

UPPER CRETACEOUS ‘RUDIST FORMATIONS’

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With 3 figures and 5 plates

Abstract: The Late Cretaceous hippuritids and radiolitids were able for rapid colonization of large areas of substrate, and for growth in densely packed, mono- to paucispecific aggregations. The rudist biostromes were vulnerable to storm damage and to churning by burrowing, and were terminated either by frequent toppling/fragmentation of rudists, or by burial with sediment, or by environmental restriction. The rudists were relatively resistant to siliciclastic input.

Hippuritids and radiolitids co-existed in mounds with scleractinians and skeletal sponges. These mounds are up to some tens of meters thick and hundreds of meters in lateral extent, and typically are topped by a rudist biostrome. As hippuritids and radiolitids lived together with corals and sponges as well as in environments unfavourable to corals and sponges, and because these rudists were able for both rapid colonization and growth in dense aggregates, the result is a larger number of rudist constructions and a smaller number of coral-sponge-rudist constructions, irrespective of coral-sponge-rudist synecology.

Rudist colonization and -growth occurred during intervals of time much shorter than parasequence development. Rudist formations, thus, may be present in the shallow neritic sector of each systems tract of a depositional sequence. The Late Cretaceous elevator rudists were not able to build wave-resistant bioherms comparable to Holocene coralgall reefs, but were mainly a source for bioclastic sediment. This, in turn, exerted a profound influence on the facies architecture and stratigraphic development of Late Cretaceous carbonate shelves, which are characterized by a wide external platform belt that gradually merges into an open lagoonal environment.

The radiolitid-dominated rudist faunas from the Southern Tethys contrast markedly with the hippuritid-dominated faunas from the shelves on the northern fringe of Tethys (Southern France, Northern Calcareous Alps). The hippuritid-dominated fauna of the Northern Calcareous Alps is also quite impoverished. The dominance of hippuritids and the depauperation of the rudist fauna may result from geographic barriers, or from the relatively northerly Late Cretaceous position of the area of the Northern Calcareous Alps, which thus may have been apt to short-term changes in water temperature and/or nutrients or, possibly, seasonal changes in oceanic surface currents.

During early diagenesis of rudist shells an early, open mould phase during/after aragonite dissolution is indicated by compaction-induced deformation and endogenic brecciation of both the ostracal parts of the rudist shells and the sedimentary infill of the intertabular spaces. Meteoric dissolution of rudist shells associated with the formation of emersion surfaces may lead to substantial taphonomic loss, down to complete diagenetic ‘erosion’ of biostromes. A certain amount of loss by shell dissolution appears to be a common step in the taphonomy of rudist biostromes.

Zusammenfassung:

Die Hippuritiden und Radiolitiden der späten Kreide konnten große Flächen von Substrat in dichtgepackten, mono- bis paucispezifischen Aggregaten rapide kolonisieren. Die von diesen Rudisten gebildeten Biostrome wurden häufig durch Stürme und bioturbationsverursachte Durchwühlung der Matrix zerstört. Die Akkumulation der Biostrome wurde entweder durch häufige Kippung und Fragmentierung der Rudistenschalen während Hochenergie-Ereignissen, durch Begrabung des Biostromes mit Sediment, oder durch zunehmende Milieueinschränkung beendet. Die Hippuritiden und die Radiolitiden waren vergleichsweise unempfindlich gegenüber siliziklastischem Eintrag.

In flachhügeligen Biokonstruktionen koexistierten Hippuritiden und Radiolitiden zusammen mit Skleraktinien und Skelettschwämmen. Die flachhügeligen Biokonstruktionen sind bis einige Zehnermeter dick und von einigen hundert Metern seitlicher Ausdehnung, und sind meist von einem Rudistenbiostrom überlagert. Da die Hippuritiden und Radiolitiden sowohl zusammen mit Korallen und Schwämmen als auch in Milieus lebten, die den beiden letzteren unzugänglich waren, und da diese Rudisten zu rapider Substratkolonisation und Wachstum in dichten Aggregaten fähig waren steht eine größere Zahl reiner Rudistenkonstruktionen einer kleineren Zahl von Korallen-Schwamm-Rudisten-Konstruktionen gegenüber.

Da Rudistenkolonisation und -wachstum während Zeitintervallen erfolgten, die wesentlich kürzer sind als die Zeitintervalle der Parasequenzentwicklung, können Rudistenformationen im flachneritischen Anteil jedes Systemtrakts einer Ablagerungssequenz vorhanden sein. Die spätkretazischen „Elevator-Rudisten“ waren nicht zum Aufbau wellenresistenter Bioherme vergleichbarer holozäner Korallen-Algen-Riffe imstande, sondern fungierten vor allem als Lieferanten für bioklastisches Sediment; dies übte einen weitreichenden Einfluss auf Faziesarchitektur und stratigraphische Entwicklung spätkretazischer Karbonatschelfe aus. Diese Karbonatschelfe sind durch eine breite externe Plattformzone charakterisiert, welche landwärts graduell in ein offen lagunäres Milieu übergeht.

Den radiolitidendominierten Rudistenfaunen des südlichen Tethysbereiches stehen die hippuritiden-dominierten Faunen der Schelfe vom Tethys-Nordrand (Südfrankreich, Nördliche Kalkalpen) gegenüber. Darüber hinaus ist die Hippuritiden-dominierte Fauna der Nördlichen Kalkalpen auch deutlich artenärmer; dies mag zum Teil auf geographische Barrieren und/oder auf die relativ nördliche paläogeographische Position des Bereiches der Nördlichen Kalkalpen zurückzuführen sein, welcher dadurch möglicherweise saisonalen Wechseln in Wassertemperatur, Nährstoffgehalt und im Muster der ozeanischen Strömungen ausgesetzt war.

Im Verlauf der frühen Diagenese von Rudistenschalen wurde häufig ein Abschnitt durchlaufen, während dessen die aragonitischen Schalenanteile völlig herausgelöst wurden, sodass offene Hohlräume verblieben. Gleichzeitig mit oder nach der Aragonitlösung erfolgten häufig auch Kompaktions-verursachte Verformung und endogene Brekzierung sowohl des restlichen, primär kalzitischen (ostrakalen) Anteils der Rudistenschale und der Sedimentfüllungen der Intertabularräume der Schalen. Meteorische Lösung von Rudistenschalen in Verbindung mit der Bildung subaerischer Freilegungsflächen kann zu starkem taphonomischen Verlust in Biostromen führen, bis hin zur völligen „Auslöschung“ eines Biostromes. Ein gewisses Ausmaß taphonomischen Verlusts durch frühdiaogenetische Schalenlösung scheint ein häufiger Abschnitt in der Taphonomie von Rudistenbiostromen zu sein.

1. Introduction

The term ‘rudist formations’ has been designed by ROSS & SKELTON (1993) for all rudist-bearing lithologies, irrespective of any other connotations. This paper provides a short overview of Upper Cretaceous rudist formations with respect to rudist colonization and features of rudist biostromes, biotic relations between corals and rudists, rudists versus siliciclastics, stratigraphic development and paleobiogeography of rudist-bearing shelves, and some characteristics of rudist taphonomy. The examples are derived from the Gosau Group of the Northern Calcareous Alps in Austria, from the carbonate platform successions exposed in northern and central Italy, and from the Upper Cretaceous succession in the south-central Pyrenees in Spain.

