Geol Rundsch (1998) 86:852–874

ORIGINAL PAPER

B. Pittet · A. Strasser

Long-distance correlations by sequence stratigraphy and cyclostratigraphy: examples and implications (Oxfordian from the Swiss Jura, Spain, and Normandy)

Received: 4 November 1996/Accepted: 24 August 1997

Abstract The Oxfordian sedimentary successions studied in the Swiss Jura, in Normandy, and in the Soria and Cazorla regions of Spain display complex facies evolution and stacking patterns. Based on biostratigraphy and absolute age dating, it is suggested that the shallow-water depositional settings in the Jura, Normandy, and the Soria region as well as the deeper-water environments in the Cazorla region, recorded climatic and sea-level fluctuations in the Milankovitch frequency band. Beds and bedsets corresponding to 20-, 100-, and 400-ka cyclicities can be identified. Facies evolution inside such small-scale sequences and also in the larger sequences of million-year scale is interpreted in terms of sequence stratigraphy. Superposition of high-frequency cyclicity on a longer-term sea-level trend led to multiplication of diagnostic surfaces: sequence-boundary and maximum-flooding zones in the large-scale sequences can thus be defined. These zones are correlated between closely spaced sections, but also from the Swiss Jura to Normandy and to Spain. The narrow time lines given by Milankovitch cyclicity then allow comparison of facies evolution in the different regions on a scale of 100 ka or less. By filtering out local effects of differential subsidence and sediment supply, a long-term sea-level curve valid for the northwestern margin of the Tethys ocean can be reconstructed for the Middle to Late Oxfordian. Differential subsidence is implied from varying thicknesses of the sequences as well as from the distribution of siliciclastics which have been channelized through depressions. Tilted blocks, reduced sedimentation, or increased input of siliciclastics appearing at the same time in all study areas point to a widespread regional tectonic event. Distribution through the sequences of climate-dependent facies components such as corals, ooids, palynomorphs, and siliciclastics indicates that climate changes were dependent on atmospheric circulation patterns and thus on paleolatitude. Rainy periods and related increase of siliciclastics in the Swiss Jura were more abundant during low sea-level stands, whereas in the Soria region they coincided with sea-level highs. Through the combination of high-resolution sequence stratigraphy and cyclostratigraphy, and supported by biostratigraphy and absolute dating, it becomes possible to analyze paleoenvironmental changes in a very narrow time framework.

Key words Oxfordian · Sequence stratigraphy · Cyclostratigraphy · Stratigraphic correlation · Swiss Jura · Spain · Normandy

Introduction

One of the main goals of sedimentary research is the reconstruction of ancient sedimentary environments and the understanding of the processes controlling their evolution. The major governing factors are eustatic sea level, climate, and tectonics, but also substrate morphology, oceanic currents, water properties, and ecology are important parameters. Such reconstructions are often rendered difficult because of lacking precise time control. Classical methods, such as biostratigraphy or magnetostratigraphy, do not have the resolution required to monitor environmental changes happening on a hundred- to thousand-year scale. Sequence stratigraphy correlates genetically related, time-equivalent sedimentary bodies by using seismic sections, well logs and/or outcrops (e.g., Wilgus et al. 1988; Loucks and Sarg 1993; Weimer and Posamentier 1993; Posamentier et al. 1993), but again needs independent age dating. High-resolution sequence stratigraphy (e.g., Howell and Aitken 1996) refines the

B. Pittet (✉) · A. Strasser
Institut de Géologie et Paléontologie, Pérolles,
CH-1700 Fribourg, Switzerland
Fax: +41 26 300 97 42
E-mail: bernard.pittet@unifr-ch

sequence-stratigraphic approach by using as many parameters as possible on a timescale as fine as possible. One of the best time resolutions can be obtained by using cyclostratigraphy (e.g., Schwarzacher 1993; De Boer and Smith 1994; House and Gale 1995): if a hierarchical, quasi-periodic stacking of small-scale sedimentary sequences can be observed and independent time control implies frequencies corresponding to orbital cycles (Milankovitch 1941; Berger et al. 1989), a resolution on the 10- to 100-ka scale becomes feasible.

In this study we combine high-resolution sequence stratigraphy with cyclostratigraphy. The Middle to Late Oxfordian time interval was chosen because of its relatively well-established biostratigraphic framework, and because its sediments display periodic changes from a carbonate-rich mode to a siliciclastic-rich one, thus monitoring climatically, eustatically, and/or tectonically induced fluctuations of terrestrial runoff from the hinterland. In order to filter out local tectonic and climatic effects and to distinguish between autocyclic and allocyclic processes, correlations have been made from one sedimentary basin to another, and from one climatic zone to another.

Study areas, paleogeography, and biostratigraphic framework

Fifteen sections were studied with sedimentological, sequence-stratigraphic, and cyclostratigraphic methods. They belong to different paleotectonic domains on the northwestern margin of the Tethys Ocean (Fig. 1; Ziegler 1988) and are of Middle to Late Oxfordian age.

The main study area is the Swiss Jura (study area 1, Fig. 1) where seven reference sections were sampled (750 thin sections, 50 marl washings, 40 palynofacies analyses, 110 clay-mineral analyses; Pittet 1996). These sections show strongly variable facies of a shallow carbonate platform influenced by siliciclastic input (clays, quartz, and feldspars) and frequent emersions. Three complementary sections were measured, two on the shallow platform and one in the adjacent epicontinental basin where large quantities of siliciclastics and detrital carbonate accumulated.

One section of Normandy (France; study area 2, Fig. 1), already interpreted in terms of sequence stratigraphy by Rioult et al. (1991), was integrated into this study. It shows facies of a platform margin with shoal sedimentation, but also of protected lagoons and estuaries.

In Spain two areas were selected. The two Oxfordian sections of the Soria region (northeastern Spain; study area 3, Fig. 1) contain the record of shallow carbonate–siliciclastic platform environments (Dragastan et al. 1987; Alonso and Mas 1990). The two sections of the Cazorla region (southwestern Spain; study area 4, Fig. 1) show facies of the Prebetic intermediate platform (Marquez et al. 1991) where material exported

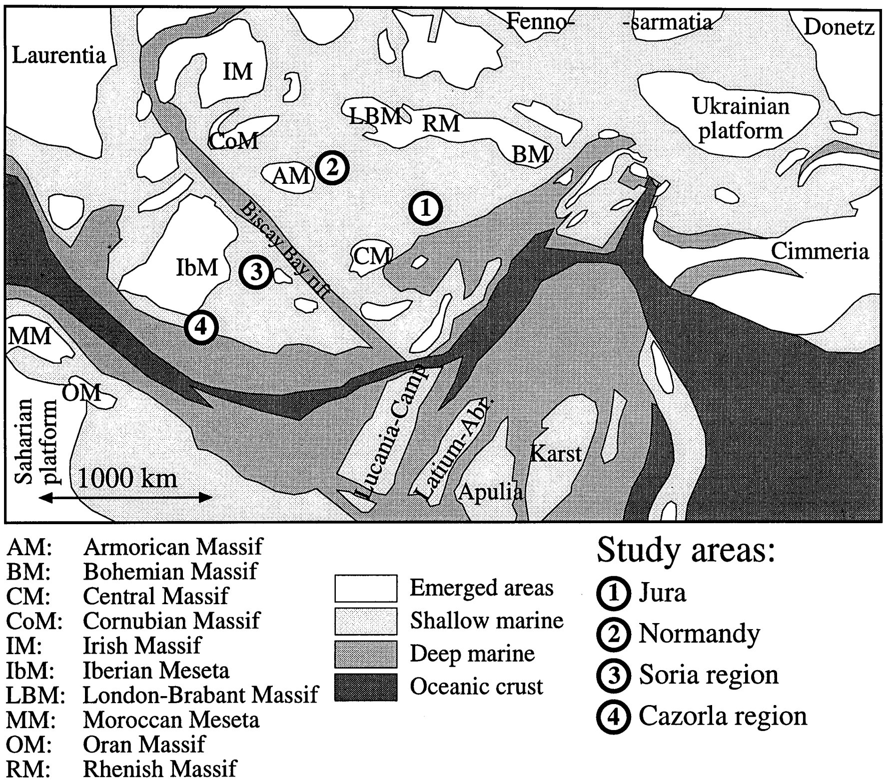


Fig. 1 Simplified paleogeographic map for the Oxfordian to Tithonian and location of the study areas. (After Ziegler 1988)

from the shallow platform (clays and carbonates) mixed with more distal carbonate elements (sponges, globochaetes, ammonites, belemnites). Sedimentation rates were low, as indicated by common glauconitization of peloids and oncoids. On highs, Ammonitico Rosso facies was deposited, whereas in lows more marls accumulated.

The biostratigraphy for the Oxfordian in the Swiss Jura has been well established by Gygi and Persoz (1986) and Gygi (1995). The ammonite zonation in the Prebetic zone is given by García-Hernández et al. (1979), Acosta (1989) and F.J. Rodriguez-Tovar (pers. commun.), and the one for Normandy by Rioult et al. (1991). The biostatigraphic framework in the Soria region is not as well constrained as in other regions but can be implied from the work of Dragastan et al. (1987), Alonso and Mas (1990), Meléndez (1989), Mensink et al. (1990), Aurell (1990, 1991), Aurell and Meléndez (1993), and Aurell et al. (1995). The correlation between Tethyan and boreal ammonite zonations (Fig. 2) is mainly based on Cariou et al. (1991). However, there is increasing evidence that the uppermost Oxfordian of the Tethyan realm corresponds to the lowermost boreal Kimmeridgian (Matyja and Wierzbowski 1988, 1994; Schweigert 1995a, b). The timescale used for the absolute dating is the one of Gradstein et al. (1994, 1995).

Definition of sequences

Sequence-stratigraphic and cyclostratigraphic interpretations are based on the detailed analysis of facies and sedimentary structures, and on the hierarchical stacking pattern of depositional sequences. Sedimentological studies, integrating complementary methods such as palynofacies (Pittet and Gorin 1997) and clay-mineral analyses (Pittet 1996), allow definition of depositional sequences that are related to relative sea-level variations and/or environmental changes.

Sequences of any scale can be interpreted using the terminology of sequence stratigraphy (e.g., Posamentier et al. 1993), and diagnostic surfaces or intervals can be defined: Sequence boundaries (SB) record the relatively fastest fall in sea level, transgressive surfaces (TS) are the first record of a relative sea-level rise, and maximum-flooding surfaces (MFS) correspond to the relatively fastest and most extensive rise of sea level (Fig. 3). Maximum flooding (MF) designates an interval of fastest rise in sea level, generally exhibiting the deepest or most open facies, and/or reduced sedimentation rates. Based on a single section or on small-scale sequences related to high-frequency sea-level variations, it is not possible to interpret the geometry of the sedimentary bodies (systems tracts; Vail et al. 1991). Therefore, the terms "lowstand deposits" (LSd), "transgressive deposits" (TSd), and "highstand deposits" (HSd) are used to describe the sedimentary record related to the corresponding part of sea-level change (Fig. 3). Small-scale sequences of shallow carbonate platforms are commonly dominated by highstand deposits (Strasser 1991), and facies changes allow in many cases to distinguish between "early highstand deposits" (eHSd) and "late highstand deposits" (lHSd). Sediments related to a first marine flooding phase can be identified in some cases ("early transgressive deposits," eTSd).

Due to superposition of high-frequency oscillations of relative sea level on a long-term trend, diagnostic sequence-stratigraphic surfaces may be multiplied (Montañez and Osleger 1993; Strasser et al. 1994). Thus, it is in many cases useful to define sequence-boundary zones and maximum-flooding zones, corresponding to the relatively fastest fall or rise in the long-term sea level. Similarly, transgressive-surface zones can be introduced (Fig. 3).

Four orders of depositional sequences have been distinguished in the studied outcrops:

1. *Elementary sequences* correspond, in shallow-water environments, to the smallest identifiable transgressive–regressive or shallowing-up trend of facies evolution. There they commonly consist of a single bed and are separated by emersive surfaces (e.g., Figs. 5 and 6, legend in Fig. 4). In deeper environments elementary sequences correspond to repetitive changes in facies such as limestone–marl alternations. In the Prebetic mid-shelf environments (Cazorla region; Fig. 7), e.g., these are due to rapid changes from high-energy conditions for the formation of limestone beds to low-energy conditions for marl deposition. Differential subsidence may strongly influence facies distribution and sequence thicknesses (Pittet 1996). Elementary sequences thus vary in thickness from a few centimetres to 10 m; thick elementary sequences may be composed of several beds. Elementary sequences can form through autocyclic processes, such as lateral migration of shoals or tidal flats (e.g., Pratt and James 1986; Strasser 1991), and/or they can be allocyclically controlled by climatic and eustatic fluctuations (Pittet et al. 1995). Consequently, elementary sequences may have durations that differ from one locality to another, and from one time period to another.
2. *Small-scale composite sequences* correspond to packages of stacked elementary sequences which are commonly visible in the erosional profile (Figs. 5, 6 and 8). In shallow-water settings, such packages display a general transgressive–regressive trend of facies evolution (Fig. 5). Their uppermost part generally consists of intertidal to supratidal facies, and they are bounded by well-defined emersion surfaces. In deeper-water environments, the small-scale composite sequences are defined by a repetitive stacking of elementary sequences evolving from marl dominated to limestone dominated, or vice versa (Fig. 7). In addition, changes of color, bioturbation intensity,

