Geologia Croatica	56/2	187–198	11 Figs.	1 Tab.		ZAGREB 2003

Depositional Environment of Coral–Rudist Associations in the Upper Cretaceous Cardenas Formation (Central Mexico)

Armin **SCHAFHAUSER**[1], Stefan **GÖTZ**[1], Rosemarie **BARON-SZABO**[2] and Wolfgang **STINNESBECK**[1]

Key words: Upper Cretaceous, Maastrichtian, Reefs, Corals, Rudists.

Abstract

In the Cardenas Formation (central Mexico), a 175 m thick sedimentary sequence of Maastrichtian age was analyzed with respect to its palaeontology and sedimentology. A wide variety of lithological and palaeontological features characterize this sequence comprising unfossiliferous and fossil-bearing sand- and siltstones, and diverse rudist and coral–rudist associations in carbonate or mixed carbonate/clastic lithologies. A total of 24 rudist and coral–rudist associations are exposed in the investigated section, which are grouped into 5 limestone units. Radiolitid assemblages, coral–rudist reefs, coral-dominated reefs, and hippuritid-dominated reefs are present. The stacking pattern of these reef intervals indicates a general transgressive trend through the entire section. Smaller-scale facies trends could be distinguished within each limestone unit, comprising deepening-upward sequences, defined by a shoreface–calcareous algae–radiolitid–marl facies transition, and shallowing-upward sequences defined by a hippuritid–actaeonellid–coral/rudist facies transition. This cyclic sedimentation pattern is obscured by an episodic input of clastic sediments derived from the uplifting Sierra Madre Oriental, which in turn triggered either the development or decline of reefs.

1. INTRODUCTION

In late Cretaceous times rudist bivalves became the most important benthic carbonate producers in both the Tethyan and Caribbean realms (KAUFFMAN, 1973; ROSS & SKELTON, 1993). They predominantly built widespread mono- to paucispecific associations but were also able to co-exist successfully with corals yielding complex and diverse coral–rudist reefs (e.g., KAUFFMAN & SOHL, 1973; MASSE & PHILIP, 1981; LAVIANO, 1984; CAMOIN et al., 1988; SCOTT et al., 1990; HÖFLING, 1997; SANDERS & BARON-SZABO, 1997; SANDERS & PONS, 1999; GÖTZ, 2001, 2003; MITCHELL, 2002). The spatial distribution of coral–rudist reefs was mainly controlled by environmental conditions (e.g., sedimentation rate, palaeobathymetry, current regimes, salinity) (GILI et al., 1995; GILI & SKELTON, 2000; GÖTZ, 2003). Like many other taxa, rudists became extinct at or close to the Cretaceous/Tertiary (K/T) boundary. As a result of the scarcity of outcrops and the poor stratigraphic constraints of rudist associations, the timing and pattern of rudist demise is still controversial (JOHNSON & KAUFFMAN, 1996; STEUBER et al., 2002).

The Upper Cretaceous Cardenas Formation contains abundant rudist and coral–rudist associations, which belong to the youngest known late Cretaceous assemblages worldwide. These assemblages may potentially provide new data about latest Cretaceous rudist history (JOHNSON & KAUFFMAN, 1996). Since the monograph of BÖSE (1906) the diverse faunal assemblages of the Cardenas Fm. have been studied by several authors (BÖSE & CAVINS, 1927; BURCKHARDT, 1930; MUELLERRIED, 1930; MYERS, 1968; HURTADO-GONZALEZ, 1984; VEGA et al., 1995; ALENCASTER et al., 1999; CAUS et al., 2002). Nevertheless, a detailed analysis of these coral–rudist associations is lacking in the literature.

Herein we present a detailed description of an approximately 170 m thick sequence selected from an approximately 900 m thick section of the Cardenas Fm. It is exposed in a river bed called the Arroyo de la Atarjea (MYERS, 1968), situated approximately 3 km north of the city of Cardenas (Fig. 1). MYERS (1968) first described the composition and tectonic structures of the Cardenas Fm. from this locality. The selected sequence contains one radiolitid assemblage and 23 coral–rudist reefs. Subsequently, we use the term “reef” in the general sense of “calcareous deposits created by essentially in place sessile organisms” (RIDING, 2002, p. 165).

2. GEOLOGIC SETTING AND LITHOLOGIES OF THE CARDENAS FORMATION

The Upper Cretaceous Cardenas Formation exposed in central Mexico (State of San Luis Potosí) is a mixed

[1] Geological Institute, University of Karlsruhe (TH), Kaiserstraße 12, 76131 Karlsruhe, Germany;
e-mail: armin.schafhauser@bio-geo.uni-karlsruhe.de

[2] Department of Invertebrate Zoology, Smithsonian Institution, Washington, DC 20560, USA

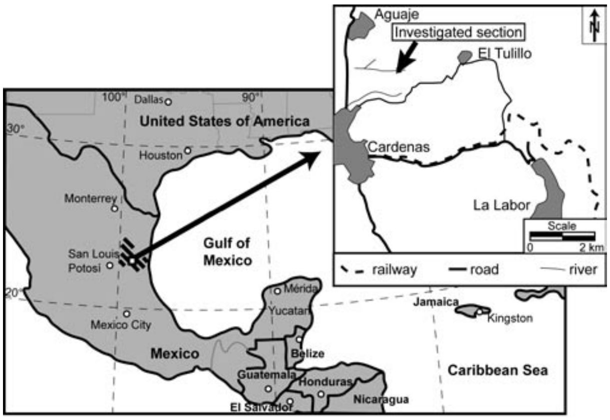

Fig. 1 Location of the investigated section in the Arroyo de la Atarjea riverbed (MYERS, 1968).

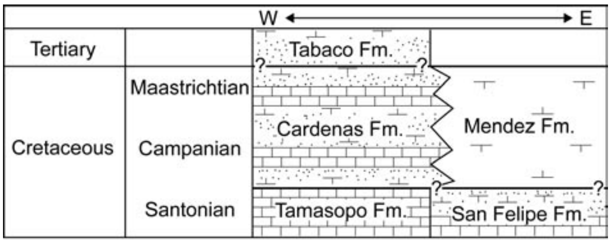

Fig. 2 Stratigraphy of the formations of the Cardenas area. The marls of the Mendez Formation interfinger with the mixed clastic–carbonate units of the Cardenas Formation. The Cardenas Fm. overlies the shallow water carbonates of the Valles–San Luis Potosí carbonate platform (Tamasopo Formation). The Cardenas Fm. is covered by the red beds of the Tabaco Formation. Similar to the marl and limestone units of the San Felipe Formation, the age range and geologic context of the Tabaco Fm. is not well defined in central Mexico.

clastic–carbonate sedimentary sequence approximately 1800 m in thickness. Laterally, the sedimentary rocks of the Cardenas Fm. pass into the deep water marls of the coeval Mendez Formation, which in turn overlie marl and limestone units of the San Felipe Formation (Fig. 2) (SOHL et al., 1991; VEGA et al., 1995). The Cardenas Fm. conformably overlies the uppermost limestone units of the Valles–San Luis Potosí (V. S. L. P.) carbonate platform (Tamasopo Formation), which are of Cenomanian to Santonian age (BASAÑEZ-LOYOLA et al., 1993). The Cardenas Fm. is overlain by the red beds of the Tabaco Formation, which are of unknown age (MYERS, 1968). According to our results, the Tabaco Fm. consists of sandstones, claystones, and varicoloured conglomerates that conformably overlie the Cardenas Fm. Tectonically the sediments of the Tamasopo Fm., the Cardenas Fm., and Tabaco Fm. are part of the fold and thrust belt of the Sierra Madre Oriental of eastern Mexico (TORRE, 1964; FUENTE-NAVARRO, 1964; SUTER, 1987).

