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Rudist formations in mixed siliciclastic-carbonate depositional environments, Upper Cretaceous, Austria: stratigraphy, sedimentology, and models of development

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Abstract

The upper Turonian to lower Campanian succession (Lower Gosau Subgroup) of the Northern Calcareous Alps, Austria, provides a model for the development of rudist formations on wave-dominated, mixed siliciclastic-carbonate shelves that were situated on top of an accretionary wedge. The rudist formations are present either within parasequences or in non-cyclic transgressive successions, and include (a) skeletal mounds up to about 20 m thick that are composed of corals, rudists and, locally, skeletal sponges; and (b) rudist biostromes of less than a metre to several meters in thickness. In the coral–rudist mounds hippuritids and radiolitids thrived together with scleractinians, skeletal sponges and diverse encrusters. The mounds are topped by a hippuritid biostrome. We distinguish hippuritid biostromes, radiolitid biostromes and ‘composite biostromes’ with a vertical succession from hippuritids to radiolitids. The biostromes are less than a metre to a few meters thick and show autochthonous rudist fabrics, parautochthonous rudist fabrics, and vertical combinations thereof. Autochthonous rudist fabrics had a simple trophic structure composed of epifaunal suspension feeders, whereas parautochthonous rudist fabrics had a more complex trophic structure. The rudist biostromes were either terminated by frequent toppling and fragmentation of rudists, by burial with sediment, or by environmental restriction. Hippuritids and radiolitids could both colonize and persist in siliciclastic depositional environments. Overall, however, the presence/abundance of rudists and of intervals of shallow-water limestones correlate. Because the Late Cretaceous rudists thrived together with hermatypic corals as well as in environments precluded to the latter, a larger number of rudist formations and a smaller number of coral–rudist formations results. In siliciclastic-dominated depositional sequences, both in the transgressive and in the highstand systems tract, coral–rudist mounds and rudist biostromes locally accumulated in areas of intermittently reduced siliciclastic input in open lagoons and in the shoreface to inner shelf environment. Transgression of rocky coasts or of gravelly carbonate beaches is recorded by a basal interval either of cliff talus breccia or of beachface and shoreface conglomerates, overlain by a coral–rudist mound and/or a rudist biostrome with associated bioclastic limestones. Where siliciclastic input was persistently low, the highstand systems tract developed as a regressive carbonate shelf succession that consists, in its lower part, of coral–rudist mounds, hippuritid biostromes and bioclastic packstones to grainstones deposited from bioclastic sand bodies, whereas the upper part consists of radiolitid biostromes and bioclastic wackestones to packstones. The regressive carbonate shelves were narrow and included, on a reconstructed internal-to-external transect, micro-tidal flats, an open lagoon with radiolitid biostromes, a dissipative shore

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zone with bioclastic sand bodies, and an inner shelf facies belt with coral–rudist mounds and hippuritid biostromes. In the contemporaneous mid- to outer shelf environment, siliciclastics were deposited. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

On Late Cretaceous shelves, the hippuritids and radiolitids were the most important groups with respect to their influence on facies architecture, stratigraphic development and porosity development (e.g. Kauffman and Sohl, 1974; Haas, 1979; Carbone and Sirna, 1981; Masse and Philip, 1981; Bilotte, 1985; Simo et al., 1993; Cestari and Sartorio, 1995; Moro, 1997). The Late Cretaceous hippuritids and radiolitids were gregarious bivalves that commonly were not bound by epibionts into a framework comparable to Tertiary coralgal reefs. The architecture of rudist constructions and of their associated facies thus is different from that of Tertiary coralgal reefs and, consequently, also the patterns of stratigraphic development (Ross and Skelton, 1993).

The Upper Cretaceous rudist formations of the Northern Calcareous Alps were deposited on top of the Eo-Alpine accretionary wedge (Wagreich and Faupl, 1994), in mixed siliciclastic-carbonate depositional environments that exhibit an exceptionally wide range both of facies and in the patterns of stratigraphic development (Sanders et al., 1997; Sanders, 1998a). Because the rudist formations are present within widely variable mixed siliciclastic-carbonate successions, the Upper Cretaceous of the Northern Calcareous Alps provides many different examples that are pertinent to the questions on the relation between rudists and corals, the relation of rudists to siliciclastic input, and the place and types of rudist formations within mixed siliciclastic-carbonate sequence development. The present paper is derived from inspection of all outcrops of Upper Cretaceous rudist formations in the Northern Calcareous Alps. Based on field investigation (including mapping) and inspection of more than 600 thin sections, the characteristics of the rudist formations are described and integrated into models of facies architecture and mixed siliciclastic-carbonate sequence development.

2. Geological context

The Northern Calcareous Alps are part of the Upper Austroalpine tectonic unit (Fig. 1). From Early to Late Jurassic times, the area of the Northern Calcareous Alps was part of the Austroalpine microplate that was situated along the northern, passive continental margin of the larger Adriatic plate (Channell et al., 1990; Dercourt et al., 1993; Wagreich and Faupl, 1994). During the latest Jurassic and Early Cretaceous, in a tectonic regime of oblique convergence, the Austroalpine microplate became deformed into a stack of west- to northwest verging, detached sedimentary cover nappes in the area of the Northern Calcareous Alps. Subsequently, large parts of the Austroalpine unit were uplifted and subaerially eroded. The uplift was accompanied by extensional exhumation of the orogen (Platt, 1986; Krohe, 1987; Ratschbacher et al., 1989; Polino et al., 1990; Froitzheim et al., 1994, 1997; Neubauer et al., 1995). In the area of the Northern Calcareous Alps, the subaerial erosion is recorded by a deeply incised truncation surface.

From Turonian to Santonian times, the exposed areas became re-submergent, and deposition resumed at high rates of subsidence (Wagreich, 1991). The development of the depocenters on top of the orogenic wedge was controlled both by strike-slip and extension (Ratschbacher et al., 1989; Wagreich, 1991, 1995; Froitzheim et al., 1994, 1997; Neubauer et al., 1995). The investigated upper Turonian to lower Campanian succession (Lower Gosau Subgroup; Wagreich and Faupl, 1994) consists of mixed siliciclastic-carbonate depositional sequences that, in their preserved parts, record deposition in nearshore-terrestrial to upper bathyal environments (compare Fig. 2). Sequence development was mainly controlled by the tectonism of the accretionary wedge (Sanders et al., 1997).

During the Late Cretaceous, the area of the Northern Calcareous Alps was situated at 30–35° north paleolatitude (Mauritsch and Becke, 1987; Dercourt

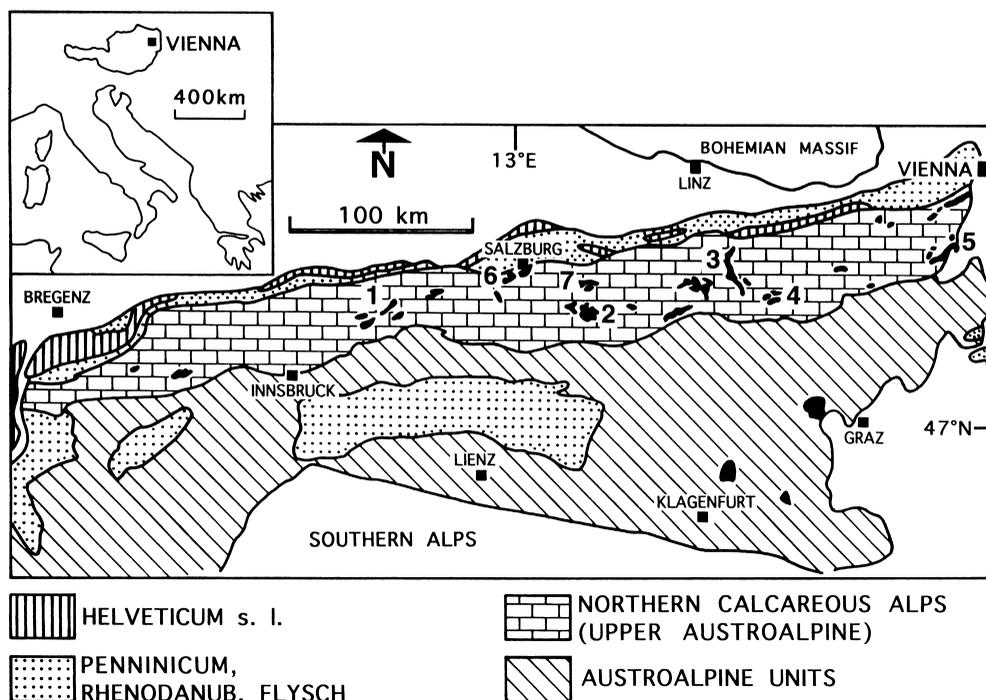


Fig. 1. Position of the Northern Calcareous Alps. The major Upper Cretaceous outcrops are indicated in black. The Northern Calcareous Alps are part of the Austroalpine tectonic unit, a stack of detached cover thrust nappes that are dominated by Triassic shallow-water carbonates. The described larger outcrops with rudist formations are labelled by numbers. 1 = Brandenburg; 2 = Gosau (type location of Gosau Group) and Rigaus; 3 = Weisswasser; 4 = Gams; 5 = Grünbach; 6 = Lattenberg; 7 = St. Gilgen and Strobl. The sedimentary successions at outcrops 1 to 5 are shown in Fig. 2.

et al., 1993), within the Late Cretaceous monsoonal belt (Parrish and Curtis, 1982; Price et al., 1995). Seasonally humid, subtropical to tropical climate prevailed during deposition of the Lower Gosau Subgroup, but intermittent environmental deteriorations related to climate and/or oceanographic conditions also are indicated (Sanders et al., 1996, 1997; Sanders, 1996a, 1997a). In the following, the depositional systems of the Lower Gosau Subgroup will be briefly described. For detailed descriptions and interpretations of specific facies, the reader is referred to Butt (1980), Höfling (1985), Faupl et al. (1987), Wagneich (1986a,b, 1988, 1989), Sanders (1996a,b, 1997a, 1998a), and Sanders and Baron-Szabo (1997).

3. Depositional systems

During deposition of the Lower Gosau Subgroup the articulated morphology of the basal trun-

cation surface, facies compartmentalization in the nearshore-terrestrial to marine shelf environment, high rates of fault-induced subsidence, high rates of sediment accumulation, mixed siliciclastic-carbonate deposition, and environmental changes related to climate and/or oceanographic conditions combined to result in an exceptionally wide range of both facies and facies associations (Sanders, 1998a; see also Wagneich and Faupl, 1994). The predominance of siliciclastics in the Lower Gosau Subgroup indicates a persistent supply from rivers that drained the more internal, emergent parts of the accretionary wedge farther towards the south. The siliciclastic rivers co-existed with fan deltas that were fed from catchment basins within the Northern Calcareous Alps (Faupl et al., 1987; Wagneich, 1989).

In areas of siliciclastic input from deltas or from longshore drift, wave-dominated siliciclastic shelves with mainland beaches or with barrier beaches developed (Fig. 3). In the siliciclastic shelf successions,

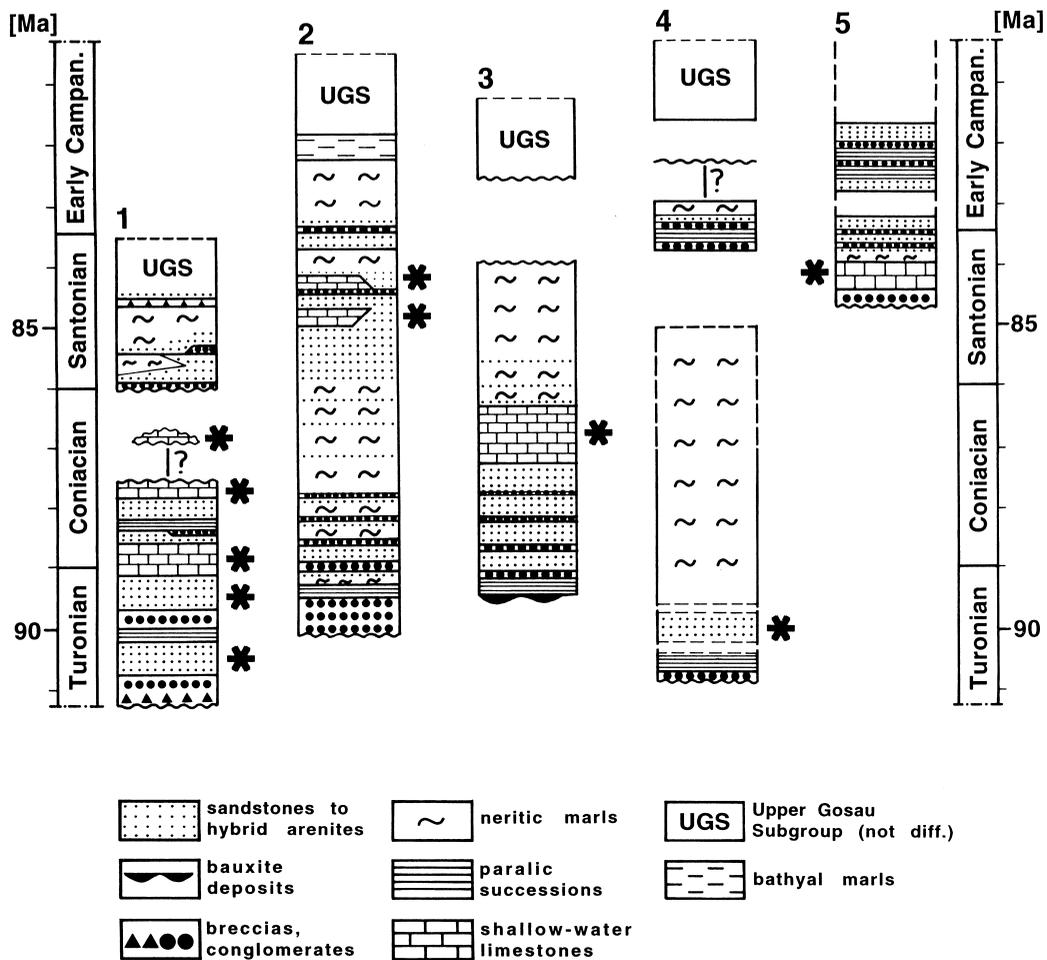


Fig. 2. Lower Gosau Subgroup at the major rudist-bearing outcrops, in the time-scale of Gradstein et al. (1994). In the Lower Gosau Subgroup, only the major hiatuses are indicated. * = stratigraphic position of the most important rudist formations. 1 = Brandenburg; 2 = Gosau; 3 = Weisswasser; 4 = Gams; 5 = Grünbach.

a microtidal to low-mesotidal environment is indicated by an overall very scarce record of tide-influenced deposition in the marsh to shoreface facies belt, rare and thin tidal-inlet fills, and by evidence for the co-existence of barrier beaches, tidal inlets and lagoons (Sanders, 1998a; compare, e.g. Boothroyd, 1978; Hayes, 1980; Imperato et al., 1988). Restricted-marine to schizohaline to freshwater marsh areas were inhabited by a low-diversity assemblage of gastropods, small-sized bivalves and ostracods. In open lagoons, silts to sand to, locally, carbonates with nerineids, actaeonellids, radiolitids, skeletal sponges, calcareous green algae, miliolids and lituolaceans were deposited. The shelf arenites range in composition

from pure sandstones to hybrid arenites composed of variable proportions of siliciclastic sand, bioclastic sand, and calcilithic sand that has been derived from erosion of older carbonate rocks (Wagreich, 1986; Sanders, 1998a). On the inner shelf, in areas of intermittently reduced siliciclastic input, coral–rudist calcareous muds locally accumulated. On the outer shelf to slope, mainly silt and mud with planktonic foraminifera were deposited. Near the base of slope and in the basins, turbiditic sands and hemipelagic calcareous muds accumulated (Wagreich and Faupl, 1994; Sanders et al., 1997; Sanders, 1998a). Along transgressive shorelines, where river deltas or fan deltas were absent rocky shores and gravelly carbon-