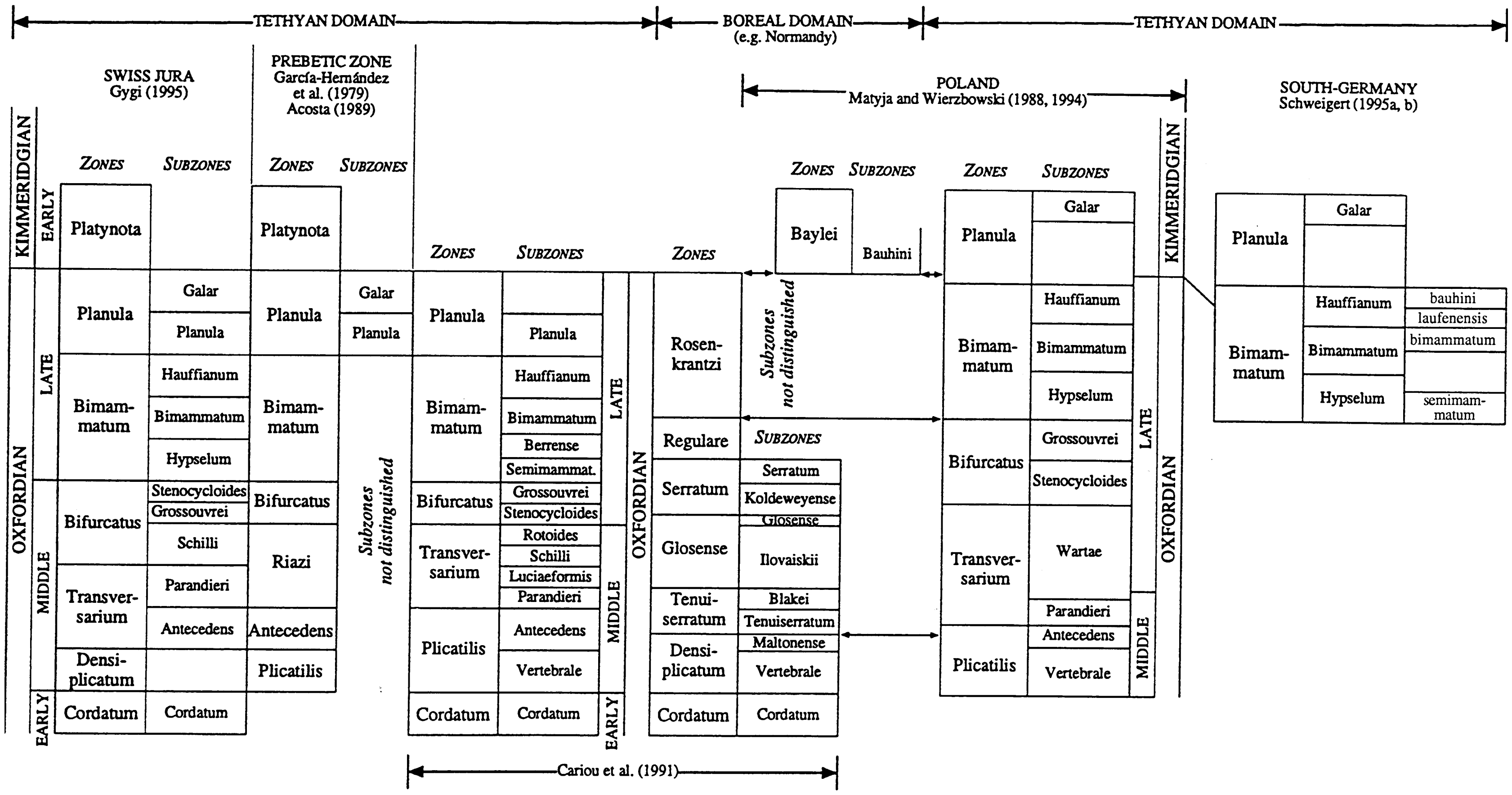


Fig. 2 Middle to Late Oxfordian biostratigraphy for the Tethyan and boreal domains according to different authors

Fig. 3 Composite curve of long-term and short-term sea-level variations, and resulting large-scale and small-scale depositional sequences. Superposition of high-frequency fluctuations on a long-term trend results in multiplication of small-scale diagnostic surfaces which define a diagnostic zone in the large-scale sequence. *SB* Sequence boundary; *MF* maximum flooding; *TS* transgressive surface; *LSd* lowstand deposits; *TSd* transgressive deposits; *eHSd* early highstand deposits; *lHSd* late highstand deposits

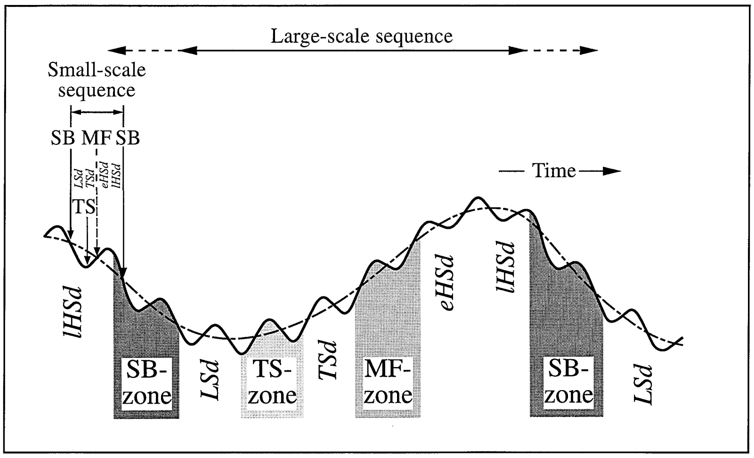
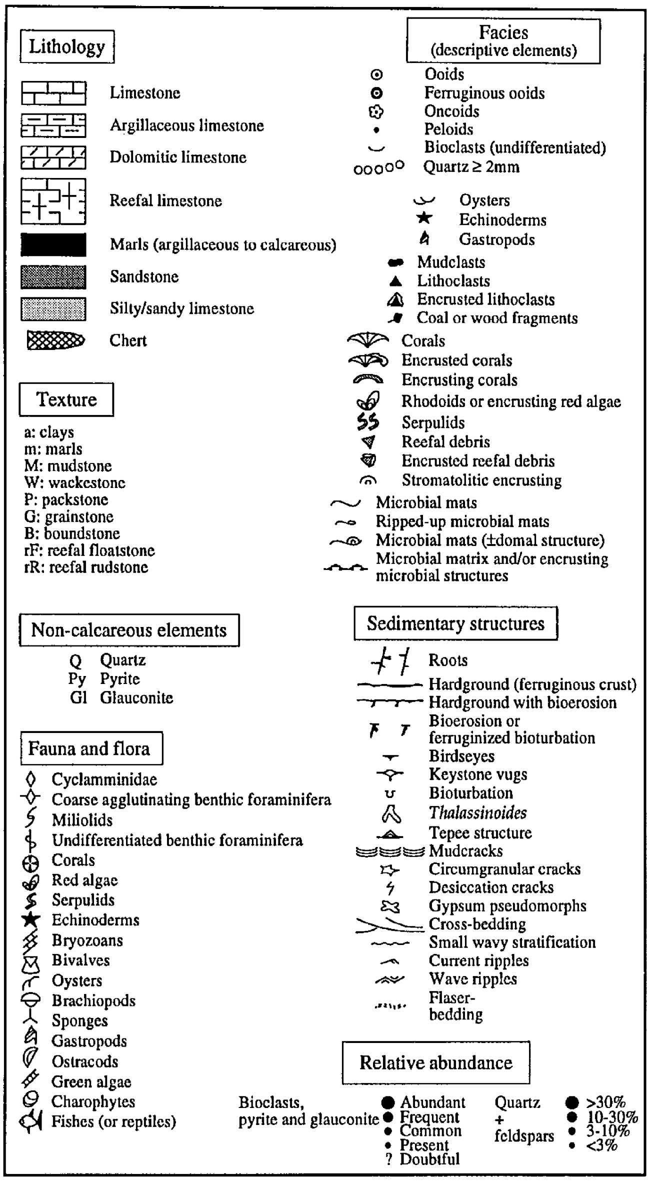


Fig. 4 Legend for the detailed logs



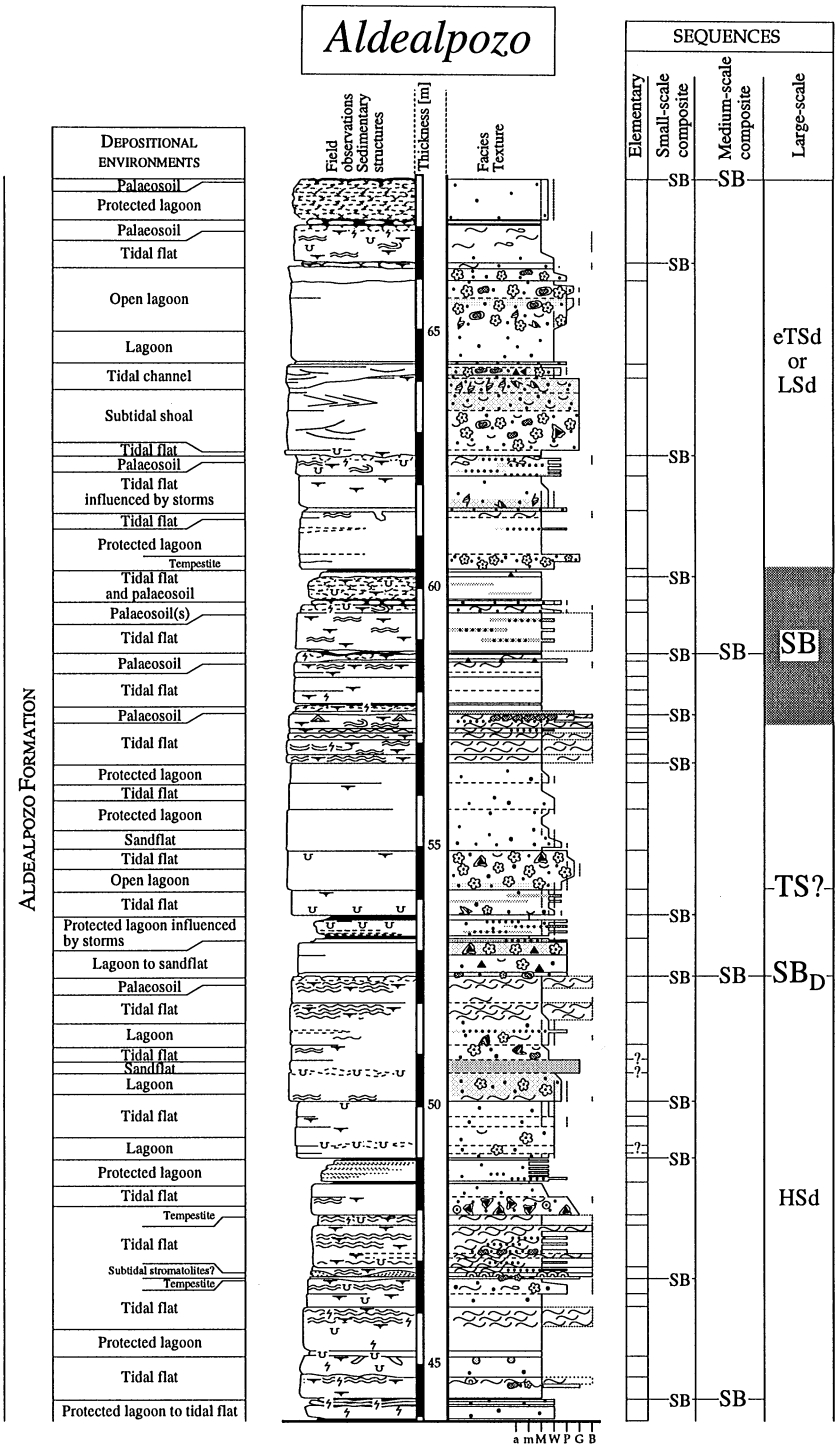
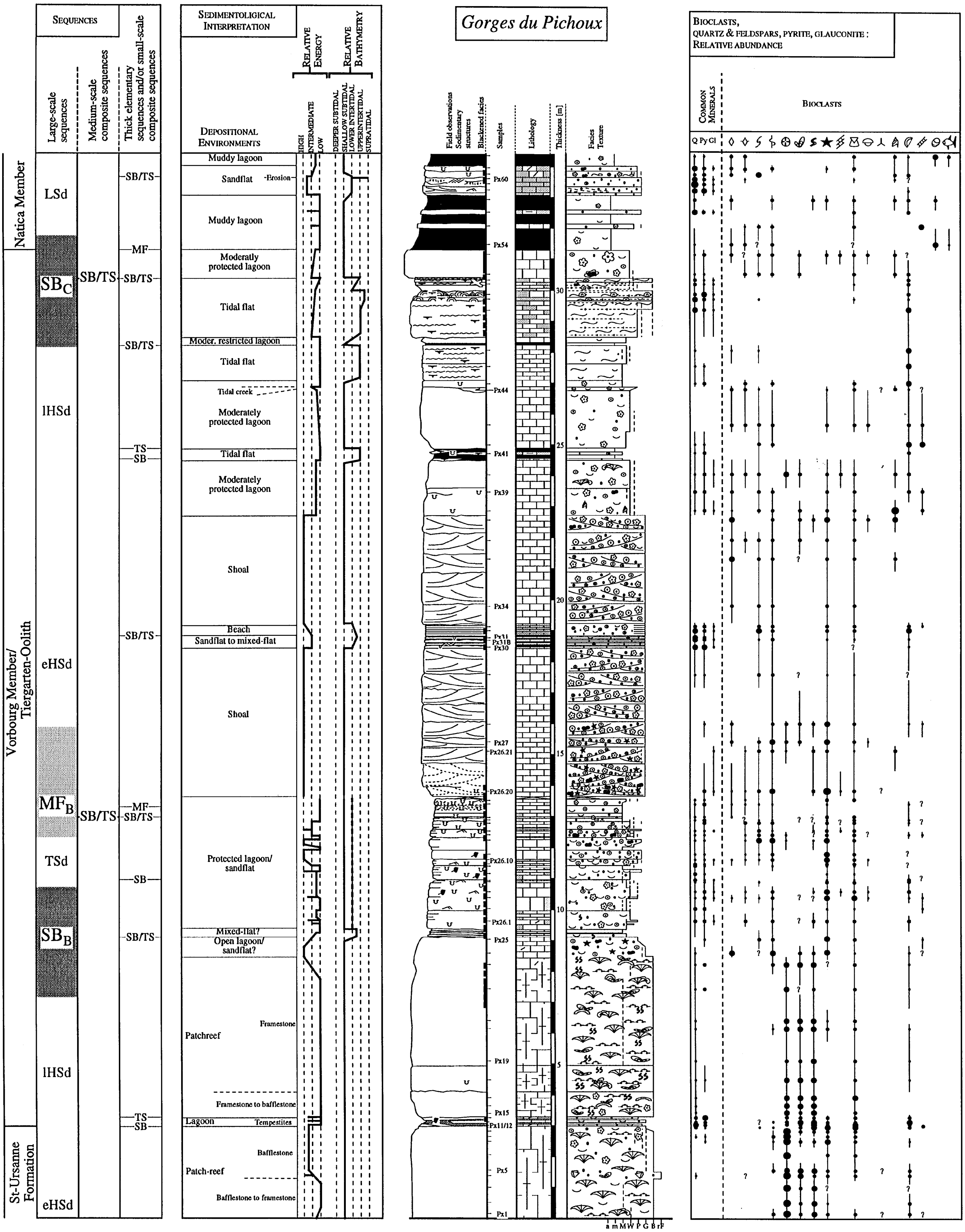


