Geol. Mag. **141** (*6*), *2004, pp. 717–733.* © *2004 Cambridge University Press*
DOI: 10.1017/S0016756804009963 *Printed in the United Kingdom*

Facies and depositional sequence evolution controlled by high-frequency sea-level changes in a shallow-water carbonate ramp (late Kimmeridgian, NE Spain)

M. AURELL* & B. BÁDENAS

Dpto. Ciencias de la Tierra, Universidad de Zaragoza, 50.009 Zaragoza, Spain

(*Received* 27 November 2003; *accepted* 27 August 2004)

Abstract – The outcrops of the Sierra de Albarracín (NE Spain) allow a precise reconstruction of the shallow sedimentary domains of a late Kimmeridgian carbonate ramp, developed in western marginal areas of the Iberian Basin. The sedimentary record shows a hierarchical sequence stratigraphic organization, which implies sea-level changes of different frequencies. The studied succession is arranged in a long-term transgressive–regressive sequence, which is likely to reflect local variation in the subsidence rates. This sequence includes four higher-order sequences A to D, which have variable thickness (from 3 to 21 m). The similar sedimentary evolution observed in distant localities suggests the existence of high-frequency sea-level fluctuations controlling the sequence development. The average amplitude of these cycles would range from 5 to 10 m. The precise estimation of their duration (some few hundreds of kyr) and their possible assignment to any of the long-term orbital cycles (the 100 or the 400 kyr eccentricity cycles) is uncertain. Sequences A and B, formed during the long-term transgressive interval, are relatively thin (from 3 to 9 m) give-up sequences that were never subaerially exposed. These sequences are locally formed by five shallowing-upward elementary sequences. Sequences C and D are catch-down sequences with evidence of emersion of subtidal facies. Sequence C, formed during the stage of maximum gain of long-term accommodation, is the thickest sequence (from 13 to 21 m) and includes coral–microbial reefs (pinnacles up to 16 m in height). The increased production rates were able to fill part of the accommodation created during the early stage of high-frequency sea-level rise and the shallow platform was eventually exposed to subaereal erosion and meteoric cementation.

Keywords: Kimmeridgian, Iberia, carbonate platforms, sea-level changes, sequence stratigraphy.

1. Introduction

Shallow-water carbonate platform deposits usually display distinct hierarchical stacking patterns and facies changes, which allow the identification of depositional sequences (or sedimentary cycles) at different scales. The smaller-scale sequences (fourth-, fifth- and sixth-order sequences) are commonly explained by climatically controlled sea-level fluctuations in the Milankovitch frequency band (e.g. Vail *et al*. 1991; D'Argenio *et al*. 1999; Strasser *et al*. 2000; Bádenas, Salas & Aurell, 2004). Another alternative model proposes that metre-scale cycles in shallow carbonate platforms mainly reflect the random migration of various sedimentary subenvironments over specific platform localities during long-term accumulation of peritidal carbonate (e.g. Wilkinson, Diedrich & Drummond, 1996). In this model, the small-scale sequences are interpreted as largely constituting unordered assemblages of various peritidal lithologies, rather than cyclic or upward-shallowing lithofacies associations. In order to consider one of these two alternative models, reliable reconstruction of the sequence stratigraphic framework and stacking patterns of the shallow carbonate platform successions have to be achieved. The precise control of the vertical and lateral facies distribution and the correlation of sequence boundaries and flooding surfaces between different localities may demonstrate whether or not the small-scale sequences are found at the basin scale, reflecting the possible influence of periodic extra-basinal forcing during sediment accumulation.

Upper Jurassic (Kimmeridgian) shallow carbonate platform deposits are excellently preserved in outcrops around the Sierra de Albarracín in northeastern Spain (Fig. 1a). In particular, the upper Kimmeridgian outcrops located between the villages of Jabaloyas, Tormón and Arroyo Cerezo allow the precise documentation of the vertical and lateral facies distribution (a three-dimensional facies analysis through time) of a set of small-scale depositional sequences developed in the shallow environments of the Iberian carbonate ramp. Coral–microbial reefs of variable dimension are locally found in some of these sequences. The more prominent reefs of the Jabaloyas–Arroyo Cerezo outcrops occur as irregularly spaced, cylindrical to

* E-mail: maurell@unizar.es

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

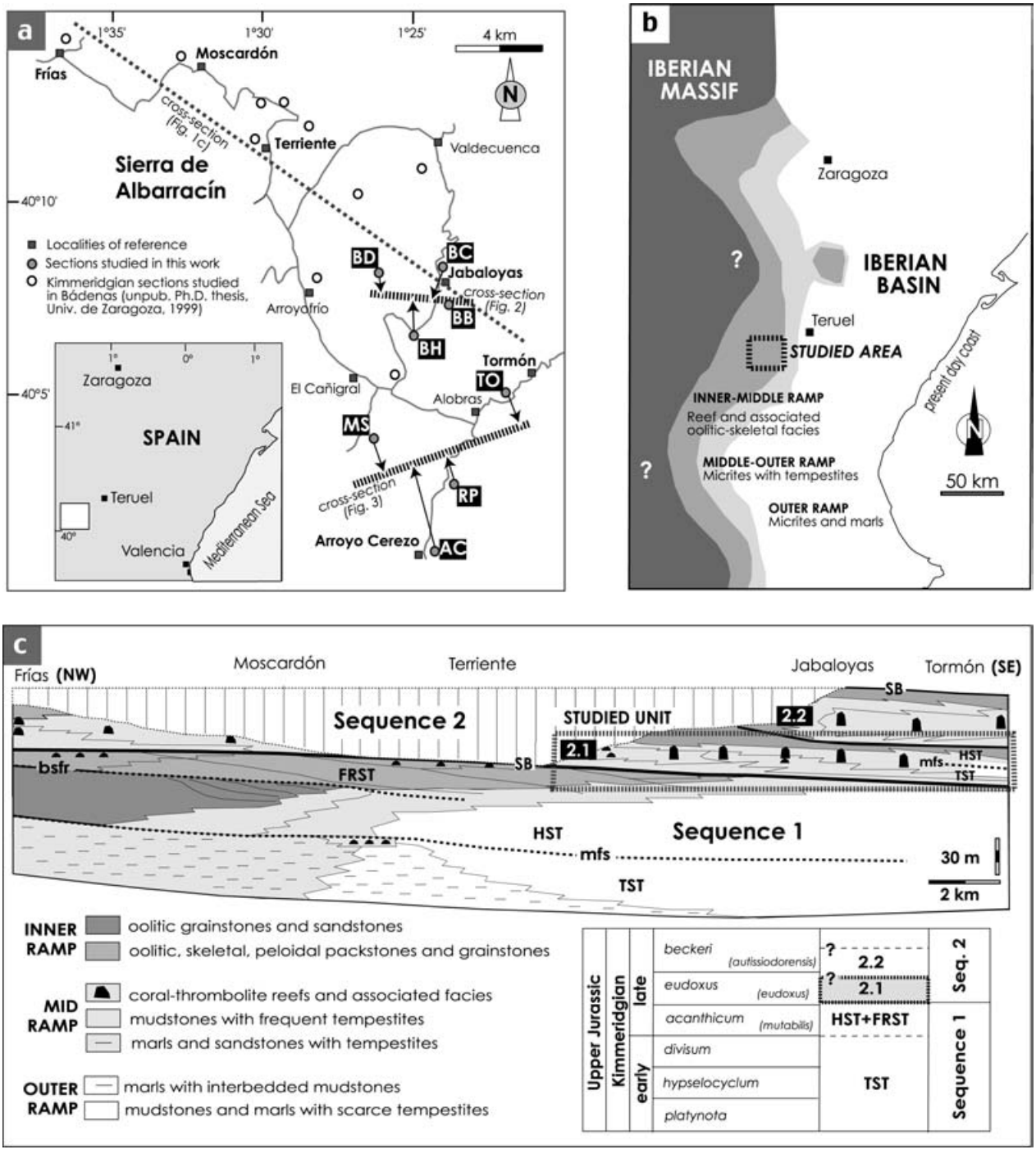


Figure 1. (a) Geographical location of the sections studied around the Sierra de Albarracín (NE Spain). (b) Palaeogeography of the northeastern Iberian Plate during late Kimmeridgian times (modified from Bádenas & Aurell, 2001). (c) Cross-section from Frías to Tormón localities, showing the main facies distribution and systems tracts interpretation for the Kimmeridgian units of the Sierra de Albarracín (compiled from Aurell *et al*. 1998 and Bádenas & Aurell, 2001). TST – Transgressive Systems Tract; HST – Highstand Systems Tract; FRST – Forced Regressive Systems Tract; SB – Sequence boundary; mfs – maximum flooding surface; bsfr – basal surface of forced regression. The probable equivalence between the late Kimmeridgian biozones defined in southwestern and northwestern Europe is given in the table at the lower right.

conical-shaped build-ups (pinnacles up to 16 m in height). In a broader palaeogeographical context, coral–microbial reefs and associated shallow carbonate facies were developed in the inner and middle ramp setting of the western marginal areas of the Iberian basin during late Kimmeridgian times (Fig. 1b).

Previous studies of the Kimmeridgian outcrops of the Jabaloyas-Arroyo Cerezo area were mainly focused on the coral–microbial reef facies. The early works by Giner & Barnolas (1979), Fezer (1988) and Errenst (1990) provided preliminary information on their coral fauna and associated facies. Further

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

data on the stratigraphy, sedimentology, palaeoecology and composition of the reef fabric were reported in Leinfelder (1993), Leinfelder *et al*. (1993, 1994), Baumgärtner & Reyle (1995) and Nose (1995). The growth of the pinnacle reefs and the development of the associated facies were related to successive stages of sea-level variation by Aurell & Bádenas (1997). An initial fast rise of sea-level resulted in the growth of scattered coral thrombolites. The aggradation of the pinnacles, with increasing proportion of metazoan builders, was followed during the continuous rise and eventual stillstand of sea-level.

The main aim of this work is to demonstrate the relationship between the facies distribution and sedimentary evolution of a set of small-scale sequences to high-frequency cycles of sea-level fluctuations. In particular, the method proposed in Hillgärtner & Strasser (2003) has been used for the quantification of the amplitude of the high-frequency sea-level variations. In addition, the palaeoenvironmental reconstruction of the shallow platform domains (inner to middle ramp areas) and the maps showing the distribution of the reefs and associated facies over space and time provide a three-dimensional view of the upper Kimmeridgian carbonate ramp, which may be useful for the sedimentological interpretation of similar shallow platform carbonate successions.

