The pinnacle reefs of Jabaloyas (Late Kimmeridgian, NE Spain): Vertical zonation and associated facies related to sea level changes

M. AURELL and B. BÁDENAS

Departamento de Ciencias de la Tierra,
Universidad de Zaragoza, 50.009 Zaragoza, Spain

ABSTRACT

The outcrops located near Jabaloyas (Northeast Spain, Iberian basin) allow the reconstruction of the sedimentary environments of a late Kimmeridgian carbonate ramp. In the middle ramp areas, above storm wave base level, grew a set of reefs which generally display a pinnacle geometry. The fabric of these reefs consists of different proportions of colonial forms (mainly corals), internal sediment and microbial crusts to associated encrusting organisms. Four pinnacles have been sampled along a 6 Km proximal-distal section across the ramp. The relative proportion of corals and microbial crusts evaluated in these samples allows to differentiate between coral thrombolites and coral-microbial crust reefs fabrics. Changes in these fabrics allow to define some vertical and lateral zonation in the pinnacle reefs. The variation of the fabrics in the pinnacle reefs and the transition between the different associated facies have been related to sea level changes. An initial fast rise of sea level resulted in both the drowning of the mid ramp grain-supported facies and in the grow of scattered coral thrombolites. The aggradation of the pinnacles, with increasing proportion of metazoan builders, was initiated and/or followed during the continuous riser of sea level, and coeval carbonate sedimentation recovered in the inner areas of the middle ramp. The total rise of sea level was between 12 to 15 m. During a subsequent stillstand of sea level, the successive observation of aggradational and progradational stacking patterns in the coevally developed inter-reef facies allows the differentiation of an early and late highstand systems tract.

Key words: Late Jurassic, Iberian basin, carbonate ramp, reef, sea level changes

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RESUMEN

Los afloramientos localizados en las proximidades de Jabaloyas (Cordillera Ibérica, Teruel) han permitido reconstruir los distintos ambientes sedimentarios de la rampa carbonatada del Kimmeridgiense superior. En las partes medias de esta rampa, sobre el nivel de base de oleaje de mal tiempo, tuvo lugar el crecimiento de una serie de arrecifes aislados, que generalmente presentan morfología de pináculo. La fábrica básica de estos arrecifes está formada por diferentes proporciones de formas coloniales (corales en mayor abundacia), sedimento interno y costras microbianas, que incluyen organismos encostrantes asociados. Se ha evaluado la proporción relativa entre estos componentes a partir de cuatro pináculos, localizados en los diferentes dominios de sedimentación. Los cambios en la fábrica arrecifal permiten definir cierta zonación vertical y lateral en los pináculos arrecifales. Se han relacionado las variaciones en las fábricas arrecifales y los diferentes cambios en las facies asociadas, con sucesivas variaciones del nivel del mar. Una etapa inicial de ascenso rápido del nivel del mar implicó la estabilización de las facies granosostenidas interarrecifales, así como el crecimiento local de arrecifes dominados por costras microbianas. El crecimiento vertical de los pináculos, con un predominio de las formas coralinas, se inició o continuó durante esta etapa de ascenso del nivel del mar, que también permitió la recuperación de la sedimentación carbonatada en las zonas más internas de la rampa. El ascenso total del nivel del mar durante este intervalo fue de 12 a 15 m. En la etapa siguiente de estabilización del nivel del mar, la observación sucesiva de geometrías agradacionales y progradacionales, ha permitido diferenciar entre los cortejos de alto nivel del mar temprano y tardío (early and late highstand systems tract).

Palabras clave: Jurásico, cuenca Ibérica, rampa carbonatada, arrecifes, cambios del nivel del mar.

INTRODUCTION

The growth of organisms that construct reefs is controlled by factors like wave energy, background sedimentation, nutrient supply or oxygen fluctuations. Because some of these factors may change with depth, the internal variation of the composition and fabric of the reefs may reflect variations in sea level. The interplay between reef and carbonate platform growth and sea level changes has been reported in several studies (e.g., Kendall and Schlager, 1981; James and Macintyre, 1985). The resulting data have been applied to the geological record to define sea level cycles of different order and magnitude. To achieve reliable reconstructions of sea level cycles, a precise control on the vertical and lateral distribution of facies on ancient carbonate platforms is needed. If reefs are coevally developed on these platforms the study of the variation of the reef fabric may provide independent control of sea level changes.

The Sierra de Jabalón (Iberian Chain, Teruel province, northeast Spain) offers nearly undeformed and continuous outcrops, which include a set of Late Kimmeridgian patch reefs. These reefs were developed in the shallow areas of a low-angle carbonate ramp. Most of them are 12 to 16 m high and display a cylindrical to conical shape, with very steep slopes. Based on this morphology, early studies by Geyer (1965) and Giner and Barnolas (1979) described them as pinnacles. Fezer (1988) and Errenst (1990a,b) provided a more detailed study of these reefs, especially on their coral fauna and associated facies. Further data on the composition, morphology and stratigraphical and sedimentological context these reefs, have been provided by Leinfelder (1993), Leinfelder *et al.* (1993, 1994), Nose (1995) and Baumgärtner and Reyle (1995). The results reported on these works, which include detailed descriptions of the reef fabric and discussions about the factors which controlled the origin and development of the Upper Jurassic Iberian reefs, have provided the basis for our analysis.

The outcrops located near Jabaloyas allow the reconstruction of a 6 Km long cross-section, which extends from inner to mid ramp areas. Four pinnacle reefs have been sampled along this section, establishing their vertical zonation based on the variation of the proportion between microbial crusts and metazoan builders. In addition, the lateral and vertical distribution of the different inter-reef facies have been studied. The main aims of this paper are: (1) to propose a preliminary model, showing the overall vertical and lateral zonation of these reefs; (2) to place the reefs in their sedimentological context by interpreting the associated facies; (3) to relate the initiation, development and demise of the pinnacle reefs and associated facies with the related sea level changes.

GEOLOGICAL AND STRATIGRAPHICAL SETTING

The Iberian Chain, a montainous system located in the northeastern part of the Iberian Peninsula, contains well-preserved and continuous outcrops of Mesozoic sedimentary rocks. The Upper Jurassic outcrops of Jabaloyas are located Southeast of Teruel (Northeast Spain), in the western-central part of the Iberian Chain (Fig. 1). The reef studied were developed in marginal areas of the so-called Iberian basin. Marine sedimentation in the Iberian basin took place in shallow and extensive carbonate ramp settings (several hundreds of kilometres across) during Late Jurassic times. These ramps were open to the Tethys sea to the East. However, during major flooding episodes

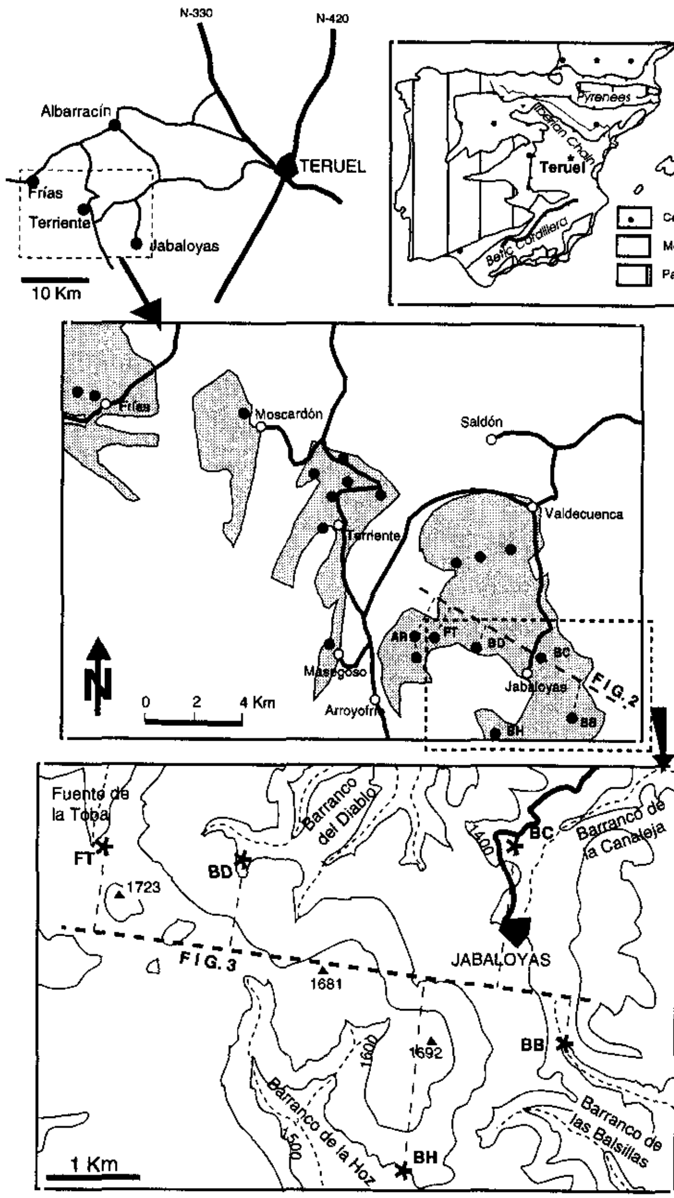

Fig. 1.—Location of the studied area and distribution of the upper Jurassic outcrops between Frías and Jabaloyas localities. The lower inset locates the five sections studied around Jabaloyas.
Fig. 1.—Situación del área estudiada y distribución de los afloramientos del Jurásico superior entre Frías y Jabaloyas. La parte inferior muestra la situación de los perfiles estudiados en torno a Jabaloyas.

connection with the boreal realm was possible across the so-called Soria Seaway to the Northwest (Aurell and Meléndez, 1993).