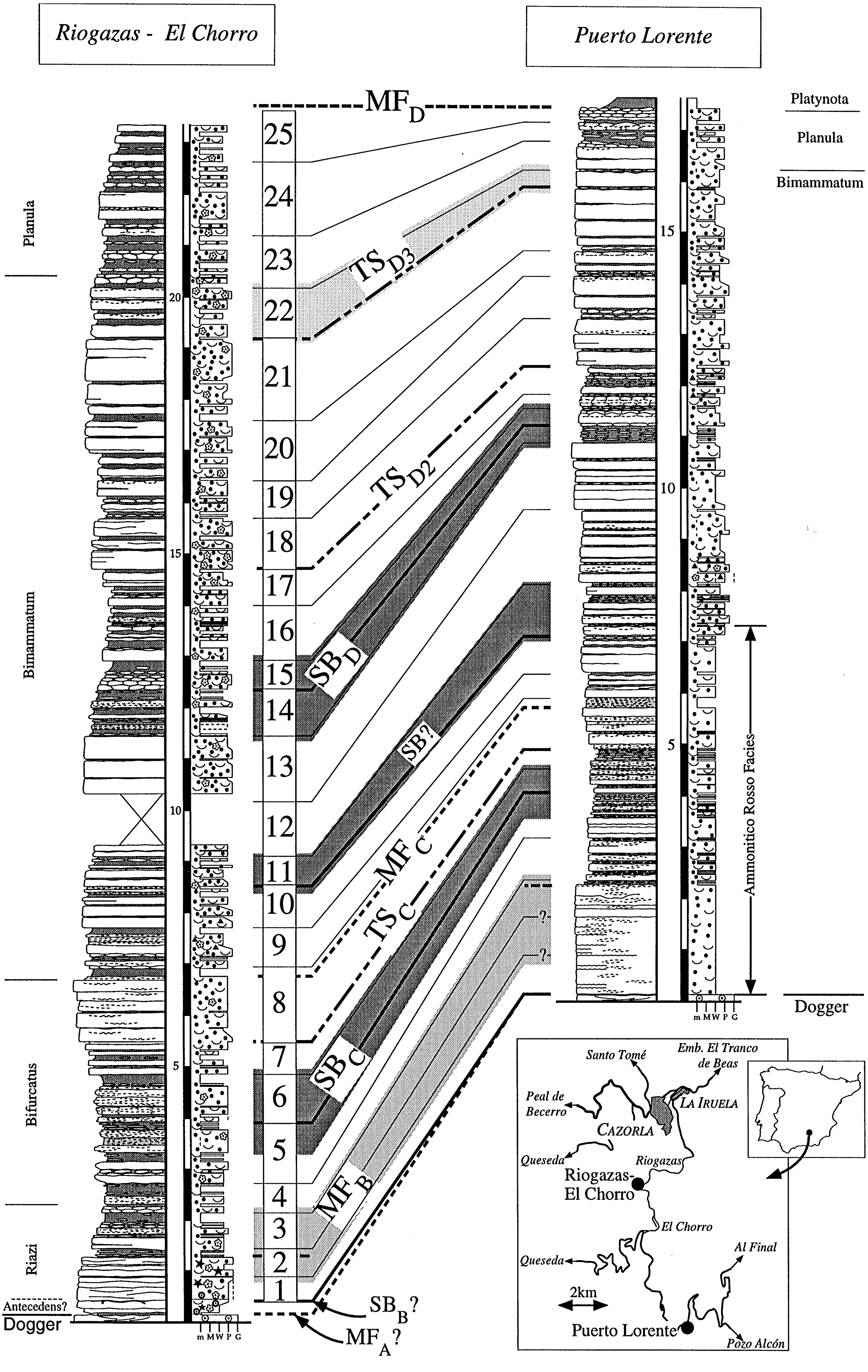
Fig. 5 Part of the Aldealpozo section showing a well-structured sedimentary record: Four orders of depositional sequences can be distinguished: elementary sequences (possibly corresponding to the 20-ka orbital precession cycle), small- and medium-scale composite sequences (probably corresponding to the 100- and 400-ka eccentricity cycles), and large-scale sequences attributed to long-term tectono-eustasy and/or climate changes. Legend same as in Fig. 4; sequence-statigraphic terms as in Fig. 3. For correlations (SBD) compare with Fig. 12

and/or levels of nodularization may locally be used to delimit these sequences. Small-scale composite sequences have thicknesses ranging from a few decimetres to a few tens of meters.

3. *Medium-scale composite sequences* are composed of small-scale composite sequences or of thick elementary sequences (e.g., Figs. 5 and 6). If they formed in shallow-water settings, they again exhibit a general

Fig. 6 Detail of Gorges-du-Pichoux section (legend same as in Fig. 4). Example of detailed analysis and interpretation of facies, sedimentary strutures, and stacking pattern of the beds allows for the identification of small-, medium-, and large-scale sequences. For correlations refer to Figs. 9 and 12. *SB* sequence boundary; *MF* maximum flooding; *TS* transgressive surface. *B*, *C* labels for long-distance correlation in Fig. 12


Gorges du Pichoux
Sequences
Large-scale sequences
Medium-scale composite sequences
Thick elementary sequences and/or small-scale composite sequences
Sedimentoligical Interpretation
Depositional Environments
Relative Energy
High
Intermediate
Low
Relative Bathymetry
Deeper subtidal
Shallow subtidal
Lower intertidal
Upper intertidal
Supratidal
Field observations
Sedimentary structures
Blackened facies
Samples
Lithology
Thickness [m]
Facies
Texture
Bioclasts, quartz & feldspars, pyrite, glauconite : relative abundance
Common minerals
Q Py Gl
Bioclasts
Natica Member
Vorbourg Member/ Tiergarten-Oolith
St-Ursanne Formation
LSd
SB$_C$
lHSd
eHSd
MF$_B$
TSd
SB$_B$
lHSd
eHSd
SB/TS
MF
SB/TS
SB/TS
SB/TS
TS
SB
SB/TS
MF
SB/TS
SB/TS
SB
SB/TS
TS
SB
Muddy lagoon
Sandflat
Erosion
Muddy lagoon
Moderatly protected lagoon
Tidal flat
Moder. restricted lagoon
Tidal flat
Tidal creek
Moderately protected lagoon
Tidal flat
Moderately protected lagoon
Shoal
Beach
Sandflat to mixed-flat
Shoal
Protected lagoon/ sandflat
Mixed-flat?
Open lagoon/ sandflat?
Patchreef
Framestone
Framestone to bafflestone
Lagoon
Tempestites
Patch-reef
Bafflestone
Bafflestone to framestone
Px60
Px54
Px44
Px41
Px39
Px34
Px31
Px31B
Px30
Px27
Px26.21
Px26.20
Px26.10
Px26.1
Px25
Px19
Px15
Px11/12
Px5
Px1
30
25
20
15
10
5
a m M W P G B r F


Riogazas - El Chorro
Puerto Lorente
MF_D
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
TS_D3
TS_D2
SB_D
SB?
MF_C
TS_C
SB_C
MF_B
SB_B?
MF_A?
?
Planula
Bimammatum
Bifurcatus
Riazi
Antecedens?
Dogger
20
15
10
5
m M W P G
Platynota
Planula
Bimammatum
Ammonitico Rosso Facies
Dogger
Santo Tomé
Emb. El Tranco de Beas
Peal de Becerro
La Iruela
Cazorla
Queseda
Riogazas
Riogazas-El Chorro
El Chorro
Al Final
Queseda
2km
Puerto Lorente
Pozo Alcón

transgressive–regressive facies evolution and well-marked emersion surfaces at their tops. Important facies changes may occur at the boundaries (Pittet 1994, 1996; Pittet et al. 1995). Medium-scale composite sequences range from a few meters to a few tens of meters in thickness.

4. *Large-scale composite sequences* correspond to a long-term (million-year scale) transgressive–regressive evolution of the depositional environments. Where elementary, small-scale and medium-scale composite sequences display the relatively deepest facies, a maximum-flooding zone can be placed; where emersion features and/or relatively shallowest facies are concentrated, a sequence-boundary zone is implied. In shallow-water environments, the relative thicknesses of elementary, small-scale, and medium-scale composite sequences roughly translate accommodation: sequences generally become thinner towards a sequence-boundary zone, and they expand in the part of the sections corresponding to transgression, maximum flooding, and early highstand on the long term (e.g., Figs. 5 and 6). Sequence-boundary and maximum-flooding zones of the large-scale composite sequences have been labeled A, B, C, and D, in order to facilitate the sequence-stratigraphic correlations between the studied sections (see below).

Elementary, small-scale and medium-scale composite sequences are hierarchically stacked. Many of the small-scale composite sequences contain five elementary sequences, and most medium-scale composite sequences are built up of four small-scale composite or thick elementary sequences (e.g., Fig. 5). Such stacking patterns suggest an orbital (Milankovitch) control on the formation of these sequences: the thin elementary sequences would correspond to the precession cycle (20 ka in the Oxfordian; Berger et al. 1989; Berger and Loutre 1994), the small-scale composite and thick elementary sequences to the first eccentricity cycle (100 ka), and the medium-scale composite sequences to the second eccentricity cycle (400 ka). This interpretation is confirmed by the absolute dating of the ammonite zones (Gradstein et al. 1994, 1995) within which the depositional sequences can be counted (see below).

Sequential interpretation and correlation of the studied sections

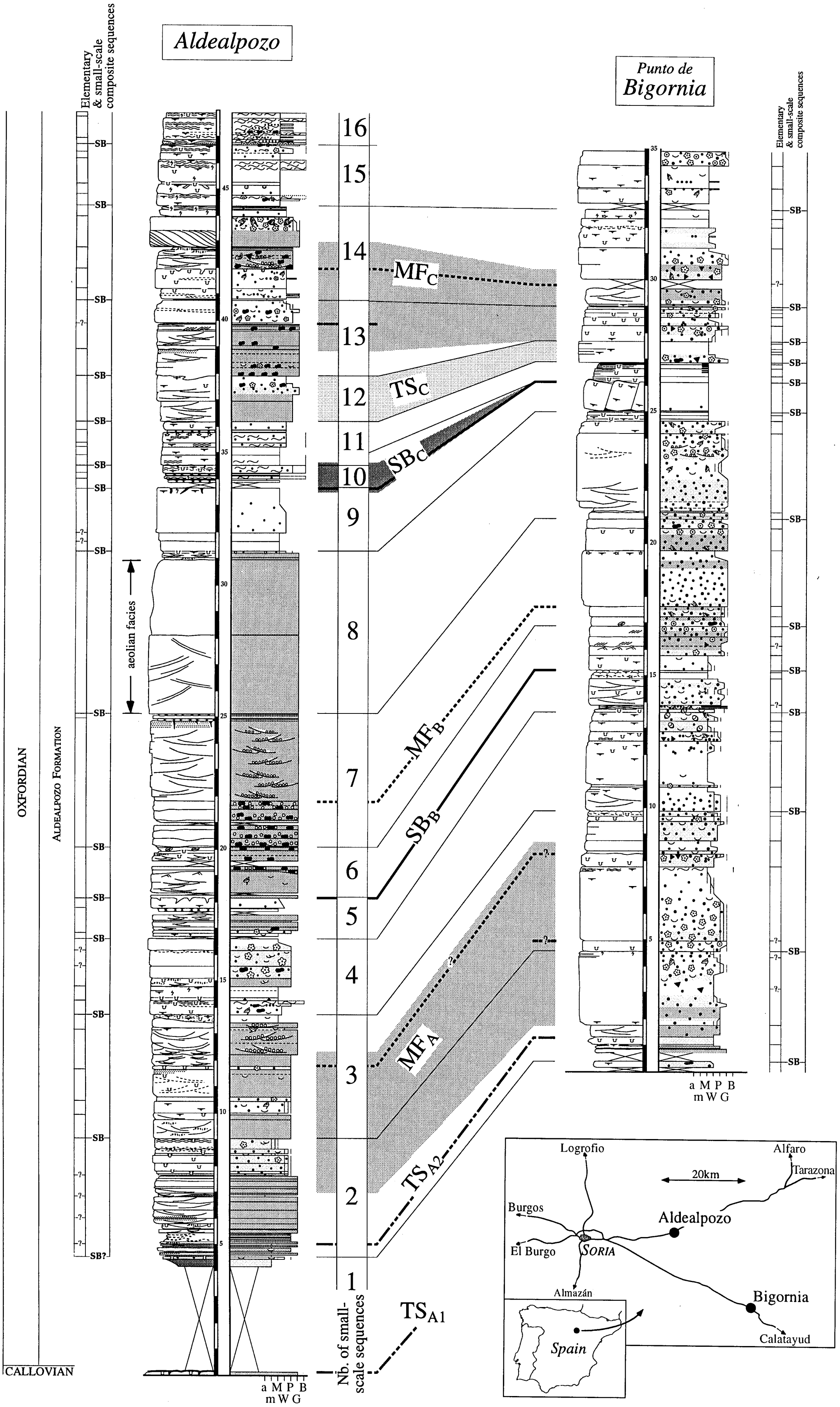
Correlation criteria

In order to reconstruct the evolution of the sedimentary systems through time, it is important to correlate the measured sections as precisely as possible. In this study the following approach was applied:

1. Detailed facies analysis and interpretation of each profile in terms of elementary, small-scale, and medium-scale composite sequences, as well as in terms of the large-scale sequence-stratigraphic evolution. For a complete description and interpretation of the facies refer to Pittet (1996), Pittet et al. (1995), and Pittet and Gorin (1997).
2. Correlation at the regional scale (e.g., Swiss Jura) based on lithostratigraphic units or boundaries which are dated biostratigraphically, and on the identification of the sequence-boundary and maximum-flooding zones of the large-scale composite sequences. By comparing the number of small-scale and medium-scale composite sequences between these sequence-stratigraphic zones, a best-fit solution is searched for which satisfies the observed stacking pattern and facies evolution in each section as well as the biostratigraphic framework.
3. Correlation between the different study areas (Swiss Jura, Soria region, Cazorla region, Normandy) based on the integration of each regional correlation, first on the long term (large-scale composite sequences with sequence-boundary and maximum-flooding zones constrained by biostratigraphy), then on the level of medium- and small-scale composite sequences. Again, a best-fit solution is looked for by comparing the number of small-scale composite sequences within the available biostratigraphic framework.
4. If a hierarchical stacking pattern suggesting an orbital control on sequence formation is recognized, the small-scale composite sequences are counted within ammonite zones, and the results compared with the absolute ages of Gradstein et al. (1994, 1995). Once a small-scale sequence is identified as orbitally controlled, it allows correlation between sections on a 100-ka scale. In the ideal case, each small-scale composite sequence has a defined position in a medium-scale and large-scale composite sequence (e.g., second above SBD; Fig. 5). Even if the

Fig. 7 Logs and correlation of the two sections in the Cazorla region (legend same as in Fig. 4). Diagnostic surfaces or zones of large-scale sequences are marked as in Fig. 6; *A–D* labels for long-distance correlation in Fig. 12

Fig. 8 Logs and correlation of the two sections in the Soria region (legend same as in Fig. 4). Note that the Aldealpozo section is rich in siliciclastics. Diagnostic surfaces or zones of large-scale sequences are marked as in Fig. 6; *A–C* labels for long-distance correlation in Fig. 12


Aldealpozo
Punto de Bigornia
Elementary & small-scale composite sequences
OXFORDIAN
ALDEALPOZO FORMATION
CALLOVIAN
SB
SB?
-?-
aeolian facies
a M P B
m W G
Nb. of small-scale sequences
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
MFC
TSC
SBC
MFB
SBB
MFA
TSA2
TSA1
5
10
15
20
25
30
35
40
45
Logroño
Alfaro
Tarazona
20km
Burgos
Aldealpozo
El Burgo
SORIA
Almazán
Bigornia
Calatayud
Spain

sequence is not dated biostratigraphically in each outcrop, it can be attributed to a biostratigraphic position through correlation with dated sections.