2. Palaeogeography and stratigraphical setting

Marine sedimentation in the NW Iberian Plate during late Kimmeridgian times took place in an extensive carbonate ramp, which was open to the Tethys Sea towards the east (Bádenas & Aurell, 2001; Aurell *et al*. 2003). Three depositional domains have been defined in the ramp. Coral–microbial reefs and oolitic-skeletal shoals were developed in inner ramp and proximal mid-ramp areas. The distal mid-ramp area was characterized by the deposition of lime mudstones and coarse-grained tempestites. Well-bedded lime mudstones and marls are found in the outer ramp area to the east (Fig. 1b).

The overall facies and systems tracts distribution of the Kimmeridgian outcrops of the Sierra de Albarracín area is shown in the Frías-Tormón transect (Fig. 1c). The Kimmeridgian units of the Iberian Basin are arranged in two long-term (third-order) depositional sequences (Aurell *et al*. 1998; Bádenas & Aurell, 2001). Sequence 1 is latest Oxfordian (*galar* Subzone) to late Kimmeridgian (middle part) in age. In the Sierra de Albarracín, two sedimentary units are found in the upper part of Sequence 1: a lower oolitic–sandy unit up to 50 m thick and an upper oolitic–peloidal–skeletal unit, including some scattered, metre-size patch reef. These two units define two stages in the evolution of the carbonate ramp, which were assigned by Aurell *et al*. (1998) to a lower highstand systems tract (HST) and to a rapidly progradational (with offlapping geometry) forced regressive systems tract (FRST, *sensu* Hunt & Tucker, 1993).

Following a widespread stage of sea-level fall at the end of Sequence 1, the lower boundary of Sequence 2 is indicated by a significant backstepping of mid-ramp facies (Fig. 1c). This flooding event is observed all across the marginal areas of the Iberian Basin, and is located around the boundary between the *acanthicum* and *eudoxus* zones (Bádenas & Aurell, 2001). In the Sierra de Albarracín, the sequence is significantly eroded (Fig. 1c). Sequence 2 is best exposed in the more eastern profiles, where it is formed by two higher-order depositional sequences (Sequence 2.1 and Sequence 2.2 in Fig. 1c), each including levels with coral–microbial reef development. Based on the microfossil association (in particular, lituolids) and on the scarce ammonites found in the area, these reefs have been assigned to the middle part of late Kimmeridgian by different authors (e.g. Fezer, 1988; Nose, 1995; Bádenas & Aurell, 2001, 2003). The location of the boundary between the two latest Kimmeridgian biozones (the *eudoxus* and the *beckeri* Zones) and the age assignment of the two high-order Sequences 2.1 and 2.2 cannot be precisely established. According to the available stratigraphic data, the lower Sequence 2.1 studied in this work was probably developed during the *eudoxus* Zone.

3. Facies analysis

Facies analysis carried out on the outcrops located around Jabaloyas, Tormón and Arroyo Cerezo focuses on the high-order Sequence 2.1. The sequence has been studied in detail along eight sections (see Fig. 1a for location). The lateral and vertical facies distribution based on the correlation of these sections in two transects is shown in Figures 2 and 3. Four depositional sequences (named Sequences A to D) are recognized. The description of these sequences will be given in Section 4, after the facies description and interpretation.

Different groups of facies were distinguished in the shallow domains of the upper Kimmeridgian carbonate ramp: carbonate Facies 1 to 7, reefal and inter-reef Facies 1R to 4R and siliciclastic facies. The siliciclastic facies are found in the lower and upper part of the studied sequence, associated with the sequence boundaries, and are more abundant in the sections located in the more proximal (western) areas (that is, BD section, Fig. 2). They generally consist of poorly bedded medium to coarse sandstones, with abundant plant remains, deposited in terrestrial (marsh) to interior lagoon environments. However, marly dominated successions (with interbedded sandstones) found in the lower part of Sequence A are interpreted to be deposited in marine waters, down to the proximal mid-ramp settings.

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

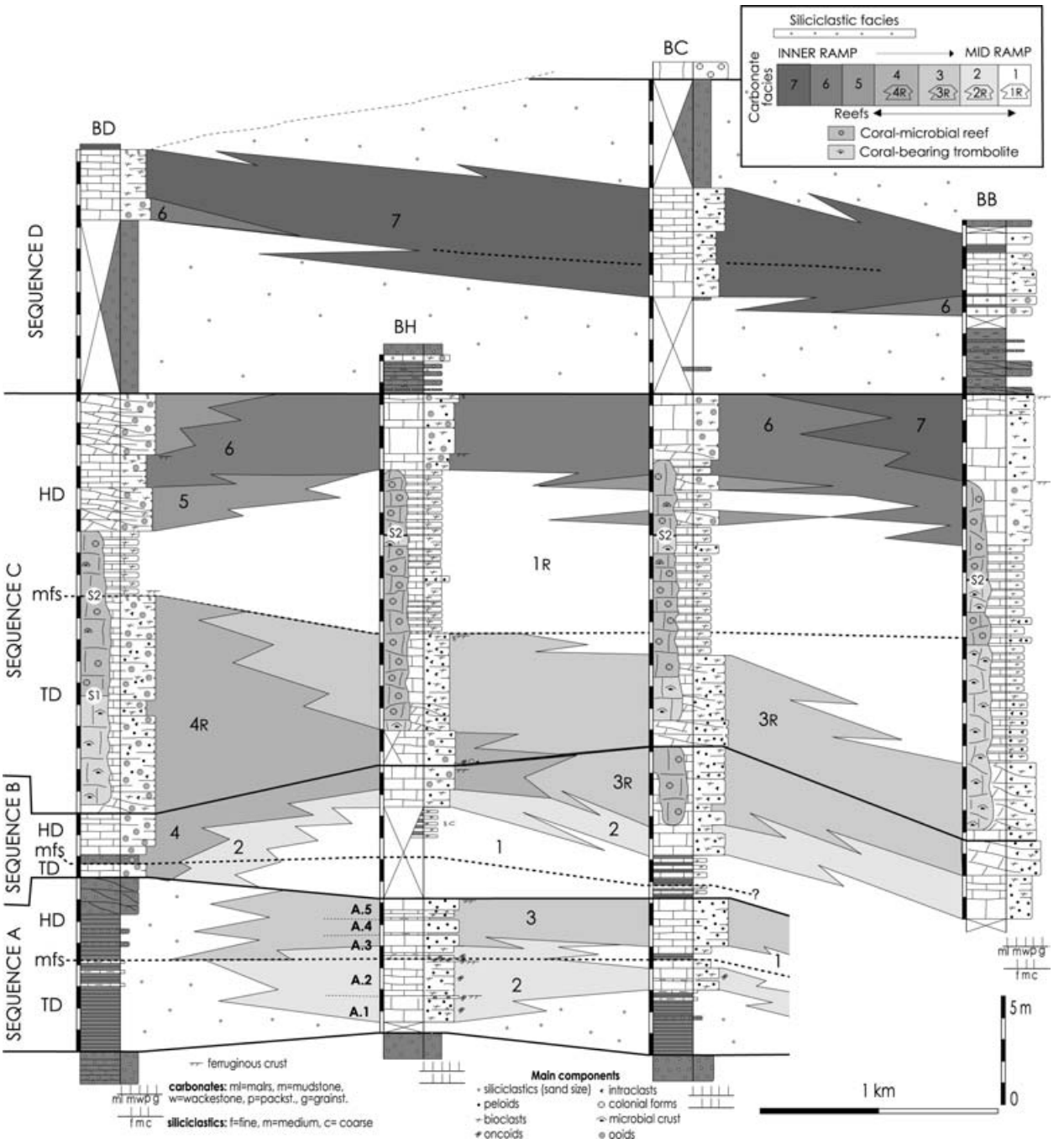


Figure 2. Cross-section showing the facies distribution around Jabaloyas, from BD to BB sections (see Fig. 1a for location). Transgressive deposits (TD), maximum flooding surface (mfs) and highstand deposits (HD) of Sequences A–D have been differentiated. The distribution of higher order sequences A.1 to A.5 is also indicated.

3.a. Reefal facies

The description of the morphology and fabric of the reefs located around Jabaloyas and Arroyo Cerezo, including aspects such as the identification and spatial distribution of the different fossil groups or the nature of the microbial crust, have been described in different works (in particular, Fezer, 1988; Leinfelder *et al*. 1993, 1994; Nose, 1995; Baumgärtner & Reyle, 1995; Bádenas & Aurell, 1997). Most of the reefs are irregularly distributed in a discrete level (middle part of Sequence C, Figs 2, 3), although smaller-size reefs are occasionally found in lower levels. The reefs found in Sequence C display very steep slopes (usually, more than 45°). They show pinnacle morphology (conical to cylindrical shape) up to 16 m high and from 10 to 20 m in diameter in most cases (Fig. 4). The reefs had some depositional relief above the sea floor. The analysis of the relationship between the reefs and associated facies in certain outcrops (e.g. the BH section) indicates depositional relief up to 5 m (Aurell & Bádenas, 1997).