The sedimentary rocks of the Cardenas Fm. were deposited during the Campanian–Maastrichtian time period (MYERS, 1968; CAUS et al., 2002), when a facies change from carbonate dominated deposition to mainly clastic sedimentation took place in northern and central Mexico (LOPEZ-RAMOS, 1985; SOHL et al., 1991; MORAN-ZENTENO, 1994; YE, 1997). In central Mexico this facies change is represented by the transition from the limestone units of the V. S. L. P. carbonate platform to the mixed clastic–carbonate sediments of the Cardenas Fm. and the marls of the Mendez Fm. (SOHL et al., 1991; MORAN-ZENTENO et al., 2000; GOLDHAMMER & JOHNSON, 2001). The input of clastic sediments during the Upper Cretaceous may be attributed to early orogenic phases of the Sierra Madre Oriental (SOHL et al., 1991; YE, 1997). Due to this uplift underlying older sedimentary units of the V. S. L. P. carbonate platform were eroded and deposited as clastic sediments in the foreland basin east of the Sierra Madre Oriental (Fig. 3) (YE, 1997). In the Cardenas region, the shallow water units of the Cardenas Fm. were deposited in a narrow depositional area in front of the Sierra Madre Oriental, whereas the Mendez Fm. represents the deeper parts of the foreland basin farther east. In the Tertiary, the main orogenic phases of the Sierra Madre Oriental involved the sediments of the Cardenas Fm., resulting in their deformation into broad anticlines and synclines (TORRE, 1964; FUENTE-NAVARRO, 1964; MYERS, 1968).

MYERS (1968) subdivided the Cardenas Fm. into 3 lithological members (Fig. 5; for explanation of symbols see Fig. 4), which comprise clastic intervals consisting of marls, silt- and sandstones as well as conglomeratic layers intercalated in the sandstone beds at the base of the upper member. The lower and upper members are characterized by rudist- and coral–rudist limestones, which are absent in the middle member of the Cardenas Fm. (MYERS, 1968).

3. LITHOLOGIES OF THE INVESTIGATED SECTION

The sediment succession investigated herein is 175 m thick and belongs to the upper member of the Cardenas Formation. The section is generally well exposed despite a few intervals that are partly covered by soil and calcretes (Fig. 6). Sedimentary rocks consist of interlayered marls, fine-grained sandstones, oolithic and bioclastic grainstones, and algal packstones. These sediments are described in detail below. In addition, 5 units (*u1–u5*) with rudist and coral–rudist associations, intercalated with the clastic sediments, are described in the following sections.

The age of the section is considered to be Maastrichtian, based on the ammonite *Sphenodiscus pleurisepta* (CONRAD) found in the lower member of the Cardenas Fm. that is also exposed in the Arroyo de la Atarjea.

In the lower part of the section fine-grained sandstones are predominant and are intercalated with

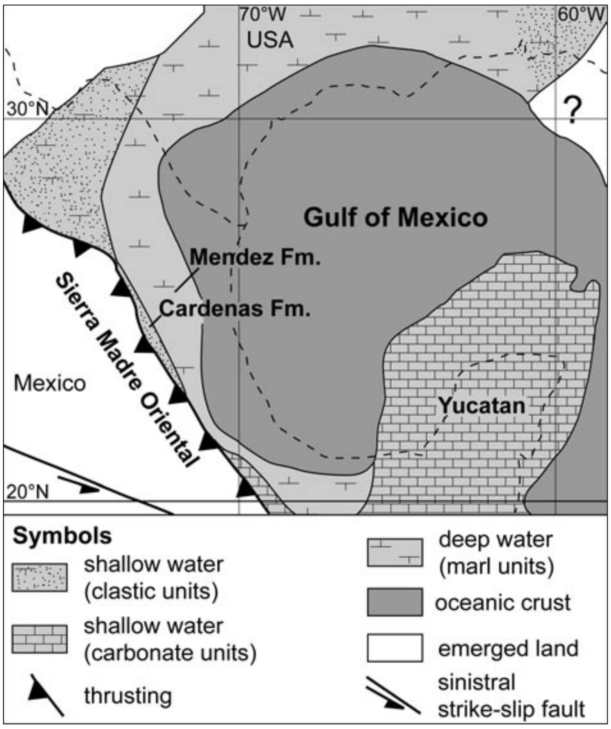

Fig. 3 Palaeogeography of the Gulf of Mexico in the Late Cretaceous (modified after PINDELL et al., 1988, and SOHL et al., 1991). The mixed clastic–carbonate sediments of the Cardenas Formation and the marls of the Mendez Formation were deposited in the foreland basin east of the Sierra Madre Oriental. In southern Mexico the rudist-bearing Yucatan carbonate platform developed.

1.5–6 m thick oolithic and bioclastic grainstones. The sandstone beds are between 20 cm and 3 m in thickness and characterized by lamination and cross-bedding. The sandstones are fine-grained calclithites (PETTIJOHN et al., 1984) and consist of more than 50% non-skeletal limestone clasts and abundant quartz clasts. The clasts are subangular to subrounded and well sorted. Matrix is absent. Generally, the sandstones are nonfossiliferous but two 3.5 cm and 0.5 m thick sandstone layers below unit *u1* contain slightly fragmented radiolitids. A bioturbated horizon separates these sandstone layers from the overlying reef.

The bioclastic grainstones contain abundant coral, rudist (plagioptychids, radiolitids, hippuritids) and echinoderm fragments, benthic foraminifera (orbitoids, miliolids), dasycladaceans, and red algae as well as abundant non-skeletal carbonates and detrital quartz.

The allochems in the oolithic grainstones consist of superficial ooids with a radial microframe and coated grains, which are well rounded and sorted. The nuclei of the ooids are miliolid foraminifera, quartz fragments, and molluscan shells. Interstitial spaces of the components are filled by dog-tooth spar cement and blocky calcite cement. The uppermost 10 cm of the oosparite bank are bioturbated.

In the upper part of the section (from approximately 15 m below unit *u2* to the top) the faunal diversity increases comprising single individuals and clusters (4–5 specimens) of plagioptychids (*Coralliochama* sp.), non-rudist bivalves (e.g., *Exogyra costata* SAY*,* *Pycnodonte mutabilis* (MORTON), *Lopha* sp., *Trigonia* sp., *Pholadomya* sp., *Cardium* sp.), and gastropods (actaeonellids, turritellids). The sandstones are interlayered with 5 cm to 5 m thick beds of sandy marls and one algal packstone bed containing dasycladaceans, miliolid foraminifera, and detrital quartz. Between units *u2* and *u4* the sandstone layers are approximately 5–10 cm thick and interlayered with thin-bedded (5–10 cm) sandy marls. Molluscan fragments, benthic foraminifera (orbitoids, miliolids), and dasycladaceans were observed in the sandstones. In the uppermost marl layers abundant ornamented ostracods were found.

4. RUDISTS AND CORALS OF THE CARDENAS FORMATION

Since BÖSE (1906) documented rudist species of the Cardenas Formation in his monograph, they have been the object of numerous articles (e.g., BÖSE &

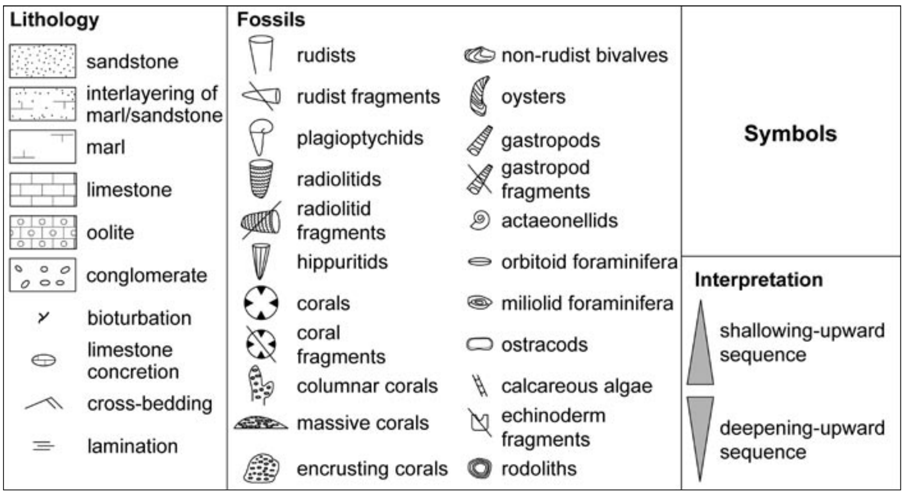

Fig. 4 Explanation of lithological and fossil symbols used in the following Figures (Figs. 5–8, 10, 11).

