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Depositional sequences in the Kimmeridgian of the Vocontian Basin (France) controlled by carbonate export from shallow-water platforms

Les séquences de dépôt du Kimméridgien du Bassin vocontien (France) : exportation de carbonates depuis les plates-formes peu profondes

Claude Colombié *, André Strasser

Department of Geosciences, Geology-Palaeontology, University of Fribourg, 1700 Fribourg, Suisse

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Abstract

Detailed sedimentological analyses and sequential and cyclostratigraphic interpretations in the Kimmeridgian of the Swiss Jura and the Vocontian Basin lead to a high-resolution correlation from the platform to the basin where the biostratigraphy is well established. Several orders of depositional sequences are defined. Their duration is estimated from the time frame given in the sequence-chronostratigraphic chart of Hardenbol et al. (1998). It is suggested that an elementary sequence formed in tune with the 20 ky precession cycle. Small-scale and medium-scale sequences correspond to the 100 and 400 ky eccentricity cycles, respectively. The platform-to-basin correlation shows that the composition of the hemipelagic and pelagic deposits depends to a large part on cyclical variations of carbonate production in shallow-marine environments and subsequent export to the basin. The distribution of thick versus thin marl-limestone alternations and carbonate-dominated versus marl-dominated intervals observed in the basinal sections is explained by the superposition of high- and low-frequency sea-level changes that controlled the carbonate productivity on the platform and the export potential of carbonate mud to the basin.

Résumé

L'analyse sédimentologique détaillée et l'interprétation séquentielle et cyclostratigraphique du Kimméridgien du Jura suisse et du Bassin vocontien permettent de corréler très précisément les coupes de la plate-forme avec celles du bassin où la biostratigraphie est bien établie. Plusieurs ordres de séquences de dépôt sont définis. Leur durée respective est estimée d'après le cadre stratigraphique proposé par Hardenbol et al. (1998). Une séquence élémentaire dure environs 20 ka, ce qui correspond à la période du cycle de la précession. Les séquences de court et de moyen terme correspondent au premier et au deuxième cycle de l'excentricité (100 et 400 ka). Par ailleurs, les corrélations entre la plate-forme et le bassin montrent que la composition des dépôts hémipélagiques et pélagiques dépend en partie des variations de la production de carbonates dans les environnements marins peu profonds. L'exportation de boue carbonatée de la plate-forme vers le bassin est également un facteur important dans la formation des séquences de dépôt du Kimméridgien du Bassin vocontien. Leur formation est expliquée par la superposition de plusieurs ordres de variations du niveau marin qui contrôlent la production de boue carbonatée dans les environnements marins peu profonds ainsi que son transport de la plate-forme vers le bassin.

Keywords: Kimmeridgian; Swiss Jura; Vocontian Basin; High-resolution sequence stratigraphy; Platform-to-basin correlation

Mots clés : Kimméridgien ; Jura Suisse ; Bassin vocontien ; Stratigraphie séquentielle haute-résolution ; Corrélations plate-forme - bassin

* Corresponding author. Université Claude-Bernard-Lyon 1, UFR sciences de la terre, bât. Géode, 2, rue Dubois, 69622 Villeurbanne cedex, France.
E-mail address: Claude.Colombie@univ-Lyon1.fr (C. Colombié).

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1. Introduction

Detailed sedimentological analyses and sequential and cyclostratigraphic interpretations have been made from six Kimmeridgian sections (Fig. 1). Three sections, located in the Swiss Jura (Gorges du Pichoux, Gorges de Court, and Péry-Reuchenette), are composed of lagoonal to peritidal carbonates. Hierarchically stacked depositional sequences suggest that high frequency, low-amplitude sea-level fluctuations in the Milankovitch frequency band controlled accommodation space on the shallow platform (Colombié, 2002). The Vocontian Basin sections (Crussol, Châteauneuf-d'Oze, and La Méouge) contain marl-limestone alternations characteristic of deeper-water depositional environments (Fig. 1). In this paper, the focus is set on the platform-to-basin relationships during the Kimmeridgian. The factors controlling the hemipelagic to pelagic sedimentation are defined, and a model explaining sequence formation in the Vocontian Basin is proposed.