The main lithologies and stratigraphic distribution of the Kimmeridgian sedimentary rocks of the Sierra the Jabalón, between the Arroyofrío and Jabaloyas localities, is shown in Fig. 2. The lower marly unit corresponds to the Sot the Chera Formation and spans from Late Oxfordian to Early Kimmeridgian. This unit changes offshore to the rhythmic mudstone and marl alternations of the Loriguilla Formation. The sandstones and oolithic grainstones of the Pozuel Formation prograde above these units (Aurell, 1990; Bádenas and Aurell, 1997).

The topmost Kimmeridgian unit includes the reefal unit studied in this work. Based on their micropalontological content, Fezer (1988) dated the studied reefs and associated facies as Late Kimmeridgian. According to Nose (1995), they belong to the the lowermost Late Kimmeridgian biozone (i.e. acanthicum biozone). Lithostratigraphically, they have traditionally been assigned to the Higueruelas Formation. However, according to both its lithology, its fossil content and its lateral equivalence with the offshore micrites of the Loriguilla Formation we propose the use of the term Torrecilla Formation for this reefal unit (Fig. 2). The Torrecilla Formation is a Kimmeridgian reefal unit, defined by Alonso and Mas (1990) in the north-western part of the basin.

A sequence boundary below the Torrecilla Fm. is indicated by a significant backstepping of facies (Aurell, 1990; Fig. 2). In earlier works, we correlated this sequence boundary with the unconformity which is found offshore between the Loriguilla and Higueruelas Formations (Aurell, 1990; Aurell and Meléndez, 1993). This boundary was developed during the Early Tithonian. However, the precise dating reported by Nose (1995) makes unlikely this assignment. Consequently, the studied reefs are located in the lower part of a depositional sequence which spans from Late Kimmeridgian to Early Tithonian. This sequence would correspond to the upper part of the Kimmeridgian Sequence used in our previous works, and is also recognized in northern areas (i.e., Facies Association II and III in Bádenas *et al.,* 1993, Ricla outcrops). A third order sequence boundary below the studied reefs has been also proposed by Nose (1995) and Baumgärtner and Reyle (1995).

OVERALL FACIES DISTRIBUTION IN THE TORRECILLA FORMATION

The Torrecilla Formation reaches a maximum thickness of 72 m eastwards, in the Barranco de las Balsillas section (see BB section in Fig. 2). To the West, the upper part of the unit is partly eroded, and is unconformably overlain by Albian fluvial sandstones (i.e. Utrillas Formation). The lower

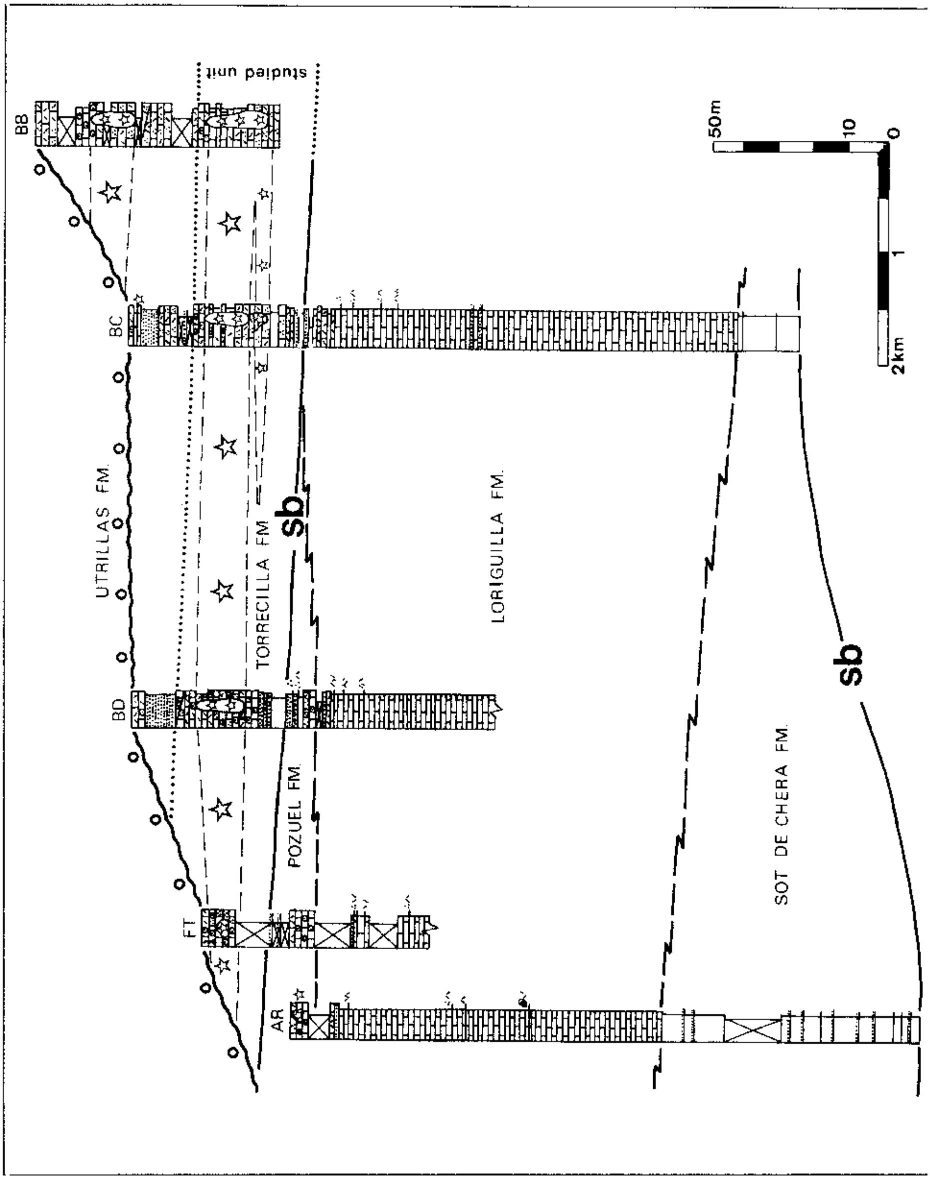

Fig. 2.—Stratigraphy of the Kimmeridgian between the Arroyofrío and Jabaloyas localities (see Fig. 1 for location of the correlated sections).
Fig. 2..—Estratigrafía del Kimmeridgiense entre Arroyofrío y Jabaloyas (situación de perfiles en la Fig. 1)

part of the Torrecilla Formation consists of marls and burrowed sandstones with abundant plant remains, deposited in transitional lagoonal environments. Two cyclic parasequences, including levels with pinnacle reefs, are identified in the more eastern complete sections (Giner and Barnolas, 1979).

The results presented in this work are based on a facies analysis in the lower parasequence, which has been preserved of the Early Cretaceous erosion along the studied outcrops (Fig. 2). The facies analysis is based on the measurement of five key sections (see Fig. 1 for location) and the lateral tracing of the main distinguished facies associations. From proximal western areas to distal eastern ones, these sections are named: Fuente de la Toba (FT), Barranco del Diablo (BD), Barranco de la Hoz (BH), Barranco de la Canaleja (BC) and Barranco de las Balsillas (BB). The correlation of the studied sections and the lateral and vertical distribution of the main facies associations distinguished in the lower parasequence is shown in Fig. 3. The pinnacle reefs included in these sections were sampled from bottom to top. The proportion between the different components of the reef fabric was established by point/counting along thin sections. Three main facies associations have been distinguished: reefal facies, inter-reef facies (A,B,C) and the topmost post-reef facies D.

REEFAL FACIES

The morphology and the fabric of the reefs of Jabaloyas has been described by Fezer (1988), Errenst (1990a,b), Leinfelder *et al.* (1993, 1994) and Nose (1995). These works include the identification and description of the different fossils and their distribution along the reefs. Below, we outline the main features observed in the reefal facies.

