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Carbonate deposition in mixed siliciclastic–carbonate environments on top of an orogenic wedge (Late Cretaceous, Northern Calcareous Alps, Austria)

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Abstract

In the Middle Turonian to Lower Campanian (Lower Gosau Subgroup; LGS) of the Northern Calcareous Alps, Austria, in the highstand systems tract of mixed siliciclastic–carbonate depositional sequences, small carbonate shelves locally developed that were mainly controlled by a differentiated morphology of the substratum and siliciclastic input onto a storm-dominated shelf.

The LGS was deposited above thrust nappes of the Alpine orogen. The transgressive systems tracts of depositional sequences consist of local fan delta or fluvial deposits, overlain by a succession mainly of siliciclastics that records deepening from paralic to outer shelf environments. Locally, rudist biostromes and coral–rudist mounds accumulated in lagoonal/bay to inner shelf environments, but were buried by paralic siliciclastics. Along coastal sectors of low siliciclastic input, because of a high-relief truncation surface at the base of the LGS, the transgressive systems tracts consist of an upward-deepening succession of clastic carbonates deposited from gravelly to rocky carbonate shores. The highstand systems tracts are dominated by siliciclastics, and record shoaling to inner shelf depths and, near the basin margins, to lagoonal to marsh environments. During highstand conditions, delta progradation combined with shoreline compartmentalization by headlands locally led to establishment of inner shelf compartments of low siliciclastic input. In these compartments, carbonate shelves developed. Along strike, the carbonate shelves were up to more than 10 km in length (beyond limits of larger outcrops), and about 1 km to, possibly, 10 km wide down dip. The carbonate shelves consisted of (a) an inner shelf belt with coral–rudist mounds, rudist biostromes and bioclastic sand bodies, (b) a dissipative shore zone of bioclastic sand bodies, (c) open lagoons/bays with radiolitid biostromes, and (d) narrow, micro-tidal flats or lithoclastic/bioclastic beaches. Up-section, inner shelf to shore zone carbonate parasequence tracts consist of a coral–rudist mound, a rudist biostrome, and of shore zone bioclastic limestones. Parasequence tracts deposited in lagoons/bays commonly shoaled incompletely, and mainly consist of more-or-less marly limestones deposited in shallow subtidal environments with radiolitid biostromes, substrata of bioclastic sand or lime mud, and with local mass accumulations of gastropods or of epibenthic non-rudist bivalves.

The carbonate shelf successions are up to 100 m thick and, in vertical section, consist of stacked parasequence tracts that become thinner up-section and record a shoaling of mean depositional water depth. Carbonate deposition was confined to the actual inner shelf to tidal flat/beach compartment. Down dip, the coral–rudist mounds scattered along the seaward fringe of the carbonate shelves graded into small haloes composed mainly of disoriented, fragmented rudists and corals. Larger carbonate slope depositional systems were not individuated, and the carbonate shelves interfingered with and pinched out into inner shelf siliciclastics. The development of larger carbonate slopes was prevented by the low relief of the coral–rudist mounds, combined

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with high input and effective dispersal of siliciclastics ahead. Carbonate shelf progradation over a possible distance of up to a few kilometres was linked with aggradation of shelf siliciclastics.

Keywords: Alps; Cretaceous; Carbonates; Rudists; Sequence stratigraphy; Tethys

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1. Introduction

Both the facies and stratigraphical development of carbonate shelves largely result from the ecological needs of the carbonate-secreting biota which, in turn, is controlled mainly by sea-level change, input of siliciclastics and nutrients, and marine climate (e.g. Schlanger and Konishi, 1975; Wilson, 1975; Schlager, 1981; Hallock and Schlager, 1986; Handford and Loucks, 1993). In mixed siliciclastic–carbonate successions, as a result of the mentioned controls the carbonate intervals exhibit a broad range of lateral extent, thickness and facies. Successions from wide shelves with either reciprocal or mixed siliciclastic–carbonate deposition are comparatively well-known (e.g. Wilson, 1975; Walker et al., 1983; Driese and Dott, 1984; Simo, 1993; Southgate et al., 1993). In the Holocene, however, small carbonate depositional systems surrounded by shelf siliciclastics are widespread (e.g. Schneidermann et al., 1976; Beach, 1983; Morelock et al., 1983; Harris et al., 1996; Guozhong, 1998; Woolfe and Larcombe, 1998), but are little documented from the geological record (Coates, 1977; Luttrell, 1977; Watkins, 1993). Because of both their small size and the close association with clastics, these carbonate depositional systems show distinct facies architectures and styles of stratigraphical development.

In the Upper Cretaceous of the Northern Calcareous Alps, mixed siliciclastic–carbonate successions with diverse rudist formations are present (Fig. 1) (Sanders and Pons, 1999). The limestones within these successions accumulated from small carbonate

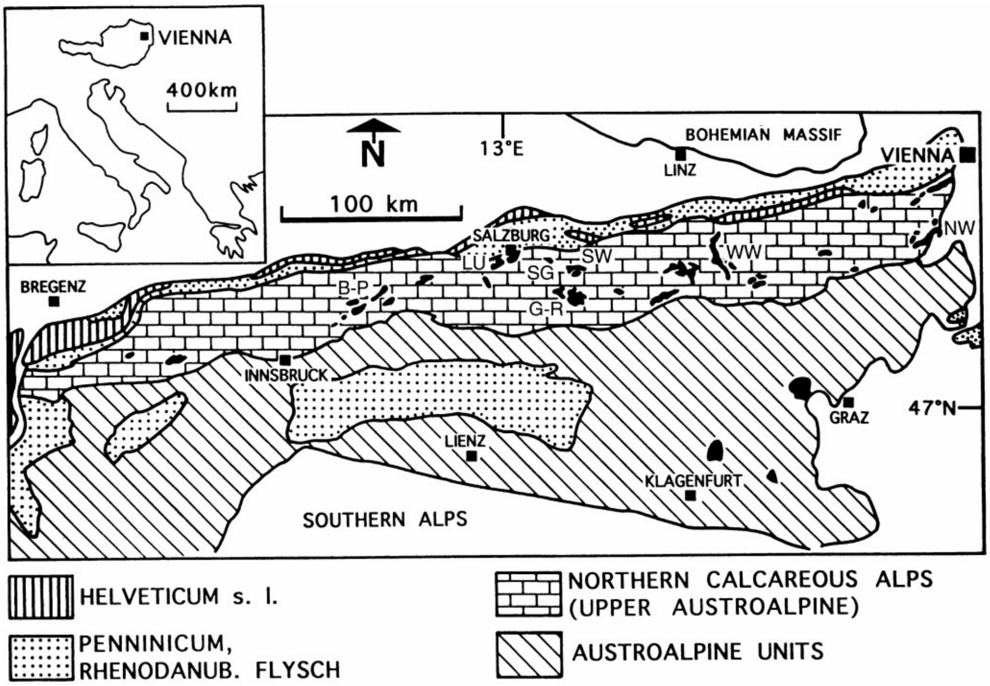

Fig. 1. The Northern Calcareous Alps consist of stacked, detached cover thrust nappes dominated by Triassic–Jurassic carbonates. Upper Cretaceous outcrops (black) with thicker intervals of shallow-water limestones are lettered. B-P: Brandenberg–Pendling; G-R: Gosau–Rigaus; LU: Lattenberg–Untersberg; NW: Neue Welt (Grünbach); SG: Sankt Gilgen; SW: Strobler Weissenbachtal; WW: Weisswasser.

