Sedimentology (2005) **52**, 1207–1227 doi: 10.1111/j.1365-3091.2005.00736.x

Facies, cycles, and controls on the evolution of a keep-up carbonate platform (Kimmeridgian, Swiss Jura)

CLAUDE COLOMBIÉ* and ANDRE STRASSER†
*UMR 5125, UFR Sciences de la Terre, Université Claude Bernard Lyon 1, Domaine Scientifique de la Doua, Bât. GÉODE, 2 rue Raphaël Dubois, 69622 Villeurbanne Cedex, France (E-mail: claude.colombie@univ-lyon1.fr)
†Department of Geosciences, Geology-Palaeontology, University of Fribourg, 1700 Fribourg, Switzerland

ABSTRACT

During the Late Jurassic, accelerated ocean-floor spreading and associated sea-level rise were responsible for a worldwide transgression, which reached its maximum in the Late Kimmeridgian. In many Western European basins, this major sea-level rise led to the formation of marly and condensed sections. In the Swiss Jura, however, a shallow carbonate platform kept growing and only subtle changes in the stratigraphic record suggest an increasingly open-marine influence. Field observations and thin-section analyses reveal that the central Swiss Jura was at that time occupied by tidal flats and by more or less open marine lagoons where shoals and bioherms developed. The evolution through time of sedimentary facies and bed thicknesses permits the definition of small-, medium-, and large-scale depositional sequences. The diagnostic features of these sequences are independent of scale and seem largely controlled by the Kimmeridgian second-order transgression. A high-resolution sequence-stratigraphic correlation with biostratigraphically well-dated hemipelagic and pelagic sections in the Vocontian Basin in France reveals that: (i) The most important increase in accommodation recorded in the Kimmeridgian of the central Swiss Jura occurs in the Eudoxus ammonite zone (Late Kimmeridgian) and corresponds to the second-order maximum flooding recognized in many sedimentary basins. (ii) The small- and medium-scale sequences have time durations corresponding to the first and second orbital eccentricity cycle (i.e. 100 and 400 ka, respectively), suggesting that sedimentation on the platform and in the basin was at least partly controlled by cyclic environmental changes induced by insolation variations in the Milankovitch frequency band. The comparison of the high-resolution temporal framework defined in the Swiss Jura and Vocontian Basin with the sequence-stratigraphic interpretation realized in other Western European basins shows that the large-scale sequence boundaries defined in the Kimmeridgian of the Swiss Jura appear in comparable biostratigraphic positions in most Western European basins. Discrepancies that occur are probably because of local or regional tectonics.

Keywords Cyclostratigraphy, high-resolution sequence stratigraphy, keep-up carbonate platform, Kimmeridgian, stratigraphic correlation, Swiss Jura.

INTRODUCTION

Variations in subsidence and eustatic sea level are responsible for the formation of transgressive–regressive sedimentary sequences. Relative sea-level rise commonly leads to a transgression and deepening facies trend. However, high sedimentation rate may keep pace with or exceed the increase of accommodation, and result in aggradational or progradational deposits respectively

(Kendall & Schlager, 1981; Jones & Desrochers, 1992; Posamentier *et al.*, 1992; Handford & Loucks, 1994; Hunt & Tucker, 1995). In this paper, a case study from the Kimmeridgian (Late Jurassic) in the Swiss Jura Mountains is presented, where a shallow-water carbonate platform kept growing with rising sea level over several million years.

During the Kimmeridgian, the break-up of Pangea was in an active phase (Ziegler, 1988; Dercourt *et al.*, 1993; Thierry, 2000). Accelerated ocean-floor spreading, associated sea-level rise, and high atmospheric carbon dioxide levels were probably responsible for the worldwide transgression (Hallam, 1985; Weissert & Mohr, 1996), which started in the Late Oxfordian and ended in the Late Kimmeridgian (Hardenbol *et al.*, 1998). The related major transgressive trend can be traced in successions from southern England to Greenland (Wignall, 1994; Taylor *et al.*, 2001), and is recognized in many other Western European basins (e.g. Marques & Olóriz, 1989; Proust *et al.*, 1995). In Portugal and northern France, this major sea-level rise resulted in the formation of marly and condensed sections. In the Swiss Jura, however, only subtle changes in the stratigraphic record suggest an increasingly open-marine influence.

In this study, a detailed sedimentological, sequence-stratigraphic and cyclostratigraphic analysis was carried out on three sections in the Swiss Jura. The sedimentary sequences are placed into a sequence-stratigraphic framework and the controls on their formation are discussed. A comparison is drawn subsequently between the high-resolution stratigraphic framework defined in the Kimmeridgian of the Swiss Jura with the sequence-stratigraphic interpretation developed for successions from other Western European basins (north-eastern Spain, western and central Portugal, northern France, and southern England).

PALAEOGEOGRAPHIC AND STRATIGRAPHIC SETTING

The Jura platform was located between the Paris Basin to the NW and the Ligurian segment of the Mesozoic Tethys to the SE (Fig. 1). This SW–NE trending shallow carbonate platform was bounded in the south and SE by more or less continuous bioclastic and oolitic barriers, and by coral reefs (Enay *et al.*, 1988). Small quantities of terrigenous material (quartz, clays, plant debris) occur episodically in the Kimmeridgian of the Swiss Jura, derived from the emerged massifs located to the west, north and east (Bolliger & Burri, 1970; Gygi & Persoz, 1986).

In the central Swiss Jura, the Kimmeridgian corresponds to the Reuchenette Formation (Thalmann, 1966; Gygi, 1995; Fig. 2). It is a thick succession (140 m on the average) of shallow-water limestones. Precise biostratigraphic dating is lacking, but the lower and upper boundaries of this formation correspond to lithological marker beds that are thought to be more or less isochronous (Gygi, 2000). The lower boundary of the Reuchenette Formation coincides with the top of the white oolitic limestones of the Late Oxfordian Verena Member. It is characterized by an abrupt texture change (from packstone/grainstone to mudstone), the development of restricted ecological conditions, and an increase of quartz content (Colombié, 2002). The upper boundary of the formation is indicated by the 'Banc à Nérinées'

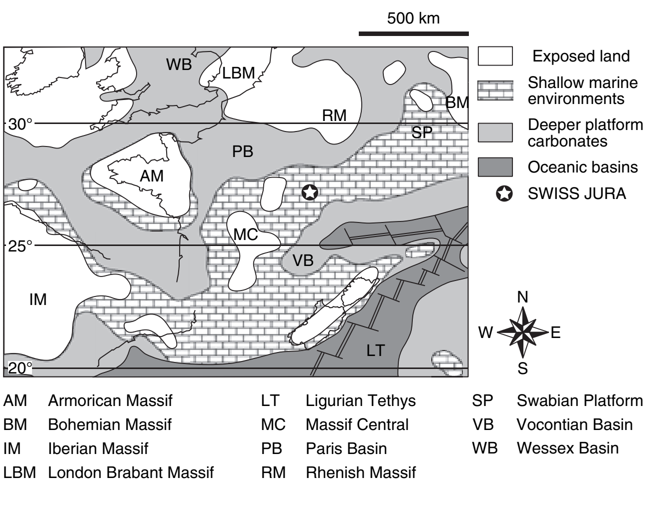

Fig. 1. Palaeogeographical map for the Early Kimmeridgian (146–144 Ma) modified from Thierry *et al.* (2000).

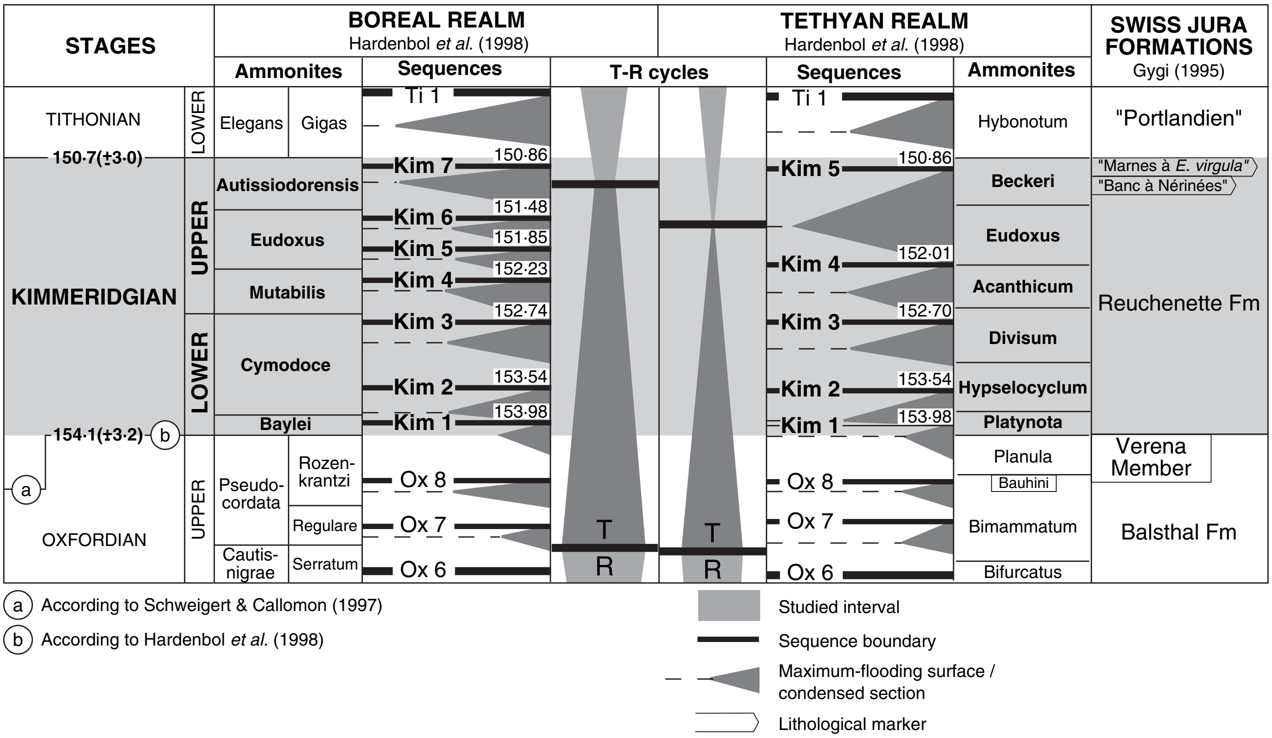

Fig. 2. Stratigraphic chart of the studied interval and associated formations in the Swiss Jura. Ages of stage and sequence boundaries in Ma.

