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Coral-Rudist Bioconstructions in the Upper Cretaceous Haidach Section (Gosau Group; Northern Calcareous Alps, Austria)

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KEYWORDS: CORAL-RUDIST BIOCONSTRUCTIONS – NORTHERN CALCAREOUS ALPS – UPPER CRETACEOUS (GOSAU GROUP)

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SUMMARY

In the area of Haidach (Northern Calcareous Alps, Austria), coral-rudist mounds, rudist biostromes, and bioclastic limestones and marls constitute an Upper Cretaceous shelf succession approximately 100 meters thick. The succession is part of the mixed siliciclastic-carbonate Gosau Group that was deposited at the northern margin of the Austroalpine microplate.

In its lower part, the carbonate succession at Haidach comprises two stratal packages that each consists, from bottom to top, of a coral-rudist mound capped by a rudist biostrome which, in turn, is overlain by bioclastic limestones and, locally, marls. The coral-rudist mounds consist mainly of floatstones. The coral assemblage is dominated by *Fungiina*, *Astracoina*, *Heterocoeniina* and *Agathelia asperella* (Stylinina). From the rudists, elevators (*Vaccinites* spp., radiolitids) and recumbents

(*Plagioptychus*) are present. Calcareous sponges, sclerospores, and octocorals are subordinate. The elevator rudists commonly are small; they settled on branched corals, coral heads, on rudists, and on bioclastic debris. The rudists, in turn, provided settlement sites for corals. Predominantly plocoid and thamnasterioid coral growth forms indicate soft substrata and high sedimentation rates. The mounds were episodically smothered by carbonate mud. Many corals and rudists are coated by thick and diverse encrustations that indicate high nutrient level and/or turbid waters.

The coral-rudist mounds are capped by *Vaccinites* biostromes up to 5 m thick. The establishment of these biostromes may result from unfavourable environmental conditions for corals, coupled with the potential of the elevator rudists for effective substrate colonization. The *Vaccinites* biostromes are locally topped by a thin radiolitid biostrome. The biostromes, in turn, are overlain by bioclastic limestones; these are arranged in stratal packages that were deposited from carbonate sand bodies. Approximately mid-section, an interval of marls with abundant *Phelopecteria* is present. These marls were deposited in a quiet lagoonal area where meadows of sea grass or algae, coupled with an elevated nutrient level, triggered the mass occurrence of *Phelopecteria*.

The upper part of the Haidach section consists of stratal packages that each is composed of a rudist biostrome overlain by bioclastic wackestones to packstones with diverse smaller benthic foraminifera and calcareous green algae. The biostromes are either built by radiolitids, *Vaccinites*, and *Pleurocora*, or consist exclusively of radiolitids (mainly *Radiolites*). Both the biostromes and the bioclastic limestones were deposited in a low-energy lagoonal environment that was punctuated by high-energy events. *In situ* rudist fabrics typically have a matrix of mudstone to rudist-clastic wackestone; other biogens (incl. smaller benthic foraminifera) are absent or very rare. The matrix of rudist fabrics that indicate episodic destruction by high-energy

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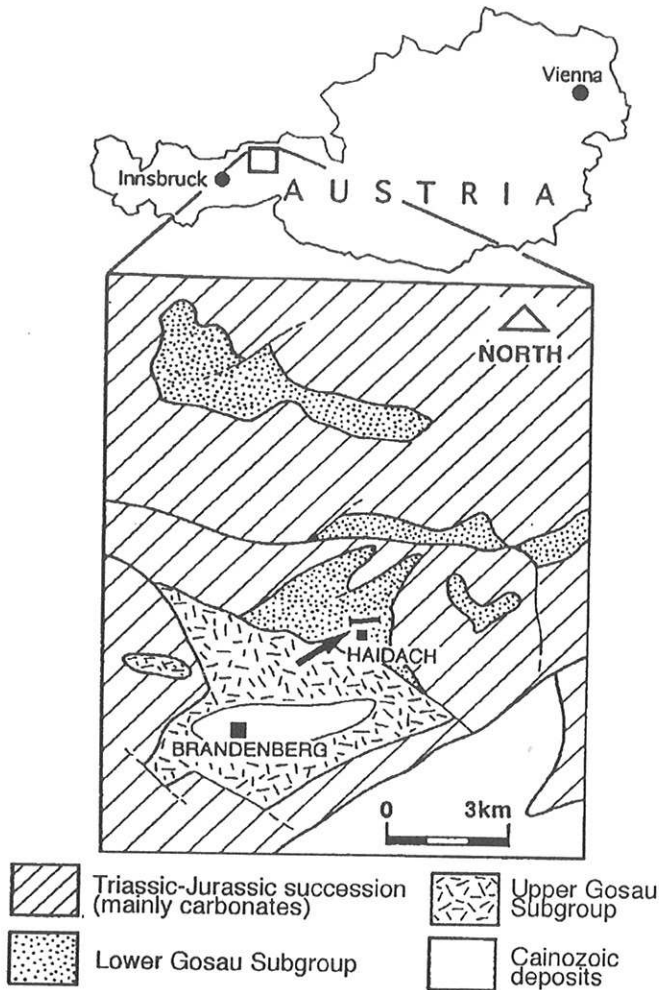


Fig. 1. Position of working area in Austria, and simplified geologic map of the Brandenburg area. The location of the investigated section near Haidach is indicated by an arrow.

events contain a fossil assemblage similar to the vertically associated bioclastic limestones. Substrata colonized by rudists thus were unfavourable at least for smaller benthic foraminifera.

The described succession was deposited on a gently inclined shelf segment, where coral-rudist mounds and hippuritid biostromes were separated by a belt of bioclastic sand bodies from a lagoon with radiolitid biostromes. The mounds document that corals and Late Cretaceous elevator rudists may co-occur in close association. On the scale of the entire succession, however, mainly as a result of the wide ecologic range of the rudists relative to corals, the coral-dominated mounds and the rudist biostromes are vertically separated.

1 INTRODUCTION

During Late Cretaceous times, the elevator rudists (hippuritids, radiolitids) were the most characteristic faunal element of the tropical-subtropical shelves (e.g. PHILIP 1972; KAUFFMAN & SOHL 1974; CARBONE & SIRNA 1981; KAUFFMAN & JOHNSON 1988; ROSS & SKELTON 1993; SAND-

ERS 1994, 1996 a; PHILIP et al. 1995). Relative to corals, the Late Cretaceous elevator rudists were of wider ecologic range, and they could thrive under widely different environmental conditions, including the slightly restricted lagoonal areas of both isolated and attached carbonate platforms, and in association with siliciclastics and volcaniclastics (eg. FREYTET 1973; KAUFFMAN & SOHL 1974; KERR 1977; CAMOIN et al. 1988; KAUFFMAN & JOHNSON 1988; ROSS & SKELTON 1993; SANDERS 1994, 1996 a; SCHUMANN 1995). The Late Cretaceous rudists and the corals commonly occur in separate bioconstructions. Locally, however, combined coral-rudist constructions are present that bear the potential for a better understanding of the relations between corals and rudists (cf. GILI et al. 1995; SCOTT 1995; SANDERS 1996 b).

In the area of Brandenburg, Austria, a package approximately 100 meters thick of shallow-water limestones is present that represents the thickest succession of Upper Cretaceous shallow-water carbonates in the Northern Calcareous Alps (Figs. 1 and 2). This carbonate succession contains different types of both coral-rudist bioconstructions and rudist biostromes.

In this paper, the carbonate succession is described and interpreted in terms of depositional setting and environments. The coral-rudist bioconstructions and the rudist biostromes are described by a combined sedimentologic and paleontologic approach. The factors that controlled the stratigraphic development of the entire succession, and the controls over the growth of the coral-rudist bioconstructions and the rudist biostromes are discussed.

2 GEOLOGICAL SETTING

Since the Liassic, the area of the Northern Calcareous Alps was part of the Austroalpine microplate that was situated along the northern, passive continental margin of the Adriatic plate (CHANNELL et al. 1990; WAGREICH & FAUPL 1994). During the latest Jurassic, a convergent plate tectonic regime was established. During Early Cretaceous convergence, the sedimentary succession of the Northern Calcareous Alps was deformed into a stack of cover nappes that are completely detached from their substratum. During "middle" Cretaceous times, large parts of the future Eastern Alps were uplifted and eroded (PLATT 1986; RATSCHBACHER et al. 1989). In the area of the Northern Calcareous Alps, subaerial exposure and erosion are recorded by karstification below a deeply dissected truncation surface, and by bauxite accumulations.

From Turonian to Santonian times, the exposed areas became gradually re-submergent, and deposition of the so-called Gosau Group started. In the area of Brandenburg, the Gosau Group unconformably overlies Triassic-Jurassic rocks (Fig. 1). The Gosau Group is subdivided into the Lower Gosau Subgroup (Turonian-Campanian) that consists of terrestrial to neritic deposits, and the Upper Gosau Subgroup (Santonian-Eocene), which is made up by deep marine deposits (Fig. 1) (WAGREICH & FAUPL 1994). An overall tropical-subtropical environment during deposi-

tion of the Lower Gosau Subgroup is indicated by bauxite deposits and by the presence of fossils from the Tethyan paleobiogeographic realm (corals, rudists). The coral-rudist bioconstructions described in this paper are part of the Lower Gosau Subgroup (Fig. 1).

3 METHODS

The Upper Cretaceous succession was mapped on a scale of 1/5000. The section described in this paper is located along a dirt road, and many beds can be traced laterally over approximately 300 meters (Fig. 2). The section is well-exposed, and the underlying Upper Cretaceous succession and its relation to the older substratum can be mapped. The section can be correlated with another one (see HERM et al. 1979) that is situated farther towards the south; the two sections are laterally separated by faults (Fig. 2).

In the described section, approximately 300 megafossils were collected and examined, and approximately 100 polished slabs and 71 thin sections were used for the documentation of the lithologies. The fossils are stored in the collections of the Bayerische Staatssammlung für Paläontologie und historische Geologie, Munich, Germany, and of the Geological Institute of the University of Innsbruck, Austria. The rock samples are stored at the Geological Institute of the University of Innsbruck.

4 BIOSTRATIGRAPHY

In the middle part of the section, in an interval of marls ("*Phelopteria* marls" in Fig. 4, section B), the biomarkers *Cremnoceramus? rotundatus*, *Inoceramus* sp. aff. *ernsti*, and *Mytiloides? sp. aff. stantoni* are present, and were assigned an Early to middle Coniacian age (HERM et al. 1979: 36, 81). Following the revisions of the Cretaceous stage boundaries and biozone correlations (GRADSTEIN et al. 1994), these bivalves are now considered to mark the lower Lower Coniacian (SUMMESBERGER & KENNEDY 1996, and references therein). In the marls, the assemblage of *Bipodorhabdus brooksi*, *Calculites ovalis*, *Eiffellithus eximius*, *Eprolithus floralis*, *Lucianorhabdus maleformis*, *Lithastrinus septenarius* and *Marthasterites furcatus* (det. M. Wagreich, Vienna) also indicates a latest Turonian to Early Coniacian age. Above and below the marls, precise biomarkers are absent. Below the carbonate succession, in an interval dominated by sandstones (Fig. 4, section A), scarce biostratigraphic data include specimens of *Actaeonella obtusa* and the nannofossil *Lithastrinus moratus*, which together indicate a Late Turonian to Coniacian age. The carbonate succession thus is assigned a ?Late Turonian to Early Coniacian age.

The "Atzl reef" (see Fig. 4, section B) is strongly dominated by slender *Vaccinites* with pronounced, relatively sharp-crested ribs. These *Vaccinites* were previously designated as *Vaccinites sulcatus* (HERM 1977). Preliminary results from a revision of the Late Cretaceous rudist fauna of the Northern Calcareous Alps, including

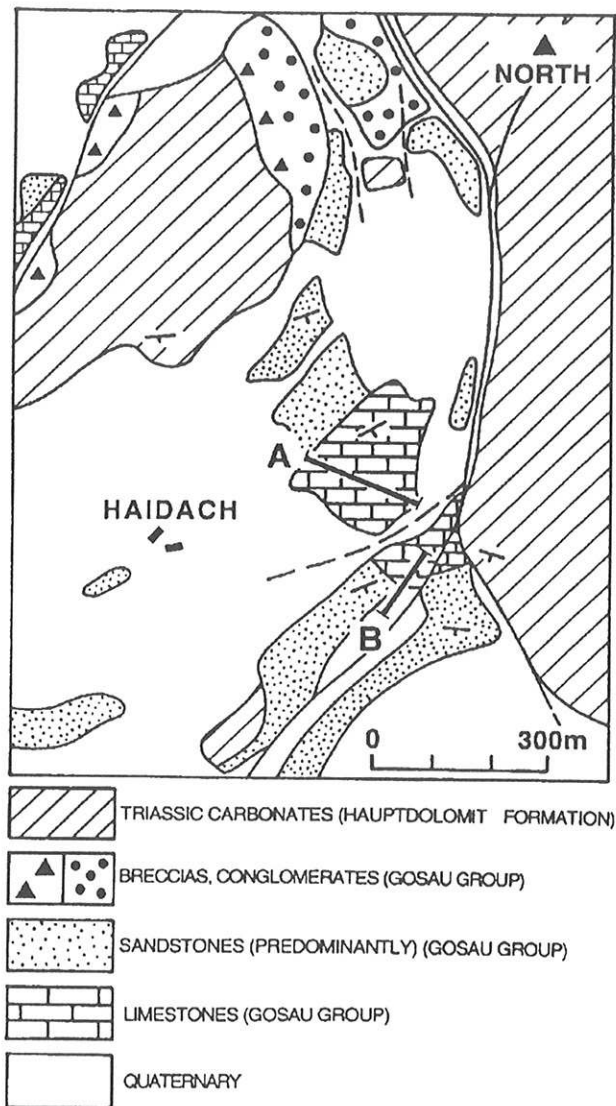


Fig. 2. Simplified geologic map of the area near Haidach. In this area, the Upper Cretaceous succession unconformably overlies the Middle Triassic Hauptdolomit Formation. A: Carbonate section described in this paper. B: Section described by HERM et al. (1979).

the "Atzl reef", indicate that this determination may be incorrect (J. M. Pons, pers. comm. 1996). Since this type of rudist is quite common in the Haidach section, to distinguish it from other *Vaccinites*, in the following it is designated as *Vaccinites "sulcatus"*.