The comparison of long- and short-term sequence-stratigraphic and cyclostratigraphic interpretations in the different study areas (Fig. 1) permits bringing into evidence similarities and differences in their sedimentary evolution. Orbital (Milankovitch) cycles have a short-term climatic and eustatic influence on a global scale, even if the sedimentary signatures may differ from one study area to the other, depending mainly on changing climatic conditions in different paleolatitudes (Perlmutter and Matthews 1989). The comparison of the long-term evolution of the different study areas allows discrimination of eustatic and tectonic factors influencing all study areas from more regional, mostly tectonic factors acting on one particular area only.

Sections in the Cazorla region (deeper platform to hemipelagic facies)

The two studied sections of Riogazas–El Chorro and Puerto Lorente (Fig. 7) are well dated by ammonites (F.J. Rodriguez-Tovar, pers. commun.). At Riogazas–El Chorro, the base of the Oxfordian consists of ferruginous hardgrounds and amalgamated tempestites. Then, the outcrop is dominated by limestone–marl alternations with intervals of thicker limestone beds and intervals of nodular beds and marl predominance. The Puerto Lorente section starts with beds of Ammonitico Rosso facies which then pass into limestone–marl alternations. These sediments have been deposited in an intra-shelf basin and/or ramp setting which was structured in highs (dominated by carbonates: Puerto Lorente section) and lows (enriched in marls: Rio Gazas–El Chorro section; Marquez et al. 1991).

The amalgamated, carbonate-dominated beds at the base of the sections are interpreted as having been deposited during a long-term transgression, when siliciclastics were pushed back on the platform. Maximum flooding is indicated by the top of this massive interval (MFB, Fig. 7). Highstand deposits are suggested by input of more clays, leading to marl-dominated sedimentation on the ramp and in the basin, and long-term sequence boundaries have been placed at the most marly and most nodular parts in the sections (SBC, SBD). Lowstands of sea level are again dominated by marls, but also contain relatively thick limestone beds (Jan du Chêne et al. 1993). Sedimentation in the Planula zone is marl dominated, whereby the marly intervals in Riogazas–El Chorro already appear in the uppermost Bimammatum zone (TSD3). At the top of the Planula zone the sedimentary system drowns, as implied by a well-developed hardground (MFD) followed by thick marls at Puerto Lorente.

On the smaller scale, the limestone–marl couplets (considered to represent elementary sequences) group into bundles of 4–8. These small-scale composite sequences (1–25 in Fig. 7) can be correlated between the two sections, and their number appears to be constant between the interpreted diagnostic surfaces of the large-scale sequences in both sections.

Sections in the Soria region (shallow platform facies)

The Middle to Upper Oxfordian sections of Aldealpozo and Punto de Bigornia (Fig. 8) have a poor biostratigraphic control which does not allow for detailed correlation (Alonso and Mas 1990; Mensink et al. 1990). According to Aurell (1991) and Aurell and Meléndez (1993), the base of the Aldealpozo Formation is roughly placed in the Plicatilis–Antecedens zones (Fig. 2), and its top corresponds to the top of the Oxfordian (top of the Planula zone). Other data concerning this study area can be found in Dragastan et al. (1987), Alonso and Mas (1990), Meléndez (1989), Mensink et al. (1990), and Aurell et al. (1995). The sedimentary record is well structured into elementary and composite sequences (Fig. 5). Aldealpozo is siliciclastic dominated, whereas Bigornia, approximately 25 km to the southeast, contains more carbonate facies.

After a gap following a Callovian hardground, facies indicate marly lagoonal and mixed-flat facies. Depositional environments then became gradually deeper, and a first maximum flooding is indicated by bioturbated, oncoid-bearing lagoonal sediments (MFA zone, Fig. 8). Coarse-grained subtidal dunes, shallow lagoons, lakes with charophytes, and paleosols lead up to sequence boundary SBB. Water depth then increased rapidly to reach MFB, implied by subtidal bars in Aldealpozo and open lagoons at Bigornia. Increased accommodation space is suggested by relatively thick beds. In Aldealpozo, after a paleosol attributed to a smaller-scale sequence boundary, reddish beds of fine-grained, well-sorted sandstone follow with high-angle cross-bedding. These are interpreted as aeolian dunes. A paleosol with possible karstification in Aldealpozo and tilted blocks of tidal-flat facies in Bigornia mark another long-term sequence boundary (SBC, top of the small-scale sequence 9, Fig. 8). After a transgressive surface (TSC), tidal-flat facies are overlain by subtidal bars and lagoons, and maximum flooding (MFC) is suggested by more lagoonal and bioturbated sediments. The Aldealpozo section continues upward into the Lower Kimmeridgian, but the outcrop at Bigornia is truncated by Weald-type facies of the Upper Kimmeridgian (Alonso and Mas 1990).

For both sections the number of small-scale composite sequences is consistent within the above-defined long-term intervals: four small-scale sequences from the base of the sections to SBB, four between SBB and SBC, and four from SBC to the small-scale sequence boundary below MFc (top of the small-scale sequence 13, Fig. 8).

Sections in the Swiss Jura (shallow platform facies)

The studied interval in the Swiss Jura spans the upper Middle and Late Oxfordian (Parandieri subzone to Planula zone; Fig. 2). Based on the biostratigraphic data of Gygi (1982, 1995) and the biostratigraphic and clay-mineralogical correlations of Gygi and Persoz (1986), three correlation lines can be traced between some lithostratigraphic units of the studied sections (Pittet 1996): on top of the St. Ursanne Formation (Parandieri subzone sensu Gygi 1995), on top of the Vorbourg Member (transition Schilli subzone–Bifurcatus subzone), and on top of the Natica Member (Hypselum subzone). On the scale of the Jura platform, these three correlation levels are considered to be synchronous (Gygi and Persoz 1986; Gygi 1995). They correspond to sequence boundary zones SBb and SBc, and to the transgressive surface TSd1, respectively (Fig. 9).

The sedimentary record is structured by elementary sequences, small-scale and medium-scale composite sequences, as well as by large-scale sequences. Important sedimentary events, such as rapid changes from carbonate predominance to siliciclastic predominance and back to carbonate facies, also mark the studied sections. The number of small- and medium-scale composite sequences, their sedimentary signature, and the main changes in sediment type have been used for the correlation.

In the lowermost part of the studied interval, a transgressive phase leads to a level of relatively deepest facies (MFa, Fig. 9) that precedes the deposition of up to 15-m-thick beds locally containing coral patch reefs. This flooding phase could correspond to, or just follow, the transgression described by Gygi (1986) and is marked by the occurrence of the thickest coral patch reefs of the St. Ursanne Formation in many localities.

A rapid evolution towards protected depositional environments then suggests an important sequence boundary zone on the long-term trend of relative sea-level change (SBb, Fig. 9). A new phase of inundation led to a level of reduced sedimentation (MFb) followed by more open facies deposited in higher energy conditions (ooid bars in Pichoux section, Figs. 6 and 9). In the Vorbourg section, this level is marked by thin, bioturbated elementary sequences. Sedimentary evolution then was clearly regressive, leading to more protected environmental conditions, to more frequent emersion periods, and finally to a general emersion of the shallow proximal platform (SBc zone). This sequence boundary announces the beginning of abundant terrigenous input characterizing the Natica Member (Gygi and Persoz 1986; Pittet 1996).

Siliciclastic input decreased again and, especially in the southern part of the study area, gave way to carbonate-dominated sedimentation. Patch reefs and shallow, commonly oncoid-rich lagoons developed. Maximum flooding is implied by hardgrounds and strongly bioturbated intervals (MFc, Fig. 9). At Reuchenette, the condensation related to this MF marked the beginning of the progradation of platform facies (Günsberg Member) over the deeper-water marly deposits of the Effingen Member (Gygi and Persoz 1986). Thick patch-reefs and ooid shoals then dominate especially in the southern part of the study area (Reuchenette, Moutier, Hautes-Roches, Pertuis), whereas to the north siliciclastics still prevail (Gorges du Pichoux, Vorbourg). A level characterized by coal and in situ root traces marks a medium-scale sequence boundary (top of small-scale sequence 13, Fig. 9). The large-scale sequence-boundary zone (SBd) is placed where siliciclastics (mainly clays) start invading the entire platform.

After this general regression, the onset of thick limestone beds, commonly including cross-bedded ooid grainstones and reefal framestones, point to an important transgressive event (TSd1). A second transgressive surface (TSd2) marks a renewed transgressive pulse on the long term. It is followed by even thicker beds with oncoid facies which terminate the studied interval.

Within the biostratigraphically constrained framework of long-term evolution of depositional environments, it is now possible to correlate the smaller-scale sequences which have already been established separately for each section (e.g., Fig. 6). Allowing for uncertainties in the interpretation due to lateral facies changes on the shallow Jura platform and for autocyclic processes such as migration of ooid shoals or tidal channels, the same number of thick elementary sequences or small-scale composite sequences can be counted in each section within each interval of long-term evolution (Fig. 9): four between MFb and SBc, four between SBc and the medium-scale sequence boundary characterized by coal (top of small-scale sequence 13), four between there and SBd, and two between SBd and TSd1.

Section in Normandy (shallow platform facies)

Based on the work of Rioult et al. (1991), the well-dated section of Les Roches Noires–Hennequeville (Fig. 10) has been analyzed in the same way as the other sections

Fig. 9 Best-fit correlation between the sections studied in the Swiss Jura. Diagnostic surfaces or zones of large-scale sequences are marked as in Fig. 6; *A–D* labels for long-distance correlation in Fig. 12