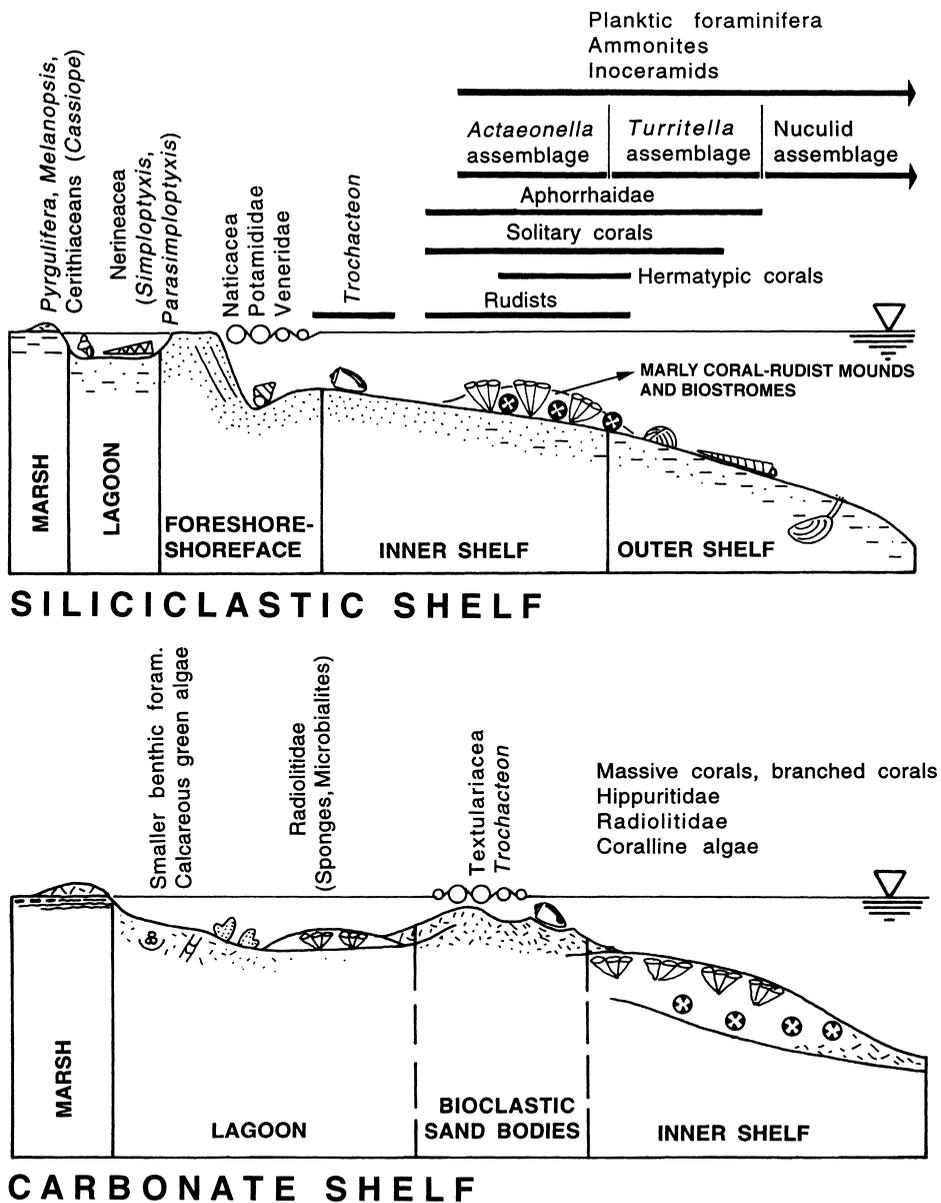


Fig. 3. Generalized shelf models for the Lower Gosau Subgroup, with the most characteristic fossils indicated (from Sanders et al., 1997). Above: On the siliciclastic shelf, a lagoonal to marsh environment was separated by a reflective sandy beach from a wave-dominated shoreface to inner shelf environment. On the inner shelf, biostromes and mounds composed of corals and rudists, and with a matrix of marl locally accumulated. Below: Regressive carbonate shelf. On the carbonate shelf, an open lagoonal environment was separated from the inner shelf by a dissipative shore zone of bioclastic sand bodies. The regressive carbonate shelves were relatively narrow. Deposition of significant amounts of biogenic carbonates was confined to the inner shelf to tidal flat segment.

ate beaches developed. In the shoreface to inner shelf environment in front of the rocky to gravelly shores, coral–rudist mounds, rudist biostromes and bioclastic

carbonates formed (Sanders, 1997a, 1998a). In areas of low siliciclastic input, carbonate shelves developed (Fig. 3, lower part). These were characterized by an

inner shelf facies belt with skeletal mounds (corals, rudists) and rudist biostromes, a dissipative shore zone (cf. Long and Ross, 1989) of bioclastic dunes, an open lagoon with radiolitid biostromes and a narrow, microtidal flat belt (Sanders et al., 1997; Sanders, 1998a). In the contemporaneous mid- to outer shelf environment, mainly siliciclastic silt and mud were deposited.

4. Stratigraphy of rudist formations

The rudist formations commonly are part of upward shoaling cycles a few meters to some tens of meters thick that fit the definition of parasequence

(cf. Van Wagoner et al., 1988). In the Lower Gosau Subgroup, (a) siliciclastic-dominated parasequences, and (b) carbonate-dominated parasequences are distinguished (Sanders et al., 1997). In the following, from the complete spectrum of cycle types only those are described that are pertinent with respect to rudist formations (see Figs. 4 and 5). The lettering of cycle types is adapted for the purpose of this paper.

4.1. Siliciclastic-dominated cycles

4.1.1. Type A cycles

At their base, type A siliciclastic-dominated cycles locally contain a transgressive record that con-

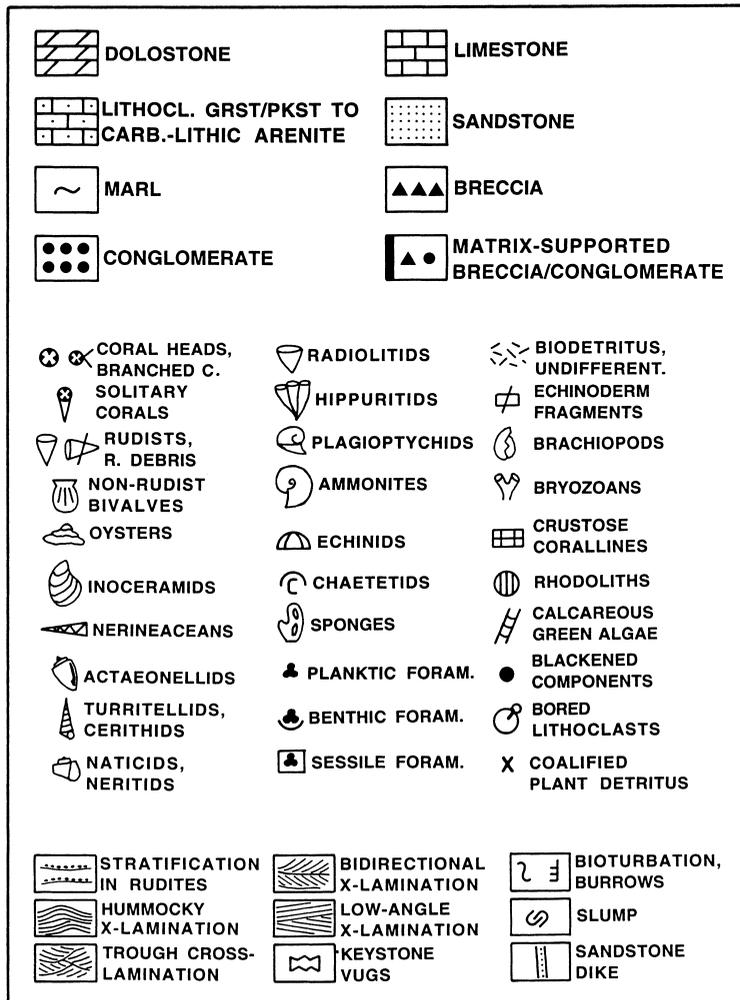


Fig. 4. Key to symbols used in the following figures.

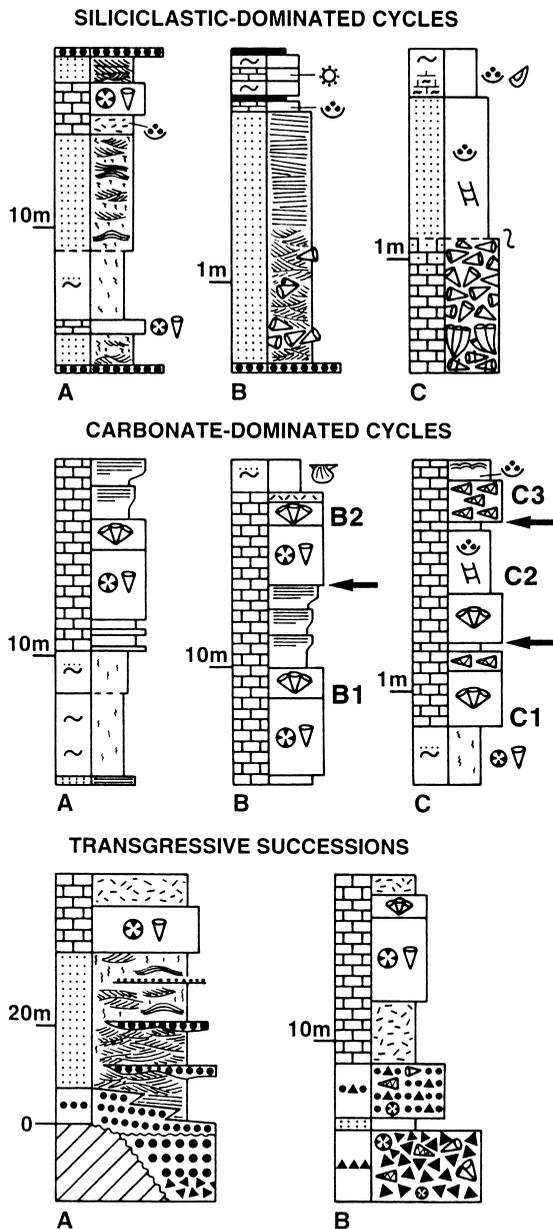


Fig. 5. Stratigraphic position of rudist formations, with characteristic thickness scales indicated. Top: Siliciclastic-dominated upward shoaling cycles, with rudist formations. Center: Carbonate-dominated upward shoaling cycles, with rudist formations. Arrowtips indicate boundaries between different cycle subtypes. Bottom: Position of rudist formations in transgressive successions. See text for description and interpretation.

sists of a beachface conglomerate and/or cross-laminated shore zone arenites overlain by a thin interval of coral–rudist limestone or a rudist biostrome (Fig. 5). Elsewhere, the basal and lower part of these cycles consists of marly siltstones to marly, bioturbated sandstones to hybrid arenites with non-rudist bivalves, gastropods, echinoids, a few isolated hippuritids and radiolitids, coral heads, solitary corals and smaller benthic foraminifera (lagenids, rotaliids). Sandstone beds with hummocky cross-lamination and inclined cross-lamination are locally intercalated. The fossiliferous siltstones to arenites are overlain by more or less sandy, bioclastic packstones to grainstones with smaller benthic foraminifera (miliolids, textulariaceans) and an interval up to a few meters thick mainly of floatstones to rudstones to, locally, boundstones of corals, rudists, skeletal sponges and nerineaceans. The coral–rudist limestones are overlain by cross-laminated hybrid arenites and, in the topmost part of the cycle, by low-angle cross-laminated hybrid arenites to sandstones. Alternatively, the topmost part of the cycle consists of an interval of low-angle cross-stratified conglomerate composed of very well-rounded, spherical to oblate lithic gravels and a few abraded marine fossils (e.g. corals, actaeonellids, rudists) (Fig. 5). Type A siliciclastic-dominated cycles are present in the upper Turonian to Coniacian of Brandenburg (cf. Fig. 1).

4.1.2. Type B cycles

Type B siliciclastic cycles (Fig. 5) locally contain a thin veneer of conglomerate at their base and consist, in their lower part, of cross-laminated to bioturbated sandstones with clusters and isolated specimens of radiolitids, and with *Trochactaeon*. The radiolitids are well preserved, only scarcely bored by a few lithophagids, and locally bear epibionts (e.g. serpulid tubes) on their surface. The cross-laminated sandstones are followed up-section by an interval of unfossiliferous, low-angle cross-laminated sandstone; the latter, in turn, is sharply overlain by a comparatively thin bedset that consists mainly of organic-rich wackestones and cryptmicrobially laminated lime mudstones, sandy marls with rhizoliths and, locally, coal seams. This cycle type has been observed in the upper Turonian and Coniacian of Brandenburg; similar cycles also are present at Weisswasser (Fig. 1).

4.1.3. Type C cycles

Type C siliciclastic-dominated cycles (Fig. 5) may contain a thicket or a biostrome of hippuritids or of radiolitids at their base. In other cycles of this group, the rudist thicket or the biostrome develops from a basal veneer of bioclastic packstone to wackestone to hybrid arenite with miliolines and textulariaceans, fragments from calcareous green algae, nerineaceans and cerithiaceans. The upper part of these cycles consists of bioturbated, marly sandstones to hybrid arenites with fragments from dasycladaceans and codiaceans, lituolids, textularids, miliolids, ataxophragmiines, serpulids, bryozoans, echinoderms, cryptomicrobial lumps and coalified plant debris. Locally, the topmost part of the cycles consists of organic-rich sandy marls to marly limestones with miliolids, *Cuneolina*, *Vidalina*, ostracods, a few fragments from codiaceans and Dasycladales and, locally, with abundant coalified plant fragments (leaves, wood). Type C siliciclastic-dominated cycles are present in the upper Turonian to Coniacian of the Brandenburg area and in the upper Turonian of Gams (Fig. 1).

4.1.4. Interpretation

In the lower part of the type A siliciclastic-dominated cycles, the marly siltstones to hybrid arenites with marine megafossils and with the intercalated hummocky cross-laminated sandstone beds record an inner shelf to transitional inner to outer shelf environment, respectively. The overlying interval of bioclastic packstones to grainstones and the vertically associated coral–rudist limestones were deposited in the shoreface to inner shelf environment (Sanders, 1998a). The cross-laminated and low-angle cross-laminated arenites above the coral–rudist limestones were deposited in an upper shoreface to foreshore environment. In Holocene mixed siliciclastic-carbonate environments, growth of coral patch reefs and accumulation of bioclastic limestones in the shoreface environment is common, closely adjacent to siliciclastic deposition (e.g. Schneidermann et al., 1976; Acker and Stearn, 1990; Bush, 1991). The local interval of low-angle cross-stratified siliciclastic conglomerate at the top of some of these cycles is interpreted as a beachface conglomerate (cf. Sanders, 1997a, 1998a).

In the type B cycles, the vertical succession of facies records a shoaling from the shoreface into

the foreshore and, in the topmost bedset of the cycle, into a marsh environment that was characterized by shallow ponds and vegetated areas (Herm, 1977; Sanders, 1996a). In the cross-laminated sandstones, the typical good preservation of the radiolitids suggests that they lived in the shoreface, together with *Trochactaeon*; the latter characteristically thrived on sandy substrata in the shoreface and in open lagoons (Sanders et al., 1997).

In the type C siliciclastic-dominated cycles, the vertical succession of facies records, at least to the largest part, a shoaling trend. The accumulation of the rudist biostrome and/or the bioclastic limestones at or near the base of the cycles probably occurred during to shortly after relative sea-level rise, when siliciclastic input was minimal. The bioclastic packstones and hybrid arenites overlying the biostrome were deposited in a normal-marine lagoonal environment, as indicated by the calcareous green algae, miliolines, textulariaceans and nerineaceans (Sanders and Baron-Szabo, 1997; Sanders, 1998a; see also Höfling, 1985; Schlagintweit, 1992). Progradation of siliciclastics over the rudist biostrome is indicated by the bioturbated vertical transition from the rudist biostrome below to hybrid arenites or sandstones above. The organic-rich, sandy marls to marly limestones at the top of some cycles were deposited in a shallow, restricted lagoonal environment with dysaerobic to anaerobic conditions below the sediment–water interface.

4.2. Carbonate-dominated cycles

4.2.1. Type A carbonate-dominated cycles

These represent a transitional type between siliciclastic-dominated cycles and carbonate cycles. The type A carbonate cycles (Fig. 5) consist, in their lower part, of silty marls to marly hybrid arenites with solitary corals, infaunal and epifaunal non-rudist bivalves, gastropods, echinoids, smaller benthic foraminifera (rotaliids, miliolines, lagenids), and with endichnial trace fossils (e.g. *Thalassinoides*, *Ophiomorpha*). The marls to arenites grade up-section into an interval a few meters thick of nodular, bioturbated, marly wackestones to floatstones with corals and rudists. The wackestones to floatstones, in turn, are overlain by an interval a few meters to about 20 m thick of floatstones to bafflestones to,

locally, boundstones rich in corals and rudists, and with a matrix of more or less marly wackestone to packstone. The upper part of the type A carbonate-dominated cycles consists of an hippuritid biostrome and, at the top, of an interval a few meters thick of poorly to moderately sorted, medium to coarse bioclastic grainstones to rudstones. The bioclastic limestones at the top of these cycles are typically arranged into a single or several stacked upward thickening/coarsening packages a few decimeters to a few meters thick. This type of carbonate-dominated cycle is present in the Upper Santonian at Gosau and, with some modification, in the Campanian of Lattenberg (Fig. 1).

4.2.2. Type B carbonate cycles

In their lower part, type B 1 carbonate cycles (Fig. 5) contain an interval up to more than 15 m thick of floatstones to bafflestones to boundstones rich in rudists and corals. The interval of coral–rudist limestones is locally based by a veneer of poorly sorted bioclastic packstone to grainstone of heavily micritized, bored, abraded and encrusted fragments from rudists, corals, echinoderms, and calcareous algae. The interval of coral–rudist limestones is commonly overlain by an hippuritid biostrome which, in turn, is followed up-section by an interval up to about 10 m thick of bioclastic limestones. The bioclastic limestones typically are arranged in stratal packages up to a few meters thick that each shows an upward thickening/coarsening from bioclastic packstones to grainstones in the lower part to winnowed, bioclastic grainstones to rudstones with subparallel lamination at and near the top. The bioclastic packstones to grainstones to rudstones consist of well-rounded, micrite-rimmed fragments from rudists, and a few percent of textulariaceans, miliolids, a few fragments from red algae, bryozoans, calcareous green algae, echinoderms and, locally, a few percent of siliciclastic sand.