2. Rudist colonization and fabrics

The Late Cretaceous hippuritids and radiolitids were able for rapid colonization of very large areas

of substrate, probably by spatfalls of larvae (SANDERS, 1996 a). This is indicated by thickets hundreds of meters in lateral extent that consist of a single genus/species of rudist of apparently a single generation (plate 1/1). Such thickets were observed both in shallow subtidal carbonate and sandstone depositional environments, respectively. With respect to packing of the rudist shells, rudist fabrics may show an open texture (matrix-supported; plates 1/2 to 1/4) or a packed texture (supported by the rudist shells; plates 1/5, 2/1, 2/2) (SANDERS, 1996 a). The open texture corresponds to rudist floatstone or rudist bafflestone in the extended Dunham classification (JAMES, 1984). The packed texture corresponds to rudist rudstone, rudist bafflestone or rudist boundstone. With respect to biostratinomy, autochthonous and parautochthonous rudist fabrics are distinguished (SANDERS, 1996 b). In the autochthonous fabrics, at least most of the rudists are embedded in growth position, with or without the free valve (plates 1/1, 2/1, 2/3, 3/3). In the parautochthonous rudist fabrics most of the rudists are preserved, with or without the free valve, in a position that is not identical with their place and orientation in life (plates 1/2 to

1/4). In vertical section, a rudist biostrome may consist either of a single sheet of limestone of a single texture and with the rudists in a similar biostratinomic state, or shows both a variable texture and/or biostratinomy of the rudists.

Sharply 'kinked' rudist shells because of toppling during life locally are common. Continuously curved 'horn-shaped' shells of isolated rudists or clusters of a few rudists typically are present in open rudist fabrics with a matrix of lime mudstone to wackestone. The 'horn shape' results from a quasi-continuous upward shell curvature during growth (as also indicated by a continuous change in the upward orientation of the tabulae in the lumen of the shell) by progressive sinking of the rudist shell into the relatively soft mud.

3. Rudist biostromes

Biostromes built by hippuritids and/or radiolitids occur (1) directly above coral-sponge-rudist mounds (fig. 1; see description below), and (2) as 'isolated' biostromes of hippuritids and/or of radiolitids. In thicker, regressive successions of shallow-water limestones, a vertical trend from coral-sponge-rudist mounds to hippuritid biostromes and, higher up-section, to radiolitid biostromes can be observed (e. g. SANDERS & BARON-SZABO, 1997; SANDERS et al., 1997). The biostromes that overlie coral-sponge-rudist mounds are up to a few meters thick, are dominated by hippuritids (plates 1/5, 2/2) and, locally, are topped by a radiolitid biostrome that commonly shows an open to packed, parautochthonous fabric (fig. 1). By themselves, the rudist biostromes that overlie the coral-rudist mounds are not different from 'isolated' rudist biostromes.

Among the 'isolated' biostromes, both the hippuritid- and the radiolitid-dominated biostromes may overlie substrata of sandstones to hybrid arenites, or of bioclastic packstones to wackestones to floatstones. In addition, in lagoonal successions, sheeted to gently mounded mass accumulations of nerineids or actaeonellids locally provided a substrate for a rudist biostrome (SANDERS,

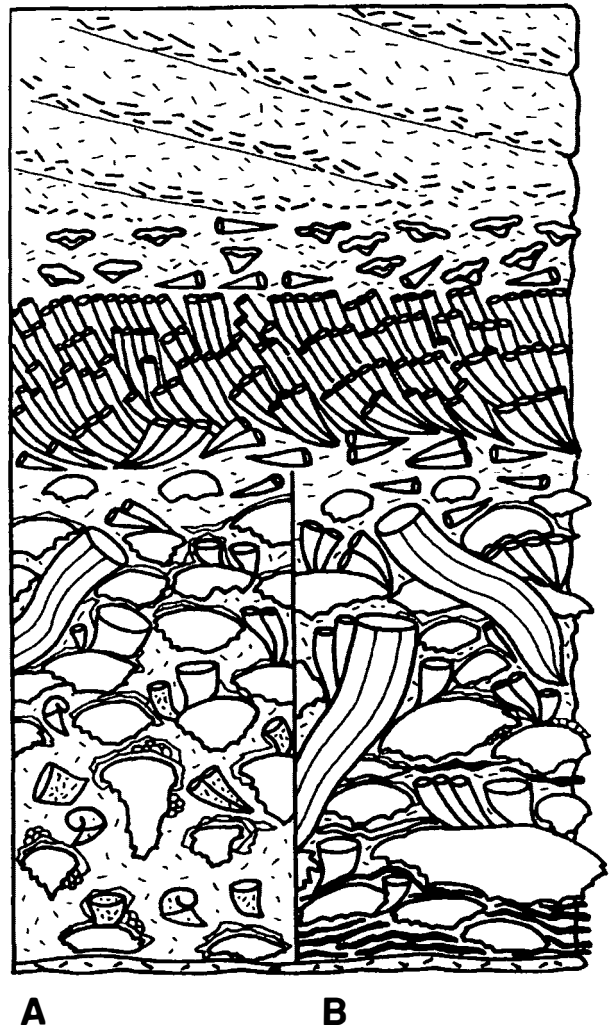


Fig. 1: Schematic section through a coral-rudist mound topped by a rudist biostrome. Two typical patterns of vertical development of a coral-rudist mound are shown.

A: A basal veneer of bioclastic limestones is overlain by more or less marly floatstones to wackestones with columnar corals, skeletal sponges and rudists, mainly *Plagioptychus*, small hippuritids and radiolitids. The corals, sponges and rudists typically are encrusted by red algae, bryozoans, sessile foraminifera and serpulids. Higher up, the corals become more abundant and, locally, boundstones with corals, sponges, large rudists (e. g. *Vaccinites giganteus major*) and small rudists (e. g. *Hippurites socialis*) develop.

B: A basal veneer of bioclastic limestones is overlain by a boundstone composed mainly of large coral heads and foliose skeletal sponges (e. g. stromatoporoids); rudists are subordinate. Higher up, both large and small rudists are common, and evidently grew in close association with corals and skeletal sponges. Both the type A and type B mounds are most commonly followed up-section by a packed, paucispecific hippuritid biostrome. The hippuritid biostrome may be overlain by a radiolitid biostrome which, in turn, is overlain by bioclastic limestones that have been deposited from migrating sand bodies.

1998 b, and in press). Typically, hippuritid biostromes are a few decimeters to a few meters thick and show a packed-autochthonous fabric or a packed-parautochthonous fabric (plates 1/2, 1/5, 2/1, 2/2). The packed-autochthonous fabrics consist of hose-shaped shells of hippuritids that grew in close contact and, locally, are attached with each other along 'shared' shells (HÖFLING, 1985; SANDERS & BARON-SZABO, 1997). Within the packed hippuritid textures, a few *Plagioptychus*, radiolitids, small caprotinids, and small coral heads are locally present. Within a hippuritid biostrome, an upright to inclined orientation of the rudist shells relative to bedding may be quite constant (HÖFLING, 1985; SANDERS & BARON-SZABO, 1997), or may vary between large groups of rudist clusters (SANDERS, 1996 a). In some successions, the shell orientation can be quite constant over large areas and over long intervals of time (SANDERS & PONS, unpubl. data). The uniform dip of the rudist shells may result from either an upstream or from a downstream orientation of the free valves, respectively. In the nearshore environment, save tsunamis the surge exerted by shoaling storm- and swell waves has a high capacity for uprooting, and is one of the strongest currents that may prevail for days to weeks. It is thus most feasible that the rudist shells were inclined downstream the onshore-surge exerted by shoaling waves and swell. The hippuritid biostromes locally are topped by a radiolitid biostrome.