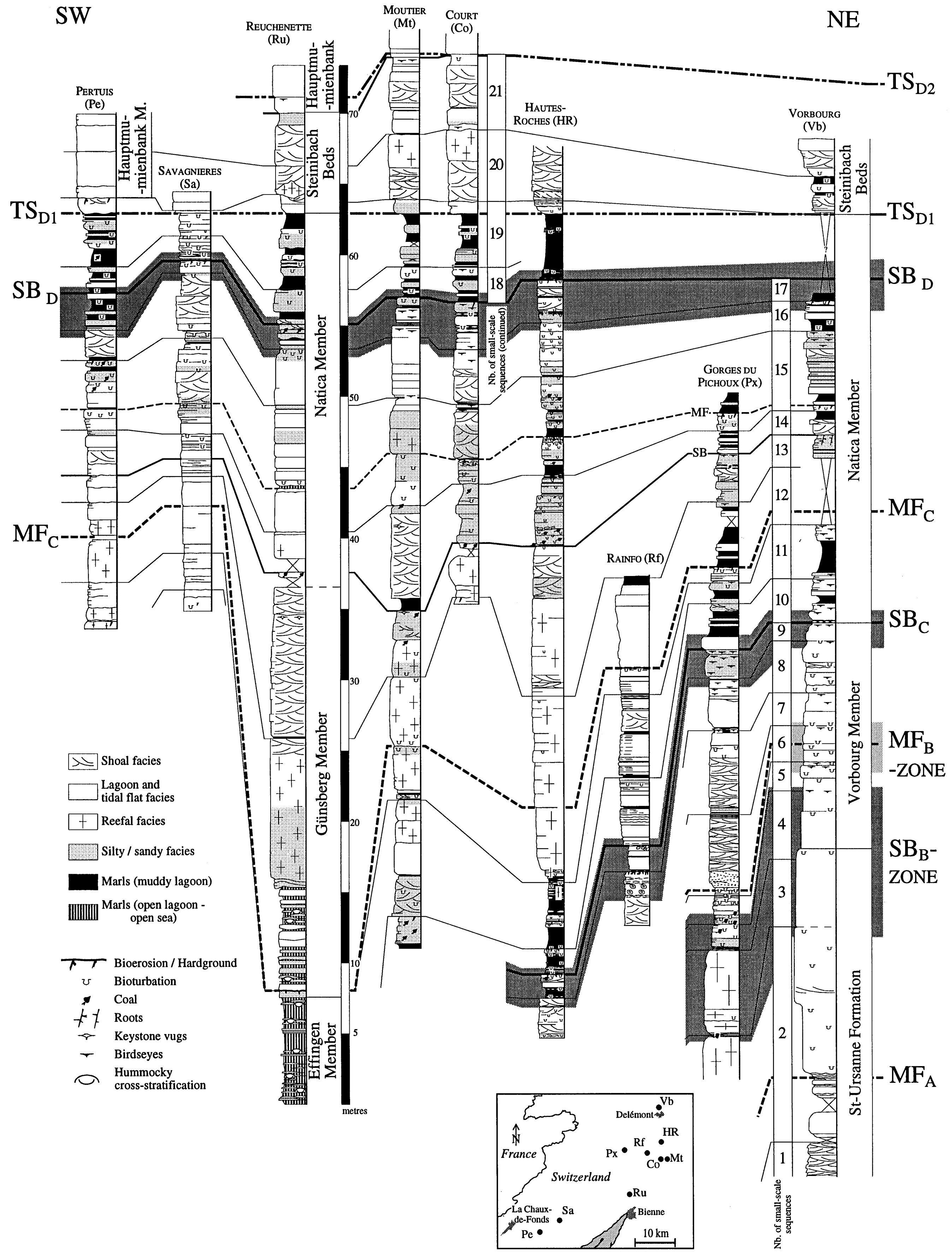
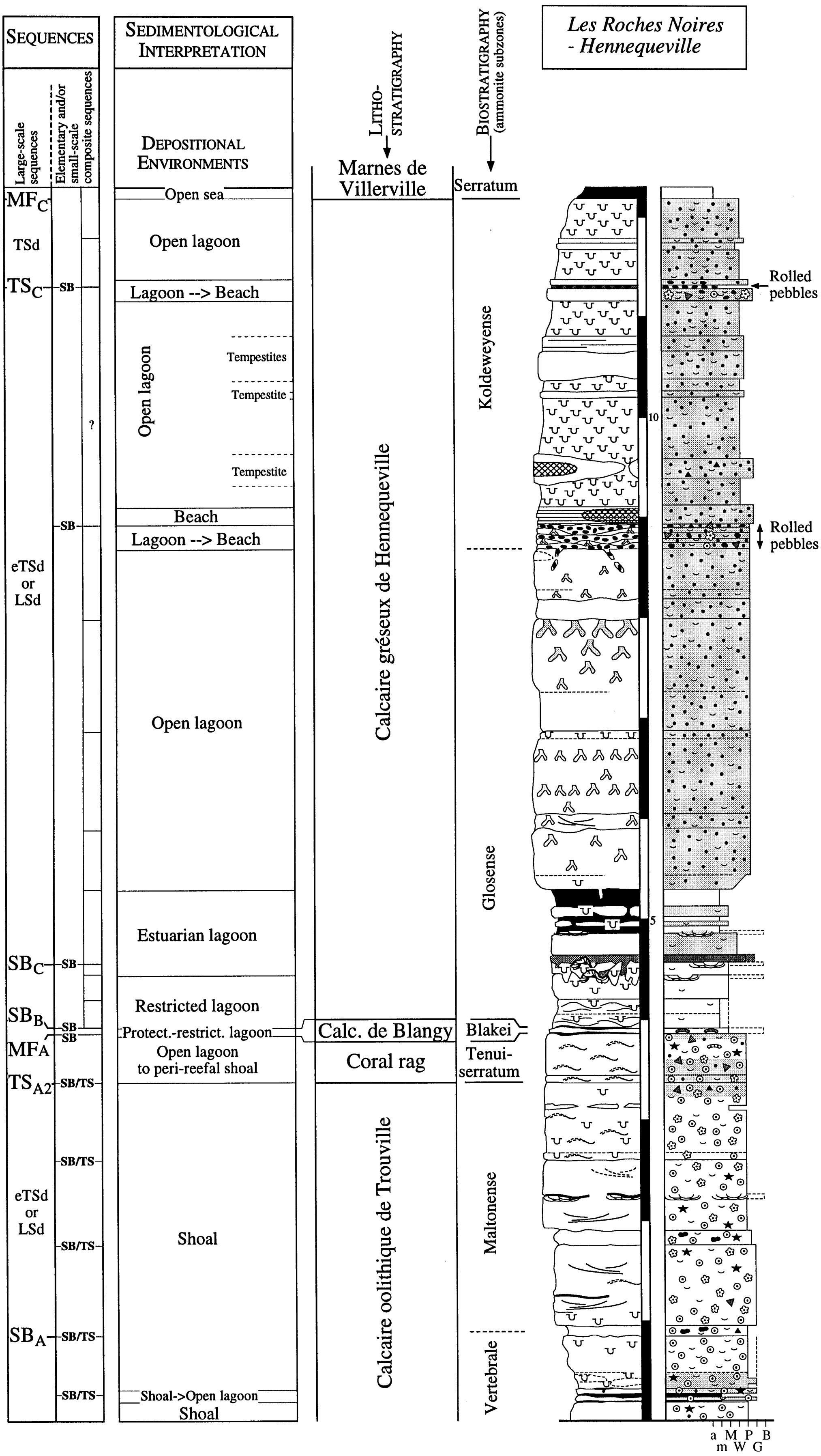

SW
NE
PERTUIS (Pe)
SAVAGNIERES (Sa)
REUCHENETTE (Ru)
MOUTIER (Mt)
COURT (Co)
HAUTES-ROCHES (HR)
RAINFO (Rf)
GORGES DU PICHOUX (Px)
VORBOURG (Vb)
Hauptmu-mienbank M.
Hauptmu-mienbank
Steinibach Beds
Natica Member
Günsberg Member
Effingen Member
Vorbourg Member
St-Ursanne Formation
TS_{D2}
TS_{D1}
SB D
SB C
MF C
MF B -ZONE
SB B-ZONE
MF A
MF
SB
Nb. of small-scale sequences
Nb. of small-scale sequences (continued)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
5
10
20
30
40
50
60
70
metres
Shoal facies
Lagoon and tidal flat facies
Reefal facies
Silty / sandy facies
Marls (muddy lagoon)
Marls (open lagoon - open sea)
Bioerosion / Hardground
Bioturbation
Coal
Roots
Keystone vugs
Birdseyes
Hummocky cross-stratification
Vb
Delémont
HR
Rf
Px
Co
Mt
N
France
Switzerland
Ru
La Chaux-de-Fonds
Sa
Bienne
Pe
10 km

Fig. 10 Section of Les Roches Noires–Hennequeville in Normandy (legend same as in Fig. 4). Interpretations are given in text. Diagnostic surfaces or zones of large-scale sequences are marked as in Fig. 6; *A–C* labels for long-distance correlation in Fig. 12



presented here. However, due to common high-energy facies masking the smaller-scale sequences and to gaps caused by synsedimentary tectonics, the interpretation is not straightforward.

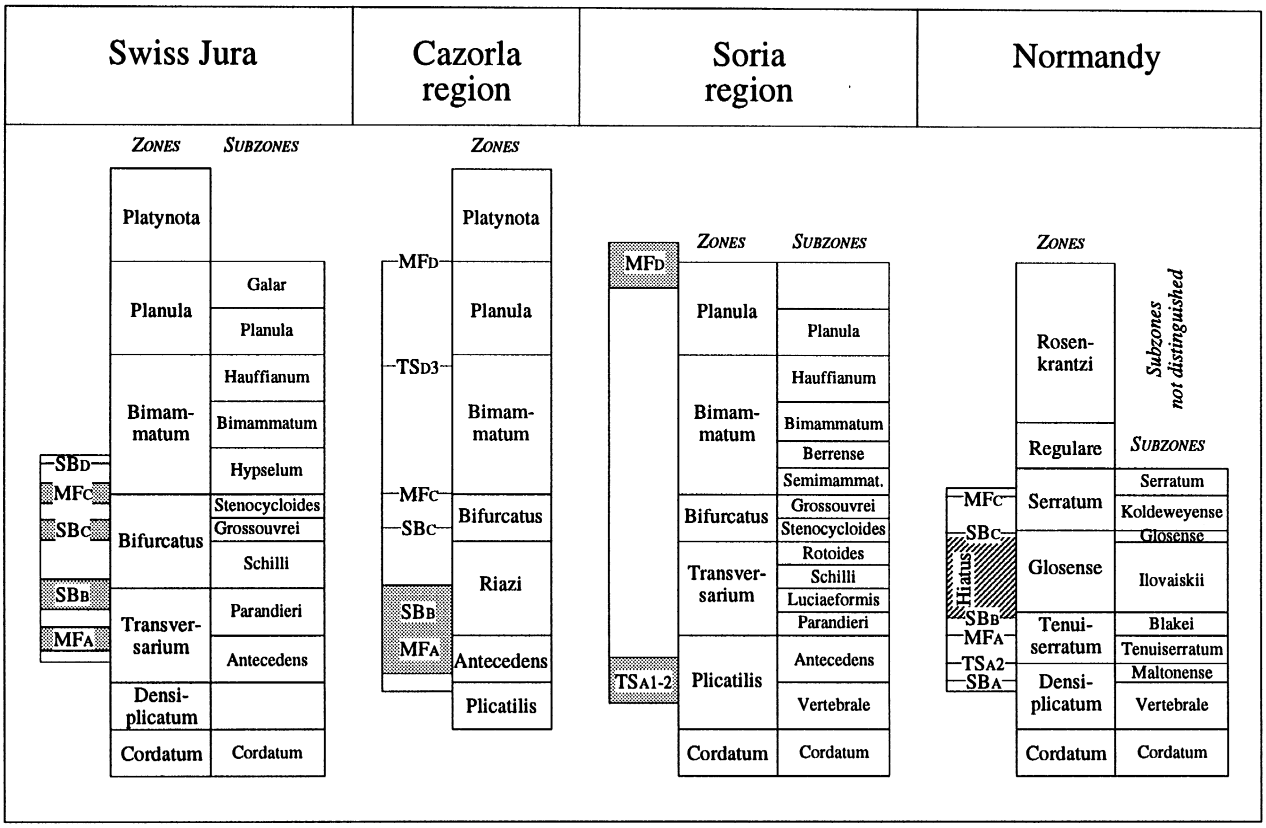
A long-term sequence boundary may be placed at an important erosion surface followed by a lag deposit in the lower part of the oolite bars (SBA). The ooid shoals then give way to lagoonal and peri-reefal facies, and a maximum-flooding surface is implied by a well-developed hardground (MFA). It is immediately followed by a second hardground, and the strongly reduced Blakei subzone suggests that there is time missing (SBB; Rioult et al. 1991). SBC is placed at a complex erosion surface. Accommodation is then increased, as indicated by thick beds of bioturbated open-lagoonal facies. A small-scale sequence boundary is placed at a level with beach lamination. Above, facies are bioturbated and punctuated by tempestites. After a second beach level (TSC), facies indicate deepening, and true open-marine conditions are reached after MFC (Fig. 10). This surface is situated at the base of the Serratum subzone. The corresponding maximum-flooding zone in the epicontinental basin of the Swiss Jura is represented by three successive condensation levels in the Gerstenhübel beds (Pittet 1996; Pittet and Gorin 1997) in which the taxon *Amoeboceras serratum* has been found (Gygi and Persoz 1986).

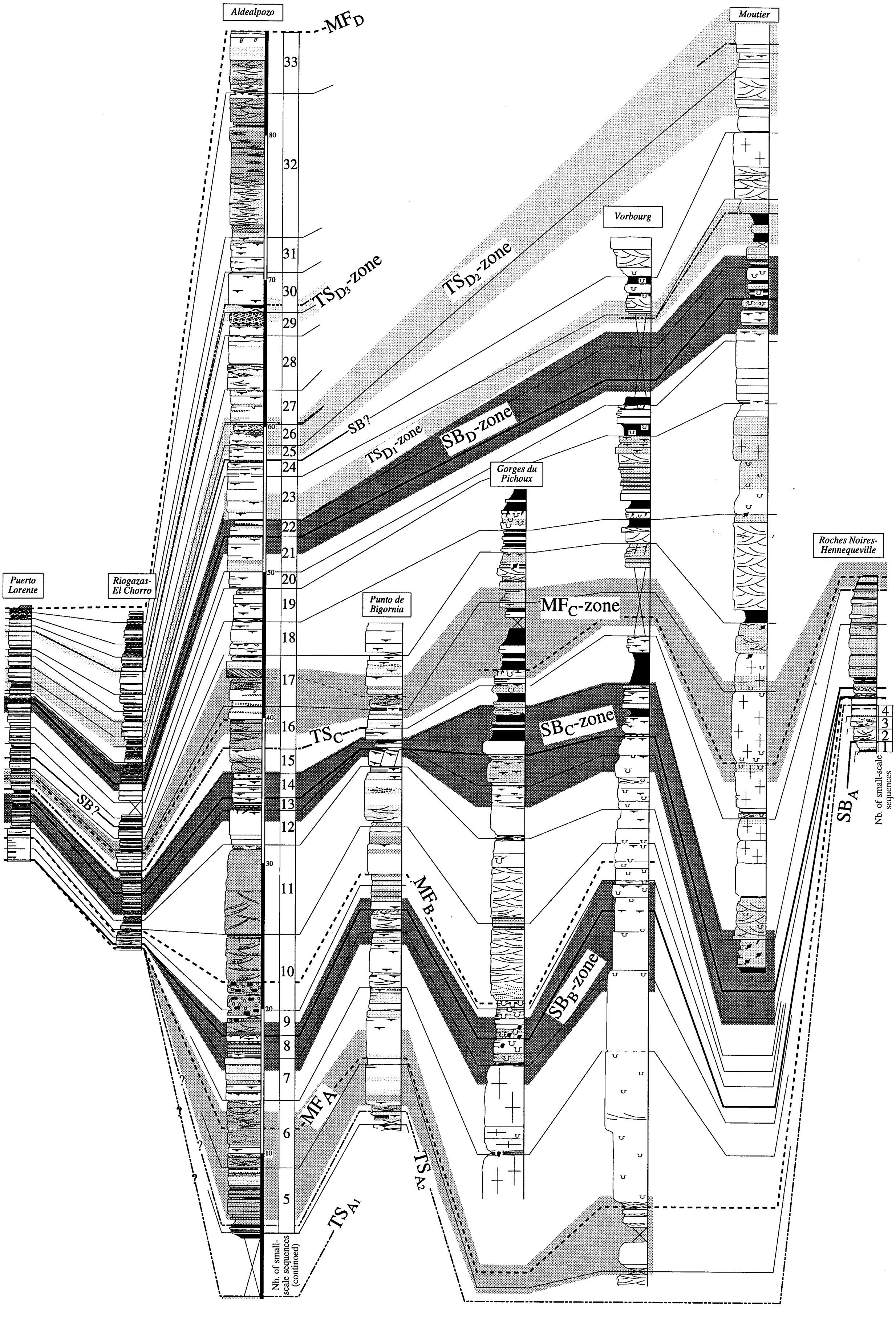
Different types of small-scale sequences are present in the Les Roches Noires–Hennequeville section (Fig. 10). Elementary sequences have been identified in the Calcaire de Trouville and in the Coral rag. The Calcaire de Blangy corresponds to a very condensed bed in which small-scale sequences have not been recognized. An important sedimentary hiatus encompasses the whole Ilovaiskii subzone. The lowermost part of the Calcaire gréseux de Hennequeville is condensed, whereas the rest of the formation is structured into elementary and small-scale composite sequences.