In the type B 2 carbonate cycles (Fig. 5), the couplet of coral–rudist limestones/hippuritid biostrome is overlain by a relatively thin interval of poorly sorted rudist–clastic packstone to grainstone to rudstone which, in turn, is overlain by marls to marly packstones that build the topmost part of the cycles. The marls to marly packstones are composed of shallow-water bioclastic material (mainly rudist frag-

ments, smaller benthic foraminifera, fragments from calcareous green algae) and, locally, small inoceramids and abundant articulate shells of *Phelopteria* (cf. Herm et al., 1979; Tröger and Summesberger, 1994). The type B 1 and type B 2 carbonate cycles, respectively, locally overlie each other (Fig. 6). Type B carbonate cycles are present in the ?uppermost Turonian to lower Coniacian of Brandenburg, in the upper Coniacian of Weisswasser, in the Santonian of St. Gilgen, and in the upper Santonian of Gosau (Fig. 1).

4.2.3. Type C carbonate cycles

Type C carbonate cycles (Fig. 5) are a few decimeters to a few meters thick, and exhibit a wide variation of facies. The lower part of type C 1 cycles consists of sandy marls with a few corals, *Plagiogyptichus* and miliolines and textulariaceans. More commonly, however, the lower part of these cycles consists of an hippuritid biostrome or a radiolitid biostrome (C 2 in Fig. 5), or of a thick bed or a bedset of floatstone to rudstone of nerineids or actaeonellids (C 3 in Fig. 5). The upper part of the type C carbonate cycles consists of, locally marly, bioclastic packstones to wackestones to floatstones that contain highly variable relative amounts of rudist fragments, green algal fragments, smaller benthic foraminifera (miliolids, lituolaceans), cerithiaceans and nerineaceans, peloids and coalified plant fragments. Locally, thin intervals of black pebble wackestones to packstones to floatstones, or of organic-rich limestones with ostracods, characean fragments and cryptmicrobial lamination and with thin lenses of coal are present at the top of these cycles. Type C carbonate cycles are present in the Coniacian of the Brandenburg area, in the upper Coniacian of Weisswasser, and in the upper Santonian of Gosau (Fig. 1).

4.2.4. Interpretation

In the type A carbonate-dominated cycles, the bioturbated silty marls to marly hybrid arenites in the lower part of these cycles were deposited in a shallow shelf environment of overall moderate water energy (cf. Höfling, 1985; Wägrich, 1988; Sanders, 1998a). Near the top of the interval of marls to marly arenites, the gradual upward development into the overlying interval of coral–rudist floatstone to

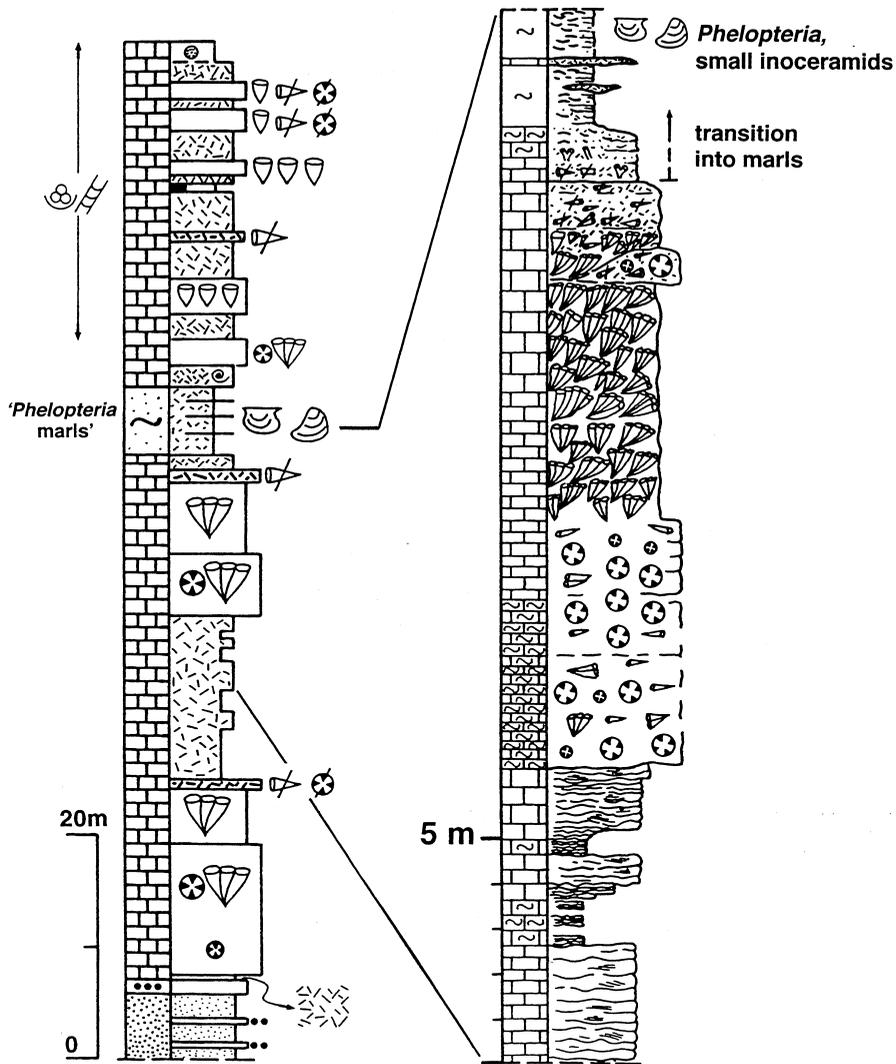


Fig. 6. Succession of lower Coniacian shallow-water limestones in the area of Haidach, Brandenburg. In its lower part, the succession consists of intervals of coral–rudist limestones, of rudist biostromes, intervals of bioclastic limestones and, locally, marls that are rich in *Phelopteria*. Each interval of coral–rudist limestone is overlain by a hippuritid biostrome. The bioclastic limestones between are arranged in upward-thickening/coarsening packages. The upper couplet of coral–rudist limestone and hippuritid biostrome is topped by bioclastic rudstones to grainstones which, in turn, grade up-section into ‘*Phelopteria* marls’. The upper part of the succession consists of stratal packages of bioclastic wackestones to packstones with intercalated radiolitid biostromes.

boundstone, the absence of beds of winnowed, sand- to gravel-sized bioclastic material, the absence of bioclastic event beds or mass flows of bioclastic/calclithic composition and, in the coral–rudist mounds, the predominant floatstone texture and the matrix of marly wackestone all indicate that the coral–rudist mounds accumulated in a neritic environment of moderate to low water energy. Because of limitations

of outcrop, however, the syndepositional relief of the interpreted mounds is poorly constrained (see below for discussion). With respect to thickness and vertical succession of sedimentary facies, the type A carbonate-dominated cycles are similar to upward shoaling cycles described from the Upper Cretaceous of the south-central Pyrenees (Gili et al., 1995b; Skelton et al., 1995).

Intervals of coral–rudist limestones are present within the type A siliciclastic-dominated cycles (see above), in the type A and the type B carbonate-dominated cycles, respectively, and in transgressive successions (see below). Intervals of coral–rudist limestones locally are exposed over hundreds of meters without pinching out, and everywhere show a sheeted to gently mounded shape. Even the best exposures, however, are not large enough to display the relations between coral–rudist limestones and laterally juxtaposed, contemporaneous facies within the same outcrop. The lateral relationships thus must be reconstructed from correlation of vertical sections. In the intervals of coral–rudist limestones, steep cliniform bedding has not been observed, nor have lithologies indicative for the flanks of steep-sided buildups been found (e.g. deposits from mass flows or from grain flows; cf. Bosellini, 1984; Kenter, 1990). In addition, no evidence for marine reef flat- to reef slope cementation was found. The intervals of coral–rudist limestones thus were deposited from skeletal mounds with a relatively gentle relief rather than from steep-flanked, high-relief buildups (Sanders and Baron-Szabo, 1997; Sanders et al., 1997).

The upward thickening/coarsening packages of bioclastic packstones to grainstones to rudstones that constitute the upper part of both the type A and the type B 1 carbonate cycles were deposited as bioclastic sand bodies. In the type B carbonate cycles the local, basal veneer of poorly sorted bioclastic packstones to grainstones is interpreted as a transgressive lag deposit (Sanders and Baron-Szabo, 1997). The ensemble of a coral–rudist mound at the base, a rudist biostrome in the central part and, at the top, of bioclastic packstones to grainstones is interpreted in terms of aggradational-progradational shoaling of a small, gently inclined carbonate shelf (compare Figs. 3 and 5). For the described marls on top of the type B 2 carbonate cycles, both the local mass occurrence and the typical articulated preservation of the delicate shells of the pteroid *Phelopteria*, as well as the associated assemblage of small inoceramids and the shallow-water bioclastic material indicate a quiet lagoonal environment of high nutrient input (Sanders and Baron-Szabo, 1997).

The type C carbonate cycles have been deposited from open lagoonal to marsh environments. The

superposition of the rudist biostromes, of the gastropod limestones, or of the coral–rudist–sponge floatstones by wackestones to packstones that are rich in fragments from calcareous green algae and in milioline and textulariine smaller benthic foraminifera indicates both a shoaling of depositional water depth, and deposition in a normal-marine lagoonal environment (Sanders and Baron-Szabo, 1997; Sanders, 1998a; cf. Höfling, 1985). These cycles often record incomplete shoaling to shallow subtidal depths. Complete shoaling to inter- to supratidal depths is indicated by the intervals of black pebble wackestones to packstones and by the thin intervals of organic-rich limestones with cryptomicrobial lamination (cf. Shinn et al., 1969; Strasser, 1984). The thin lenses of coal and the thin intervals of organic-rich lime mudstones and wackestones with characean fragments probably were deposited in schizohaline to freshwater environments. In the type C cycles, no evidence for the existence of well-developed, muddy carbonate tidal flats is present, as, e.g., thicker intervals of fenestral mudstone (Sanders, 1998a).

4.3. *Transgressive successions*

4.3.1. *Type A transgressive successions*

Less commonly, within the transgressive systems tract of depositional sequences (see below), rudist formations are present in transgressive successions that exhibit no distinct cyclicity. At their base, type A transgressive successions locally contain alluvial fan successions that record an upward transition from proximal to distal fan environments (Fig. 5; see Wagreich, 1989; Sanders, 1996b, 1997a). The alluvial fan deposits are sharply overlain along a ravinement surface by a succession that consists of a basal interval of beachface conglomerate and an overlying interval of calcilithic arenites with intercalated shoreface conglomerates. From bottom to top, the succession of calcilithic arenites shows a change from low-angle cross-lamination to festooned cross-lamination and, locally, beds with hummocky cross-lamination, accompanied by an increasing amount of bioturbation, an increasing content of shallow-marine bioclastic material, and an overall thinning/fining of the shoreface conglomerates. The arenite succession, in turn, is locally overlain by a coral–rudist mound with associated bioclastic limestones

(Sanders, 1997a, 1998a). Type A transgressive successions are present in the area of Brandenburg (Fig. 1). Similar transgressive successions, albeit without an interval of coral–rudist limestone, are present in the area of Gosau and at other outcrops of the Gosau Group (see Wagreich and Faupl, 1994).

4.3.2. Type B transgressive successions

The basal interval of type B transgressive successions is an extremely poorly sorted breccia to megabreccia, or a cobble conglomerate that is composed of clasts from the local carbonate rock substratum and, subordinately, of abraded and disoriented clusters and isolated specimens of rudists, nerineids and coral heads; locally, articulate brachiopods are common (Fig. 5). Some of the litho- and the bioclasts are penetrated by *Trypanites*, and/or are encrusted by red algae and sessile foraminifera. The basal ruditic deposits are overlain by overall finer-grained and better sorted lithic breccias to conglomerates that may be intercalated with bedsets of grainstone of mixed calcilithic/shallow-water bioclastic composition. Higher up-section, above an interval of bioturbated bioclastic grainstone to packstone, a coral–rudist mound or a rudist biostrome with associated bioclastic limestone is present. In the type B transgressive successions, the relative thickness of each interval is highly variable both laterally and between transgressive successions of different ages, and ranges from a few decimeters to more than 10 meters (compare Kollmann and Summesberger, 1982; Höfling, 1985; Sanders, 1997a, 1998a). This type of transgressive succession has been observed in the area of Brandenburg, at Lattenberg and at Grünbach (Fig. 1).

4.3.3. Interpretation

Type A transgressive successions were deposited in association with fan deltas (Sanders, 1997a; cf. Wagreich, 1989). Type B transgressive successions formed in association with gravelly to rocky carbonate shores. In the type B transgressive successions, the marked lateral variations mainly with respect to thickness of the lithologies, mean grain size and clast rounding and -sorting result from variations of energy regime, depositional water depth, and the morphological gradient of the transgressed substratum along a gravelly to rocky shore (Sanders,

1997a). Where a transgressive shoreline probably was fringed by wave-exposed cliffs, a basal interval of extremely poorly sorted breccia/megabreccia up to more than 10 m thick is present; these basal rudites typically are overlain by a coral–rudist construction and associated bioclastic limestones. Where transgression occurred along lower-energy sectors of a rocky shore, a basal interval a few decimeters to a few meters thick of breccias, conglomerates, or cross-laminated calcilithic arenites is overlain by rudist biostromes and associated bioclastic limestones. The coral–rudist mounds and the associated bioclastic limestones within the transgressive successions accumulated in the shoreface environment, in front of the gravelly to rocky shores (Sanders, 1998a).

4.4. Sequence development

Both the described transgressive successions and the cycles are the building blocks of mappable allostratigraphic units that are interpreted to represent mainly the transgressive and highstand systems tracts, respectively, of depositional sequences (Sanders et al., 1997; Sanders, 1997b). The preserved parts of the depositional sequences are some tens to some hundreds of meters thick. Biochronostratigraphy indicates that the sequences range between about 1 to 3 Ma in duration (see compilation of biomarkers in Sanders et al., 1997, and references therein). In the Lower Gosau Subgroup, depositional sequences typically are dominated by siliciclastics both in their transgressive and highstand systems tract. The rudist formations accumulated intermittently, within the frame of paracycle development, whenever siliciclastic input was sufficiently low and a stable substrate was provided (see above).

Where siliciclastic input was persistently low, the transgressive systems tracts of depositional sequences is dominated by a type B transgressive succession, whereas the highstand systems tracts developed as a stack of carbonate paracycles that up-section become progressively thinner and record an overall shoaling of facies (Sanders et al., 1997; cf. Sanders and Baron-Szabo, 1997). Highstand systems tracts up to about 100 m thick that consist of more or less pure successions of shallow-water limestones are preserved in the area of Brandenburg (section 1

in Fig. 2) and in the area of Weisswasser (section 3 in Fig. 2). In Brandenburg, the carbonate highstand systems tract consists of a lower part composed of type A and type B carbonate cycles, whereas the upper part consists of stacked meter-scale type C carbonate cycles with radiolitic biostromes (Fig. 6; cf. Sanders and Baron-Szabo, 1997; Sanders, 1998a). The development of the described parasequence types within the frame of sequence development will be described in an integrated model farther below. In the following description of bioconstructions, the designation of rudist morphotypes is according to Gili et al. (1995a).

5. Bioconstructions

5.1. Coral–rudist mounds

In the Coniacian to lower Campanian of the Northern Calcareous Alps, intervals of limestones that have been deposited from skeletal mounds with corals and rudists are present in the areas of Brandenburg and Gosau–Rigaus, and at several smaller outcrops of the Gosau Group (Lattenberg, St. Gilgen–Strobl) (compare Figs. 1 and 2). The coral–rudist limestones are present within several types of upward shoaling cycles and in transgressive successions (Figs. 5 and 6). The mounds commonly range in thickness from a few meters to more than 15 m, and show a highly variable relative content of corals versus rudists. In vertical section, the coral–rudist mounds may gradually develop from their substratum (fossiliferous neritic marls to siltstones to arenites, bioclastic limestones; see Figs. 5 and 8) via an interval a few decimeters to a few meters thick of more or less marly wackestones to floatstones with coral heads and disoriented to upright rudists and small rudist clusters. Alternatively, the coral–rudist mounds sharply overlie bioclastic limestones, arenites or marls at the top of the underlying cycle, and locally are based by a ‘transgressive veneer’ of bioclastic grainstone to packstone (see description of cycle types above; Figs. 5–7).