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

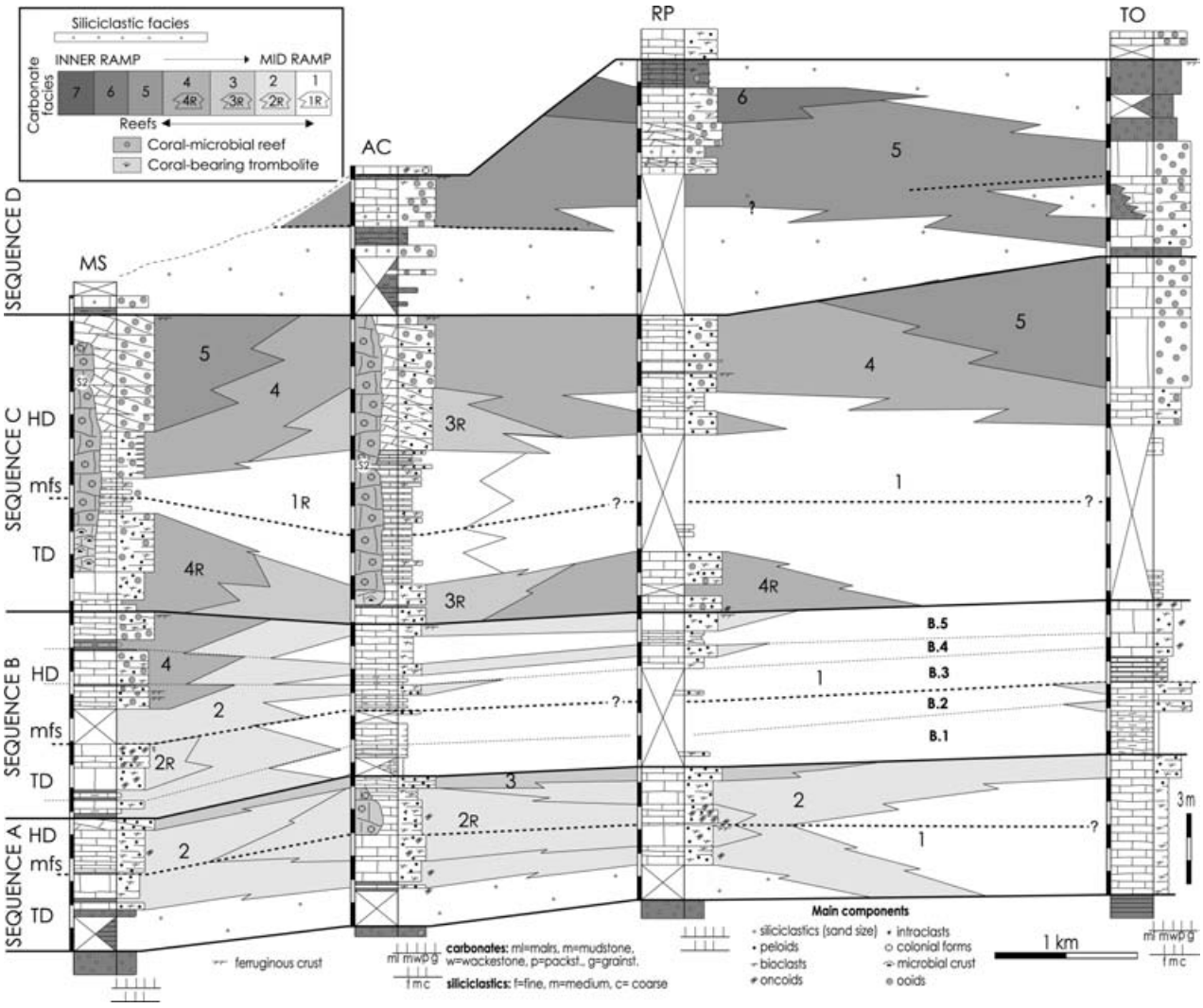


Figure 3. Cross-section showing the facies distribution between Arroyo Cerezo (AC) and Tormón (TO) localities (see Fig. 1a for location). Transgressive deposits (TD), maximum flooding surface (mfs) and highstand deposits (HD) of Sequences A to D have been differentiated. The distribution of higher order sequences B.1 to B.5 is also indicated.

The reef fabric consists of framestone textures with variable proportions of colonial organisms and microbial crusts with associated encrusters and micro-encrusters. Other organisms such as lithophagid bivalves, gastropods, echinoids and lithistid demosponges are common throughout the reefs. Cavities formed by boring inter-growth cavities form from 10 to 35 % of the volume of the reef fabric. The internal sediment filling these cavities mainly consists of mudstones with quartz silt, peloids, bioclasts and fragments of microbial crusts.

The dominant colonial organisms are corals. They display different morphology (massive, hemispherical, branching) and normally occur as a centimetric to decimetric fragments. According to Nose (1995), the dominant coral taxa are *Thamnasteria* and *Microsolena*. Also common are *Stylina, Stylosmilia, Heliocoenia, Goniocora, Convexastrea, Axosmilia, Latomeandra, Microphyllia, Calamophylliopsis, Ovalastrea, Fungiastrea* and *Comoseris* (Fezer, 1988; Leinfelder *et al*. 1994; Nose, 1995). Stromatoporoids (*Actinostromaria*, *Disparistromaria*, *Dehornella*, *Millepordium*, *Cladocoropsis)*, chaetetids (*Chaetetes*, *Ptychochaetetes*) and solenoporacean algae (*Solenopora)* are less common.

A dense micritic to peloidal (packstone) microbial crust is found around the colonial forms. The microbial crust plays a primary role in the stabilization and development of the reef, bonding together the debris of the metazoan builders and also forming variable proportions of the reef fabric. The relative proportion of microbial crust can be used to separate two groups of reefs (based on the classification of Leinfelder, 1993): (1) coral–microbial reefs, when there is a larger proportion of colonial forms, and (2) coral-bearing thrombolites, composed of microbial crust with a considerable amount of reef macrofauna (up to an equal proportion of colonial forms and microbial crust). A rich association of encrusting organisms is normally found, including serpulids, bryozoans, *Tubiphytes*,

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

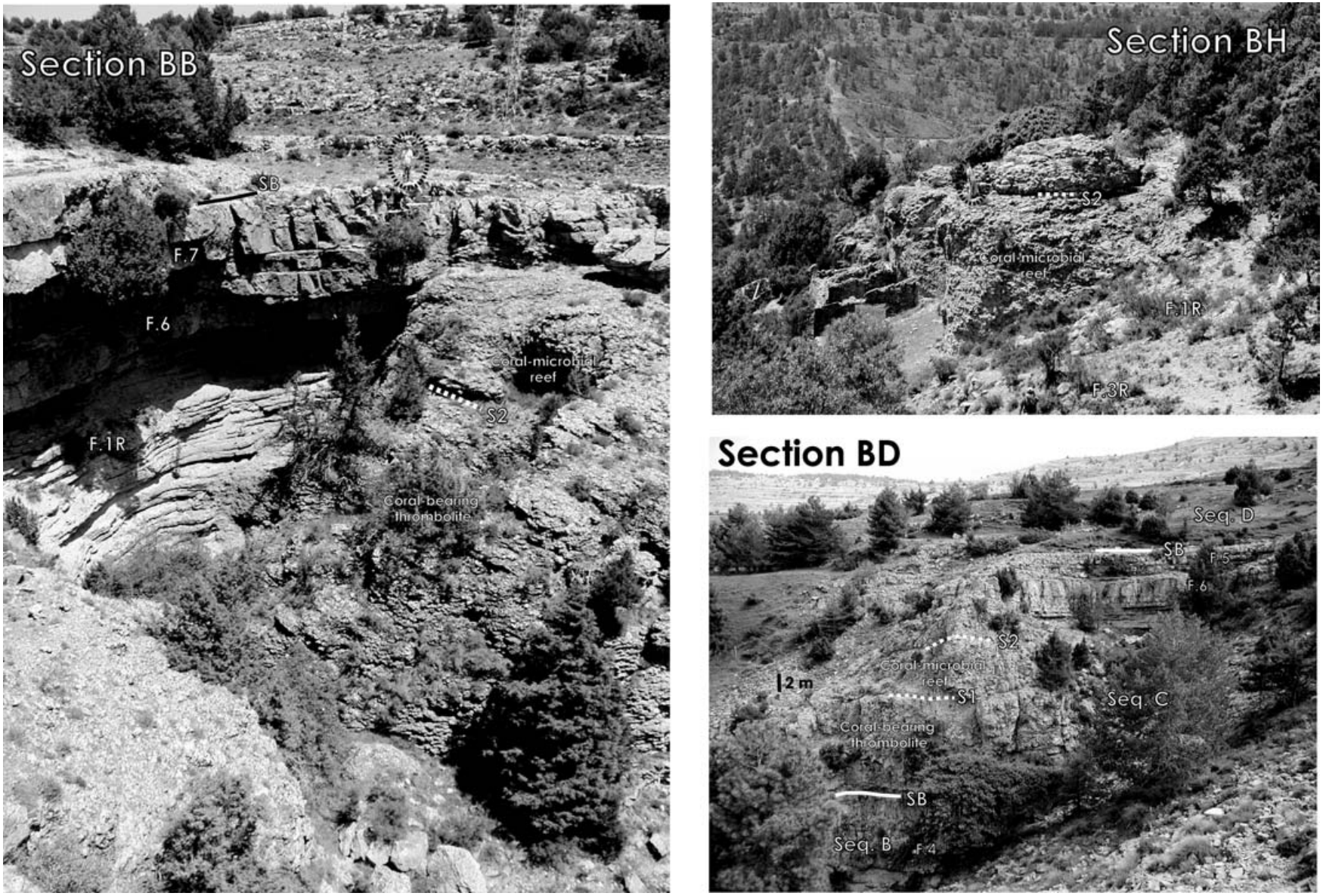


Figure 4. Panoramic view of the pinnacle reefs and associated facies (Sequence C) in three different sections located around Jabaloyas. The sharp and planar S1 and S2 surfaces found in the cores of the reefs separate reefal fabrics dominated either by microbial crusts (coral-bearing thrombolites) or by colonial forms (coral–microbial reefs). In the BB section, there is an onlap of Facies 1 (F.1R) over the flank of the reefs.

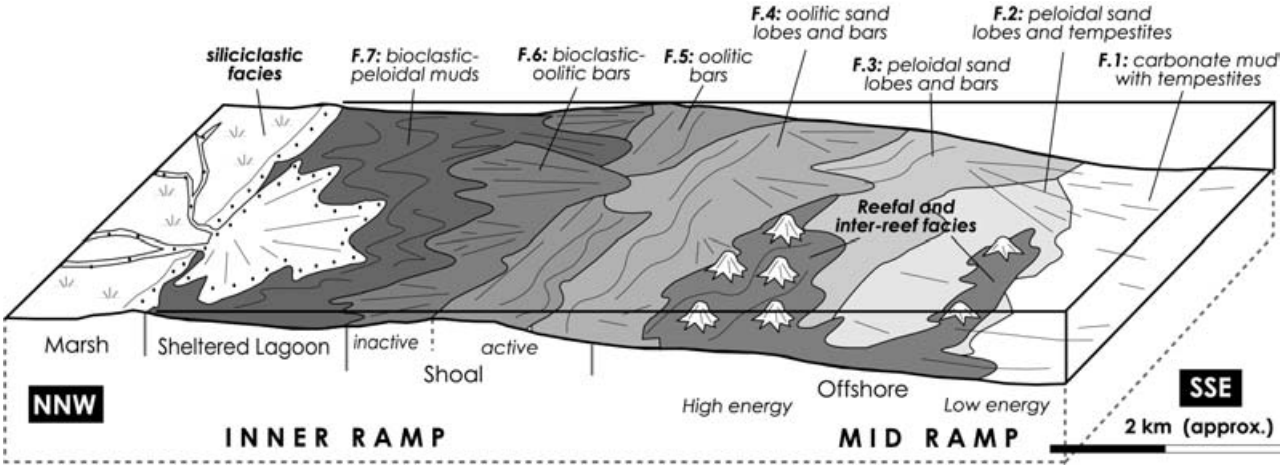


Figure 5. Sedimentary domains of the late Kimmeridgian carbonate ramp (marginal areas of the Iberian Basin). The distribution of the Facies 1 (F.1) to Facies 7 (F.7) is indicated.