Morphology of reefs

The studied parasequence includes scattered patch reef with variable morphology. Most of them have a pinnacle morphology and are distributed in a discrete horizon, from the BD to the BB sections (Fig. 4). Westward, in the FT section, the pinnacles are absent and they laterally grade to a set of metric patch reefs. The pinnacles have a height/width ratio close to 1 and very steep slopes, more than 45°. The local coalescence of these pinnacles may result in reefs some tens of meter in height. The highness of the pinnacles increases eastward, with maximum vertical development in the BB section, where they can reach 16 m. Around this outcrop, metric patch reefs are also laterally found to the top of the pinnacles. Between the BC and the BD sections, the pinnacles are generally up to 12-13 m high. Locally on some of

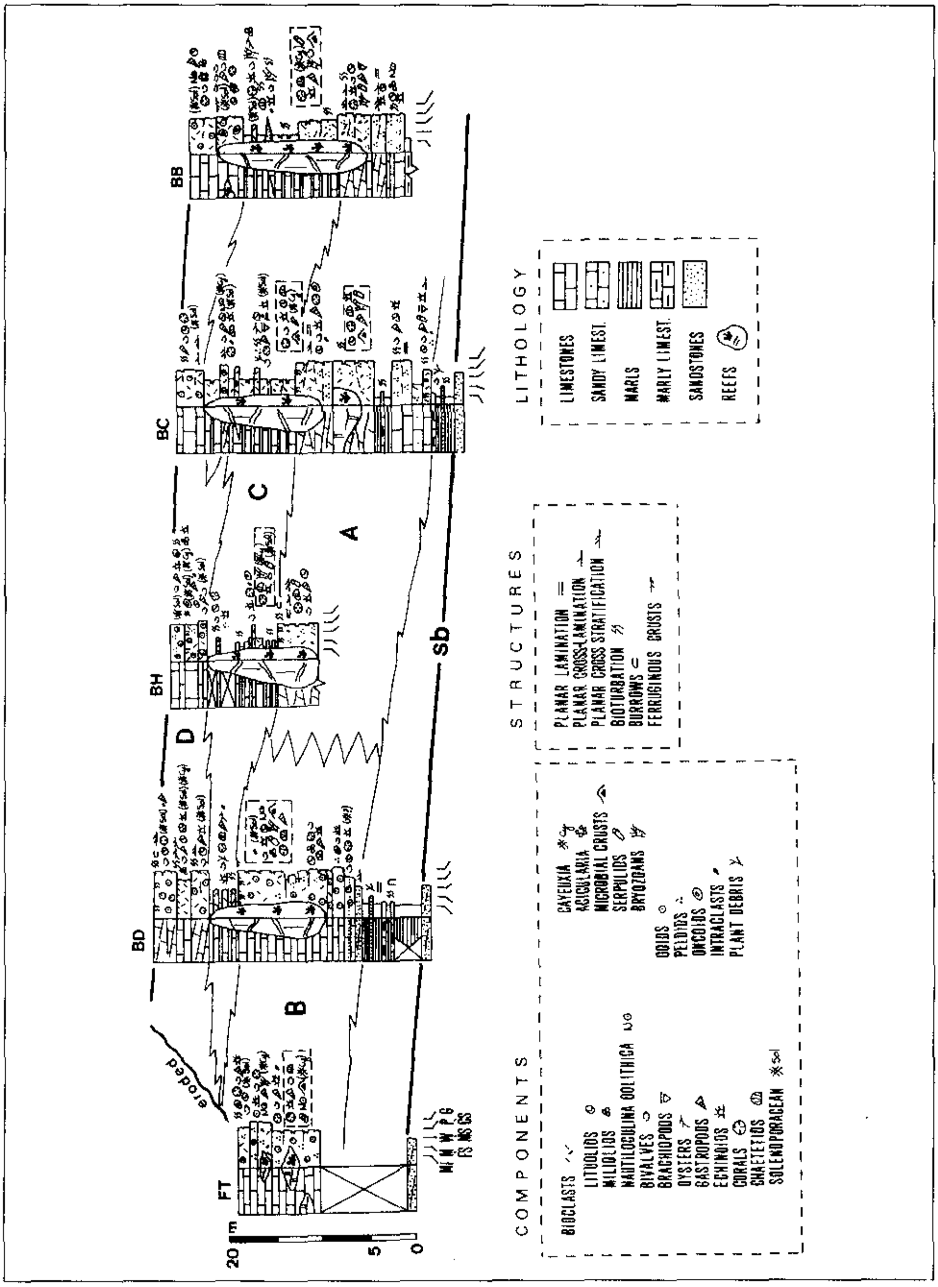

Fig. 3.—Facies distribution in the studied parasequence (see Fig. 1 for location).
Fig. 3.—Distribución de facies en la parasecuencia estudiada (situación en la Fig. 1)

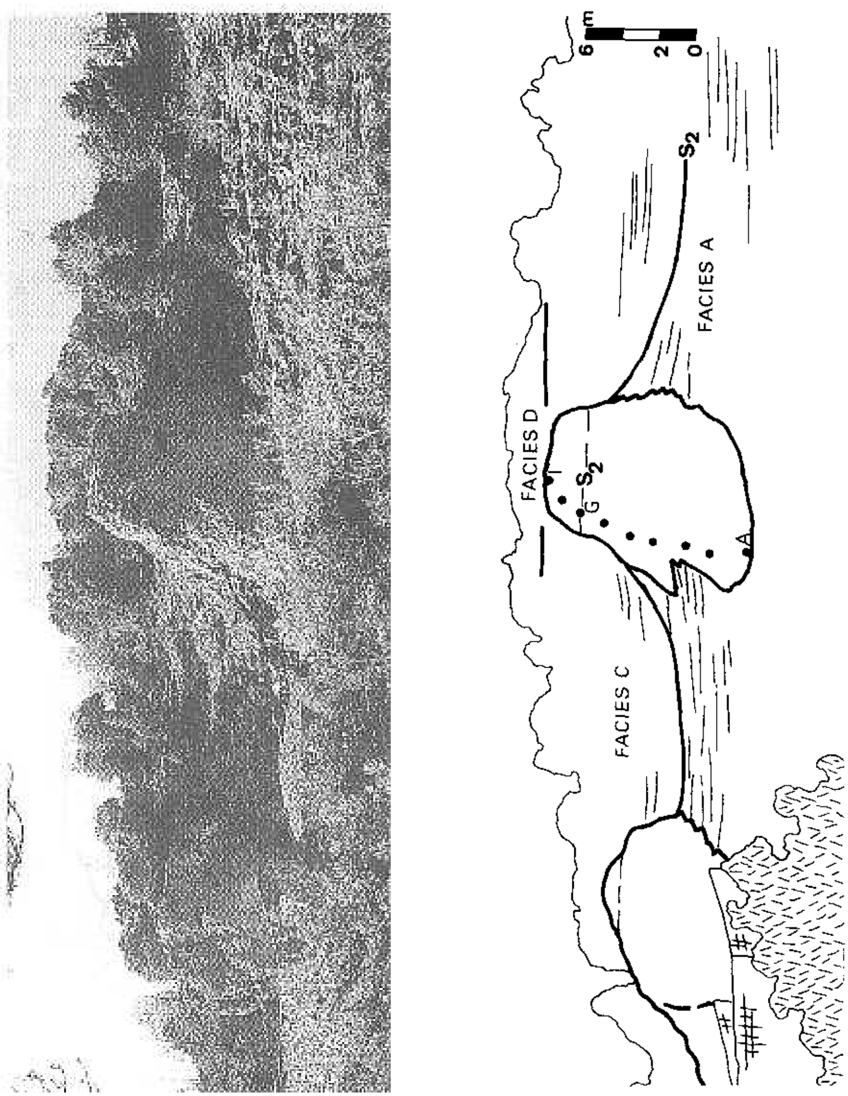

Fig. 4.—Facies distribution in the BH outcrop. The boundary between facies A and C is an encrusted and burrowed surface that can be traced up into the pinnacle core (i.e. S2 surface). The distribution of the samples in the BH pinnacle is also shown (the topmost sample J is out of the scope of the photograph). See text for facies explanation.
Fig. 4.—Distribución de facies en el perfil BH. El límite entre las facies A y C es una superficie bioturbada y encostrada que se puede prolongar hacia el interior del pináculo (superficie S2). Se muestra asimismo la distribución de las muestras analizadas (la muestra J queda fuera de la fotografía).