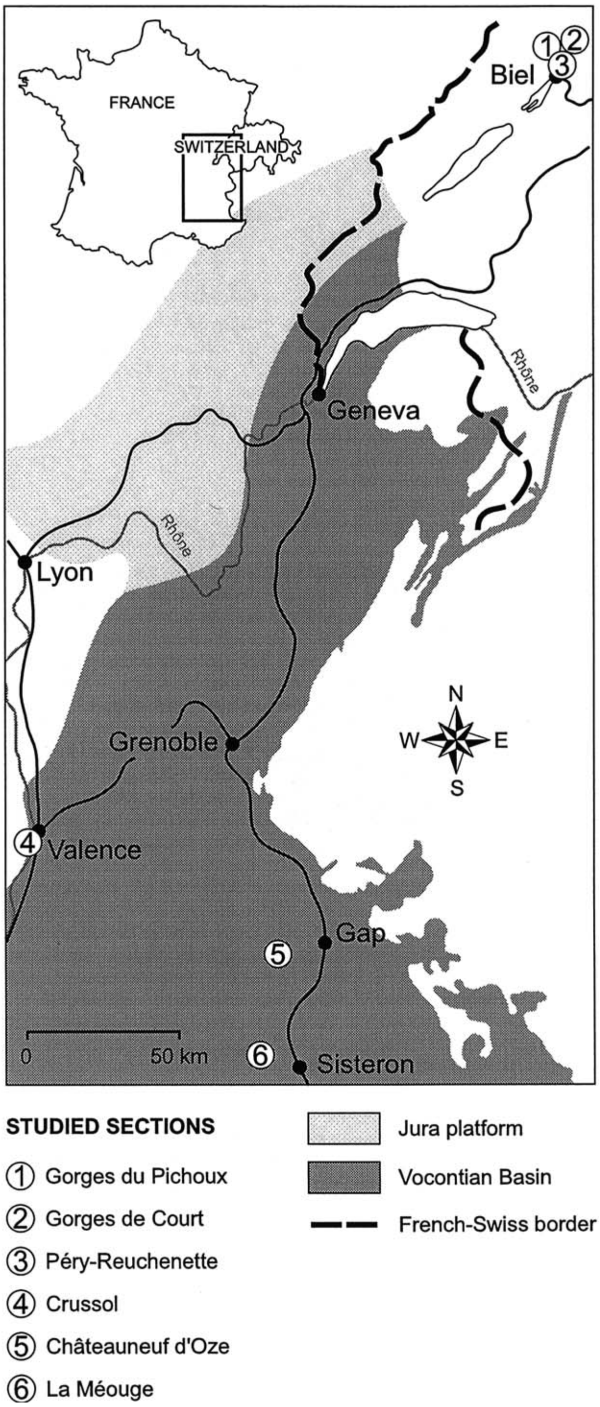

Fig. 1. Geographical location of the studied sections in the Swiss Jura and the Vocontian Basin in France. Facies are taken from the Lower Kimmeridgian palaeogeographical map of Enay and Debrand-Passard (1984).

Fig. 1. Position géographique des coupes étudiées dans le Jura Suisse et le Bassin Vocontien en France. Les faciès sont tirés de la carte paléogéographique du Kimméridgien inférieur de Enay et Debrand-Passard (1984).

2. Sedimentary facies in the basinal sections

A marl-limestone alternation is defined as a couplet of a marl-dominated layer and a limestone-dominated bed and contains several lithologies. Each of these lithologies corresponds to an intermediate stage in the evolution of the sediment composition from a calcareous pole to an argillaceous pole. Five lithologies (limestone, limestone with thin argillaceous layers, limestone with thick argillaceous layers, marl with lenses of limestone, and marl) have been described in the Crussol section, four (limestone, argillaceous limestone, calcareous marl, and marl) in the Châteauneuf-d'Oze and La Méouge sections.

At Châteauneuf-d'Oze and La Méouge, the limestone beds are mudstones or wackestones with benthic foraminifera, *Saccocoma*, calcispheres, *Globochaete*, radiolarians, protoglobigerinids, and filaments (thin-shelled bivalves), which are characteristic of the pelagic realm. In the Crussol section, limestones also contain some Textulariina, Nubeculariidae and other Miliolina, gastropods, brachiopods, and tuberoids that originate from sponge reefs. These components are typical of hemipelagic facies. The matrix is composed of micrite, quartz, clays, opaque minerals, and dolomite. Scanning-electron-microscope analyses do not reveal any nannofossils. Sedimentary structures (slumps, normal graded bedding, and parallel lamination) resulting from resedimentation processes occur locally. The upper parts of the Crussol and the Châteauneuf-d'Oze sections are characterised by laminoid and peloidal crusts and wavy ferruginous surfaces, respectively, which indicate decreasing bathymetry (Flügel and Steiger, 1981; Atrops and Moussine-Pouchkine, 2000).

3. Depositional sequences in the basinal sections

Sedimentary facies variations in the Kimmeridgian of the Vocontian Basin are small. Consequently, the definition of the depositional sequences is principally based on the identification of condensed sections, which are characterised by high clay contents, intense bioturbation, mineralisation, and accumulation of ammonites. The sequential interpretation