CAVINS, 1927; MYERS, 1968; MUELLERRIED, 1930; ALENCASTER et al., 1999; SCHAFHAUSER et al., 2002). In addition, they are also well-known from the Caribbean region (CHUBB, 1971; MITCHELL, 2002; STEUBER, 2002; STEUBER et al., 2002) as well as from coeval sediments of Chiapas in southern Mexico (ALENCASTER, 1971) and the Yucatan carbonate platform in Guatemala (SCOTT, 1995; STEUBER, 2002). Their taxonomy was described in detail by many authors, including BÖSE (1906), MYERS (1968), and ALENCASTER (1971). In contrast, the coral fauna of the Cardenas Fm. is nearly unknown. A list of all coral species collected during this field work from several outcrops of the upper member of the Cardenas Fm. is presented in Table 1.

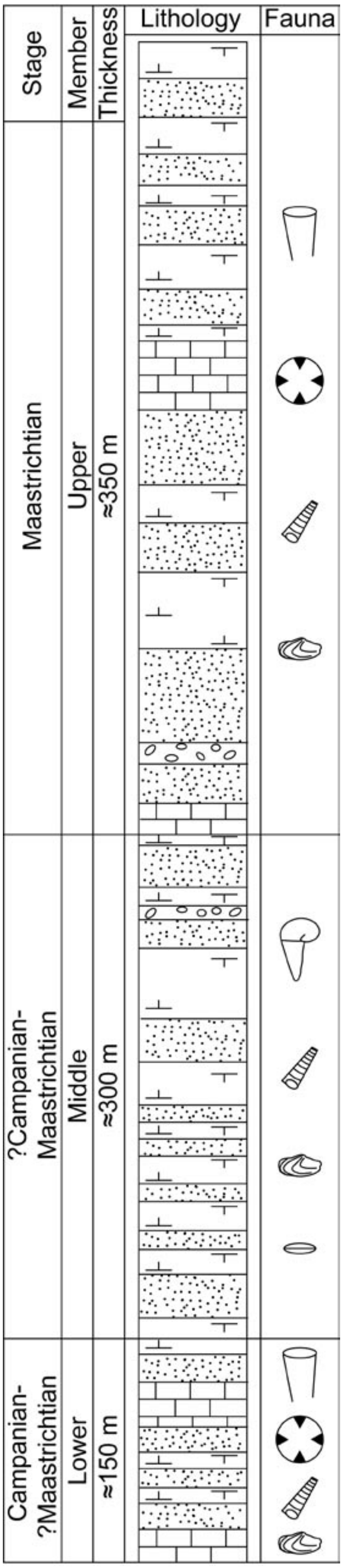

Fig. 5 Schematic illustration of lithology, lithostratigraphic units and faunal content of the Cardenas Formation as described by MYERS (1968) (for explanations of symbols see Fig. 4).

5. RUDIST ASSOCIATIONS WITHIN THE CARDENAS FORMATION

One layer comprising individuals or clusters of radiolitids (*r1*) and 23 coral–rudist reefs (*r2–r24*) is exposed in the investigated section of the Cardenas Formation (Figs. 6–8, 10). The reefs are concentrated in 5 limestone units (Fig. 6): unit *u1* encompasses radiolitid assemblage *r1* and coral–rudist reef *r2* (Fig. 7), unit *u2* reefs *r3* and *r4* (Fig. 8), unit *u3* reefs *r5–r8* (Fig. 8), unit *u4* reefs *r9–r15* (Fig. 8), and unit *u5* reefs *r16–r24* (Fig. 10). In general, the number of units and their thickness increase towards the top of the section (Fig. 6). Within each unit, reef-thickness ranges from 0.5 to 2 m. Towards the tops of units *u3*, *u4*, and *u5* reef thicknesses decrease gradually. The reefs are separated by marls, sandy marls or fine-grained sandstones. Generally, the unsorted bioclasts and the well preserved fossils in the reef limestones indicate autochthonous embedding of the coral–rudist reefs. In the following description we group rudist and coral–rudist associations of similar character and distinguish four different types: radiolitid assemblages, mixed coral–rudist reefs, coral-dominated reefs, and hippuritid-dominated reefs.

Dictuophyllia conferticostata (VAUGHAN,1899)
Cladocora jamaicaensis VAUGHAN, 1899
Cladocora gracilis (D'ORBIGNY, 1850)
Antiguastrea cellulosa (DUNCAN, 1863)
Multicolumnastraea cyathiformis (DUNCAN, 1865)
Placocoenia major FELIX, 1903
Siderastrea vancouverensis VAUGHAN, 1923
Siderastrea adkinsi (WELLS, 1934)
Actinhelia elegans (GOLDFUSS, 1826)
Meandrophyllia oceani (FROMENTEL, 1873)
Dermosmiliopsis orbignyi ALLOITEAU, 1952
Trochoseris catadupensis VAUGHAN, 1899
Cyathoseris formosa D'ACHIARDI, 1875
Actinacis parvistella OPPENHEIM, 1930
Actinacis haueri REUSS, 1854
Goniopora sp.

Table 1 Coral species collected from the upper member of the Cardenas Formation.

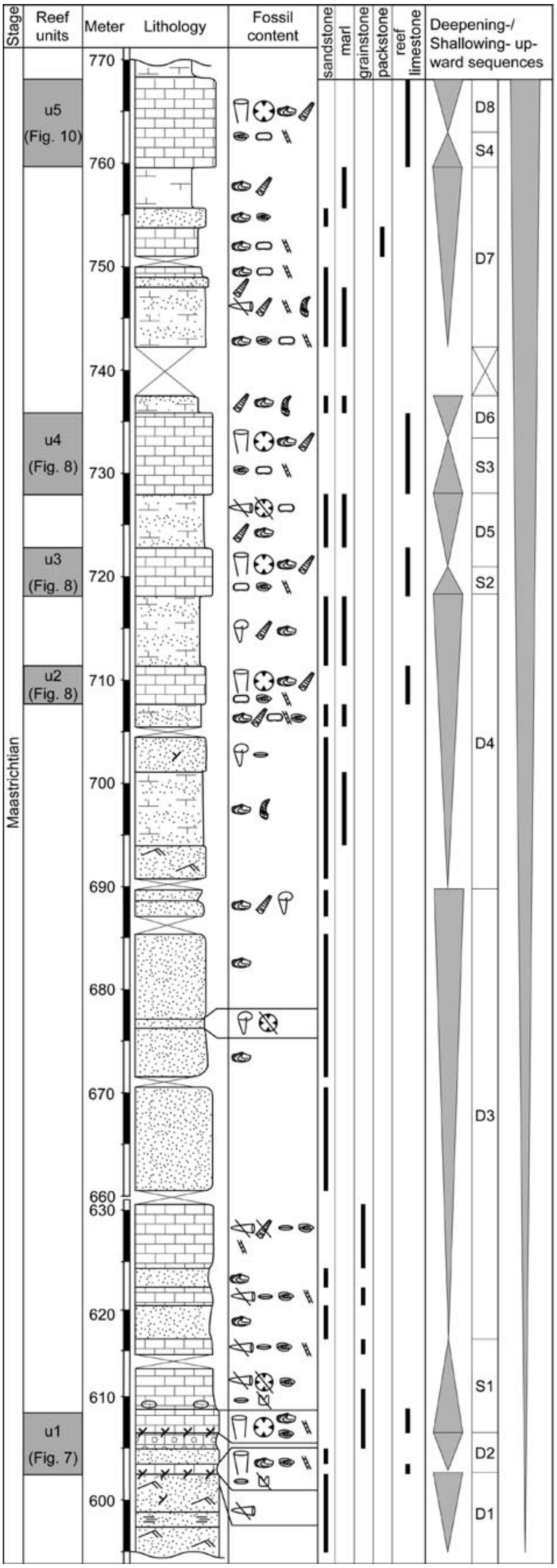

Fig. 6 Lithologic succession and fossil content of the investigated section of the Cardenas Formation. The section contains 5 limestone units illustrated separately in Figs. 7, 8, 10. The whole sedimentary succession is interpreted as a transgressive facies sequence that consists of 8 deepening-upward (D1–D8) and 4 shallowing-upward (S1–S4) facies sequences (for explanation of symbols see Fig. 4).