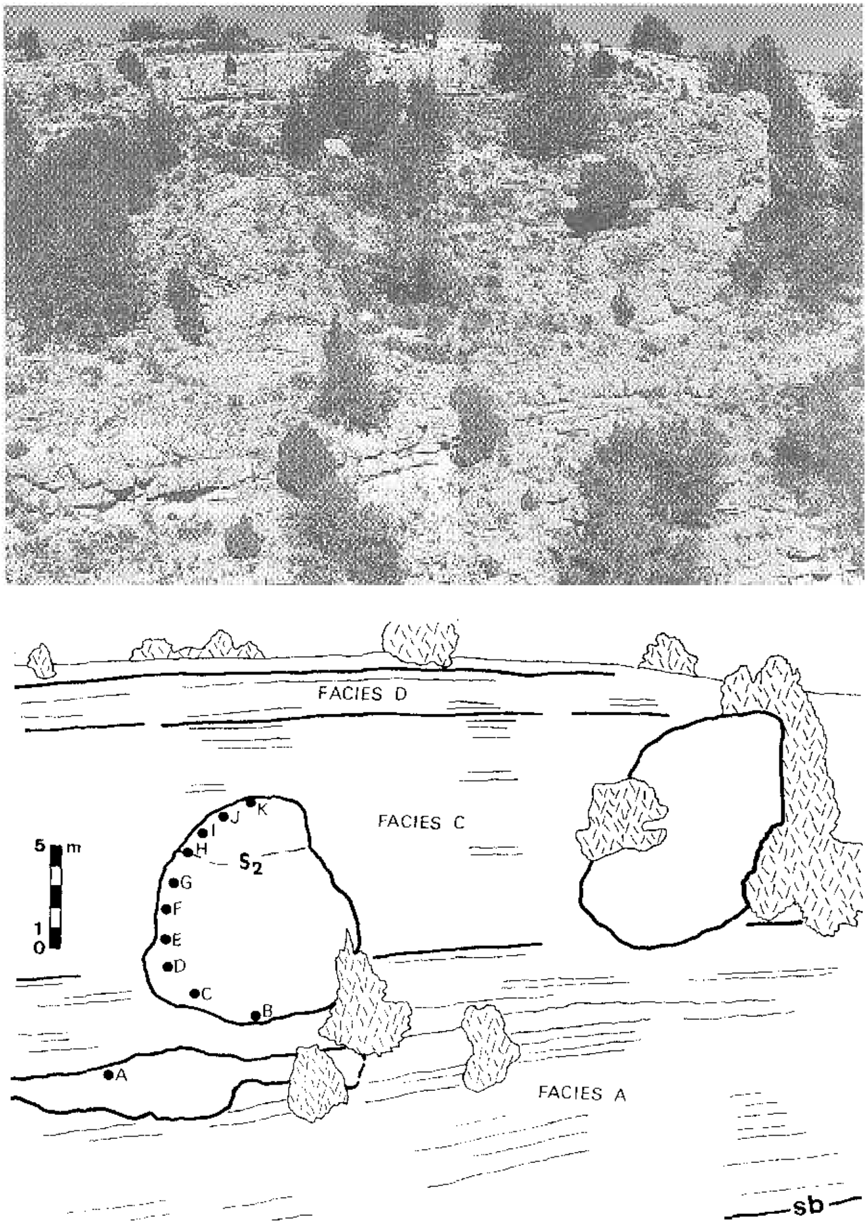

Fig. 5.—Facies and sample distribution in the BC outcrop. Below the studied pinnacle, a patch reef with a stratal morphology is observed. See text for facies explanation.
Fig. 5.—Distribución de facies y de muestras en el perfil BC. Por debajo del pináculo se observa un parche arrecifal con geometría tabular. Ver texto para la explicación de facies.

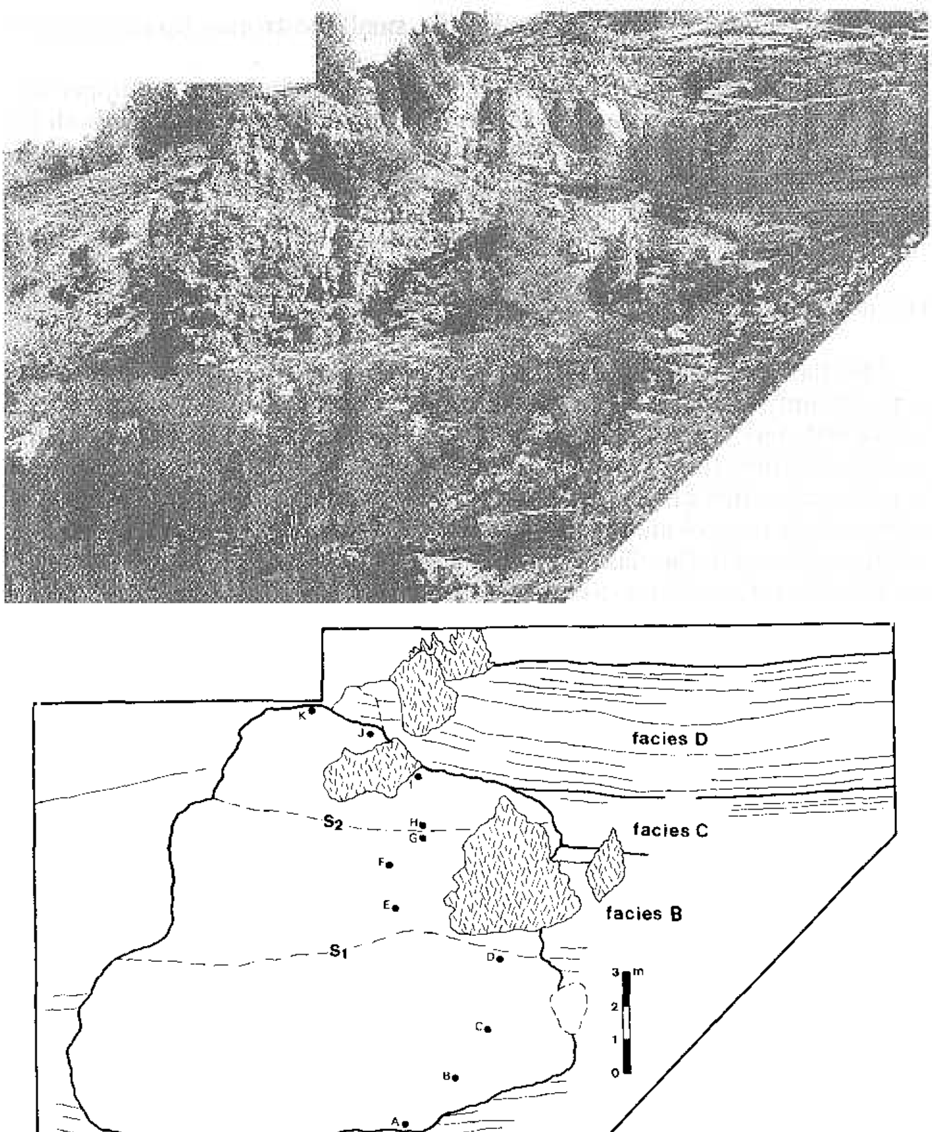

Fig. 6.—Facies and sample distribution in the BD outcrop. Two prominent discontinuities (i.e. S1 and S2 surfaces) are found in the pinnacle core. See text for facies explanation.
Fig. 6.—Distribución de facies y de muestras en el perfil BD. Dentro del núcleo del pináculo se reconocen dos superficies de discontinuidad (superficies S1 y S2). Ver texto para la explicación de facies.

these sections (e.g., BC section, see Fig. 5), small biostromes up to 3 m thick are found below the pinnacles.

Flat and sharp surfaces occur in the core of the pinnacles. An upper surface, located 8 to 9 m above the bottom of the reef is recognized in both the BD, BH and BC pinnacles (see S2 in Figs. 4 and 6), whereas a lower surface, located some 5 m above the bottom is recognized in the more western pinnacles, located around the BD outcrop (see S1 in Fig. 6).

THE REEF FABRIC

The basic reef fabric consists of variable proportions of both colonial forms (mainly corals: 5-60%), microbial crusts and associated encrusters and microencrusters (10-80%) and internal sediment (15-40%), giving rise to framestone textures (Fig. 7). Other organisms such us lithophagid bivalves, gastropods and echinoids are common throughout the reef. The different proportions between colonial forms and microbial crusts allows to separate two reef types (based in the classification of Leinfelder, 1993): (1) coral-microbial crust reefs (refereed here as coral reefs), when the proportion of colonial forms is larger than the proportion of microbial crusts, and (2) coral-bearing thrombolites (refereed here as coral thrombolites), composed of microbial crusts with a considerable amount of reef macrofauna (up to equal proportions of metazoans and crusts).

1. *Colonial forms:* Leinfelder *et al.* (1994) and Nose (1995) have classified these reef as coral-chaetetid-stromatoporoid microbial crust reefs. The dominant colonial forms are corals and, in much lower abundance, stromatoporoids, chaetetids, solenoporarean algae and sponges (mainly «lithistid» demosponges, according to Nose, in Leinfelder *et al.,* 1994). The corals include a number of different massive, hemispherical and branching species. They normally occur as centimetric to decimetric debris. Locally, large branching corals are found in growth position. According to Nose (1995), the dominant coral taxa are *Thamnasteria* and *Microsolena.* Also frequent are *Calamophylliopsis, Stylina excelsa, Ovalastrea delgadoi, Milleporidium formosum, Chaetetes chabaisensis* and *Solenopora jurassica.*

2. *Microbial crusts:* A dense micritic to peloidal (packstone) crust is found around the colonial forms. This crust may also form important volumes of the reef framework. The fabric on these crusts is mostly clotted and display an irregular growing with common domal morphologies. A particular crust type described by Schmid (in Leinfelder *et al.,* 1994) for the base of the Jabaloyas reef is represented by «downward facing nodular hemispheroids». The microbial crust comprise variable proportions of both micro-encrusters, including *«Tubiphytes» morronensis* (see discussion in Schmid, 1995), *Koskinobullina socialis, Lithocodium, Bacinella, Thaumatoporella, Placopsilina,*