(Dauwalder & Remane, 1979), a heavily bored hardground (Meyer, 1994), the 'Marnes à *Exogyra virgula*' (Aubert, 1932, 1950), and/or the appearance of the 'Calcaires en Plaquettes', thinly bedded peritidal limestones and dolostones attributed to the base of the 'Portlandien' (i.e. Tithonian).

In the Tethyan realm, the Kimmeridgian comprises the interval between the Platynota and the Beckeri ammonite zones (Fig. 2). It would thus correspond to the Baylei to Autissiodorensis zones of the northern European region (Hardenbol *et al.*, 1998). However, based on amoebocerati ammonites, Schweigert & Callomon (1997) correlate the base of the boreal Kimmeridgian with the Bauhini horizon at the top of the Tethyan Bimmamatum zone. The two versions of correlation are included in Fig. 2. Moreover, although the ammonites of the Swiss Jura show a Tethyan affinity in the Early Kimmeridgian, they suggest boreal influences in the Late Kimmeridgian (Gygi, 1995). The boreal zonation is therefore used in the upper part of the studied sections.

According to regional platform-to-basin correlations based on ammonites as well as on quartz and clay-mineral contents (Gygi & Persoz, 1986), the top of the Verena Member lies at the top of the Planula ammonite zone. The upper boundary of the Reuchenette Formation is located in the Autissiodorensis zone, corresponding to the Tethyan Beckeri zone (Meyer & Pittman, 1994; Gygi, 1995). *Gravesia polypleura* HAHN was found 35 m above the 'Banc à Nérinées' (Thalmann, 1966) and indicates that the 'Calcaires en Plaquettes' (Portlandien) has to be placed in the Gigas zone (equivalent to the lower part of the Tethyan Hybonotum zone). This is confirmed by the occurrence in the lowermost 'Portlandien' of the ostracod *Macrodentina (M.) klingeri* MALZ, which is characteristic of the Autissiodorensis and Gigas zones (Häfeli, 1966; Meyer, 1993).

The studied interval includes five third-order sequence boundaries (Kim 1 to Kim 5; Hardenbol *et al.*, 1998), which are calibrated to the absolute time scale of Gradstein *et al.* (1994). However, the ages attributed to the stage boundaries have large margins of error (Fig. 2), and the apparently precise dating of the sequence boundaries is an artefact of interpolation.

METHODS

A detailed sedimentological, sequence and cyclostratigraphic analysis has been performed on three sections located to the north of Biel in the

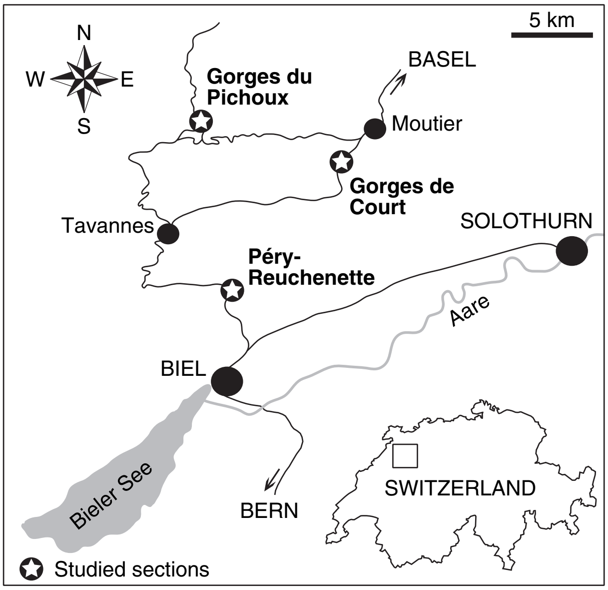

Fig. 3. Geographical location of the studied sections in the central Swiss Jura.

central Swiss Jura (Fig. 3). The Gorges du Pichoux section measures 180 m, the Gorges de Court section 140 m, and the Péry-Reuchenette section 173 m. The horizontal distances between the sections are about 10 km. The outcrops are almost continuous and relatively undeformed. Field observations include weathering profile, lithology, and sedimentary structures, whereas analysis of 650 slabs and 530 thin sections allowed for the definition of microfacies (Flügel, 1982). From these data, the depositional environments are interpreted.

According to the sedimentological interpretation and the stacking pattern of beds, depositional sequences are defined independently in each section and then correlated to filter out autocyclically created beds (Strasser, 1991; see also methodology described in Strasser *et al.*, 1999). Several orders of depositional sequences are identified. They are hierarchically stacked, suggesting an orbital control on sedimentation. In order to confirm this interpretation, the platform sections, where a precise biostratigraphic and chronostratigraphic framework is lacking, are correlated with the time-equivalent and biostratigraphically well-dated succession in the Vocontian Basin in France (Atrops, 1982). The durations of the depositional sequences (as deduced from their number between dated sequence boundaries or dated limits of ammonite zones) confirm that they formed in tune with Milankovitch orbital parameters. The resulting high-resolution temporal framework is then compared with the chronostratigraphic chart of Hardenbol *et al.* (1998) and with the sequence boundaries defined in other Western European basins.

FACIES ANALYSIS AND ENVIRONMENTAL INTERPRETATION

Sedimentary facies reflect the physical and chemical conditions of depositional environments. In carbonate systems, facies analysis also permits interpretation of the ecology of the carbonate-producing organisms, which are influenced by temperature, salinity, energy and depth of water, as well as by siliciclastic input, nutrient supply, oxygen content and light (e.g. Hallock & Schlager, 1986; Schlager, 1993; Homewood, 1996; James, 1997).

In the studied sections, 19 facies have been identified based on texture, main constituents, fabrics, early diagenetic features, as well as fossil content (Fig. 4). These are interpreted to represent 12 sub-environments that group into four environments. For example, the tidal flat environment contains marsh, pond, intertidal flat, and tidal channel sub-environments, each of which has characteristic facies. In accordance with studies on modern and ancient peritidal carbonate systems (Laporte, 1967; Hardie & Ginsburg, 1977; Shinn, 1983; Strasser & Davaud, 1983; Pratt & James, 1992), the sedimentological interpretation leads to a facies model reflecting the spatial distribution of the different environments and sub-environments defined in the Kimmeridgian of the central Swiss Jura (Fig. 5).

Tidal flat environment

Marsh sub-environment

Bioturbated mudstones with desiccation features (circum-granular cracks, desiccation cracks, tepees, and/or fenestrae) indicate low-energy depositional environments between the upper intertidal and supratidal zones (Laporte, 1967; Shinn *et al.*, 1969; Shinn, 1983; Pratt & James, 1992). Peloids and bioclasts constitute up to 50% of coarse sediment layers that are several millimetres to centimetres thick, graded or ungraded, with or without planar lamination. They result from spring- or storm-tide deposition in the upper intertidal and supratidal zones (Shinn, 1983). Thin layers of dolomite or peloids alternating with micrite are considered to be stromatolites (Dupraz, 1999). They occur on tidal flats from