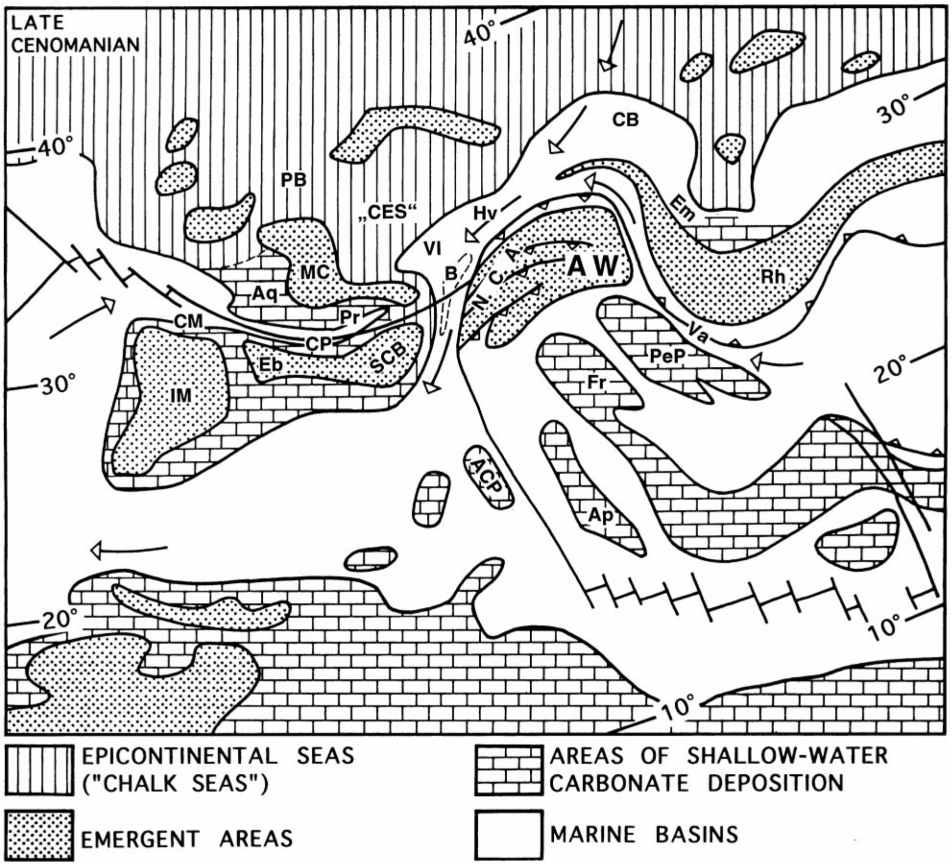

Fig. 2. (Simplified from Philip et al., 1993.) During the Late Cretaceous, the area of the Northern Calcareous Alps (NCA) was situated at the northern fringe of the Alpine accretionary wedge (AW), along the narrow "north-tethyan" seaway. Arrows indicate possible directions of oceanic surface currents (partly from Philip et al., 1993). ACP = Apennine carbonate platform; Ap = Apulian carbonate platform; Aq = Aquitaine shelf; B = Brianconnais submarine high; CB = Carpathian flysch basin; "CES" = Central European Chalk Sea; CM = Cantabrian Mountains; CP = Central Pyrenees; Eb = Ebro Massif; Em = Emine Trough; Fr = Friuli platform; Hv = Helvetic Zone; IM = Iberian Massif; MC = Massif Central; PB = Paris Basin; PeP = Pelagonian carbonate platform; Pr = Provence area; Rh = Rhodope Massif; SCB = Sardo-Corsian Block; VI = Valais Trough.

depositional systems adjacent to shelf siliciclastics (Sanders et al., 1997). Despite their local thickness of up to 100 m, these limestone successions went practically undescribed throughout the geological investigation of the Alps. Because of tectonic deformation and Alpine outcrop conditions, the large-scale facies architecture of the carbonate depositional systems and their relation to laterally equivalent strata are not visible in outcrop, but must be reconstructed from integrated field mapping, estimates of later tectonic shortening, facies analysis and biostratigraphy. In the present paper, the facies inventory, facies architecture and stratigraphical development of the carbonate successions are described and integrated into a model. With respect to their small size and the close control, in space and time, by siliciclastic input and dispersal, the reconstructed Late Cretaceous carbonate depositional system is comparable with small reefal to peri-reefal depositional systems in Holocene mixed siliciclastic–carbonate environments along active margins.

2. Geological setting

During Jurassic times, the area of the Northern

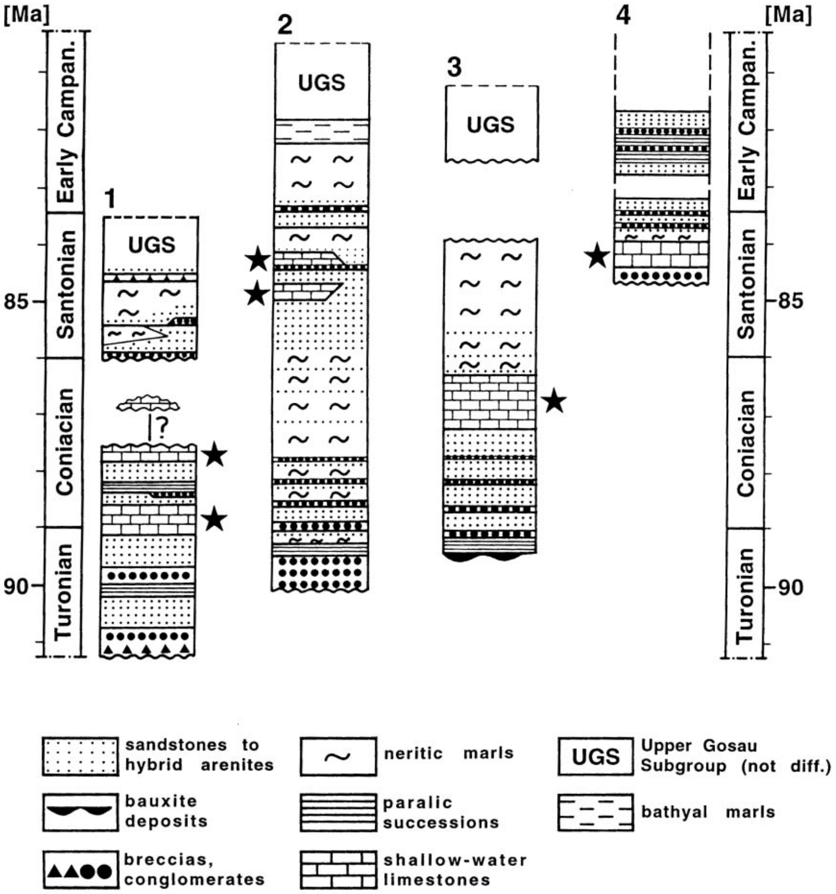

Fig. 3. Summary sections of the Lower Gosau Subgroup, with major intervals of shallow-water limestones indicated by stars (time-scale of Gradstein et al., 1995). Only major hiatuses are indicated. 1 = Brandenberg. 2 = Gosau. 3 = Weisswasser. 4 = Grünbach. Based on Wagreich and Faupl (1994), Höfling (1997), and Sanders (1998).

Calcareous Alps was part of the Austroalpine microplate (Channell et al., 1990). During the latest Jurassic to Early Cretaceous Eo-Alpine convergence, in the area of the Northern Alps, a stack of detached sedimentary cover nappes formed (Fig. 1). Subsequently, large parts of the Eo-Alpine orogen were exhumed and subaerially eroded (Fig. 2) (Ratschbacher et al., 1989; Froitzheim et al., 1994, 1997). In the Northern Calcareous Alps, subaerial erosion produced a truncation surface with a differentiated relief cut mainly into Triassic to Jurassic carbonate rocks. During the Late Cretaceous, the area of the Northern Alps was situated at 30–32° north, and faced the deep "north-tethyan seaway" that was connected to the central tethyan realm by narrow straits (Fig. 2) (Camoin et al., 1993; Philip et al., 1993).