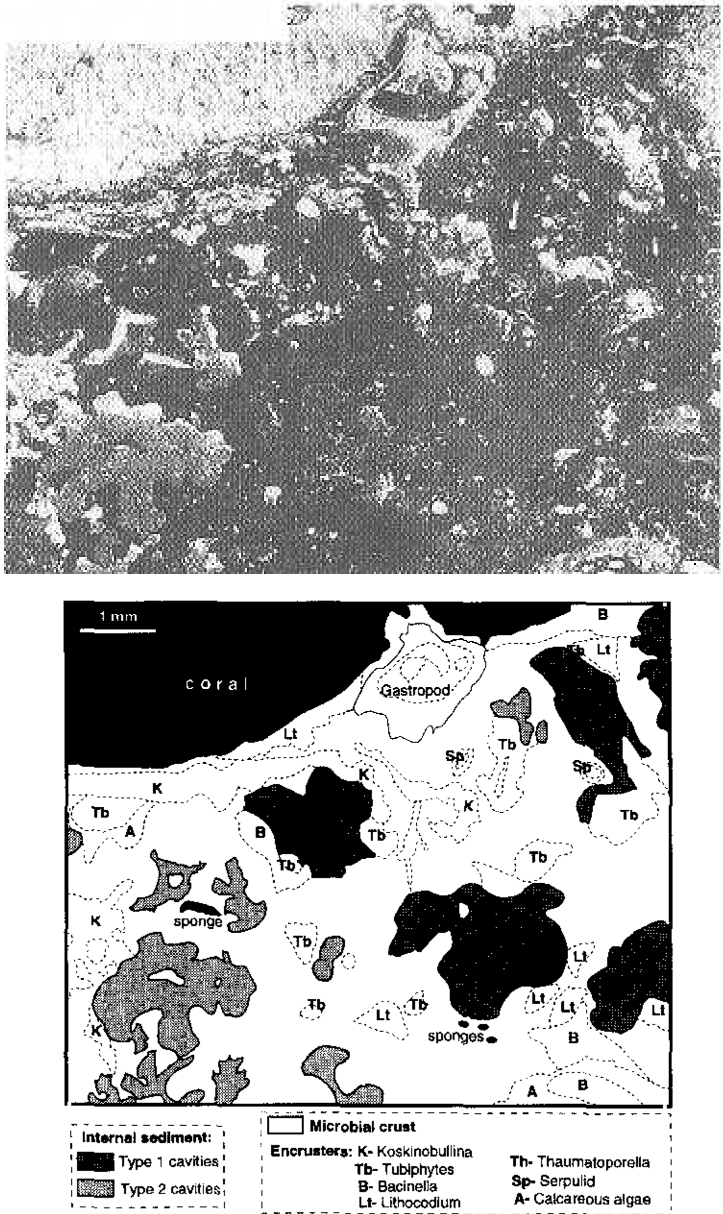

Fig. 7.—Example of the reef fabric, showing the distribution of different encrusting organisms (sample D in the BH pinnacle).
Fig. 7.—Ejemplo de fábrica arrecifal, en el que se muestra la distribución de diversos organismos incrustantes (muestra D del Pináculo BH).

and larger encrusters like serpulids or bryozoans (Fig. 7). They usually form less than 10% of the total volume of the rock. However, when the fabric is dominated by microbial crusts, they can reach up to 20%. In these instances, the diversity of micro-encrusters is lower, being dominated by *«Tubiphytes» morronensis*. Both the microbial crusts and the metazoan builders are largely bored by lithophagid bivalves.

3. *Internal sediment:* Two types of internal cavities are distinguished (Fig. 7): (1) type 1 cavities correspond to the holes left during the growing of both colonial forms and microbial crusts; (2) type 2 cavities were originated by the bioerosion and boring of the metazoan builders or the microbial crusts. The cavities are generally filled by internal sediment. The internal sediment mostly consists of silty biomicrites (mudstones to wackestones), with scattered debris of bivalves, echinoderms, gastropods, benthic forams, corals and microbial crusts. These micritic fillings may be interrupted by the growing of microbial crusts at several levels. Grain-supported facies (i.e. peloidal and ooidal packstones-grainstones) may also occur as internal sediment. Both grain-supported and micritic facies may be associated, forming graded and laminated structures in geopetal fillings.

General trends of vertical and lateral zonation on reefs

Four pinnacles regularly distributed in a proximal-distal ramp section have been sampled in order to evaluate the general trend of the vertical and lateral variation on the proportion between colonial forms and microbial crusts.

1. *BD pinnacle:* The distribution of the studied samples and the location of the two planar surfaces along the core of the BD pinnacle is shown in Fig. 6. The vertical variation of the proportion of both colonial forms and microbial crusts (cf/mc ratio) is reported in Fig. 8. The reef shows an overall upward increase of the cf/mc ratio. Proportions of microbial crusts (45-75%) are larger than colonial forms below S1. The cf/mc ratio ranges from 1.5 to 4 between S1 and S2. In this zone, an important volume of the internal sediment contains ooidal particles, similar to the ones located in the inter-reef areas (facies B, see below). Above S2, the internal sediment is micritic and the cf/mc ratio is larger than 2.5.

2. *BH pinnacle:* The distribution of the studied samples in the BH pinnacle is shown in Fig. 4. The results reported in Fig. 8 shows overall volumes of colonial form between 40-70%, clearly larger than microbial crusts (generally below 30%). However, there are two areas with larger proportion of microbial crusts: the bottom of the pinnacle (sample A) and the zone located around the S2 surface (sample G). The cf/mc ratio is also different below and above the S2 surface, i.e from 1.3 to 3.2 and larger than 6 respectively.

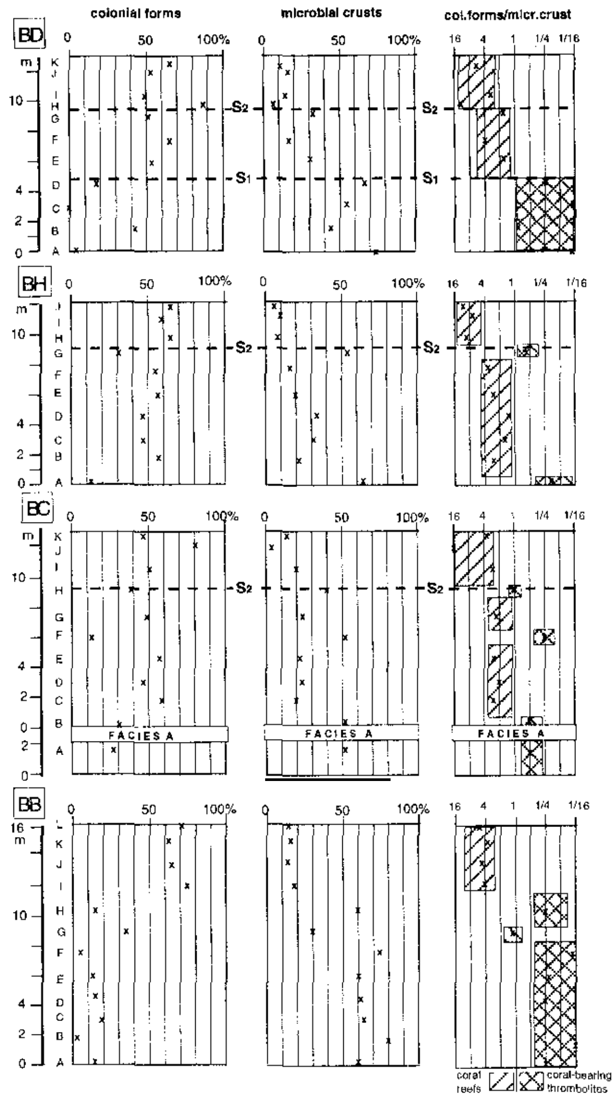

Fig. 8.—Vertical variation on the proportion of colonial forms and microbial crust (including associated encrusters) in the four sampled pinnacles, based on point/counting along thin sections (% refers to the total volume of the reef fabric). The columns located to the right shows the vertical evolution of the ratio between colonial forms and microbial crusts.

Fig. 8.—Variación vertical de la proporción de formas coloniales y costras microbianas (incluyendo los organismos encostrantes asociados) en los cuatro pináculos estudiados, basado en contaje de puntos en láminas delgadas (el % se ha referido al volumen total de la fábrica arrecifal). Las columnas localizadas a la derecha muestran la evolución vertical de la proporción entre formas coloniales y costras microbianas.

3. *BC pinnacle:* Like in the previous pinnacles, there is an overall upward increase of the cf/mc ratio, only interrupted by samples F and H (52 and 39% of microbial crust respectively), the latter located on S2 surface. The biostrome located below the BC pinnacle was also sampled (sample A, Figs. 5 and 8). Samples A and B show a close to 0.5 cf/mc ratio and therefore correspond to coral thrombolites. The coral reef samples located below S2 show ratios up to 2.8, whereas the ones located above have ratios down to 2.6.

4. *BB pinnacle:* The studied samples show a lower part (up to 12 m) dominated by microbial crusts (60 to 80 %, with less than 20% of corals) and an upper part dominated by corals (less than 20% of microbial crusts and 60-70% of corals). Only sample G, located 9 m above bottom reef, shows an amount of microbial crust (30%) lower than colonial forms (35%). It has been not possible to recognize interior surfaces in the reef core from outcrop observation. However, the comparison to the other pinnacles, suggest the location of S2 in the boundary between a lower coral thrombolite area (ratios ranging between 0.03 and 0.3) and the upper coral reef one (ratios around 4).