Texture	Main constituents	Fabrics and diagenetic features	Fossil content
TIDAL FLAT ENVIRONMENT			
Marsh subenvironment (supratidal to upper intertidal)			
Mudstone		Circum-granular cracks, desiccation cracks, tepees, fenestrae, coarse sediment layers (peloids, bioclasts), alternating dolomite-rich and micrite laminae, alternating peloid-rich and micrite laminae, bioturbation	Lack of fossils or low fossil diversity (ostracods, pelecypods, miliolids)
Pond subenvironment (supratidal to intertidal)			
Mudstone	Charophytes (gyrogonites and stems)	Bioturbation	Low fossil diversity (ostracods, pelecypods, miliolids)
Intertidal flat subenvironment (lower intertidal)			
Mudstone		Alternating micrite and dolomite-rich laminae, alternating micrite and peloid-rich laminae, bioturbation	Low fossil diversity (ostracods, pelecypods, miliolids)
Tidal channel subenvironment (upper subtidal)			
Grainstone and Wackestone/ packstone	Peloids	Alternating planar oblique bedding and strong bioturbation	Moderate fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules)
BEACH ENVIRONMENT			
Packstone/ grainstone	Peloids, oncoids	Planar bedding, keystone vugs	Low fossil diversity (ostracods, pelecypods, miliolids)
LAGOON ENVIRONMENT			
Restricted lagoon subenvironment			
Mudstone	Dolomite, ostracods	Gypsum pseudomorphs, bioturbation	Low fossil diversity (ostracods, pelecypods, miliolids), calcispheres
Grainstone	Peloids		
Semi-restricted lagoon subenvironment			
Mudstone		Bioturbation	Moderate fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules), calcispheres, *Bacinella, Cayeuxia, Marinella, Thaumatoporella, Cladocoropsis*
Wackestone	Ostracods, pelecypods, sponge spicules, dasycladaceans, oncoids		
Wackestone/ packstone	Ostracods, pelecypods, sponge spicules, *Marinella,* peloids, oncoids, ooids (type 1, 2 or 4)		
Grainstone	Peloids		
Sheltered lagoon subenvironment			
Wackestone	Ostracods, pelecypods, sponge spicules, peloids, oncoids	Bioturbation	High fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules, abundant echinoderms), *Bacinella, Cayeuxia, Marinella, Cladocoropsis*
Wackestone/ packstone	Pelecypods, peloids, oncoids, ooids (type 2 or 4)		
Patch reef subenvironment			
Framestone	Microsolenid corals	Irregularly shaped, unbedded and laterally limited build-up	Microsolenid corals
Open lagoon subenvironment			
Packstone/ grainstone	Peloids, oncoids, ooids (type 1, 2 and 4)	Bioturbation	High fossil diversity (cf. above for details)
SHOAL ENVIRONMENT			
Internal shoal subenvironment			
Active grainstone	Dasycladaceans, benthic foraminifera, lithoclasts, peloids, oncoids, ooids (type 1 or 2)		Moderate fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules)
Inactive packstone/ grainstone		Encrustation, bioturbation	
External shoal subenvironment			
Active grainstone	Lithoclasts, peloids, ooids (type 2, 3 and/or 4)	Cross-bedding	High fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules, abundant echinoderms)
Inactive grainstone		Encrustation, bioturbation, microbial colonisation	

Fig. 4. Depositional environments and sub-environments defined in the Kimmeridgian of the central Swiss Jura according to texture, main constituents, fabrics and diagenetic features, and fossil content.

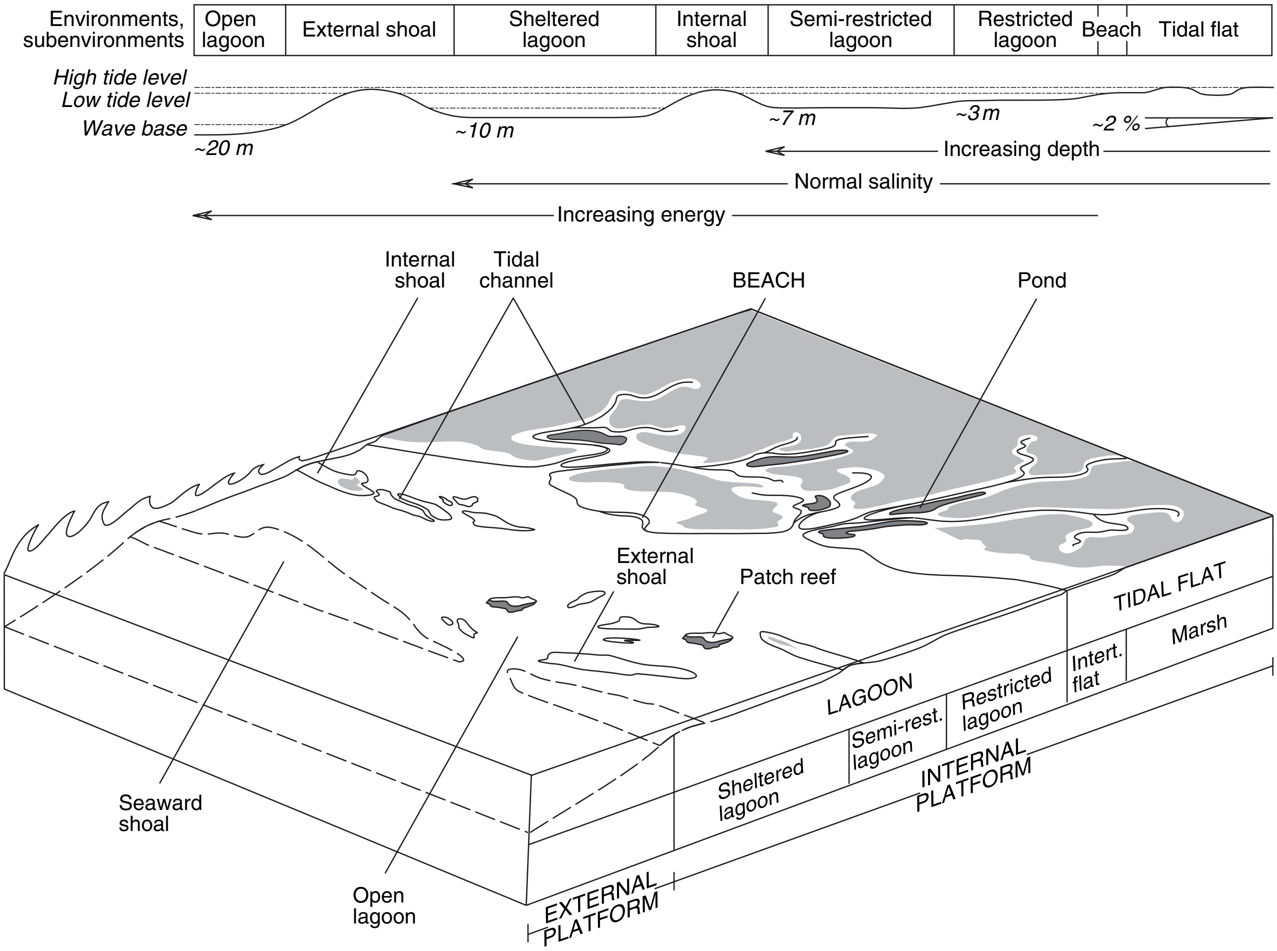

Fig. 5. Spatial distribution of the depositional environments defined in the Kimmeridgian of the central Swiss Jura.

lower intertidal to supratidal zones (Laporte, 1967; Hardie & Ginsburg, 1977; Shinn, 1983). In the Reuchenette Formation, superimpositions of planar and slightly wavy stromatolites are common. The latter are generally associated with numerous desiccation features and may locally evolve into tepees. These successions probably result from alternating sub-aerial exposure and flooding of the upper intertidal to supratidal zones. Lack of fossils, or low-diversity assemblages, including ostracods, pelecypods, and miliolids, indicate depositional environments that are particularly subject to variable salinity. The absence of evaporite pseudomorphs suggests humid to semi-arid climatic conditions associated with a marsh rather than a sabkha.

Pond sub-environment

Gyrogonites and stems of charophytes occur locally in bioturbated mudstones with fossils of euryhaline organisms (ostracods, pelecypods, miliolids). They indicate ponds between channel systems that became brackish during periods of heavy rainfall (Shinn *et al.*, 1969; Mojon & Mouchet, 1992; Joachimski, 1994).

Intertidal flat sub-environment

Bioturbated mudstones containing alternating micrite and dolomite-rich laminae or alternating micrite and peloid-rich laminae are interpreted as having formed on tidal flats, in the presence of microbial mats. The low-diversity fossil assemblage (ostracods, pelecypods, miliolids) indicates variable salinity; the lack of desiccation features suggests the lower intertidal zone.

Tidal channel sub-environment

Alternating well-sorted peloid grainstones with planar–oblique bedding and peloid wackestones/packstones with strong bioturbation are interpreted as corresponding to changing high- and low-energy deposits. These facies are characterized by moderate fossil diversity including ostracods, pelecypods, gastropods, miliolids, other

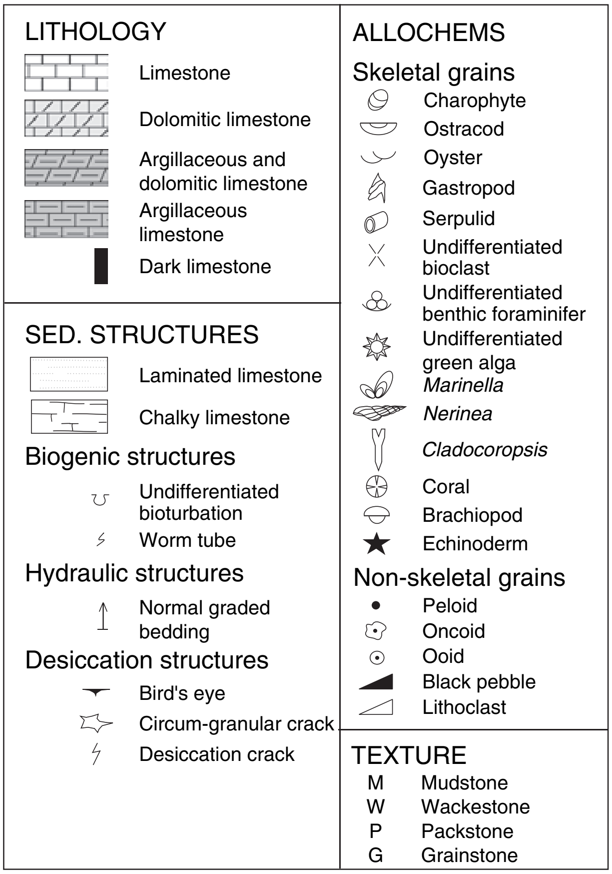

Fig. 6. Legend for the studied sections.

benthic foraminifera, dasycladaceans and sponge spicules. Dasycladaceans and sponge spicules, usually characteristic of more marine condition, are probably reworked and reflect an intermediate position between coastal and shallow marine environments. Sponge spicules are predominantly rhaxes from the siliceous sponge *Rhaxella* (Dupraz, 1999).