From Turonian to Santonian times, in the formerly exposed areas, deposition of an Upper Cretaceous to Eocene succession (Gosau Group) started in depocenters that probably originated by extension and strike-slip (Ratschbacher et al., 1989; Wagreich and Faupl, 1994; Neubauer et al., 1995). The Gosau Group is subdivided into the Lower Gosau Subgroup that consists of terrestrial to deep neritic deposits and the Upper Gosau Subgroup made up by deposits from bathyal to abyssal environments (Fig. 3). During Gosau deposition, siliciclastic rivers co-existed with carbonate–clastic fan deltas that were fed from

Table 1
Common carbonate facies in the Lower Gosau Subgroup (Northern Calcareous Alps)

Facies	Description	Thickness	Typical fossils	Interpretation
Coral–rudist-sponge limestones	Floatstones to bafflestones to boundstones of corals, rudists, skeletal sponges	Up to more than 20 m thick, hundreds of metres wide, sheeted to mounded	Fungiina, Stylinina Stromatoporoidea *Vaccinites* spp. *Hippurites* spp. Radiolitidae	Mounds built by corals, rudists and skeletal sponges
Rudist limestones	Floatstones to bafflestones to boundstones of rudists	Sheets 10 cm to more than 10 m thick, tens to hundreds of metres wide	*Vaccinites* spp. *Hippurites* spp. *Radiolites* spp. *Durania*	Rudist biostromes
Bioclastic floatstones to rudstones	Poorly sorted angular bioclasts, shelter pores	Up to a few dm thick	Coarsely fragmented and toppled rudists and corals	Deposition during high-energy events
	Winnowed rudstones of well-rounded bioclasts	Up to more than 1 m thick	Fragments from rudists, corals, gastropods	Deposition close to/within wave base
	Floatstone to rudstone of nerineid shells	Sheets 10 cm to 1.5 m thick, hundreds of metres wide	*Simploptyxis*	Mass accumulation of nerineids
Bioclastic grainstones to packstones	Fragments from rudists, echinoderms, calcareous algae, bryozoans. Benthic foraminifera, peloids	Few dm to 15 m thick. Locally thickening-coarsening packages from bioturb. Biocl. pkst. at base to parallel-laminated biocl. grst./rudst. at top	Miliolidae, Lituolacea Ataxophragmiacea Nezzazatidae *Moncharmontia Trochactaeon*	Open lagoon to inner shelf. Thickening-coarsening packages: carbonate sand bodies topped by dissipative beach
Bioclastic wackestones to packstones	Partly micritized fragments from molluscs, echinoderms, calcareous green algae. Benthic foraminifera, peloids.	Up to a few metres thick	*Quinqueloculina Cuneolina* Lituolidae Haplophragmidae *Permocalculus Neomeris Boueina*	Lagoon
Foraminiferal/peloidal wackestones to packstones	Benthic foraminifera, peloids, calcareous green algae. Locally organic-rich, plant fossils	Few dm thick	*Quinqueloculina Cuneolina* Textulariina *Boueina*	Lagoon, intermittently slightly restricted
Bioclastic–siliciclastic shelfal siltstones	Microbioclasts, siliciclastic silt, clay. Solitary corals, non-rudist molluscs, benthic foraminifera. With beds of hummocky cross-laminated sandstone	Few metres to tens of metres thick	*Nummofallotia Quinqueloculina* Rotaliina, Lagenina Neritidae, Naticidae Aporrhaidae	Storm-influenced inner shelf

Table 1 (*continued*)

Facies	Description	Thickness	Typical fossils	Interpretation
Bioclastic–siliciclastic lagoonal siltstones	Shallow-water bioclasts to microbioclasts, siliciclastic silt, clay. Benthic foraminifera, bryozoans, echinoderms, serpulids.	Up to a few metres thick	Miliolidae *Cuneolina Moncharmontia Phelopteria*	Lagoon with siliciclastic input
Clastic carbonates	Breccias to megabreccias with calcilithic/ bioclastic matrix.	Few dm to 10 m thick. Thickness laterally highly variable	Few. Corals, rudists, skeletal sponges, gastropods	Cliff talus breccias (high-energy shore), beachface breccias (low-energy shore) along transgressive shore
	Conglomerates of well-rounded gravels to small boulders.	Up to 10 m thick. Thickness laterally highly variable	Very rare. Small fragments from rudists, corals, gastropods.	Beachface conglomerates along transgressive shore
	Calcilithic/bioclastic arenites. Low-angle cross-lamination, cross-lamination, hummocky cross-lamination. Locally intervals of shoreface conglomerate	Few metres to tens of metres thick	Few. Disoriented and fragmented rudists, corals, skeletal sponges, gastropods.	Foreshore to inner shelf deposits along transgressive shore. Shoreface conglomerates deposited during high-energy events

catchment basins within the Northern Calcareous Alps (Wagreich and Faupl, 1994). The Lower Gosau Subgroup consists of allostratigraphic units that were interpreted as parts of depositional sequences. The sequences record two distinct types of shelf. “Type A” shelves were characterized by mixed siliciclastic–carbonatic deposition. In areas of low clastic input, coral–rudist buildups, bioclastic dunes and carbonate lagoons were present. “Type B” shelves consisted of rocky to gravelly shores and a narrow shallow neritic facies tract that dipped to a deep, muddy shelf. Type B shelf deposition was predated by truncation and accompanied by faulting, and prevailed during the deepening that led to deposition of the Upper Gosau Subgroup (cf. Sanders, 1998). The carbonate successions described in the present paper all were deposited from type A shelves.

3. Sedimentary facies

3.1. Coral–rudist–sponge limestones

Marly to pure limestones with hermatypic corals, rudists and, locally, skeletal sponges build sheets to gentle mounds a few metres to more than 20 m thick (see Table 1). No lithologies indicating steep-sided build-ups nor steep clinostratification were observed. These limestones were deposited from skeletal mounds in a shallow neritic environment of moderate to episodically high water energy (Sanders and Baron-Szabo, 1997). The coral fauna is dominated by hemispherical, columnar and lamellar-encrusting growth forms. The coral polyparia commonly show a thamnasterioid, plocoid or stylinid arrangement, suggesting soft substrata and sediment stress (Baron-Szabo, 1997). From the rudists, hippuritids are dominant both with respect to abundance and size. Radiolitids typically are small. A few *Plagioptychus* are always present. Encrusters were red algae, sponges, corals, foraminifera, bryozoans and serpulids. The matrix typically is a poorly sorted bioclastic wackestone to packstone. Locally, the matrix of coral–sponge–rudist floatstones is a microbialite composed of laminated, microfenestral, micropeloidal packstone to grainstone, or cauliflower-like laminated lime mudstone (Sanders and Pons, 1999).

The most spectacular Upper Cretaceous (Upper Turonian-Coniacian) scleractinian reef of the Eastern Alps is an interval about 30 m thick of coral boundstone to rudstone that is exposed over about 600 m. The boundstone consists mainly of lamellar-encrusting and hemispherical, thamnasterioid and plocoid corals up to more than a metre in size. The coral assemblage is dominated by Microsolenina, Fungiina and Heterocoeniina. Sizeable rudists are accessory, and occur as isolated specimens and clusters of *Vaccinites*, and a few *Plagioptychus* and radiolitids. The coral limestone is overlain by an interval a few metres thick of bioclastic packstones to grainstones (Sanders et al., 1999).

3.2. Rudist limestones

These were deposited from biostromes tens to hundreds of metres in lateral extent, between the limits of typical Alpine outcrops. Across and along the biostromes, decimetre- to metre-scale vertical and lateral changes in both rudist fabric and biostratinomy are common. Three types of biostromes are distinguished: (a) hippuritid biostromes; (b) radiolitid biostromes, and (c) “composite biostromes” of a hippuritid biostrome overlain by a radiolitid biostrome. The hippuritid biostromes accumulated in inner shelf to deeper, open lagoonal environments, whereas radiolitid biostromes characterized lagoons. The composite biostromes possibly represent a shoaling succession. The elevator rudists, particularly radiolitids, are locally associated with nerineids and/or actaeonellids within intervals of rudist–gastropod rudstone to floatstone. Locally, intervals of nerineid rudstone are directly overlain by a radiolitid biostrome. The gastropod shells provided a settling substratum for the rudists (Herm and Schenk, 1971). The diversity spectrum of the rudist fauna is dominated by hippuritids. Radiolitids are less diverse. Locally *Plagioptychus*, caprotinids and requienids are accessory to the rudist assemblage (Pons and Sanders, 1999).