Typically, radiolitid biostromes are a few decimeters to about three meters thick and show an open to packed, parautochthonous fabric (SANDERS, 1996 a, b; SANDERS & BARON-SZABO, 1997). The matrix is a bioturbated shallow-water bioclastic wackestone to packstone to rudstone that may contain a few hippuritids and *Plagioptychus*. Locally, lenses up to several decimeters thick of floatstone composed of fragments from the radial funnel plates and from the upper valve of the radiolitid shell, and/or layers of floatstone to rudstone with abundant toppled, juvenile radiolitids are intercalated into radiolitid biostromes. Radiolitid biostromes composed entirely of an autochthonous fabric are comparatively rare (cf. plate 2/3). In thicker radiolitid biostromes, vertical

transitions from parautochthonous to autochthonous fabrics and vice versa are common (SANDERS, 1996 a, b; SANDERS & BARON-SZABO, 1997). Both in the rudist thickets and the biostromes, the rudists commonly are unencrusted or bear encrustations of, at most, a few square centimeters in size. The epibionts mainly are Cheilostomata, corallinaceans and serpulids, whereas Cryptostomata, thecideids, Rupertininae, Placopsilininae, and cf. *Placunopsis* are less common.

In a few biostromes in the Northern Calcareous Alps, rudstones are intercalated that are composed of angular, unmicritized bioclasts and very well-rounded, spherical to oblate lithoclasts that probably were derived from gravelly beaches, and were spilled during storms onto the biostrome. A co-existence of rudist biostromes and adjacent gravelly beaches is also strongly suggested by a close vertical association of the lithoclast-bearing rudist biostromes with beachface conglomerates.

Near their top, many biostromes show an increasing proportion of open-parautochthonous fabric, locally with shelter pores and intercalations of rudist-clastic grainstone. These biostromes were terminated by frequent uprooting and fragmentation of rudist shells, i. e. by 'fragmentation termination'. Alternatively, the rudists at the top of a biostrome are preserved in growth position and with the upper valve in place, and are sharply overlain by the lithology immediately above the biostrome. These biostromes were terminated by burial with sediment, accompanied by a change of environmental conditions unfavourable to a recolonization with rudists. The rudists on top of the biostrome, however, may have been dead for some time before their ultimate burial. Locally, at the top of a biostrome, the upper part of the lower valve and the free valve of the rudists are embedded in the lithology that sharply overlies the biostrome (mudstone to bioclastic wackestone, packstone to bioclastic grainstone, sandstone or hybrid arenite). These rudists probably were choked *in vitro* by rapid deposition of sediment. Both cases where the rudists on top of the biostromes were already dead before burial with sediment, and burial of living rudists are termed 'burial termination' (plate 1/5) (cf. SANDERS, 1996 a). Locally, at the

top of a biostrome, a lateral transition from fragmentation termination to burial termination can be observed, probably as a result of fragmentation of rudists by storm waves and choking of rudists during storm-induced migration of carbonate sand bodies (SANDERS, 1994). More rarely, on top of a biostrome an interval a few centimeters to several decimeters thick is present that shows a parautochthonous rudist fabric with strongly bored, micritized and encrusted rudists. This interval is overlain by lithologies that have been deposited in a more or less restricted shallow marine environment, e. g. organic-rich marls with ostracods, smaller benthic foraminifera and green algal fragments. In these cases, biostrome growth probably was shut down by environmental restriction ('restriction termination').

In coral-sponge-rudist mounds and in the biostromes, *Plagioptychus* is present yet always of subordinate abundance. This mussel was found in limestones, in marls and in sandstones to hybrid arenites. No obvious correlation between sediment petrography and -texture versus presence/abundance of *Plagioptychus* was observed.

4. Biotic relations

In the Upper Cretaceous of the Dinarids, the Alps and of the Pyrenees, mounds of boundstones to floatstones with scleractinians, stromatoporoids, demosponges, calcisponges, hippuritids, radiolitids, *Plagioptychus*, caprotinids, requienids, alcyonarians and, locally, large 'Tridacna-like' spondylids are quite common (plate 3/2) (POLSAK, 1981; SCOTT et al., 1990; SANDERS, 1996 c; SANDERS et al., 1997; SANDERS & BARON-SZABO, 1997). The mounds are up to some tens of meters thick and hundreds of meters in lateral extent. In vertical section, two types of mound development can be distinguished, (a) a gradual upward increase in packing density and size of corals, sponges and rudists (fig. 1A), and (b) a lower interval of densely packed foliose skeletal sponges and/or foliose to globose corals (plate 2/4) with only a few rudists, followed up-section by an interval of more

or less densely packed corals, sponges and rudists that may be quite large, as for instance *Vaccinites giganteus major* of up to more than 1 m in length, *V. galloprovincialis* and *V. oppeli* (fig. 1B; plates 3/1, 3/2, 3/3). The rudists and the corals grew in close association with each other (plates 3/2, 3/3, 4/1). Encrusters and binders mainly are red algae, bryozoans, sponges and sessile foraminifera (plates 4/2, 4/3); microbialites are locally present as encrustations, as matrix and in kryptic habitats (SANDERS & BARON-SZABO, 1997; SANDERS et al., 1997). These two types of mound development occur over a wide range of thicknesses and may record mound development in lower-energy shelf environments (type A development) and higher-energy shelf sectors (type B development).

The mounds typically are topped by a rudist biostrome (see fig. 1). A lateral transition from a coral-sponge construction into a coral-sponge-rudist construction and, finally, into a rudist biostrome can locally be observed over a distance of hundreds of meters (SCOTT et al., 1990; SANDERS, 1996 c, 1998 b). The coral-sponge construction corresponds to the bathymetrically deepest part of the mound, while the rudist biostrome accumulated in the shallowest sector. Both across and along a mound-biostrome interval, the rudist fauna shows marked changes with respect to presence, abundance and growth form of rudist species. In the coral-sponge-rudist mounds, the rudists locally are thickly encrusted by corallinaceans, squamariaceans, Cheilostomata, placopsilinines, hyaline sessile foraminifera, sponges, microbialites, and serpulids.

In the coral-rudist mounds, the nearly ubiquitous presence yet invariably subordinate abundance of the rudists suggests that a reduction in the number of living corals was a prerequisite for the development of a dense rudist population, i. e. a rudist biostrome closely above the mounds. Although a clear-cut tendency was observed for large hippuritids (*Vaccinites giganteus major*, *V. galloprovincialis*, *V. oppeli*) to co-occur preferentially in association with corals the same hippuritid species, albeit typically of smaller size, were also observed within rudist biostromes. The rudists thus did not eke out the corals in direct competition, i.e. the ver-

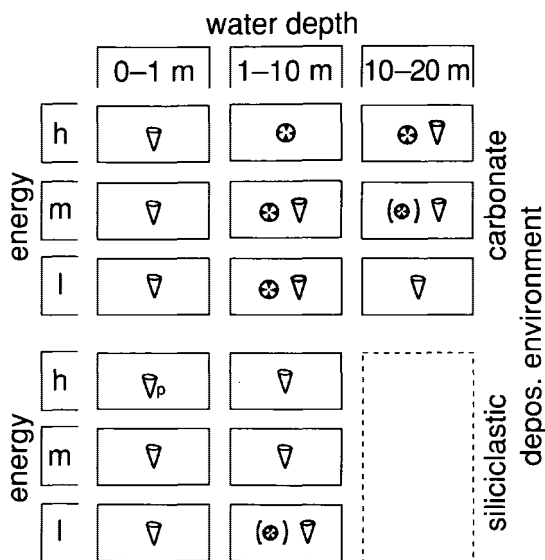


Fig. 2: Idealized summary scheme of the presence of rudists and corals in successions from carbonate and siliciclastic depositional environments, respectively. The scheme is subdivided into three categories of depositional water depth, and high-energy (h), medium-energy (m) and low-energy (l) environments. Symbols in parentheses indicate rare presence. Small index p indicates a presence exclusively in parautochthonous rudist fabrics. The dashed area was inhabited neither by rudists nor corals. The scheme reflects the overall wider ecological tolerance of the rudists relative to colonial corals, i. e. the rudists could grow together with colonial corals but equally well in environments unaccessible to corals.

tical change from a coral- to a rudist-dominated community is an allogenic succession rather than an autogenic succession (GILI et al., 1995; cf. WALKER & ALBERSTADT, 1975).