5.1. Radiolitid assemblages

In the investigated section the lowermost rudist-bearing bed (*r1*) is approximately 1 m thick and contains single specimens or clusters of small radiolitids, which reach maximum heights of approximately 5 cm (Fig. 7). The sediment consists of a radiolitid floatstone with packstone matrix that contains rare benthic foraminifera (rotaliidae, miliolidae), coralline algae as well as fragments of echinoderms. The bioclasts are unsorted and angular, suggesting only minor current energy. Rudists are not in life position, but parautochthonous embedding is suggested by the low degree of shell fragmentation.

5.2. Coral–rudist reefs

The majority of the reefs in the Cardenas Formation are mixed coral–rudist reefs (*r2–r4*, *r6*, *r7*, *r10–r14*) (Figs. 7–8). Their thickness ranges from 0.5 to 2 m. Upsection, in units *u3* and *u4*, the reefs continuously decrease in thickness. Reefs *r3* and *r4* are laterally exposed. They are lens-shaped biostromes and reach lateral extensions of approximately 14 m. Within the units the reefs are separated by marls, sandy marls or fine-grained sandstones. The latter contain abundant actaeonellid gastropods. In unit *u3* plagioptychids are also very common.

Generally, this reef-type contains a diverse coral–rudist fauna. The rudists are dominated by radiolitids (*T. floriformis*, *Bournonia cardenasensis* (BÖSE), *Biradiolites* sp.) and plagioptychids (*Coralliochama gboehmi* BÖSE, *Coralliochama* sp.), but hippuritids (*Hippurites muellerriedi* TRECHMANN, *Hippurites ceibarum* MUELLERRIED) were also observed, which occur in thickets of more than 10 species. The radiolitid *Tampsia* and plagioptychid *Coralliochama* reach maximum heights of approximately 40 cm. Hippuritids are up to 15 cm in height. The coral fauna encompasses columnar, massive, and encrusting growth-forms. Species comprise abundant *Multicolumnastraea cyathiformis* as well as *Siderastrea adkinsi*, *Actinhelia elegans*, *Cladocora gracilis*, *Dictuophyllia conferticostata*, *Dermosmiliopsis orbignyi*, *Placocoenia major*, *Actinacis parvistella*, and *Actinacis haueri*. In reef *r2* a large number of *Neithea*, a non-rudist bivalve, settled onto the corals. The reef fauna of the coral–rudist reefs is generally well preserved and appears in growth position. Only in reef *r6* and on the top of *r2* rudists and branched corals are reworked but still well preserved and unfragmented, thus indicating the absence of significant transport. Upsection from the reworked layer of *r6*, the prior reef fauna is reestablished. In thin sections coralline algae frequently encrust both rudists and corals, whereas hippuritid shells suffered strong bioerosion.

Clinger morphotypes (SKELTON & GILI, 1991) of plagioptychids build the pioneer fauna at the base of reefs *r3* and *r4* (Fig. 9). They settled in scour marks

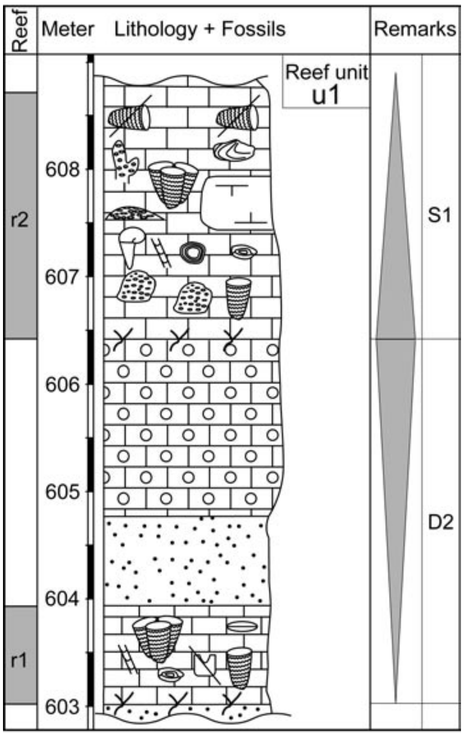

Fig. 7 Detailed illustration of limestone unit *u1* (see also Fig. 6). The section contains 1 radiolitid assemblage (*r1*) and 1 mixed coral–rudist reef (*r2*). The sedimentary succession includes 1 deepening-upward (D1) and 1 shallowing-upward sequence (S1) that are also illustrated in Fig. 6 (for explanation of symbols see Fig. 4).

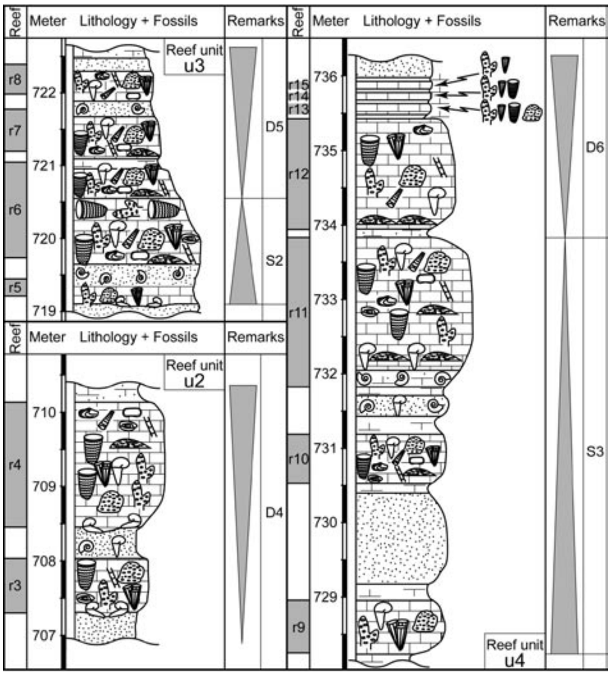

Fig. 8 Detailed illustration of units *u2–u4*, (see also Fig. 6). The 3 units contain 9 coral–rudist reefs (*r3*, *r4*, *r6*, *r7*, *r10*, *r11*, *r12*, *r13* and *r14*) and 4 hippuritid-dominated reefs (*r5*, *r8*, *r9* and *r15*), and include 3 deepening-upward (D4–6) and 2 shallowing-upward (S2, S3) sequences that are also illustrated in Fig. 6 (for explanation of symbols see Fig. 4).

that are incised into the underlying sandstones and might have provided a stable substrate for the overlying reef-fauna. Reef sediment consists of coral–rudist rudstones with packstone and wackestone matrix that contains unsorted and angular fragments of rudists, corals, gastropods, and non-rudist bivalves as well as detrital quartz. Microfossil constituents comprise abundant dasycladaceans, ?gymnocodiaceans, and benthic foraminifera (miliolids and rotaliids) as well as coralline algae and ostracods with articulated valves. In addition, rodoliths are abundant components in the packstones and wackestones of reef *r2* and present nuclei of radiolitid and plagioptychid fragments.

5.3. Coral-dominated reefs

The reefs *r17–r24* in the uppermost section (unit *u5*) are dominated by corals (Fig. 10). Upsection, reef-thickness decreases from 1–2 m at the base to 15–40 cm at the top. The 9 reefs are separated by layers of marls, which are 1–25 cm in thickness.

The number and diversity of rudists in coral-dominated reefs is considerably lower than in the underlying coral–rudist reefs (*r1–r16*). The rudist fauna consists of radiolitids (*Biradiolites* sp.), plagioptychids, and sparse hippuritids (e.g., *H. ?perkinsi*). Rudists are small and reach up to 10 cm in height. Although the diversity of corals is very low, they are the main reef builders. The coral fauna is conspicuously dominated by columnar and ramose growth forms of the species *M. cyathiformis* and *D. conferticostata*, but massive growth forms of the species *A. cellulosa* also occur. Numerous specimens of *Neithea* were found on top of the corals and are characteristic components of the coral-dominated reefs.

The matrix of the reef bafflestone consists of packstone with abundant miliolid foraminifera, dasycladaceans, and rare fragments of gastropods. Abundant ostracods and miliolid foraminifera were found in the interlayered marls.