3.3. Bioclastic floatstones to rudstones

Intervals of rudstone composed of very poorly sorted, angular, unmicritized bioclasts mainly from rudists and corals accumulated during high-energy events. Some of the disoriented rudists are embedded with the free valve in place, even if their lower valve is coarsely fragmented. Shelter pores are present below larger bioclasts. Close to or within fairweather wave base, winnowed rudstones of moderately to very well-sorted, well-rounded bioclastic gravels derived from rudist shells, corals, corallines, and echinoderms were deposited. Locally, the components bear thin fringes of isopachous cement, or are coated by irregular fringes to pore-filling masses of micritic cement. In open, shallow lagoons with a substrate of lime-muddy sand to lime mud, intervals up to 1.5 m thick of floatstone to rudstone of nerineid shells accumulated. The shells typically are abraded, fragmented, and bored. The matrix is a bioclastic wackestone that may contain small radiolitids and hippuritids, benthic foraminifera, and fragments from calcareous green algae.

3.4. Bioclastic grainstones to packstones

These consist mainly of micrite-rimmed fragments from rudists, unidentifiable biodetritus and a low, persistent content of benthic foraminifera, fragments from echinoderms, bryozoans, calcareous algae and, locally, a few percent of siliciclastic sand. In their lower part, bedsets up to about 15 m thick consist of marly, bioturbated, fine to medium sand bioclastic packstone; the upper part is built by increasingly thicker, gently wavy to plane beds of bioclastic grainstone to winnowed rudstone with crude subparallel-horizontal lamination. These bedsets were deposited from carbonate sand bodies topped by a dissipative beach. In open lagoons, intervals up to a few metres thick of nodular to wavy bedded, bioturbated grainstones to packstones accumulated. At the crest of coral–rudist mounds, bioclastic grainstone was locally deposited that may show inclined cross-lamination and subparallel-horizontal lamination. Locally, directly below coral–rudist–sponge mounds, a transgressive lag is present that consists of poorly sorted bioclastic grainstone to packstone to floatstone of heavily micritized, bored and encrusted fragments mainly from corals, rudists, red algae, calcareous green algae, echinoderms and gastropods. The crusts on the bioclasts typically consist of corallines, sessile foraminifera and microbialites.

3.5. Bioclastic wackestones to packstones

These are poorly sorted, bioturbated, and contain variable relative amounts of micrite-rimmed fragments from rudists, echinoderms, calcareous green algae, branched corallines, gastropods, sponges, bryozoans and brachiopods, benthic foraminifera, peloids and coalified plant fragments. These limestones accumulated in quiet, shallow subtidal environments, probably lagoons and sheltered bays. Another, volumetrically insignificant facies is represented by very poorly sorted wackestones to packstones rich in both micrite-rimmed and blackened bioclasts and intraclasts. The black pebble limestones formed in an inter- to supratidal environment.

3.6. Foraminiferal/peloidal wackestones to packstones

These limestones are more or less marly, and were deposited in shallow, possibly slightly restricted lagoons. The foraminiferal assemblage is characterized by miliolids, *Cuneolina*, and small textulariines. Locally, fragments from calcareous green algae are common. In areas of high input of particulate organic matter, upon dysaerobic to anaerobic conditions below the sediment–water interface, organic-rich wackestones to packstones with plant leaves and coalified wood clasts formed.

3.7. Bioclastic–siliciclastic shelfal siltstones

These are texturally floatstones to wackestones with a matrix of microbioclastic material, siliciclastic silt and clay. Fossils and larger bioclasts include solitary corals, non-rudist bivalves, gastropods, echinoids and a distinct foraminiferal assemblage (see Table 1). Trace fossils from the *Glossifungites–Cruziana* association are characteristic. This facies is locally intercalated with beds of parallel-laminated to hummocky cross-laminated, fine to medium sandstone. The siltstones accumulated in a storm-influenced inner shelf environment.

3.8. Bioclastic–siliciclastic lagoonal siltstones

Texturally, these are bioclastic wackestones to floatstones with a matrix of microbioclastic material, siliciclastic silt and clay. The bioclasts include fragments from rudists and/or from non-rudist bivalves, bryozoans, echinoderms, serpulids, corallines, calcareous green algae, gastropods, and benthic

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

foraminifera. Locally, this lithofacies contains small inoceramids and abundant pterioids (*Phelopteria*), and/or abundant small trochids and cerithiaceans. These siltstones accumulated in overall quiet, high-nutrient lagoonal areas with siliciclastic input. Locally, thin beds of bioclastic packstone to grainstone rich in debris from rudists are intercalated that probably were deposited during high-energy events.

3.9. Clastic carbonates

In the Lower Gosau Subgroup, clastic carbonates deposited upon transgression are common. Cliff talus consists of thick-bedded to "massive", extremely poorly sorted, clast-supported breccias to megabreccias of clasts up to about a metre in size that are derived from the local substratum. The matrix ranges from mixed calcilithic/bioclastic calcarenite to