Terebella, Koskinobullina, *Lithocodium*, *Placopsilina*, *Cayeuxia*, *Bacinella* and *Thaumatoporella*. However, when the microbial crust dominates the reef fabric (in coral-bearing thrombolites), there is a lower diversity of micro-encrusters (a large abundance of *Tubiphytes* and *Terebella*).

Flat and sharp surfaces associated with intense microbial crust development occur in the core of some of the studied reefs. A lower surface (S1) is found some 2 to 5 m above the bottom of the reefs located around the BD section (Fig. 4). An upper surface (S2) is located 7 to 12 m above the bottom of most of the studied reefs. The relative proportion of microbial crusts varies from one reef to another and even inside a single reef. However, as a general rule, there is a progressive upward increase of the proportion of corals inside the reefs (e.g. Giner & Barnolas, 1979; Leinfelder *et al*. 1993; Aurell & Bádenas, 1997). Coral-bearing thrombolites are the dominant reefal fabric below the S1 surface. Between the S1 and S2 surfaces, colonial organisms generally dominate most of the reefs, although microbial crust can become locally more abundant than colonial forms (e.g. BB section, Fig. 2). Above the S2 surface, the microbial crust becomes scarce and colonial forms largely dominate the reef fabric.

3.b. Carbonate facies

Carbonate facies have been grouped in seven types. Each facies type was deposited in different subenvironments of the shallow carbonate ramp (Fig. 5). The main features observed in the carbonate facies are outlined below.

3.b.1. Facies 1 (bioclastic mudstone–wackestone and marly limestone)

The facies is formed by tabular to irregular, highly burrowed bioclastic and micritic limestone beds (up to 0.5 m thick) with interbedded marls. The centimetre-thick bioclastic graded levels with quartz silt are interpreted as tempestites originated by density flows induced by storms. The traces *Chondrites* and *Planolites* are frequent. Main components are bioclasts (bivalves, lituolids, gastropods, echinoderms) and peloids. Also found are scattered plant remains and quartz grains (fine sand), indicating episodic terrigenous input from continental areas. The inter-reef Facies 1R (Sequence C) also include debris of corals, chaetetids, *Cayeuxia* and *Solenopora* and millimetric to centimetric intraclasts of microbial crusts.

3.b.2. Facies 2 (peloidal and bioclastic wackestone–packstone)

This facies consists of tabular beds (up to 0.5 m thick), with occasional planar cross-bedding and frequent centimetre-thick bioclastic tempestites (mainly formed by *lituolids*). The traces *Chondrites*, *Planolites* and *Rhizocorallium* are common. The peloids are irregular, and grade into millimetre-size micritic intraclasts. Poorly rounded bioclasts of variable size (up to 1 cm) mainly consist of lituolids (*Everticyclammina*, *Alveosepta*), bivalves and gastropods. Serpulids, brachiopods, echinoderms, corals, stromatoporoids, bryozoans and textularian foraminifera are less abundant. The observed fossil association indicates deposition in the open areas of the carbonate ramp. Episodic storm wave activity involved the formation of tempestites and the migration of subtidal bars. Quartz grains (fine sand) and plant remains are occasionally found. The inter-reef Facies 2R (Sequences A and B) also includes intraclasts (millimetre-size irregular fragments of microbial crusts and micrite) and oncoids (up to 20 % of the components). The oncoids (up to 1 cm in diameter) have bioclastic cores and are formed by laminated to poorly laminated micritic envelopes with *Bacinella, Lithocodium, Bullopora*, serpulids and bryozoans.

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

3.b.3. Facies 3 (peloidal packstone–grainstone)

The facies has a similar composition to Facies 2, but displays a lesser carbonate mud content and larger proportion of current-generated structures. It is formed by tabular beds (up to 0.3 m thick) with local planar lamination, cross-bedding and symmetric ripples. Centimetric bioclastic graded levels and *Chondrites* are also found. The peloids are well sorted (average size of 0.1 mm) and irregular. The millimetre-size bioclasts forming up to 10 % of the components are mainly echinoderms and lituolids. Other skeletal grains include gastropods, bivalves, foraminifera (textularian, miliolids) and serpulids. Quartz grains (fine sand), plant remains and micritic intraclasts are occasionally found. The inter-reef Facies 3R (Sequence C) also includes heterometric and poorly rounded peloids grading into micritic intraclasts; a large proportion of fragments of microbial crusts; debris of corals, stromatoporoids, chaetetids, lituolids, bivalves and echinoderms; other skeletal grains such as brachiopods, gastropods, bryozoans, foraminifera, serpulids, *Solenopora* and *Cayeuxia*; scattered ooids (similar to Facies 4) and oncoids (bioclastic cores and poorly laminated micritic envelopes).

3.b.4. Facies 4 (oolitic and peloidal packstone–grainstone)

This facies is formed by tabular to irregular beds (up to 0.5 m thick) with local cross-bedding and frequent bioclastic and oolitic tempestites. *Chondrites* and *Planolites* traces are abundant. The peloids are heterometric and irregular in shape. The spherical ooids (up to 3 mm) have an internal fabric indicative of agitated to intermittently agitated environments (types 1 and 3 defined by Strasser, 1986). The more abundant skeletal grains (up to 15 % of the components) are echinoderms, bivalves and lituolids. Other (less abundant) skeletal grains are corals, brachiopods, gastropods, miliolids, textularian foraminifera, bryozoans, *Solenopora*, *Cayeuxia* and stromatoporoids. Quartz grains (fine sand) and centimetre-size micritic intraclasts are occasionally found. The inter-reef Facies 4R (Sequence C) also includes millimetre-size, poorly rounded, fragments of microbial crusts.

3.b.5. Facies 5 (oolitic grainstone)

This facies is formed by tabular beds (up to 3 m thick), with frequent planar cross-bedding. The presence of graded levels and bioturbation is common. The ooids are spherical, up to 4 mm in diameter, similar to types 1 and 3 of Strasser (1986). The cores of the ooids consist of quartz grains, peloids and bioclasts and they are occasionally aggregated. The bioclasts (up to 15 % of the components) are mainly foraminifera (miliolids, lituolids and textularian), bivalves, gastropods and echinoderms. Others skeletal grains include corals, stromatoporoids, chaetetids, brachiopods, bryozoans and serpulids. The facies can be locally formed by up to 15 % quartz sand. Millimetre-size micritic intraclasts and peloids are also occasionally found.

3.b.6. Facies 6 (bioclastic and oolitic packstone–grainstone)

The facies is characterized by tabular beds (up to 1 m), with local planar cross-bedding. Bioturbation and the existence of micritic coatings around the skeletal grains and ooids are common. The bioclasts are centimetre-size fragments of bivalves, *Marinella* and gastropods. In a lower proportion are found foraminifera (miliolids, lituolids and textularian), corals, chaetetids, echinoderms and *Cayeuxia*. The ooids display variable cores (quartz grains, peloids, bioclasts), are up to 3 mm in diameter and are frequently micritized. Type 4 and 1 ooids (Strasser, 1986) have been identified. Millimetre-size micritic and oolitic intraclasts, peloids, oncoids and quartz are occasionally found.

3.b.7. Facies 7 (bioclastic and peloidal wackestone–packstone)

The facies consists of highly bioturbated tabular beds (up to 1 m). The bioclasts are micritized and are dominated by bivalves, gastropods, miliolids and lituolids. Other skeletal grains include *Marinella*, echinoderms, corals, *Acicularia*, textularian foraminifera, serpulids and ostracods. Poorly rounded peloids are common. The ooids (up to 10 % of the components) display type 4 laminae and cores formed by quartz grains and bioclasts. The type 4 ooids are indicative of semi-restricted lagoon environments (Strasser, 1986). Also found are scattered oncoids, quartz grains (silt and fine sand) and micritic intraclasts.

3.b.8. Palaeoenvironmental reconstruction

The above described facies types correspond to different sedimentary environments in the shallow inner and middle domains of the carbonate ramp (Fig. 5). There is a clear gradation between the seven facies types, indicating a low-gradient in the ramp and a progressive increase of the depositional deep from the sheltered lagoon and interior shoal Facies 6 and 7 to the offshore carbonate mud dominated facies 1, located just below the fair-weather wave-base (that is, proximal mid-ramp environment).

Facies 1 was deposited in the mid-ramp environments (low-energy offshore), dominated by deposition of carbonate mud. The presence of centimetre-thick bioclastic graded levels with quartz silt (tempestites) indicates the existence of density flows induced by storms. Facies 2 represents the transition between the distal (low-energy) and the more proximal (high-energy) offshore environments of the mid-ramp, and contains a variable amount of carbonate mud (wackestone to packstone textures).

Facies 3 and 4 consist of grain-supported facies with variable proportions of peloids, ooids and skeletal

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

grains, and are interpreted as having been deposited in a high-energy belt developed in the transition area between the interior shoal and the middle ramp. Facies 4 represents the transition between Facies 3 and 5 (Fig. 5); most of the ooids found in this facies were derived from the active oolitic shoals represented by Facies 5.

Facies 5 and 6 are dominated by ooids and skeletal grains and were developed in the high-energy, inner ramp shoals. The oolitic grainstone Facies 5 indicates the existence of an active shoal belt, located in the higher energy areas of the ramp, above fair-weather wave-base. The common bioturbation and the existence of micritic coatings around the skeletal grains and ooids in Facies 6 indicate the existence of stabilized areas in an inactive shoal. Facies 7 is a skeletal and peloidal facies formed in semi-restricted environments, in a sheltered lagoon located near the shoreline (a protected back-shoal environment).

4. High-resolution sequence stratigraphy and sedimentary evolution

The Kimmeridgian outcrops of the Sierra de Albarracín record a number of depositional sequences of different scale. The term depositional sequence applied in this work follows the definition of Strasser *et al*. (1999) and is independent of scale. The studied unit (Sequence 2.1; see Fig. 1) is included in a longer-term (third-order) depositional sequence (Sequence 2), which is bounded by regional sequence boundaries.