The resultant data on each pinnacle can be further compared, establishing a correlation between the inshore and offshore pinnacles (Fig. 9). The vertical zonation described above shows a general similar trend in all the sampled pinnacles, which consists of an overall increase of the cf/mc ratio to the top of the pinnacles. The upward increase of the corals in the Jabaloyas reefs was

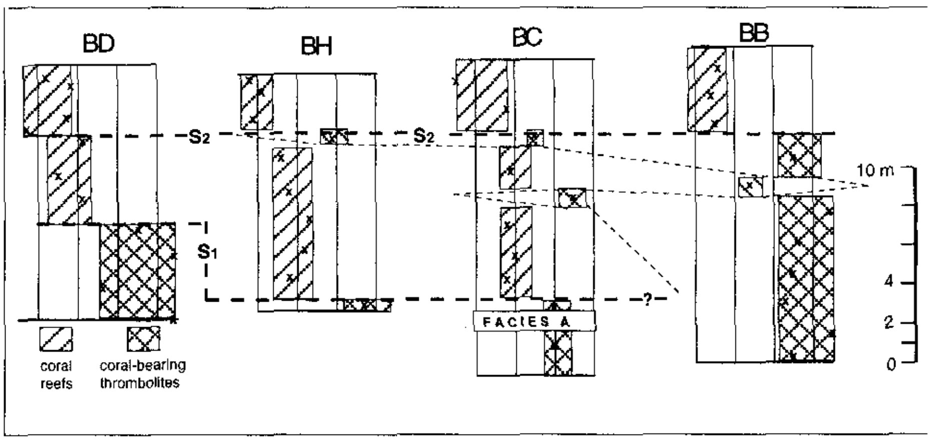

Fig. 9.—Correlation of the four sampled pinnacles based on the S1 and S2 surfaces, showing the lateral variation of the colonial forms/microbial crust ratio, defining coral-reef or coral thrombolitic facies (see right columns in Fig. 8).
Fig. 9.—Correlación entre los cuatro pináculos muestreados en base a las superficies S1 y S2, en la que se muestra la variación lateral de la proporción formas coloniales/costras microbianas (ver columnas de la parte derecha en la Fig. 8)

previously reported by Giner and Barnolas (1979) and Leinfelder *et al.* (1993). Stacked horizons with similar cf/mc ratio separated by sharp surfaces are also recognized in the studied pinnacles. On the basis of the intermediate S1 and S2 surfaces, a correlation between the pinnacles can be established. Three vertical zones are distinguished: (1) below S1, there are coral thrombolites, with variable proportion of corals; (2) between S1 and S2 surface, there is some lateral variation on the pinnacles: the proximal ones are dominated by colonial forms, whereas the distal ones are microbial crust-dominated; (3) above S2 the microbial crust become scarce, with cf/mc ratio larger than 2.

THE ASSOCIATED FACIES

The vertical and lateral distribution of the facies associations across the studied cross-section is shown in Fig. 3. As a whole, the facies distribution shows a retrogradational stacking facies in the lower part of the parasequence, followed by a rapid progradation of facies in the upper part of the parasequence. Two main groups of inter-reef facies are found: grain supported facies in the lower part (Facies A and B), followed by mud-dominated facies in the upper part (Facies C). Facies D is found covering all the reef and inter-reef facies, and therefore they correspond to the post-reef facies. However, some interfingering between Facies C and D also occur.

The boundary between the grain- and mud-supported inter-reef facies is located to the lower part of the pinnacles in the offshore sections (BB section), and to the top in the inshore sections (BD section, see Fig. 6). In these proximal sections, the boundary is marked by a sharp, burrowed *(Thalassinoides)* and partly encrusted surface. In some outcrops, this surface display some depositional slope towards the flanks of the pinnacles. In the BH outcrop (Fig. 4), the boundary reaches a minimun highness of 4 m above the bottom of the pinnacles in the inter-reef areas. This highness increases to the flank of the pinnacle, reaching 8-9 m. Moreover, this surface has continuity in the pinnacle core (i.e. S2 surface).

FACIES A: PELOIDAL AND BIOCLASTIC PACKSTONES TO GRAINSTONES

Facies A occurs below and laterally to the more western pinnacles. It is arranged both in massive and cross-laminated tabular beds 0.5 to 0.7 m thick and cross-beds up to 0.3 m thick. The peloids are variable in size and form up to 35% of the volume of the facies. There are also micritic intraclasts 2-3 mm in diameter, which consists of debris of the reef microbial crust, including encrusting organisms such as «*Tubiphytes*» *morronensis, Koskinobullina,* *Bacinella,* serpulids and bryozoans. The proportion of the intraclasts ranges from 10 to 25 %.

The bioclasts form up to 20% of the total volume of the facies and consists of debris of corals (rounded clasts of up to 3 cm in diameter), bivalves, echinoids (*Balanocidaris*) and benthic forams (lituolids). In lower proportion are found other fossils such as gastropods, *Nautiloculina oolithica, Cayeuxia,* bryozoans, brachiopods, chaetetids, miliolidae and solenoporacean algae.

Facies B: ooidal and bioclastic packstone to grainstones

Facies B is the inshore equivalent of facies A. It is found below and laterally to the more proximal pinnacle reefs. Facies B is arranged in tabular beds 0.3 to 0.5 m thick. Cross-bedded levels up to 0.3 m thick also occur. The ooids form up to 20% of the total volume of the facies. Their size is variable, displaying diameters up to 1 mm. The core of the ooids consists of siliciclastic grains and skeletal particles (bivalves, lituolids, *Cayeuxia*, echinoids, gastropods and *N. oolithica*). They show both type 3 and 4 and alternation of type 3 and micritic coatings (classification after Strasser, 1986).

The bioclasts form up to 30% of the facies and include solenoporacean algae (very abundant), lituolids, corals, chaetetids, bivalves, gastropods, *Cayeuxia*, echinoids, *N. oolithica*, bryozoans, serpulids and miliolids. The facies may also contain up to 10% of both peloids and intraclasts of microbial crusts similar to the previously described in facies A. Occasionally are also found type I and II oncoids (classification after Dahanayake, 1977), showing skeletal cores (corals, bivalves, echinoids, gastropods).

Facies C: skeletal wackestones

Facies C occurs laterally to the upper part of the pinnacles and its overall thickness increases offshore. Although the top of the FT section is eroded, we have interpreted that Facies C pinches out to the more proximal sections, where the pinnacle reefs are also thought to be absent (Fig. 3). The facies consists of burrowed tabular biomicritic beds up to 0.3 m thick, alternating with both marly levels and bioclastic levels including debris of metazoan builders (i.e. corals and chaetetids) up to 5 cm in diameter. The biomicritic beds are onlaping over the flanks of the pinnacle reefs.

The skeletal debris may form up to 30 % of the facies. Corals, chaetetids and echinoids are the more abundant skeletal grains, whereas other fossils like bivalves, lituolids, gastropods, solenoporacean algae, *N. oolithica,* miliolids, bryozoans and serpulids are more scarce. The facies also contain silt of both carbonate and siliciclastic grains. Intraclasts of microbial crusts are also common.

Facies D: peloidal, ooidal and bioclastic packstones and grainstones

Facies D is located on top of the studied parasequence, above the horizon which includes the pinnacle reefs. The lower boundary of facies D is generally a sharp an even surface. However, in some outcrops (e.g. BB and BC sections), some interlayering between facies D and the underlying biomicrites (facies C) is observed (Fig. 3).

Facies D includes a wide spectrum of facies, defined by variable amounts of peloids, ooids and skeletal grains. The facies dominated by peloids corresponds to peloidal and bioclastic packstones and peloidal grainstones. They form 0.5 to 1 m thick beds, with occasional cross-bedding. The facies contains up to 40% of peloids and 25% of skeletal grains, mainly debris of lituolids, miliolids, corals, gastropods (occasionally forming accumulations in discrete levels) and bivalves.

The ooid-dominated facies are ooidal and bioclastic packstones and grainstones. They are arranged in 0.3-1 m thick beds, locally cross-bedded and cross-laminated. The ooids are mainly of type 3 (Strasser, 1986), are up to 1 mm in diameter and generally display siliciclastic cores. The skeletal grains may form up to 20% of the facies. The more abundant fossils are bivalves, gastropods, solenoporacean algae, miliolids and lituolids. Type I and II oncoids (Dahanayake, 1977) of 5 mm of mean diameter are occasionally found.

The bioclastic facies are wackestones to packstones and are arranged in tabular beds 0.3 to 0.5 m thick. The more abundant skeletal grains are gastropods and solenoporacean algae. Bivalves, *Cayeuxia*, corals, echinoids, lituolids, miliolids, brachiopods, dasycladacean algae (*Acicularia*) and *N. oolithica* are found in lower proportion. Most of these bioclasts show thin micritic coatings. Encrusted surfaces with oysters and accumulations of bivalves giving rise to a small patches are occasionally found on these facies.

INTERPRETATION

Sedimentary realms in the late Kimmeridgian ramp

The nature and distribution of the facies in the studied parasequence, allows the reconstruction of the sedimentary realms of the Late Kimmeridgian carbonate ramp in the Jabaloyas area (Fig. 10). Facies D is considered to be deposited in inner ramp areas (internal lagoon and marginal sand shoals), whereas the pinnacle reef and associated facies (A, B, C) would growth in the open and relatively deep mid ramp domains. The inner and mid ramp areas are placed above and below fair weather wave base respectively. The mid ramp areas are above storm wave base sea level, and therefore periodically affected by high energy events (Burchette and Wright, 1992).