5. Rudists vs. siliciclastics

Rudist biostromes that are sharply intercalated into successions of sandstones or of marls typically contain a matrix of bioclastic hybrid arenite, of sandy marl, or of sandstone. Alternatively, arenites or marls may be overlain by a thin veneer of sandy bioclastic packstones to grainstones which, in turn, are overlain by a rudist biostrome; this appears to be the case where the arenite or marl and the overlying biostrome are both part of a single upward shoaling 'cycle'. In other cases, the biostromes sharply overlie arenites or marls along a

bedding plane; this typically is the case where the bedding surface across which the change of facies occurs coincides with a marine flooding surface at the base of an upward shoaling 'cycle'.

At their top, the biostromes may grade into overlying arenites or marls via an interval up to a few decimeters thick of increasingly marly to sandy bioclastic wackestone to packstone to hybrid arenite. Where a biostrome is overlain by sandstones or hybrid arenites, the topmost part of the biostrome is typically mottled by burrows filled by the sandstone or arenite. In some biostromes, a vertical change from a matrix of limestone to a matrix of friable silty marl, without a change in the biostrome fabric, indicates that the biostromes persisted even under a marked overall increase of siliciclastic input. A sharp, unburrowed vertical transition from an interval of biostromal limestone into overlying arenites is very rare and, in the one observed case, occurs across a ravinement surface that formed in association with transgression. The described relations of rudists and siliciclastics indicate that a moderate amount and/or infrequent occurrence of siliciclastic input was of subordinate influence on rudist growth. Overall, however, there is a clear-cut positive correlation between presence and abundance of rudists and shallow-water limestones.

Since most Late Cretaceous hippuritids and radiolitids grew together with corals and sponges in the described mounds, but also thrived in environments unfavourable to both corals and skeletal sponges, and because these rudists were able for both rapid substrate colonization and growth in densely packed aggregations, an inevitable result is a larger number of rudist constructions and a smaller number of coral-sponge-rudist constructions, irrespective of coral-sponge-rudist synecology (fig. 2).

6. Stratigraphy

As the Late Cretaceous hippuritids and radiolitids could thrive in a wide variety of depositional environments, and as rudist colonization

and -growth occurred within time intervals much shorter than that of parasequence development (the latter typically in the range of some thousands to some tens of thousands of years; VAN WAGONER et al., 1990), rudist formations can be encountered in the neritic sector of each systems tract of a depositional sequence. In the following, the stratigraphy of rudist formations from northern and central Italy, the Northern Calcareous Alps and from the south-central Pyrenees are shortly compared with each other.

Italy (see fig. 3A): The back-bone of the Apennine orogen of Italy consists of carbonate shelf successions thousands of meters thick. These successions were deposited from the large, isolated peri-Adriatic carbonate platforms that were situated on thinned continental crust on the southern margin of Tethys (BERNOULLI & JENKYN, 1974). The peri-Adriatic platforms came into existence during the Early Jurassic by rift-induced segmentation of the Hauptdolomit megabank; these platforms persisted until the Tertiary, when they became successively involved into folding and thrusting associated with Alpine orogenesis. The shallow-water banktop of these platforms precipitated into the proximal basin via steep escarpments up to about 1000 meters in height; the escarpments were inherited from Early Jurassic rifting (BERNOULLI & JENKYN, 1974; BICE & STEWART, 1985), but subsequently were shaped by erosion (EBERLI et al., 1993). During the Late Cretaceous, on the external part of the platforms, depositional sequences developed mainly by aggradation to progradation of rudist-clastic sand bodies within a dissipative shore zone up to several kilometers in width; records of prograding, reflective carbonate beaches are less common (SANDERS, 1994, 1996 a; see also CARBONE & SIRNA, 1981; ACCORDI et al., 1982). On the external platform, individual parasequences typically are a few meters to more than 15 meters thick. Sections in the 300 m thick, Cenomanian to Campanian external platform succession of Montagna della Maiella, for instance, contain up to about 85% rudist-clastic grainstone to, subordinately, packstone whereas preserved rudist biostromes make

up less than 10% to 15% of the column; another few percent is represented by other carbonate lithologies (e. g. black pebble floatstones). In principle, depositional sequences may be recognized by the stacking patterns of the parasequences. As the parasequence stacking patterns, however, were found to vary laterally over short lateral distances, and as cryptic emersion surfaces locally occur within apparently uniform successions of rudist-clastic grainstones, in practice both a correct interpretation and lateral correlation of depositional sequences was hardly possible (SANDERS, 1994). In the high-energy environment along the margins of the peri-Adriatic platforms, by far the most of the rudist shells were transferred to bioclastic sand by the combined effects of wave destruction and bioerosion. The rudists, thus, were mainly sediment producers, whereas the conditions necessary for both growth and preservation of rudist biostromes were comparatively rarely met (SANDERS, 1996 a). The high-energy environment along the platform margins favoured effective offbank transport of bioclastic material which, in turn, was an important factor in the progressive burial of platform escarpments, and for subsequent carbonate shelf progradation (compare EBERLI et al., 1993; SANDERS, 1994; MUTTI et al., 1996).

Northern Calcareous Alps (fig. 3B): The mixed siliciclastic-carbonate succession of the Lower Gosau Subgroup (Turonian-Lower Campanian; WAGREICH & FAUPL, 1994) of the Northern Calcareous Alps provides an example for the development of rudist formations in extension/strike-slip controlled depocenters that were situated on top of an accretionary wedge (SANDERS, 1998 a, and in press) (cf. RATSCHBACHER et al., 1989; NEUBAUER et al., 1995). The Late Cretaceous shelves in the area of the Northern Calcareous Alps were compartmentalized, wave-dominated, microtidal to low-mesotidal, and exhibit an exceptionally wide spectrum of facies. In depositional sequences, the transgressive systems tract is dominated by siliciclastics, and typically contains rudist thickets and biostromes that were deposited in lagoons with carbonatic or siliciclastic deposi-