The rudist fauna of the mounds is characterized by specimens up to about 60 cm in length of *Vaccinities oppeli* (Douvillé) and *V. oppeli santoniensis* Kühn, *V. inaequicostatus* (Münster), *V. gosaviensis*

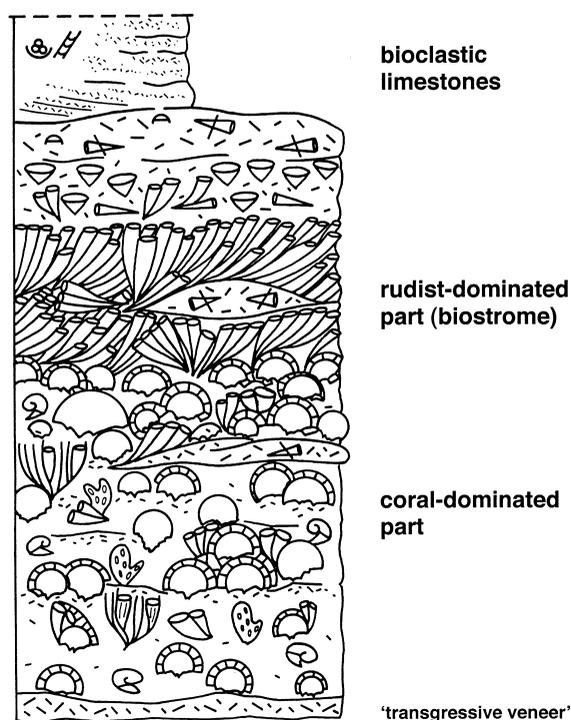


Fig. 7. Scheme of vertical section through coral–rudist mound and overlying lithologies (adapted from Sanders and Baron-Szabo, 1997). At their base, the coral–rudist mounds locally contain a ‘transgressive veneer’ of heavily bored and micritized shallow-water bioclasts. The lower part of the mounds typically is dominated by coral floatstones with scattered patches of coral boundstones. In the lower part, rudists are present, but are subordinate in abundance; the rudists grew in close association with corals. Towards the upper part of the mound, the packing of both corals and rudists increases. Layers of coarse bioclastic material are locally intercalated. The mounds commonly are topped by a hippuritid biostrome. The hippuritid biostrome may be overlain by a biostrome composed mainly of radiolitics and, higher up, by bioclastic limestones that were deposited from carbonate sand bodies.

(Douvillé) and *V. cornuvaccinum* (Bronn), whereas other hippuritids like *Hippurites matheroni* Douvillé, *H. tirolicus* (Douvillé), *H. nabresinensis* Fütterer, *H. colliciatius* Woodward, *V. sulcatus* (Defrance) and *V. cf. ‘sulcatus’* are commonly both subordinate in abundance and often relatively small. In the mounds, radiolitics are fairly common and include *Radiolites* and *Durania* as most common forms; *Lapeirousia* and *Sauvagesia* are relatively rare. The radiolitics commonly are quite small and are mainly revealed in polished slabs and thin sections (e.g. Sanders and

Baron-Szabo, 1997; Sanders, 1998b; Sanders et al., in press). In the mounds, the hippuritids and larger radiolitids are present as more or less wide-conical, isolated elevator rudists, or in clusters of a few specimens of elevators; clusters composed of more than 5 to 10 specimens are rare. In the coral–rudist mounds, specimens of hippuritids and radiolitids that lived as frictional clingers appear to be rare. *Plagioptychus aguilloni* d'Orbigny is another fairly common elevator rudist in the mounds. Many of the small radiolitids are of attached clinger morphotype.

The lower part of most of the mounds consists mainly of coral–rudist floatstone with a matrix of more or less marly to silty lime mudstone to wackestone to, less commonly, packstone (Fig. 7). Boundstones are confined to small, decimeter-sized patches that are separated by areas of floatstone to bioclastic wackestone to packstone. The corals are a few centimeters to, subordinately, a few decimeters in size, and typically show columnar and hemispherical growth forms with thamnasterioid, plocoid and stylinid integration of polyparia. Both in the boundstone patches and in the floatstones, the corals and the rudists grew in close association, and were more or less thickly encrusted by coralline algae, *Ethelia alba*, bryozoans, both agglutinating and hyaline sessile foraminifera, sponges and microbialites. The corals and the rudists commonly are perforated by borings from lithophagids and clionids. The rudists associated with the corals are isolated specimens or small clusters typically of *Vaccinites* spp., *Hippurites* spp. and small radiolitids (see above), and isolated specimens of *Plagioptychus aguilloni*. In addition, calcisponges (e.g. *Peronidella*), skeletal sponges (typically stromatoporoids and spongiomorph stromatoporoids), and alcyonarians (recorded by the sclerite *Pienina oblonga*) are locally present, but are an accessory component of the taphocoenosis. Up-section, both the packing density of the corals and rudists, and the content of boundstone texture tend to increase.

The upper part of the coral–rudist mounds contains a matrix of marly to silty to pure bioclastic wackestone to packstone composed of fragments from corals, rudists, red algae, echinoderms, and ostracods, miliolids, *Moncharmontia*, *Dictyopsella*, nezzazatids, textulariaceans, bryozoans, serpulids, sponge spicules, alcyonarian sclerites, and some peloids;

fragments from calcareous green algae are rare. The upper part of the mounds may consist of an interval a few meters to about 10 m thick of floatstones to boundstones with coral heads up to about 0.5 m in size (mainly hemispherical to foliose forms of thamnasterioids, plocoids and stylinids), branched corals, and rudists that overall occur in a similar fashion to that in the lower part of the mounds (Fig. 7). Both the corals and rudists are encrusted by coralline algae, bryozoans, sessile foraminifera, serpulids, microbialites and sponges, but the thickness and abundance of encrustations varies considerably among different mounds. The scleractinian assemblage is dominated by Fungiina and Stylinina, whereas Favina, Meandriina, and Heterocoeniina are subordinate (cf. Höfling, 1985, 1997; Sanders and Baron-Szabo, 1997).

The thickest Upper Cretaceous coral-dominated bioconstruction in the Eastern Alps (near Strobl, location 7 in Fig. 1) is about 30 m thick and at least several hundreds of meters in lateral extent, within the limits of outcrop. The coral reef is of Santonian age, and developed from an interval 10 m thick of marly to sandy bioclastic floatstones to rudstones rich in disoriented hippuritids (*V. gosaviensis*, *V. sp.*) and relatively small coral heads. The coral reef itself is about 20 m in thickness, and consists mainly of lamellar-encrusting corals up to about 1.5 m in diameter, interspersed with hemispherical and columnar corals and, more rarely, with dendroid corals. Most of the corals show a thamnasterioid or a plocoid arrangement of polyparia, respectively. The coral assemblage is dominated by Fungiina, *Microsolena* and *Heterocoeniina*. The corals bear few, thin encrustations (mainly by red algae, sessile foraminifera, bryozoans, encrusting sponges), and are only scarcely bored by lithophagids and clionids. Rudists are a subordinate component of the taphocoenosis. The rudists occur as isolated specimens and as small clusters that are embedded between and that grew on the corals as a settling substratum. The rudist fauna includes *Vaccinites oppeli santoniensis* (up to 18 cm in diameter), *V. gosaviensis* and *Hippurites* spp.; radiolitids (*Radiolites*, *Durania*) up to about 10 cm in height and *Plagioptychus* are rare. In thin section, small hippuritids and radiolitids attached to coral heads are fairly common (Fig. 9). The matrix of the reef is a slightly marly to silty, poorly

sorted coral-clastic wackestone to packstone with a few smaller benthic foraminifera (rotaliaceans, lagenids, miliolids). This bioconstruction is topped by an interval a few meters thick of bioclastic packstones to grainstones with diverse smaller benthic foraminifera (miliolids, lituolaceans) and fragments from calcareous green algae (Sanders et al., in press).

Both in the coral–rudist mounds and in the above-mentioned coral reef, primary framework pores filled by marine cement are absent. Larger, cement-filled primary pores are present as intraskeletal pores, such as the intertabular space in the lower valve of rudists, or as borings from lithophagids and/or clionids within calcareous substrata. In these pores, evidence for early submarine cementation most commonly is absent. Only locally, very thin fringes of a relic, radial-fibrous cement were found as the first generation of cement within larger intraskeletal pores. Most commonly, the intraskeletal pores are filled by dog tooth spar that is overlain by blocky calcite spar, or by blocky calcite spar only.

The coral–rudist mounds are topped by hippurid biostromes some meters in thickness (Figs. 5–8). These biostromes typically develop from a basal interval of floatstone to bafflestone to rudstone with isolated rudists and/or rudist clusters embedded parallel to inclined relative to bedding. Typical rudists in these biostromes are *Vaccinites sulcatus*, *V. cf. 'sulcatus'*, *V. gosaviensis*, *V. cornuvaccinum*, *Hippurites matheroni*, and, locally, large specimens of *Vaccinites oppeli*. Among these biostromes, the relative amount of each hippurid species is highly variable. The basal interval of the biostrome is either overlain by a paucispecific biostrome composed of densely packed, slender, sharp-ribbed hippuritids (*Vaccinites sulcatus*, *V. cf. 'sulcatus'*, *V. oppeli*, *V. gosaviensis*; Höfling, 1985, 1997; Sanders and Baron-Szabo, 1997) (Fig. 6), or by a biostrome composed both of clusters of smaller hippuritids (*Hippurites matheroni*) and clusters and isolated specimens of larger hippuritids (*Vaccinites oppeli*, *V. cornuvaccinum*, *V. gosaviensis*) that are embedded either upright or inclined to horizontal position (Figs. 8 and 9). The hippurid biostrome is locally topped by a biostrome that consists of rudist–clastic rudstone to packstone rich in more or less disoriented *Radiolites* (Fig. 8). The rudist biostromes that top the coral–rudist mounds, in turn, are typically overlain by an

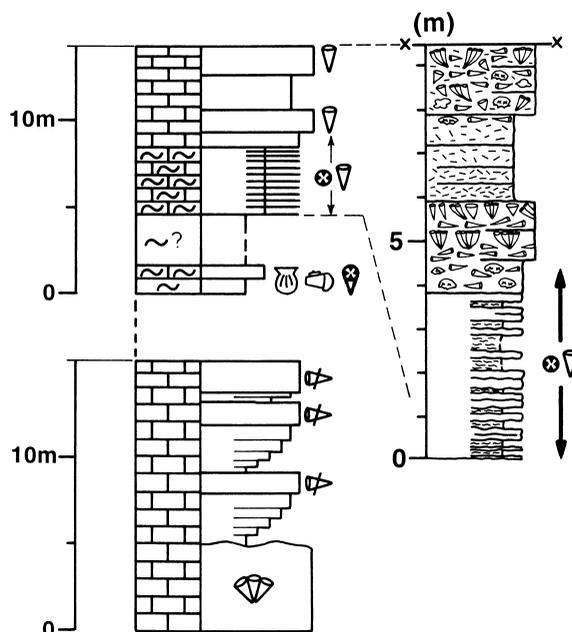


Fig. 8. Carbonate succession at Traunwandalm, Gosau. The base of outcrop is a rudist biostrome that can be traced laterally over hundreds of meters. The biostrome is overlain by three upward thickening/coarsening packages of rudist–clastic limestones each of which is topped by an interval of coarse rudist fragments. Higher up, separated by a gap in outcrop, an interval of marls rich in solitary corals, non-rudist bivalves and gastropods is exposed. The marls are followed up-section by an interval of marly limestones and marls with coral heads and rudists. This interval, in turn, is overlain by floatstones with corals and large rudists and, higher up, by floatstones, bafflestones and clusterstones with large rudists. The rudist limestones are followed up-section by poorly sorted bioclastic grainstones and, at the top, by an interval of floatstone to rudstone with disoriented corals, rudists and skeletal sponges.

interval up to about 10 m thick of rudist–clastic packstones to grainstones to rudstones, or by marls with a biotic assemblage that indicates deposition in a lagoonal environment (see Figs. 5–7).

In the Lower Gosau Subgroup of Brandenburg (location 1 in Fig. 1; section 1 in Fig. 2) a mappable, allostratigraphic unit of shallow-water carbonates is present that consists of a lower part deposited in association with a transgressive rocky to gravelly carbonate shore and an upper, regressive part that was deposited mainly from an inner shelf to open lagoonal carbonate depositional environment (Fig. 10; cf. Sanders, 1997a; Sanders et al., 1997). In the upper, regressive part of the unit,

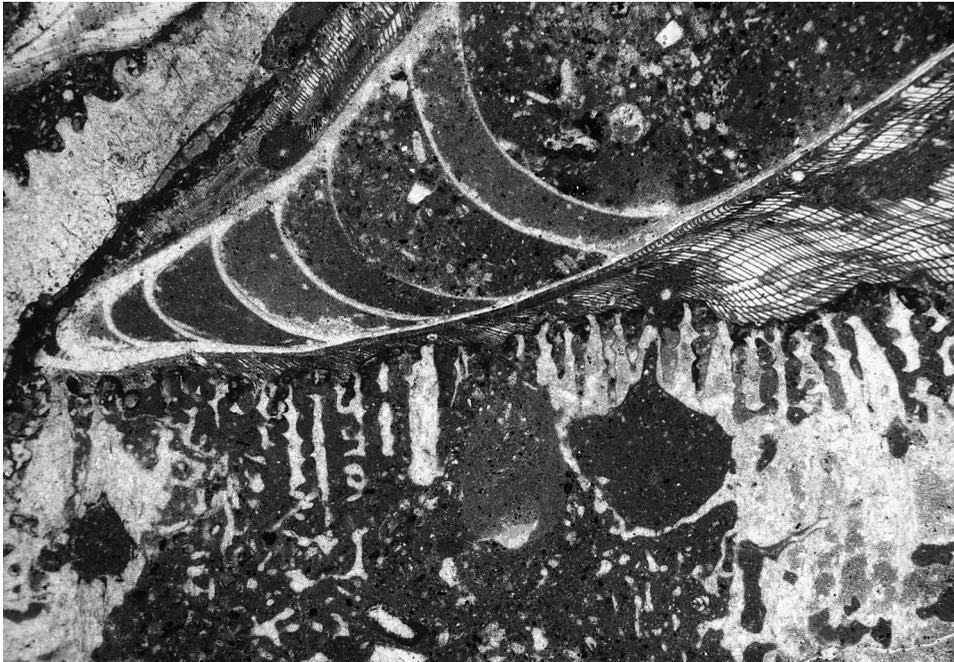


Fig. 9. Detail from a fabric composed of densely packed scleractinians. A small radiolite settled and grew directly on a coral head. Theresienstein near Strobl, Salzburg. Width of view: 17 mm.

intervals up to a few meters thick mainly of floatstones are present that contain *Vaccinites gosaviensis*, *Radiolites* ex. gr. *angeiodes* (Lapeirouse), *Durania*, *Plagioptychus aguilloni*, coral heads with either a thamnasterioid or a plocoid arrangement of polyparia, branched corals, stromatoporoids and calcisponges. The macrofossils float isolated and without preferred orientation in a matrix of burrow-mottled, poorly sorted bioclastic wackestone to, locally, packstone with miliolids, *Cuneolina*, *Dictyopsella*, ostracods, fragments from calcareous green algae, alcyonarian sclerites and pellets. Within the floatstones, patches a few centimeters to, rarely, a few decimeters in size of boundstone are present that consist of rudists, coral heads, stromatoporoids and calcisponges, all encrusted by bryozoans, serpulids, placospilinines, rupertinines, cryptmicrobial crusts, *Ethelia alba*, *Archaeolithothamnium* and nubeculariids (Fig. 11). The rudists commonly are preserved without the free valve, and many are either juvenile specimens and/or are densely perforated by clionid borings. Locally, a large part of the matrix consists of irregularly laminated, micropeloidal packstone to grainstone with a few fenestral pores, or of faintly

laminated, cauliflower-like laminated masses of lime mudstone to micropeloidal packstone (Fig. 12). The micropeloidal grainstones to packstones also are present within intraskeletal pores. The described intervals of wackestone to floatstone to boundstone are vertically associated with bioclastic wackestones to packstones to grainstones with smaller benthic foraminifera (miliolines, textulariaceans) and calcareous green algae, and with thin intervals of rudist-clastic rudstone with shelter pores, and thin intervals of black pebble floatstones to packstones.

Locally, intervals a few decimeters to a few meters thick are present that consist of silty, nodular marls to marly limestones with a diverse assemblage of corals (thamnasterioids, plocoids, stylinids, meandroids), branched corals, solitary corals, stromatoporoids, hippuritids, *Plagioptychus*, radiolites, epifaunal and infaunal non-rudist bivalves, diverse gastropods (including carnivorous forms), echinoids, bryozoans, serpulids, miliolines, rotaliids and lagenids. In these 'coral-rudist marls', the preservation of the corals and rudists is highly variable, and ranges from nearly unbored/unencrusted to heavily encrusted and bored. Locally, beds a few centime-

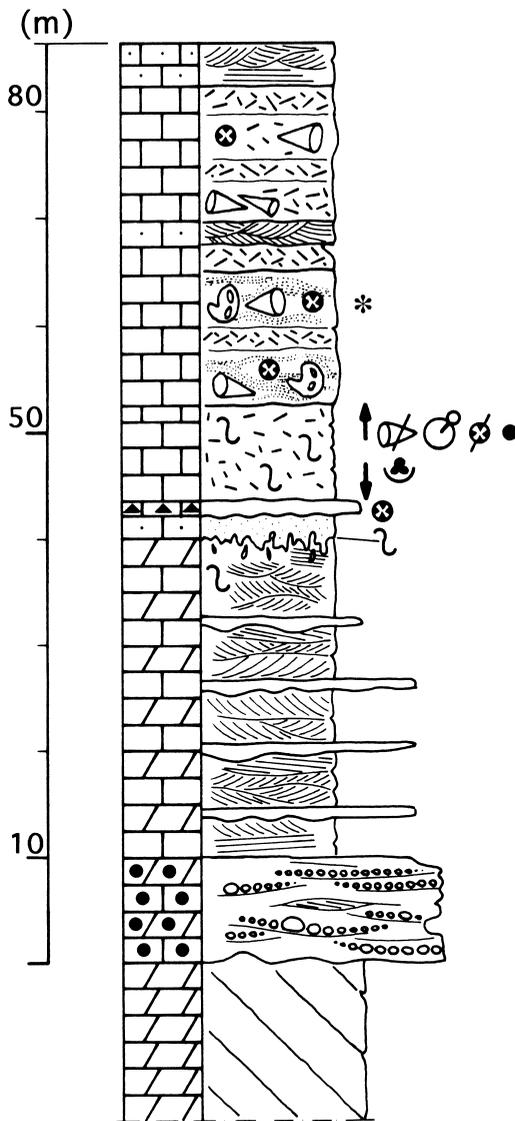


Fig. 10. Restored section of part of the Upper Cretaceous succession of Brandenburg (see Fig. 2) (from Sanders, 1997a). Truncated Middle Triassic dolomites are overlain by an interval about 10 m thick of low-angle cross-stratified conglomerates of very well-rounded, fine gravels to boulders derived from the local substratum. The conglomerates, in turn, are overlain by cross-laminated carbonate-lithic arenites with intercalated lithic conglomerates with bioclasts (corals, rudists, skeletal sponges, bryozoans, echinoid fragments). Higher up, the arenites become bioturbated, and are overlain by a succession mainly of bioclastic limestones and intervals of limestones with corals, rudists and skeletal sponges. * = position of the sample shown in Fig. 11.

ters to about 20 cm thick of very poorly sorted, angular bioclastic material that has been derived from the local faunal assemblage are intercalated (Fig. 13A). The coral–rudist marls are either overlain by rudist biostromal limestones, or by marls and siltstones with infaunal and epifaunal bivalves (including inoceramids), gastropods and solitary corals (Fig. 13A, B).