Beach environment

Peloid and oncoid packstones/grainstones with planar bedding and keystone vugs occur at the base of the Reuchenette Formation in the Gorges de Court section. Keystone vugs are generally preserved immediately above the wave swash zone on high-energy beaches (Inden & Moore, 1983). In the studied sections, oncoids are generally elliptical, micritic throughout, and locally coated by a thin and concentric lamina of darker micrite. Average size is around 1·5 mm. A millimetre-thick calcrete clast appears in the same stratigraphic interval and suggests that the base of the Reuchenette Formation was deposited under a semi-arid climate (Esteban & Klappa, 1983; Wright, 1994). Evaporite pseudomorphs in the underlying Verena Member support this interpretation (Hug, 2003).

Lagoonal environment

Restricted lagoon sub-environment

Bioturbated mudstones with clear dolomite rhombohedrons (0·2 mm on average), gypsum pseudomorphs, and low fossil diversity (ostracods, pelecypods, and miliolids) that do not display desiccation features or stromatolitic laminations indicate low water energy and variable salinity. Dolomite crystals are commonly scattered in the matrix. Gypsum pseudomorphs appear only once, in the Péry-Reuchenette section, and may reflect a temporary more arid climate. Small-sized (diameter between 20 and 150 μm) hollow spherical microfossils exhibiting micritic or sparitic thin walls occur locally. These calcispheres probably correspond to the reproductive cysts of dasycladaceans of the sub-family Acetabulariae that live in restricted to semi-restricted lagoons (Marszalek, 1975) and not to calcareous dinoflagellate cysts (Keupp, 1991). Well-sorted peloidal grainstones occur locally and imply episodic high-energy events.

Semi-restricted lagoon sub-environment

Bioturbated mudstones and wackestones with moderate fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, and sponge spicules) are attributed to semi-restricted lagoons. Calcispheres are abundant. *Bacinella irregularis*, *Cayeuxia* (Dupraz, 1999), *Marinella lugeoni* (Leinfelder & Werner, 1993), *Thaumatoporella* (Bolliger & Burri, 1970; Leinfelder *et al.*, 1993), and *Cladocoropsis mirabilis* (Turnsek *et al.*, 1981; Flügel, 1982; Jansa *et al.*, 1982; Termier *et al.*, 1985) occur locally. The semi-restricted lagoon deposits may contain ooids, which are classified according to Strasser (1986). Type 1 ooids are well rounded, micritic, with thinly laminated cortices; type 2 ooids are irregular, micritic, with thinly laminated cortices; type 4 ooids contain few fine radial laminae. Well-sorted peloidal grainstones alternating with micrite layers occur locally and imply episodic high-energy events.

Sheltered lagoon sub-environment

The sheltered lagoon sub-environment still corresponds to low-energy deposits (bioturbated wackestones to wackestones/packstones) but differs from the semi-restricted lagoon sub-environment in that it contains a high fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules, and abundant echinoderms), which reflects normal salinity. *Bacinella irregularis*, *Cayeuxia*, *Marinella lugeoni*, and *Cladocoropsis mirabilis* are common. Ooids of type 2 or 4 occur locally.

Patch-reef sub-environment

An irregularly shaped, unbedded, and laterally limited bioherm of up to 5 metres thick occurs in the upper part of the Reuchenette Formation in the Gorges de Court section. It is mainly composed of microsolenid corals and interpreted as an isolated patch-reef. This bioherm is enclosed in peloid wackestones/packstones with high fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules, and abundant echinoderms) that indicate a sheltered lagoon sub-environment.

Open lagoon sub-environment

Bioturbated packstones to packstones/grainstones with peloids, oncoids, ooids and/or high fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules and abundant echinoderms) indicate moderate to high water energy and fully marine conditions. Type 1, 2 and 4 ooids occur with type 2 being dominant.

Shoal environment

Grainstones with dasycladaceans, benthic foraminifera, lithoclasts, peloids, oncoids, and/or ooids are interpreted as having formed on shoals. High fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, sponge spicules, and abundant echinoderms) points to external shoals in contact with the open sea, whereas moderate fossil diversity (ostracods, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, and sponge spicules) implies shoals within the lagoon. Internal shoals contain type 1 or 2 ooids, whereas type 2, 3, and/or 4 ooids are common in external shoals. Type 3 includes ooids with thinly laminated fine-radial cortices (Strasser, 1986). Cross-bedding suggests rapid sediment burial of active shoals. Inactive shoals are bioturbated and contain hardgrounds reflecting low sedimentation rates or sediment bypass. The hardgrounds are mostly micritic layers interpreted as microbial films. They may be encrusted by serpulids, calcareous sponges, *Cayeuxia*, *Troglotella*, and/or *Lithocodium* (Wernli & Fookes, 1992; Schmid & Leinfelder, 1996; Dupraz, 1999). Micritic alveolar-septal structures occur locally in pore spaces and are attributed to filamentous chasmoliths (Hillgärtner *et al.*, 2001).

DEPOSITIONAL SEQUENCES AND HIERARCHICAL STACKING PATTERNS

A depositional sequence is a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Mitchum, 1977). In the Kimmeridgian of the Swiss Jura, the evolution through time of sedimentary facies and bed thicknesses allows the definition of several orders of depositional sequences: small-, medium- and large-scale sequences that are hierarchically stacked (Fig. 7). Independent of scale, bounding surfaces and deepening–shallowing facies trends suggest that sequence formation was at least partly controlled by accommodation changes and thus permit an interpretation in terms of sequence stratigraphy (Strasser *et al.*, 1999). However, because the geometry of the sedimentary bodies cannot be defined in isolated sections, lowstand, transgressive and highstand deposits rather than systems tracts (Vail *et al.*, 1991) are referred to. Moreover, because of high-frequency sea-level fluctuations superimposed on a lower-frequency sea-level change, small-scale sequence boundaries, transgressive surfaces, or maximum-flooding surfaces may be repeated. In such cases, it is adequate to speak of sequence-boundary zones, transgressive-surface zones, or maximum-flooding zones respectively (Montañez & Osleger, 1993; Osleger & Montañez, 1996; Strasser *et al.*, 1999). The sequential interpretation of the Kimmeridgian in the central Swiss Jura reveals that the expression of the small-, medium-, and large-scale sequences varies according to their position inside a lower-frequency sequence. In particular, they seem to be greatly controlled by the second-order transgression, which starts in the Late Oxfordian and ends in the Late Kimmeridgian (Hardenbol *et al.*, 1998).

Diagnostic sedimentological features

The fourth medium-scale sequence of the Gorges du Pichoux section is used here to illustrate sequence-stratigraphic interpretation (Fig. 7). The