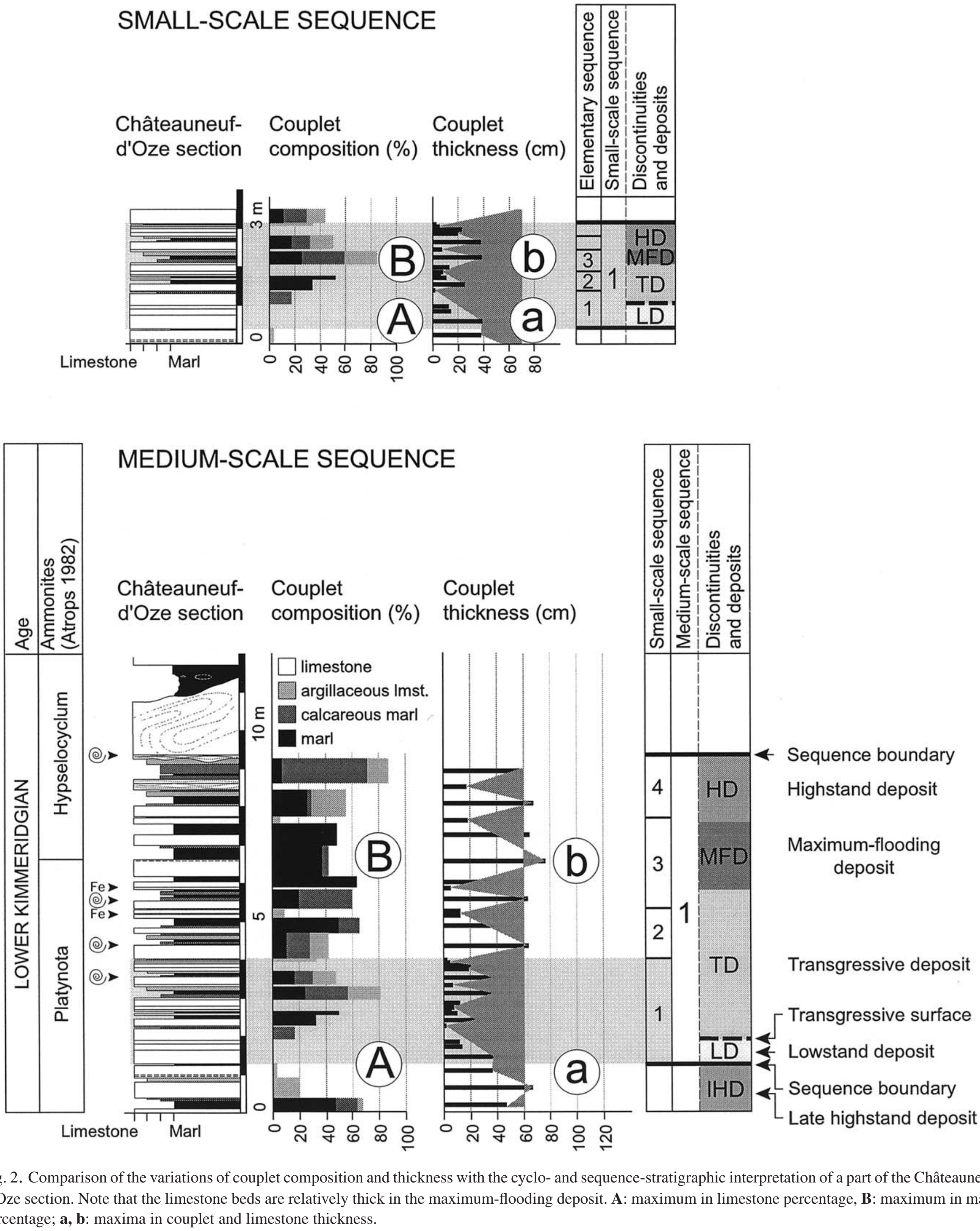

Fig. 2. Comparison of the variations of couplet composition and thickness with the cyclo- and sequence-stratigraphic interpretation of a part of the Châteauneuf d'Oze section. Note that the limestone beds are relatively thick in the maximum-flooding deposit. **A**: maximum in limestone percentage, **B**: maximum in marl percentage; **a, b**: maxima in couplet and limestone thickness.

Fig. 2. Comparaison des variations de la composition et de l'épaisseur des alternances avec l'interprétation cyclostratigraphique et séquentielle d'une partie de la coupe de Châteauneuf d'Oze. Notez que les bancs calcaires sont relativement épais dans le dépôt d'inondation maximale. **A** : pourcentage maximum de calcaires ; **B** : pourcentage maximum de marnes ; **a, b** : alternances et bancs calcaires les plus épais.