As usual in shallow-water carbonate platforms, the small-scale depositional sequences identified within Sequence 2.1 (Sequences A–D, see Fig. 6) are delimited by discontinuity surfaces or rapid facies changes (Hillgärtner, 1998). These sequences are formed by a lower deepening-upward interval or transgressive deposits (TD), a maximum flooding surface (mfs), followed by an upper shallowing-upward interval or highstand deposits (HD). According to the traditional sequence stratigraphic nomenclature, the limits of the sequences are named sequence boundaries (SB) and the surface representing maximum water depth is called maximum flooding surface (mfs). Sequence 2.1 as a whole can be regarded as a longer-term deepening–shallowing cycle. The lower deepening-upward interval extends up to the mfs of Sequence C, which corresponds to the maximum development of the more distal Facies 1 (see Figs 2, 3). Upward from this surface, there is a rapid shallowing and progradation of the inner ramp carbonates and terrestrial siliciclastic facies.

Each sequence has a particular facies distribution and indicates a different evolution of sedimentary facies. The facies distribution of the carbonate ramp along successive stages of sedimentary evolution defined during the early TD, mfs and late HD of the four sequences A–D are shown in Figure 7. The observed facies distribution indicates a change in the orientation of the shoreline, from a N–S-oriented trend during Sequences A–C (Fig. 7a–h) to a nearly E–W to NE–SW orientation from the uppermost part of Sequence C to Sequence D (Fig. 7i–k).

4.a. Sequence A

The thickness of this sequence ranges from 5.7 m (MS section) to 8 m (BD section). In some sections, up to five higher-order, elementary shallowing-upward sequences can be recognized (e.g. BH section, Fig. 2). The lower sequence boundary is the regional discontinuity located around the boundary between the *acanthicum* and *eudoxus* zones (Fig. 1c). In all the studied sections (except for the more distal locality of TO, Fig. 3), this boundary has been located on top of a cross-bedded, well-cemented sandstone bed, up to 1 m thick. This level was deposited at the end of the previous third-order depositional sequence, during the late stages of the forced regression, which involved significant siliciclastic input across the marginal areas of the basin.

Sequence A shows a deepening–shallowing trend, but is composed entirely of subtidal facies, with no subaereal exposure surface on top of the succession. Therefore it corresponds to a subtidal cycle described by Osleger (1991) and is equivalent to the give-up sequence of Hillgärtner & Strasser (2003). The onset of Sequence A is marked by a widespread flooding event, which involved the deposition of the mid-ramp facies 1 and 2 across eastern areas (Fig. 7a). The mid-ramp areas were dominated by fine-grained siliciclastic facies. The mfs is indicated by the maximum extent of Facies 1, and is usually marked by an encrusted and ferruginous surface. Coral–microbial reefs up to 2 m thick were locally developed above this surface in the southern areas (AC section; Fig. 7b). Low sedimentary rates around the mfs were thought to be favourable for microbial crust development and stabilization, and hardening of the substrate allowed the eventual growth of corals (see Leinfelder *et al*. 1993). The upper part of the sequence (HD) involves the rapid progradation of the more proximal Facies 3 (Fig. 7c).

4.b. Sequence B

Sequence B corresponds to a subtidal deepening–shallowing cycle, and is not bounded by subaereal exposure surfaces. The thickness of the sequence ranges from 3 m (BD section) to 9 m (MS section). In the southern sections (Fig. 3), the sequence consists of five coarsening-upward higher-order sequences, the lower two developed at the TD, the upper three at the HD.

The deepening event developed at the onset of Sequence B involved the emplacement of the more offshore mid-ramp Facies 1 over large domains of

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

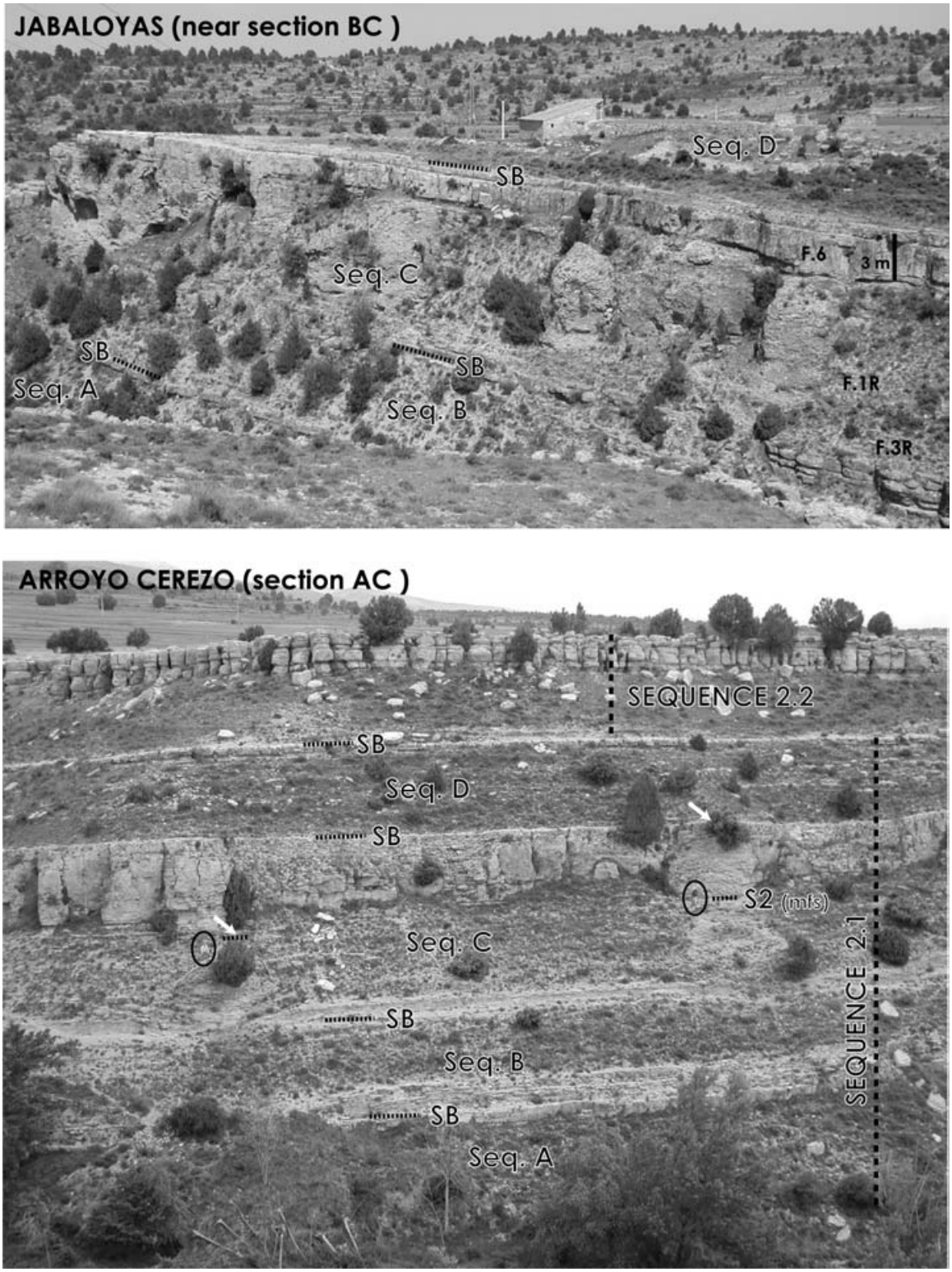


Figure 6. Panoramic view of the studied Sequence 2.1 in Jabaloyas (near section BC) and Arroyo Cerezo (AC) localities. These two sections have been used for modelling and quantification purposes (see Fig. 8). Sequences A and B are give-up (subtidal) sequences, thinner than the catch-down Sequence C. In Jabaloyas, the pinnacle reefs (Sequence C) are closely spaced and the inner ramp Facies 6 sharply overlaps the reefs. Two persons, indicated by ovals, are standing in the two pinnacles shown in the Arroyo Cerezo view. The pinnacle to the left grew up to the S2 surface (see white arrow). The one located at the right grew above this surface and is interrupted by the erosion surface linked to the upper sequence boundary (see white arrow). An erosional gap associated with the upper boundary of Sequence D is also interpreted.