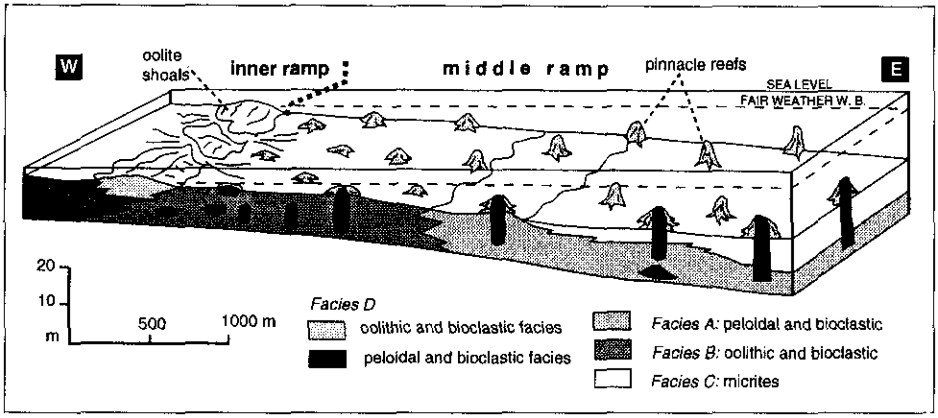

Fig. 10.—Sedimentary model for the Late Kimmeridgian carbonate ramp in the Jabaloyas area.
Fig. 10.—Modelo de sedimentación para la rampa carbonatada del Kimmeridgiense superior en el sector de Jabaloyas

Two basic types of facies are recognized in the mid ramp areas. The more internal domains are covered by grain-supported facies (facies A and B), whereas the outer realm of the mid ramp is dominated by burrowed, mud-dominated facies, which are indicative of lower energy environment (facies C). Inshore, the sediment is dominated by high energy ooids (type 3, Strasser, 1986) and by a wide spectrum of skeletal grains, which are indicative of shallow and open marine conditions (facies B). Offshore, the grain-supported sediments are peloidal and skeletal, including also a diversified and open benthic community with forams, bivalves, solenoporacean algae and echinoids (facies A).

Scattered in the mid ramp are found a set of patch reefs. The elevation of the reefs above bottom floor was variable both in time and in space. Based on the BH section, where it is possible to examine the relationship between coeval inter-reef facies and intermediate stages of growing of the pinnacle reef (Fig. 4), the maximum rise of the pinnacles above the surrounding sediments can be estimated to be around 4 to 5 m. The elevation of the patch reefs is reduced inshore. In the more internal areas of the mid ramp (i.e., FT section) only metric patch reef scattered between grain-supported oolithic and bioclastic facies are found.

Facies D is interpreted to be originated in inner ramp areas. The peloidal and skeletal-dominated facies includes a benthic community of gastropods, miliolids, lituolids, bivalves and oysters, indicating partly restricted environments. This restriction would be originated by the presence of a belt of sand shoals (oolithic and bioclastic facies), interpreted to be located in the transition between inner and mid ramp areas.

The pinnacle reefs

The relationship between the reefs and the associated facies exposed above shows that the growing of the pinnacles took place in mid ramp areas. Giner and Barnolas (1979), Fezer (1988), Aurell (1990), Nose (1995) and Baumgärtner and Reyle (1995) have proposed a similar setting for the reef growing. The nature of the organisms that constructed the reefs are also coherent to this assignment (see Nose (1995) for details). In addition, the associated micro-encrusters found commonly in the microbial crusts, with *Bacinella, Lithocodium, Koskinobullina, «Tubiphytes» morronensis* and serpulids, are considered by Leinfelder *et al.* (1993) as representative of shallow ramp areas.

The colonial forms are preserved in the reefs as debris of different size and are only occasionally found in growth position. The breakage of the skeletons was due to both storm reworking and bioerosion. Part of the debris originated by these processes were accumulated in the inter-reefs sediments or transported inshore. Accordingly, the proportion of the preserved metazoan builders in the reef is lower than the proportion during reef growing (Longman, 1981). However, the bulk of these debris remains in the reefs, forming their frameworks along to the microbial crusts.

The role of the microbial crusts in the origin and development of the Late Jurassic reefs has been examined in detail by Leinfelder *et al.* (1993, 1994). According to these authors, the microbial crusts are of paramount importance for the origin, stabilitization and development of positive buildups. The microbial crusts are binding and bounding together the debris of the metazoan builders, forming also variable proportions of the reef fabric. These crusts were rapidly hardened, as indicated by the presence of borings on the crust itself. The development of the microbial crust is discontinuous, as it is shown by both the irregular intergrowing between peloidal or micritic fabrics and the presence of the micro-encruster organisms.

The internal cavities, either left during the reef growing or originated by bioerosion, are rarely filled by marine or meteoric cements. Only some partially filled reef cavities (geopetals) have been later cemented by sparite. Most of the cavities are occupied by muddy (occasionally peloidal or ooidal) internal sediment. This mud may be originated either by bioerosion (Tucker and Wright, 1990) or by filtering and baffling the fine grain sediment suspended in the surrounding marine waters. Arguments such as the presence of ooids or siliciclastic silt in the muddy internal sediment or the occasional lamination and gradation in the peloidal fillings, demonstrate an external supply. However, it is difficult to estimate how much internal sediment has been originated either by bioerosion or by external supply.

DISCUSSION: REEF GROWTH AND SEA LEVEL CHANGES

The general trend on the vertical and lateral reef zonation described above and the inter-reef facies distribution, allows to discuss the relationship between the growing of the pinnacles and the changes of sea level. The evolution of the studied parasequence throughout four successive sea level episodes is shown in Fig. 11. Episodes 1 and 2 are coeval to a continuous sea level rise (i.e. transgressive systems tract), whereas episodes 3 and 4 show the facies distribution during the subsequent stillstand of sea level (i.e., highstand systems tract). The evolution in Fig. 11 has been illustrated upwards from the horizon including the reefs. The previous sandy, marly and grain-supported shallow carbonates present in the lower part of the studied sections (see Fig. 3) would represent a continuous flooding of the ramp, from transitional to shallow marine environments.

Transgressive systems tract

A first episode corresponds to a fast rise of sea level which involved the initial flooding of the carbonate ramp (Fig. 11.1). The top of this episode corresponds to the S1 surface. As a consequence of a rapid creation of accommodation in the basin, a sedimentary starvation in the mid ramp occurred. Only the fast vertical growing of some pinnacles is able to partly compensate for the accommodation. Stratal biostromes, with variable lateral extension, also grew during this episode. The local development of microbial crusts produced the stabilisation and hardening of the substrata, allowing the growing of the coral forms in subsequent episodes (Leinfelder *et al.*, 1993). The partial reworking of the microbial crust is indicated by the common presence of debris of the crust in the coeval peloidal, oolithic and bioclastic facies A and B.

During this first episode the reefs show widespread coral thrombolitic fabrics. As indicated by Leinfelder *et al.* (1993), the main prerequisite for the occurrence of microbial crust is a cessation of the background sedimentation which can be commonly tied to rises of sea level. However, according to this author, low sedimentation rate is also favorable for coral growth. The low proportion of corals and the low diversity of micro-encrusters during this lower episode are indicative of some restriction in the marine environment. As explained by Leinfelder (1993) and Leinfelder *et al.* (1993) a rise of the dysaerobic waters due to lowering circulation during sea level rises may exclude the extensive growing of metazoans, whilst the euroxic microbes remain.

The overall vertical growing of the reefs followed and/or initiated during the continuing riser of sea level (Fig. 11.2). The inter-reef sedimentation recovered in the internal areas of the mid ramp. The deposition of grain-supported facies A and B was coeval to the reef development, as indicated by the presence of ooids and peloids in the internal reef cavities. Both the increase of the background sedimentation and the recovery of the normal oxygenated environment after the initial flooding of the ramp in the more proximal areas, may explain the rapid shift from coral-thrombolitic to coral reefal fabrics. Therefore, the sharp boundary locally observed between both types of reef fabric in the inshore pinnacles (e.g. S1 in the BD pinnacle) is likely to reflect some nutrient and/or oxygen fluctuation.

However, thrombolitic fabrics are still dominant in the offshore reefs. Sedimentary rates were lower in the external areas of the mid ramp, as indicated by the offshore thickness reduction of the inter-reef facies. The coeval development of coral thrombolites and coral reef at apparently similar bathymetric conditions, would reflect not only some lateral variation in the oxygen and/or nutrient content, but also the off-shore decrease of the sedimentary rates across the mid ramp area.

We have placed the upper boundary of the transgressive systems tract or maximum flooding surface on the so-called S2 surface. This is a burrowed and encrusted surface covering the grain supported facies A and B between the BD and BH sections. This surface is coeval to the development of the flat surface with microbial crusts located some 9 m above the bottom of the more proximal pinnacles (i.e. S2 surface, see Figs. 4, 5 and 6). The biomicritic inter-reef facies located off-shore (facies C) are intensively burrowed, indicating also some sedimentary condensation. The decrease of the sedimentary rates in relation to the increasing accommodation rates is also indicated by a retrogradational stacking pattern, with the progressive backsteeping of the mud-supported facies C.