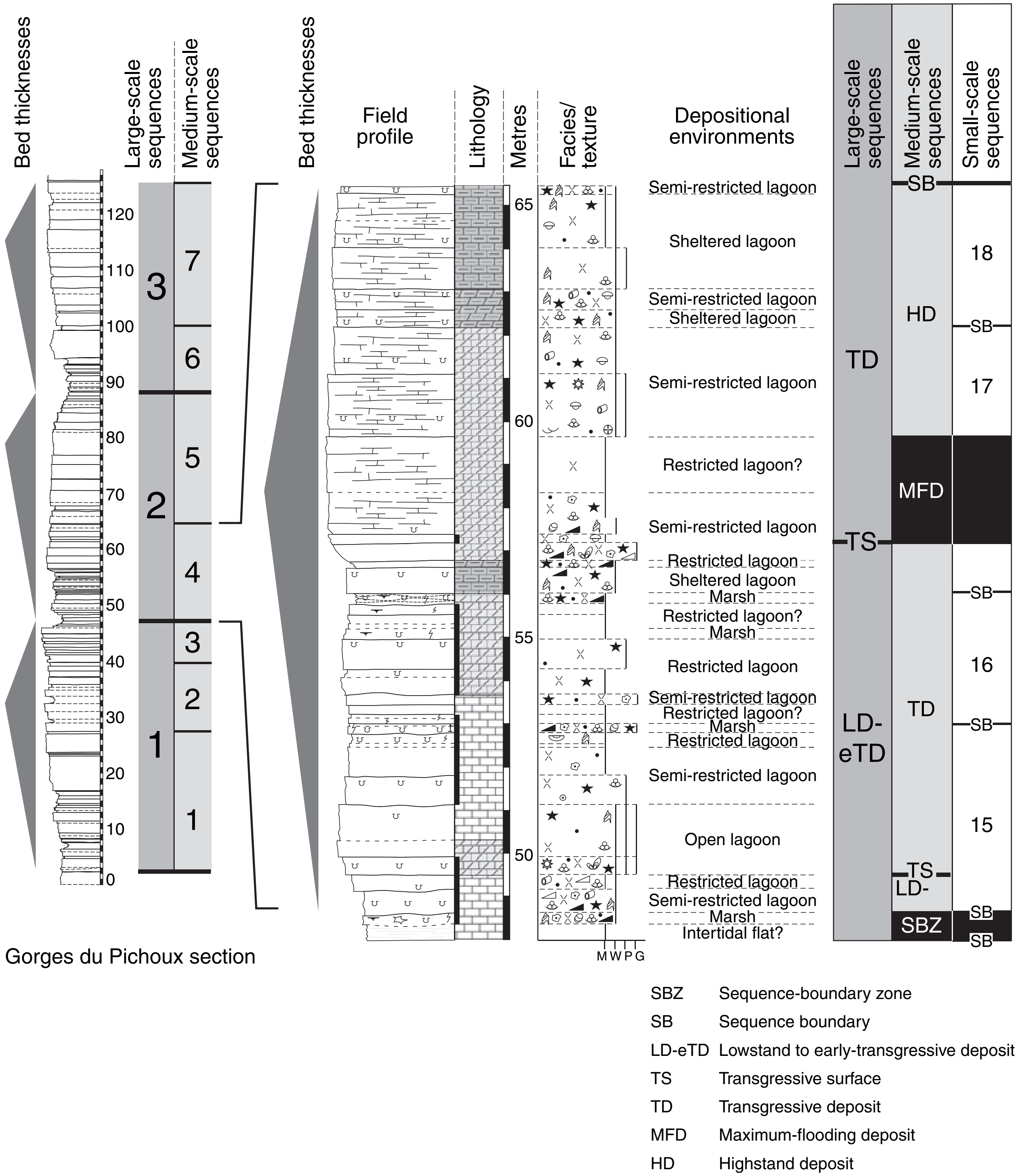

Fig. 7. Different orders of depositional sequences defined in the Kimmeridgian of the central Swiss Jura according to the evolution through time of bed thickness and sedimentary facies. Large-, medium- and small-scale sequences are hierarchically stacked.

lower part of the fourth sequence includes thin beds with laminations and desiccation features that indicate low accommodation. Moreover, encrusters such as serpulids and intense bioturbation reveal low accumulation rates. On shallow carbonate platforms, low accommodation and low accumulation rates are characteristic of lowstand and early transgressive periods. Consequently, the lower part of the fourth medium-scale sequence in the Gorges du Pichoux section is interpreted as a lowstand to early transgressive deposit (LD-eTD). Repetitive erosive bed surfaces overlain by lithoclasts, black pebbles, and mixed freshwater and marine fossils point to higher-frequency sea-level fluctuations, which are superimposed on the medium-scale LD-eTD. The fact that the erosive surfaces never cut deeply into the substrate and that the lowstand to early-transgressive deposits are relatively thick suggests that the short-term sea-level drops were attenuated by the second-order transgression (Strasser *et al.*, 1999).

Thicker beds, a textural change from wackestone to packstone, and a greater fossil diversity indicate a relative sea-level rise and a shift to more open depositional environments. This shift may have been rapid and defines a transgressive surface (TS).

Overlying, moderately thick beds with mostly sub-tidal facies indicate an increase in accommodation rate. Furthermore, high content of quartz, clays, and plant debris testify to an increased terrigenous input. Increased accommodation rate and terrigenous input are interpreted as characteristic of transgressive deposits (TD). Beds with black pebbles and charophytes indicate emersions resulting from superimposed higher-frequency sea-level fluctuations, and correspond to the sequence boundaries of small-scale sequences 15 and 16 (Fig. 7).

The thickest beds suggest the highest accommodation gain. Together with the most open-marine depositional environments they imply maximum-flooding conditions. In the studied sections, maximum-flooding surfaces generally are difficult to distinguish, and an interval of maximum-flooding deposits (MFD) is instead identified. The upper part of the fourth medium-scale sequence in the Gorges du Pichoux section is characterized by a decrease in bed thickness, which indicates loss of accommodation space during highstand conditions (HD). Finally, the thinnest beds and the most restricted depositional environments occur at the top of this sequence and indicate the fastest fall in relative sea level. These beds correspond to the sequence boundary (SB).

Small-scale sequences

In the Kimmeridgian of the central Swiss Jura, small-scale depositional sequences are 0·5–15 m thick and composed of one to nine beds (Figs 7 and 8). Sequences bounded by flooding surfaces (characterized by an increase in bed thickness, a textural change, greater fossil diversity, a high percentage of quartz, clays and plant debris, and evidence for reworking such as lithoclasts, black pebbles and mixed freshwater and marine fossils) are dominant. This is explained by the general transgressive trend on which these sequences are superimposed (Strasser *et al.*, 1999). They show shallowing-up or deepening–shallowing trends of facies evolution. Shallowing-up sequences are characterized by thinning-up beds and depositional environments becoming more restricted towards the top. Their occurrence seems to be independent of their position in a medium- or large-scale sequence. The lower part of deepening–shallowing sequences contains thickening-up beds and a facies evolution towards more open depositional environments, whereas the upper part is characterized by a shallowing-up trend. Deepening–shallowing sequences usually occur in the transgressive or maximum-flooding intervals of medium-scale sequences where accommodation gain was high.

Sequences bounded by sub-aerial exposure surfaces (indicated by desiccation features) are scarce. They generally appear in late highstand deposits of large-scale sequences where accommodation was low.

In some small-scale sequences, elementary sequences can be defined, which display a shallowing-up facies evolution (Fig. 8). They can be compared with the elementary sequences of Strasser *et al.* (1999), or to the genetic sequences defined by Homewood *et al.* (1992). Identifiable elementary sequences generally appear close to large-scale sequence boundaries where accommodation space was greatly reduced. Elsewhere, probably because of the second-order transgression, accommodation was too high to record high-frequency, low-amplitude sea-level fluctuations.

Medium-scale sequences

As a result of the Late Jurassic second-order transgression, asymmetric medium-scale sequences, showing a well-developed transgressive interval and a less well-developed regressive interval, are dominant. Transgressive deposits of medium-scale sequences commonly contain thin beds with bird's eyes and desiccation cracks, indicating intertidal to supratidal depositional environments. Especially in the lowstand to early-transgressive deposits of large-scale

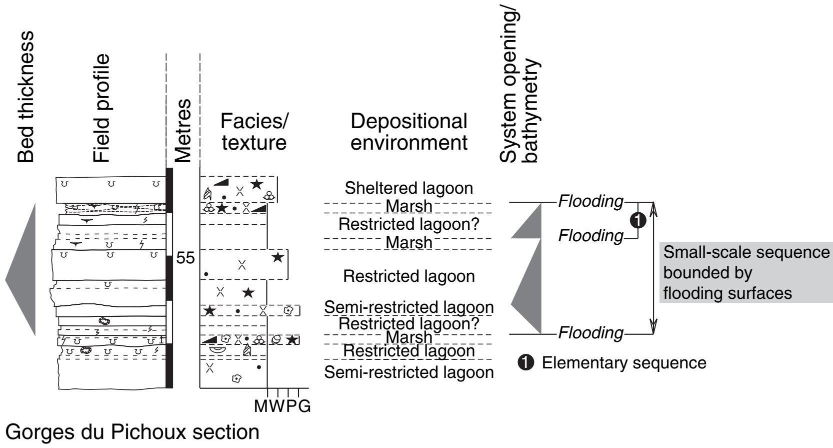

Fig. 8. Example of deepening–shallowing small-scale depositional sequence bounded by flooding surfaces. Such sequences commonly appear in transgressive or maximum-flooding intervals of medium-scale sequences, when accommodation is high.

sequences, carbonate production and accumulation were sufficient to constantly fill the relatively low accommodation created by the medium-scale transgressions. Thick beds and open-marine depositional environments only appear in the maximum-flooding interval.

Dolomitization may occur in the transgressive deposits of the medium-scale sequences located in the lowstand and early-transgressive intervals of large-scale sequences. This is comparable with the basal part of the Liassic Gibraltar Limestone Formation, where the maximum abundance of replacement dolomite coincides with the end of the highstand deposits and with the lowstand deposits of low-frequency cycles (Bosence *et al.*, 2000; Qing *et al.*, 2001). There, dolomite appears in restricted marine carbonate facies (which display no associated evaporites) and probably results from seepage reflux because of high-frequency sea-level changes. Indeed, periods of greenhouse conditions and major continental flooding, such as the Sinemurian and Kimmeridgian stages, may enhance dolomitization by seepage reflux through the development of extensive peritidal carbonates (Montañez & Read, 1992; Sun, 1994).

Bases of MFD of medium-scale sequences commonly define the transgressive surface of each large-scale sequence (Fig. 7). There, pelecypods, brachiopods, sponge spicules, and echinoderms indicate normal marine conditions. Terrigenous material may also be present. Because of the second-order transgression, each medium-scale maximum flooding reached farther into the continent than the previous one and redistributed the siliciclastics that had been trapped in the most proximal areas of the platform during the previous regression. Nutrients accompanying the terrigenous input probably favoured the development of microencrusters, which are commonly observed in the MFD of medium-scale sequences (Neuweiler *et al.*, 1996; Dupraz & Strasser, 1999).