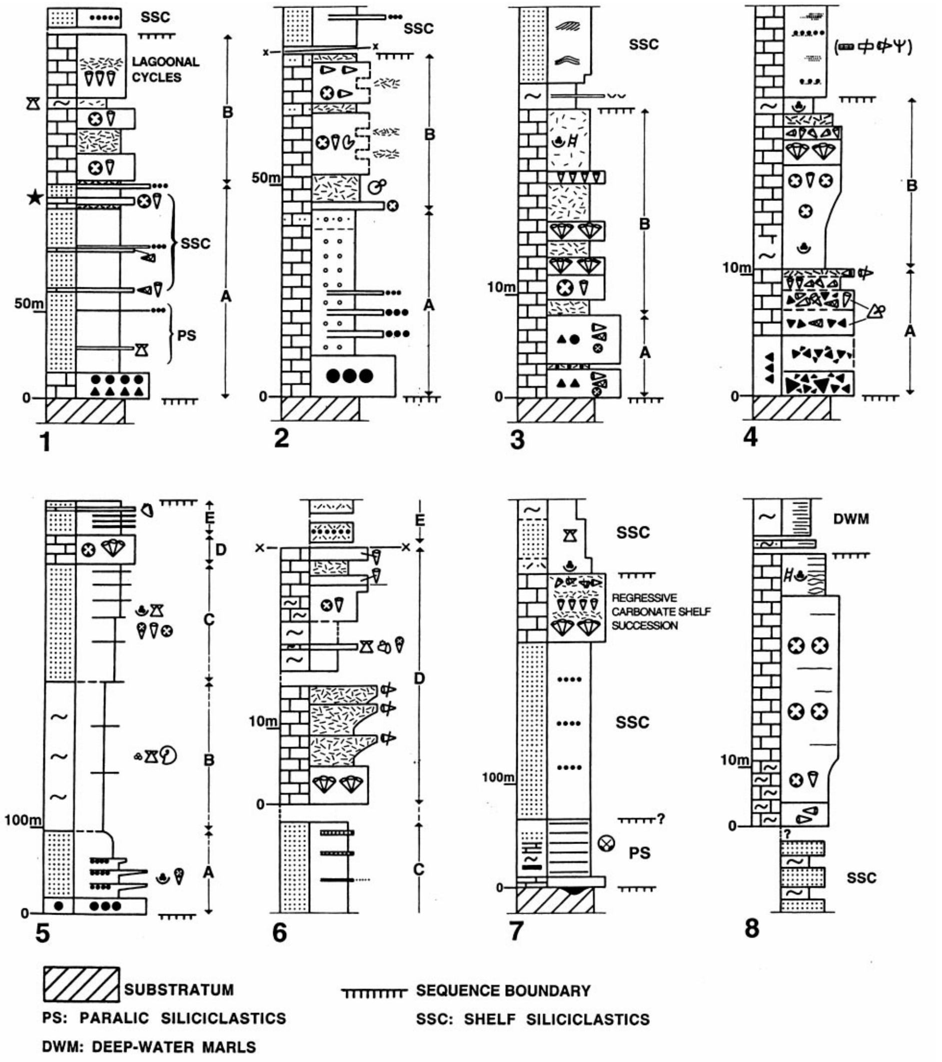

Fig. 5. Examples of carbonate successions (see Fig. 1 for locations). 1: Brandenberg. Transgressive (A) paralic/shelf siliciclastics, coral–rudist mound (asterisk). Regressive (B): coral–rudist mounds, rudist biostromes, bioclastic limestones. 2: Brandenberg. Transgressive (A): beachface conglomerate, marine calcilithic arenites. Regressive (B): coral–rudist mound, bioclastic limestones. 3: Brandenberg. Transgressive (A): cliff talus breccia. Regressive (B): coral–rudist mound, hippuritid biostrome, radiolitid biostome, bioclastic limestones. 4: Lattenberg. Interval A: subaerial breccia, beachface breccia, radiolitid biostrome. Interval B: coral–rudist limestone, rudist biostrome, bioclastic limestone, lagoonal marl. 5: Gosau, (Coniacian–Santonian). Transgressive (A): fan delta deposits, shelf siliciclastics, outer shelf marls (B). Regressive (C–E): shelf siliciclastics (C), with “coral–rudist marls”. D: shallow-water limestones. E: paralic arenites, shoreface conglomerates, actaeonellid beds. 6: Details from section 5. 7: Weisswasser (sequence boundaries tentative). Up-section: bauxite and paralic succession, shelf siliciclastics and regressive carbonate shelf succession. Carbonates ?unconformably overlain by shelf arenites to silstones, and marls. 8: Strobler Weissenbachtal. Shelf siliciclastics, overlain by coral reef, covered by bioclastic limestones. Limestones are overlain by bathyal marls.

red-weathering, shallow-water bioclastic wackestone. A few disoriented coral heads, rudists, nerineids, actaeonellids and brachiopods are typically present. Many clasts are penetrated by *Trypanites*. Along transgressive low-energy shores, beachface breccias locally accumulated that are overlain by lagoonal limestones (Fig. 4; section 4, Fig. 5). Beachface conglomerates, by contrast, typically show

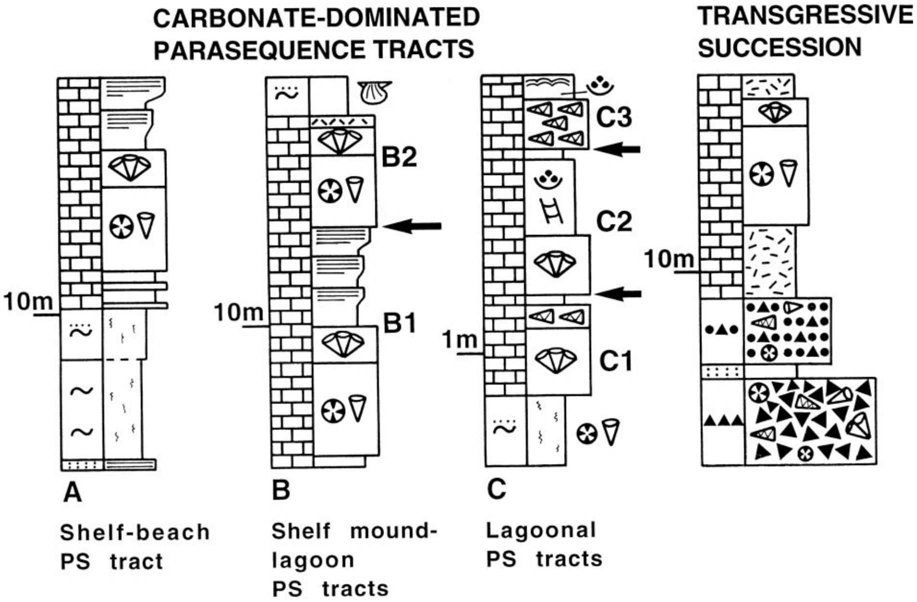

Fig. 6. Carbonate-dominated parasequence (PS) tracts. See text for description.

subparallel-horizontal bedding, low-angle cross-stratification, or cross-stratification. They consist of very well-rounded fine gravels to small boulders of carbonate rocks, contain a scarce matrix of calcilithic arenite to siltite, and are very poor in bioclasts from marine fossils. Cross-laminated calcilithic/shallow-water bioclastic arenites represent another transgressive carbonate facies. The arenites were deposited in a foreshore to shoreface environment, and contain intercalated shoreface conglomerates composed of carbonate rock clasts and a few fragmented and abraded, larger fossil fragments (Höfling, 1985, 1997; Sanders, 1998).

4. Stratal packages

The described facies are arranged into stratal packages that, from bottom to top, record either a shoaling or a deepening of depositional water depth (Fig. 6). The stratal packages that record an upward shoaling fit the definition of parasequence (cf. Van Wagoner et al., 1988; Sanders et al., 1997). In the investigated Alpine outcrops, only part of the full lateral extent, i.e. a tract of each parasequence is exposed.

4.1. Shelf-beach parasequence tracts

These consist, in their lower part, of bioclastic–siliciclastic shelfal siltstones that grade up-section into marly floatstones with corals and rudists which, in turn, are overlain by a coral–rudist mound (Fig. 6A; e.g. section 4, Fig. 5; upper part of section 6, Fig. 5). The upper part consists of a rudist biostrome and, at the top, of a single or several thickening/coarsening packages deposited from carbonate sand bodies (see chapter 3). At one location, an interval of coral reef limestone overlain by bioclastic packstones to grainstones (section 8, Fig. 5) may represent the upper part of an incompletely exposed shelf-beach parasequence tract.

4.2. Shelf mound-lagoon parasequence tracts

These contain a coral–rudist mound or a rudist biostrome at their base (Fig. 6; e.g. lower part of interval B in section 1, Fig. 5; lower part of interval D in section 6, Fig. 5). The coral–rudist mound is topped by a hippuritid biostrome which, in turn, is overlain by bioclastic packstones to grainstones. The bioclastic limestones are locally arranged in upward thickening/coarsening packages (B 1, Fig. 6). The sand