5.2. Interpretation

Within the upward shoaling cycles or in the transgressive successions that contain coral–rudist mounds, both the facies and their vertical succession indicate that the skeletal mounds accumulated in an inner shelf environment that was punctuated by high-energy events (compare Figs. 3, 5 and 7; cf. Sanders and Baron-Szabo, 1997; Sanders et al., 1997). At least the thinner intervals composed mainly of marly coral–rudist floatstones may have had very little syndepositional relief. Similarly, boundstones of lamellar-encrusting corals not necessarily formed at high elevation above the sediment surface (see Insalaco, 1998). In most intervals of coral–rudist limestones, the vertical succession from a lower part of marly floatstones to an upper part of more or less pure floatstones to boundstones to rudstones indicates a shoaling of water depth. As indicated by the vertical succession at least in the type A and type B1 cycles (see descriptions above), this ensemble pinched out down dip via a gentle slope from the relatively pure limestones in the upper part into the marly floatstones of the lower part and, finally, into inner shelf deposits. The combined evidence indicates that the coral–rudist limestones were deposited from mounds, although the slope gradients of the interpreted mounds may have varied widely.

In the lower part of the mounds, the comparatively small size of the coral heads, the predominance of floatstone texture, the matrix of marly to silty mudstone to wackestone, the abundance of both thamnasterioid and plocoid corals, and the typical thick and complex encrustations of the corals and the rudists collectively indicate environmental stress, probably from input of siliciclastic fines and nutrients (Sanders and Baron-Szabo, 1997, and references therein). Upon aggradational shoaling of a mound, mean water energy increased, the environ-

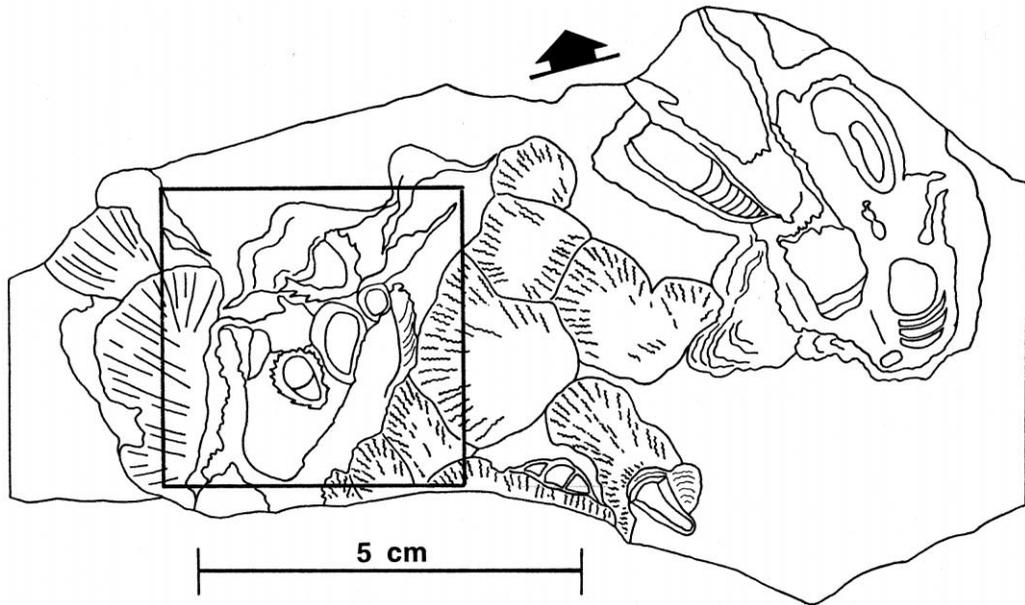


Fig. 11. Above: Line-drawing of a polished slab from an interval of floatstone that locally contains small patches of boundstone composed of corals, stromatoporoids and rudists. In the boundstone patches, the macrofossils are encrusted by microbialites, by bryozoans and sponges. Arrow points to top. Below: Negative print of thin section from the boundstone shown above, showing stromatoporoids (*S*), the empty lower valve of a radiolite overgrown by smaller radiolites (*R*) and an adjacent coral (*C*). The topmost small radiolite is encrusted by bryozoans and a sponge (arrow). The matrix is a bioclastic wackestone to packstone. Brandenberg, Tyrol. Scale bar: 5 mm.

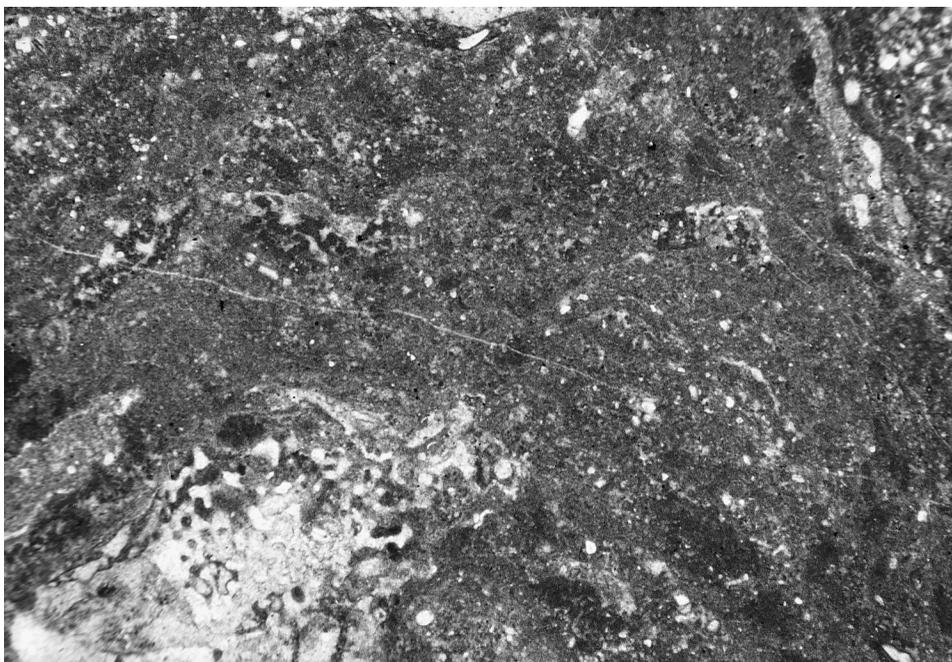


Fig. 12. Detail from the matrix of a patch of coral–rudist–sponge boundstone that, in turn, is embedded within bioclastic wackestone to packstone (see text for description). The matrix consists of a micropeloidal packstone with an irregular, cauliflower-like lamination and microfenestrae; this laminated packstone probably formed from microbial crusts. The bioclast in the lower left of the photo is a coral. Brandenberg, Tyrol. Width of view: 8.5 mm.

mental stress exerted by permanent settling of siliciclastics diminished, and both the corals and rudists typically grew to larger sizes and show a denser packing. The upper part of the coral reef near Strobl (Salzburg) consists of an interval about 20 m thick mainly of densely packed lamellar-encrusting corals that probably grew at or near optimal ecologic conditions. Aside from the close packing and the large size of the corals, optimal conditions are also indicated by the rarity of thin encrustations upon the corals, by the scarcity of borings by lithophagids and clionids (cf. Hallock, 1988), and by the relatively pure calcium carbonate composition of the limestone matrix. In recent coral reefs and in some fossil buildups, lamellar-encrusting coral growth is interpreted as a result of lowered light incidence (cf. Barnes, 1973; Insalaco, 1996; Valldeperas, 1997).

At least in the lower part of the mounds, the absence of framework pores filled by cement is related to the predominant floatstone texture and the matrix of mudstone to wackestone. The lack of cement-filled framework pores even in coral boundstones

that dominate the upper part of some mounds may result from a moderate mean water energy and/or from turbidity of the sea water. A persistent background of siliciclastics during mound accumulation is indicated by the marly to silty nature of the mound matrices. In Holocene mixed siliciclastic-carbonate depositional environments, trapping of fine-grained terrigenous material in the framework of coral reefs can lead to a substantial enrichment of terrigenous material within the reef matrix (Woolfe and Lacombe, 1998). In the mounds the poorly developed, thin fringes of radial-fibrous cement in larger intraskeletal pores may have precipitated from marine pore waters (cf. Harris et al., 1985, and references therein). The paucity of these cements may result from the low framework porosity within the mounds, which reduced the high permeability necessary for precipitation of early submarine cement. The dog-tooth spar and the blocky calcite spar that fill the larger pores precipitated in a phreatic diagenetic environment, but the chemistry of the pore waters from which these cements precipitated and the phases of

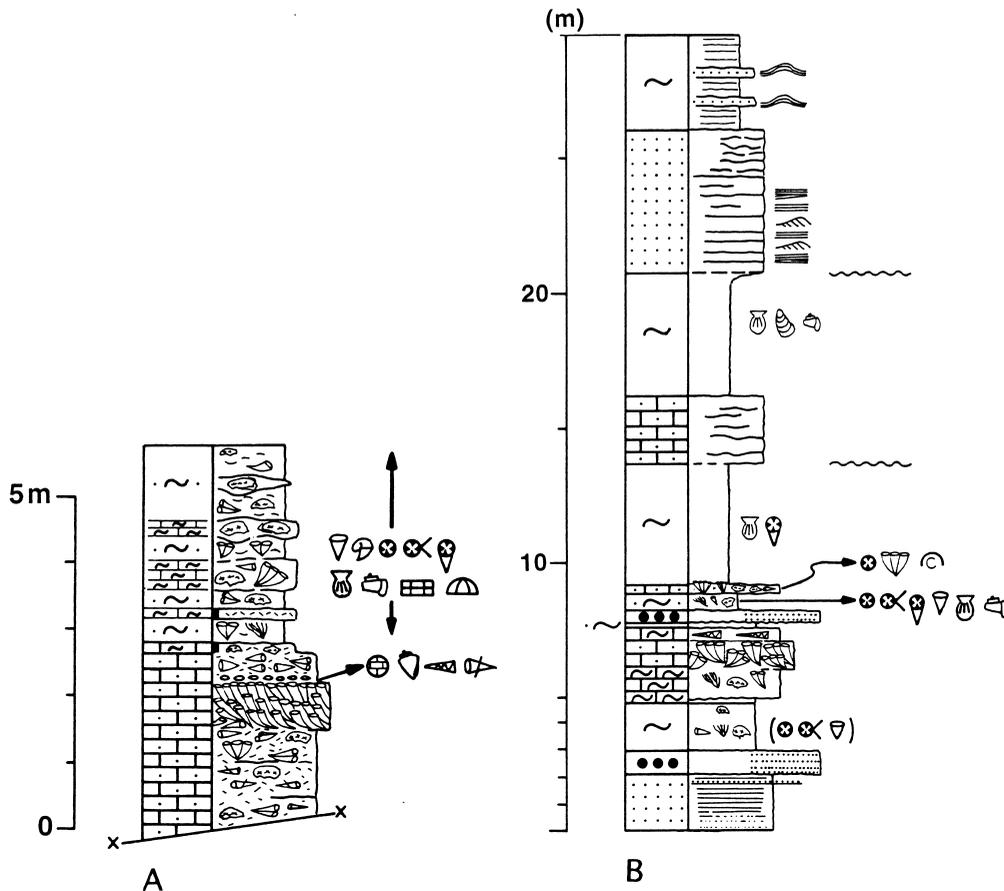


Fig. 13. (A) Outcrop at Brunftloch, Gosau. A very poorly sorted bioclastic floatstone with isolated hippuritids, toppled hippuritid clusters and coral heads is overlain by a hippuritid biostrome with a packed fabric. The biostrome, in turn, is overlain by a layer of rudstone composed of very well-rounded carbonate rock clasts and coarse, angular fragments from rudists, corals, actaeonellids and nerineids, and by an interval of bioclastic rudstone with toppled hippuritids and radiolitids. This interval is followed up-section by silty marls with a taphocoenosis of hippuritids, *Plagioptychus*, coral heads, branched corals, non-rudist bivalves, carnivorous gastropods, coralline algae and echinoids. (B) Outcrop at Wegscheidgraben, Gosau. The base of outcrop consists of low-angle cross-laminated sandstones overlain by a conglomerate with subparallel stratification. The conglomerate is sharply overlain by silty marls with coral heads, branched corals, and *Plagioptychus* and, higher up, by a packed hippuritid biostrome, an interval of nerineid rudstone, and an interval of sandy marls. The marls are sharply overlain by a stratified conglomerate with a few shallow-water bioclasts. The conglomerate is followed up-section by a thin interval of sandy marl with an assemblage of small-sized coral heads, branched corals, solitary corals, rudists and non-rudist bivalves and gastropods, and by a thin biostrome composed of coral heads, rudist clusters and stromatoporoids. The biostrome is overlain by a succession of marls with solitary corals and a rich fauna of epifaunal and infaunal non-rudist bivalves, and with intercalated bedsets of mixed lithic-bioclastic arenites.

cementation had to be clarified by more detailed investigations (cf. Melim et al., 1995).

Irrespective of size and packing of the corals, rudists are fairly common and evidently grew in close association with the corals. The large specimens of *Vaccinites oppeli* and *V. oppeli santoniensis*, *V. gosaviensis* and *V. cornuvaccinum*, and other typically smaller, yet equally abundant hippuritids and

radiolitids indicate that, even for densely packed coral fabrics, the habitat of coral growth was also favourable for rudist growth. As the hippuritids and radiolitids could rapidly colonize very large areas of substrate (Sanders, 1996c), the ubiquitous yet subordinate presence of rudists may seem paradoxical, because the corals would have provided abundant substrate for settlement of rudist larvae. The living

corals may have prevented the settlement of rudist larvae either by ingestion and/or by biochemical defense (see e.g. Barnes and Hughes, 1988). A decline of significant coral growth, or death of the corals (or part thereof), seems to have been a prerequisite for the establishment of a dense rudist population above. This is supported by the observation that corals that are overgrown by rudists commonly were bored and/or encrusted (e.g. by coralline algae, bryozoans, foraminifera) before the settlement of rudists (Sanders and Baron-Szabo, 1997; Valldeperas, 1997). Despite their potential for rapid and dense substrate colonization, the rudists could not smother a coral community by competitive replacement as long as the net effect of overall ecologic conditions was favourable for coral growth. The vertical succession of facies implies that the Late Cretaceous rudists preferred higher-energy environments closer to storm wave base as compared to the corals (see Fig. 3). Thus, upon aggradation or progradation of a mound, the overall change of environment induced a shift from a coral-dominated assemblage below to a rudist assemblage above (Sanders and Baron-Szabo, 1997). This supports the conclusions of Gili et al. (1995b) and Skelton et al. (1997) for coral–rudist mound/rudist biostrome couplets in the Pyrenees that the vertical succession from corals to rudists is an allogenic rather than an autogenic succession (cf. Walker and Alberstadt, 1975).

In themselves, the hippuritid biostromes directly above the coral–rudist mounds are not distinct from hippuritid biostromes that occur without an underlying coral–rudist mound (see below). The increasing amount of toppling and fragmentation of hippuritid shells towards the top of these biostromes, the local presence of a biostrome composed of rudist–clastic rudstone to packstone with radiolitids above the hippuritid biostrome, and the overlying bioclastic packstones to grainstones to rudstones all indicate a progressive shoaling of the environment, close to fairweather wave base.