Long-distance correlations

Within the biostratigraphic framework established for each studied region and based on the correlations of ammonite zones given in the literature (Fig. 2), a correlation between all studied sections is attempted. In a first step, only the long-term evolution of the sedimentary systems is correlated, in order to filter out effects of different tectonic regimes, variable sedimentary systems, and high-frequency climatic changes. Except for the Soria region, all long-term sequence-stratigraphic surfaces or zones are dated by ammonites (Fig. 11). A best-fit solution can be obtained which satisfies quite well the interpretations made independently for each section and region (Fig. 12; of the Jura

Fig. 11 Biostratigraphically dated sequence-stratigraphic surfaces or zones (*gray intervals*) for the four study areas




Aldealpozo
-MF_D
Moutier
Vorbourg
Gorges du Pichoux
Puerto Lorente
Riogazas-El Chorro
Punto de Bigornia
Roches Noires-Hennequeville
TS_D3-zone
TS_D2-zone
SB?
TS_D1-zone
SB_D-zone
MF_C-zone
SB_C-zone
TS_C
SB?
MF_B
SB_B-zone
MF A
TS_A1
TS_A2
SB_A
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
80
70
60
50
40
30
20
10
?
4
3
2
1
Nb. of small-scale sequences
Nb. of small-scale sequences (continued)

region, only three representative sections have been selected). It proves that the definition of sequence-boundary and maximum-flooding zones is useful, as local or regional effects can displace the best-marked diagnostic surfaces by one or more small-scale sequences.

In a second step, the small-scale composite sequences (as defined in the regional correlations; Figs. 7–9) are correlated, and again a best-fit solution is sought. This detailed correlation helps to better interpret the individual sections where the emplacement of small-scale diagnostic surfaces may be difficult (in fact, several interpretations given in Figs. 5–9 are based on such iterative reasoning). It can thus be shown that small-scale composite sequences in the Soria and Cazorla regions (Figs. 5, 7 and 8) correspond in many cases to thick elementary sequences in the Swiss Jura (Figs. 6 and 9). This implies that, on the shallow platform of the Swiss Jura, conditions were such that high-frequency (20 ka; see below) climatic and/or eustatic fluctuations were not or incompletely recorded, and that mainly lower-frequency (100 ka) changes created identifiable depositional sequences.

Timing of the sequences

A conclusion to be made from Fig. 12 is that major time gaps are present only in one interval in the Bigornia section (small-scale sequence 13 missing) and at Roches Noires–Hennequeville (the biostratigraphically constrained time gap and condensation of the Calcaire de Blangy corresponds to seven small-scale sequences). Also, there is condensation at the base of the sections in the Cazorla region. Sedimentation on the shallow-water platforms and in the storm-dominated deeper water certainly was not continuous, but non-deposition, reworking, and erosion probably happened mostly on the scale of the elementary sequences (Goldhammer et al. 1993; Strasser 1994), and not on the long-term scale.

According to Gradstein et al. (1995), the interval between the base of Antecedens zone and the top of Planula zone spans approximately 3.5 ma. SBA has been placed at the base of Maltonense zone (equivalent to Antecedens, Fig. 2) at Roches Noires–Hennequeville (Fig. 10). The top of Planula zone coincides with MFD at Puerto Lorente (Fig. 7). According to the interpretation in Fig. 12, 32 small-scale sequences have been counted between these levels. In the better constrained interval between MFA (base Blakei zone, Fig. 10) and MFC (top Bifurcatus, Fig. 7; top Koldeweyense, Fig. 10), around ten small-scale sequences are found, and the time interval corresponds to approximately 1 ma (Gradstein et al. 1995). The average duration of a small-scale composite sequence in the Spanish and French sections, of a thick elementary sequence in the Swiss Jura, and of an elementary sequence at the base of the Normandy section (0–8 m; Fig. 10) thus is approximately 100 ka.

As it has been shown above, four small-scale sequences commonly group between long-term diagnostic surfaces or zones (e.g., see Fig. 5). It is therefore suggested that this hierarchy in stacking pattern corresponds to sedimentation controlled by sea-level (and possibly climatic) changes in the Milankovitch frequency band: the small-scale composite sequences are related to the 100-ka cycle of eccentricity, and the groups of four to the 400-ka cycle of eccentricity (Berger et al. 1989). In the deeper-water sections of the Cazorla area, the 100-ka sequences are furthermore composed of 4–8 limestone–marl couplets (Fig. 7) reflecting changes from high-energy deposition in limestones (commonly amalgamated tempestites; Pittet 1996) to low-energy deposition of marls. In the shallow-water sections of the Soria region, five beds (in most cases equivalent to five elementary sequences) on the average compose a small-scale composite sequence (Figs. 5 and 8). This implies that, in the Spanish sections, an elementary sequence corresponds to approximately 20 ka and thus can be related to the precession cycle (Berger et al. 1989). In the Swiss Jura and in Normandy, however, the signal of the precession cycle is not or only locally recorded, which may be due to a predominantly autocyclic formation of these shallow water beds (e.g., Fig. 6).

Statistical analyses to test the suspected Milankovitch signal could not be performed, because locally varying sedimentary conditions on the shallow platforms and differential compaction both distort any primary signal. Also, it is natural that in the studied complex sedimentary environments autocyclic processes, such as lateral shifting of shoals or migration of tidal channels, were superimposed on the orbitally driven sea-level and climatic fluctuations and further complicated the sedimentary record (Strasser 1991). Nevertheless, the observed stacking pattern and the relatively good correspondence between absolute timing (Gradstein et al. 1995) and the duration of the sequences implied from assuming a Milankovitch cyclicity suggest that the sedimentary systems were at least partly influenced by orbitally controlled factors.

Accepting the cyclostratigraphic interpretation as a working hypothesis, a synthetic correlation chart with independent time control is established (Fig. 13). The time axis is given by the 33 100-ka small-scale composite sequences or thick elementary sequences of Fig. 12, and the long-term sequence-stratigraphic surfaces or zones observed in each studied region are integrated. The biostratigraphy is that of the Jura region, correlated to the other regions as defined in Fig. 2. This chart now allows discussion of the respective influences of eustatic sea level, subsidence, and climate on the observed sedimentation patterns.

◄

Fig. 12 Best-fit correlation between the Cazorla and Soria regions in Spain, the Swiss Jura, and Normandy (legend same as in Figs. 4 and 9)

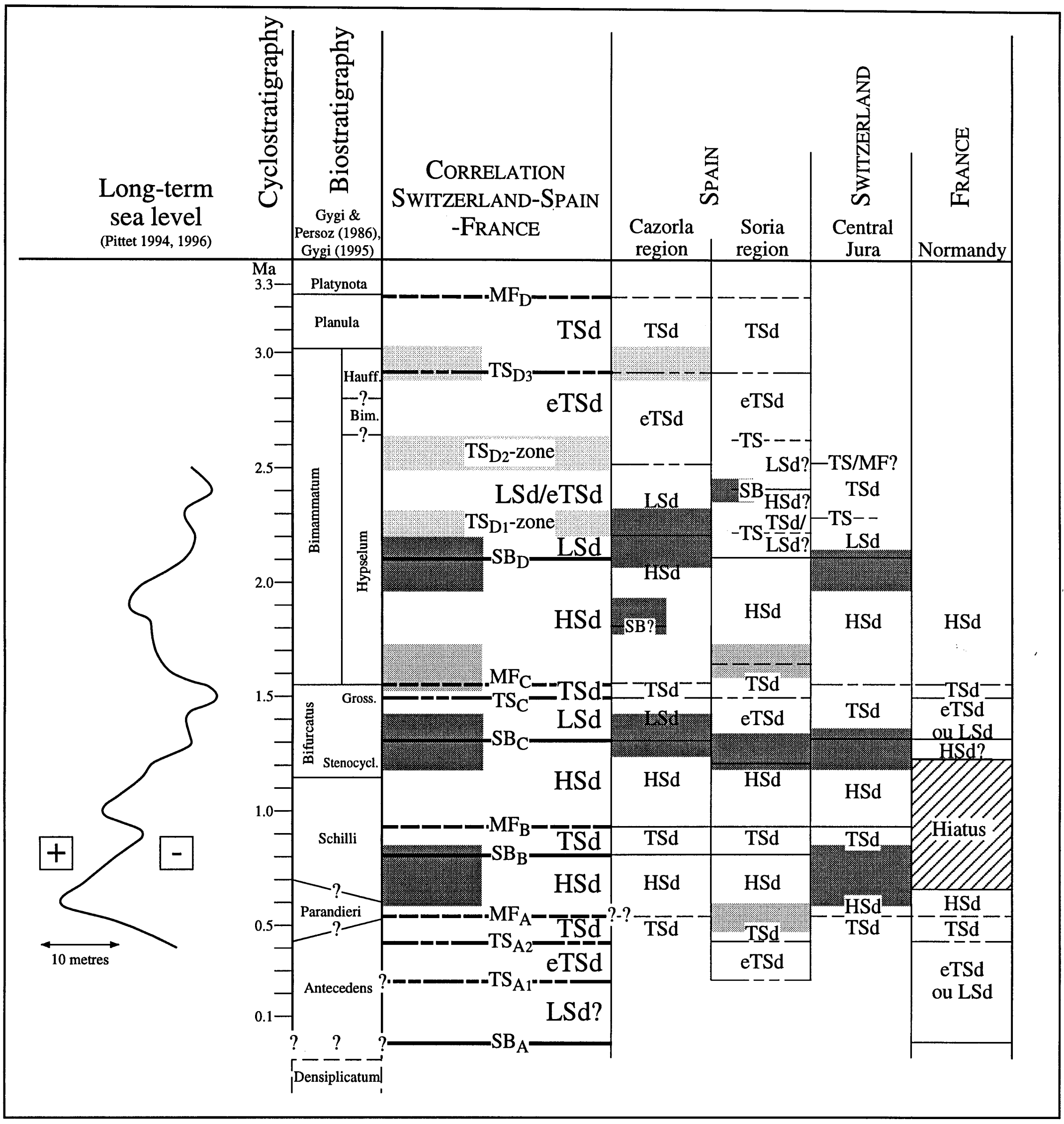


Fig. 13 Synthesis of interpreted long-term sequence stratigraphy in the various study areas, biostratigraphy, cyclostratigraphic timing based on inferred 100-ka small-scale sequences, and reconstructed long-term evolution of sea level. For discussion refer to text

Eustatic sea-level variations

In the sections studied in the Swiss Jura, most small-scale composite sequences shallow upwards into intertidal facies, indicating that accommodation space created by subsidence and eustatic sea-level rise has been completely filled by sediment. Major erosion surfaces, vadose cementation, or karstification are absent, suggesting that the rate of sea-level fall did not exceed the rate of subsidence (Pittet 1994). Decompacted sediment thickness thus corresponds fairly closely to the maximum of accommodation created. By comparing the decompacted thicknesses of each 100-ka time interval in each section and assuming a constant long-term subsidence rate, a regionally valid sea-level curve has been reconstructed (Pittet 1994, 1996). Local differences in thickness of sequences can then be attributed to local changes in subsidence rates.

In Fig. 13 this long-term sea-level curve (Pittet 1994, 1996) has been plotted against the cyclostratigraphic and biostratigraphic scales. Also in Spain and Normandy, the reconstructed major sea-level falls generally correspond well to the above-established long-term sequence boundaries, and the major sea-level rises to the intervals of maximum flooding. Shorter-term fluctuations correlate with prominent levels observed in the small-scale (100-ka) sequences.

Comparing with the sea-level chart of Haq et al. (1987), there is good correspondence between their SB 146.5 (top of the Serratum zone; Figs. 2 and 11) and SBD. Ponsot and Vail (1991) later introduced SB 148 and 147.5, corresponding to SBB and SBC, respectively. The cyclostratigraphic timing is more or less confirmed: 0.5 ma between SBB and SBC, 0.8 ma between SBC and SBD

(Fig. 13). The reconstructed long-term sea-level curve thus seems to have at least over-regional significance.

In the sequence-stratigraphic interpretation, important local or regional differences become apparent. During the time interval between SBc and TSD1 (Fig. 13), i.e., during more than a complete long-term cycle, the Jura platform prograded rapidly (Gygi and Persoz 1986), which is illustrated by strong accumulation in the southern and eastern parts of the study area, and by the progradation of platform facies over basinal sediments in Reuchenette (Fig. 9). This implies that a general progradational pattern may be maintained during lowstand, transgressive, and highstand conditions of a long-term sea-level cycle, as long as carbonate productivity and sediment supply is high (Schlager 1993; Pasquier and Strasser 1997). No particular change in sedimentation pattern is observed in the Spanish sections for the same time interval (Fig. 12). For the interval between TSD3 and MFD, the section of Aldealpozo shows a facies evolution going from carbonate tidal flats to rapidly accumulating siliciclastic subtidal bars. This led Aurell et al. (1995) to interpret the same interval as the upper part of a prograding highstand systems tract. However, the general opening of the depositional environments as well as the rapidly forming thick beds (shoal facies) suggest increasing accommodation. Furthermore, the time-equivalent sediments in the deeper-water sections in the Cazorla region clearly display a transgressive evolution leading to drowning (Fig. 7). In the proximal setting at Aldealpozo, sediment input apparently compensated rising sea level, until the system finally became fully marine just below MFD (Fig. 12). These examples illustrate well the important role of sediment supply in the formation of sequences (Schlager 1993).

The high-frequency sea-level fluctuations are explained by orbitally induced insolation changes which in turn influenced sea level through various feedback mechanisms: thermal expansion of the uppermost layer of the oceans (Gornitz et al. 1982), waxing and waning of alpine glaciers (Fairbridge 1976), and/or release and retention of water in lakes and aquifers (Jacobs and Sahagian 1993). Polar ice was possibly present (Frakes et al. 1992; Eyles 1993), but glacio-eustasy was probably of minor importance in the globally warm climate of the Oxfordian (Read et al. 1995). The combination of these mechanisms produced sea-level fluctuations with amplitudes of a few meters, enough to create the observed sedimentary sequences. Longer-term (million-year scale) sea-level variations are classically attributed to tectono-eustasy and long-term climate change (Vail et al. 1991).