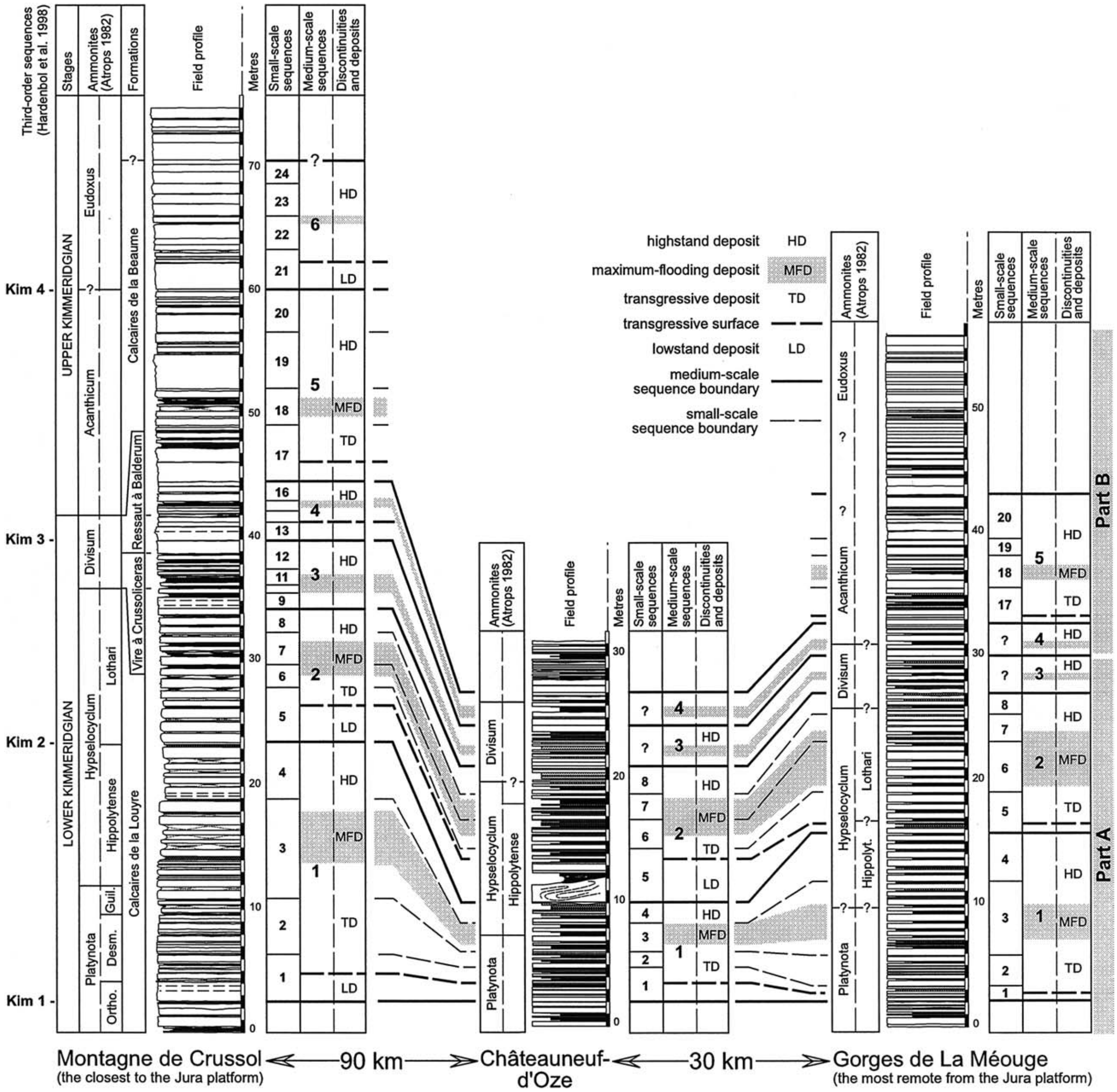

Fig. 3. High-resolution correlation of the Vocontian Basin sections, from the closest to the most remote from the Jura platform. Two main parts are defined according to the composition of the deposits. In part A, the marl percentage decreases and a condensed interval appears. Part B is limestone-dominated. For discussion see text.

Fig. 3. Corrélation haute-résolution des coupes du Bassin Vocontien, de la coupe la plus proche de la plate-forme du Jura à la coupe la plus éloignée. D'après la composition des dépôts, deux parties principales sont définies. Dans la partie A, le pourcentage de marnes décroît et un niveau condensé apparaît. La partie B est essentiellement composée de calcaires. Se référer au texte pour de plus amples explications.

rests also on the variations of the clay content and the thickness of the marl-limestone alternations (Fig. 2). Several orders of hierarchically stacked depositional sequences are defined (Colombié, 2002). An elementary sequence corresponds to one marl-limestone alternation. On the average, five elementary sequences compose a small-scale sequence, and four of the latter form a medium-scale sequence. Deposits and discontinuity surfaces of small-scale and medium-scale sequences display similar features, which are interpreted in terms of sequence stratigraphy (Fig. 2). In metre-scale depositional sequences, the geometries of the sedimentary bodies generally can not be seen and the classical systems tracts are difficult to identify (Vail et al., 1991). Instead of lowstand, transgressive, and highstand systems tracts, the terms lowstand deposits, transgressive deposits, and highstand deposits are thus used (Strasser et al., 1999). An important proportion of limestone and relatively thick alternations (maxima A and a in Fig. 2) suggest lowstand deposits (Strohmenger and Strasser, 1993; Pittet and Strasser, 1998). The transgressive surfaces (TS) coincide with the first increase of the clay content. The maximum-flooding deposits (MFD) correspond to a marl-dominated