5.4. Hippuritid-dominated reefs

Reefs *r5*, *r8*, *r9*, *r15* and *r16* (Figs. 8, 10) are between 20 cm and 1 m thick and characterized by the abundance of hippuritids and the absence of radiolitids. 10–15 cm thick marl and sandstone layers separate these hippuritid-dominated reefs from coral–rudist or coral-dominated reefs (Figs. 8, 10). The sandstones upsection from reef *r5* and below reef *r8* contain abundant actaeonellids (Fig. 8), whereas a 10 cm thick marl layer overlies reef *r16* (Fig. 10).

Except for the absence of radiolitids the faunal composition is similar to the coral–rudist reefs. The rudist fauna is exclusively composed of hippuritids (*H. ceibarum*, *Hippurites* sp.) and plagioptychids whereas coral species are generally the same as in the coral–rudist reefs. Reef sediment is also similar to the

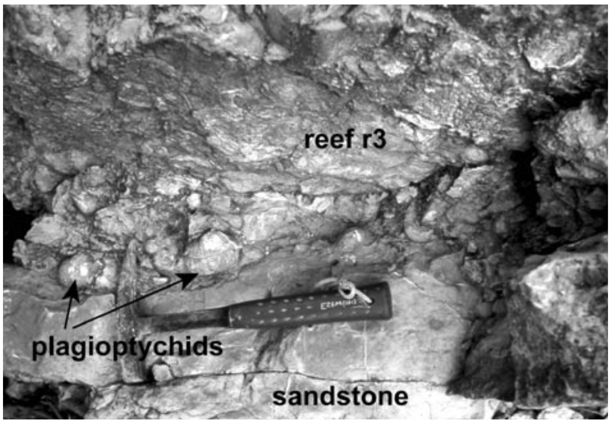

Fig. 9 Clinger morphotypes (SKELTON & GILI, 1991) of plagioptychids build the pioneer fauna at the base of reef *r3*. They settled in scour marks that are incised into the underlying sandstone units.

coral–rudist reefs, except for the absence of coralline algae and ostracods.

6. DEPOSITIONAL ENVIRONMENT OF THE CARDENAS FORMATION

Rudist and coral–rudist associations of the Cardenas Formation developed in areas of low water energy and on soft substrates, indicated by low fragmentation of the fauna and by the angular and unsorted bioclasts in the wackestones and packstones. The abundance of dasycladacean algae and miliolid foraminifera in the sediments suggest rudist and coral growth in lagoonal environments. High-energy events produced reworked layers of rudists and corals (e.g., *r2*, *r6*, *r17*; Figs. 7, 8, 10).

In the lower part of the section, a high input of terrigenous clastic sediments is indicated by the abundance of sandstone units which prevented the development of extended reefs. Only clusters of small radiolitids developed and corals are completely absent. Moreover, the radiolitid-bearing sandstone units below the radiolitid assemblage *r1* are also devoid of coral fragments. Radiolitids might have been able to sustain changes in water chemistry, salinity, and aerial exposure (KAUFFMAN & SOHL, 1973), thus indicating a near-shore environment for these assemblages, possibly in the upper subtidal area of restricted lagoons. This theory is also supported by the presence of laminated and cross-bedded sandstones below these units which are interpreted as shoreface zone deposits (TUCKER, 1990a).

In the upper part of the section the decreasing number of sandstone units indicates less influence of clastic sediments resulting in the development of abundant diverse mixed coral–rudist reefs (Figs. 6, 8). The diverse coral fauna indicates stenohaline conditions and deeper waters than is suggested by the radiolitid assemblage below. Nevertheless, the mixed

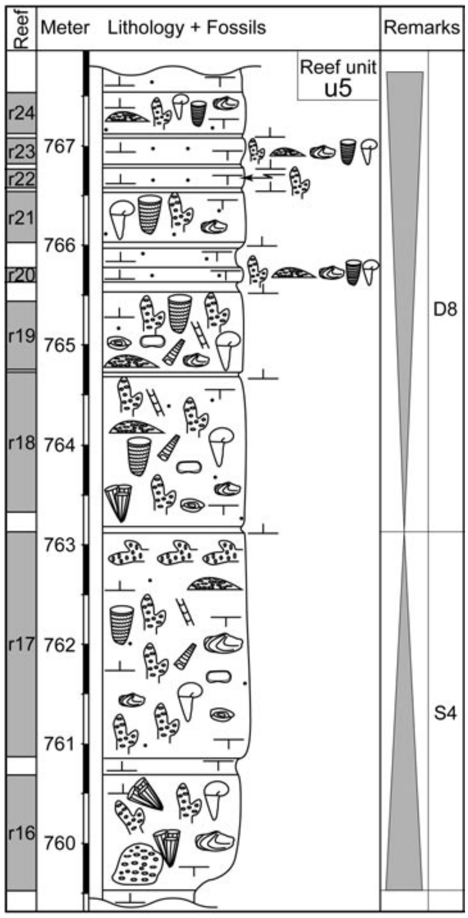

Fig. 10 Detailed illustration of limestone unit *u5* (see also Fig. 6). The unit contains 8 coral–rudist reefs (*r17–r24*) and 1 hippuritid-dominated reef (*r16*) and includes 1 deepening-upward (D8) and 1 shallowing-upward (S4) sequence that are also illustrated in Fig. 6 (for explanation of symbols see Fig. 4).

coral–rudist and coral-dominated reefs developed in shallow water environments or even in open lagoons, which is indicated by the presence of abundant miliolid foraminifera and dasycladacean algae. In the coral-dominated reefs, the absence of detrital quartz and the predominance of columnar and ramose corals indicate low water energy (CHAPPELL, 1980) and reef growth in sheltered lagoonal areas, which were not influenced by the input of clastic sediments (GÖTZ, 2001).

In the hippuritid-dominated reefs (*r5*, *r8*, *r9*, *r15*, *r16*; Figs. 7–8, 10) the absence of ostracods and radiolitids suggests that this reef type reflects the deepest environments of all reefs in the investigated section. They correspond to the hippuritid reefs described from the mixed siliciclastic–carbonate units of the Gosau basin in Austria, where hippuritid-dominated reefs grew on the inner shelf (SANDERS & BARON-SZABO, 1997; SANDERS & PONS, 1999). Also, on the Turonian–Upper Santonian Adriatic Carbonate Platform hippuritid reefs occur in the deeper parts of the outer platform (MORO, 1997). The actaeonellid-bearing sandstones that are intercalated with the hippuritid-dominated reefs and the mixed coral–rudist reefs might represent mobile sand bodies that separated the lagoonal from inner shelf environments (SANDERS & PONS, 1999).

In the Cardenas Fm. plagioptychid rudists are not restricted to reefal limestones. They occur in life position with a diverse molluscan fauna in marls and sandstones. The clinger plagioptychids, *Coralliochama*, form a pioneer fauna at the base of the coral–rudist reefs *r3* and *r4* in scour marks that are incised into the underlying clastic units. Plagioptychids also occur within mixed coral–rudist, coral-dominated, and hippuritid reefs. However, radiolitid-assemblages are devoid of plagioptychids. This indicates that plagioptychids tolerated input of terrigenous clastic sediment into their habitat, but on the other hand they were probably less tolerant to changes in salinity and temperature.

7. FACIES DEVELOPMENT WITHIN THE SECTION

Environments of rudist- and coral–rudist associations are similar in the investigated section, but allow definition of 8 deepening (D1–D8) and 4 shallowing-upward sequences (S1–S4) (Fig. 6). Reef thickness decreases in transgressive intervals and increases in regressive sequences (Figs. 8, 10). We grouped these facies sequences in 4 idealized sedimentary cycles, comprising 2 deepening- and 2 shallowing-upward cycles (Fig. 11). In the section most of the cycles are incomplete. Unfortunately, the composition of these idealized cycles is obscured by sandstone units (e.g., D3, D7 – Fig. 6). The sand derived from the uplifting Sierra Madre Oriental to the west and was episodically transported into the Cardenas area, where these beds are superimposed on the cyclic background sedimentation.

The first idealized deepening-upward cycle (Fig. 11a) consists of basal cross-bedded and laminated calclithites of the shoreface which pass into lagoonal radiolitid assemblages, that are in turn overlain by oolithic grainstones. The well-rounded and sorted ooids indicate shallow water depths and form oolite bars that were deposited seaward of the lagoons on the inner shelf (TUCKER, 1990b, c). This cycle type occurs in the lowermost part of the section and is represented by facies sequences D1 and D2 (Fig. 6). The sequences are separated from the following cycles by bioturbated horizons.