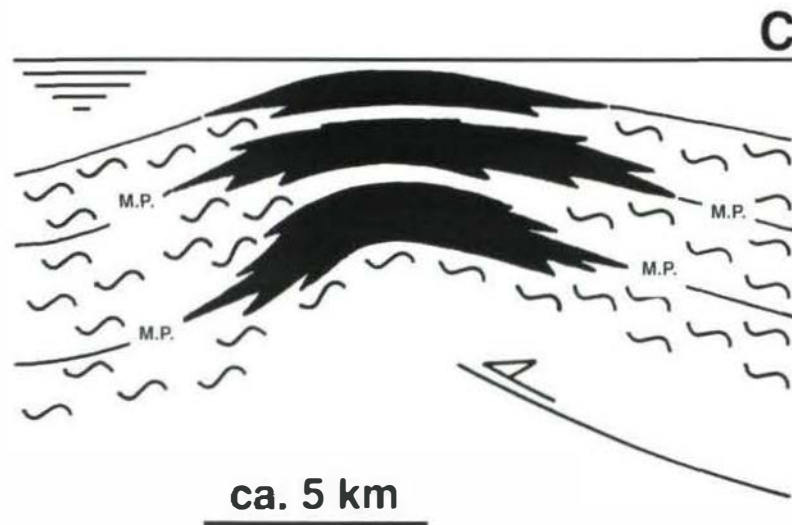
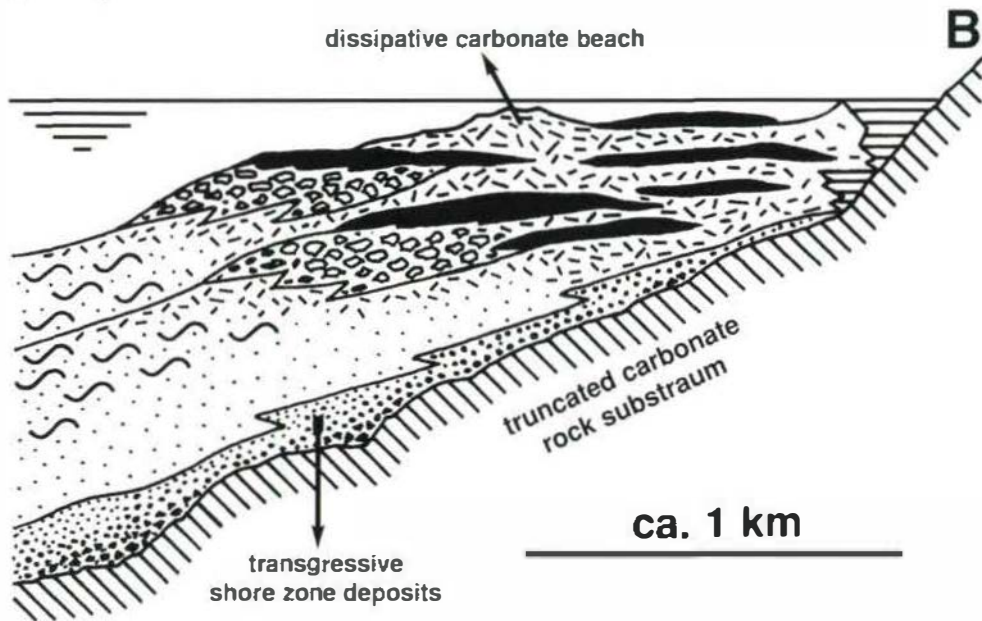
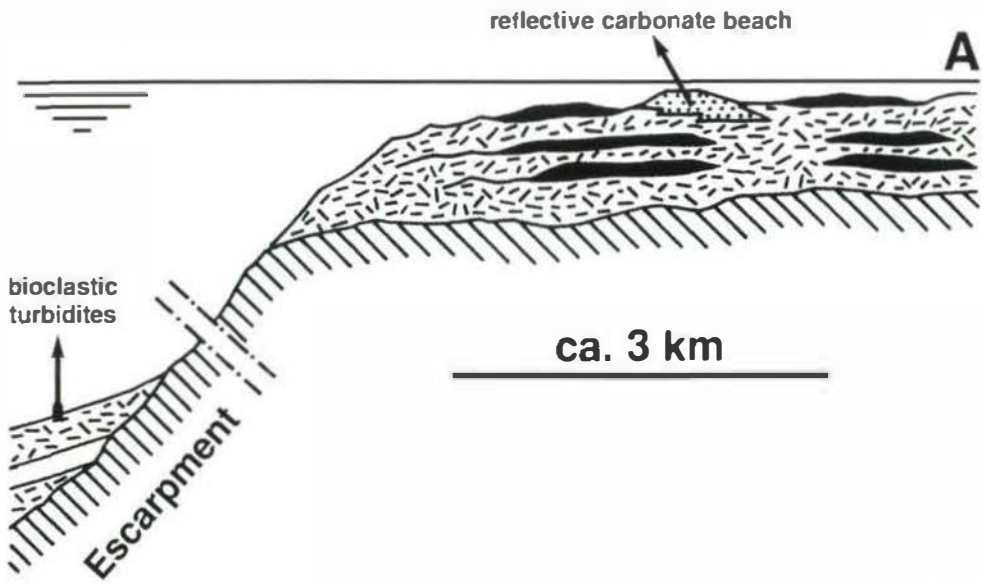


Fig. 3: Comparison of Upper Cretaceous rudist formations from the margins of the peri-Adriatic platforms (A), from the Gosau Group of the Northern Calcareous Alps (B) and from the Basturs Formation in the south-central Pyrenees (C), with characteristic scale indicated. See text for further description and discussion.

A: During large parts of Late Cretaceous times, the peri-Adriatic carbonate platforms as exposed today in the Appennines were characterized by a flat banktop and steep escarpments that precipitated into a proximal basin. On the external platform, bioclastic sand (hatched) and rudist biostromes (black) accumulated. The bioclastic limestones were mainly deposited from migrating dunes in a dissipative shore zone; successions deposited from reflective carbonate beaches (stippled) are less common. On the banktop, depositional sequences developed by stacking of para-sequences that consist mainly of rudist-clastic sand and, subordinately, of rudist biostromes. In the proximal basin, a succession mainly of bioclastic turbidites composed of shallow-water bioclastic material (hatched) and hemipelagic limestones (white) composed largely of peri-platform ooze were deposited; this succession onlaps the escarpment.

B: During the Late Cretaceous, the previously exposed and eroded parts of the Eo-Alpine accretionary wedge became onlapped and buried by the succession of the Gosau Group. In the transgressive systems tract of depositional sequences, sheets composed of cliff talus breccias, beachface conglomerates and calcilitic arenites (dense stipples) are locally present at the base and overlie a truncated substratum of Triassic-Jurassic rocks (cross-hatched). In the highstand systems tract, locally narrow carbonate shelves established that were characterized by (a) a narrow, microtidal marsh (horizontal lines), (b) an open lagoon with radiolitic biostromes, (c) a dissipative shore zone with subaqueous dunes of rudist-clastic sand, and (d) an inner shelf belt with coral-rudist mounds that are topped by hippuritid biostromes. The mid- to outer shelf environment was characterized by deposition of siliciclastic sandstones and siltstones.

C: During the Late Cretaceous, the area of the south-central Pyrenees was situated in the foreland of the advancing Pyrenean fold-and-thrust belt. On top of thrust anticlines, carbonate shelf successions (black) were deposited, and were characterized by a relatively small extent in dip section (as shown in the figure) and a significantly larger extent alongstrike of the thrust anticline. Depending on the depth of submergence below sea level and the rate and amplitude of sea-level changes, the carbonate shelves may be both initiated and prograde during relative sea-level falls, until a point of maximum progradation ("M.P." in figure). During relative sea-level rise, the carbonate shelf diminished in area until the entire carbonate shelf drowned and became draped by marls that were deposited in a neritic environment. Locally, repeated oscillations of relative sea-level lead to an interlayering of marls and carbonate shelf deposits on top of the thrust anticlines, as for instance in the Santonian Basturs Formation.

tion (SANDERS et al., 1997). Near its landward margin, where transgression occurred onto rocky headlands, the transgressive systems tract consists of lithologies that were deposited from gravelly to rocky shores (fig. 3B) (SANDERS, 1997). The highstand systems tracts commonly was deposited from wave-dominated, narrow siliciclastic shelves that were bound towards the lagoon by reflective, sandy beaches. In areas protected from siliciclastic input, in the highstand, small carbonate shelves developed that included only the inner shelf to lagoonal sector (see fig. 3B) (SANDERS, 1998 a; cf. SANDERS et al., 1997). The inner shelf environment was characterized by coral-rudist mounds and hippuritid biostromes, and was separated from an open lagoonal environment by a dissipative shore zone with bioclastic sand bodies. In open lagoons, thin coral-sponge-rudist mounds and radiolitic biostromes were deposited. In the Northern Calcareous Alps, the carbonate shelf successions are up to some tens of meters thick, and show a 'catch-up' development; no record of carbonate shelf progradation, however, at least over more than a few kilometers is known. The vertical association of transgressive successions deposited from rocky to gravelly shores with overlying, regressive carbonate shelf successions to date has been described only from the Gosau Group of the Northern Calcareous Alps, and results from sea-level rise onto the inclined, articulated truncation surface on top of the older substratum (SANDERS, 1997, 1998 a). In vertical section, the regressive carbonate shelf successions consist of subequal amounts of bioconstructions and bioclastic limestones and, locally, a subordinate proportion of marls that have been deposited in a shallow neritic environment (SANDERS & BARON-SZABO, 1997). The bioclastic limestones typically are bioturbated grainstones to packstones to wackestones; well-washed grainstones with preserved primary hydrodynamic structures are both relatively rare and confined to intervals a few meters thick at most. The subordinate presence of well-washed grainstones, the overall moderate amount of bioclastic limestones, their bioturbation and their matrix of lime mud indicates that the small carbonate shelves in the area of the Northern

Calcareous Alps were characterized by an overall moderate to low water energy.