Tectonic implications

The small-scale sequences show variable thicknesses, laterally from one section to another as well as vertically in each section. If the vertical trends are similar, a common change of accommodation among the studied sections can be assumed. Eustatic sea-level variations probably were homogeneous along the northern margin of the Tethys Ocean. Thus, lateral thickness variations of shallow-platform sequences must have been caused by differential changes in subsidence rates.

In the Swiss Jura, siliciclastics are generally more abundant along a NNE–SSW striking sector and also invade reefs and ooid shoals (Reuchenette, Moutier, Court, and Hautes Roches sections; Fig. 9). This is explained by the channelizing effect of a shallow trough created by differential subsidence (Pittet 1996). Morphology of the substrate is important also for the initiation of reef growth or formation of ooid shoals, and for the accumulation of muddy facies in depressions. The relief may further be enhanced by differential compaction (Hunt et al. 1996).

Subsidence in the Jura was generally relatively strong in the Middle to Late Oxfordian (55–75 m/ma; Pittet 1996). This led to the formation of well-developed transgressive deposits (Fig. 13). Lowstand deposits are uncommon which is due to missing accommodation on the shallow platform during sea-level lows. In the Soria region (Aldealpozo), a well-defined smaller sequence can be observed above SBD, suggesting that the interplay between sea level and subsidence was such that facies changes were strong enough to differentiate lowstand, transgressive and highstand deposits (Figs. 5, 12 and 13). The Cazorla region had low subsidence rates, and deeper water allowed for the accumulation of lowstand deposits (Fig. 7 and 13). This comparison suggests that deposits with lowstand characteristics can form at the same time as deposits with a transgressive character (e.g., above SBc, Fig. 13), depending on the combined effects of subsidence rate, sea-level change, sediment supply, and depositional setting (Pasquier and Strasser 1997; Pittet 1996).

An important tectonic event is evidenced by synsedimentary fracturing and tilting of blocks at Punto de Bigornia (Fig. 8), and by a drastic change in subsidence rate at Roches Noires–Hennequeville (Fig. 10). According to the sequence-stratigraphic correlation, the tectonic event at Bigornia happened before the sea-level drop leading to SBc, whereas in Normandy sedimentation rates increased rapidly after the gap between MFA and SBB, and the strongly condensed interval between SBB and SBc (Fig. 14). In the Swiss Jura, siliciclastic input generally increases above SBc (Fig. 9), giving rise to the marl-rich interval of the Natica Member. This may be explained by tectonic uplift and increased erosion rates in the hinterland. SBc is situated in the Bifurcatus ammonite zone (Fig. 13). Tectonic instabilities at that time have been noted by several authors in various regions: by Arnaud (1988) in the French Jura, by Enay (1984) in southeastern France, and by

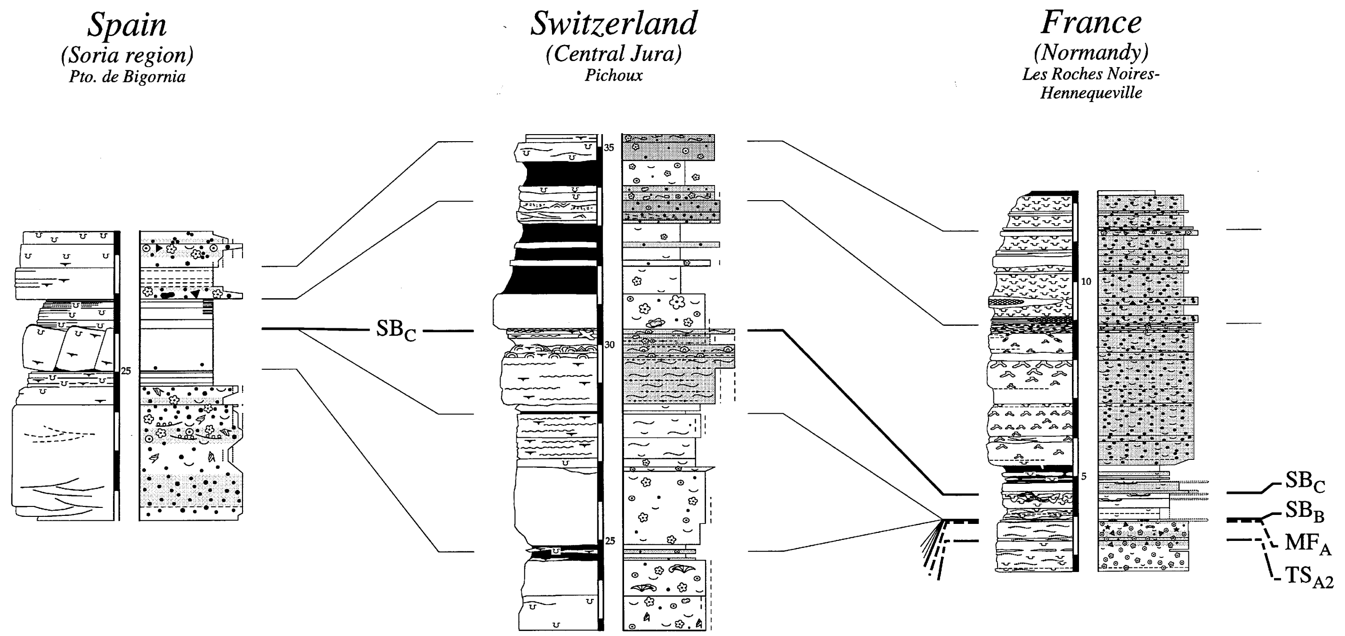


Fig. 14 Detail of logs around sequence boundary SBc, illustrating the effects of tetonic instability on the sedimentary record. For explanations refer to text; legend same as in Fig. 4

Marquez et al. (1991, 1993) in southern Spain and Portugal. Rioult et al. (1991) attribute this event to the late-Cimmerian tectonic phase (Ziegler 1982) which included rifting in the North Atlantic and spreading in the Ligurian Tethys.

Climatic implications

The vertical distribution of siliciclastics in the studied sections follows a pattern which varies from one study area to the other. In the Swiss Jura, the very tops and the bases of small-scale composite sequences commonly contain quartz, sand and silt, feldspars, and clays, whereas the central parts of the sequences are carbonate dominated (e.g., Fig. 6). Furthermore, these intervals are commonly associated with coal fragments and a relative increase of bisaccate pollen vs non-saccate pollen and spores (Pittet 1996; Pittet and Gorin 1997). This implies that siliciclastic input was related to late highstands, lowstands, and early transgressive phases of sea-level change. In the Soria area, the pattern is inversed: siliciclastics preferentially occur in the middle of small-scale sequences (e.g., Fig. 5). Proximity of the source area controls the abundance of siliciclastics (e.g., Aldealpozo vs Bigornia; Fig. 8), but the trend in the distribution inside the small-scale sequences is maintained. The further the distance from the source area, the longer is the Milankovitch period which records this distribution: 20–100 ka in the Soria region (Fig. 5), and 100–400 ka in the Swiss Jura (Fig. 9). During sea-level lowstands, siliciclastics can potentially be eroded from the hinterland and thus appear at and around sequence boundaries. In order to concentrate them in the middle of sequences during periods of maximum flooding, however, a climatic control has to be invoked. The recurrent appearance of siliciclastics in well-defined parts of the small-scale composite sequences permits exclusion of a predominant tectonic influence at the scale of 20–100 ka. Tectonics probably have a major control on the availability of siliciclastics (e.g., increase of siliciclastics in the Swiss Jura above SBc), whereas climatic conditions define at which moment they are transported into the marine environments.

During the Oxfordian, the Swiss Jura was situated at a paleolatitude of approximately 26–27 °N according to Dercourt et al. (1993), or at around 37–38 °N according to Smith et al. (1994). For the Soria region, 23–24 °N (Dercourt et al. 1993) and 34–35 °N (Smith et al. 1994), respectively, are estimated. Despite these inconsistent values, a paleolatitudinal difference of 3–4° between the two regions is maintained. This difference may have been responsible for different climatic regimes with inversely related periods of stronger rainfall causing increased terrigenous runoff (Matthews and Perlmutter 1994). Oschmann (1990) proposes that the paleogeographic position of our study areas corresponds to the interface of seasonally shifting high- and low-pressure atmospheric cells. Statistical analyses of the distribution of climate-related facies components (e.g., corals, ooids, palynomorphs, siliciclastics) throughout the studied small-scale sequences in the Swiss Jura confirm periodic changes of temperature and relative humidity (Pittet et al. 1995; Pittet 1996). It has been shown above that the small- and medium-scale composite sequences are related to sea-level fluctuations in the Milankovitch

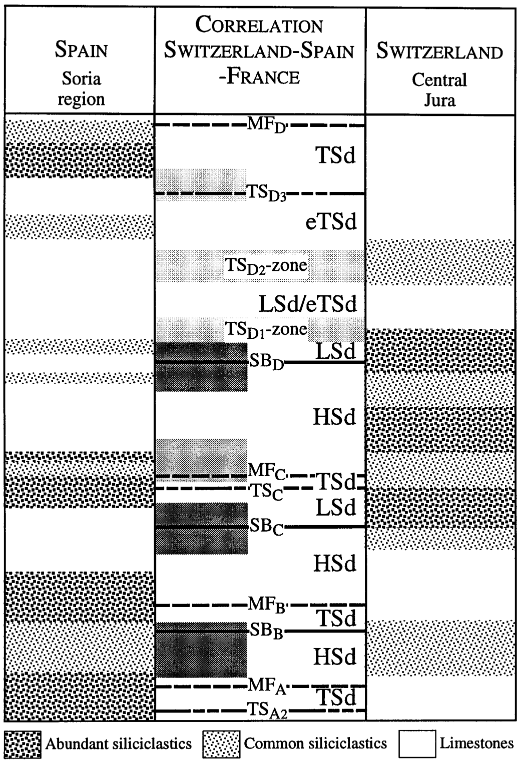


Fig. 15 General distribution of siliciclastics in the Soria region and in the Swiss Jura (including data of Gygi and Persoz 1986). Note that siliciclastics concentrate around large-scale sequence boundaries in the Jura, but around zones of maximum flooding in the Soria region. For discussion refer to text

frequency band. According to the distribution of siliciclastics it is also implied that insolation changes on the 100- and 400-ka scale caused periodic shifting of the atmospheric cells and, consequently, changes in the rainfall pattern which depended on paleolatitude (Matthews and Perlmutter 1994). Facies changes on the 20-ka scale have been suggested in the Soria and Cazorla regions (Figs. 5 and 7), but it is not clear what the respective roles of sea level and climate were in their formation.

When analyzing the long-term trend of vertical distribution of siliciclastics (averaged for the sections in the Swiss Jura and for those in the Soria region), the same general pattern of inverse concentration appears (Fig. 15). In the Soria region, siliciclastics are clearly concentrated around zones of maximum flooding (MFA, MFB, MFC, MFD). In the Swiss Jura, siliciclastic input was favored in times of long-term sea-level falls, i.e., around sequence boundaries SBB, SBC and SBD. Again, a climatic control dependent on paleolatitude is suggested. Siliciclastics are abundant also in the highstand of sequence C in the Jura. This interval contains a small-scale sequence boundary with abundant coal fragments and root traces and is rich in quartz, sand and silt (Fig. 9), implying relatively humid climatic conditions on a regional scale.

The interpretations resulting from our study are consistent with the global climatic regime in the Oxfordian. After a warming in the Bajocian and Bathonian, climate stayed generally warm until the end of the Jurassic (Frakes et al. 1992). Superimposed on this general trend were fluctuations of the atmospheric cells driven by orbital insolation cycles (Matthews and Perlmutter 1994). The observed interrelation between long-term sea-level fluctuations and long-term climate change may be a result of complex feedback mechanisms involving global carbon and nutrient cycling (Föllmi et al. 1994).

Conclusions

Based on detailed analysis of facies, sedimentary structures, and stacking pattern, the Oxfordian sections studied in the Swiss Jura, in Spain, and in France have been interpreted in terms of high-resolution sequence stratigraphy and cyclostratigraphy. The hierarchical nesting of depositional sequences of different scales and time control given by biostratigraphy and absolute dating suggest that the depositional systems were influenced by parameters in tune with orbital cycles. Elementary sequences corresponding to the precision cycle of 20 ka were identified in the shallow- and deeper-water settings in Spain. Small-scale composite sequences related to the 100- and 400-ka eccentricity cycles are recognized in all study areas. The orbital (Milankovitch) cycles caused changes in insolation which in turn influenced–through intricate feedback mechanisms–sea level, climate, and other physical, chemical and ecological parameters.

Comparing the vertical evolution of facies and stacking pattern between the sections in each study area and then between the four study areas, a best-fit correlation is proposed which is consistent with the biostratigraphic framework as well as with the absolute timing. For a time interval of approximately 2 ma a sea-level curve has been constructed which is valid for all study areas (Fig. 13). Differences of the sequence-stratigraphic signature between sections and study areas are explained by differential subsidence and by differences in sediment supply. The best-marked sequence-stratigraphic surfaces may be displaced from one section or from one study area to the other due to local differences in the sedimentary systems.

In this well-constrained time interval it is now possible to follow individual 100-ka sequences for distances of over 1000 km. Thus, the evolution through time of laterally variable sedimentary systems can be studied with a high time resolution. It is shown that paleolatitude had a significant influence on the rainfall pattern and thus on the input of siliciclastics: in the Swiss Jura, siliciclastics were flushed into the system when sea level was low, whereas in Spain the rainy periods occurred during high sea level. Detailed correlation also shows that a phase of tectonic instability affected simultaneously the Soria region (Spain), Normandy, and the Swiss Jura.

This study demonstrates that there is great potential for very detailed analyses of environmental change on a timescale comparable to that of the Pleistocene and Holocene. By comparing the sedimentary record in closely spaced sections, the local and regional variabilities can be studied. By correlating over long distances and from one paleogeographic or paleotectonic region to the other, local and regional effects can be filtered out, and the over-regional or global patterns appear. High time resolution over long distances also will make it possible to quantify sedimentary and ecological processes acting at the same time but in different depositional settings and different paleolatitudes. Thus, the combined approach of high-resolution sequence stratigraphy and cyclostratigraphy becomes an important tool for better understanding paleoenvironmental changes.

Acknowledgements We thank M. Aurell, R. Mas, and A. Alonso for having introduced us to the Soria region, and F. Rodriguez-Tovar for his assistance and precious help with the biostratigraphy in the Cazorla area. We also thank M. Rioult who pointed out the best outcrops in Normandy. We greatly appreciated the thorough and constructive reviews of J. Reijmer and D. Bosence which significantly improved the original manuscript. This study was part of a larger project which was funded by the Swiss National Science Foundation (project nos. 21–32185.92 and 20–41888.94).