The second type of deepening-upward cycle (Fig. 11b) is represented by facies sequences D3–8 (Figs. 6, 8, 10) and comprise cross-bedded shoreface calclithites which pass into lagoonal marls or limestones, which contain miliolid foraminifera and dasycladacean algae. Upsection they are overlain by coral–rudist associations (coral–rudist, coral-dominated or hippuritid-dominated reefs) passing into thin bedded marls and sandstones, which are rich in gastropods (turritellids), plagiopty-

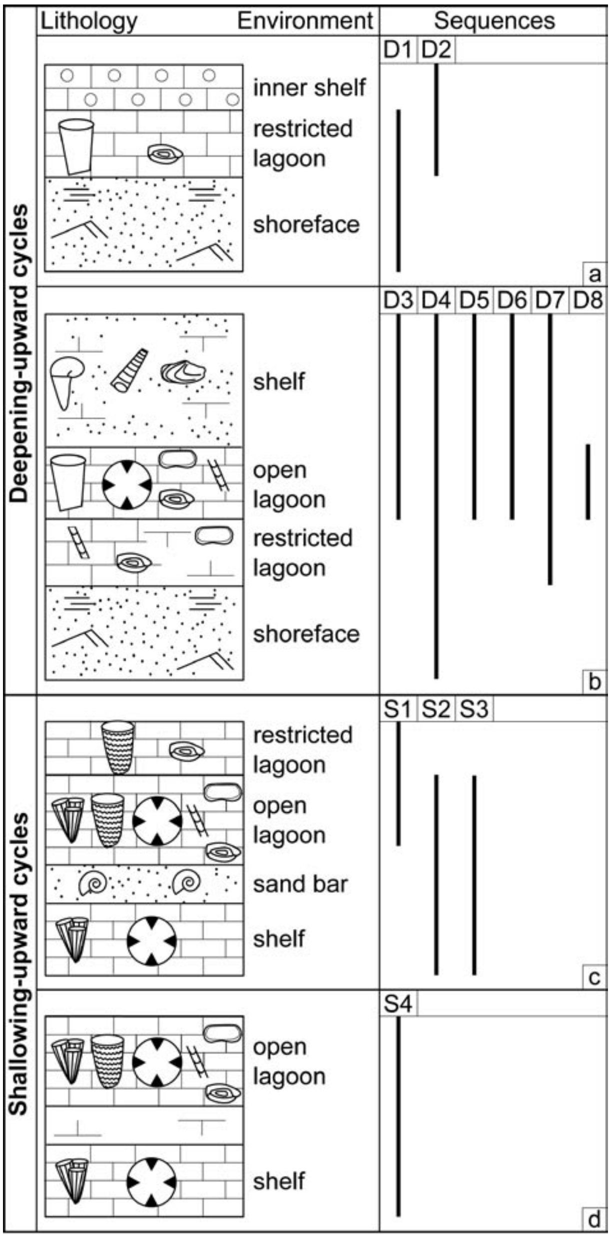

Fig. 11 Idealized sedimentary cycles observed in the investigated section (Fig. 6). Frequently, however, these cycles are incompletely developed and obscured by sandstone units (see text). In the right column, facies are marked that occur in the deepening- and shallowing-upward sequences of the investigated section (for explanation of symbols see Fig. 4).

chids (*Coralliochama* sp.), and non-rudist bivalves. Our interpretation is that these interlayered marls and sandstones represent the deepest part of the depositional area and were deposited on the inner shelf indicated by the diverse molluscan fauna, sparse miliolid foraminifera, and the absence of calcareous algae.

The abundance of sandstones makes interpretation of facies sequence D3 difficult. Limestones containing rudist fragments, miliolid foraminifera, and dasycladacean algae are interpreted as the talus of rudist dominated lagoonal assemblages. The diverse fauna in the uppermost part of the sequence is similar to the inner shelf fauna described above from the deepening-upward cycle (Fig. 11b). The lack of coral-rudist reefs may be due to the high input of clastic sediments, which was indeed tolerated by the inner shelf fauna comprising gastropods, plagioptychids, and non-rudist bivalves. Therefore, we interpret this sequence as a transgressive succession, which passes from lagoonal to inner shelf environments like the idealized deepening-upward cycle of Fig. 11b.

At its base, the first idealized type of shallowing-upward cycle (Fig. 11c) consists of hippuritid-dominated reefs from the inner shelf, which are overlain by actaeonellid sand bar deposits. Upsection mixed coral–rudist reefs of the inner lagoon follow.

The second type of shallowing-upward cycle (Fig. 11d) occurs only in the uppermost rudist unit *u5* (Figs. 6, 10) and differs from the shallowing-upward cycle described above by the lack of sand bar deposits. Coral-dominated reefs grew in sheltered areas with less sediment input (see chapter 6): actaeonellid-bearing sand bar deposits are replaced by marls.

Shallowing-upward cycles commonly terminate in layers containing reworked reef fauna (S2, S4; Figs. 8, 10). We interpret these reworked layers as having been derived from reefs situated above the storm wave base, which were therefore subject to erosion.

The investigated section of the Cardenas Fm. consists of interlayered fine-grained sandstones, marls, and limestones. In the lower part of the section, sediments of the shoreface and lagoonal sediments are predominant and are represented by cross-bedded and laminated sandstones, and radiolitid assemblages. In the upper part of the section the number of sandstone units decrease, whereas limestone units are abundant. In addition, units of marl layers occur, which contain a diverse inner shelf fauna, indicating a general deepening-upward trend from the base of the section towards the top. Such transgressive phases together with the low sediment input permitted the development of the diverse coral–rudist reefs in the Cardenas area.

8. CONCLUSIONS

The investigated section of the upper Cardenas Formation is of Maastrichtian age and comprises a transgressive sequence that consists of sandstones, marls, and limestones. The limestone units contain 4 types of rudist and coral–rudist associations. Radiolitid assemblages were deposited in restricted lagoons. Mixed coral–rudist and coral-dominated reefs developed in open stenohaline lagoons. Reefs dominated by corals are indicative of sheltered areas with less input of clastic sediments. Hippuritid-dominated reefs grew seaward of the lagoons on the inner shelf. Only plagioptychids occur in both the coral–rudist associations and the clastic sediments of the outer shelf, but are absent in the radiolitid assemblages of restricted lagoons. Plagioptychids were able to live in environments strongly influenced by changing sediment input, but were probably less tolerant to salinity or temperature changes of the seawater.

The investigated transgressive sequence encompasses several deepening- and shallowing-upward facies sequences, which can be grouped in idealized types of deepening- and shallowing-upward cycles. The deepening-upward cycles pass from cross-bedded sandstones of the shoreface into calcareous algal or radiolitid dominated limestones and marls of restricted lagoons. They are in turn overlain by lagoonal coral–rudist associations and marls of the outer shelf containing diverse molluscan assemblages (gastropods, plagioptychids and non-rudist bivalves).

The shallowing-upward cycles consist of basal hippuritid-dominated reefs that pass into actaeonellid sand bar deposits or marls, which are overlain by coral–rudist reefs.

This cyclic background sedimentation was obscured by the episodic input of clastic sediments derived from the uplifting Sierra Madre Oriental to the west. This sediment input decreases in the upper part of the transgressive sequence, resulting in an increasing number of coral–rudist reefs. So rudist reefs of the Cardenas Formation flourished in times of low sediment input during transgressive phases.

Acknowledgements

We gratefully acknowledge the CALDERON family and José Miguel DÍAZ from Cardenas and Prof. Dr. Lopéz OLIVA from the Universidad Autónoma de Nuevo León for support during field work. We thank Stefan UNREIN and Elke HERRMANN for preparing thin sections and acknowledge the constructive review of this paper by Robert W. SCOTT and Jose M. PONS. We also thank the German Academic Exchange Service (DAAD) and Deutsche Forschungsgemeinschaft (project STI 128/7, GO 1021/2–1 and BA 1830/3) for financial support.

9. REFERENCES

D'ACHIARDI, A. (1875): Coralli eocenici del Friuli [*Eocene corals of Friuli* – in Italian].– Atti della Societa Toscana di Scienze Naturali resindente in Pisa, 1, 67–86.