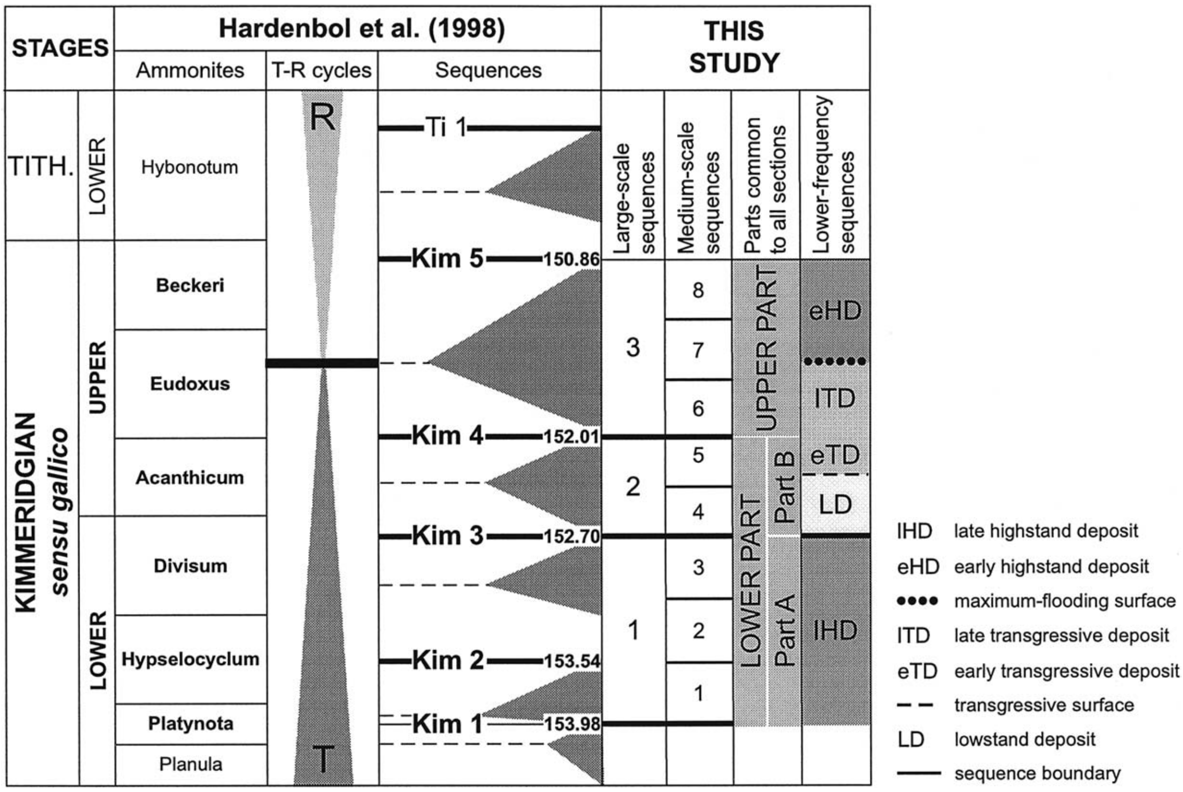

Fig. 4. Comparison of sequences identified in this study with the sequence-chronostratigraphic chart of Hardenbol et al. (1998). For discussion refer to text.
Fig. 4. Comparaison des séquences définies dans ce travail avec celles proposées par Hardenbol et al. (1998) pour le même intervalle de temps. Se référer au texte pour de plus amples explications.

interval (maximum B) and relatively thick alternations (maximum b). Decreasing marl content defines the highstand deposits (HD).

Depositional sequences of all orders are first defined for each studied section. In a second step, a detailed correlation of depositional sequences between the three sections is proposed (Fig. 3). The guide lines used to correlate the Vocontian Basin sections are defined according to the detailed ammonite biostratigraphy established by Atrops (1982) in the Crussol and the Châteauneuf-d'Oze sections. In the La Méouge section, the ammonite content is insufficient to give precise ages but a correlation with the Châteauneuf-d'Oze section has been realised according to the variations in the manganese concentrations of the sediments (De Rafélis, 2000). Moreover, the Kimmeridgian displays lithostratigraphic markers, which have been described in different parts of the Vocontian Basin. According to the ammonite biostratigraphy, these markers are synchronous. They correspond to two argillaceous intervals, which appear in the lower part of the Platynota zone and in the Hippolytense subzone, the "Vire à Crussoliceras", and the "Ressaut à Balderum" (Atrops, 1982; Fig. 3). The correlation of the medium-scale sequences is verified by the biostratigraphic and the lithostratigraphic markers. However, they do not justify the correlation of the small-scale sequences, which constitute a stratigraphic framework of higher resolution. The comparison of the evolution through time of the composition and the thicknesses of the marl-limestone alternations from one section to another is the most appropriate way to correlate the small-scale sequences. It happens that several solutions are possible. In this case, the solution combining the highest number of correlation elements is chosen ("best fit").

A sequential analysis of the Kimmeridgian has already been established from the Crussol section (Atrops and Ferry, 1989; Ferry and Atrops, 1989) and from the Châteauneuf-d'Oze section (Jan du Chêne et al., 2000). Moreover, Moussine-Pouchkine et al. (1998a, 1998b) display detailed bed-by-bed correlation of the Lothari ammonite subzone.

4. Cyclostratigraphy

The precise biostratigraphy available in the Vocontian Basin allows us to compare the studied sections with the Late Jurassic chronostratigraphy published by Hardenbol et al. (1998) and to estimate the duration of the different orders of depositional sequences. In the Kimmeridgian of the Tethyan realm, five third-order sequence boundaries, from Kim 1 to Kim 5, are indicated between the Platynota and the Beckeri ammonite zones (Fig. 4). In concordance with the ammonite zones defined by Atrops (1982), these third-order sequence boundaries coincide with five of the nine medium-scale sequence boundaries identified in this study (Colombié, 2002). The La Méouge section, which is the most remote from the Jura platform (Fig. 3), was relatively protected from resedimentation processes and displays regular marl-limestone alternations and few amalgamated limestone beds. There, 97 alternations are counted between the sequence boundaries interpreted as Kim 1 and Kim 4.

The chronostratigraphic chart of Hardenbol et al. (1998) compiles depositional sequences defined in Mesozoic and Cenozoic European basins. The position of the sequence boundaries is calibrated to the biostratigraphy and to the temporal framework of Gradstein et al. (1994, 1995). However, the large error margins on the absolute ages make the estimation of the durations of the depositional sequences uncertain. Other Jurassic time scales have been proposed but they concern only a small part of the studied interval (Weedon et al., 1999) and/or do not display a sequence-stratigraphic framework that can be compared to the one defined in the Swiss Jura and the Vocontian Basin (Weedon et al., 1999; Pálfy et al., 2000). Therefore, the sequence-chronostratigraphic chart of Hardenbol et al. (1998) is used for the present study.