South-central Pyrenees (fig. 3C): In the external part of the Pyrenean fold-and-thrust belt, during the Late Cretaceous small carbonate shelves characterized by coral-sponge-rudist mounds, rudist biostromes and bioclastic limestones locally developed on top of thrust anticlines (cf. PONS, 1977; GILI et al., 1992). These carbonate shelves were of limited extent in dip section, but of significantly larger extent along strike.

Depending on the depth of submergence of a thrust anticline below sea-level, the carbonate shelves may show marked lateral shifts of facies during relative sea-level changes. In the Santonian Basturs Formation (480 m thick), for instance, sequence development records carbonate shelf progradation during late sea-level highstand and during sea-level fall, retrogradation of the carbonate shelf during relative sea-level rise, and drowning of the carbonate shelf during continued rise and highstand (SANDERS & PONS, unpubl. data) (see fig. 3C) During late sea-level highstand and sea-level fall, the carbonate shelf rapidly prograded, over a lateral distance of at least 5 kilometers, above shelf marls. During the subsequent rise of relative sea-level, the carbonate shelf stepped back ahead of the shelf marls, and finally became draped by the marls (fig. 3C). The lateral transition from well-defined upward shoaling stratal packages of shelf carbonates, i. e. carbonate parasequences into the laterally adjacent shelf marls occurs within a few tens of meters. Within the shelf marls, despite superb exposure, the geologic time surfaces as defined by the tops of laterally adjacent parasequences are unrecognizable. In the shelf marls, storm beds of bioclastic composition locally are present, but overall are subordinate in abundance. Preliminary results from geometric analysis and facies analysis indicates that the carbonate shelf exported only a small amount of bioclastic sand.

With respect to their gross facies architecture, their low progradation potential, the subequal amount of preserved bioconstructions and bioclastic sand, and the evidence for an overall mod-

erate to low water energy, the small carbonate shelves of both the Northern Calcareous Alps and of the Basturs Formation contrast with the large, isolated peri-Adriatic carbonate platforms that are characterized by a marked prevalence of bioclastic sand, a small amount of preserved bioconstructions, and an external platform belt several kilometers in width. As the Late Cretaceous elevator rudists did not build wave-resistant bioherms comparable to Holocene corallgal reefs, none of the described successions displays a narrow, external high-energy belt and a wide, protected internal shelf environment. Instead, the lateral transition from the shelf edge to the lagoon was a more or less wide belt that was characterized by a highly variable depositional topography both in space and time, by an overall gradual transition into an open lagoon, and a prevalence of bioclastic facies.

7. Paleobiogeography

As for the rudists a larval drift stage of possibly some days to weeks was the only possibility to spread, their biogeography was mainly controlled by oceanic surface currents, water temperature, and size of ocean basins (KAUFFMAN & JOHNSON, 1988). An increasing amount of provinciality of rudist faunas during the Late Cretaceous is ascribed to the break-up of the formerly continuous Tethyan belt during opening of the Atlantic and an overall change in the patterns of ocean currents, leading to a Caribbean and a Mediterranean rudist paleobiogeographic province, respectively (COATES, 1973; KAUFFMAN, 1973).

A marked difference exists between the radiolite-dominated rudist faunas from the Southern Tethys and the hippuritid-dominated rudist faunas from the shelves on the northern fringe of Tethys, i. e. in the areas of Southern France and of the Northern Calcareous Alps. In addition, the rudist fauna of the Northern Calcareous Alps is impoverished with respect to contemporaneous rudist faunas of Southern France and of the Southern Tethys (SANDERS et al., 1996, 1997; compare PHILIP & BILOTTE, 1983; PONS & VICENS,

1988; PONS & SIRNA, 1992; CESTARI & SARTORIO, 1995). In the Gosau Group of Krappfeld, situated in the Central Alps, debris flow deposits contain rudist genera that are absent in the Upper Cretaceous of the Northern Calcareous Alps, as for instance *Joufia* and *Pseudopolyconites* (SANDERS, PONS & CAUS, unpubl. data). Paleobiogeographic boundaries thus were situated within the area of the Alps.

The Late Cretaceous paleogeography of the Eastern Alps is still poorly known, and recent paleogeographic reconstructions differ markedly (ÖBERHAUSER, 1995; FROITZHEIM et al., 1997). At least some of the Late Cretaceous Central Alpine basins, however, were separated from the area of the Northern Calcareous Alps by emergent ridges (cf. NEUBAUER et al., 1995). During the Late Cretaceous, the area of the Northern Calcareous Alps was situated at about 30-35° north paleolatitude (MAURITSCH & BECKE, 1987; DER COURT et al., 1993), within a belt that was characterized by a monsoonal climate (PARRISH & CURTIS, 1982; PRICE et al., 1995). Thus, geographic barriers, seasonal changes in water temperature and/or nutrients as a result of climate and, possibly, seasonal changes in oceanic surface currents may have produced the impoverished, hippuritid-dominated rudist fauna of the Northern Calcareous Alps. At present, none of these factors can be definitely discarded.

8. Diagenesis

The shells of the Late Cretaceous hippuritids and radiolitids consisted of both hypostracal aragonite and ostracal calcite (e. g. KAUFFMAN & JOHNSON, 1988). In all observed cases, the aragonite is replaced by blocky calcite spar or by internal sediment. Locally, selective removal of the boxwork ostracum of the lower valves of radiolitids occurred by calcitic burrowing and abrasion, and, probably, by early diagenetic dissolution; this process led to radiolitid relics that are composed only of a thin ostracal shell layer and the hypostracal, formerly aragonitic shell parts. Both

the selective removal of the boxwork ostracum and the dissolution of the aragonitic shell parts associated with meteoric diagenesis may lead to a marked taphonomic loss within the radiolitid biostromes (plate 5/1). Within a former biostrome all of the rudist shells may be dismantled from the ostracum and the aragonite dissolved, save some relics like e. g. the inner, dense calcitic shell layer of the ostracum and the ligamentary crest (plate 5/2). The dissolution moulds may show evidence for compaction-induced deformation, and are typically filled by bioclastic wackestone to packstone to grainstone that may be identical or similar to the limestones immediately above an emersion surface. In many cases, a stage of open mould left by the dissolved aragonite is indicated by gravitational settling of the crescent-shaped, semilithified sedimentary fillings of the intertabular spaces (plate 5/3). Aragonite dissolution in an early stage is indicated by compaction-induced fracture of the rudist shells, with consequent endogenic brecciation of both the rudist shell and the sedimentary infill of the intertabular spaces (SANDERS, 1997). Alternatively, dissolution was selective, removing only certain rudist taxa, or only the aragonitic shell parts. Rudists with a shell of dense calcite, as e. g. *Bournonia*, most commonly escaped dissolution (plate 5/4). The ultimately preserved rudist fauna of a biostrome thus may represent only a very small, selective fraction of the original fauna. Except both superb outcrop and detailed investigation, such 'ghost biostromes' as well as the corresponding emersion surfaces (plate 5/5) most probably would escape recognition in the field. Results from outcrops in Italy and in the Alps, however, indicate that a certain amount of taphonomic loss by selective shell disintegration and -dissolution is a common step in the taphonomy of rudist biostromes (SANDERS, 1994, 1997).