5 SEDIMENTARY SUCCESSION

The Upper Cretaceous succession of the Haidach section unconformably overlies the Middle Triassic Hauptdolomit Formation (Fig. 2). The Upper Cretaceous succession starts with breccias and conglomerates (Fig. 4, section A) that are composed of clasts of Hauptdolomit embedded in a matrix of terra rossa. These are followed up-section mainly by marly, bioturbated sandstones, lenticular- to flaser-bedded sandstones, and bioturbated sandstones with

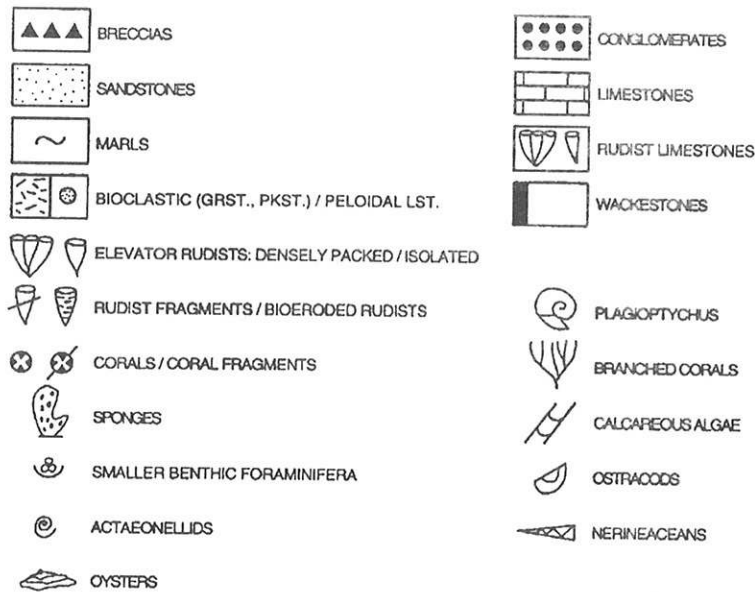


Fig. 3. Key to symbols used in figures 4 to 8.

gastropods (actaeonellids, cassiopids, cerithids) (Fig. 4, section A). Higher up, the succession is mainly composed of upward shoaling cycles that locally contain an interval of coral-rudist limestone or a siliciclastic conglomerate at their base, overlain by sandstones with hummocky cross-lamination, megaripple trough cross-lamination and low-angle cross-lamination. At the top of some cycles, laminated mudstones to wackestones with miliolids or with characean fragments are present.

The sandstone-dominated part of the section is overlain by a succession that consists nearly exclusively of more or less marly limestones with corals and rudists, and bioclastic limestones (Fig. 4, section A) (see below for further description). From bottom to top, the limestone succession consists of stratal packages that each is defined by a lower interval of coral-rudist limestone and/or rudist limestone and an upper interval of bioclastic limestones to, locally, bioclastic marls (Fig. 4, section B). Up-section, these packages become both thinner and contain an increasing proportion of limestones from shallow subtidal environments. The entire limestone succession thus records an upward shoaling of facies, accompanied by an upward thinning of its constituent stratal packages. Within each package, the bioclastic limestones contain a fossil assemblage that suggests deposition in more shallow subtidal depths than the underlying coral-rudist limestone or rudist limestone (see description below). No lithologies, however, were found that indicate deposition at intertidal to supratidal depths. At least most of the packages thus represent incomplete upward shoaling cycles. For the sake of description, the succession has been vertically subdivided into four intervals (labelled 1 to 4 in Fig. 4, section B). The limestone succession is followed up-section by sandstones with parallel lamination, dune cross-lamination, and hummocky cross-lamination. In the following, the lithologies of the limestone succession and their fossil content are described and interpreted.

6 LITHOLOGIES

6.1 Coral-rudist limestones

Marly limestones rich in corals and rudists are best developed in interval 1 and 2 (Fig. 4, section B). The intervals of coral-rudist limestones are both under- and overlain by bioclastic limestones. Within interval 1, the coral-rudist limestones are based by a bed some decimeters thick of poorly sorted bioclastic grainstone. The grainstone consists mainly of heavily micritized and bored fragments from corals and rudists that are coated by thick crusts of coralline algae and sessile foraminifera. Some fragments from echinoderms, and miliolids, nezzatids, *Cuneolina*, textulariaceans, and a few percent of siliciclastic sand are admixed.

The coral-rudist limestones comprise intervals up to more than 10 m thick (Fig. 4). These intervals can be traced laterally over hundreds of meters (see chapter 3), and display

a gentle mound-shaped to sheet-like geometry. In outcrop, the intervals of coral-rudist limestones do not display significant lateral and vertical changes of internal construction, aside from both small and gradual changes in thickness. Upon weathering, the coral-rudist limestones typically show a nodular fabric. Individual nodules are separated from each other by marly limestones that locally contain thin, non-stylolitic solution seams. The nodules may consist of a coral head surrounded by a halo of bioclastic wackestone, or of floatstone with corals and rudists. Some nodules consist of small blocks of coral-rudist boundstone.

The coral-rudist limestones typically are floatstones with coral heads, branched corals, and rudists embedded in a matrix of bioclastic wackestone to, locally, packstone. Less commonly, patches of less than a decimeter to some decimeters in size of coral-rudist boundstones are present. In the boundstones, coral heads and rudists are encrusted and bound mainly by coralline algae, bryozoans and sessile foraminifera. The boundstones typically bear a matrix of bioclastic packstone, and are embedded in coral-rudist floatstone. Both in the floatstones and the boundstones, the coral heads typically are some centimeters to a decimeter in size. Larger coral heads of up to 4 dm in diameter are uncommon.

6.1.1 Corals and rudists

In Tab. 1, the distribution of corals (order Scleractinia) in the intervals of coral-rudist limestones is indicated. A total of 82 samples has been determined at the species level. For a discussion of the taxonomy of the corals listed in Tab. 1, the reader is referred to BARON-SZABO (1996). From the octocorals, individuals of *Pseudopolytrema* cf. *spino-septata* (family Helioporidae) were found in the coral-rudist limestones of the intervals 1, 2 and 4, respectively. In addition, the possible alcyonarian sclerite *Pienina oblonga* (cf. GRANIER 1986) is fairly common.

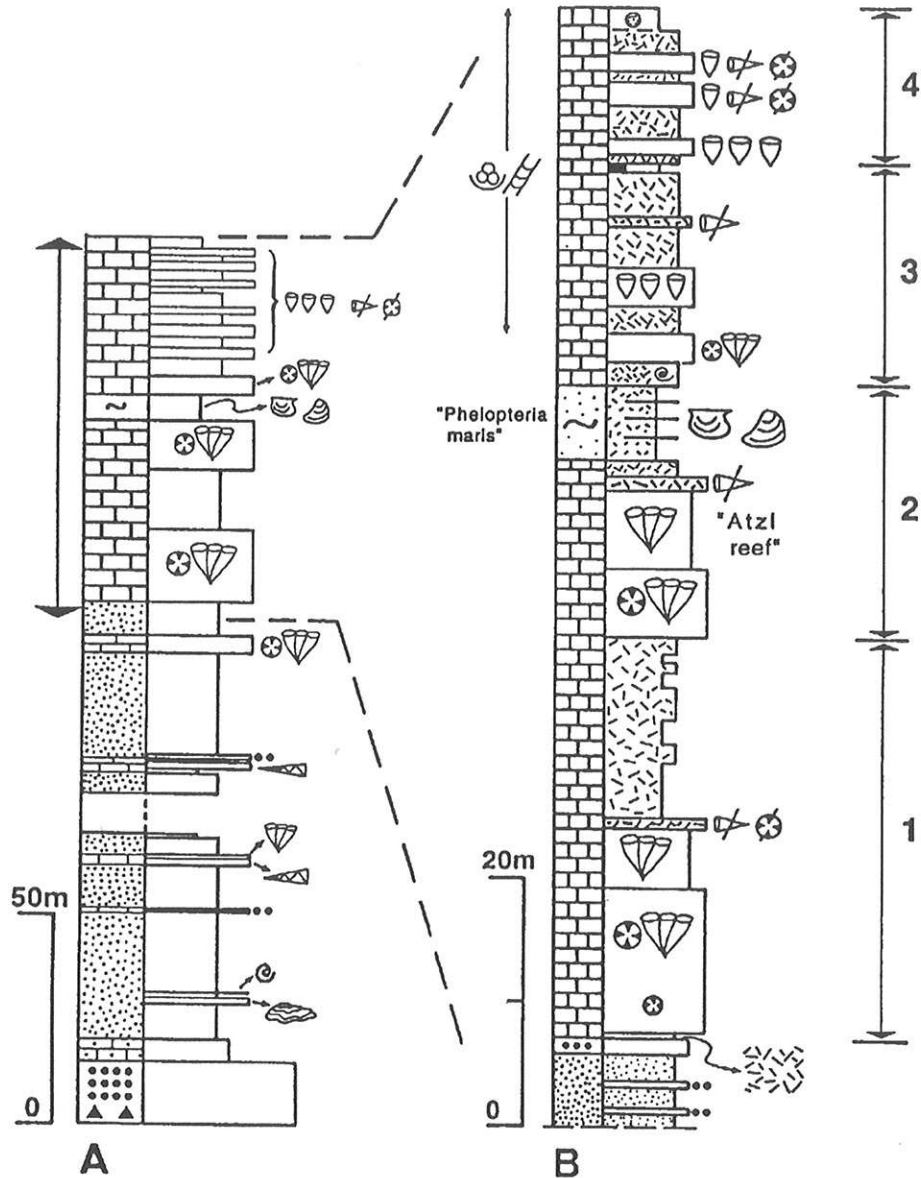


Fig. 4A,B. Upper Cretaceous succession of the area near Haidach (see Fig. 3 for legend). For the sake of description, the carbonate succession (Fig. 4B) is subdivided in four intervals labelled 1 to 4. The lower part of interval 3 is poorly exposed; its total thickness is estimated at approximately 16m.

The scleractinian taphocoenosis is dominated by *Fungiina* (see Pl. 21/1, 2, 4-7; and Tab. 1) and *Stylinina* (family *Agatheliidae*), whereas species of the suborders *Astraeoina* (Pl. 21/3), *Meandriina*, and *Heterocoeniina* are subordinate (Tab. 1). From the *Stylinina*, only the species *Agathelia asperella* was found, but is quite common (Pl. 21/8). In the intervals 1 and 2, from a total of nineteen coral species, five species were found only in interval 1, and four species were found only in interval 2 (see Tab. 1). Most of the corals are of plocoid or thamnasterioid growth form, whereas a small part of the coral assemblage shows branched forms (*Pleurocora*), foliose-encrusting forms, or a conical shape (*Aulosmilia*) (see Tab. 1).

In the coral-rudist limestones, elevator rudists (hippuritids, radiolites; terminology of SKELTON & GILI 1991) are common, but due to their typical small size comprise an unobvious element of the fossil assemblage. From the

hippuritids, to date only *Vaccinites* was identified. At least a large part of the radiolites can be assigned to *Radiolites*. Since many radiolites are small and are preserved without the upper valve and the proper section between lower and upper valve is rarely present, the presence of other radiolite taxa could not be assessed. The elevator rudists typically range between a centimeter to some centimeters in length. Canaliculate rudists are represented by fairly common specimens of *Plagioptychus* of some centimeters to approximately 10 cm in size.