According to this chart, the interval between Kim 1 and Kim 4 corresponds to about 2 my (Fig. 4). Consequently, the duration of a marl-limestone alternation (i.e., an elementary sequence) is approximately 20 ky, which suggests that it formed in tune with the orbital precession cycle (Berger et al., 1989). According to the hierarchical stacking, the small-scale and the medium-scale sequences therefore coincide with the first and the second eccentricity cycles, respectively (i.e., 100 and 400 ky).

5. Carbonate production on the Jura platform

The platform sections can be subdivided into two parts showing distinct sedimentological features. By sequence-stratigraphic correlations with the basinal sections and a few biostratigraphic tie points (Gygi and Persoz, 1986; Colombié, 2002), the lower part can be attributed to the interval between the Platynota and the Acanthicum ammonite zones. It contains thinly bedded limestones with siliciclastic sediments and desiccation structures (see example of the Gorges du Pichoux section in Fig. 5). The upper part corresponds to the Eudoxus and the Beckeri ammonite zones and is characterised by thickly bedded limestones, the quasi-disappearance of siliciclastic grains and desiccation features, and the development of green algae. The transition between the lower and the upper parts coincides with sediments indicative of the greatest increase of accommodation and carbonate production recorded in the central Swiss Jura during the Kimmeridgian (Colombié, 2002). Furthermore, the lower interval contains two different parts, which are equal to large-scale sequences (Fig. 4). Part A, comprised between the Platynota and Divisum ammonite zones, is characterised by a decrease of accommodation and carbonate production. Part B coincides with the Acanthicum zone and records an important increase of accommodation and carbonate production (Colombié, 2002). The lower interval corresponds to the late highstand deposit (lHD) of a first low-frequency depositional sequence and to the lowstand and early transgressive deposits

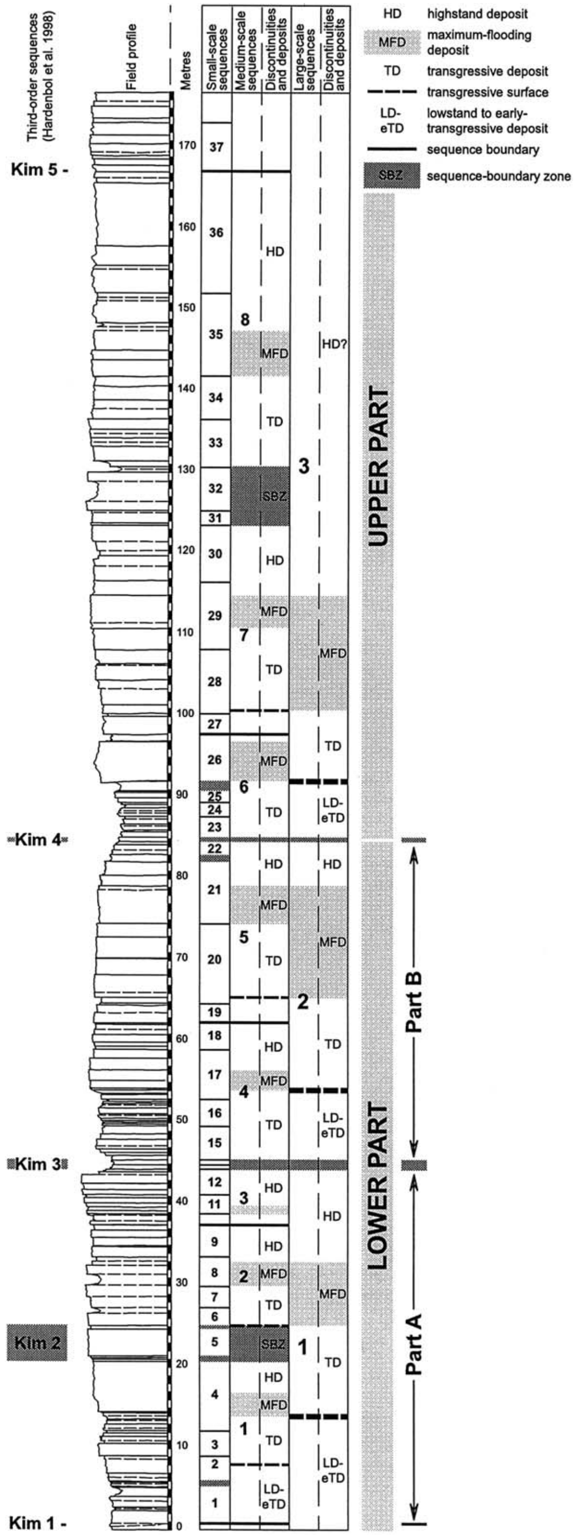

Fig. 5. Sequential and cyclostratigraphic interpretation of the Gorges du Pichoux section.

Fig. 5. Interprétation séquentielle et cyclostratigraphique de la coupe des Gorges du Pichoux.

(LD and eTD) of a second one, while the upper part coincides with the late transgressive and early highstand deposits (lTD and eHD) of this second low-frequency sequence.