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

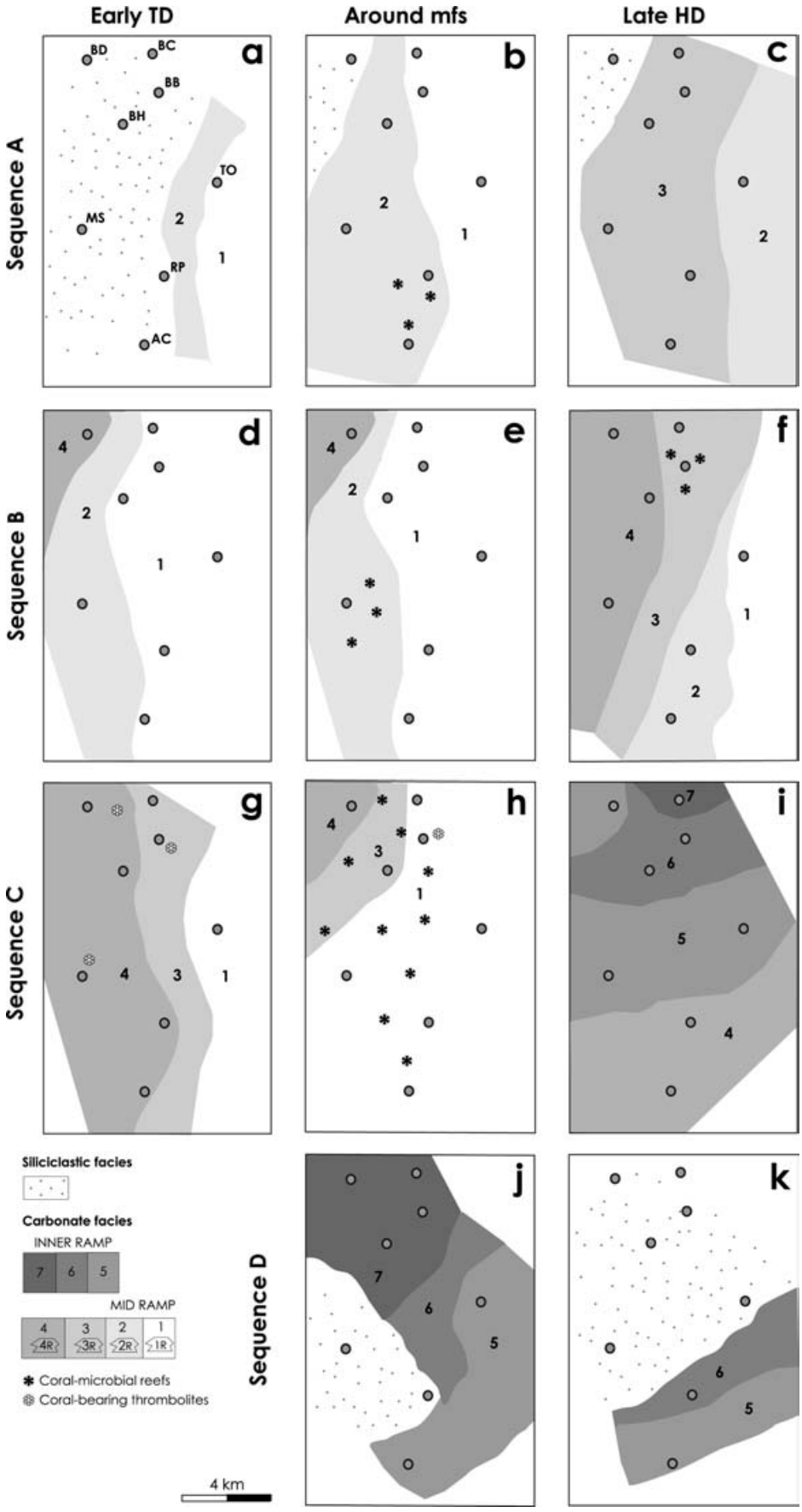


Figure 7. Facies distribution maps along the successive stages of evolution of the ramp, defined at the lower (early transgressive), middle (maximum flooding interval) and upper (late highstand) part of the four distinguished Sequences A–D.

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

the ramp (Fig. 7d). The proximal high-energy oolitic Facies 4 is only found in the more proximal BD section (Fig. 2). The vertical facies trend during the TD is aggradational, and therefore facies distribution around the mfs (Fig. 7e) is similar to the one observed at the early TD. In contrast, the HD show the rapid progradation of the proximal high energy Facies 4 (Fig. 7f). The local hardening of the substrate by microbial crust during the stages of low sedimentary rates, allowed the development of coral–microbial reef around the mfs (near the MS section, Fig. 3) and at the late HD (around the BC section, Fig. 2).

4.c. Sequence C

The thickness of the sequence ranges from 13 m (AC–RP sections) to 21 m (BB section). The lower sequence boundary is indicated by the onset of the facies retrogradation (Figs 2, 3). The observed retrogradational–progradational facies arrangement allows the TD and HD assignment in this sequence. In the more proximal sections (BD, BH) the mfs is an encrusted surface involving a sharp facies change. In the rest of the sections, the mfs has been tentatively located in the middle part of Facies 1. As observed from outcrop analysis (in particular in the area around the BD and BH sections), the flat and sharp surface S2 found in the core of most of the studied reefs (see Fig. 4) correlates with the mfs defined from facies analysis.

During the early stages of the TD (that is, below the S1 surface) proximal Facies 3 and 4 covered most of the ramp (Fig. 7g). Coral-bearing thrombolites were developed in the northwestern areas, around the BD section. These are characterized by the predominance of microbial crusts with associated micro-encrusters dominated by *Tubiphytes* and *Terebella*, adapted to low oxygen rates and sediment supply (Leinfelder *et al*. 1993; Dupraz & Strasser, 2002). Around the mfs development (that is, at the late TD and at the early HD), the more distal Facies 1 covered most of the studied ramp, and coral–microbial reefs occupied wide areas (Fig. 7h). Most of the vertical growth of the pinnacle reefs took place during the late TD. This growth was interrupted at the stage of maximum flooding of the platform, resulting in the formation of the S2 surface (mfs). After this flooding event, at the early HD, the lowering of the rates of creation of accommodation allowed the recovery of carbonate production. The accommodation available in inter-pinnacle areas became progressively filled up by the onlapping of the distal mid-ramp facies, and the growing of the pinnacles above the S2 surface continued up to the earliest stages of the late HD (Aurell & Bádenas, 1997). During the late HD the inner ramp shoal Facies 5 and 6 prograded over most of the ramp (Fig. 7i). The sharp transition from the distal Facies 1 to the inner ramp facies indicates a rapid shallowing of the platform.

The upper sequence boundary is a planar and erosive surface developed on top of the inner ramp or even on mid-ramp facies. The nature of the facies below and above the sequence boundary indicates that this erosion occurred after subaereal exposure of Sequence C. The amplitude of the associated erosive gap can be significant in localities such as AC (see Figs 3, 6), where Sequence C ends with Facies 4 with erosion down to the top of some of the pinnacle reefs exposed in this locality. Accordingly, Sequence C is interpreted to correspond to the catch-down type sequences defined by Hillgärtner & Strasser (2003). Typical facies evolution in these sequences shows a gradual deepening, followed by an incomplete shallowing succession with evidence of emersion.

4.d. Sequence D

The thickness of the sequence ranges from 6 m (AC section) to 14.5 m (BC section) and it also shows a deepening- to shallowing-upward evolution. The terrigenous facies found in the lower and upper part of Sequence D represent deposition in supratidal (siliciclastic, marsh environments) to interior lagoon environments. A low-amplitude sea-level rise involved the emplacement of the inner ramp facies across most of the studied area around the mfs (Fig. 7j). The more interior skeletal and peloidal Facies 7 were dominant around Jabaloyas (Fig. 2), whereas the oolitic shoal Facies 5 formed an almost continuous belt between Tormón and Arroyo Cerezo. The progradation linked to the shallowing interval at the upper part of Sequence D, involved the progradation of siliciclastic environments in the more marginal areas located around Jabaloyas (Fig. 7k). However, the oolitic shoal development still remained in the more distal locality of Arroyo Cerezo.

The upper sequence boundary is only locally exposed. Normally, it is a planar surface developed above the siliciclastic or lagoonal siliciclastic facies found on top of the sequence. In some sections (e.g. AC), the thickness reduction of the sequence along with the development of a sharp surface above the inner ramp carbonate facies suggest the existence of an erosive gap. Sequence D is interpreted to correspond to a catch-down type sequence, as shown by the widespread emplacement of supratidal facies in the upper part of the sequence.

5. Modelling and quantification of sea-level fluctuations

5.a. Assumptions and input data

The detailed facies reconstruction provided in our study allows the application of the approach proposed by Hillgärtner & Strasser (2003) for quantification of high-frequency sea-level fluctuations. Two assumptions were considered for the reconstruction of the

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

relative sea-level curve: a linear mean subsidence pattern and a fixed cycle period. These are also the two basic assumptions necessary for the construction of the Fischer plot (e.g. Fischer, 1991; Read & Goldhammer, 1998). In this work, the four sequences A to D are assumed to represent a constant time interval. For the estimation of the mean subsidence rate, we have considered the average decompacted thickness of all the studied sections to be around 57 m. The studied succession was most probably developed during most of the *eudoxus* Zone. Considering 740 kyr for the duration of this biozone (Hardenbol *et al*. 1998), the resultant subsidence rate is in the order of 10–12 cm/kyr. However, Weedon, Coe & Gallois (2004) have proposed a considerably longer duration for this biozone (at least 1.486 kyr). If this duration is correct, the resultant subsidence rates fit better with the average subsidence rates proposed for the Kimmeridgian units of the marginal areas of the Iberian Basin (5–6 cm/kyr: Aurell *et al*. 1998).

The two best-exposed and more representative sections have been selected for the reconstruction of the sea-level curve: the BC section, located in the northern areas, and the AC section, located 13 km southward (Figs 1, 6). Three variables were considered in the analytical approach: the amount of decompacted sediment, the water depth at sequence boundaries and maximum flooding intervals, and the mean subsidence rates. The factors used for decompaction were different according to the observed textures, from 1.2 for cemented carbonate sand (grainstones) and reefal facies to 2–3 for mud supported facies (mudstones and wackestones) and marls (e.g. Bond & Kominz, 1984; Hillgärtner & Strasser, 2003).

The water depth ranges were estimated according to the palaeoenvironmental reconstruction of the carbonate ramp. We have considered a progressive increase of the depositional depth from Facies 7 to 1, based on the low depositional gradient of the carbonate ramp. The low-angle morphology of the carbonate ramp is indicated by the existence of gradual transitions between the different facies. The facies located in the interior shoals (Facies 5–6) and in the sheltered lagoon (Facies 7) were deposited in a very shallow environment, from 0.5 to 2 m. The range of water depth considered for the grain-supported Facies 3 and 4, located offshore to the interior shoals, lies between 2 and 5 m.

Facies 2 was deposited around the fair-weather wave-base, which in the studied carbonate ramp is thought to be quite shallow, between 5 and 10 m (Aurell *et al*. 1998). In the low-angle carbonate ramp developed in the Iberian epeiric sea, the tides and the waves were damped out by the frictional effect over the very extensive shallow sea-floor. The fair-weather wave-base would have been similar to the depth considered for ancient epeiric platforms (less than 5 m: Tucker & Wright, 1990, p. 53) and to the lower values observed in comparable modern platforms (10 m for the Yucatan shelf: Logan *et al*. 1969; 8 m in the Persian Gulf: Purser & Evans, 1973). Facies 1 was deposited below fair-weather wave-base. Considering its gradual transition from Facies 2 and the coeval development of coral–microbial reefs, a conservative depth of 10–20 m has been estimated. Accordingly, the depositional depth of most of the coral reefs (with depositional relief up to 5 m above the coeval Facies 1–3) would range from 2 m to 10 m.

5.b. Results

The results of the modelling and quantification analysis are shown in Figure 8. The inferred sea-level curve is similar in the two studied sections and shows a long-term relative sea-level cycle (coeval to the Sequence 2.1 development) and four higher-frequency sea-level cycles with average amplitudes between 5 to 10 m. The stages of microbial-reef growth in BC and AC sections is also indicated in the accumulation curve (Fig. 8). There was incipient reef development in Sequences A and B at around the mfs and upper sequence boundary, respectively. However, the larger vertical development of the coral microbial reefs took place in Sequence C, around the stage of larger creation of accommodation on the ramp during Sequence 2.1 development. The pinnacles had some relief above the sea-floor (up to 5 m near the mfs of Sequence C). This relief along with the estimation of the water depth has been also considered for the reconstruction of the sea-level curve (Fig. 8).