In Brandenburg, the vertical association of coral–rudist–sponge limestones with bioclastic wackestones to packstones to grainstones, with thin intervals of poorly sorted rudist–clastic rudstones with shelter pores, and with black pebble floatstones to packstones records deposition in a quiet shallow subtidal to supratidal environment that was punc-

tuated by high-energy events. The bioconstructions from which the coral–rudist–sponge limestones accumulated may have been low mounds that consisted largely of carbonate mud with admixed sand-sized bioclastic material, and that were colonized on their surface by scattered rudists, corals and skeletal sponges; these organisms only locally grew onto each other into small aggregates with boundstone texture. The texture of the mounds was significantly influenced by burrowing, which probably was also important in undermining and toppling of the small coral–rudist–sponge aggregates. The encrustation of the macrofossils by thick and diversified crusts mainly of red algae and bryozoans, the preservation of the rudists without the free valve and in a toppled position, and the dense boring of the rudist shells all suggest that the biotic assemblage on these mounds was ecologically stressed, at least intermittently. In the coral–rudist–sponge limestones, the local matrix of irregularly laminated, micropeloidal packstone to grainstone with fenestral pores, or of faintly laminated, cauliflower-like laminated masses of lime mudstone to micropeloidal packstone are interpreted as microbialites (Behr and Behr, 1976; Burne and Moore, 1987) that formed soon after intermittent/local termination of a coral–rudist–sponge community (cf. Jones and Hunter, 1991).

The intervals of coral–rudist marls with a diversified biotic assemblage were deposited in a shallow neritic environment of overall moderate to low water energy that was punctuated by storms. In the environment of marl deposition, small areas and short intervals of time were favourable for colonization and growth of corals and rudists. Because of a high rate of input of siliciclastic fines and, probably, of nutrients the establishment of a persistent, dense coral–rudist community was precluded. Thus, large areas of muddy substrate persisted (and became re-established after intermittent smothering of corals and rudists) that favoured a level-bottom community with carnivorous gastropods, non-rudist bivalves, echinoids and solitary corals. No outcrop has been found that exposed the lateral relationships of the coral–rudist marls. The vertical succession of facies, however, suggests that these marls were deposited from low mounds and coral–rudist biostromes in a muddy, inner siliciclastic shelf environment (Figs. 3 and 13A), and as a lateral equivalent

to rudist biostromes in quiet, open lagoonal environments with an overall high rate of accumulation of fine-grained siliciclastics (Fig. 13B). A lateral transition from coral–rudist marls into rudist biostromes has been documented from mixed siliciclastic-carbonate successions in the Pyrenees (Skelton et al., 1995).

5.3. Rudist biostromes

5.3.1. Biostrome fabrics and types

With respect to shell packing, rudist fabrics may be ‘open’, with the rudist shells supported by matrix, or ‘packed’ with the rudist shells or rudist clusters providing mutual support (Sanders, 1996c). The open texture corresponds to a rudist ‘clusterstone’ (Ross, 1992), a rudist floatstone or a rudist bafflestone. The packed texture corresponds to rudist rudstone or a rudist boundstone. With respect to biostratinomy, autochthonous and parautochthonous rudist fabrics are distinguished (Zapfe, 1937). In the autochthonous fabrics, at least most of the rudists are embedded at their very site of life, with or without the free valve. In the parautochthonous fabrics most of the rudists are preserved, with or without the free valve, at a site that is not identical with their site of life. A packed fabric that consists of elevator rudists orientated with the long axes of their lower valves subparallel to bedding, and that is characterized by a relatively uniform facing of the rudist shell commissures has been termed ‘dense horizontal fabric’ by Skelton et al. (1995). In the Lower Gosau Subgroup, no biostrome with a dense horizontal fabric has been found, but biostromes with a packed fabric of rudists that are inclined to bedding are common. For reasons discussed below, the fabrics composed of inclined rudists here are included into the autochthonous fabrics. The classification of both shell packing and biostratinomy enables a relatively comprehensive, rapid characterization of the fabric of a biostrome, or a part thereof, with few terms. Because short-distance transport of rudists can be readily recognized, the interpretive character of the terms ‘autochthonous’ and ‘parautochthonous’ is not a drawback.

Among the rudist biostromes, (a) hippuritid biostromes, (b) radiolitid biostromes, and (c) ‘composite biostromes’ built of a lower hippuritid biostrome

overlain by a radiolitid biostrome are distinguished. The rudist biostromes are at least tens to hundreds of meters in lateral extent, mostly beyond the limits of typical Alpine outcrops. With the exception of paucispecific rudist thickets of apparently a single generation of rudists (see below), no thicker biostrome was found that consists exclusively of either hippuritids or of radiolitids and, in addition, invariably contains accessory taxa; the relative amount and composition of the accessory fauna is highly variable. The designation, hippuritid biostrome or radiolitid biostrome, thus, refers to the rudists that dominate the faunal assemblage. The biostromes developed upon a substratum of sandy mud to muddy sand to hybrid sand, or upon carbonate ooze with a more or less high content of arenitic to ruditic bioclastic material, or upon muddy carbonate sand, or a substratum of abundant shells of nerineids or actaeonellids (compare description of cycle types, Fig. 5). The types of rudist biostromes and the patterns of encrustation and bioerosion are described next.

5.3.2. Hippuritid biostromes

These range from thickets about 0.1 m thick to biostromes of several meters in thickness. The thickets consist of apparently a single generation of hippuritids that typically are preserved in upright to uniformly inclined clusters embedded in a matrix of sandstone to hybrid arenite with smaller benthic foraminifera (*Quinqueloculina*, *Vidalina*, *Cuneolina*). These thickets always are strongly dominated by a single species, typically *Hippurites requieni* Matheron, or *H. matheroni*, or *Vaccinites sulcatus*; only locally a few, isolated specimens of another hippuritid (e.g. *Vaccinites gosaviensis*) are present within the clusters. Such thickets are present within sandstones to hybrid arenites, or directly above intervals of nerineid rudstone, or at the base of a composite biostrome (Fig. 14B). In one case, a thicket of *Hippurites requieni* is overlain by an interval of rudstone with abundant stromatoporoids, plocoid coral heads, dendroid corals, and a few nerineids and *Plagioptychus* (Fig. 14B, upper part; Fig. 15).

The thicker hippuritid biostromes commonly show a packed, autochthonous fabric, and are dominated by a single hippuritid species (Figs. 6, 8 and 13A). In the packed hippuritid fabrics, the lower valves of the rudist shells most commonly are of

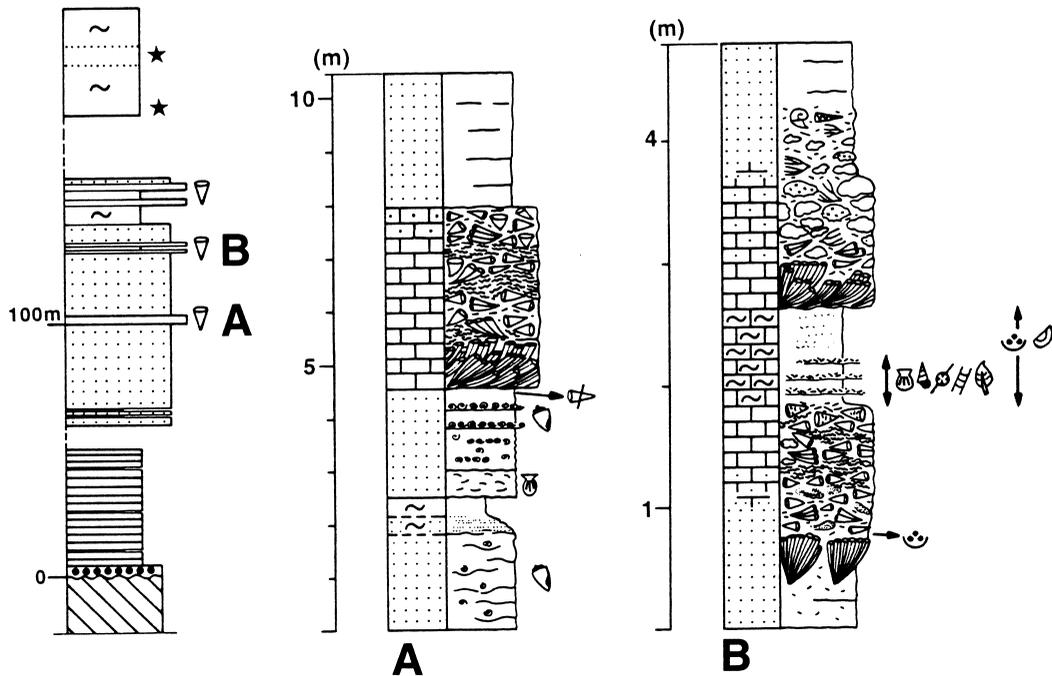


Fig. 14. Lower part of Gosau Group at Gams (see Fig. 2; modified from Kollmann (1964) and Summesberger and Kennedy (1996). The substratum (cross-hatched) is overlain by a cyclic paralic succession with coal seams which, in turn, is overlain by a succession mainly of paralic sandstones and rudist biostromes. Higher up, separated by a gap in outcrop, a succession of marls with Turonian ammonites (stars) is exposed. (A) A hybrid arenite with smaller benthic foraminifera and abundant *Trochactaeon* is sharply overlain by a biostrome that is composed, in its lower part, of densely packed *Vaccinites* cf. *sulcatus*, whereas the upper part consists of an open to packed, parautochthonous fabric of radiolitids and, subordinately, hippuritids. Lenses of floatstone composed of fragments from the radial funnel plates of radiolitids (zig-zag pattern) are intercalated. In the topmost part of the biostrome, the wackestone- to floatstone matrix contains a few percent of siliciclastic sand, and is mottled with burrows that are filled with sandstone. The biostrome is overlain by sandstone. (B) In hybrid arenites with abundant *Quinqueloculina* and *Cuneolina*, a monospecific thicket of *Hippurites requieni* is intercalated, and is overlain by an interval of burrow-mottled sandy limestone with toppled *H. requieni* and *Radiolites*. This interval, in turn, is overlain by a bioturbated, open parautochthonous biostrome of radiolitids, and with a matrix of 'radial funnel plate floatstone'. At its top, the biostrome grades into an interval of organic-rich, marly wackestones with miliolids, *Cuneolina*, ostracods and coalified plant fragments. These marls are sharply overlain by a monospecific thicket of *H. requieni* which, in turn, is followed up-section by an interval of increasingly sandy rudstones with abundant stromatoporoids, plocoid corals, branched corals, *Plagioptrychus* and nerineids (see Fig. 15).

slender, hose-shaped form, and show reduced shell ornamentation and numerous closely spaced tabulae. The ostracum of the lower valve is typically thinner than in specimens that grew isolated. In addition, the shells of adjacent hippuritids may be intergrown along thinned 'shared shells' (Höfling, 1985). Within most packed, autochthonous hippuritid biostromes, the rudist shells are preserved with a relatively constant inclination relative to bedding (Fig. 16). The facing of the shell commissures is as equally constant as the inclination of the shells. In addition, the tabulae of the rudist shells typically are perpendicular to oblique relative to the outer wall of the rudist shell. The oblique tabulae, however, in most

cases also are tilted relative to bedding. The packed, autochthonous hippuritid fabrics typically are poor to nearly devoid of matrix, and the rudist shells often are crushed by mechanical compaction. In the less common parautochthonous, packed fabrics the orientation of the hippuritid shells is highly variable, and a proportion of the rudists may be coarsely fragmented.

The most common species in packed, autochthonous fabrics are *Vaccinites sulcatus* and *V.* cf. '*sulcatus*', *V. gosaviensis*, *Hippurites matheroni*, *H. requieni*, *Vaccinites inaequicostatus*, *V. oppeli* and *V. oppeli santoniensis* (see also Pons and Vicens, 1988). The latter three species may be up to 60 cm

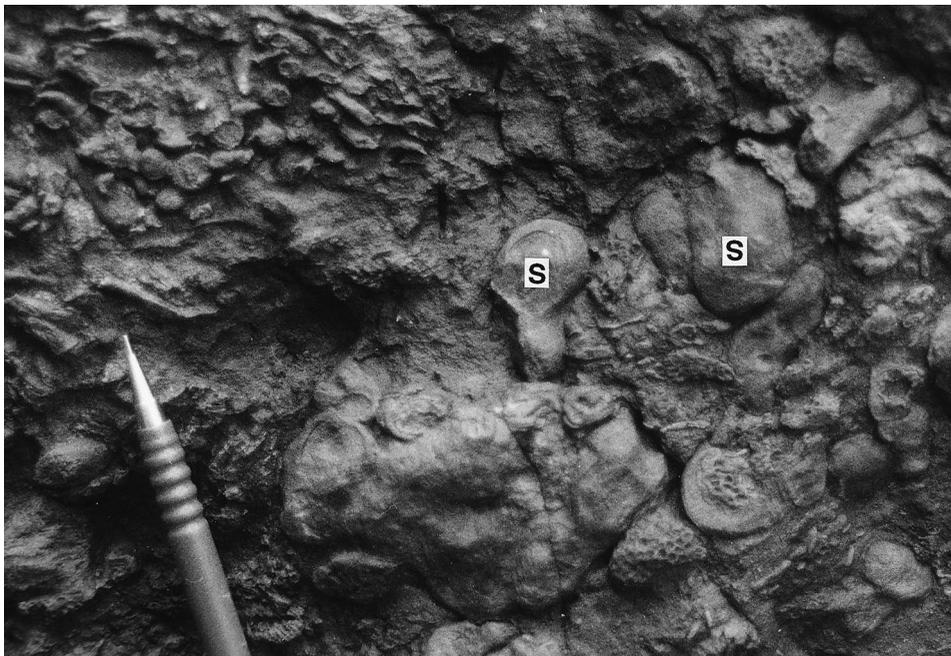


Fig. 15. Detail from Fig. 14B. Rudstone with abundant, disoriented stromatoporoids (S), fragments from plocoid coral heads and toppled colonies of dendroid corals (upper left margin). Pen for scale. Noth-Klamm near Gams, Styria.

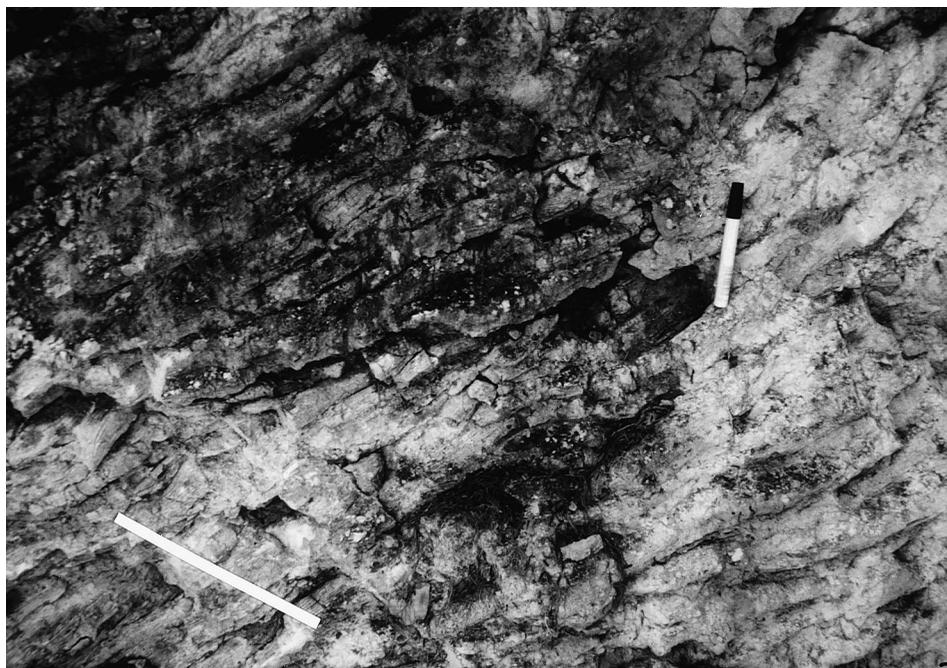


Fig. 16. Portion of a paucispecific biostrome composed mainly of *Vaccinites oppeli* and *V. gosaviensis*. Note the elongate form of the lower shell valves, and both the dense packing and uniform orientation of the rudist shells. The outcrop intersection of bedding is shown by white line. Pen is 14 cm long. 'Krönner-Reef', Lattenberg (Germany).

in length and 15 cm in diameter. In thicker hippurid biostromes, even in densely packed rudist fabrics, in the interstices between the rudist clusters and on the flanks of the hippuridids other epifaunal sessile organisms most commonly are present, including radiolitids, *Plagioptychus*, small scleractinian colonies, calcisponges, sclerosponges, caprotinids, cf. *Placunopsis*, bryozoans, small brachiopods (thecideids, terebratulids: *Gisilina*; Höfling, 1997) and, rarely, requeniids and monopleurids. In autochthonous hippuridid fabrics, benthic foraminifera are rare to absent, and typically are small and of low diversity (miliolids, textulariaceans). In the lithologies overlying the biostromes, in contrast, benthic foraminifera are diverse and common, and are associated with a wide range of other taxa, mainly calcareous algae, non-rudist bivalves, gastropods and echinoderms (Höfling, 1985; Sanders and Baron-Szabo, 1997).

Locally, layers of rudist–clastic rudstone are intercalated in the hippuridid biostromes. At one location, a layer of poorly sorted rudstone composed of coarse bioclastic material (actaeonellids, nerinids, rudists) and very well-rounded lithoclasts of oblate to highly spherical shape is intercalated within a biostrome (Fig. 13A). The lithoclasts are very well-rounded fine to medium gravels of dolostones, limestones and chert that have been derived from the local Triassic–Jurassic substratum.