Highstand systems tract

The rapid rise of the sea level resumes at the onset of this episode, dominated now by a sea level stabilisation, which allows the recovery of the carbonate production. The successive observation of aggradational and progradational facies arrangement in the sediments deposited during this stillstand episode, allows to differentiate between early and late highstand systems tract.

At the onset of a first episode or early highstand systems tract (Fig. 11.3)

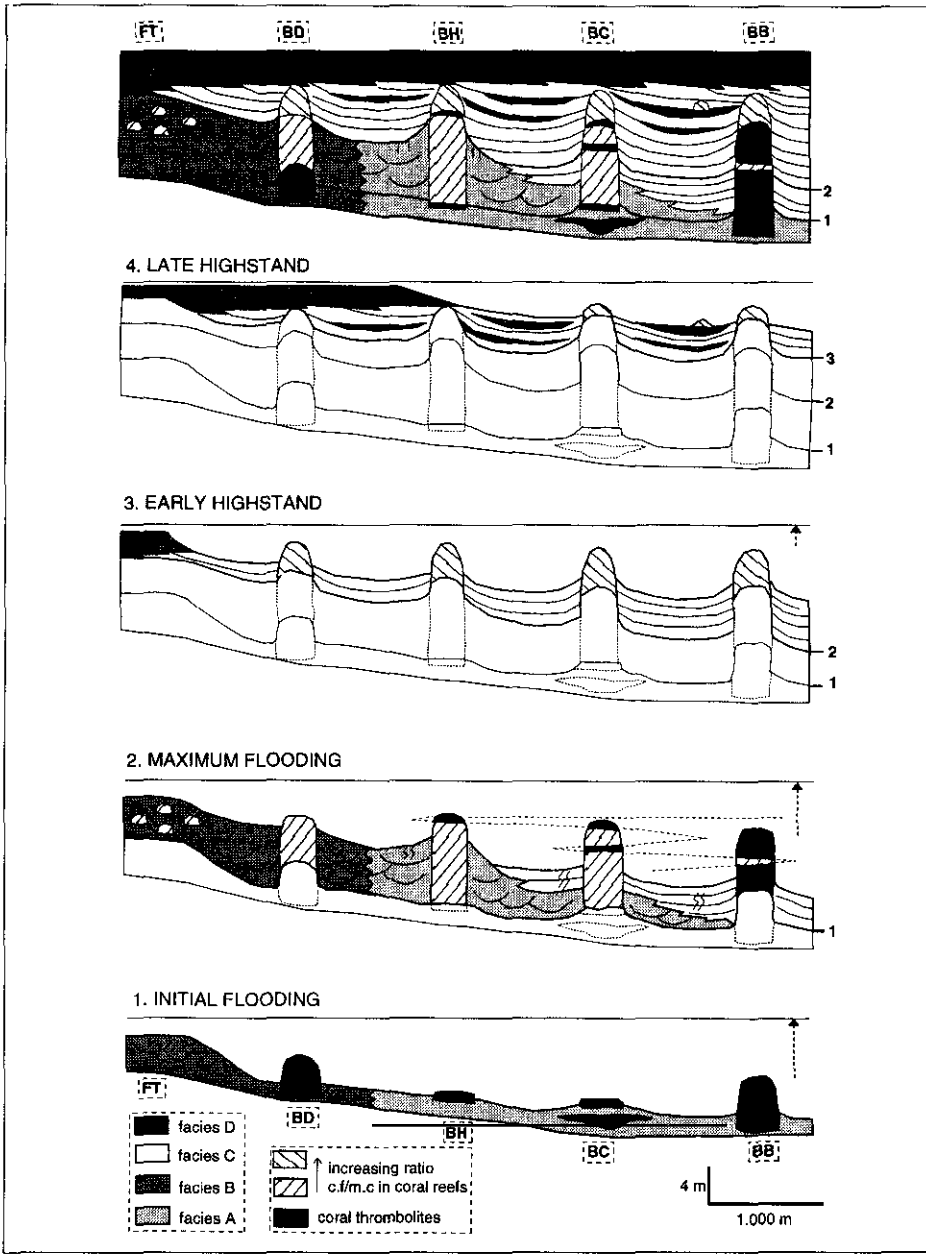

Fig. 11.—Evolution of the pinnacle reefs and associated facies related to sea level variation.
Fig. 11.—Evolución de los pináculos arrecifales y facies asociadas en relación con las variaciones del nivel del mar.

there was still an important accommodation available in the inter-reef areas. They were relatively deep sites, which become progressively filled up by the onlapping of the offshore biomicrites. As a result, the elevation of the pinnacles above bottom sediment was reduced. On the other hand, the restoration of the oxygenated environments during this highstand episode allows the recovery of the growing of the colonial forms all across the studied pinnacles. This results in some vertical aggradation of the reef above S2 surface. The aggradation of the pinnacles, larger than the accommodation created, would produce some shallowing upward on them. Both, the composition of the internal sediment found in the reefs cavities and the high proportion of debris of colonial forms (mainly corals and chaetctids) in the inter-reefs biomicrites, indicate the coeval development of the reefs and the inter-reef biomicrites during this episode.

During the late highstand episode (Fig. 11.4), the rapid progradation of the inner ramp facies resulted in the complete filling of the available accommodation. This progradation was favoured by both the relatively flat and shallow topography of the mid ramp left after the filling of the inter-pinnacle depressions and the high carbonate production. Skeletal and oolithic levels interbedded in the biomicritic inter-reef facies indicate the progressive shallowing upward of the inter-reef areas. Over this skeletal levels are small coral patch reef developed.

FINAL REMARKS

1. The pinnacle reefs of the Jabaloyas area show some vertical and lateral variation in the relative proportion of microbial crusts and metazoan builders. The overall pattern of reef zonation presented in our work is based on vertical logs across four separated pinnacles, along to field observation in intermediate reefs. However, there are some lateral varibility in the reef fabric within individual reefs. This should be due to coral aggressivity and, particularly, to internal differences in sedimentation (Leinfeder, per. com.). Therefore, the ratios of cf/mc presented in Figs.8 and 9, which are based on vertical logs along the pinnacles, should not be taken as exact ratios. Also, in order to achieve a more realistic pattern of the lateral variation of the reef fabric along to the proximal-distal section, more intermediate reefs should be evaluated under the scope of this work. However, we believe that the preliminary results presented in this work give a reliable idea on the overall trending of the vertical and lateral reef fabric variation. Both, the similarity between the vertical variation on all the sampled pinnacles and the presence of correlatable horizons, which display comparable cf/mc ratios separated by discontinuity surfaces, give support to this assumption.

2. The sedimentological analysis of the reefs of Jabaloyas and of their as-

sociated facies presented in our work, has allowed to explain several aspects related to their origin and development in the Late Kimmeridgian Iberian carbonate ramp. Questions addressed in our work, such us the relationship between reef and inter-reef facies or its evolution during successive sea level variation along to a proximal-distal section, gives additional information and support to the results obtained in previous works, concerning the factors which controlled the origin and evolution of the Upper Jurassic reefs (see especially Leinfelder, 1993; Leinfelder *et al.,* 1993, 1994; Baumgärtner and Reyle, 1995 and Nose, 1995). Results reported in these studies, such us the intense development of microbial crust due to very low background sedimentation rates and to partial exclusion of corals by fluctuating oxygen/nutrient levels related to sea level rises, are fully supported with our data.

3. The studied sediments belong to a cyclic parasequence located in the lower part of a third order depositional sequence, which spans from Late Kimmeridgian to Early Tithonian. The variation of accommodation deduced from facies analysis shows a rapid initial sea level rise at the onset of the parasequence, followed by a later stillstand of sea level. Taking into account both the nature of the facies below and above the pinnacles, the mean thickness of the studied parasequence and the poorly compaction observed in the reef fabric, the total accommodation created in the basin from the initial development of the reefs to their late burial should be around 20 m. This accommodation is a combination of both, local subsidence and eustatic variations. Most of this sea level rise was concentrated during the deposition of the transgressive systems tract deposits, where it can be estimated to be around 12-15 m (see dashed arrows in Fig. 11, episodes 1 and 2). Leinfelder (1993) and Nose (1995) have suggested an strong regional or global eustatic control on this rise of sea level.

4. The shallow carbonate ramp developed at Jabaloyas allows to analyse the response to the carbonate production on a carbonate ramp during a rapid relative sea level rise. Reduced carbonate production in the studied Late Jurassic ramp during initial sea level rise resulted in a partly condensed section in mid ramp areas, followed by a landward shift (backstepping) of the deeper biomicritic facies. However, the vertical aggradation of some reefs was able to compensate for most of the accommodation created during sea level rise in outer middle ramp areas, resulting in a facies distribution similar to the catch up type platforms defined by Kendall and Schlager (1981). During late stages of rising sea level, carbonate production was recovered in shallower areas, resulting in an aggradational stacking pattern (see lateral transition between facies A and B in Fig. 11.2). High carbonate productivity during the ulterior stillstand of sea level resulted in the facies agradation in the inter-reef facies followed by a fast progradational pattern (i.e., early and highstand systems tracts).

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