Sequences A and B are give-up sequences unable to fill the accommodation created in the basin, developed during the long-term transgressive sea-level trend of Sequence 2.1. In these two sequences, the maximum water depth (mfs) is nearly coincident with the inflexion point of the sea-level curve, representing the interval of maximum accommodation gain (Hillgärtner & Strasser, 2003). In fact, the almost planar-shape of the 'sea floor surface' (Fig. 8) on these two sequences shows that sedimentary rates were quite similar to the subsidence rates. The additional accommodation created during the sea-level rise could not be filled by the carbonate production.

Sequences C and D were developed during the neutral to regressive long-term sea-level trend of Sequence 2.1. The change in the long-term relative sea-level trend may explain the recovery of the carbonate production rates and the formation of the catch-down type sequences C–D, bounded by emersion surfaces. In the catch-down sequences, the intersection between the accumulation curve and the accommodation curve in the late highstand occurs in the falling leg of the sea-level curve (Hillgärtner & Strasser, 2003). Therefore, the mfs pre-dates the interval of the maximum accommodation gain of the sea-level curve.

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

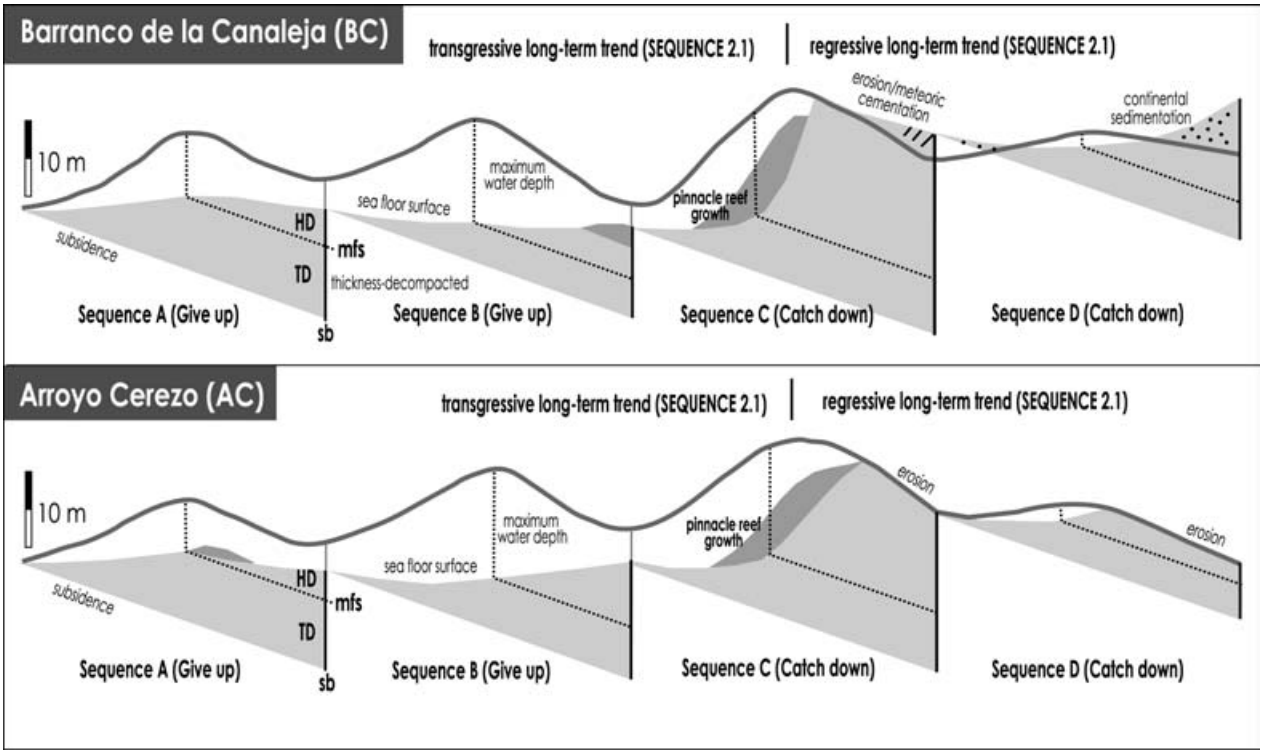


Figure 8. Modelling of the four high-frequency sea-level fluctuations during the deposition of Sequences A–D. The approach is based on Hillgärtner & Strasser (2003). The observed thickness of the transgressive deposits (TD) and highstand deposits (HD) were decompacted according to the observed lithology. Estimation of water depth at sequence boundary (sb) and maximum flooding surface (mfs) is based on the environmental assignment of the different types of facies. Give-up sequences are subtidal sequences that were never exposed. In catch-down sequences, there is a gradual deepening, followed by an incomplete shallowing succession with evidence of emersion. Therefore, the accumulation curve intersects the sea-level curve in its falling leg.

Sequence C is a catch-down sequence, which ends with a subaereal erosive surface. However, the rise of the sea-level during the lower part of Sequence C is similar to the Sequences A and B (Fig. 8). In this case, the production rate was larger than in previous sequences, and it was able to fill part of the accommodation created during the late stage of sea-level rise. The presence of well-developed coral reefs is clear evidence of the increase of carbonate production. The reason for the largest development of reefs in Sequence C remains uncertain. The existence of a limiting palaeoenvironmental factor (amount of nutrient supply, terrigenous input, oxygen content in sea waters) may have precluded the widespread reef development in Sequences A and B.

5.c. Discussion

The Sequence 2.1 as a whole corresponds to a cycle of relative rise and fall of sea-level. This cycle is likely to reflect the local tectonic development, involving different subsidence rates along the evolution of the sequence. A key argument supporting the influence of the tectonic activity in the facies distribution is the observed change in the polarity of the carbonate ramp around the mfs of the Sequence 2.1 (from a N–S distribution of the facies belts to a NE–SW orientation: Fig. 7). Further evidence for the local tectonic development and uplift of the western marginal areas of the Iberian basin at the end of the Kimmeridgian times has been also reported (e.g. Bádenas & Aurell, 2001).

Sequence 2.1 is formed by four high-order sequences A to D. The lateral continuity of these small-scale sequences and the correlation of the SB, mfs and TD and HD between different localities suggest that high-frequency sea-level changes affecting the entire area of the shallow platform studied in this work, controlled the observed facies distribution. The amplitude of the high-frequency cycles deduced here (5–10 m; see Fig. 8) has a similar range to the amplitude proposed by Crevello (1991) for the eccentricity related cycles of the Lower Jurassic of Morocco (4–5 m) or by Koerschner & Read (1989) for the Late Cambrian peritidal cycles of the Appalachians (10 m).

The precise age of the studied unit, developed in shallow platform areas during the middle part of late Kimmeridgian times, remains uncertain. Most probably, it was developed during the *eudoxus* Zone, although the lower and upper boundaries of this biozone cannot be established in the studied outcrops. In addition, the proposed duration for this biozone varies from one author to another (around 0.7 Myr and 1.5 Myr according to Hardenbol *et al*. 1998 and

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

Weedon, Coe & Gallois, 2004, respectively). Therefore, the estimation of the duration of sequences A–D and their assignment to any of the long-term orbital cycles (the 100 and 400 kyr eccentricity cycles) is very much open to discussion. The existence of eccentricity cycles during Kimmeridgian times has been reported in the shallow carbonate successions of the Jura platform and in the equivalent deeper-water environments of the Vocontien basin (Colombié & Strasser, 2003). However, the most prominent cycle recorded in the Kimmeridge clay of southern England is the obliquity cycle, with only indirect evidence for the eccentricity forcing (Weedon *et al*. 1998, 2004).

The results obtained in our work can be discussed in the light of previous research in the late Kimmeridgian successions of the Iberian basin. The facies, stratal and spectral analysis of the lime mudstone successions deposited during late Kimmeridgian times in the outer ramp areas of the Iberian Basin (Aguilón section; see Fig. 1b for location) resulted in the identification of bundles of micritic beds and sets of bundles. Considering the absolute time calibration proposed in Hardenbol *et al*. (1989), these cycles were related to the orbital precession and short eccentricity cycles respectively (Bádenas *et al*. 2003). The sets of bundles defined in the outer ramp succession of Aguilón have average thickness (from 5.6 to 8.3 m) lower than the possible equivalent-scale Sequences A–D (average thickness from 6 to 15 m). The general thinning–thickening upward evolution of limestone beds observed in the sets of Aguilón was related to the progressive loss in the carbonate exported to outer ramp areas followed by a stage of greater export of the carbonate produced in shallow areas (Bádenas *et al*. 2003). The proposed process is coherent with the sedimentary evolution of the sequences A–D, with a lower transgressive interval with evidence of loss in the carbonate production up to the mfs development.

6. Conclusions

The shallow-water domains of the carbonate ramp developed in the marginal (western) areas of the Iberian Basin during late Kimmeridgian times have been characterized. The inner ramp environment includes high-energy oolitic and skeletal shoals and a sheltered lagoon located near the shoreline. The lower energy areas of the mid-ramp environments were dominated by deposition of carbonate mud including siliciclastic and bioclastic tempestites. A transitional (high-energy) area between the inner and mid-ramp was characterized by grain-supported facies with a variable proportion of carbonate mud, peloids, ooids and skeletal grains. The local hardening and stabilization of these grain-supported facies by the microbial crusts, allowed the growth of coral–microbial reef and coral-bearing thrombolites of variable size.

Quantification of the high-frequency sea-level changes has been attempted in this work. A similar relative sea-level curve is inferred to explain the observed sequences and facies distribution in two distant localities. A long-term relative sea-level cycle most probably reflects the local tectonic development and the changes in the subsidence rates. Four higher-frequency sea-level cycles with average amplitudes between 5 to 10 m superimposed on the long-term subsidence curve affected the entire platform area studied in this work.

The most evident imprint of the high-frequency sea-level changes in the studied successions is a hierarchical stacking pattern, with the more prominent presence of the small-scale sequences A–D. Sequences A and B are give-up sequences developed during a long-term transgressive relative sea-level trend. The reduced carbonate production during the formation of these sequences can be explained by significant gain of accommodation or other limiting environmental factors, which precluded the widespread coral–microbial reef development. Sequences C and D were catch-down type sequences developed during the neutral to regressive long-term sea-level trend. Larger carbonate production (including intense coral–microbial reef development in Sequence C) was able to fill part of the accommodation created during the stage of sea-level rise, and the shallow platform was eventually exposed to subaereal erosion and meteoric cementation at the late highstand.