6.1.2 Fossil assemblage

Both in the coral-rudist floatstones and in the boundstones, the matrix is a bioclastic wackestone to packstone (Pl. 22/1) with variable proportions of poorly sorted, more or less micritized fragments from corals, rudists, red algae, and

Suborder	Family	Genus	Species	Occurrence*	Growth Form
STYLININA	Agatheliidae	<i>Agathelia</i>	<i>A. asperella</i>	1, 2	plocoid
HETEROCOENIINA	Heterocoeniidae	<i>Heterocoenia</i>	<i>H. provincialis</i>	1	plocoid
ASTRAEOINA	Placocoeniidae	<i>Placocoenia</i>	<i>P. major</i>	1	plocoid
	Heliastriidae	<i>Neocoenia</i>	<i>N. lepida</i>	1, 2	plocoid
		<i>Neocoenia</i>	<i>N. subpolygonalis</i>	2	plocoid
	Montlivaltiidae	<i>Complexastrea</i>	<i>C. cf. seriata</i>	2	plocoid
	Placosmiliidae	<i>Placophyllia</i>	<i>P. cf. curvata</i>	4	phaceloid
MEANDRIINA	Meandriidae	<i>Aulosmia</i>	<i>A. cuneiformis</i>	1	conical
	Hemiporitidae	<i>Nefocoenia</i>	<i>N. edelbachensis</i>	2	foliose-encrusting
FUNGIINA	Haplaraeidae	<i>Pleurocora</i>	<i>P. cf. alternans</i>	1, 2, 4	dendroid
	Microsoleniidae	<i>Microsolena</i>	<i>M. distefanoi</i>	1, 2	thamnasterioid
			<i>M. kobyi</i>	1, 2	thamnasterioid
			<i>A. martiniana</i>	1, 2	plocoid
	Actinacidae	<i>Actinacis</i>	<i>Actinaraea</i>	1, 2	massive-foliose
			<i>Thamnaraea</i>	1	thamnasterioid
	Kobyastreidae	<i>Kobyastrea</i>	<i>Kobyastrea</i> sp.	4	thamnasterioid
			<i>Thamnasteria</i>	1, 2	thamnasterioid
	Thamnasteriidae	<i>Fungiastrea</i>	<i>F. exigua</i>	2	thamnasterioid
	Latomeandridae	<i>Fungiastrea</i>	<i>F. crespoid</i>	1	thamnasterioid
			<i>Thamnoseria</i>	1, 2	thamnasterioid-subcerioid
			<i>Thamnoseria</i>	1, 2	thamnasterioid-subcerioid

Table 1. Corals in the stratigraphic intervals 1 to 4 (cf. Fig. 4B). The numbers in the column "Occurrence" denote the intervals as indicated in Fig. 4B.

echinoderms (including echinoid spines), and ostracods, miliolids, cf. *Montcharmontia*, nezzazatids, textulariaceans, bryozoans, serpulids, sponge spicules, *Pienina oblonga*, and some peloids. Fragments from calcareous green algae are rare.

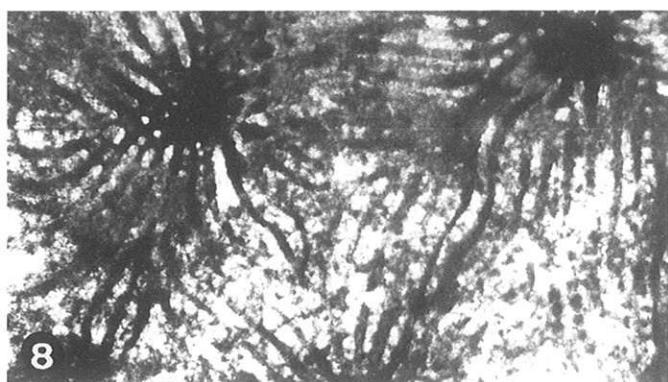
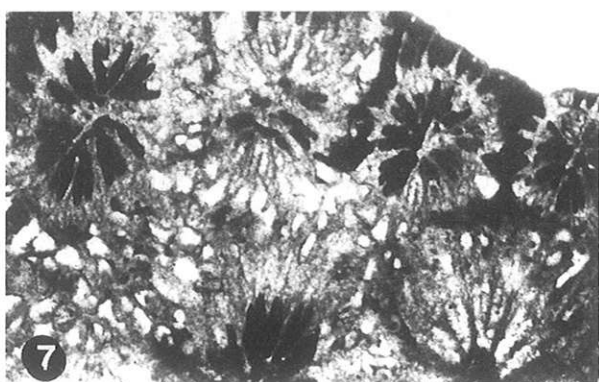
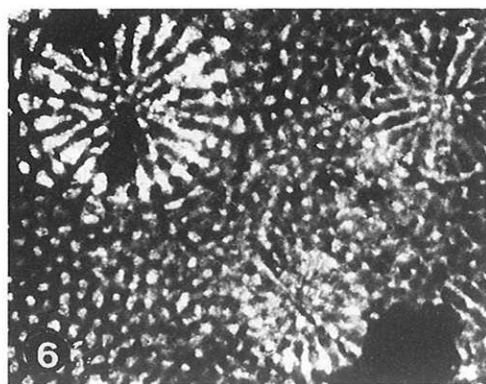
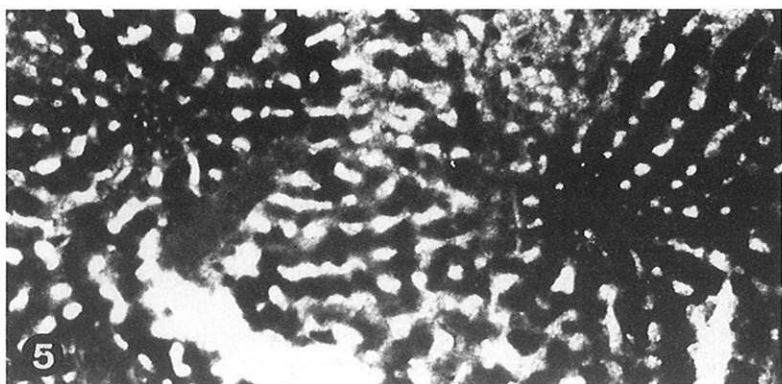
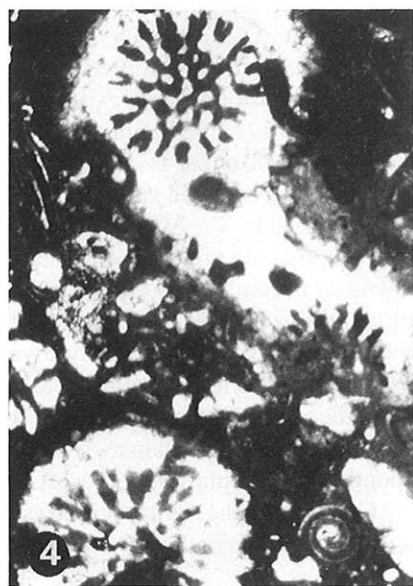
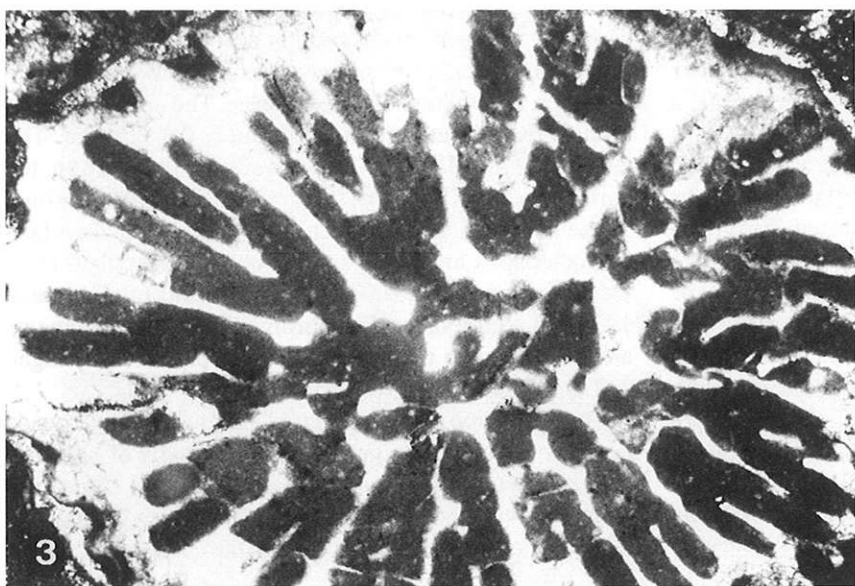
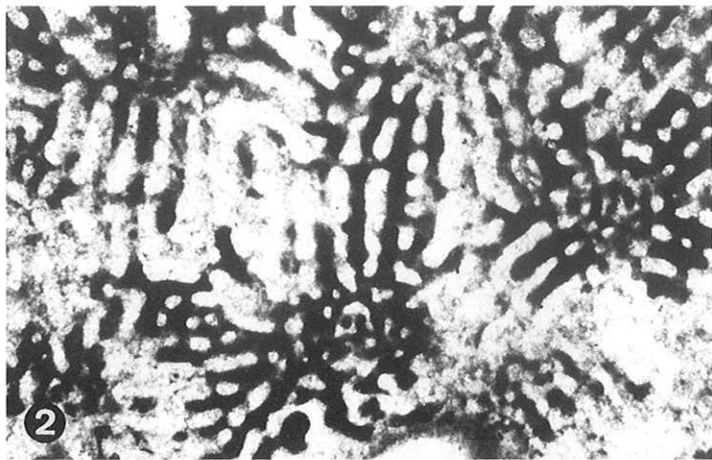
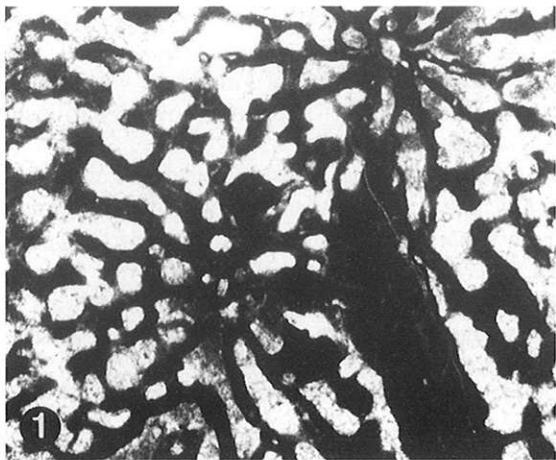
Both in the floatstones and the boundstones, the rudists and the corals are closely associated with each other (Pl. 22/2, 3). Most of the corals and the rudists are coated by more or less thick crusts that consist mainly of coralline algae (*Lithothamnium*, *Archaeolithothamnium*), intergrown with sessile foraminifera (Placopsilininae, Ataxophragmiinae), *Ethelia alba*, bryozoans (Cheilostomata, Cryptostomata), serpulids, cryptmicrobial crusts and encrusting sponges (Pl. 22/2, 4). At least on some coral heads, an upper side dominated by red algal crusts and a lower side

with bryozoan-serpulid encrustations can be distinguished. The coral *Agathelia asperella*, however, typically bears only local, thin crusts of coralline algae and/or cheilostomate bryozoans. The dendroid coral *Pleurocora* cf. *alternans* may be preserved without encrustations, but most typically is coated by a thin, single layer of coralline algae and, locally, may bear sessile foraminifera, serpulids, and thin cryptmicrobial crusts. Rarely, the coralline algae form bridges between the branches of *Pleurocora* or may, together with bryozoans and sessile foraminifera, completely "wrap in" the colonies.

The elevator rudists had settled and grown on all types of hard substrata, including (1) coral colonies/coral fragments (Pl. 22/3), (2) the free valves of *Plagioptychus*, (3) the outer surface of elevator rudists, (4) the inner surface

Plate 21 Corals from Upper Cretaceous coral-rudist limestones near Haidach in Brandenburg, Austria.

- Fig. 1. *Thamnaraea cladophora* FELIX 1903. Coral-rudist limestones of interval 1, Haidach section. Sample 23 C/XIX. x 13.5
- Fig. 2. *Thamnoseria arborescens* FELIX 1891. Coral-rudist limestones of interval 1, Haidach section. Sample 23C/XIII. x 13.5
- Fig. 3. *Placophyllia* cf. *curvata* TURNSEK 1974. Coral-rudist limestones of interval 3, Haidach section. Sample 48/XV. x 12.5
- Fig. 4. *Pleurocora* cf. *alternans* MILNE-EDWARDS & HAIME 1849. Coral-rudist limestones of interval 1, Haidach section. Sample B 1/10. x 13.5
- Fig. 5. *Microsolena kobyi* PREVER 1909. Coral-rudist limestones of interval 2, Haidach section. Sample 35/XV. x 13.5
- Fig. 6. *Actinacis martiniana* D'ORBIGNY 1849. Coral-rudist limestones of interval 3, Haidach section. Sample 44/VII. x 12.5
- Fig. 7. *Fungiastrea crespoid* (FELIX 1891). Coral-rudist limestones of interval 1, Haidach section. Sample B 6/9. x 6.5
- Fig. 8. *Agathelia asperella* REUSS 1985. Coral-rudist limestones of interval 1, Haidach section. Sample B 7. x 3



of the lower valves of elevator rudists, and (5) encrusted, large bioclastic debris. Where the elevator rudists settled on coral heads, locally a concomitant growth of rudist and coral is suggested by both deformed coral polyparia and a deformed and thinned rudist shell along the contact. In addition, both the rudist and the coral are overgrown by the same coralline algal-foraminiferal crust. The attached and encrusted rudists are locally preserved with their free valve still in position. In colonies of the branched coral *Pleurocora* cf. *alternans*, both *Vaccinites* and radiolitids have settled on the coral branches, and are intercalated in growth position and with their free valve preserved within the coral colony. The branches of *Pleurocora* as well as the intercalated rudists are often overgrown by the same coralline algal-foraminiferal crust (Pl. 22/5). In addition, locally both the coral branches and the overgrown rudists are deformed, probably because of concomitant growth. These *Pleurocora*-rudist associations are embedded in a matrix of fine, mollusc bioclastic wackestone with ostracods, a few smaller benthic foraminifera (?lituolaceans), and a few, small non-rudist bivalves. Where the rudists settled and grew on encrusted coral heads, at least the lower part of the attached valve of the rudists is encrusted. The crusts on the rudists are of overall identical composition than the crusts on the corals. Locally, individuals of *Vaccinites* or of radiolitids that are grown on corals and preserved with their upper valve are completely covered by encrustations. Where only the lower valve of the rudists is preserved, both the outer and the inner surface of the valve are encrusted by coralline algae, sessile foraminifera, sclerospenges, and cryptmicrobial crusts.