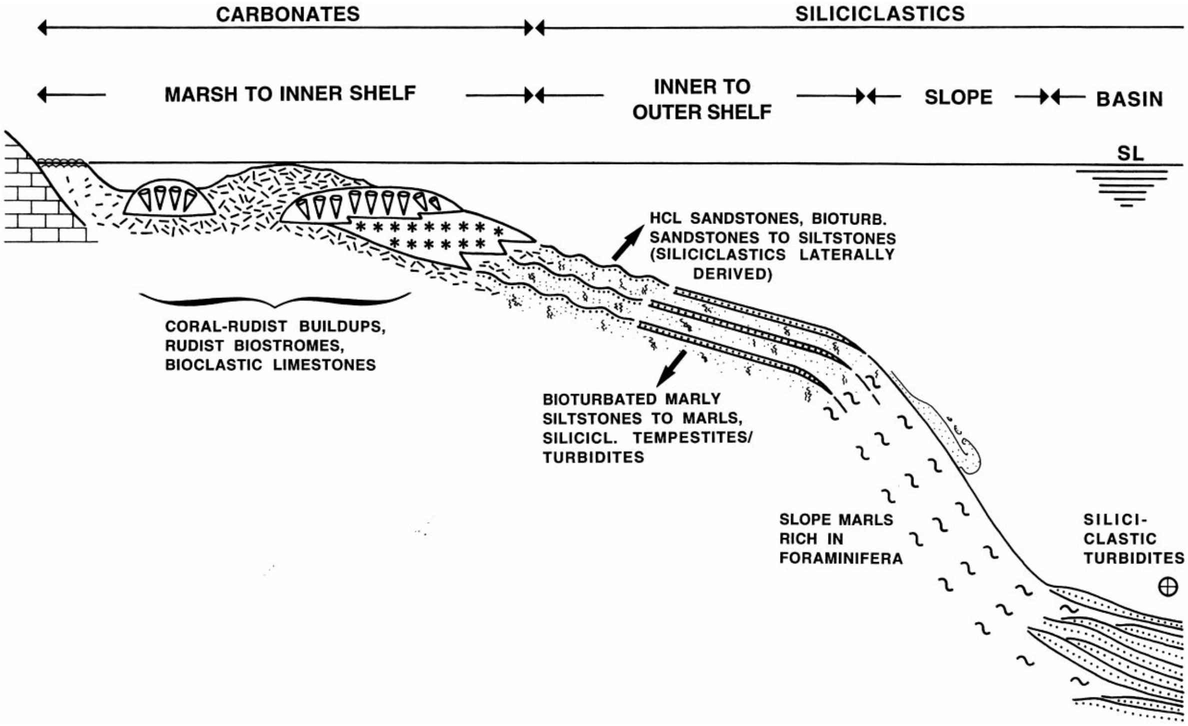

Fig. 7. Reconstruction of Late Cretaceous mixed siliciclastic–carbonate shelf (not to scale). From lagoon to inner shelf, lime mud, rudist biostromes, bioclastic sand and skeletal mounds accumulated. Farther seaward, bioclastic–siliciclastic shelfal siltstone, hummocky cross-laminated sand and bioturbated sand to silt were deposited. The siliciclastics were laterally derived, by dispersal on a storm-dominated shelf. On the outer shelf silt, silty to clayey carbonate ooze, and siliciclastic event beds accumulated. Slope deposits were clayey carbonate ooze rich in planktic foraminifera. Near the base of slope and in the basin, deposition of turbiditic sands (shed laterally and/or axially), of clayey carbonate ooze or of clay prevailed.

bodies migrated over and buried the coral–rudist mound/biostrome ensemble, but probably represented also a lateral equivalent to the buildups. Alternatively, the biostrome above a coral–rudist mound is overlain by a relatively thin interval of poorly sorted packstone to grainstone to rudstone mainly of rudist fragments (B 2, Fig. 6). The bioclastic limestone, in turn, is overlain by an interval of bioclastic–siliciclastic lagoonal siltstones. The described two subtypes of parasequence tract may succeed each other in vertical succession (lower part of interval B in section 1, Fig. 5).

4.3. Lagoonal parasequence tracts

These are a few decimetres to a few metres thick. In some parasequence tracts, the lower part consists of sandy marls to marly limestones with a few coral heads, branched corals, *Plagioptychus*, miliolines and textulariines. (C 1, Fig. 6). Most commonly, the lower part of lagoonal parasequence tracts consists of a hippuritid biostrome or a radiolitid biostrome (C 2, Fig. 6), of floatstones with corals, rudists and skeletal sponges, or of an interval of nerineid limestone (C 3, Fig. 6). The upper part consists of bioclastic packstones to wackestones or, less commonly, of foraminiferal/peloidal wackestone to packstone. Rarely, the topmost part consists of marly, organic-rich black pebble limestone that was deposited in an inter- to supratidal environment. Most lagoonal parasequence tracts, however, shoaled incompletely.

4.4. Transgressive successions

Successions deposited from transgressive shores are based by an interval of clastic carbonate rocks as

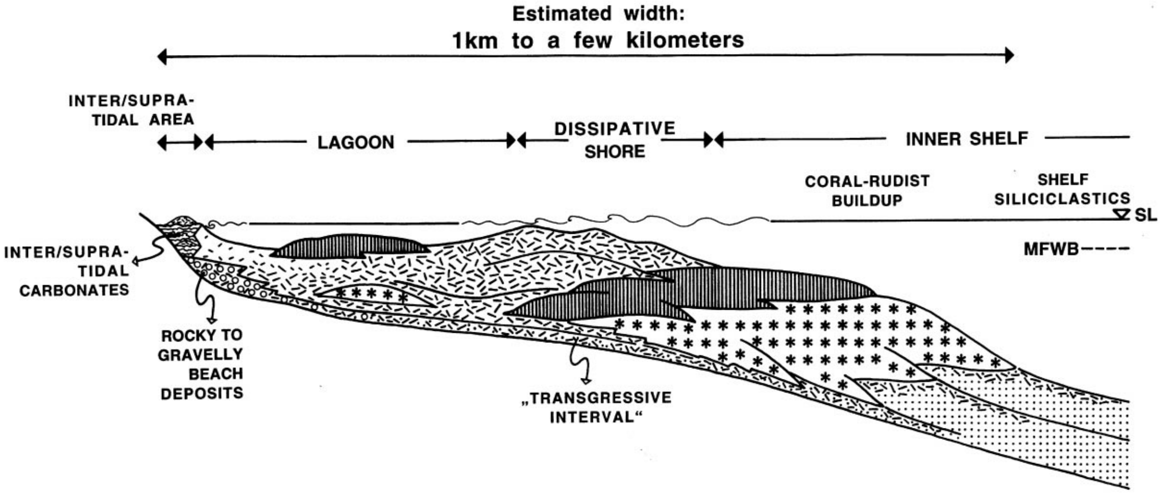

Fig. 8. Reconstruction of carbonate shelf (MFWB = mean fairweather wave base). At the base, a “transgressive interval” of reworked bioclasts is locally present. The landward end of the shelf is built by beaches and/or narrow, micro-tidal flats. In the open lagoon radiolitid biostromes, thin coral–sponge–rudist mounds, and muddy bioclastic sand to sandy lime mud with benthic foraminifera and calcareous green algae accumulated. Towards the sea, bioclastic sand bodies, rudist biostromes and skeletal mounds (corals, rudists) were present. The sand bodies occupied a dissipative shore zone near the crest of the mounds, and were lateral equivalents to the mounds. At their down-dip end, the coral–rudist mounds pinched out into shelfal siltstones. No carbonate slope was devloped.

described (Fig. 6; cf. sections 2–4, Fig. 5). Thicker transgressive intervals record a deepening from beachface/talus rudites at the base into shoreface to inner shelf deposits at the top. Transgressive successions that can be mapped and correlated over a few kilometres show marked lateral variations mainly with respect to total thickness, the thickness of specific facies, mean grain size, clast rounding and sorting, and fossil content. The lateral variations result from variations of energy regime, depositional water depth, and the morphological gradient of the transgressed substratum. The stratigraphic position of some of the coral–rudist mounds (e.g. section 3, Fig. 5) indicates that they accumulated seaward of gravelly to rocky shores.

5. Shelf reconstruction

Shelf width during deposition of the Lower Gosau Subgroup is estimated at 20–35 km, but locally may have been less (M. Wagreich, pers. comm., 1999). The carbonate depositional systems were about 1 km to, possibly, 10 km in width down dip, and were confined to inner shelf compartments of low siliciclastic input (Fig. 7). The along-strike extent of carbonate shelves was a few kilometres to more than 10 km, beyond the limit of larger outcrops. Locally, the described parasequence tracts are stacked into regressive carbonate shelf successions up to about 100 m thick. The stratigraphic relations of shelf siliciclastics and shallow-water limestones (cf. Figs. 5 and 6) indicate that the regressive carbonate shelves consisted of (a) micro-tidal flats and/or carbonate-lithic/bioclastic beaches at the landward end, (b) an open lagoon/bay with radiolitid biostromes, (c) a dissipative shore zone with bioclastic sand bodies and (d), a belt with coral–rudist mounds topped by rudist biostromes, and with bioclastic sand bodies (Fig. 8). Larger carbonate slopes fed by the shallow-water carbonate factory were not individuated. At their distal end, the carbonate shelves pinched out and graded into bioclastic–siliciclastic shelfal siltstones (Figs. 7 and 8).