Acknowledgements. Financial support was provided by M. C. T., Spain (Project BTE2002-04453) and by the Aragon Government (Financiación de Grupos Emergentes). The authors are grateful to the comments provided by the reviewers D. Bosence, V. P. Wright and I. N. McCave, who greatly improved the original version of the manuscript.

References

AURELL, M. & BÁDENAS, B. 1997. The pinnacle reefs of Jabaloyas (Late Kimmeridgian, NE Spain): vertical zonation and associated facies related to sea level changes. *Cuadernos de Geología Ibérica* **22**, 37–64.

AURELL, M., BÁDENAS, B., BOSENCE, D. W. J. & WALTHAM, D. A. 1998. Carbonate production and offshore transport in a late Jurassic carbonate ramp (Kimmeridgian, Iberian Basin, NE Spain). In *Carbonate Ramps* (eds V. P. Wright and T. Burchette), pp. 137–61. Geological Society of London, Special Publication. no. 149.

AURELL, M., ROBLES, S., BÁDENAS, B., QUESADA, S., ROSALES, I., MELÉNDEZ, G. & GARCÍA-RAMOS, J. C. 2003. Transgressive/Regressive Cycles and Jurassic palaeogeography of Northeast Iberia. *Sedimentary Geology* **162**, 239–71.

BÁDENAS, B. & AURELL, M. 2001. Kimmeridgian palaeogeography and basin evolution of northeastern Iberia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **168**, 291–310.

BÁDENAS, B. & AURELL, M. 2003. Análisis comparado y controles en la sedimentación de dos arrecifes de la zona

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

media de una rampa carbonatada del Jurásico Superior de la Cordillera Ibérica. *Revista Sociedad Geológica de España* **16**, 151–66.

BÁDENAS, B., AURELL, M., RODRÍGUEZ TOVAR, F. J. & PARDO-IZUZQUIZA, E. 2003. Sequence stratigraphy and bedding rhythms in an outer ramp limestone succession (Late Kimmeridgian, northeast Spain). *Sedimentary Geology* **161**, 153–74.

BÁDENAS, B., SALAS, R. & AURELL, M. 2004. Three order of regional sea-level changes control facies and stacking patterns of shallow carbonates in the Maestrat Basin (Tithonian–Berriasian, NE Spain). *International Journal of Earth Sciences* **93**, 144–62.

BAUMGÄRTNER, M. & REYLE, M. 1995. Oberjurassische Rampenentwicklung in the region von Jabaloyas und Arroyo Cerezo (Keltiberikum, Spanien). *Profil* **8**, 339–61.

BOND, G. C. & KOMINZ, M. A. 1984. Construction of tectonic subsidence curves for the early Paleozoic Miogeosincline, southern Canadian Rocky Mountains: implications for subsidence mechanisms, age of breakup and crustal thinning. *Geological Society of America Bulletin* **95**, 155–73.

COLOMBIÉ, C. & STRASSER, A. 2003. Depositional sequences in the Kimmeridgian of the Vocontian basin (France) controlled by carbonate export from shallow-water platforms. *Geobios* **36**, 675–83.

CREVELLO, P. D. 1991. High frequency carbonate cycles and stacking patterns: interplay of orbital forcing and subsidence on a lower Jurassic rift platform, High Atlas, Morocco. In *Sedimentary modelling: Computer simulations and methods for improved parameter definition* (eds E. K. Franseen, W. L. Watney, C. G. Kendall and W. Ross), pp. 207–30. *Kansas Geological Survey Bulletin* **233**.

D'ARGENIO, B., FERRERI, V., RASPINI, A., AMODIO, S. & BUONOCUNTO, F. P. 1999. Cyclostratigraphy of a carbonate platform as a tool for high-precision correlation. *Tectonophisics* **315**, 357–85.

DUPRAZ, C. & STRASSER, A. 2002. Nutritional modes in coral-microbialite reefs (Jurassic, Oxfordian, Switzerland): Evolution of trophic structure as a response to environmental change. *Palaios* **17**, 446–71.

ERRENST, CH. 1990. Das korallenführende Kimmeridgium der nordwestlichen Iberischen ketten und agrenzender Gebiete (Fazies, Pallaogeographie und Beschreibung der korallenfauna). *Palaeontographica Abt A* **214**, 121–207.

FEZER, R. 1988. Die oberjurassische karbonatische Regressionsfazies im südwestlichen Keltiberikum zwischen Griegos und Aras de Alpuente (Prov. Teruel, Cuenca, Valencia, Spanien). *Arb Institut für Geologie und Paläontologie, Universitat Stuttgart* **84**, 1–119.

FISCHER, A. G. 1991. Orbital cyclicity in Mesozoic strata. In *Cycles and events in stratigraphy* (eds G. Einsele, W. Ricken and A. Seilacher), pp. 48–62. Berlin: Springer-Verlag.

GINER, J. & BARNOLAS, A. 1979. Las construcciones arrecifales del Jurásico Superior de la Sierra de Albarracín. *Cuadernos de Geología Univ. Granada* **10**, 73–82.

HARDENBOL, J., THIERRY, J., FARLEY, M. B., JACQUIN, T., DE GRACIANSKI, P. C. & VAIL, P. R. 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins* (eds P. C. De Gracianski, J. Hardenbol, T. Jacquin and P. R. Vail), charts 1–8. SEPM (Society for Sedimentary Geology) Special Publication no. 60.

HILLGÄRTNER, H. 1998. Discontinuity surfaces on a shallow marine carbonate platform (Berriasian, Valanginian, France and Switzerland). *Journal of Sedimentary Research* **68**, 1093–1108.

HILLGÄRTNER, H. & STRASSER, A. 2003. Quantification of high-frequency sea-level fluctuations in shallow-water carbonates: an example from the Berriasian–Valanginian (French Jura). *Palaeogeography, Palaeoclimatology, Palaeoecology* **200**, 43–63.

HUNT, D. & TUCKER, M. E. 1993. The sequence stratigraphy of carbonate shelves with an example from the Middle Cretaceous of SE France. In *Sequence Stratigraphy and facies associations* (eds H. W. Possamentier *et al.*), pp. 307–41. International Association of Sedimentologists, Special Publication no. 18.

KOERSCHNER, W. F. & READ, J. F. 1989. Field and modelling studies of Cambrian carbonate cycles, Virginia Appalachians. *Journal of Sedimentary Petrology*, **59** 654–87.

LEINFELDER, R. R. 1993. Upper Jurassic reef types and controlling factors. *Profil* **5**, 1–45.

LEINFELDER, R. R., KRAUTER, M., LATERNSER, R., NOSE, M., SCHMID, D., SCHWEIGERT, G., WERNER, W., KEUPP, H., BRUGGER, H., REHFELD, U., SCHROEDER, J., REINHOLD, C., KOCH, R., ZEISS, A., SCHWIEZER, V., CHRISTMAN, H., MENGES, G. & LUTERBACHER, H. 1994. The origin of Jurassic reefs: current research development and results. *Facies* **31**, 1–56.

LEINFELDER, R. R., NOSE, M., SCHMID, D. & WERNER, W. 1993. Microbial crusts of the late Jurassic: composition, palaeoecological significance and importance in reef construction. *Facies* **29**, 195–230.

LOGAN, B. W., HARDY, J. L., AHR, W. M., WILLIAMS, J. D. & SNEAD, R. G. 1969. Carbonate sediments and reefs, Yucatán Shelf, Mexico. *American Associaton of Petroleum Geologists Memoir* **11**, 1–198.

NOSE, M. 1995. Vergleichende Faziesanalyse und Palökologie korallenreicher Verflachung-sabfolgen des Iberischen Oberjura. *Profil* **8**, 1–237.

OSLEGER, D. 1991. Subtidal carbonate cycles: Implications for allocyclic vs. autocyclic controls. *Geology* **19**, 917–20.

PURSER, B. H. & EVANS, G. 1973. Regional sedimentation along the Trucial Coast, SE Persian Gulf. In *The Persian Gulf* (ed. B. H. Purser), pp. 211–32. Berlin: Springer-Verlag.

READ, J. F. & GOLDHAMMER, R. K. 1988. Use of Fischer plots to define third-order sea-level curves in Ordovician peritidal cyclic carbonates, Appalachians. *Geology* **16**, 895–9.

STRASSER, A. 1986. Ooids in Purbeck limestones (Lowermost Cretaceous) of the Swiss and French Jura. *Sedimentology* **33**, 711–27.

STRASSER, A., HILLGÄRTNER, H., HUG W. & PITTET, B. 2000. Third-order depositional sequences reflecting Milankovitch cyclicity. *Terra Nova* **12**, 303–12.

STRASSER, A., PITTET, B., HILLGÄRTNER, H. & PASQUIER, J. B. 1999. Depositional sequences in shallow carbonate-dominated sedimentary systems: concepts for a high-resolution analysis. *Sedimentary Geology* **128**, 201–21.

TUCKER, M. E. & WRIGHT, V. P. 1990. *Carbonate Sedimentology*. Blackwell Scientific Publications, 482 pp.

VAIL, P. R., AUDEMARD, F., BOWMAN, S. A., EISNER, P. N. & PÉREZ-CRUZ, C. 1991. The stratigraphic signatures of

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press

tectonics, eustasy and sedimentology- an overview. In: *Cycles and events in Stratigraphy* (eds G. Einsele, W. Ricken and A. Seilacher), pp. 617–59. Berlin: Springer.

WEEDON, G. P., COE, A. L. & GALLOIS, R. W. 2004. Cyclostratigraphy, orbital tuning and inferred productivity for the type Kimmmeridge Clay (Late Jurassic), Southern England. *Journal of the Geological Society, London* **161**, 655–66.

WEEDON, G. P., JENKINS, H. C., COE, A. L. & HESSELBO, S. 1999. Astronomical calibration of the Jurassic timescale from cyclostratigraphy in British mudrock formations. *Philosophical Transactions of the Royal Society of London Series A* **357**, 1787–1813.

WILKINSON, B. H., DIEDRICH, N. W. & DRUMMOND, C. N. 1996. Facies successions in peritidal carbonate sequences. *Journal of Sedimentary Research* **66**, 1065–78.

https://doi.org/10.1017/S0016756804009963 Published online by Cambridge University Press