Conversely, the rudists served as settling site for corals and other sessile benthos. On the upper valve of the rudists,

sessile agglutinated foraminifera, cheilostomate bryozoans, and small coral heads often are present. In addition, isolated individuals and clusters of *Vaccinites* were found that are more or less completely overgrown by foliose-encrusting corals (Pl. 22/6).

In the coral-rudist limestones, sclerospenges are rarely preserved as body fossils, and their presence is commonly indicated by isolated spicules. Locally, the coral *Pleurocora* cf. *alternans* is associated with calcisponges, like *Peronidella ?robusta* (Pl. 22/7). The presence of octocorals is indicated by the subordinate occurrence of *Polytremacis* and fairly common *Pienina oblonga*.

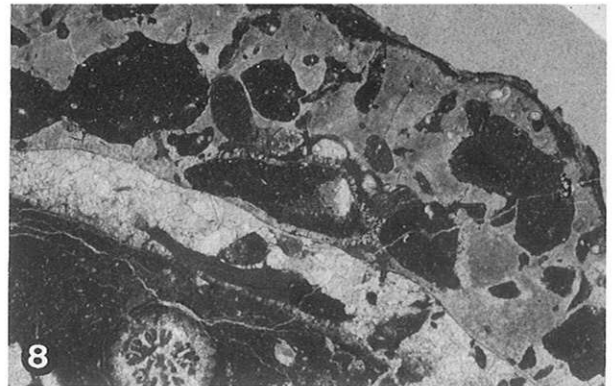
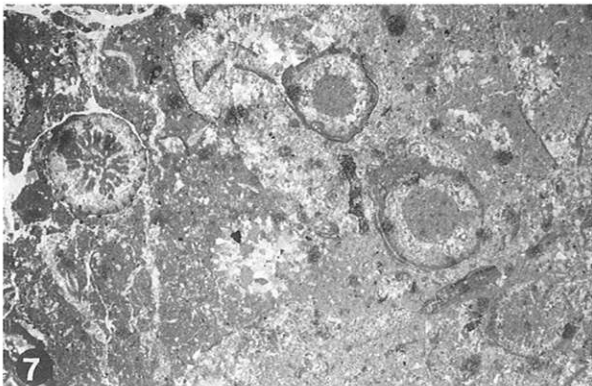
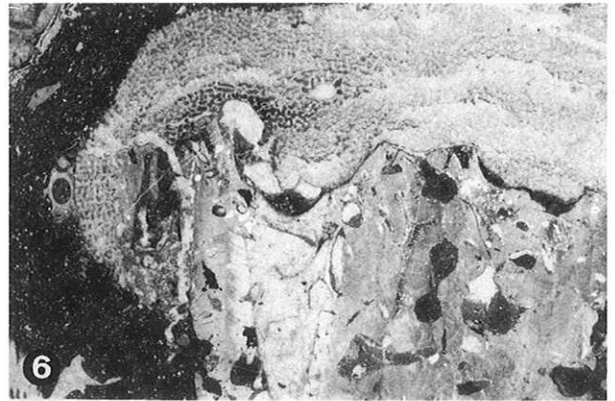
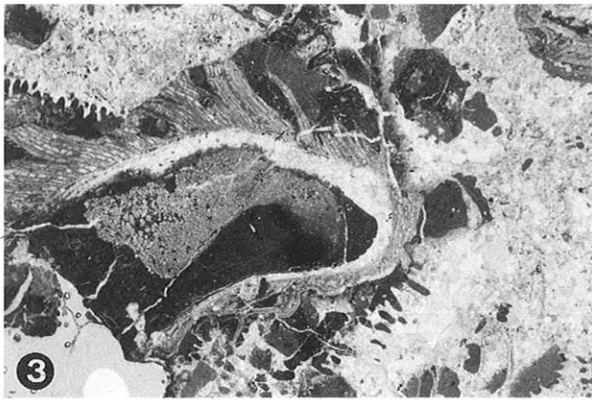
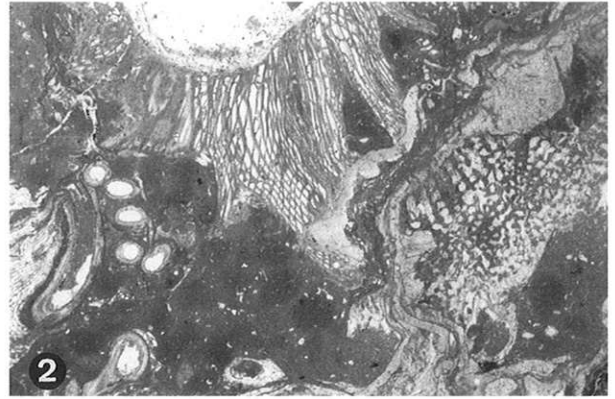
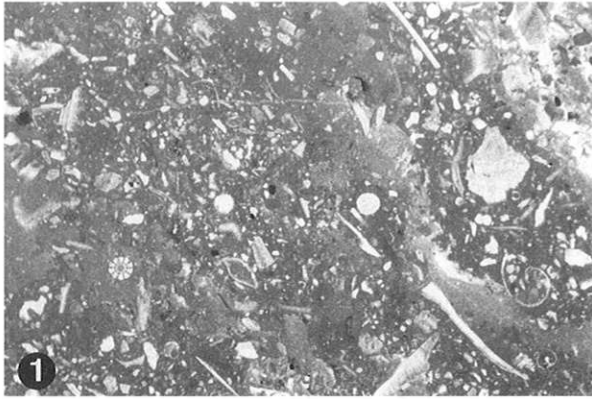
6.1.3 Bioerosion

Both in the corals and the rudists, networks of borings are common that consist of straight to curved tunnels and larger, subspherical chambers (Pl. 22/8). From a single chamber, several tunnels may emerge. The diameter of the tunnels ranges between approximately 0.1-0.5 mm. The chambers typically are 1-2 mm in size. In thin section, the surfaces of the chambers show a finely serrated outline. These borings are identical in size, geometry and surface characteristics to clionid sponge borings described from recent carbonate depositional environments (cf. FÜTTERER 1974). In addition, smaller borings of different geometry are also common that may have been produced by algae and fungi (cf. KOBLUK & RISK 1977).

Another type of boring that is common in coral heads consists of straight to gently curved tunnels of approximately 3-10 mm in diameter; the diameter of the boring increases with increasing length. These borings may extend for more than 10 cm down into the coral heads and, at

Plate 22 Upper Cretaceous coral-rudist limestones near Haidach in Brandenburg, Austria.

- Fig. 1. Matrix of the coral-rudist limestones. Packstone composed mainly of fragments from molluscs (rudists), coralline algae, echinoderms, bryozoans, calcareous algae, spicules, smaller benthic foraminifera, and the problematicum *Pienina oblonga*. Haidach section. Sample 4.12.93/5. x 6.3
- Fig. 2. Coral-rudist boundstone. Coral and radiolitid, both encrusted mainly by coralline algae, *Ethelia alba*, and serpulids. The matrix is a poorly sorted wackestone to floatstone with fragments from rudists and corals, and some *Pienina oblonga*. Haidach section. Sample B 3/8. x 6.3
- Fig. 3. Coral-rudist limestones. Radiolitid in close association with a coral head. Haidach section. Sample B 5/14. x 6.3
- Fig. 4. Coral-rudist limestones. Portion of coral-rudist boundstone. Hippuritid, thickly encrusted by coralline algae, *Ethelia alba*, bryozoans, serpulids, and sponges. Haidach section. Sample B 4/9 B. x 6.3
- Fig. 5. Coral-rudist limestones. Transverse section through *Vaccinites* that settled and grew within a colony of *Pleurocora*. Note the deformation of the branches of *Pleurocora* at the contact with the rudist. The branches of *Pleurocora* and the test of *Vaccinites* are overgrown by the same coralline algal crust. Haidach section. Sample B 1/10. x 6.3
- Fig. 6. Rudist limestone. Lower valve of *Vaccinites*, overgrown by an encrusting coral, that is "wrapped" around the top of the shell. Haidach section, "Atzl reef". Sample AZ 6. x 6.3
- Fig. 7. Coral-rudist limestones. Portion of a colony of a branched (cf. *Pleurocora*), associated with the sponge *Peronidella ?robusta*. These fossils are embedded in a matrix of poorly sorted bioclastic wackestone. Haidach section. Sample B 1/15. x 6.3
- Fig. 8. Bioerosion of rudists in coral-rudist limestones. Transverse section through test of *Vaccinites "sulcatus"*. Note the strong perforation of the shell by borings with a subcircular to ellipsoidal cross-section. Haidach section, "Atzl reef". Sample AS 3/7. x 9



their end, locally contain a lithophagid bivalve. Overall, the degree of boring of the corals seems to be of moderate intensity, and is comparable to cut coral heads from recent coral reefs (cf. WARME 1977).

In the shells of *Vaccinites* and in the hypostracum of radiolitids, clionid borings are very common. In the tests of *Vaccinites*, the density of perforation by clionids ranges from a few borings to very dense perforation, to result in vague shell "ghosts" of entire *Vaccinites* shells (or large fragments thereof). In the ostracum of radiolitids, perforations reminiscent of clionid-borings are rare. In the thick shells of large *Vaccinites* and in the ostracum of radiolitids, by contrast, lithophagid borings are common (Pl. 23/1). The upper, canaliculate valve of *Plagioptychus* commonly is unperforated by clionids or lithophagids. On *Plagioptychus* overgrown by *Vaccinites "sulcatus"*, the latter is perforated by clionid sponge borings, whereas the upper valve of *Plagioptychus* commonly is unbored. Some orbital borings of 2-4 mm in diameter and with a slightly larger diameter at the outer end of the boring locally penetrate the *Plagioptychus* shells. These borings are closely similar in shape to borings from recent naticid gastropods (compare BOUCOT 1981: figures 181-183).