The carbonate successions are devoid of inter- to supratidal facies of wide tidal flats (e.g. loferite, ribbon rock, “intertidal pond fills”) and of “muddy cycles” generated by tidal flat progradation (cf. Shinn et al., 1969; Shinn, 1983; Wright, 1984; Cloyd et al., 1990; Demicco and Hardie, 1994). If a meso- to macro-tidal range prevailed, abundant features of tide-influenced deposition should have developed. Only the rare, thin intervals of intraclastic black pebble limestone at the top of some lagoonal parasequence tracts indicate inter- to supratidal conditions. The carbonate shelves thus were micro-tidal, with narrow tidal flats, and/or with carbonate-lithic/bioclastic beaches (Fig. 8). This fits the scarce evidence for tide-influenced deposition in the siliciclastic paralic successions of the Lower Gosau Subgroup, where a micro-tidal to low-meso-tidal range is indicated by facies and sedimentary structures (Sanders, 1998).

In the lagoon bioturbated, lime-muddy bioclastic sand to bioclast-bearing lime ooze mainly with calcareous green algae and smaller benthic foraminifera accumulated. Moreover, radiolitid biostromes, mass accumulations of nerineids and, less commonly, muddy level-bottoms to mounds of corals, sponges and rudists were deposited (Fig. 8). Upon high input of organic matter, mass accumulations of epifaunal pteriomorphs locally formed. In the shore zone, bedsets of bioclastic packstone to grainstone were deposited from carbonate sand bodies that, in part, may have represented lateral equivalents to coral–rudist mounds. Thinner intervals of bioclastic limestones atop coral–rudist mounds were deposited close to within fairweather wave base. The coral–rudist mound/rudist biostrome ensembles accumulated within storm wave base. The mounds nucleated on the inner shelf and, upon aggradational shoaling, typically became topped by a rudist biostrome (cf. Gili et al., 1995; Sanders and Pons, 1999). An alternative might be that the coral–rudist mounds were onlapped and buried by flank beds (cf. Wilson, 1975). The overlying biostrome then should, over most of its extent, be vertically separated from the mound by flank beds and other intermound strata; this is not the case. At their seaward end, the coral–rudist mounds graded into a halo of sandy to silty, argillaceous lime-mud with disoriented, fragmented rudists and corals that are heavily encrusted and bored. A separate, larger carbonate slope depositional system was not developed (Fig. 8).

Seaward, siliciclastic shelf deposition prevailed (Fig. 7). On the inner shelf, under waters about 15–50 m deep (Wagreich, 1988), bioturbated silty sand to clayey silt and storm beds of hummocky cross-laminated sand accumulated. Storm beds rich in debris from corals and rudists are very rare (Wagreich and Faupl, 1994). Carbonate shelf-derived bioclastic sand thus either was not transported far offshore, and/or was strongly diluted by siliciclastics. The shelf siliciclastics bear an indigenous fauna of non-rudist bivalves, gastropods, solitary corals and benthic foraminifera. In successions deposited on the inner siliciclastic shelf silty to sandy, nodular marls with corals and rudists are locally present (cf. Kollmann and Summesberger, 1982). The “coral–rudist marls“ build intervals up to a few metres thick, and contain scattered hermatypic corals, rudists, solitary corals, non-rudist bivalves and gastropods. Coral heads typically are up to 10 cm in size and, from polyparia arrangement and growth form, record sediment stress (Höfling, 1989; Baron-Szabo, 1997). Storm beds rich in fragmented corals and toppled rudists are intercalated. The coral–rudist marls accumulated from low-relief mounds to level-bottoms. Establishment of build-ups was quenched by siliciclastic input and by sediment re-suspension during storms (Sanders and Pons, 1999).

On the outer shelf, in waters down to about 150 m deep, silty to clayey ooze with both planktic and benthic foraminifera, and beds of parallel- and cross-laminated fine sand to silt accumulated (Wagreich and Faupl, 1994). In the outer shelf successions, bioclastic storm beds are rare and consist of an indigenous foraminiferal assemblage. The slope successions consist of hemipelagic marls rich in both planktic and benthic foraminifera (Fig. 7). Locally, beds of turbidite sandstone are intercalated. Near the base of slope and in the basins, turbidite sandstones, marls and claystones accumulated. In the basinal successions equivalent to the Lower Gosau Subgroup, shallow-water bioclastic turbidites are very rare (Butt, 1980; Faupl et al., 1987; Wagreich, 1988).

6. Sequence development

The regressive carbonate successions are part of mappable allostratigraphic units up to a few hundreds of metres thick. The allostratigraphic units were interpreted as preserved parts of depositional sequences that range from 0.5 to 3 m.y. in duration (Sanders et al., 1997). In the incompletely preserved sequences of