Definition of large-scale sequences and correlation of the studied sections

Two distinct lithological units are identified in each of the three studied sections (Fig. 9). The lower unit is characterized by thin to moderately thick beds, a relatively high content of siliciclastics, many desiccation structures, and dolomite. This interval displays two general deepening–shallowing trends that are interpreted as the first two large-scale sequences (corresponding to parts A and B in Fig. 9), which in turn consist of the first five medium-scale sequences. The upper boundary of these large-scale sequences corresponds to an interval of relatively thin and marly beds that is expressed as depressions in the weathering profile (Fig. 9). Because of the Late Jurassic second-order transgression, the first two large-scale sequences are asymmetric, showing a well-developed transgressive interval and a less well-developed regressive interval (Einsele & Bayer, 1991). Nevertheless, the upper part of the first large-scale sequence is characterized by a thinning-up of medium- and small-scale sequences and a shift to more restricted depositional environments. This loss of accommodation results probably from a superimposed higher-frequency sea-level fall as well as from the healthy carbonate productivity that was able to catch up and keep up with the second-order sea-level rise (Kendall & Schlager, 1981; Jones & Desrochers, 1992; Posamentier *et al.*, 1992; Handford & Loucks, 1994; Hunt & Tucker, 1995).

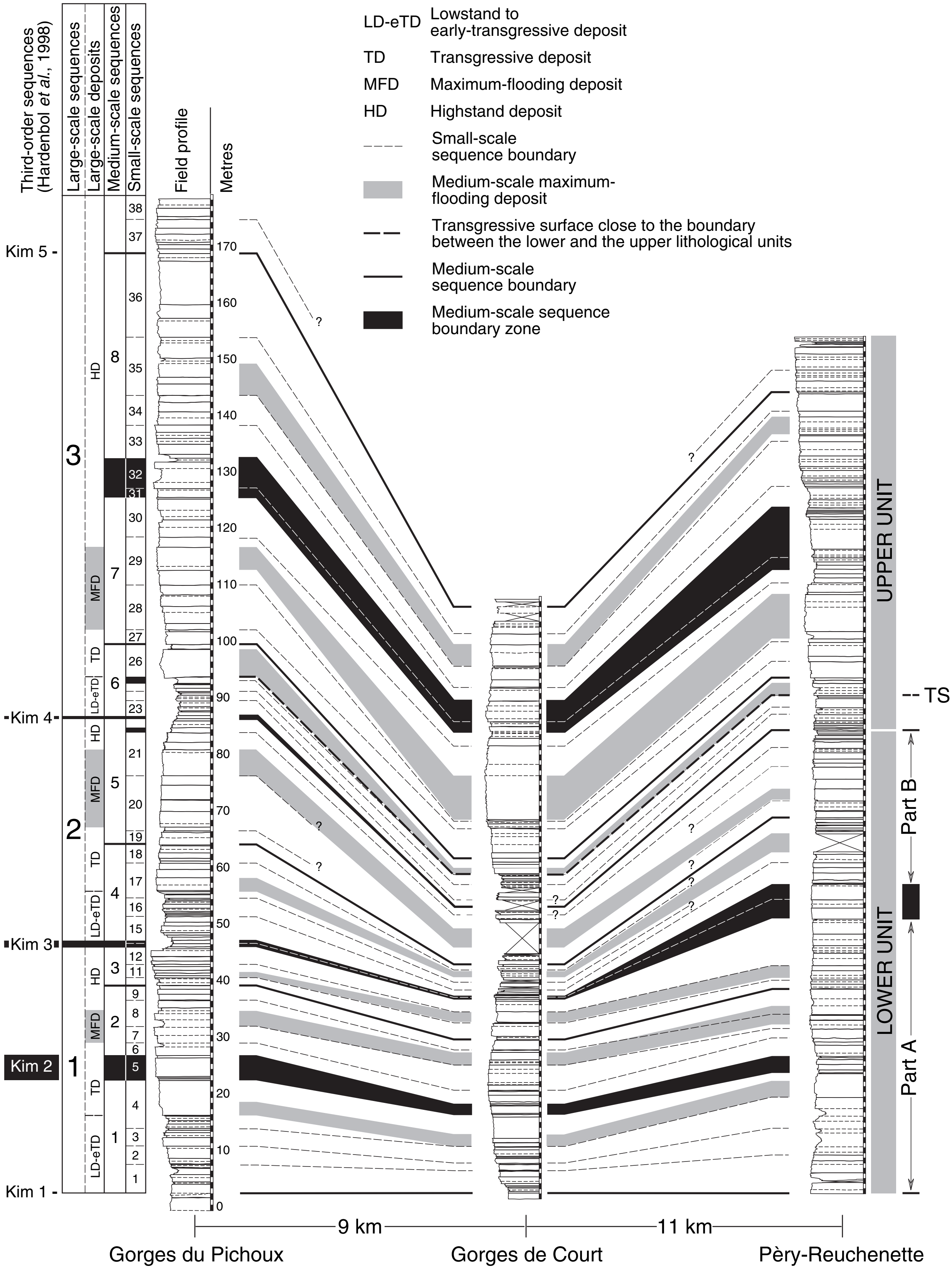

Fig. 9. Correlation of the studied sections. A lower unit, which contains parts A and B, and an upper unit are distinguished. These three intervals correspond to large-scale sequences.

The upper unit of the Kimmeridgian in the central Swiss Jura is characterized by thick beds of massive limestone and the quasi-disappearance of terrigenous material, desiccation structures, and dolomite. Conversely, carbonate-producing organisms such as green algae and corals are common. This interval corresponds to a general deepening-shallowing trend that is interpreted as the third large-scale sequence, including medium-scale sequences 6 to 8 (Fig. 9).

No major hiatuses have been detected in the three studied sections, which is in accordance with the general transgressive trend and greenhouse conditions during the Kimmeridgian: low amplitudes of high-frequency sea-level fluctuations could not create deep erosion (Read *et al.*, 1995). Moreover, carbonate production and accumulation were sufficient to constantly fill the created accommodation space. Finally, the studied sections are essentially composed of low-energy lagoonal deposits, in which lateral facies changes are reduced. The Kimmeridgian of the central Swiss Jura is therefore well-suited for high-resolution sequence-stratigraphic correlation (Fig. 9). Lithologic datum are provided by markers such as the base of the Reuchenette Formation, the 'Marnes à *Exogyra virgula*', and the 'Calcaires en Plaquettes' of the 'Portlandien' that are presumed to be more or less isochronous at the scale of the studied platform area (Gygi, 2000). In all studied sections, this interval includes three large-scale sequences that contain the same number of medium- and small-scale sequences. This implies that medium- and small-scale sequences are laterally continuous. Thickness changes in the sections are attributed to differential compaction and subsidence.

The boundary between the lower and the upper lithological units defined in the studied sections precedes the most important increase in accommodation that is recorded in the Kimmeridgian of the central Swiss Jura, as indicated by the thick beds and the most open-marine facies in the medium-scale sequence 7 (Fig. 9). The correlation of the platform sections with three biostratigraphically well-dated sections located in the Vocontian Basin in France shows that this major increase in accommodation occurs most probably in the Eudoxus ammonite zone (Late Kimmeridgian) and corresponds to the second-order maximum flooding recorded in most of the other West European basins (Colombié, 2002; Colombié & Strasser, 2003; Fig. 10).

CYCLOSTRATIGRAPHY

In order to constrain the time involved in the sedimentary processes reigning on the Jura platform, a cyclostratigraphic analysis of the studied sections has been attempted. The first step involves a sequence-stratigraphic correlation with sections in the Vocontian Basin where biostratigraphic control is excellent (Atrops, 1982; Fig. 10). The base of the Kimmeridgian in the Swiss Jura is a lithostratigraphic marker of regional importance that lies in the Platynota ammonite zone (Gygi & Persoz, 1986) and corresponds to the first medium-scale sequence boundary. The Swiss Jura sections are correlated with the Vocontian Basin sections relative to this medium-scale sequence boundary, which is also located in the basin successions in the Platynota zone (Atrops, 1982). Furthermore, the number of small-scale sequences counted between two medium-scale sequence boundaries is the same in the basin and on the platform, suggesting that the medium-scale sequences are laterally continuous. Consequently, the medium-scale sequence boundaries recorded on the platform can be correlated with the ones defined in the basin (Fig. 10). The precise biostratigraphy allows the comparison of the sequence-stratigraphic interpretation established in the Swiss Jura and Vocontian Basin with the Late Jurassic sequence-chronostratigraphic chart published by Hardenbol *et al.* (1998), and an estimation of the duration of the different orders of depositional sequences.