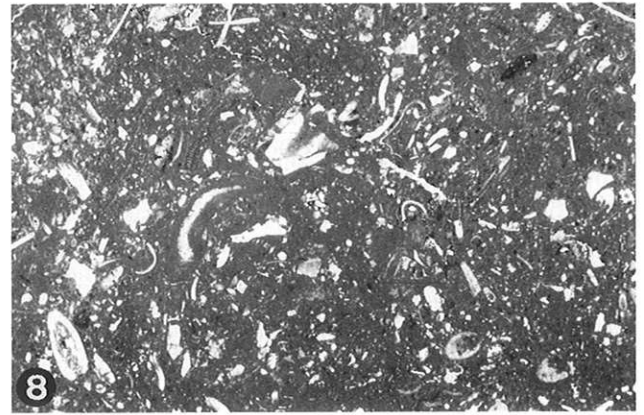
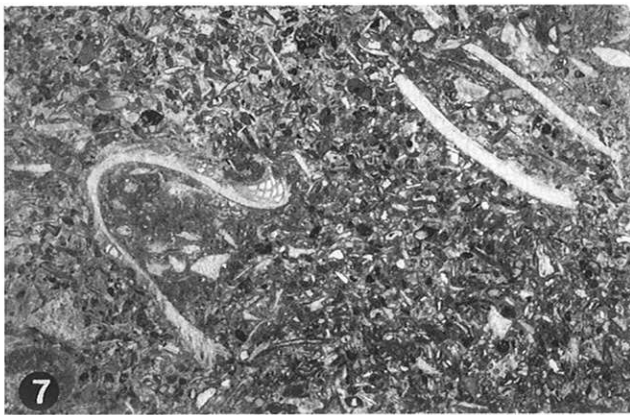
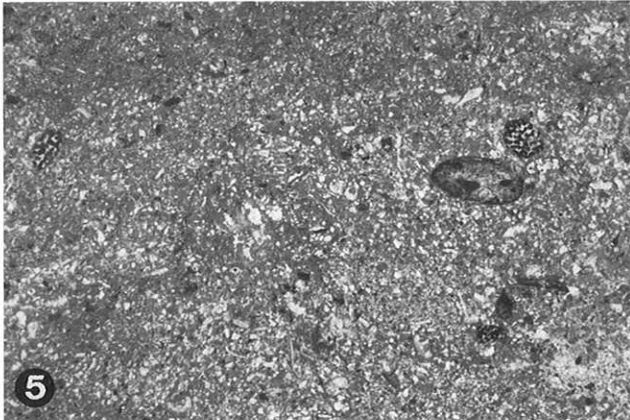
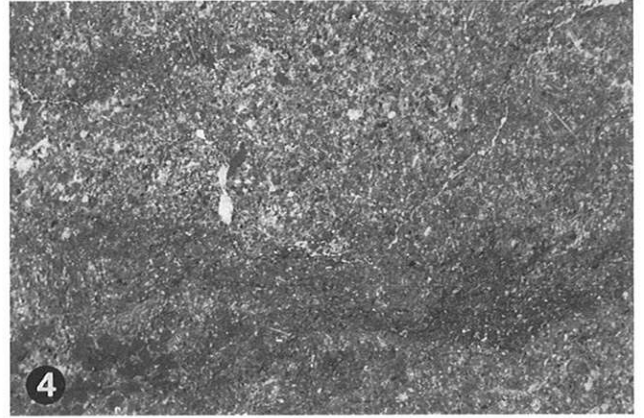
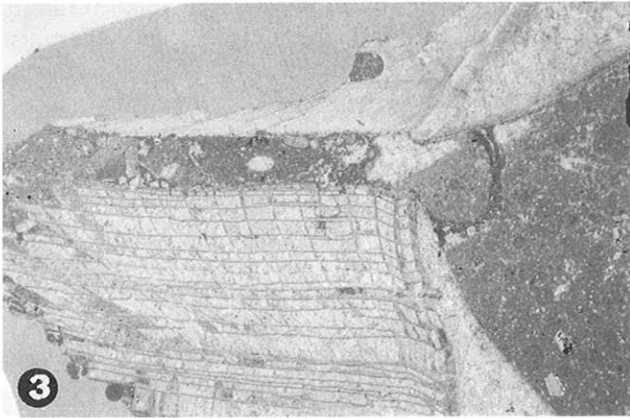
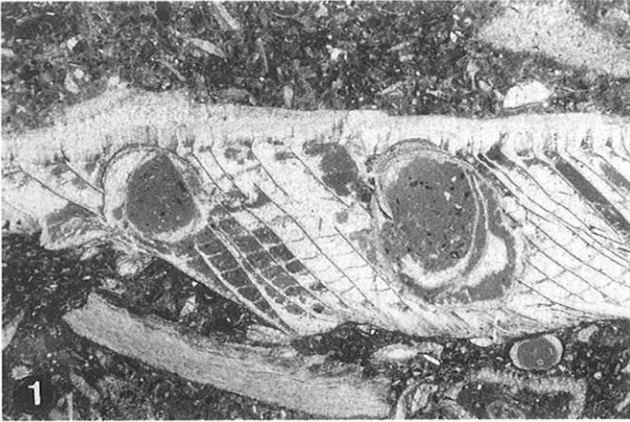
6.1.4 Interpretation of the coral-rudist limestones

The sheet-like to gently mounded shape of the intervals of coral-rudist limestones, their predominant floatstone texture, the common presence of the delicately branched *Pleurocora* and its intergrowth with elevator rudists and calcareous sponges, and the complete preservation of rudist shells that are very densely perforated by borings all indicate that the coral-rudist limestones were deposited from skeletal mounds in a medium- to low-energy environment (cf. WILSON 1975; JAMES & BOURQUE 1992; BOSENCE & BRIDGES 1995). At the base of interval 1, the bioclastic limestone with the diverse fossil assemblage, the heavily micritized and encrusted fossil fragments, and with the admixture of siliciclastic sand is interpreted as a transgressive lag deposit (see e.g. PARKINSON & MEEDER 1991).

By comparison to growth forms of recent corals (HUBBARD & POCKOCK 1972; CHASE 1983; GEISTER 1983), the dominance of plocoid and thamnasterioid forms indicates soft substrata and high sediment input (see also HÖFLING 1985, 1994; BARON-SZABO 1994). By analogy with recent branched corals (see GINSBURG 1972, and references therein; GEISTER 1983, and references therein), the branched coral *Pleurocora*

Plate 23 Upper Cretaceous rudist limestones, bioclastic limestones, and bioclastic marls near Haidach in Brandenberg, Austria.

- Fig. 1. Bioerosion of rudists. Lithophagid borings within the ostracum of a radiolitid. The lithophagids are preserved within their borings. Haidach section, "Atzl reef". Sample Ph 1. x 10
- Fig. 2. Rudist limestone. Transverse section through three adjacent individuals of *Vaccinites "sulcatus"*. Note the deformation of the shell ribs close to the contact, and the local intergrowth of shell ribs along the contact. Note also the absence of bioerosion (micritization, boring) in the shells. Haidach section, "Atzl reef". Sample AS 1/5. x 6.3
- Fig. 3. Rudist limestone. Longitudinal section through a radiolitid with preserved upper valve. Note the agglutinating sessile foraminifera in the commissure between lower and upper valve. Haidach section, "Atzl reef". Sample AS 4/7. x 6.3
- Fig. 4. Bioclastic limestone. Well sorted, bioturbated, fine to medium bioclastic grainstone to packstone. This limestone is composed mainly of fine, more or less micritized mollusc fragments, fragments from calcareous lags, miliolids, intraclasts, and peloids. A small fraction of the components typically is stained or blackened. Haidach section. Sample 16.7.95/19. x 6.3
- Fig. 5. Bioclastic limestone. Moderately well sorted, bioturbated, medium to coarse sand bioclastic grainstone to packstone composed mainly of fragments from molluscs (rudists), corals, calcareous algae, and smaller benthic foraminifera. Note the presence of larger, blackened biogens. Haidach section. Sample 15.7.95/9. x 6.3
- Fig. 6. "*Phellopteria* marl". In thin section, the "*Phellopteria* marl" commonly appears as bioclastic packstone with a matrix of micro- to pseudosparite, and with non-stylolitic solution seams. The bioclastic fraction consists mainly of angular fragments from non-rudist bivalves, including inoceramids. Subordinately, smaller benthic foraminifera, ostracods and calcispheres are present. Haidach section, "*Phellopteria* marl". Sample PH 3. x 6.3
- Fig. 7. Detail of a shallow-water bioclastic layer intercalated in the "*Phellopteria* marl". Note the small radiolitid, and the well rounding and sorting of the carbonate grains, and their micrite rims. The carbonate sand is mainly composed of mollusc debris, and fragments from corals and echinoderms, and diverse smaller benthic foraminifera. A fraction of the components is blackened. Haidach section. Sample PH 1. x 6.3
- Fig. 8. Bioturbated bioclastic packstone. The packstone consists mainly of mollusc fragments with more or less thick micrite rims, fragments from calcareous green algae, and diverse smaller benthic foraminifera. Haidach section. Sample 16.7.95/9. x 6.3



most probably grew upward at a much higher rate than the plocoid and thamnasterioid corals, but was vulnerable to fracture. This is supported by common fragments from *Pleurocora* in bioclastic limestones (see description below), and by the fact that completely preserved colonies of *Pleurocora* are invariably embedded in wackestone to mudstone. In recent carbonate depositional environments, conical corals (e.g. *Manicina areolata*) are able to actively move upward through the sediment; these corals are present in areas of high sediment accumulation rates (GINSBURG 1972; GEISTER 1983). The conical coral *Aulosmilium* of the described Upper Cretaceous section might also have been able to actively move upward, and thus possibly represents an adaptation to high sediment input. The rare foliose-encrusting corals had the highest degree of wave resistance, but the least resistance to high sediment input (BARON-SZABO 1994, 1996).

The overall small size of the coral heads, coupled with a normal size of the polyparia, and the small size of the rudists indicate that the corals and the rudists often died in a juvenile to early adult stage. They most probably were choked by mud that has been stirred up during storms (see also HÖFLING 1985). The coral-rudist community thus was under more or less persistent sediment stress. Episodic sedimentation of carbonate mud reduced the number of substrate sites suited for coral and rudist settlement, and promoted the development of the predominant floatstone texture of the mounds. Intermittent choking of the corals and rudists by mud fallout alone, however, cannot explain the common thick and diverse encrustation of both the corals and the rudists.

In recent carbonate depositional environments, coralline algae predominate in areas of continuous heavy wave surf, or in areas of medium to high nutrient levels (LITTLER & LITTLER 1984). In the described section, as discussed, continuous heavy wave surf is precluded. The thick and complex encrustations thus are most probably related to an elevated nutrient level (cf. HALLOCK 1988). An at least intermittently elevated nutrient level and high turbidity is also suggested by the marly nature of the limestones, which is related to input of siliciclastic fines and nutrients from the emergent areas of the Alpine accretionary wedge. The encrustation of the rudists and the corals probably began *in vitro*, and proceeded after death until the entire coral skeleton or a rudist shell was covered.

The described differences in the type and intensity of boring of the rudist shells are, at least in part, related to the structure of the rudist shell (SANDERS 1996 c). For the delicately branched growth of clionids, the highly porous radiolitid ostracum probably was an unfavourable substratum. The clionids evidently preferred substrata of dense calcium carbonate, as was provided by the shell of hippuritids and by the radiolitid hypostracum. In relation to the significantly larger lithophagids, however, the structure of the radiolitid ostracum was still dense enough to provide a suitable substrate for boring. The free valve of *Plagioptychus* may have been unfavourable for clionid boring because of its canaliculate structure, but was also unsuitable for

lithophagid boring because of its thinness relative to the typical size of the lithophagids.

6.2 Rudist limestones

The intervals of rudist limestones are between a metre to some meters thick (Fig. 4, section B), and can be traced or correlated laterally over hundreds of meters without rapid changes in thickness. The rudist limestones either overlie the described coral-rudist mounds (intervals 1 and 2), or develop above bioclastic wackestones to packstones (intervals 3 and 4; see Fig. 4, section B). The rudist limestones are either sharply overlain by bioclastic packstones to wackestones (see description below), or grade into the overlying limestones by an interval with toppled rudists and coarse rudist debris. In the intervals 1 and 2, the rudist limestones are strongly dominated by *Vaccinites*, whereas in the intervals 3 and 4, radiolitids are dominant. No clear-cut vertical trend, however, with respect to presence and abundance of *Plagioptychus* was recognized.

In the intervals 1 and 2 (Fig. 4, section B), the described coral-rudist limestones are overlain by sheets of marly limestones rich in *Vaccinites* spp.; radiolitids are common or dominant in the uppermost decimeters of these rudist limestones. In its lower part, the "Atzl reef" (see interval 2 in Fig. 4, section B) consists of marly floatstones with *Vaccinites "sulcatus"*, some *Vaccinites* spp., *Plagioptychus*, and a fraction of small-sized biogens (including echinoderm fragments, fragments from non-rudist bivalves, bryozoans, serpulids). In these floatstones, individuals of *Vaccinites* locally are more or less completely overgrown by and interspersed with small coral heads. The larger, upper part of the "Atzl reef" consists of a densely packed bafflestone dominated by *Vaccinites "sulcatus"*. Similar densely packed *Vaccinites* bafflestones are present above the coral-rudist limestones in interval 1, but are less well exposed. In upper part of the "Atzl reef", the matrix is a wackestone to mudstone with some poorly sorted, angular rudist debris and, locally, small miliolids and textulariaceans. The shells of *V. "sulcatus"* are slender and reach more than 25 cm in length. Locally, between the clusters of *V. "sulcatus"*, larger *Vaccinites* (*V. cf. gosaviensis*, *V. ? spp.*), small radiolitids, *Plagioptychus* and small coral heads are intercalated. Over the thickness of the upper part of the "Atzl reef", the densely packed shells of *V. "sulcatus"* are gently inclined relative to bedding and show a persistent southward orientation of the free valves. A high number of *Vaccinites* shows a more or less moderate and smooth, continuous curvature of the shell. In addition, individuals and clusters of shells of *Vaccinites* were observed that show a sharp kink with an angle of 60°-90° ("kinked" *Vaccinites*). Furthermore, *Vaccinites* and clusters of *Vaccinites* are present that show a marked, but continuous curvature of their shells, which results in a crescent shape of individuals and entire clusters.

Younger individuals of *Vaccinites* settled and grew upward both along the lower valves and on the free valves of older individuals. The spots of settlement are not en-

crusted by red algae or other organisms. The ribs of adjacent *V. "sulcatus"* are interlocking to, locally, intergrown (Pl. 23/2). The rudists most commonly are free of encrustations. On the attached valves, small patches of thin coralline algal crusts, small colonies of cheilostomate bryozoans, and some serpulid tubes are locally present. On the free valve, placopsilinids and small colonies of cheilostomate bryozoans are relatively common. The *Vaccinites* bafflestone of the "Atzl-reef" is overlain by a metre-thick interval rich in *Radiolites*. The lower valves of the radiolitids are of broad-conical to cup-shaped form. The radiolitid limestone, in turn, is overlain by a coarse bioclastic limestone composed mainly of radiolitid debris and with a few completely preserved radiolitids. In the bioclastic limestones, shelter pores are locally present below larger rudist fragments. The radiolitids extend in presence into the lowermost part of the overlying "Phelopteria marls" (see description below) where they are, at least in part, preserved with their free valve (see Fig. 4, section B).