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Plate 1

- 1: Part of a thicket (dashed interval) that appears to consist of a single generation of radiolitids. This thicket can be traced in outcrop over about 600 meters, without pinching out. Hammer is 33 cm long. Monte Acquaviva, Montagna della Maiella, Italy.
- 2: Toppled clusters of hippuritids (mainly *Hippurites matheroni*), embedded subhorizontally relative to bedding. The matrix is a bioturbated, poorly sorted bioclastic wackestone to packstone. Pen is 14 cm long. Traunwandalm near Russbach, Salzburg, Austria.
- 3: Coarse, silicified fragments from *Praeradiolites* and *Biradiolites* embedded in a matrix of bioturbated fine sand to silt bioclastic grainstone. Pen for scale is 6 mm in diameter. Collades des Basturs, Province Lleida, Spain.
- 4: Part of a level with scattered, isolated specimens and clusters of *Durania*, embedded in a lying position within a slightly marly, bioturbated, poorly sorted bioclastic wackestone to packstone. Pen is 14 cm long. Gosauschmied, Upper Austria.
- 5: Cluster of large *Vaccinites oppeli*, embedded subhorizontally relative to bedding, in a matrix of poorly sorted bioclastic wackestone to floatstone with small coral heads. This layer is intercalated between layers with upright hippuritids. Pen is 14 cm long. Traunwandalm near Russbach, Salzburg, Austria.

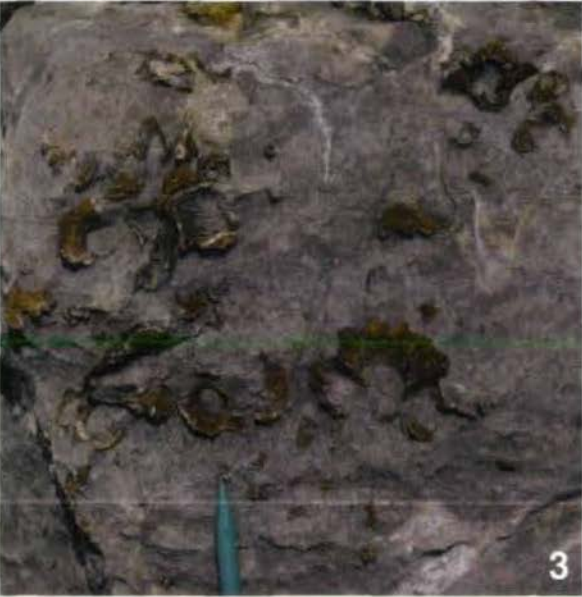


Plate 2

- 1: Packed-autochthonous hippuritid biostrome, overlain by bioclastic grainstones. The relief formed by the rudist clusters on top of the hippuritid biostrome is buried by a downlapping bedset of poorly sorted bioclastic grainstones that were deposited from a migrating carbonate sand body. The dip of the beds of bioclastic grainstone is shown by black lines. Head of hammer is 12 cm long. Cima delle Murelle, Montagna della Maiella, Italy.
- 2: Top of a hippuritid-dominated biostrome, with upright clusters of large *Vaccinites oppeli*. This interval overlies an interval with lying hippuritids as shown in plate 1/2. Hammer for scale is 33 cm long. Traunwandalm near Russbach, Salzburg, Austria.
- 3: Longitudinal section through the commissure between the right valve and the left valve of a radiolitid shell. The attached, right valve shows the formerly aragonitic hypostracum (A), now replaced by blocky calcite spar, and the outer, calcitic ostracum (O) that is characterized by a boxwork structure. The upper, left valve consists of a hypostracum of former aragonite (A), an ostracal layer of 'massive' calcite (C), and an outer, ostracal layer composed of delicate calcite lamellae (L). Note that the commissure gapes, and that the margins of the upper and the lower valve, respectively, are micritized and penetrated by microborings. Within the gap, sessile foraminifera (white arrowtip) and, possibly, a sponge thrived (indeterminate structure to right). Width of view: 5.3 mm. Location Haidach in Brandenburg, Tyrol, Austria.
- 4: Stacked, foliose microsolenid corals up to more than a metre in width, seen from their lower side. Pen for scale is 14 cm. Middle part of 'Theresienstein reef' near Strobl at Wolfgangsee, Salzburg, Austria.

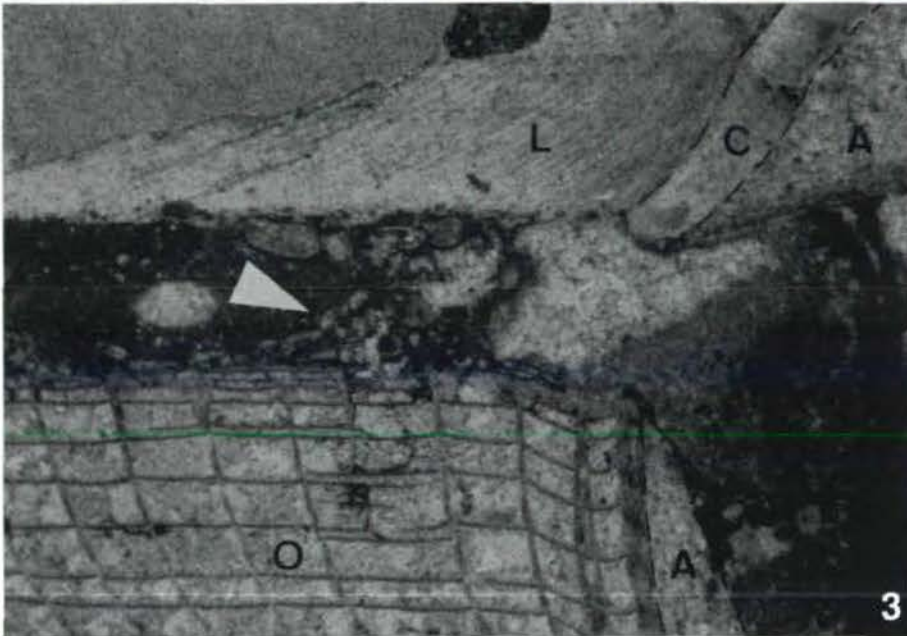


Plate 3

- 1: Densely packed boundstone composed mainly of foliose microsolenids and columnar thamnasterioid corals, with well-visible growth rugae on the epitheca (arrowtip 1). Locally, *Vaccinites* is intercalated between the corals (arrowtip 2). Hammer is 33 cm long. 'Theresienstein reef' near Strobl at Wolfgangsee, Salzburg, Austria.
- 2: Cluster of *Vaccinites oppeli santoniensis*, embedded in an inclined position within a boundstone dominated by corals. Pen for scale is 14 cm. 'Theresienstein reef' near Strobl at Wolfgangsee, Salzburg, Austria.
- 3: Detail of mound composed of colonial corals, skeletal sponges and rudists. In the photo, a foliose stromatoporoid (S) is overgrown by a coral (C) and two juvenile specimens of *Vaccinites giganteus major*. Pen is 14 cm long. Collades des Basturs, Province Lleida, Spain.