5.3.3. Radiolitid biostromes

Intervals of bafflestones that contain apparently a single generation of radiolitids in growth position and with their free valve in place are very rare; the only example known to date is exposed in the Brandenburg area (1 in Fig. 1; Sanders et al., 1997, pl. 2/3). There, *Radiolites angeiodes* (Lapeirouse) is present in an interval about 20 cm thick with an open, autochthonous rudist fabric with a matrix of lime mudstone to rudist–clastic wackestone. At Gosau, an interval a few decimeters thick consists of widely scattered, isolated specimens of large, disoriented *Durania* embedded in a matrix of bioclastic wackestone to packstone (Sanders, 1998b).

The thicker radiolitid biostromes range in thickness from less than a metre to several meters, and typically are dominated by *Radiolites* ex gr. *angeiodes* [e.g. *R. angeiodes*, *R. trigeri* (Coquand)]. Other radiolitids include *Radiolites squamosus* d'Orbigny, *R. ex*

gr. *radiosus* d'Orbigny, *Lapeirousia* (*L. zitteli* Douville), *Durania* and *Sauvagesia* (Pons and Vicens, 1988), but these forms are subordinate in abundance and not all of them are found within a single biostrome. In addition, at Lattenberg (location 6 in Fig. 1) radiolitids with a capuloid canaliculate upper valve are present (*Neoradiolites*; Höfling, 1985). The radiolitid biostromes typically are dominated by parautochthonous, open or packed rudist fabrics (Figs. 6, 14, 17 and 18). The matrix of the parautochthonous radiolitid fabrics is a burrow-mottled marly hybrid arenite to silty marl, or a bioturbated or burrow-mottled rudist–clastic floatstone to packstone to wackestone with toppled juvenile rudists, fragments of branched corals, red algae, calcareous green algae, echinoderms, bryozoans, serpulids, smaller benthic foraminifera (miliolids, lituolaceans), and crustacean pellets; the abundance and relative proportion of these bioclasts is highly variable. Larger radiolitid clasts are bored by clionids and lithophagids, and are locally encrusted by corallines, serpulids, sessile foraminifera, and microbialites. In parautochthonous radiolitid fabrics, the cellular boxwork of the ostracum of the lower radiolitid valves commonly has been partly or completely removed, probably by a combination of physical abrasion (storms, burrowing) and early diagenetic dissolution (Sanders, 1998b). The resulting relic radiolitid shells consist of a thin, inner layer of the ostracum and the (formerly aragonitic) hypostracum.

Some radiolitid biostromes contain sharp- to erosive-based layers (interval marked by wavy line in Fig. 17A) a few centimeters to a few decimeters thick of rudstones of disoriented, more or less coarsely fragmented radiolitids. Another characteristic lithology within radiolitid biostromes is floatstone composed of large fragments from the radial funnel plates and from the calcitic part of the upper radiolitid valve (cf. Sanders and Baron-Szabo, 1997). These floatstones are present in thin lenses a few centimeters to a few meters in length or, locally, comprise the entire matrix of a radiolitid biostrome (Fig. 14A, B). Within the radiolitid biostromes, autochthonous rudist fabrics are rare, confined to intervals of a few decimeters at most, and are present either at the top of or are intercalated between parautochthonous fabrics within the biostrome (arrowed interval in Fig. 17B). The matrix of the autochthonous radiolitid fabrics typically is a lime mudstone to rudist–

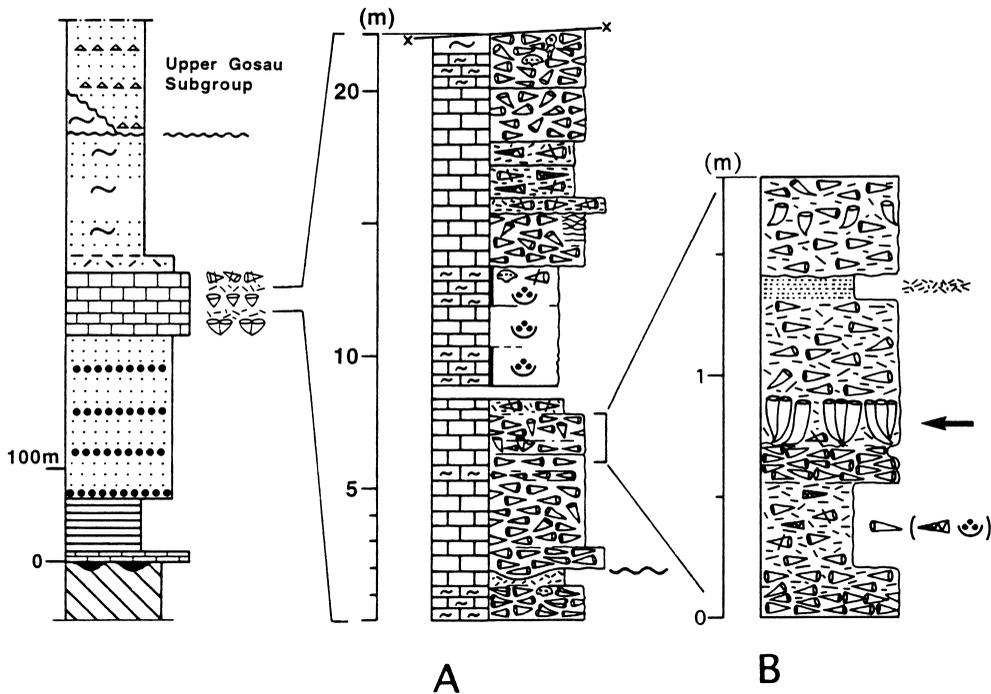


Fig. 17. Summary section of Gosau Group at Weisswasser (see Fig. 2; modified from Ruttner and Woletz (1955), and Faupl et al. (1987). Up-section, the truncated substratum (cross-hatched) is overlain by bauxite and freshwater limestones, a cyclic paralic succession with coal seams, and a succession of paralic sandstones and conglomerates. The sandstones are followed up-section by a succession of shallow-water limestones that consists of rudist biostromes and associated bioclastic limestones. The shallow-water limestones are overlain by an interval of mixed siliciclastic-bioclastic composition which, in turn, is followed by a succession of shelf marls with inoceramids and planktic foraminifera. (A) At the base, the top of a biostrome composed of both clusters and isolated specimens of small hippuritids, radiolitids and a few coral heads is present, and is overlain by an interval of rudist-clastic packstones. These, in turn, are overlain along an erosive boundary by a biostrome with a predominantly parautochthonous, packed fabric that consists exclusively of radiolitids (see Fig. 18). (B) Near its top, the biostrome contains an intercalated thicket of apparently a single generation of radiolitids that are embedded in growth position (arrow) and, higher up, an interval of parallel-laminated rudist-clastic grainstone. The biostrome is overlain by marly foraminiferal wackestones (*Quinqueloculina*, *Cuneolina*) and, higher up, by a radiolitid biostrome with an open, parautochthonous fabric, and by rudstones to poorly sorted grainstones with rudist fragments and with nerineids. At the top, a radiolitid biostrome is present that contains a matrix of pure wackestone to packstone that up-section grades into a matrix of friable, silty marl, without a change in biostrome fabric.

clastic wackestone to packstone in which non-rudist bioclasts (miliolids, lituolaceans, textulariaceans, ostracods) are scarce to absent.

5.3.4. Composite biostromes

Where biostromes composed of both hippuritids and radiolitids occur, the lower part is dominated by hippuritids, and the upper part may consist of an open, parautochthonous rudist fabric of both radiolitids and hippuritids, or of radiolitids (Figs. 6, 7 and 14A, B). The composite biostromes typically are several meters thick. They exhibit a vertical change in both the most abundant taxa and the accessory

taxa (hippuritids, radiolitids, *Plagioptychus*, caprotinids, corals, sponges), as well as in rudist packing texture and fabric.

5.3.5. Epibionts and bioerosion

Both in the rudist thickets and in the biostromes, the rudists commonly are sparsely covered by epibionts. Among the epibionts, cheilostomate bryozoans and serpulids are most common, whereas red algae (corallines, squamariaceans, *Ethelia alba*), cryptostomate bryozoans, small thecideid brachiopods, sessile foraminifera (Rupertiniinae, Placopsiliinae, Rotaliidae) and cf. *Placunopsis* are subordi-



Fig. 18. Detail of parautochthonous, packed radiolitid fabric. This is the most common rudist fabric in the radiolitid biostromes of the Lower Gosau Subgroup. Weisswasser, Upper Austria. Width of view: 30 cm.

nate. Most commonly, the epibionts are confined to small areas a few square millimeters to a few square centimeters in size. In the rudist shells, borings from clionid sponges are very common, but show marked variations in abundance. In the boxwork ostracum of radiolitids and in the lower valves of large hippuritids, lithophagid borings also are common.

In packed, autochthonous hippuritid fabrics and in open, autochthonous radiolitid fabrics, coverage of rudist shells by epibionts ranges from zero to a few small patches. Similarly, the density of boring in these rudist fabrics typically is very low. In the packed, parautochthonous rudist fabrics, the density of boring and coverage by epibionts is quite variable, both between adjacent rudists (or large fragments thereof) and between vertically juxtaposed layers within a biostrome. The abundance and density of boring and the coverage by epibionts typically are highest in open, parautochthonous rudist fabrics. In these fabrics, macroids of heavily bored and thickly encrusted rudist shells are common.

5.4. Interpretation

The lateral extent of paucispecific thickets apparently composed of a single generation of hippuritids or radiolitids suggests that these rudists could rapidly colonize large areas of substrate. In the thicker hippuritid biostromes with a packed fabric, intense competition for space between adjacent rudists is inferred from the hose-shaped and densely tabulate lower valves, valve thinning, reduced ornamentation, and the 'shared wall' between some adjacent shells. The paucity of clionid boring in the packed, autochthonous hippuritid fabrics may result from the combined effects of rapid upward growth, dense packing of the rudist shells and, possibly, from an inferred constrictal mode of life of the elevator rudists (cf. Skelton et al., 1995).

In the packed autochthonous hippuritid fabrics, the typical inclination, relative to bedding, of the rudist shells and their tabulae indicates that the rudists were embedded in a disoriented position (cf. Skelton et al., 1995). The dense packing of the shells, their uniform orientation and the paucity of

matrix collectively suggest that this fabric mainly results from winnowing of matrix during storms (Skelton et al., 1995; Sanders, 1996c). During the storms, the rudist clusters most probably were tilted out of their original life position, but not uprooted and transported. If most of the rudists were uprooted and transported, even for a small distance, the resulting deposit should be a rudist rudstone composed of more or less coarsely fragmented rudists that show no consistent dip and facing of both the tabulae and the shell commissures. The packed hippuritid fabrics composed of inclined hippuritids, thus, are considered as a type of autochthonous fabric. Storms deposited layers of bioclastic rudstones with sharp basal contacts in some hippuritid biostromes. The very well-rounded, oblate to spherical lithoclasts in one of these rudstone layers were derived from an adjacent beach that abutted the local rock substratum.

Because the radiolitids grew, at least in most cases, in open rudist fabrics, during storms they were relatively easily washed out from their substratum and toppled. This is indicated by the marked predominance of the open to packed, parautochthonous fabrics of more or less adult radiolitids, and by the sharp- to erosive-based layers composed of radiolitid rudstone. The bioturbation and burrow-mottling both in the open and the packed, parautochthonous radiolitid fabrics indicates that the radiolitid fabrics were, at least intermittently, accessible for larger burrowers. Churning and undermining of the sediment by burrowing probably induced or favoured disorientation and toppling of the radiolitid shells (cf. Clifton and Hunter, 1973). In recent muddy shelf environments, the quasi-permanent instability of bioturbated muds prevents the establishment of dense populations of infaunal and epifaunal suspension feeders (see Scott, 1978, and references therein). The final fabric of the radiolitid biostromes results mainly from the interaction of rudist colonization and growth, bioturbation, and toppling/fragmentation of rudist shells by burrowing as well as by uprooting during high-energy events. The often observed association of nerineids and/or actaeonellids with radiolitids within the same bed results from the shared lagoonal habitat of these groups (Sanders et al., 1997). The observation that some radiolitid biostromes directly overlie intervals of nerineid/actaeonellid rudstones, and a direct overgrowth of ra-

diolitids onto shells of nerineids (Herm and Schenk, 1971) indicate that the shells of the gastropods provided a substratum for rudist settlement.

In the 'composite biostromes', the vertical succession from hippuritid-dominance below to radiolitid-dominance above may result from a shoaling of depositional water depth. This is suggested by the vertical succession from coral–rudist mound to hippuritid biostrome to radiolitid biostrome and, higher up, into '*Phelopteria* marls' that have been deposited in a lagoonal environment (see description of type B2 carbonate cycles). At present, however, no clear-cut criteria decipher whether the geologically sharp skip from hippuritid dominance to radiolitid dominance was mainly controlled by water depth, mean water energy, turbidity or nutrient level, or a combination of them.

In the biostromes with a parautochthonous rudist fabric the taphocoenosis of rudists, smaller benthic foraminifera, calcareous green algae, echinoids, gastropods, bryozoans, sponges and crustacean pellets suggests that the 'active surface' of the future biostromal lithosome was inhabited by a diverse biota. Because of sparse rudist colonization, this biotope showed little clue of a future rudist biostromal lithosome. In recent shallow neritic environments, removal of mud during high-energy events can lead to a marked enrichment in the shells of opportunistic bivalves that colonize the bottom only every few years. The resulting benthic community is dominated by the opportunistic bivalves, whereas the other taxa that thrived on the substratum prior to the high-energy event are underrepresented (cf. Levinton, 1970; Staff et al., 1986). A similar effect may have occurred at least in some of the biostromes with a parautochthonous rudist fabric.

The trophic structure in the autochthonous rudist fabrics was different from that of laterally adjacent environments (cf. Scott, 1978). In the autochthonous rudist fabrics, both bioturbation and non-rudist bioclasts are rare to absent, but bioclasts from diverse non-rudist taxa are abundant in the vertically adjacent lithologies. The muddy, faeces-rich matrix of the autochthonous rudist fabrics may have been an unfavourable substrate for burrowing metazoans and foraminifera because of a high level of inimical or repellent substances resulting from bacterial decomposition and/or from oxygen depletion. The resulting

conditions helped to sustain the dense population of epifaunal suspension feeders, similar to aggregates of recent gregarious epibenthic bivalves (see Thorson, 1957; Purdy, 1964; Barnes and Hughes, 1988, and references therein). In addition, the very densely packed rudist aggregates of the autochthonous fabrics inhibited the invasion by infaunal organisms. Only epifaunal organisms (e.g. corals, echinoids, bryozoans, brachiopods) could settle on the rudist shells, but evidently remained accessory within the rudist-dominated community. Both the packed and the open autochthonous rudist fabrics, thus, were characterized by a simple trophic structure dominated by epifaunal suspension feeders. The structure of an autochthonous rudist fabric, however, could have been disrupted by severe damage during a storm, for instance, and the substrate became available for a more diversified infaunal and epifaunal biota. In summary, autochthonous rudist fabrics and parautochthonous rudist fabrics are quite different with respect to their trophic structure and biostratigraphy, but are linked by destructive events.

5.5. Termination of rudist biostromes

The topmost part of the biostromes and the immediately overlying intervals are characterized by wide variations in rudist biostratigraphy, and in sediment type and texture. At their top, a number of biostromes show an overall increasing degree of fragmentation and disorientation of the rudist shells; these biostromes are topped by an interval up to a few decimeters thick of poorly sorted rudist rudstones (Figs. 6 and 13A) that may locally contain thin intercalations of parallel-laminated rudist-clastic grainstone (Fig. 17B). Alternatively, the rudists at the top of a biostrome are preserved in situ and, commonly, with their free valve in place, and are immediately overlain by the lithology above the biostrome (e.g. Sanders et al., 1997, pl. 3/2; Sanders and Baron-Szabo, 1997). In one case, the lower valve of the topmost radiolitids is settled within the biostrome matrix, whereas the uppermost part of the lower valve and the free valve are embedded in a bioclastic grainstone that immediately overlies the biostrome (Sanders, 1998a).

On top of a few biostromes an interval up to several decimeters thick is present with a parautochtho-

nous, open rudist fabric composed of strongly bored, micritized and encrusted rudists. This interval grades upwards into organic-rich bioclastic wackestones or organic-rich marls with ostracods, miliolids, *Cuneolina*, codiacean plates, and coalified plant fragments (Fig. 14B). Alternatively, the rudists are preserved in upright position, and are either directly overlain by organic-rich marls with mixed dysaerobic/deep shelf foraminiferal assemblages (Höfling, 1985, p. 155; Höfling, 1988), or marly wackestones that are rich in *Cuneolina*, miliolines, ostracods and fragments from calcareous green algae.

5.6. Interpretation

The biostromes that show both an increasing degree of disorientation and fragmentation of the rudists and an interval of very poorly sorted rudist rudstones at their top probably were terminated by frequent toppling and fragmentation of the rudists during high-energy events ('fragmentation termination'). The accumulation of intervals of rudist limestone that contain the rudists at their top in situ, and that are sharply overlain and buried by bioclastic wackestone to packstone to grainstone, or by arenites, has been terminated by burial of rudists ('burial termination'), at least at that site. The biostromes with a parautochthonous fabric composed of strongly bored, micritized and encrusted rudists at their top, and that grade vertically into organic-rich wackestones or organic-rich marls, and the biostromes that are directly overlain by organic-rich marls to wackestones probably were terminated by environmental restriction ('restriction termination').