In the intervals 3 and 4, the rudist limestones are bafflestones and floatstones rich in radiolitids (Fig. 5). The radiolitid bafflestones occur in sheets up to several decimeters thick. These may develop gradually from their base, by a vertical increase in the number of radiolitids, or may comprise well-defined intervals. In the bafflestones, the radiolitids are embedded in upright to inclined position, with their free valve mostly in place (Pl. 23/3). The matrix of these bafflestones is a mudstone to wackestone with angular radiolitid fragments. On the radiolitid fragments, including the sand-sized fraction, micrite rims typically are thin and uncommon. Aside from radiolitid fragments, other biogens are commonly absent. Only locally, a few benthic foraminifera (small miliolids, small textulariaceans), ostracods, and peloids are present in the matrix. In the radiolitid bafflestones the rudists are locally in point contact with each other, but more commonly are preserved with some small distance between the shells. Most of the radiolitids are unbored or only weakly perforated by borings. Most of the specimens are *Radiolites*, whereas other radiolitid genera were not unequivocally identified. Locally, the radiolitid bafflestones are intercalated with lenses up to several decimeters thick of floatstone that is nearly exclusively composed of coarse, angular radiolitid fragments (mainly from the radial funnel plates and from the calcitic portion of the upper valve).

The rudist floatstones are characterized by a wide range of composition and of preservation of the megafossils. In the floatstones, a number of rudists may be preserved more or less in growth position and with their upper valve in place, or the largest part of the rudists may be toppled, and more or less fragmented and bioeroded. The floatstones with a high proportion of toppled and fragmented radiolitids typically contain some *Vaccinites*, *Plagiopychus*, and fragments from *Pleurocora* (Fig. 5). Angular, unmicritized/unperforated rudist fragments are typically mixed with more or less micritized and bored rudists and rudist fragments. The toppled rudists and the coarse rudist fragments often are heavily encrusted by coralline algae, sessile

agglutinated foraminifera, *Ethelia alba*, serpulids and bryozoans. The matrix of these floatstones typically is a bioturbated wackestone to packstone with variable proportions of toppled juvenile rudists, fragments of branched corals, red algae, calcareous green algae, echinoderms, bryozoans, serpulids, diverse smaller benthic foraminifera (miliolids, nezzatids, lituolids, *Cuneolina*) and, rarely, sessile agglutinated foraminifera. In addition, fecal pellets that are comparable in size and shape to crustacean pellets are locally common in the matrix.

6.2.1 Bioerosion

On the surface of *Vaccinites*, perforations reminiscent of clionid borings (see section 6.1.3 for description) tend to occur in patches. On *Vaccinites "sulcatus"*, the clionid perforations on the outer shell surface are preferentially located at and near the crests of the sharp, longitudinal ribs of the shell (SANDERS 1996c). *Vaccinites* shells that appear only weakly perforated on their surface often reveal a more or less dense network of borings when viewed in longitudinal section and in cross-section. Even in tightly packed *Vaccinites* bafflestones, shells without any clionid perforation on their surface are uncommon, but the overall density of perforation is markedly less when compared to rudist floatstones. Clusters of *Vaccinites* that grew with mutually interlocking or intergrown shell ribs are only weakly bored.

The ostracum of radiolitids is typically bored by lithophagids, which are locally preserved within the borings. In the radiolitid hypostracum, borings from clionid sponges are common. Within borings from clionids and lithophagids, both in *Vaccinites* and in the radiolitids often a geopetal infill of very small peloids is present. In addition, sessile agglutinated foraminifera, worm tubes, cryptmicrobial crusts with microtubuli, and ?sponges/?boring foraminifera were observed within the empty borings.

6.2.2 Interpretation of the rudist limestones

The sheet-like shape of the intervals of rudist limestones indicates that they were deposited from biostromes. The intervals of *Vaccinites* bafflestones were deposited from biostromes with a "packed" rudist fabric (cf. SANDERS 1996a), and under higher mean water energy than the underlying coral-rudist limestones. This is indicated by the presence of the *Vaccinites*-biostromes in a position above the coral-rudist mounds and below intervals of shallow-water bioclastic limestones (see below). As mentioned, the "Atzl reef" can be subdivided into a lower interval of *Vaccinites* floatstones and an upper, thicker interval of bafflestone rich in *Vaccinites "sulcatus"*. This indicates that the *Vaccinites* biostrome developed from a bottom of bioclast-bearing lime mud with scattered clusters of *Vaccinites*, and a variety of associated organisms (see above). Also in the fully developed, densely packed stage of the *V. "sulcatus"* biostrome, *Vaccinites* spp.,

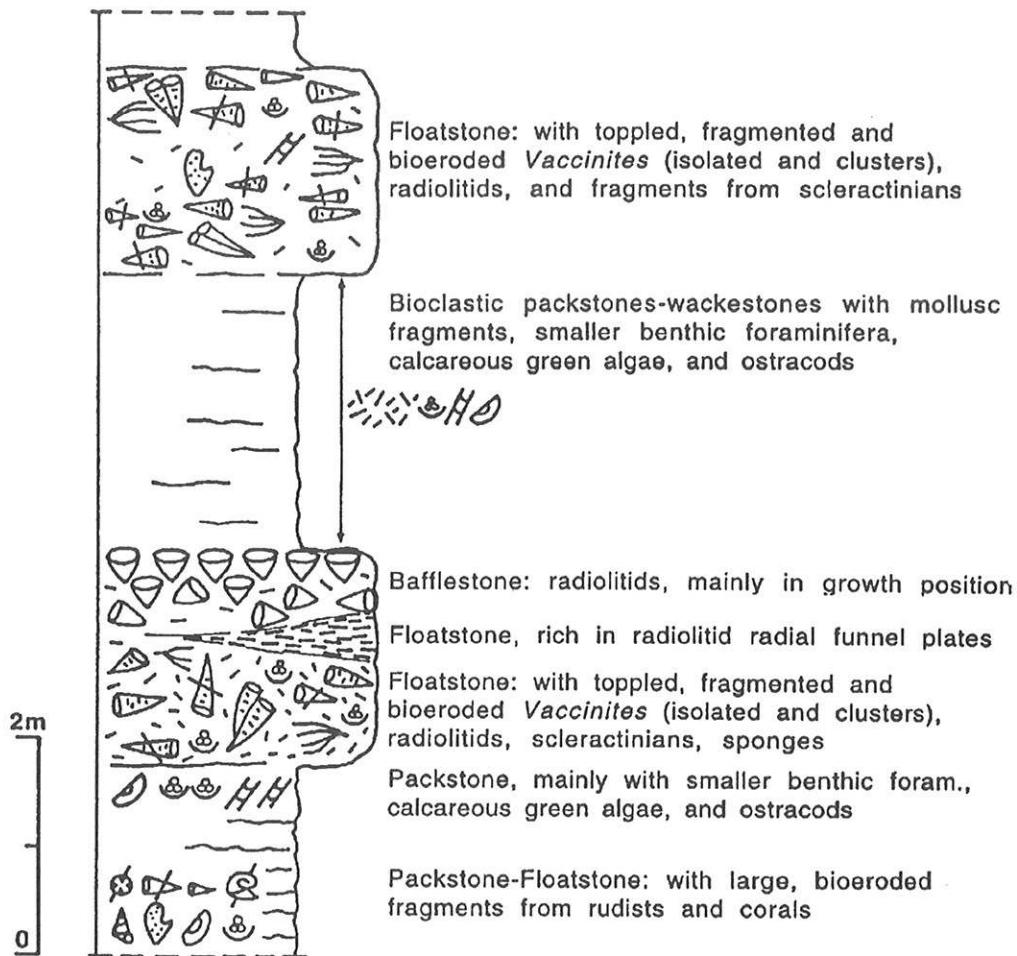


Fig. 5. Detail of the upper part of the carbonate succession, lower part of interval 4 (see Fig. 4B). Here, two sheets of rudist limestone are vertically separated by intervals that consist mainly of bioclastic packstones. The rudist limestones show vertical and lateral variations with respect to limestone texture and rudist preservation.

radiolitids, corals and *Plagiocyclus* thrived between the clusters of *V. "sulcatus"*, but comprise only a small, fraction of the biostrome.

Because of the interlocking and intergrown ribs of *Vaccinites "sulcatus"*, the packed biostromes built by this hippuritid type probably had some degree of wave resistance. The paucity of encrusting organisms on *Vaccinites* may result from the ability of the hippuritids to actively prevent encrustation by mantle protrusion (SKELTON 1976, 1979; KAUFFMAN & JOHNSON 1988), and/or because of constrictal growth of the hippuritids (cf. SKELTON et al. 1995). Dense packing of rudists alone does not provide an explanation for the paucity of encrusters, because also isolated *Vaccinites* and small clusters of *Vaccinites* that grew isolated are scarcely encrusted.

The moderate, smooth upward curvature of many shells of *Vaccinites* suggests continuous upward growth that started from a more or less inclined to lying position. The crescent-shaped shells of *Vaccinites* are interpreted as a result of slow, quasi-continuous sinking of the rudists into the lime-mud matrix during life. By contrast, the "kinked" *Vaccinites* probably were toppled during high-energy events, but survived and subsequently recurved into a more steeply

inclined growth position. In the upper part of the "Atzl reef", in the densely packed *Vaccinites* bafflestone the consistent, inclined shell orientation of successive generations of *V. "sulcatus"* probably results from tilting of clusters under the prevailing water currents. In the densely packed to intergrown fabrics of *Vaccinites*, borings of clionid sponge-type are significantly less common to, locally, absent. This indicates that growth in densely packed to intergrown fabrics provided some protection against clionid boring. Only in areas of dense constrictal rudist growth and continuous re-colonization, however, the protective effect was probably sustained. On top of the "Atzl reef", the flat-conical to cup-shape of the radiolitids, the coarsely fragmented and toppled radiolitids embedded in a coarse bioclastic matrix with local shelter pores, and the gradual upward transition into bioclastic limestones all record an overall increase in water energy.

The radiolitid floatstones with many radiolitids preserved in growth position were deposited from biostromes with an "open" rudist fabric (cf. SANDERS 1996a) in a low-energy environment. This type of floatstone represents the lowest water energy level recorded by the rudist limestones. Episodic high-energy events of moderate impact

and/or transient interruptions of biostrome growth are recorded by the locally intercalated lenses of radiolitid-bioclastic floatstone. Upon further lowering of water energy and, possibly, beginning environmental restriction, the radiolitids disappeared, and packstones to wackestones with smaller benthic foraminifera and green algae were deposited.

The floatstones with radiolitids, *Vaccinites* and *Pleurocora* were deposited from biostromes with an "open" rudist fabric. These biostromes essentially consisted of a substrate of muddy, bioclastic sand with scattered radiolitids, some clusters of *Vaccinites*, and some *Pleurocora*. In "open" rudist fabrics, effective winnowing of matrix was possible during high-energy events. Destruction during high-energy events is recorded by the common toppled, fragmented and bioeroded rudists and corals. The local abundance of fecal pellets indicates that, in the open rudist fabrics, churning from bioturbation also contributed to substrate instability. In addition, in areas of intense bioturbation, colonization of the bottom with rudists was set back by persistent churning of the substrate.

Floatstones that contain exclusively disoriented, toppled rudists/rudist clusters that are more or less fragmented, bioeroded and encrusted represent a transitional type to bioclastic wackestones to packstones. These latter floatstones record open rudist fabrics that were both frequently destroyed by storms and continuously modified by bioerosion and bioturbation.

The rudist fabrics that record intermittent disturbance or destruction ("parautochthonous rudist fabrics") contain a matrix with a fossil assemblage that is similar to the vertically associated bioclastic limestones, notably diverse smaller benthic foraminifera and fragments from calcareous green algae (see above). By contrast, the fabrics that record more or less undisturbed rudist growth ("autochthonous rudist fabrics", with most or all of the rudists in growth position and with the upper valve in place) have a matrix of mudstone to wackestone with some angular rudist debris, whereas other biogens are absent or rare (small miliolids, small textulariaceans, some ostracods; see above). This holds for both the *Vaccinites* biostromes and the radiolitid biostromes, and indicates an environmental control over the life distribution of the smaller benthic foraminifera (SANDERS 1996 d). Since the rudists were suspension feeders, smaller benthic foraminifera should be common at least in the "open", autochthonous rudist fabrics. The foraminifera thus probably actively avoided substrata colonized by rudists. The reason for this is unclear. It is possible that substrata colonized by rudists were of unfavourable consistence, or that the feces produced by the rudists could not be exploited as a food source by the benthic foraminifera (cf. BARNES & HUGHES, 1988: 82 f.).

In the rudist shells, within both the clionid and lithophagid borings the local, geopetal infills of micropeloidal grainstone are closely similar to micropeloidal grainstones that result from bacterial metabolism in cryptic cavities of recent reefs (eg. SCOFFIN 1993). In addition, the empty borings in

the rudist shells provided a cryptic habitat for sessile agglutinated foraminifera, worms with calcareous tubes, cryptomicrobial aggregates and for ?sponges/?boring foraminifera.