In the Tethyan realm, the Kimmeridgian includes five third-order sequence boundaries, Kim 1 to Kim 5 (Hardenbol *et al.*, 1998). 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 (Fig. 11). The La Méouge section, which is the most remote section from the Jura platform, is relatively free of resedimented facies and displays regular marl–limestone alternations and only a few amalgamated limestone beds (Colombié & Strasser, 2003). There, 97 alternations (i.e. elementary sequences) are counted between the sequence boundaries interpreted as Kim 1 and Kim 4 (Colombié, 2002). According to Hardenbol *et al.* (1998), this interval corresponds to about 2 Ma. Consequently, the duration of a marl-limestone alternation is *ca* 20 ka, which suggests that it formed in tune with the orbital precession cycle (Berger *et al.*, 1989). Furthermore, the detailed analysis of the platform sections (Fig. 7)

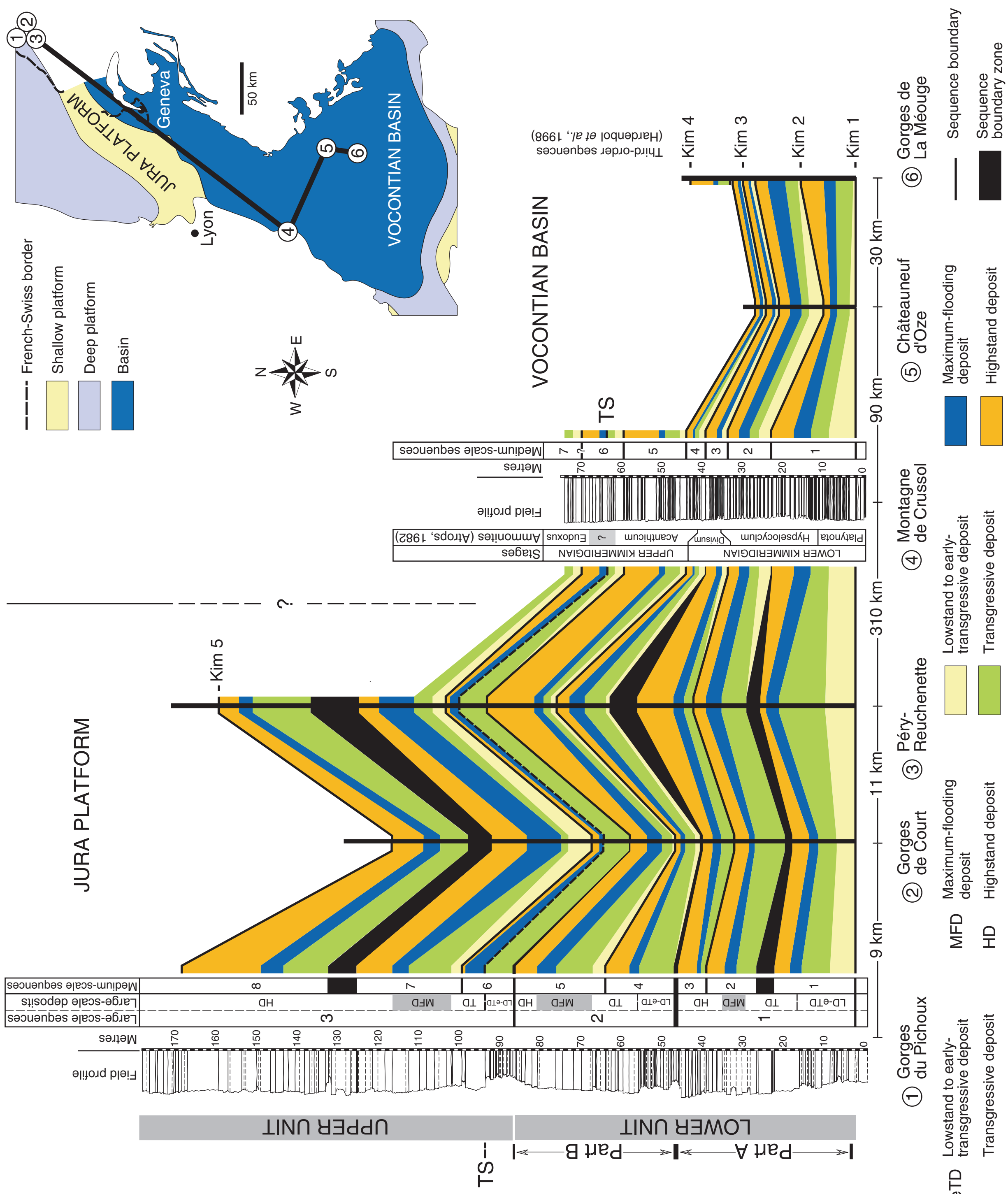

Fig. 10. Sequence-stratigraphic correlation between the Jura platform and the Vocontian Basin. For details on the Châteauneuf d'Oze and Gorges de La Méouge sections see Colombié & Strasser (2003).

Stages		Ammonite zones	Third-order sequence boundaries	Age of third-order sequence boundaries	Time spans between third-order SBs	Time span between Kim 1 and Kim 5	Large-scale sequences	Medium-scale sequences	Small-sc. sequences per medium-sc. sequence	Time spans between medium-sc. sequences comparable with third-order sequences	Time span between Kim 1 and Kim 5
			Hardenbol *et al.* (1998)				**This study**				
KIMMERIDGIAN (*sensu gallico*)	UPPER		Kim 5	150·86		3·12 Ma					3·2 Ma (or 3·6 Ma)
		Beckeri			1·15 Ma		3	8	4	1·2 / 1·4 Ma	
		Eudoxus						7	4/6*		
								6	4		
			Kim 4	152·01							
		Acanthicum			690 ka		2	5	4	800 ka	
								4	4		
			Kim 3	152·70							
	LOWER	Divisum			840 ka		1	3	4/5*	800 / 900 ka	
								2	4		
		Hypselocyclum	Kim 2	153·54							
					440 ka			1	4/5*	400 / 500 ka	
		Platynota	Kim 1	153·98							

Fig. 11. Comparison of the time spans proposed by Hardenbol *et al.* (1998) with the ones defined in the Kimmeridgian of the Swiss Jura. Uncertainties in interpretation (*) are discussed in the text.

and the high-resolution platform-to-basin correlation reveal that depositional sequences are hierarchically stacked. Small-scale sequences are generally composed of five elementary sequences, and medium-scale sequences contain four small-scale sequences. Accordingly, the small- and the medium-scale sequences are interpreted to coincide with the first and the second eccentricity cycle respectively (i.e. 100 and 400 ka).

In the central Swiss Jura, the Kimmeridgian includes eight medium-scale sequences and 32–36 small-scale sequences that would correspond to 3·2–3·6 Ma (Fig. 11). According to Hardenbol *et al.* (1998), the same interval covers 3·12 Ma. This supports the suggestion that the sedimentation was at least partly controlled by cyclic environmental changes induced by insolation variations in the Milankovitch frequency band. However, some discrepancies occur between the timing suggested by this cyclostratigraphical interpretation and the dating of the sequence boundaries by Hardenbol *et al.* (1998) for the same time interval (Fig. 11). This may be linked to the margin of error in the absolute dating of Gradstein *et al.* (1994), and/or to uncertainties in the sequence-stratigraphic interpretation. It is therefore useful to compare the results obtained in this study with the sequence stratigraphy established in other Western European basins.

COMPARISON WITH OTHER WESTERN EUROPEAN BASINS

The sequence stratigraphic and cyclostratigraphic interpretations of the central Swiss Jura and the Vocontian Basin sections and the high-resolution platform-to-basin correlation lead to a biostratigraphically well-constrained temporal framework. In particular, the large-scale and the medium-scale sequences revealed in this study can then be compared with the sedimentary sequences defined in other Western European basins (north-eastern Spain, western and central Portugal, northern France, and southern England; Fig. 12).

The large-scale sequence boundaries, and notably the ones equivalent to Kim 3 and Kim 4, appear in comparable biostratigraphic positions in most of the basins indicated in Fig. 12. In particular, the sequential interpretations proposed by Taylor *et al.* (2001) in the Wessex-Weald Basin (southern England) and by Marques & Olóriz (1989) in the Algarve Basin (Portugal) are very similar to the one proposed in this study. The slight deviations concerning the location of Kim 1, Kim 3, Kim 4 and Kim 5 probably result from uncertainty in the biostratigraphic dating and in the correlations between the Tethyan and the boreal realms.

The sequence-boundary zone between medium-scale sequences 7 and 8 appears distinctly in the central Swiss Jura but is not mentioned in other places. In the central Swiss Jura, medium-scale sequences 7 and 8 belong to the third large-scale sequence that contains three medium-scale (i.e. 400 ka) and 12 small-scale (i.e. 100 ka) sequences. The third large-scale sequence would therefore represent 1·2 Ma (Fig. 11). This large-scale sequence is comprised between third-order sequence boundaries Kim 4 and Kim 5, and Hardenbol *et al.* (1998) attribute about 1·15 Ma to this interval (Fig. 11). Consequently, the duration of the third large-scale sequence proposed in this study is consistent with the one inferred