6. Rudists and siliciclastics

With respect to underlying sandstones, hybrid arenites or sandy marls, rudist limestones may gradually develop over some decimeters of bioturbated, sandy to marly bioclastic floatstone with rudists and a few branched corals and coral heads (Fig. 13B). This gradual vertical development occurs where the underlying arenite or marl and the overlying rudist limestone are both part of a single upward shoaling cycle, like the type C 1 carbonate cycles (see Fig. 5). Alternatively, the intervals of rudist lime-

stone sharply overlies sandstones, hybrid arenites, marls or marly wackestones to packstones along a marine flooding surface at the base of an upward shoaling cycle, as for instance in type C siliciclastic-dominated cycles and in type C 2 carbonate cycles (see also Fig. 14A, B upper part; Sanders, 1998a, for another example).

At their top, biostromal limestones with a parautochthonous rudist fabric grade into overlying sandstone, hybrid arenite or marl via an interval up to a few decimeters thick of burrow-mottled wackestone to packstone; the burrows are filled with the stratigraphically overlying sandstone, hybrid arenite or marl. In the Lower Gosau Subgroup at Weisswasser, a radiolitid biostrome with a packed, parautochthonous fabric shows a gradual vertical change from a matrix of pure wackestone in the lower part into a matrix of soft, friable, silty marl in the upper part of the biostrome, without a change in the rudist fabric and the taxonomic composition of the biostrome (Fig. 17A). Mono- to paucispecific rudist thickets are embedded in situ within sandy marls or sandstones to hybrid arenites (e.g. Fig. 14B). Irrespective of their rudist fabric, a number of biostromes bear a matrix of silty to sandy marl or of medium to coarse hybrid arenite, either throughout the biostrome or in its lower or upper part, respectively. In these biostromes, the rudists may contain an infill of more or less marly lime mudstone, or of arenite.

6.1. Interpretation

The close vertical association of rudist limestones and siliciclastics within the same upward shoaling cycle or within the same transgressive succession (see Fig. 5), and the burrow-mottled vertical transitions from rudist limestones into overlying sandstones to hybrid arenites record laterally adjacent, contemporaneous deposition of rudist limestones and siliciclastics. The rudist thickets and the biostromes that are intercalated into sandstones, hybrid arenites and marls, and that may bear a matrix of marl, sandstone or hybrid arenite indicate that the rudists could thrive within siliciclastic depositional environments. In some of the rudist biostromes at Weisswasser and at Gosau, the vertical change from a matrix of limestone into a matrix of friable silty marl, with

or without a change in the biostrome fabric or taxonomic composition indicates that the biostromes persisted even under a marked overall increase in siliciclastic input. The described relations between rudists, rudist limestones and siliciclastics thus suggest that a moderate amount of siliciclastic input was not a major control neither over presence/absence of rudists nor over the composition of the rudist assemblages. The hippuritids probably were well-adapted to a life in turbid, siliciclastic depositional environments because of their potential for rapid upward growth (up to more than 30 mm/a, as inferred from systematic variations in $\delta^{18}\text{O}$ of hippuritid shells; Steuber, 1997) and their probable filter feeding mode of life. Probably only under a high rate of siliciclastic accumulation or under frequent shifting of the siliciclastic substrate, the colonization of a siliciclastic depositional environment by rudists was precluded. Overall, however, there is a clear-cut positive correlation between both presence and abundance of rudists and intervals of shallow-water limestones.

7. Integrated model

In the following, the rudist formations are described in the context of sequence development. In the depositional sequences of the Lower Gosau Subgroup, the transgressive systems tracts record widely variable depositional systems, as a result of an accommodation-dominated, autochthonous depositional regime (cf. Swift and Thorne, 1991), an overall high rate of siliciclastic input near point sources, and transgression onto a substratum with an articulated morphology (Sanders et al., 1997). In areas of high siliciclastic input either near a deltaic source and/or from shoreface reworking, the transgressive systems tract is dominated by siliciclastics. In the paralic environment near the basin margins (transgressive shelf A in Fig. 19), the transgressive systems tracts may consist of a stack of coal-bearing upward shoaling cycles that were deposited from shifting shoreface to lacustrine marsh environments (Sanders, 1996a). In these cyclic paralic successions, rudists are present in type B siliciclastic-dominated cycles or in type C carbonate cycles that were deposited in lagoonal environments of intermittently reduced siliciclastic input (section

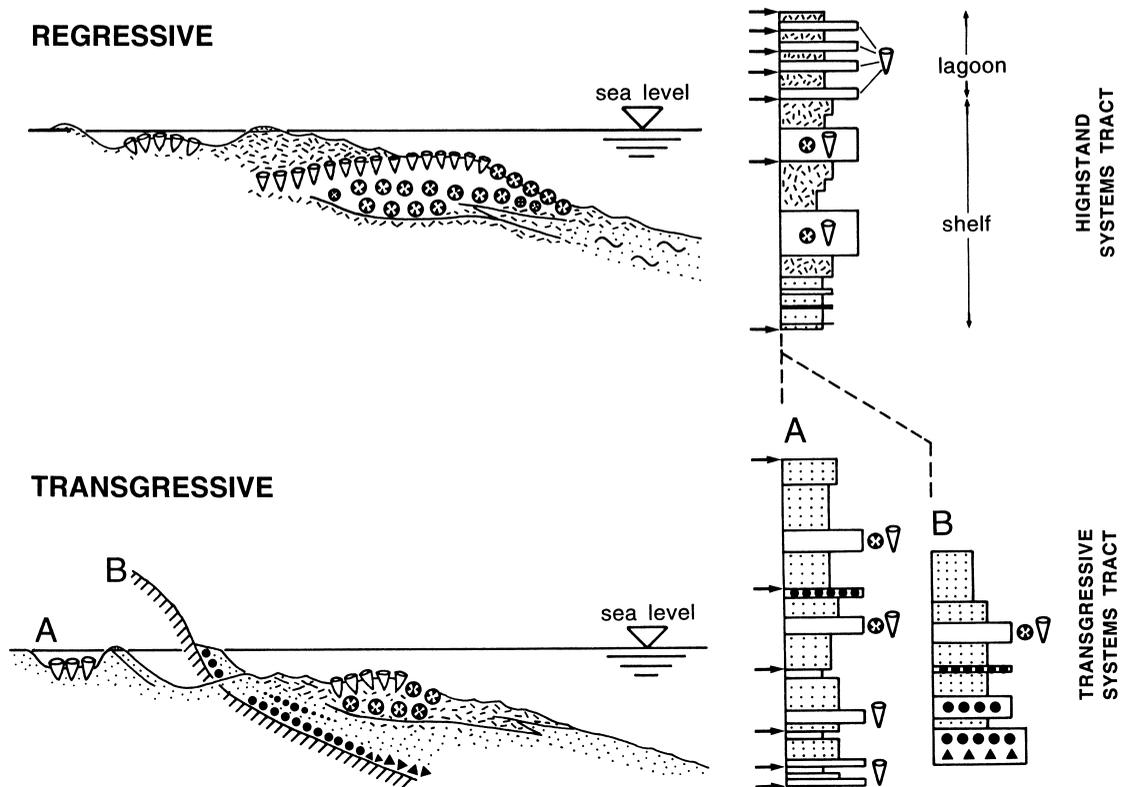


Fig. 19. Scheme of transgressive and regressive shelf, development of the transgressive and highstand systems tracts, and the place of rudist formations within sequence development. Below: Rudist formations on a transgressive shelf with a sandy beach (A), or with a gravelly to rocky shore (B). In both cases (A) and (B), coral–rudist mounds and/or rudist biostromes with associated bioclastic limestones accumulated in the shoreface to inner shelf environment in front of the coast. In case (A), rudist thickets and biostromes locally also accumulated in open lagoons, in areas of intermittently reduced siliciclastic input. Schematic sections through a transgressive systems tract resulting from transgression of a mixed siliciclastic-carbonate shelf with a sandy beach (A) and of transgression of a gravelly to rocky shore (B) are shown to the left. Above: On the regressive carbonate shelves, deposition of biogenic carbonates was confined to the inner shelf to lagoonal to tidal flat environment (compare Fig. 3), while siliciclastics were deposited on the mid- to outer shelf. In the lagoon radiolitic biostromes and, less commonly, low mud-rich mounds with corals, rudists and sponges were deposited. The lagoon was separated from the inner shelf by a dissipative shore zone of bioclastic dunes. On the inner shelf, coral–rudist mounds topped by hippuritid biostromes were deposited. A schematic section through a highstand systems tract resulting from aggradation and progradation of this type of carbonate shelf is shown to the right. The siliciclastic highstand systems tract would be roughly an inverted image of the transgressive systems tract shown in column (A). See text for further description and discussion.

A in Fig. 19) (Sanders, 1998a). In the foreshore to inner shelf facies tract of the transgressive systems tract, type A siliciclastic-dominated cycles with thin coral–rudist mounds and rudist biostromes developed (Fig. 19). Where transgression occurred in association with fan deltas, the transgressive systems tract may consist of a cyclic interlayering of shelf siltstones, shoreface sandstones and channel mouth bar conglomerates (Wagreich, 1986a,b, 1989), or of a type A transgressive succession from alluvial fan deposits into beachface–shoreface conglomer-

ates and shoreface–shelf arenites that are locally associated with thin coral–rudist mounds and bioclastic limestones (Sanders, 1996b, 1997a). Where both fan deltas and siliciclastic input were absent, transgression took place with rocky coasts and gravelly carbonate beaches (shelf B in Fig. 19); the resulting type B transgressive successions show no distinct cyclicality (section B in Fig. 19).

Upon a decrease in the rate of production of accommodation space, a supply-dominated, allochthonous depositional regime established (cf. Swift

and Thorne, 1991) and led to the formation of regressive siliciclastic shelves with aggradational–progradational shoreface to lagoonal depositional systems. Within the highstand systems tracts of siliciclastic-dominated sequences thin, marly coral–rudist mounds locally accumulated in protected inner shelf to shoreface environments (type A siliciclastic-dominated cycles). In the shoreface of prograding siliciclastic beaches thin, reworked radiolitid biostromes locally accumulated (type B siliciclastic-dominated cycles), while intervals of rudist biostromal limestone formed in lagoonal areas of intermittently reduced siliciclastic input (type C carbonate cycles) (Sanders, 1998a). Where siliciclastic input was reduced for some interval of time, within an overall siliciclastic highstand systems tract locally a few stacked type A and type B carbonate cycles were deposited (Fig. 8). Except for their regressive development, the highstand systems tracts of the siliciclastic-dominated sequences thus are not basically different from the transgressive systems tract with respect to the development of rudist formations.

Where siliciclastic input had strongly diminished during transgression or was persistently low, highstand systems tracts composed of a regressive carbonate shelf succession up to about 100 m thick were deposited. The carbonate highstand systems tracts record an inner shelf facies belt with coral–rudist mounds and hippuritid biostromes, a dissipative shore zone with bioclastic sand bodies, an open to intermittently restricted lagoon with radiolitid biostromes and, at the landward end, poorly developed microtidal flats (Fig. 3, Fig. 19, upper part). The lower part of the regressive successions consists of stacked type A and type B carbonate cycles, respectively, whereas the upper part is built by stacked type C carbonate cycles (section in Fig. 19, upper part; cf. Sanders and Baron-Szabo, 1997). At several locations, transgressive systems tracts that were deposited in association with gravelly to rocky carbonate shores (type B transgressive successions) are overlain by a highstand systems tract deposited from a regressive carbonate shelf (e.g. Fig. 10; Sanders et al., 1997).

In the Lower Gosau Subgroup, no carbonate succession deposited in a mid- to outer shelf environment is present. Where gradual vertical transitions from siliciclastics into carbonates are present, as for instance in the type A carbonate-dominated cycles,

the paleobathymetrically deepest part of the carbonate interval records an inner shelf environment. In mid- to outer shelf successions, pure siliciclastic event beds are common whereas bioclastic event beds are rare, as are bioclastic turbidites in the slope to basinal successions (Butt, 1980; Wagneich and Faupl, 1994). Despite regressive carbonate shelf development in vertical section, within each time-slice deposition of more or less pure shallow-water carbonates thus was confined to the actual inner shelf to lagoonal to tidal flat area, while on the contemporaneous mid- to outer shelf the accommodation space was filled mainly by fine siliciclastic sand, silt and mud.

The described relations between corals and rudists do not support the hypothesis of Kauffman and Johnson (1988) on a competitive replacement of Late Cretaceous corals by rudists, but support the ‘coexistence hypothesis’ of Scott (1988, 1995) that the Late Cretaceous rudists and corals could co-occur in the same bioconstruction, over a wide range of environmental overlap (see also Sanders and Baron-Szabo, 1997; Skelton et al., 1997). Because the Late Cretaceous rudists, however, could also colonize environments inaccessible to scleractinians, for instance lagoonal areas with high input of siliciclastics and/or nutrients, an inevitable result is a larger number of rudist formations and a smaller number of coral–rudist formations (Sanders, 1998b).

8. Summary

The upper Turonian to lower Campanian (Lower Gosau Subgroup) of the Northern Calcareous Alps provides a model for the development of rudist formations on wave-dominated, narrow shelves with mixed siliciclastic-carbonate deposition. These shelves were situated on top of the Eo-Alpine accretionary wedge that, during the Late Cretaceous, was partly emergent and underwent extension and strike-slip faulting. The immediate hinterland of the shelves was an exposed carbonate rock terrain that nourished fan deltas. The fan deltas coexisted with siliciclastic river deltas that were fed by rivers which drained the more internal part of the accretionary wedge. Along coastal sectors of low siliciclastic input, rocky coasts and gravelly carbonate beaches existed. The articu-

lated pattern of pre-existing morphology, siliciclastic input and local clastic input, and mixed siliciclastic-carbonate sequence development gave rise to wide variations in the stratigraphic context and facies development of the rudist formations.

In the investigated succession, (a) skeletal mounds a few meters to more than 20 m thick composed of corals, rudists and, locally, skeletal sponges, and (b) rudist biostromes are present. The coral–rudist mounds and the rudist biostromes developed whenever sediment accumulation (particularly siliciclastic input) was lowered for some interval of time, where a stable substrate with enough settlement sites was provided or could be developed by successive colonization, and where mean water energy was in the proper range to allow for sustainment of the bioconstructions.

In siliciclastic-dominated depositional sequences, both in the transgressive and in the highstand systems tract, respectively, coral–rudist mounds and rudist biostromes locally accumulated during phases of reduced siliciclastic input in open lagoons and in the shoreface to inner shelf environment. Transgressive successions from rocky coasts consist of a basal interval of cliff talus breccias and calcilitic arenites, locally overlain by coral–rudist mounds and/or by rudist biostromes with associated bioclastic limestones. Locally, the highstand systems tracts consist of a carbonate shelf succession composed of stacked upward shoaling cycles that up-section become both successively thinner and record an overall shoaling of depositional water depth. The lower part of the regressive carbonate shelf successions consists of coral–rudist mounds and/or hippuritid biostromes, and bioclastic limestones; the upper part is dominated by bioclastic limestones and radiolitid biostromes. Carbonate shelf deposition was confined to the inner shelf to tidal flat environment, whereas on the contemporaneous mid- to outer shelf siliciclastics were deposited.

In coral–rudist mounds, hippuritids, radiolitids and *Plagioptychus* always were present, but the coral-dominated habitat was not accessible to dense rudist colonization. The coral–rudist mounds commonly are topped by a hippuritid biostrome. The rudist biostromes are subdivided into hippuritid biostromes, radiolitid biostromes and ‘composite biostromes’ with a vertical succession from hip-

puritids to radiolitids. Monospecific rudist thickets appear to consist of a single generation of rudists. In thicker biostromes, a single rudist species typically is most abundant, but other hippuritaceans (hippuritids, radiolitids, *Plagioptychus*, caprotinids, requienids, monopleurids) and accessory taxa (bryozoans, brachiopods, echinoderms, non-rudist bivalves) are present.

In autochthonous rudist fabrics, the absence or paucity of both bioturbation and non-rudist fossils indicate that the trophic structure was different from that of adjacent environments, where both bioturbation and non-rudist fossils are abundant. In parautochthonous rudist fabrics, bioturbation and a diversified taphocoenosis suggest that during biostrome accumulation the substrate was colonized at least intermittently by a diverse biota, including burrowers. Autochthonous rudist fabrics and parautochthonous rudist fabrics are quite different with respect to their trophic structure and biostratigraphy, but are linked by events of community destruction. The accumulation of the rudist biostromes was mainly influenced by toppling and fragmentation of rudists during high-energy events and by burrowing. The rudist biostromes were terminated either by frequent toppling and fragmentation of rudists (‘fragmentation termination’), by burial with sediment (‘burial termination’), or by environmental restriction (‘restriction termination’). Both hippuritids and radiolitids could colonize and persist in siliciclastic depositional environments. Overall, however, there is a clear-cut positive correlation between presence/abundance of rudists and intervals of shallow-water limestones. As the Late Cretaceous rudists could thrive both together with hermatypic corals as well as in environments unaccessible to the latter, a larger number of rudist formations and a smaller number of coral–rudist formations results.

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