Plate 4

- 1: Detail from a floatstone with a colony of a branched coral (cf. *Pleurocora*) on which a radiolitid (R 1) had settled and grown. After death, the free valve of the radiolitid was removed, and another radiolitid (R 2) grew from the brim of the lower valve of the dead radiolitid. The younger radiolitid, in turn, died in a juvenile stage, but the free valve remained in place. Note that the formerly aragonitic shells or shell parts contain a geopetal infill of micropeloidal grainstone to packstone at their base (arrowtips); the space above the geopetals is filled by blocky calcite spar. Width of view 17 mm. Krumbachalm in Brandenburg, Tyrol, Austria.
- 2: Detail from a boundstone composed of spongiomorph stromatoporoids, corals, hippuritids and radiolitids. The detail shows the right valve of a small radiolitid that is overgrown and encrusted by bryozoans and, near the upper left corner of the photo, by a spongiomorph stromatoporoid. The matrix is a poorly sorted bioclastic wackestone. Width of view 17 mm. Krumbachalm in Brandenburg, Tyrol, Austria.
- 3: Section through a colony of a dendroid stylinid coral that is overgrown by sessile foraminifera. The matrix is a poorly sorted bioclastic wackestone. Width of view: 10.5 mm. Uppermost part of 'Theresienstein reef' near Strobl at Wolfgangsee, Salzburg, Austria.

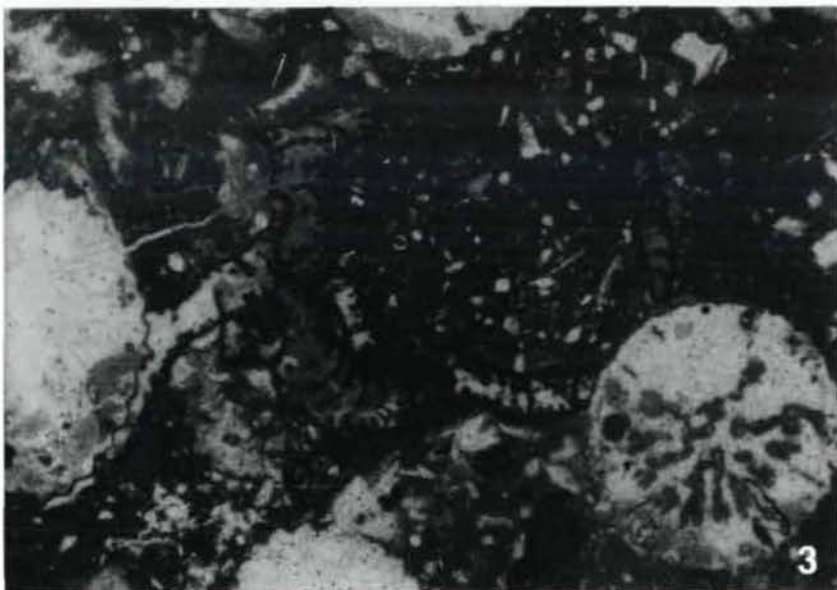
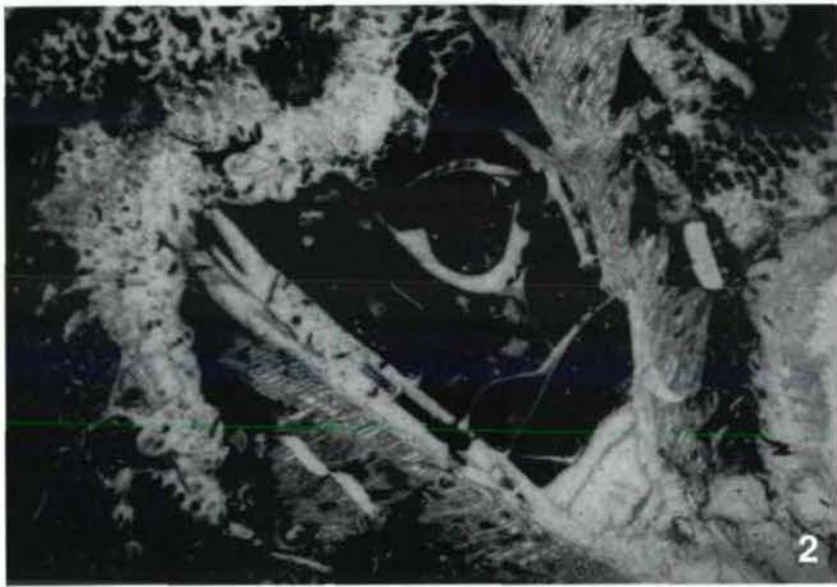
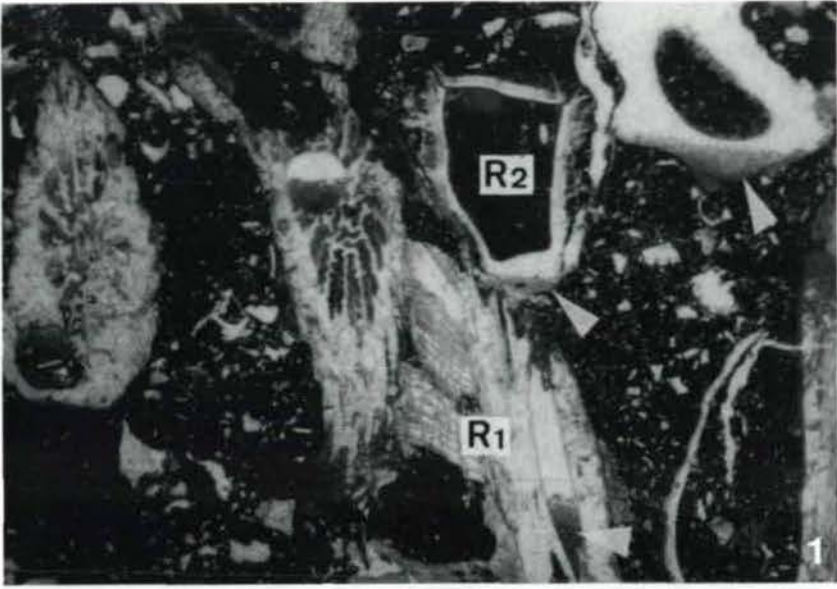


Plate 5

- 1: Emersion surface (stippled), separating a former rudist floatstone with a matrix of bioclastic packstone below from a bioclastic grainstone with a few floating rudist shells above. In the limestone below the emersion surface, the rudists are completely dissolved; the solution moulds are filled by grey bioclastic packstone to grainstone. Width of view about 60 cm. Nabresina, Karst, Italy.
- 2: Relic of a radiolitid below an emersion surface, embedded in a matrix of poorly sorted bioclastic packstone. From the rudist shell, the aragonitic hypostracum as well as the cellular part of the ostracum are absent. The only shell part remaining is the inner ostracal shell layer of dense calcite, which extends into the preserved ligamentary crest (arrow). The solution mould is filled by bioclastic grainstone. Width of view about 8 cm. Nabresina, Karst, Italy.
- 3: Longitudinal section through the lower valve of an elevator rudist that has been completely removed by dissolution. The geopetal fills of lime mudstone to bioclastic wackestone of the intertabular spaces of the rudist shell are preserved as an array of segments that show a characteristic crescent-shape in section. Because of dissolution of the aragonite and concomitant/subsequent compaction, the crescent-shaped fills are in direct contact with each other. The formerly aragonitic and calcitic parts of the shell are filled by a grey weathering bioclastic packstone. Pen is 14 cm long. Nabresina, Karst, Italy.
- 4: Dissolution mould of large rudist (stippled), filled by bioclastic grainstone. The shell of the large rudist to be dissolved later provided a substratum for a cluster of small *Bournonia*. Scale bar is 5 cm long. Nabresina, Karst, Italy.
- 5: Rudist dissolution mould, truncated along an emersion surface (stippled). Note the characteristic crescent-shaped fills of the intertabular spaces, as well as the grey weathering fill of bioclastic packstone in the former shell of the rudist. Scale bar is 2 cm long. Nabresina, Karst, Italy.