ALENCASTER, G. (1971): Rudistas de Cretácico superior de Chiapas, parte 1 [*Upper Cretaceous rudists from Chiapas, Part 1* – in Spanish].– Paleontología mexicana, 34, 1–91.

ALENCASTER, G., OMAÑA, L., PONS, J.M., TORRES, J.R., TRISTAN, M. & VAZQUEZ, N. (1999): Upper Cretaceous rudists and larger foraminifera from the Cárdenas region, San Luis Potosí, México.– Erlanger Geologische Abhandlungen, 3, 6–7.

ALLOITEAU, J. (1952): Embranchment de Coelentérés. II. Madréporaires post-paleozoiques [*Branching of*

Coelenterates. II. Post-paleozoic madrepores – in French].– In: PIVETEAU, J. (ed.): Traité de Paléontologie. Publ. sous la dir. de Jean Piveteau, 1, 539–684.

BASAÑEZ-LOYOLA, M.A., FERNANDEZ-TURNER, R. & ROSALES-DOMINGUEZ, C. (1993): Cretaceous platform of Valles–San Louis Potosi, northeastern Central Mexico.– In: SIMO, T.J.A., SCOTT, W.R. & MASSE, J.-P. (eds.): Cretaceous Carbonate Platforms. AAPG Memoir, 56, 51–59, Tulsa.

BÖSE, E. (1906): La fauna de moluscos del Senoniano de Cárdenas, San Luis Potosí [*Molluscan fauna of the Senonian from Cárdenas, San Luis Potosí* – in Spanish].– Boletín del Instituto Geológico de México, 24, 95 p.

BÖSE, E. & CAVINS, O.A. (1927): The Cretaceous and Tertiary of southern Texas and northern Mexico.– University of Texas Bulletin, 2784, 7–142.

BURCKHARDT, C. (1930): Etude synthétique sur le Mésozoique mexicain [*Integrated study on the Mexican Mesozoic* – in French].– Société Paléontologique de Suisse Memoir, 49–50, 280 p.

CAMOIN, G., BERNET, R.M.C. & PHILIP, J. (1988): Rudist–coral frameworks associated with submarine volcanism in the Maastrichtian of the Pachino area (Sicily).– Sedimentology, 35, 123–138.

CAUS, E., TAMBAREAU, Y., COLIN, J.-P., AGUILAR, M., BERNAUS, J.-M., GOMEZ-GARRIDO, A. & BRUSSET, S. (2002): Upper Cretaceous microfauna of the Cárdenas Formation, San Luis Potosí, NE Mexico. Biostratigraphical palaeoecological, and palaeogeographical significance.– Revista Mexicana de Ciencias Geológicas, 19, 137–144.

CHAPPELL, J. (1980): Coral morphology, diversity and reef growth.– Nature, 286, 249–252.

CHUBB, L.J. (1971): Rudists of Jamaica.– Palaeontographica Americana, 7, 161–257.

DUNCAN, P.M. (1863): On the fossil corals of the West Indian Islands.– Quarterly Journal of the Geological Society of London, 19, 406–458.

DUNCAN, P.M. (1865): A notice of the geology of Jamaica, especially with reference to the district of Clarendon; with descriptions of the Cretaceous, Eocene and Miocene corals of the islands.– Quarterly Journal of the Geological Society of London, 21, 1–14.

FELIX, J.P. (1903): Studien über die korallenführenden Schichten der oberen Kreideformation in den Alpen und in den Mediterrangebieten [*Studies on the coral–bearing beds from the Upper Cretaceous formation of the Alps and the Mediterranean regions* – in German].– Palaeontographica, 49, 163–359.

FROMENTEL, E. DE (1873): Zoophytes, terrains crétacés [*Zoophytes, Cretaceous terrains* – in French].– In: ORBIGNY, A. DE (ed.): Paléontologie Francaise. Masson, Paris, 9, 385–432.

FUENTE-NAVARRO, M.J. DE LA (1964): Estudio geológico del area Cárdenas–Rio Verde, S.L.P., y Arroyo Seco, Qro., México [*Geological study of the area Cárdenas-Rio Verde, S.L.P., and Arroyo Seco, Qro, Mexico* – in Spanish].– Boletín de la Asociación Mexicana de Geólogos Petroleros, 16, 237–249.

GILI, E. & SKELTON, P.W. (2000): Factors regulating the development of elevator rudist congregations.– In: INSALACO, E., SKELTON, P.W. & PALMER, T.J. (eds.): Carbonate Platform Systems: Components and Interactions. Geological Society of London Special Publications, 178, 109–116.

GILI, E., MASSE, J.-P. & SKELTON, P.W. (1995): Rudists as gregarious sediment-dwellers, not reef-builders, on Cretaceous carbonate platforms.– Palaeogeography, Palaeoclimatology, Palaeoecology, 118, 245–267.

GOLDFUSS, A. (1826): Petrefacta Germaniae (1) [*Fossils (petrefacts) of Germany* – in German].– ARNZ, Düsseldorf, 1–114.

GOLDHAMMER, R.K. & JOHNSON, C.A. (2001): Middle Jurassic–Upper Cretaceous paleogeographic evolution and sequence-stratigraphic framework of the northwest Gulf of Mexico rim.– In: BARTOLINI, C., BUFFLER, R.T. & CANTU-CHAPA, A. (eds.): The Western Gulf of Mexico Basin. AAPG Special Memoir, 75, 45–82.

GÖTZ, S. (2001): Rudisten-Assoziationen der keltiberischen Oberkreide SE-Spaniens: Paläontologie, Palökologie und Sediment–Organismus–Wechselwirkungen [*Rudist associations of the celtiberian Upper Cretaceous of SE Spain: paleontology, palecology and sediment-organism interactions* – in German].– Abhandlungen Bayerische Akademie der Wissenschaften, Naturwissenschaftliche Klasse, 171, 112 p.

GÖTZ, S. (2003): Biotic interaction and synecology in a Late Cretaceous coral–rudist biostrome of southeastern Spain.– Palaeogeography, Palaeoclimatology, Palaeoecology, 193, 1–14.

HÖFLING, R. (1997): Eine erweiterte Riff-Typologie und ihre Anwendung auf kretazische Biokonstruktionen [*An expanded riff-typology and its application on Cretaceous bioconstructions* – in German].– Abhandlungen Bayerische Akademie der Wissenschaften, Naturwissenschaftliche Klasse, 169, 127 p.

HURTADO-GONZALEZ, B. (1984): Implicaciones paleoecologicás de los moluscos cretácicos (bivalvia y gastropoda) de la región de Ciudad del Maíz, San Luis Potosí, México [*Paleoecological implications of Cretaceous molluscans (bivalvia and gastropoda) from the region Ciudad del Maíz, San Luis Potosí, México* – in Spanish].– Memoria del III Congreso Latinoamericano de Paleontología, 415–421.

JOHNSON, C.C. & KAUFFMAN, E.G. (1996): Maastrichtian extinction patterns of Caribbean province rudistids.– In: MACLEOD, N. & KELLER, G. (eds.): Cretaceous–Tertiary Mass Extinctions: Biotic and Environmental Changes. Norton, W.W. & Company, New York, 231–273.

KAUFFMAN, E.G. (1973): Cretaceous Bivalvia.– In: HALLAM, A. (ed.): Atlas of Paleobiogeography. Elsevier, Amsterdam, 353–383.

KAUFFMAN, E.G. & SOHL, N.F. (1973): Structure and evolution of Antillean Cretaceous rudist frameworks.– Verhandlungen der Naturforschenden Gesellschaft Basel, 84, 400–467.

LAVIANO, A. (1984): Preliminary observation on the Upper Cretaceous coral–rudist facies of Ostuni (south-eastern Murge, Apulia).– Rivista Italiana di Paleontologia e Stratigrafia, 90, 177–204.

LOPEZ-RAMOS, E. (1985): Geologia de Mexico, Tomo II [*Geology of Mexico, Part II* – in Spanish].– INEGI, Ciudad de Mexico, 454 p.

MASSE, J.P. & PHILIP, J. (1981): Cretaceous coral–rudist buildups of France.– In: TOOMEY, D.F. (ed.): European Fossil Reef Models. Society of Economic Paleontologists and Mineralogists SEPM (Society of Sedimentary Geology), Special Publications, 30, 399–426.