References

Acosta P (1989) Estudio del Jurásico de une sector de a Sierra de Cazorla (zona Prebética). Tésis Lic Univ Granada, 117 pp

Alonso, A, Mas R (1990) El Jurásico superior marino en el Sector Demanda-Cameros (LaRioja-Soria). Cuad Geol Ibérica 14: 173–198

Arnaud H (1988) Subsidence in certain domains of southeastern France during the Ligurian Tethys opening and spreading phases. Bull Soc Géol France 8/4/5: 725–732

Aurell M (1990) El Jurassico superior en la Cordillera Iberica Central (provincias de Zaragoza y Teruel). Analisis de cuenca. Tesis Doct, Dpto Geol, Serv Public Univ Zaragoza

Aurell M (1991) Identification of systems tracts in low angle carbonate ramps: examples from the Upper Jurassic of the Iberian Chain (Spain). Sediment Geol 73: 101–105

Aurell M, Meléndez A (1993) Sedimentary evolution and sequence stratigraphy of the Upper Jurassic in the central Iberian Chain, northeast Spain. In: Posamentier HW, Summerhayes CP, Haq BU, Allen GP (eds) Sequence stratigraphy and facies associations. Int Assoc Sedimentol Spec Publ 18: 343–368

Aurell M, Bosence D, Waltham D (1995) Carbonate ramp depositional systems from a late Jurassic epeiric platform (Iberian Basin, Spain): combined computer modelling and outcrop analysis. Sedimentology 42: 75–94

Berger A, Loutre MF (1994) Astronomical forcing through geological time. In: Boer PL de, Smith DG (eds) Orbital forcing and cyclic sequences. Int Assoc Sedimentol Spec Publ 19: 15–24

Berger A, Loutre MF, Dehant V (1989) Astronomical frequencies for pre-Quaternary palaeoclimate studies. Terra Nova 1: 474–479

Boer PL de, Smith DG (eds) (1994) Orbital forcing and cyclic sequences. Int Assoc Sedimentol Spec Publ 19: 1–559

Cariou E (coord), Atrops F, Hantzpergue P, Enay R, Rioult M (1991) Réactualisation des échelles d'ammonites: Oxfordien. Abstr 3rd Int Symp Jurassic Stratigraphy, Poitiers, France, p. 132

Dercourt J, Ricou LE, Vrielynck B (eds) (1993) Atlas: Tethys palaeoenvironmental maps. CCGM, Paris

Dragastan O, Mensink H, Mertmann D, Wilde S (1987) Küstennahe Sedimentationzyklen im Ober-Jura der westlichen Madero, Nord-Spanien. N Jahrb Geol Paläontol 175: 377–398

Enay R (coord) (1984) Jurassique supérieur–Malm. In: Debrand-Pasard S (ed) Synthèse Géologique du Sud-Est de la France. Mém Bur Rech Géol Min 125: 223–286

Eyles N (1993) Earth's glacial record and its tectonic setting. Earth Sci Rev 35: 1–248

Fairbridge RW (1976) Convergence of evidence on climatic change and ice ages. Ann NY Acad Sci 91: 542–579

Föllmi KB, Weissert H, Bisping M, Funk H (1994) Phosphogenesis, carbon-isotope stratigraphy, and carbonate-platform evolution along the Lower Cretaceous northern Tethyan margin. Geol Soc Am Bull 106: 729–746

Frakes LA, Francis JE, Syktus JI (1992) Climate modes of the Phanerozoic. Cambridge Univ Press, London

García-Hernández M, López-Garrido AC, Olóriz F (1979) El Oxfordense y el Kimmeridgense inferior en la zona Prebética. Cuad Geol Univ Granada 10: 527–533

Goldhammer RK, Lehmann PJ, Dunn PA (1993) The origin of high-frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso Gp, west Texas): constraints from outcrop data and stratigraphic modeling. J Sediment Petrol 63: 318–359

Gornitz V, Lebedeff S, Hansen J (1982) Global sea level trend in the past century. Science 215: 1611–1614

Gradstein FM, Agterberg FP, Ogg JG, Hardenbol J, van Veen P, Thierry J, Huang Z (1994) A Mesozoic time scale. J Geophys Res 99: 24051–24074

Gradstein FM, Agterberg FP, Ogg JG, Hardenbol J, van Veen P, Thierry J, Huang Z (1995) A Triassic, Jurassic and Cretaceous time scale. In: Berggren WA, Kent DV, Aubry MP, Hardenbol J (eds) Geochronology, time scales and global stratigraphic correlation. Soc Econ Paleontol Mineral Spec Publ 54: 95–126

Gygi RA (1982) Sedimentation und Fazies des Späten Jura im zentralen Juragebirge. Jber Mitt Oberrhein Geol Ver [NF] 64: 17–28

Gygi RA (1986) Eustatic sea-level changes of the Oxfordian (Late Jurassic) and their effect documented in sediments and fossil assemblages of an epicontinental sea. Eclogae Geol Helv 79: 455–491

Gygi RA (1995) Datierung von Seichtwassersedimenten des Späten Jura in der Nordwestschweiz mit Ammoniten. Eclogae Geol Helv 88: 1–58

Gygi RA, Persoz F (1986) Mineralostratigraphy, litho- and biostratigraphy combined in correlation of the Oxfordian (Late Jurassic) formations of the Swiss Jura range. Eclogae Geol Helv 79: 385–454

Haq BU, Hardenbol J, Vail PR (1987) Chronology of fluctuating sea levels since the Triassic. Science 235: 1156–1167

House MR, Gale AS (eds) (1995) Orbital forcing timescales and cyclostratigraphy. Geol Soc Spec Publ 85: 1–210

Howell JA, Aitken JF (eds) (1996) High-resolution sequence stratigraphy: innovations and applications. Geol Soc Spec Publ 104: 1–374

Hunt D, Allsop T, Swarbrick RE (1996) Compaction as a primary control on the architecture and development of depositional sequences: conceptual framework, applications and implications. In: Howell JA, Aitken JF (eds) High-resolution sequence stratigraphy: innovations and applications. Geol Soc Spec Publ 104: 321–345

Jacobs DK, Sahagian DL (1993) Climate induced fluctuations in sea level during nonglacial times. Nature 361 : 710–712

Jan Du Chêne R, Busnardo R, Charollais J, Clavel B, Deconinck JF, Emmanuel L, Gardin S, Gorin G, Manivit H, Monteil E, Raynaud JF, Renard M, Steffen D, Steinhauser N, Strasser A, Strohmenger C, Vail PR (1993) Sequence-stratigraphic interpretation of upper Tithonian-Berriasian reference sections in southeast France: a multidisciplinary approach. Bull Centres Rech Explor Prod Elf Aquitaine 17 : 151–183

Loucks RG, Sarg JF (eds) (1993) Carbonate sequence stratigraphy. Am Assoc Petrol Geol Mem 57 : 1–545

Marquez B, Olóriz F, Rodriguez-Tovar FJ (1991) Interactions between tectonics and eustasy during the Upper Jurassic and lowermost Cretaceous. Examples from the south of Iberia. Bull Soc Géol France 162 : 1109–1124

Marquez B, Olóriz F, Caetano PS, Rodriguez-Tovar FJ (1993) Relative sea-level fluctuatins and ecostratigraphy; applications to Middle/Upper Oxfordian fossil asemblages of east–central Algarve, Portugal. Acta Geol Polonica 43 : 289–298

Matthews MD, Perlmutter MA (1994) Global cyclostratigraphy: an application to the Eocene Green River Basin. In: Boer PL de, Smith DG (eds) Orbital forcing and cyclic sequences. Int Assoc Sedimentol Spel Publ 19 : 459–481

Matyja BA, Wierzbowski A (1988) The two *Amoeboceras* invasions in the submediterranean Late Oxfordian of Central Poland. 2nd Int Symp Jurassic Stratigraphy, Lisboa 1 : 421–432

Matyja BA, Wierzbowski A (1994) On correlation of submediterranean and boreal ammonite zonations of the Middle and Upper Oxfordian: new data from Central Poland. Geobios 17 : 351–358

Meléndez G (1989) El Oxfordiense del sector central de la Cordillera Ibérica (Provincias de Zaragoza y Teruel). Institucion Fernando el Católico and Instituto de Estudios Turonenses, Zaragoza

Mensink H, Mertmann D, Wilde S (1990) Cyclic lagoonal sedimentation of the Oxfordian/Kimmeridgian within the Sierra del Madero, northwestern Iberian Range, Soria province. Cuad Geol Ibérica 14 : 215–224

Milankovitch M (1994) Kanon der Erdbestahlung und seine Anwendung auf das Eiszeitenproblem. K Serb Akad, 133 pp

Montañez IA, Osleger DA (1993) Parasequence stacking patterns, third-order accommodation events, and sequence stratigraphy of Middle to Upper Cambrian platform carbonates, Bonanza King Formation, southern Great Basin. In: Loucks RG, Sarg JF (eds) Carbonate sequence stratigraphy: recent developments and applications. Am Assoc Petrol Geol Mem 57 : 305–326

Oschmann W (1990) Environmental cycles in the late Jurassic northwest European epeiric basin: interaction with atmospheric and hydrospheric circulations. Sediment Gel 69 : 313–332

Pasquier JB, Strasser A (1997) Platform-to-basin correlation by high-resolution sequence stratigraphy and cyclostratigraphy (Berriasian, Switzerland and France). Sedimentology 44 (in press)

Perlmutter MA, Matthews MA (1989) Global cyclostratigraphy: a model. In: Cross TA (ed) Quantitative dynamic stratigraphy. Prentice Hall, Englewood Cliffs, New Jersey, pp 233–260

Pittet B (1994) Modèle d'estimation de la subsidence et des variations du niveau marin: un exemple de l'Oxfordien du Jura suisse. Eclogae Geol Helv 87 : 513–543

Pittet B (1996) Contrôles climatiques, eustatiques et tectoniques sur des systèmes mixtes carbonates-siliciclastiques de plate-forme: examples de l'Oxfordien (Jura suisse, Normandie, Espagne). Thesis Univ Fribourg, 258 pp

Pittet B, Gorin GE (1997) Distribution of sedimentary organic matter in a carbonate-siliciclastic platform environment: Oxfordian in the Swiss Jura Mountains. Sedimentology 44 : 915–937.

Pittet B, Strasser A, Dupraz C (1995) Palaeoecology, palaeoclimatology and cyclostratigraphy of shallow-water carbonate–siliciclastic transitions in the Oxfordian of the Swiss Jura. 16th IAS Regional Meeting of Sedimentology, 5ème Congrès Français de Sédimentologie ASF, Field Trip Guide Book, Publ ASF 23 : 225–254

Ponsot CM, Vail PR (1991) Sequence stratigraphy of the Jurassic: new data from the Paris–London basin. Terra Abstracts 3 : 308

Posamentier HW, Summerhayes CP, Haq BU, Allen GP (eds) (1993) Sequence stratigraphy and facies associations. Int Assoc Sedimentol Spec Publ 18 : 1–644

Pratt BR, James NP (1986) The St. George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas. Sedimentology 33 : 313–343

Read JF, Kerans C, Weber LJ, Sarg JF, Wright FM (1995) Milankovitch sea-level changes, cycles, and reservoirs on carbonate platforms in greenhouse and ice-house worlds. Soc Econ Paleontol Mineral Short Course 35 : 1–81

Rioult M, Dugué O, Jan Du Chêne R, Ponsot C, Fily G, Moron JM, Vail PR (1991) Outcrop sequence stratigraphy of the Anglo-Paris basin, Middle to Upper Jurassic (Normandy, Maine, Dorset). Bull Centres Rech Explor Prod Elf Aquitaine 15 : 101–194

Schlager W (1993) Accommodation and supply: a dual control on stratigraphic sequences. Sediment Geol 86 : 111–136

Schwarzacher W (1993) Cyclostratigraphy and the Milankovitch Theory. Dev Sedimentol 52 : 1–225

Schweigert G (1995a) *Amoebopeltoceras* n.g., eine neue Ammonitengattung aus dem Oberjura (Ober-Oxfordium bis Under-Kimmeridgium) von Südwestdeutschland und Spanien. Stuttgarter Beitr Naturk B 227, 12 pp

Schweigert G (1995b) Zum Auftreten der Ammonitenarten *Amoeboceras bauhini* (OPPEL) und *Amoeboceras schulginae* MESETZHNIKOV im Oberjura der Schwäbischen Alb. Jh Ges Naturkde Württemberg 151 : 171–184

Smith GA, Smith DG, Funnell BM (1994) Atlas of Mesozoic and Cenozoic Coastlines. Cambridge Univ Press, London

Strasser A (1991) Lagoonal-peritidal sequences in carbonate environments: autocyclic and allocyclic processes. In: Einsele G, Ricken W, Seilacher A (eds) Cycles and events in stratigraphy. Springer, Berlin Heidelberg New York, pp 709–721

Strasser A (1994) Milankovitch cyclicity and high-resolution sequence stratigraphy in lagoonal-peritidal carbonates (Upper Tithonian–Lower Berriasian, French Jura Mountains). In: Boer PL de, Smith DG (eds) Orbital forcing and cyclic sequences. In Assoc Sedimentol Spec Publ 19 : 285–301

Strasser A, Pittet B, Pasquier JB (1994) Multiplication of maximum-flooding surfaces, sequence boundaries, and transgressive surfaces as a response to high-frequency sea-level fluctuations. Abstr 14th Int Sedimentol Congress, Recife, Brazil, E29

Vail PR, Audemard F, Bowman SA, Eisner PN, Perez-Cruz C (1991) The stratigraphic signatures of tectonics, eustasy and sedimentology: an overview. In: Einsele G, Ricken W, Seilacher A (eds) Cycles and events in stratigraphy. Springer, Berlin Heidelberg New York, pp 617–659

Weimer P, Posamentier HW (eds) (1993) Siliciclastic sequence stratigraphy. Am Assoc Petrol Geol Mem 58 : 1–492

Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, Van Wagoner JC (eds) (1988) Sea-level changes: an integrated approach. Soc Econ Paleontol Mineral Spec Publ 42: 1–407

Ziegler PA (1982) Geological atlas of western and central Europe. Elsevier, Amsterdam

Ziegler PA (1988) Evolution of the Arctic–North Atlantic and the western Tethys. Am Assoc Petrol Geol Mem 43 : 1–198