6.3 Bioclastic limestones

The upper part of interval 1 consists of marly limestones that are intercalated with bedsets of bioclastic limestones. The marly limestones typically are bioturbated, wavy to nodular bedded, well-sorted, fine to medium bioclastic packstones (Pl. 23/4). Up-section, these either grade into or are sharply overlain by medium to coarse, moderately well- to well-sorted bioclastic grainstones to packstones. The latter are arranged in sets of wavy to plane beds that locally display subparallel lamination (Pl. 23/5). Together, the bedsets of bioclastic grainstones to packstones and the marly limestones are arranged in stratal packages up to some meters thick. Irrespective of clay content, the bioclastic limestones consist mainly of well-rounded mollusc fragments with micrite rims. Larger mollusc fragments include more or less bioeroded/micritized debris from radiolitids and hippuritids. Locally, smaller benthic foraminifera are fairly common and include textularids, miliolids, lituolids, nezzazatids, and cf. *Montcharmontia*. Subordinately, fragments from green algae (*Permocalculus*, *Neomeris*, *Boueina*), diverse coralline algae, *Ethelia alba*, bryozoans, echinoderms, ostracods, Ataxophragmiinae, *Pienina oblonga*, blackened bioclasts and blackened mudstone intraclasts are present.

In interval 2, the coarse bioclastic veneer on top of the "Atzl reef" is overlain by bioturbated, poorly sorted marly packstones and bioclastic marls that are rich in the bivalve *Phelopteria* ("Phelopteria marls"). This interval also contains trochid gastropods (including *Discotectus*; det. H. Kollmann 1995), in addition to inoceramids and *Mytiloides* (HERM et al. 1979; see also SUMMESBERGER & KENNEDY 1996). Aside from the mentioned fossils, the marly packstones mainly consist of debris from rudists and non-rudist bivalves, miliolids, lituolids, serpulids, green algae (*Boueina*), bryozoans, and small coral fragments. The marls contain abundant *Phelopteria*, and are nearly exclusively composed of non-rudist bivalve debris, echinoderm fragments (including echinoid spines), small miliolids, serpulid tubes, bryozoan fragments, and fine coalified plant debris (Pl. 23/6). Locally, layers of grainstone are intercalated in the marls. The grainstone layers are partly destroyed by bioturbation, and are composed of well-sorted and well-rounded shallow-water bioclastic material (mainly rudist bioclastic material and diverse smaller benthic foraminifera) (Pl. 23/7). Marls with abundant *Phelopteria* are present up to the top of the interval. The top of the "Phelopteria marls" is marked by a sharp, slightly erosive contact to overlying coral-rudist floatstones. The overlying coral-rudist limestones are similar to the coral-rudist limestones from the underlying bioconstructions and, in turn, are overlain by an interval approximately 2 meters thick of grainstone. The grainstone is very well-washed and pure,

and locally shows megaripple lamination and parallel lamination. The grainstone is composed nearly entirely of very well-rounded mollusc debris with micrite rims, and contains scattered *Trochactaeon* (det. H. Kollmann, Aug. 95).

In the intervals 3 and 4 (see Fig. 4, section B), the upper part of the stratal packages (see chapter 4) consists of bioturbated, poorly sorted grainstones to packstones (Pl. 23/8) and, subordinately, wackestones. These limestones are mainly composed of more or less micritized mollusc (rudist) fragments and, subordinately, of small fragments from corals, diverse miliolids, *Cuneolina*, *Dictyopsella*, nezzazatids, calcareous green algae, coralline algae, bryozoans, serpulids, small nerineids, small rudists, cerithiaceans, echinoderm fragments, ostracods, rare brachiopods, and coalified plant fragments. A subordinate fraction of the biogens is blackened. Locally, mud-lined burrows are present. Near the top of the carbonate succession, bioturbated peloidal packstones with admixed shallow-water bioclastic material (miliolids, small gastropods, calcareous green algae) are locally present.

6.3.1 Interpretation of the bioclastic limestones

In interval 1, the sedimentary structures, the sorting, rounding and composition of the grains, and the fossil assemblage of the bioclastic limestones indicates that they were deposited in an environment of medium to intermittently high water energy. The stratal packages of marly limestones and bioclastic limestones were deposited from carbonate sand bodies, under overall higher water energy and in more shallow water than the underlying coral-rudist limestones. The described packages are broadly similar in thickness, vertical arrangement of bedding styles and facies, grain size and sorting to carbonate sand lobes described from gently inclined shelves (AIGNER 1985). In the described section, the common bioturbation of the bioclastic limestones and the overall paucity of preserved hydrodynamic structures indicates that the sand bodies were only episodically active, possibly during storms and strong tides (cf. AIGNER 1985; WANLESS et al. 1995).

The "*Phelopteria* marls" in interval 2 were deposited in an overall quiet, low-energy subtidal environment (see also HERM et al. 1979), as indicated by the common complete preservation of the relatively thin shells of *Phelopteria*, the thorough bioturbation, and the marly sediment composition. In the marls, the "non-tropical" shallow-water bioclastic material (serpulids, bryozoans, non-rudist bivalves, echinoderms; cf. HECKEL 1974; HALLOCK 1988) indicate that these marls were deposited under environmental conditions quite different from the under- and overlying limestones. *Phelopteria* is a trans-temperate bivalve, that is a bivalve that was present in the Temperate realms on either side and within the marginal fringes of the Tethys (KAUFFMAN 1973: 358, 359).

Several factors may have induced an environmental change, including reduced salinity, input of siliciclastic material, climatic cooling, or an elevated nutrient level.

Reduced salinity because of more or less persistent fresh-water input appears improbable because, aside from *Phelopteria*, the fossils in the marls include stenohaline forms like echinids and inoceramids. A change of faunal assemblage because of input of siliciclastic material seems also improbable since marls with diverse assemblages of rudists and corals are common in the Lower Gosau Subgroup. Similarly, an overall climatic cooling is improbable because, in the "*Phelopteria* marls", the grainstone layers that consist of "tropical" shallow-water bioclastic material (see description above; cf. HALLOCK 1988) indicate that areas of tropical carbonate accumulation persisted; these grainstone layers probably were deposited during storms. In addition, no intervals of "*Phelopteria* marls" have been identified in correlative sections elsewhere in the area of Brandenburg, to suggest a climatic cooling. In tropical shallow-water carbonate environments, a shift of biotic assemblage from a "tropical" to a "non-tropical" composition may be induced either by climatic cooling or by an increase in nutrient level (cf. HECKEL 1974; HALLOCK 1988). It is thus concluded that the mass occurrence of *Phelopteria* is primarily related to an elevated nutrient level, coupled to input of siliciclastic fines. The functional morphology of *Phelopteria* indicates that it was a byssate bivalve attached to sea grass or algae (see also HERM et al. 1979), similar to *Pinctada* on the recent Florida Shelf (P. Enos, pers. comm. 1996). In the quiet, lagoonal depositional environment of the "*Phelopteria* marls", the elevated nutrient level promoted the growth of meadows of sea grass or algae, which in turn provided abundant settling sites for *Phelopteria*. The mass occurrence of *Phelopteria* thus is mainly a result of abundant settling sites in an environment of elevated nutrient content.

In interval 3 and 4, respectively, the bioclastic limestones were deposited in a shallow subtidal environment of overall low water energy. This is indicated by their fossil content (diverse smaller benthic foraminifera, calcareous green algae), the packstone to wackestone texture, the common mollusc fragments with micrite rims, and the common bioturbation. The peloidal packstones to wackestones probably record a low energy, very shallow subtidal environment.

7 CORRELATION OF SECTIONS

An attempt to correlate the section described in this paper with the section described by HERM et al. (1979) revealed similarities as well as differences (Fig. 6). Due to Alpine deformation and faulting (see Fig. 2, Fig. 6), however, the differences between the sections are not merely lateral differences in facies. The most striking similarity of both sections is the presence of the "Atzl reef" and the overlying "*Phelopteria* marls"; the base of the marls has been taken as datum level.

Below the "Atzl reef", however, the two sections are quite different (see Fig. 6). According to the description of section B by HERM et al. (1979), and own investigations, no

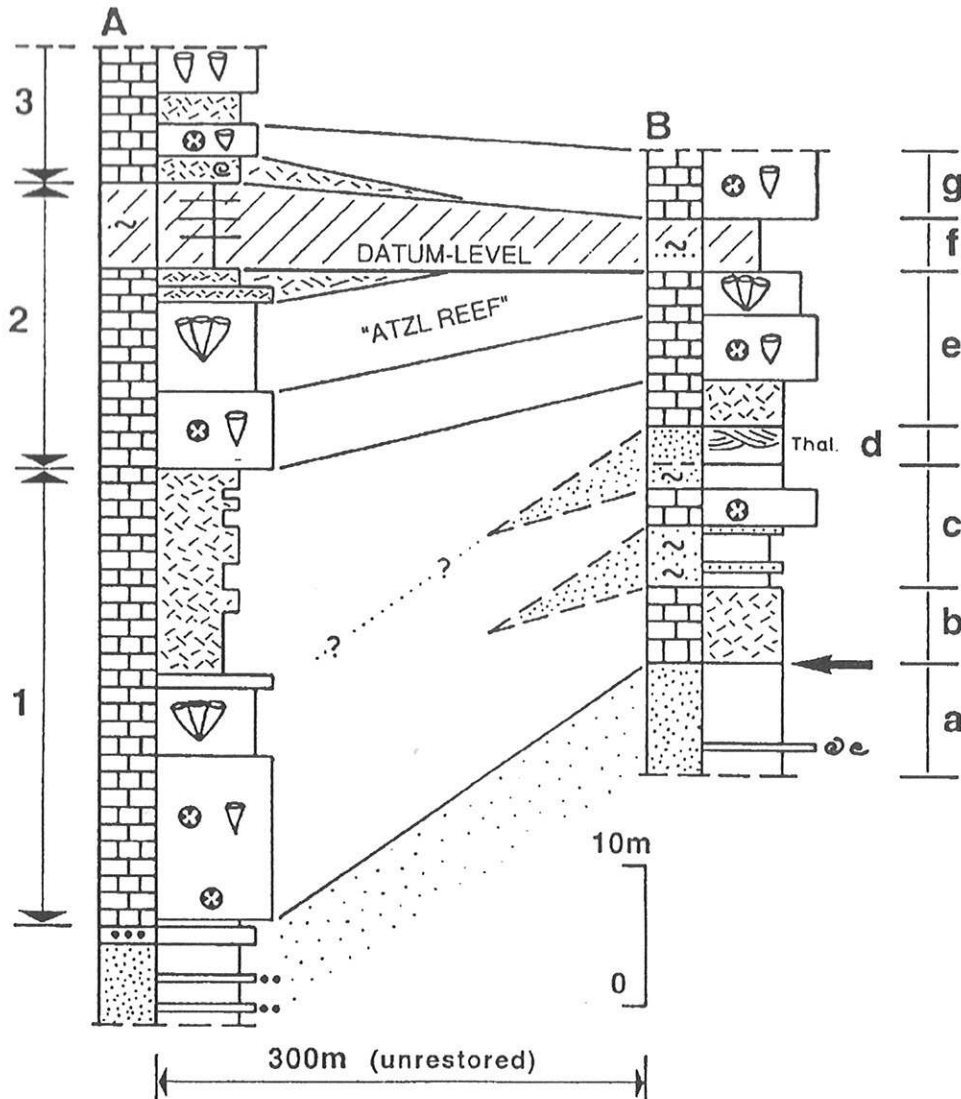


Fig. 6. Correlation of the section described in this paper (A) with the section described by HERM et al. (1979) (B). In section B, the labels a to g of the stratigraphic intervals are according to HERM et al. (1979). Datum-level for correlation is the base of the "*Phellopteria* marl" (cross-hatched) which, in each section, occurs only once, and in an identical stratigraphic position above the "Atzl reef". At the base of the shallow-water carbonate succession, the top of the underlying sandstone-dominated succession is marked by an arrow in section B.

unequivocal indication for a more landward or a more seaward position of one of the sections has been found. In section B, only in the upper part of interval d, higher water energy is indicated by cross-laminated sandstones with *Thalassinoides* (interval labelled "Thal" in Fig. 6; cf. HERM et al. 1979). The smaller thickness, the intervals of bioturbated marine sandstones and marls (cf. HERM et al. 1979), the absence of rudist biostromes below the "Atzl reef", and the paucity of deposits that indicate persistently higher water energy suggest that the more southward section B was deposited under overall lower water energy.

The lower part of section B (see Fig. 6) is thinner and contains two intervals of bioturbated sandstones and marls; no interval of coral-rudist limestones comparable to interval 1 of section A is present. In section B, the marly coral limestones within interval c may correlate with a part of the coral-rudist limestones of interval 1, section A. The top of interval d may correlate with the top of the coral-rudist

bioconstruction in interval 1, section A (dotted line with question tags in Fig. 6). Thus, the coral-rudist bioconstruction in interval 1 of section A may correlate with bioclastic limestones (interval b) and coral thickets (within interval c) of section B. The two sandstone intervals in section B may represent sandstone tongues that pinch out towards the coral-rudist bioconstructions and bioclastic limestones of section A.