6. Carbonate export to the Vocontian Basin

In the central Swiss Jura, the base of the Kimmeridgian coincides with the base of the Reuchenette Formation, which is characterised by an abrupt change of texture (from packstone/grainstone to mudstone), by the appearance of fauna indicating restricted ecological conditions, and by an increase of the quartz content (Colombié, 2002). The base of the Reuchenette Formation is a lithostratigraphic marker of regional importance. It lies within the Platynota ammonite zone (Gygi and Persoz, 1986). The Swiss Jura sections are correlated with the Vocontian Basin sections relative to the medium-scale sequence boundary, which appears in the Platynota ammonite zone and is defined on the platform as well as in the basin. Furthermore, the number of small-scale sequences counted between two medium-scale sequence boundaries is the same in the basin and on the platform. Consequently, the medium-scale sequence boundaries recorded on the platform can be correlated with the ones defined in the basin.

The high-resolution platform-to-basin correlation allows for the interpretation of the relationships between the Jura and the Vocontian Basin during the Kimmeridgian, and for the definition of the factors controlling sequence formation in the basin. The first large-scale sequence identified on the platform corresponds in the basin to a more and more marly interval, equivalent to the "Calcaires de la Louyre" and the "Vire à Crussoliceras" in the Crussol section (Fig. 3). The second large-scale sequence corresponds to the "Calcaires de la Beaume" Formation and is characterised by the appearance of thick limestone beds. The upper part identified on the platform (Fig. 5) coincides in the basin with the massive limestone cliff of the "Calcaires de Païolive" Formation.

It appears that, at the level of the large-scale sequences, a decrease of carbonate production on the platform coincides with a decrease of carbonate accumulation in the basin, while high carbonate production on the platform is time-equivalent to limestone-dominated intervals in the basin. Moreover, facies analyses imply negligible pelagic carbonate productivity in the basin. This suggests that the export of carbonate mud from the shallow-marine environments to the basin probably played an important role in sedimentation during Kimmeridgian times. At the scale of the marl-limestone alternations, it is seen that couplet thickness depends largely on limestone-bed thickness (Colombié, 2002). Consequently, variations in clay input were a subordinate controlling factor in the formation of the alternations (see also Einsele and Ricken, 1991 for a discussion of the various origins for marl-limestone alternations).

7. Model for sequence formation

Carbonate and clastic depositional systems respond differently to sea-level changes (Sarg, 1988; James and Kendall, 1992; Schlager, 1992; Miall, 1997). Carbonate-producing ecosystems have their highest growth potential during the later stages of sea-level rise and early stages of highstand when accommodation space is created on the shallow platform (Kendall and Schlager, 1981; Schlager, 1992). Moreover, the export potential of carbonate mud from platforms to deep-water environments is most important during late highstands and lowstands when accommodation is decreasing, forcing platforms to prograde. Consequently, during one sea-level cycle, carbonate productivity on the platform is high when the export potential is relatively low, and vice versa. However, the sedimentological analysis and the sequential and cyclostratigraphic interpretation of the Kimmeridgian in the Swiss Jura and the Vocontian Basin demonstrate that several orders of sea-level variations were superimposed. Thus, during short time intervals, conditions of high productivity and high export potential were given (Fig. 6).

Up to the Eudoxus zone, the Kimmeridgian corresponds to a keep-up transgressive systems tract (Colombié and Strasser, 2000). The shallow-water carbonates in the central Swiss Jura do not reveal important hiatuses and early diagenesis is relatively restricted. Even during the high-frequency sea-level lowstands, large areas of the platform were probably still under water and produced some carbonate (Pittet and Strasser, 1998). The high export potential during such phases results in the formation of thick limestone beds in the basin (Fig. 6).

The sections of the Vocontian Basin cover the interval between Kim 1 and Kim 4, corresponding to the late highstand of one lower-frequency depositional sequence, and to the lowstand and early transgressive deposits of a second one (Fig. 4). During the lower-frequency late highstand, the large-scale, medium-scale (400 ka), and small-scale (100 ka) relative sea-level rises are attenuated, while the falls are enhanced (Strasser et al., 1999). During the transgressive and early highstand phases of a medium-scale sequence, the export potential is low, resulting in marl-dominated deposits in the basin (Fig. 6). However, due to the lower-frequency late highstand conditions, the small-scale sea-level falls are sufficient to force the export of the carbonate mud to the basin and allow for the formation of thick limestone beds within the marls. Consequently, higher-frequency depositional sequences are better developed in the maximum-flooding deposit of lower-frequency sequences. During medium-scale lowstand and late highstand conditions, the export potential is increased, favouring the occurrence of thick limestone beds with few marls in the basin (Fig. 6).

In contrast to large-scale, medium-scale and small-scale depositional sequences, the late highstand and lowstand deposits of the lower-frequency sequence are marl-dominated. The lower-frequency relative sea-level fall involves a long-lasting loss of accommodation and thus a diminution of the carbonate production in shallow-water depositional environments, which results in a decreasing carbonate accumulation in the basin.

