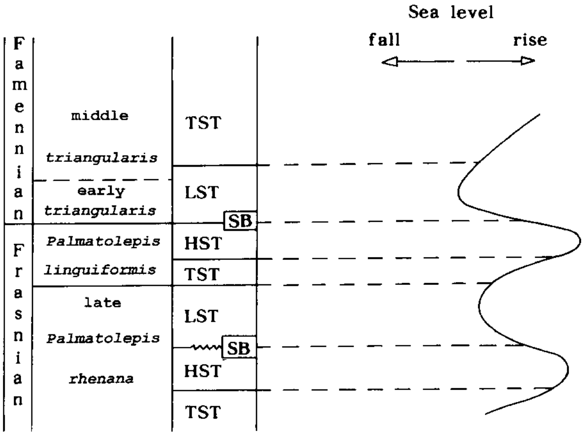

Fig. 5. The succession of systems tracts at the Frasnian–Famennian boundary in South China and Belgium.

than the available biostratigraphical schemes alone. Probably it can succesfully be applied in mineralogical and geochemical studies investigating the relation between the proposed asteroid impact and the extinction phenomena near the Frasnian–Famennian boundary.

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