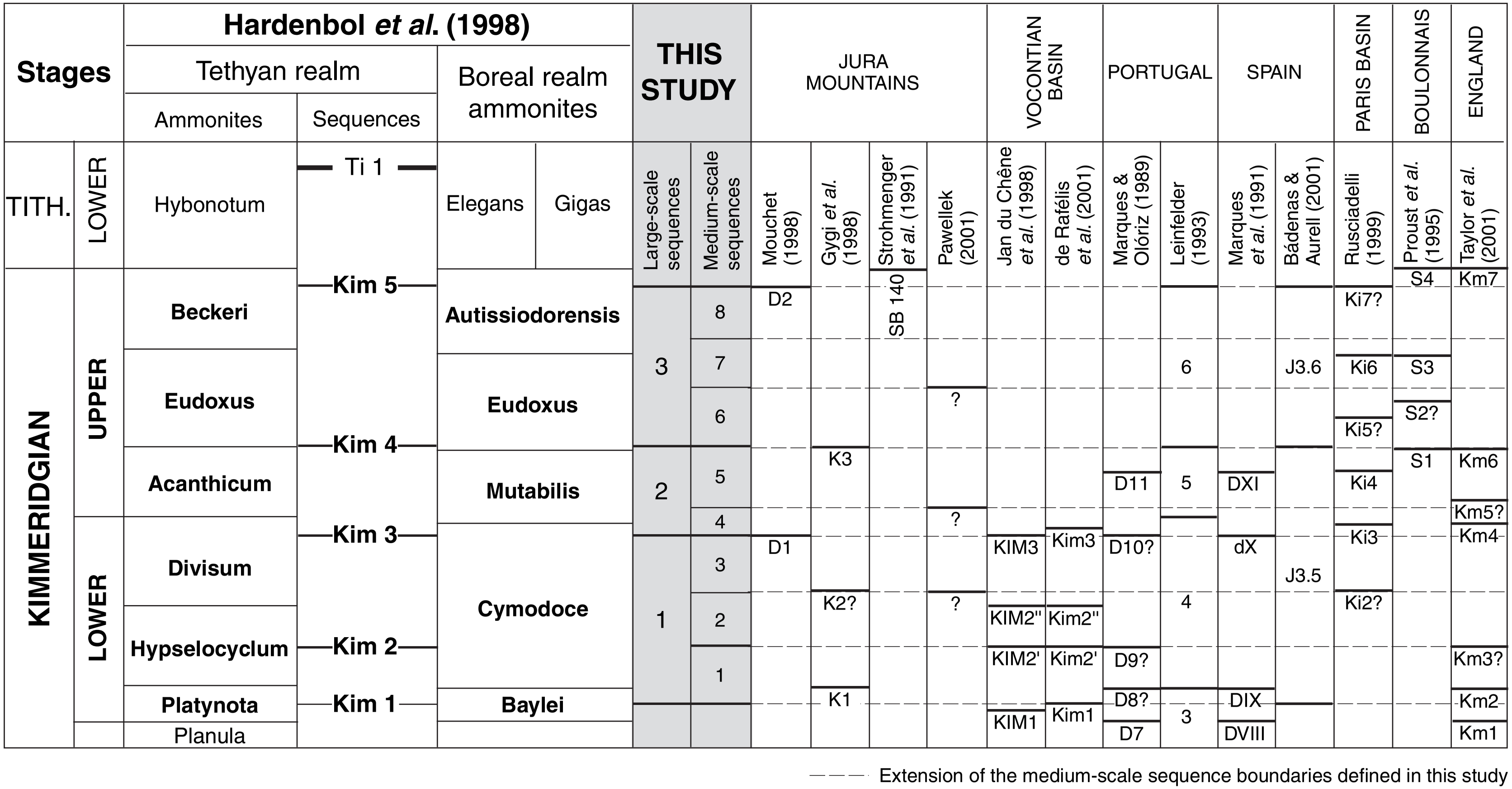

Fig. 12. Comparison between the sequential interpretation proposed in this study with the one defined by other authors in the Jura Mountains, in the Vocontian Basin, Spain, Portugal, France, and England. The medium-scale sequence boundaries equivalent to Kim 1, Kim 3 and Kim 4, also interpreted as long-term sequence boundaries, are well expressed in the other European basins. The other medium-scale sequence boundaries, which are attenuated or enhanced in the Jura Mountains by increased siliciclastic input and/or tectonic events, are poorly represented in other places.

from the sequence-chronostratigraphic chart of Hardenbol *et al.* (1998). However, it does not include small-scale sequences 31 and 32 that form the sequence boundary zone (SBZ) between medium-scale sequences 7 and 8 (Fig. 9). Moreover, the upper part of the Kimmeridgian is marked by high accommodation that should result in rather homogeneous facies and thick beds. Nevertheless, small-scale sequences 31 and 32 display important facies and thickness variations. The SBZ between medium-scale sequences 7 and 8 is therefore assumed to result at least partly from differential subsidence. Unless enhanced by local or regional tectonics, this medium-scale sequence boundary appears to be attenuated because of the high accommodation rate resulting from the Late Kimmeridgian second-order maximum flooding (Haq *et al.*, 1987; Hallam, 1988, 2001; Jacquin & de Graciansky, 1998; Taylor *et al.*, 2001; Taylor & Sellwood, 2002). Kim 2 that is only weakly developed in the central Swiss Jura, also seems difficult to define in the other basins. This sequence boundary is located close to the maximum-flooding interval of the first large-scale sequence defined in this study and is consequently attenuated (Strasser *et al.*, 1999; Fig. 9).

In most of the Western European basins, the Early Kimmeridgian sea-level rise led to relatively high siliclastic input and low sedimentation rates that resulted in marly deposits and condensed sections respectively. Within the Acanthicum ammonite zone, carbonate platform conditions were well established with the local development of reefal facies (Marques & Olóriz, 1989; Marques *et al.*, 1991; Bádenas & Aurell, 2001). A regressive trend is generally recognized in the Late Kimmeridgian (Proust *et al.*, 1995; Rusciadelli, 1999). In southern England (Wessex-Weald Basin; Taylor *et al.*, 2001; Taylor & Sellwood, 2002) and west-central Portugal (Lusitanian Basin; Leinfelder, 1993), the sedimentary record is greatly controlled by the synsedimentary tectonic regime and the related basin configuration.

In the central Swiss Jura, the Early Kimmeridgian is characterized by a general loss of accommodation up to sequence boundary Kim 3 (Fig. 9). Depositional sequences are laterally continuous and present approximately the same thickness from one section to the other, so that a tectonic control can be excluded. This general accommodation loss is interpreted as resulting from a slowing down of the second-order sea-level rise and from carbonate production and accumulation that were sufficiently influential to maintain keep-up with sea-level rise (Kendall & Schlager, 1981; Jones & Desrochers, 1992; Posamentier *et al.*, 1992; Handford & Loucks, 1994; Hunt & Tucker, 1995). The second-order trend of sea-level rise subsequently accelerated up to the maximum flooding in the Eudoxus zone that corresponds in the central Swiss Jura to the thickest beds and the most open-marine facies. Consequently, the Early Kimmeridgian of the central Swiss Jura can be classified as part of a keep-up transgressive systems tract that was initiated already in the Late Oxfordian (Fig. 2).

CONCLUSIONS

1 Field observations and thin-section analyses reveal that in Kimmeridgian times the central Swiss Jura was occupied by tidal flats and by more or less open-marine lagoons where shoals and bioherms developed. Low-energy lagoonal deposits such as mudstones and bioclast-peloid wackestones to packstones are dominant. Higher-energy grainstones composed of bioclasts, peloids, and ooids occur in lesser proportion. On the basis of temporal facies changes and stacking patterns, sequence and cyclostratigraphic interpretations are proposed.

2 Small-, medium- and large-scale depositional sequences are identified. Diagnostic sedimentological features, which are independent of scale, used for the sequence-stratigraphic interpretation are defined. However, the expression of the sequences varies according to sequence position within a lower-frequency depositional sequence. In particular, their formation is strongly controlled by the second-order transgression characterizing the lower part of the Kimmeridgian.

3 The depositional sequences defined in the central Swiss Jura are correlated with biostratigraphically well-dated sections in the Vocontian Basin. This permits comparison with the sequence stratigraphy compiled in the sequence-chronostratigraphic chart of Hardenbol *et al.* (1998). According to this chart, the Kimmeridgian lasted 3·12 Ma (Gradstein *et al.*, 1994). In the central Swiss Jura, this interval includes 32 small-scale and eight medium-scale sequences suggesting that the small-scale and the medium-scale sequences correspond to the first and the second eccentricity cycles, respectively (i.e. 100 and 400 ka). The high-resolution platform-to-basin correlation thus reveals that the platform and basin dynamics were at least partly controlled by cyclic environmental changes induced by insolation variations in the Milankovitch frequency band.

4 This high-resolution temporal framework constitutes a solid base to compare the sequence-stratigraphic interpretation established in the central Swiss Jura with the one proposed for other Western European basins, and to define the controlling factors for platform development. The correlation of the studied platform sections reveals two distinct lithological units. The lower unit is composed of deposits between sequence boundaries Kim 1 and Kim 4 and exhibits thinly bedded limestones with siliciclastics and desiccation features. The second unit lies between sequence boundaries Kim 4 and Kim 5 and is characterized by thickly bedded limestones, relatively open-marine facies, as well as the quasi-disappearance of siliciclastic sediments and desiccation features. The boundary between these two units is located near the most important increase in accommodation recorded in the central Swiss Jura during the Kimmeridgian. It occurs in the Eudoxus ammonite zone (Late Kimmeridgian) and corresponds to the second-order maximum flooding recognized in many sedimentary basins. Moreover, the large-scale sequence boundaries defined in the Kimmeridgian of the central Swiss Jura appear in comparable biostratigraphic positions in most of Western European basins. Discrepancies that occur are probably because of local or regional tectonics. Lastly, the Early Kimmeridgian sea-level rise led to the formation of marly intervals and condensed sections in most of the Western European basins. In contrast, carbonate production and accumulation on the Jura platform were sufficiently influential to maintain keep-up with the second-order transgression.

ACKNOWLEDGEMENTS

This study is part of a research project funded by the Swiss National Foundation (no. 20-56491.99). This financial support is gratefully acknowledged. We also thank reviewers M.T. Harris, B. Bádenas, and P. Blanchon, and co-editor I.P. Monañez who helped to improve the manuscript by their helpful and useful comments.

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Manuscript received 29 January 2003;
revision accepted 2 May 2005.