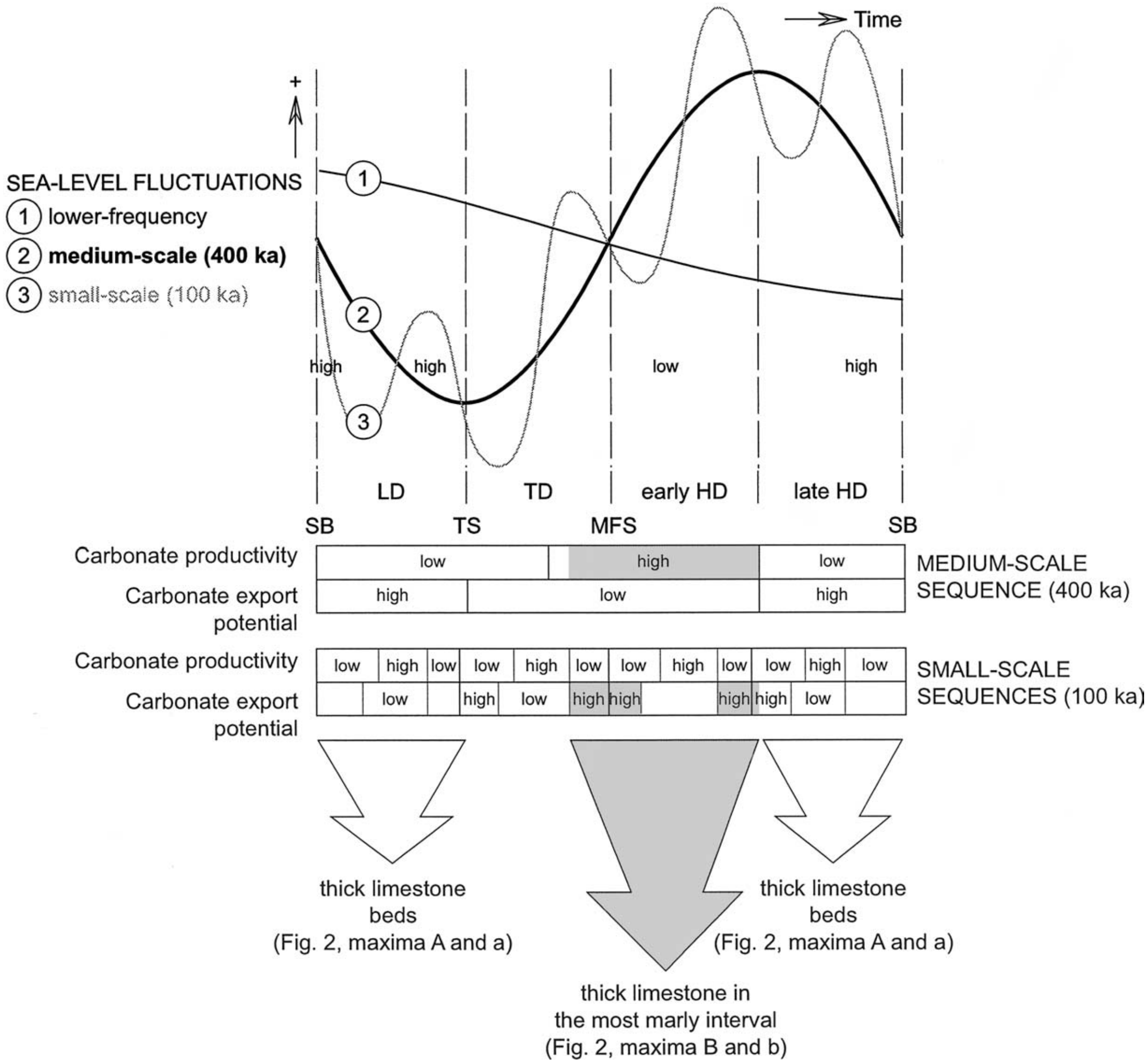

Fig. 6. Model for sequence formation in the Vocontian Basin during the Kimmeridgian, combining carbonate productivity in shallow-water depositional environments and carbonate export from the platform to the basin, most probably influenced by several superimposed orders of sea-level variations.
Fig. 6. Modèle de formation des séquences dans le Bassin Vocontien au Kimméridgien, qui tient compte de la productivité des environnements de dépôt peu profonds et de l'exportation de boue carbonatée de la plate-forme vers le bassin, qui sont probablement influencées par plusieurs ordres superposés de variations du niveau marin.

8. Conclusions

The sedimentological analysis and the sequential and cyclostratigraphical interpretation of the Kimmeridgian in the Swiss Jura and the Vocontian Basin leads to the definition of several orders of depositional sequences. In the Vocontian Basin, an elementary sequence corresponds to a marl-limestone alternation, which formed in tune with the 20 ky orbital precession cycle. The small-scale and medium-scale sequences coincide with the 100 and 400 ky eccentricity cycles, respectively. The platform-to-basin correlation reveals that the composition of the hemipelagic and pelagic deposits depends to a large part on the carbonate production in shallow-water depositional environments. The export of carbonate mud from the platform to the basin appears to have been a major factor controlling sequence formation in the Vocontian Basin during the Kimmeridgian. The combination of carbonate productivity in shallow-marine environments and carbonate export from the platform to the basin, most probably influenced by several orders of sea-level variations, results in the hierarchical stacking of depositional sequences in the basin. Superposition of sea-level cycles creates windows where both high productivity and export potential bring about carbonate mud accumulation in the basin.

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