8 DISCUSSION AND CONCLUSIONS

The described lithologies and their vertical arrangement indicate that the succession of shallow-water limestones was deposited on a gently inclined shelf segment. An outer belt of coral-rudist mounds and hippuritid-dominated biostromes was separated by a belt of bioclastic sand bodies from an open lagoonal environment with radiolitid-dominated biostromes. Such a depositional morphology

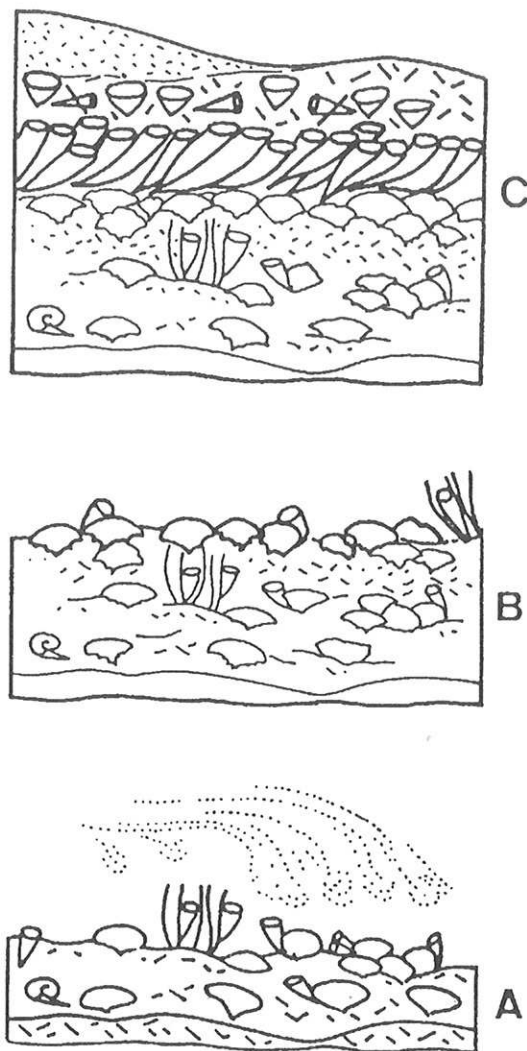


Fig. 7. Scheme of development of combined coral-rudist mounds. Stage A: During and after relative sea-level rise, a coral-dominated community initially developed above a base of bioclastic sand. The corals were associated with elevator rudists and with *Plagioplychus*, and locally were bound together with the rudists into small patches of coral-rudist-coralline algal boundstone. Water energy was intermediate. Episodic, rapid fallout of carbonate mud (stippled), possibly suspended during storms, repeatedly choked the community.

Stage B: Upon continued aggradation, mean water energy increased, and larger areas of the substrate became more densely colonized by corals and, subordinately, rudists. The gentle positive relief of the coral-rudist mounds aided to prevent choking by mud. Numerous hard substrate sites became available for rudist settlement. In addition, in the late phase of stage B, probably a large part of the coral-dominated community died (see text for discussion). In this state, the mounds became available for dense rudist colonization.

Stage C: The coral-dominated lower part of the mound has been capped by a rudist biostrome. Internally, the biostrome shows a relatively thick, lower interval of densely packed *Vaccinites*, and a thinner, upper interval rich in radiolitids. Towards the top, as a result of an overall increase in water energy, the rudists become progressively fragmented and toppled. The rudist biostrome is ultimately buried by migrating bioclastic sand bodies, or is overlain by marls that record deposition in lower energy, lagoonal environment.

and facies distribution seems to be characteristic for Upper Cretaceous carbonate shelves (cf. CARBONE & SIRNA 1981; ROSS 1992; ROSS & SKELTON 1993; SANDERS 1994, 1996a).

The stratigraphic development of the succession was controlled by relative sea-level changes, mean water energy, and intermittent increase in nutrient level (deposition of "*Phellopteria* marls"). During deposition, the water energy commonly was in the intermediate to low range, punctuated by episodic high-energy events. Evidence for more or less persistent higher water energy is confined to a single interval of bioclastic grainstones.

The coral-rudist mounds probably accumulated during and after periods of relative sea-level rise, but were under more or less persistent ecologic stress because of episodic, high sedimentation rates, increased nutrient level and water turbidity. During mound aggradation, the coral-rudist community was episodically choked by mud (Fig. 7). Both on the rudists and corals, however, thick red algal-foraminiferal encrustations are common, and record elevated nutrient levels and turbid waters (Fig. 8). The combined evidence for a juvenile to early adult death of many corals and rudists by sediment choking, and their often complete, thick and diverse encrustations suggest that the development of the coral-rudist mounds was influenced by repeated changes between smothering by mud, followed by erosion of mud, and consequent re-exposure of the dead corals and rudists to thick encrustation (cf. KIDWELL & AIGNER 1984; SEILACHER 1984). In their active stage, the mounds probably appeared as lenses of low relief, with a bottom of bioclast-bearing carbonate mud and interspersed patches of coral-rudist colonization. At least for most of their time, the mounds aggraded without profound changes in texture and biotic composition. In the mounds, the corals and the rudists intimately co-existed, and profited from each other by mutually providing hard substrate sites for settlement (Figs. 7, 8).

The vertical transition from the coral-dominated mounds to the rudist biostromes on top of the mounds records a geologically rapid change of biotic community (Figs. 7, 8). Several lines of evidence indicate that the elevator rudists could rapidly colonize large areas of substrate (ROSS & SKELTON 1993; SANDERS 1994, 1996a; SKELTON et al. 1995). By analogy to recent epibenthic, gregarious bivalves, the elevator rudists may have colonized by spatfalls (SANDERS 1996 a). Spatfalls lead to dense, mono- to paucispecific bivalve biostromes that, in turn, are less susceptible to overgrowth, predation and larval invasion by other organisms than are isolated individuals (eg. BARNES & HUGHES 1988; WOOD 1995). Upon aggradation of the coral-rudist mounds, the important limiting factor of substrate availability (WOOD 1995) thus developed in favour of the colonization potential of the elevator rudists. The rudist biostromes on top of the coral-rudist mounds are comparable to "mound caps" that are commonly interpreted as a response to the increase in water energy associated with mound aggradation (cf. WILSON 1975; JAMES 1983).

The colonization potential of the elevator rudists, however, was not the sole control factor for the vertical change from coral-rudist mounds to rudist biostromes. In interval

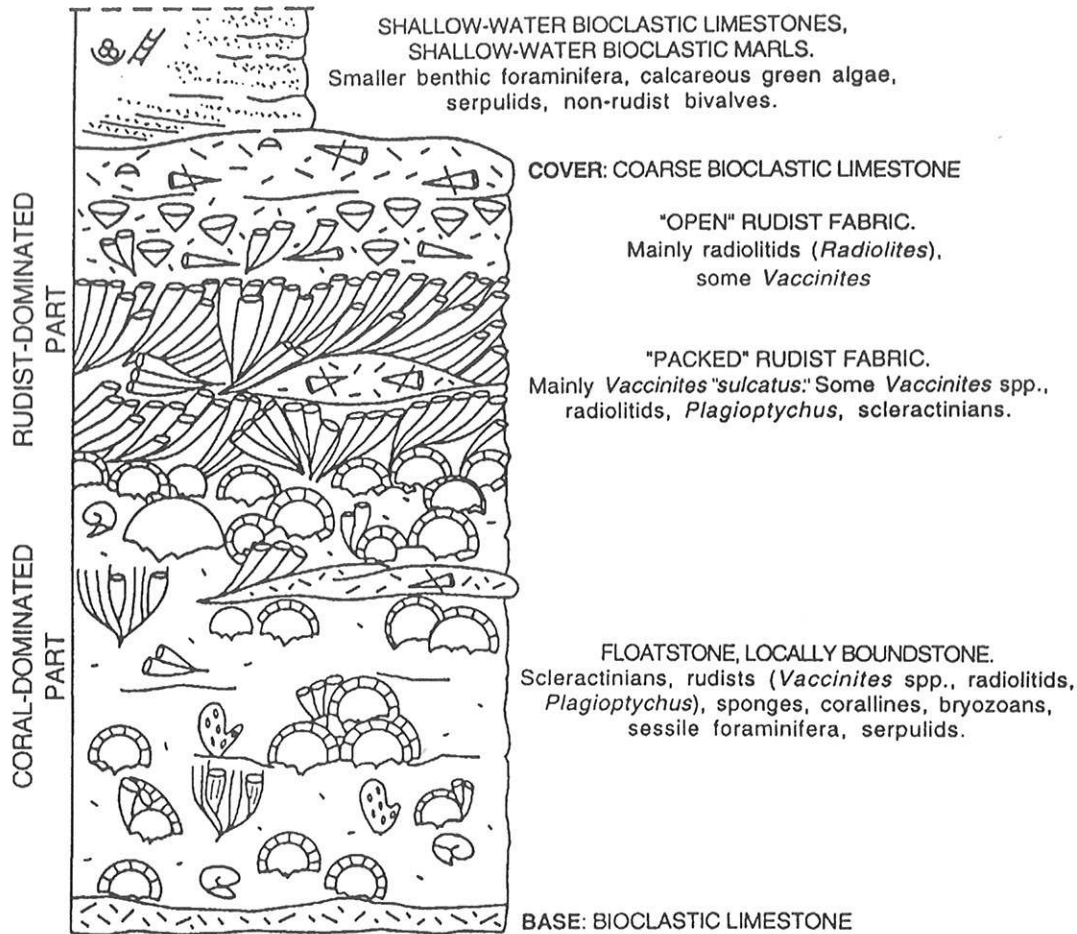


Fig. 8. Simplified, schematic summary section of a combined coral-rudist bioconstruction, overlain by shallow-water bioclastic limestones and/or bioclastic marls. See text for description and discussion.

2, the packed *Vaccinites* biostrome ("Atzl reef") above the underlying coral-rudist mound is itself based by a horizon of *Vaccinites* floatstone (see section 6.2). In the *Vaccinites* floatstones, the rock matrix is similar in texture and biogenic content to the coral-rudist mounds below, and thus provides no clues for the factors that precluded a continuation of coral growth. This suggests that (a) the underlying coral-dominated community was at least largely dead before the onset of colonization with *Vaccinites*, and (b) that the environmental conditions remained suboptimal for the corals also during the early stage of development of the *Vaccinites* biostrome.

Once established, a hippurite thicket provided numerous potential settlement sites for rudist larvae and, in addition, could recruit from itself. During accumulation of the "Atzl reef", episodic storms led to toppling or inclination of many of the *Vaccinites* clusters. During biostrome growth, however, the overall environmental conditions remained near optimum for *Vaccinites*. Only later, probably because of an increase in mean water energy, the packed *Vaccinites* biostrome was substituted by an open biostrome dominated by broad-conical to cup-shaped radiolitids. Ultimately, the radiolitid biostrome was terminated by shallowing into fairweather wave base and/or because of frequent storm destruction. Carbonate sand

bodies ultimately prograded over the biostromes (Figs. 7 and 8).

The "*Phelopteria* marls" above the "Atzl reef" were deposited in an overall quiet, low-energy subtidal environment with meadows of sea grass or algae. The abundance of *Phelopteria* is here related to an intermittently elevated nutrient level that came along with local input of siliciclastic fines. The depositional episode of the "*Phelopteria* marls" was followed by accumulation of limestones in a lagoonal environment of overall medium to low water energy. In this environment, open biostromes developed from bottoms of bioclast-bearing mud and muddy bioclastic sand; these biostromes consist of radiolitids and, subordinately, of *Vaccinites*, or exclusively of radiolitids. The branched coral *Pleurocora* thrived within the rudist thickets, and provided settlement sites for rudist growth. These thickets persisted only for a short interval of time, i.e. over a few generations of rudists, and were episodically destroyed by storms and modified by bioturbation.

Both hippuritid- and radiolitid-biostromes with rudists preserved *in situ* ("autochthonous rudist fabrics") commonly have a matrix of mudstone to wackestone with angular rudist debris, whereas other biogens, particularly smaller benthic foraminifera, are very rare or absent. The matrix of rudist biostromes that record intermittent distur-

bance or destruction ("parautochthonous rudist fabrics"), however, contains a fossil assemblage that is similar to the vertically associated bioclastic limestones. This indicates that substrata colonized by rudists were avoided by smaller benthic foraminifera.

On Late Cretaceous shelves, the hippuritids and the canaliculate rudists occupied higher-energy, external platform environments, whereas radiolitids were present from the external platform to slightly restricted, quiet lagoonal environments (eg. CARBONE & SIRNA 1981; ROSS & SKELTON 1993; SANDERS 1994, 1996a). The wide environmental range of the radiolitids is also recorded in the described carbonate succession. The coral-rudist mounds document that corals and Late Cretaceous elevator rudists may occur in close association. On the scale of the entire succession, however, the coral-dominated mounds and the rudist biostromes are vertically separated, at least in part as a result of the wide ecologic range of the rudists relative to corals.

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