MITCHELL, S.F. (2002): Palaeoecology of corals and rudists in mixed volcaniclastic–carbonate small-scale rhythms (Upper Cretaceous, Jamaica).– Palaeogeography, Palaeoclimatology, Palaeoecology, 168, 1–23.

MORAN-ZENTENO, D. (1994): The geology of the Mexican republic.– AAPG Studies in Geology, 39, 160 p.

MORAN-ZENTENO, D.J., MARTINY, B., TOLSON, G., SOLIS-PICHARDO, G., ALBA-ALDAVE, L., HERNANDEZ-BERNAL, S.M., ROMO-MACIAS, C., MARTINEZ-SERRANO, R.G., SCHAAF, P. & ROMO-SILVA, G. (2000): Geocronología y características geoquímicas de las rocas magmáticas terciarias de la Sierra Madre del Sur [*Geochronology and geochemical characteristics of the Tertiary magmatic rocks of the Sierra Madre del Sur* – in Spanish].– Boletín de la Sociedad Geológica Mexicana, 53, 27–58.

MORO, A. (1997): Stratigraphy and paleoenvironments of rudist biostromes in the Upper Cretaceous (Turonian–upper Santonian) limestones of southern Istria, Croatia.– Palaeogeography, Palaeoclimatology, Palaeoecology, 131, 113–131.

MUELLERRIED, F.K.G. (1930): Un Hippurites de la región de Cárdenas, S.L.P. [*One hippuritid from the Cardenas region* – in Spanish].– Anales del Instituto de Biología, 1, 165–168.

MYERS, R.L. (1968): Biostratigaphy of the Cardenas Formation (Upper Cretaceous) San Luis Potosí, Mexico.– Paleontología Mexicana, 24, 89 p.

OPPENHEIM, P. (1930): Die Anthozoen der Gosauschichten in den Ostalpen [*The anthozoans of the Gosau beds from the Eastern Alps* – in German].– Privately published, Berlin–Lichterfelde, 604 p.

ORBIGNY, A. DE (1850): Prodrôme de Paléontologie stratigraphique universelle [*Harbinger of universal stratigraphic paleontology* – in French].– Masson, Paris, 2, 428 p.

PETTIJOHN, F.J., POTTER, P.E. & SIEVER, R. (1984): Sand and Sandstone.– Springer Verlag, New York, Berlin, Heidelberg, London, Paris, Tokyo, 552 p.

PINDELL, J.L., CANDE, S.C., PITMAN, W.C. III, ROWLEY, D.B., DEWEY, J.F., LABRECQUE, J. & HAXBY, W. (1988): A plate-kinematic framework for models of the Caribbean evolution.– Tectonophysics, 155, 121–138.

REUSS, A.E. (1854): Beiträge zur Charakteristik der Kreideschichten in den Ostalpen, besonders im Gosauthale und am Wolfgangsee [*Contributions to characterize the Cretaceous beds in the Eastern alps, especially in the valley of Gosau and at the Lake Wolfgang* – in German].– Denkschriften der kaiserlichen Akademie der Wissenschaften, Mathematisch–Naturwissenschaftliche Classe, 7, 73–133.

RIDING, R. (2002): Structure and composition of organic reefs and carbonate mud mounds: concepts and categories.– Earth-Science Reviews, 58, 163–231.

ROSS, D.J. & SKELTON, P.W. (1993): Rudist formations of the Cretaceous: a palaeoecological, sedimentological and stratigraphical review.– Sedimentology Review, 1, 73–91.

SANDERS, D. & BARON-SZABO, R.C. (1997): Coral–rudist bioconstructions in the Upper Cretaceous Haidach Section (Gosau Group; Northern Calcareous Alps, Austria).– Facies, 36, 69–90.

SANDERS, D. & PONS, J.P. (1999): Rudist formations in mixed siliciclastic–carbonate depositional environments, Upper Cretaceous, Austria: stratigraphy, sedimentology, and models of development.– Palaeogeography, Palaeoclimatology, Palaeoecology, 148, 249–284.

SCHAFHAUSER, A., STINNESBECK, W., GÖTZ, S. & LOPEZ-OLIVA, J.G. (2002): Maastrichtian rudists of the Cardenas Formation (central Mexico) connect Northern Gulf of Mexico and Yucatan Fauna.– In: VLAHOVIĆ, I. & KORBAR, T. (eds.): 6th International Congress on Rudists, Abstracts and Excursion Guidebook. Institute of Geology, Zagreb, 67.

SCOTT, R.W. (1995): Cretaceous rudists of Guatemala.– Revista Mexicana de Ciencias Geológicas, 12/2, 294–306.

SCOTT, R.W., FERNANDEZ-MENDIOLA, P.A., GILI, E. & SIMO, A. (1990): Persistence of coral–rudist reefs into the Late Cretaceous.– Palaios, 5, 98–110.

SKELTON, P.W. & GILI, E. (1991): Palaeoecological classification of rudist morphotypes.– In: SLADIĆ-TRIFUNOVIĆ, M. (ed.): 1st International Conference on Rudists. Serbian Geological Society, Spec. Publ., 2, 265-287 [Issued only as reprint from unpublished volume].

SOHL, N.F., MARTINEZ, E.R., UREÑA-SALMERON, P. & JARAMILLO-SOTO, F. (1991): Upper Cretaceous.– In: SALVADOR, A. (ed.): The Geology of North America: The Gulf of Mexico Basin. Geological Society of America Boulder, J, 205–244.

STEUBER, T. (2002): Depository item 2002022, List of occurrences of rudist bivalves (Hippuritoidea) in the Americas. Plate tectonic control on the evolution of Cretaceous platform-carbonate production.– Geology, 30, 259, 71 p.

STEUBER, T., MITCHELL, S.F., BUHL, D., GUNTER, G. & KASPER, H.U. (2002): Catastrophic extinction of Caribbean rudist bivalves at the Cretaceous–Tertiary boundary.– Geology, 30, 999–1002.

SUTER, M. (1987): Structural traverse across the Sierra Madre Oriental in east–central Mexico.– Geological Society of America Bulletin, 98, 249–264.

TORRE, H.C. DE LA (1964): Estudio geológico del area Cerritos–Cardenas [*Geological study of the area Cerritos–Cardenas* – in Spanish].– Boletín de la Asociación Mexicana de Geólogos Petroleros, 16, 221–235.

TUCKER, M. (1990a): Coastal and offshore environments.– In: TUCKER, M. & WRIGHT, V.P. (eds.): Carbonate Sedimentology. Blackwell Scientific Publications, London, 101–126.

TUCKER, M. (1990b): Modern carbonate environments.– In: TUCKER, M. & WRIGHT, V.P. (eds.): Carbonate Sedimentology. Blackwell Scientific Publications, London, 101–126.

TUCKER, M. (1990c): Shelf margin sand bodies.– In: TUCKER, M. & WRIGHT, V.P. (eds.): Carbonate Sedimentology. Blackwell Scientific Publications, London, 101–126.

VAUGHAN, T.W. (1899): Some Cretaceous and Eocene corals from Jamaica.– Bulletin of the Museum of Comparative Zoology, 34, 227–250.

VAUGHAN, T.W. (1923): Fauna of the Sooke Formation, Vancouver Island, Description of a new coral.– Publications of Geology, University of California, 14, 175–176.

VEGA, F.J., FELDMANN, R.M. & SOUR-TOUVAR, F. (1995): Fossil crabs (crustacea: decapoda) from the late Cretaceous Cárdenas Formation, East–Central Mexico.– Journal of Paleontology, 69, 340–350.

WELLS, J.W. (1934): Some fossil corals from the West Indies.– Proceedings of the U.S. Natural Museum, Washington, 83, 71–110.

YE, H. (1997): The arcuate Sierra Madre Oriental orogenic belt, NE Mexico: Tectonic infilling of a recess along the southwestern North American Continental Margin.– In: SOEGAARD, K., GILES, K., VEGA, F.J. & LAWTON, T. (eds.): Structure, Stratigraphy and Paleontology of Late Cretaceous–Early Tertiary Parras–La Popa Foreland basin near Monterrey, northeast Mexico. AAPG Field Trip, 82–115.

Manuscript received March 24, 2003.

Revised manuscript accepted November 04, 2003.