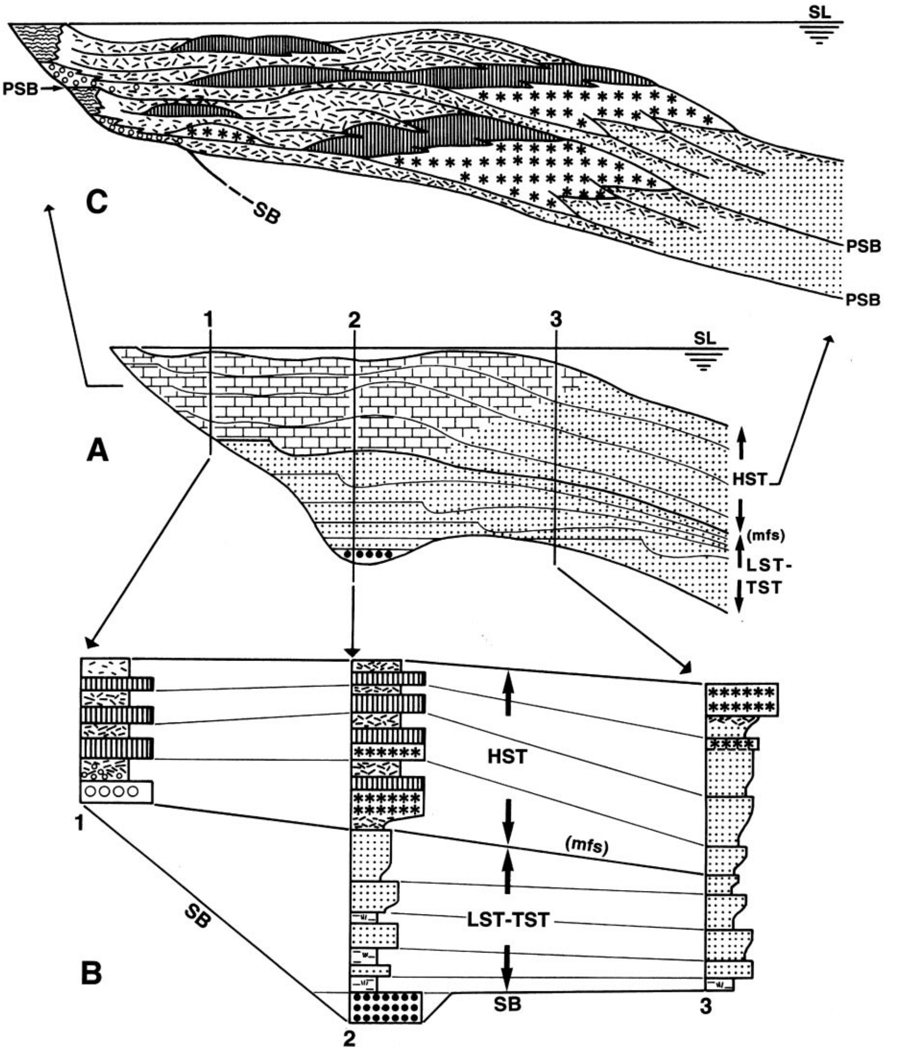

Fig. 9. Mixed siliciclastic–carbonate sequence development. A: LST/TST of siliciclastic parasequences that record deepening from fluviatile to outer shelf environments. The HST consists of an inner shelf to lagoonal facies tract of shallow-water carbonates, and an inner to outer shelf tract of siliciclastics. B: In section, the carbonate tract of the HST shows upward thinning of parasequence tracts and shoaling of depositional water depth. Section 1: HST of a thin transgressive interval overlain by lagoonal parasequence tracts. Section 2: part of the LST/TST and entire HST preserved. Up-section, the HST consists of shelf-beach parasequence tracts and of shelf mound-lagoon and lagoonal parasequence tracts, respectively. Section 3: HST mainly of shelf siliciclastics topped by one or a few shelf-beach parasequence tracts and, locally, shelf mound-lagoon parasequence tracts. C: Regressive carbonate shelf, shown as two stacked parasequences (PSB = parasequence boundaries). After marine flooding, coral–rudist mounds and overlying rudist biostromes aggraded and, probably, prograded over a limited distance. Upon aggradation of bioclastic dunes or of coral–rudist mound/biostrome build-ups, a lagoon established. Farther seaward, the accomodation space was filled by siliciclastics.

the Lower Gosau Subgroup, a clear-cut distinction of the landward part of the lowstand systems tract (LST) and of the transgressive systems tract (TST) is not possible (cf. Haq, 1991; Dalrymple et al., 1994). Recognition of the TST, or parts of it, is possible for successions based by a marine flooding surface, that show an upward thickening of stratal packages and/or record deepening, and that are overlain by a regressive, unconformity-topped succession that can be interpreted as a highstand systems tract (HST) (Sanders et al., 1997). For poorly exposed or largely eroded successions, the systems tract position cannot be assessed.

In most sequences, the landward part of the LST/TST consists of fan delta deposits, or of siliciclastic fluvial to paralic deposits. Up-section, the TST consists of siliciclastic parasequences that record a deepening from paralic into shelf environments (Fig. 9A and B; e.g. sections 1, 4, Fig. 5). Locally, rudist biostromes and thin coral–rudist mounds accumulated in inner shelf to shoreface and in lagoon/bay environments, but were buried by paralic siliciclastics (cf. Sanders, 1998, Figs. 8 and 11). In the storm-dominated shelf energy regime that prevailed during deposition of the Lower Gosau Subgroup, the siliciclastics were dispersed on the shelf by longshore drift and by shore-parallel to shore-oblique storm currents (shoreface bypassing, Swift and Thorne, 1991; cf. Morelock et al., 1983; Snedden et al., 1988). Where siliciclastic input was intrinsically low or ceased during sea-level rise the entire TST, or the upper part of it, consists of a transgressive succession of carbonate-lithic shore zone deposits (e.g. interval A in section 2, Fig. 5).

When relative sea-level rise slowed, most of the river load was flushed onto the shelf by river-mouth bypassing (Bush, 1991; Swift and Thorne, 1991), while longshore drift was trapped along the flanks of shelf deltas (e.g. Dominguez et al., 1987). Both processes and the local presence of rocky headlands favoured the establishment of inner shelf compartments with little siliciclastic input. In these compartments, and on offshore highs that became isolated upon sea-level rise, the regressive carbonate shelves developed. The carbonate HST developed as a stack up to 100 m thick of parasequences that up-section become both successively thinner and record a shoaling of depositional water depth (Fig. 9B and C). Where the carbonate shelves onlapped a steeply dipping substratum, thin transgressive intervals (e.g. in section 4, Fig. 5) may also have formed in the "early" HST (Fig. 9).

Correlated sections indicate that the stratigraphical development of the small carbonate shelves was both aggradational and progradational (Figs. 8 and 9), but outcrops are not large enough to show depositional geometries diagnostic for progradation. If the carbonate shelves prograded into deep water, carbonate slopes should have formed that downlapped (or overlaid, in vertical section) outer shelf siliciclastics. Carbonate slopes can form in front of even small fringing reef systems, provided that siliciclastic input is low (e.g. Frost et al., 1983). At their seaward end, however, the carbonate shelves of the Lower Gosau Subgroup pinched out into inner shelf siliciclastics. The individuation of carbonate slopes probably was prevented by the combination of the gentle relief of the coral–rudist mounds and high input and effective dispersal of siliciclastics. Carbonate shelf progradation was linked with aggradation of siliciclastics ahead (Figs. 8 and 9C). Because of tectonic deformation and limited outcrop, the distance of progradation of the small carbonate shelves can hardly be quantified, but might have ranged up to a few kilometres. The sequence boundaries on top of the carbonate successions are recorded by erosional truncation, facies shift combined with a sharp change to siliciclastic paralic deposition and, in the limestones, by karstic cavities filled with overlying Upper Cretaceous rocks (Sanders et al., 1997).

7. Discussion

The shelves of the Lower Gosau Subgroup are comparable with respect to their position in a convergent tectonic setting, lateral scale and physiographic setting to recent mixed siliciclastic–carbonate shelves of the Antilles and Southeast Asia. On the narrow, steep shelf of Puerto Rico, despite high siliciclastic input from the island, shallow-water carbonates are common. The carbonate depositional areas are a few hundreds of metres (coral patch reefs, bioclastic dunes) to more than 10 kilometres wide (coral reefs, bioclastic dunes, open carbonate lagoons), and interfinger with siliciclastic shelf deposits. Both location and duration of the carbonate depositional areas are strictly controlled by siliciclastic input and dispersal. Some reefs also are situated on offshore highs well landward of the shelf break. Around coral pinnacles, haloes of reefal bioclastic material mixed with shelf siliciclastics are present (Beach, 1983; Morelock et al., 1983; Bush, 1991). Carbonate slopes, however, are absent. The slope around Puerto Rico is covered by sandy to silty siliciclastic mud with a few percent of planktic foraminifera and pteropod fragments (Schneidermann et al., 1976).

With respect to strongly compartmentalized, mixed siliciclastic–carbonate depositional environments above a deeply truncated substratum, recent analogues to the Lower Gosau Subgroup are present in Southeast Asia. In south Thailand, for instance, a highly differentiated morphology of folded, deeply truncated and karstified limestones is onlapped by the Holocene succession with river deltas, bays and marshes, siliciclastic beaches, rocky shores and carbonate depositional areas including reefs, bioclastic sand bodies, carbonate beaches, and small open lagoons/bays. The carbonate depositional areas are a few hundreds of metres to a few kilometres wide, developed both along the mainland and around rocky islands, and rise from a siliciclastic shelf of about 10–20 m water depth. Carbonate tidal flats are absent, and the coral reef-bioclastic sand depositional systems abut the substratum along narrow beaches of highly variable, lithoclastic/bioclastic composition (D.S., own observations). The comparison with recent analogues indicates that the style of carbonate deposition in the Lower Gosau Subgroup is characteristic for an active tectonic setting with mixed siliciclastic–carbonate accumulation.

8. Conclusions

The Middle Turonian to Lower Campanian (Lower Gosau Subgroup) of the Northern Calcareous Alps consists of unconformity-bounded stratal packages that represent the preserved parts of mixed siliciclastic–carbonate depositional sequences. Up-section, the transgressive systems tracts record a deepening from predominantly siliciclastic, paralic deposition to outer shelf environments. Locally, rudist biostromes and coral–rudist mounds accumulated in lagoonal/bay and shoreface to inner shelf environments, but were buried by paralic siliciclastics during parasequence development. Along coastal sectors of low siliciclastic input, because of a high-relief truncation surface at the base of the Lower Gosau Subgroup, the transgressive systems tracts largely consist of a non-cyclic, upward-deepening succession of clastic carbonate rocks that were deposited from gravelly to rocky carbonate shores.

The highstand systems tracts commonly consist of a stack of siliciclastic parasequences that record shoaling to inner shelf depths and, near the basin margins, to lagoonal to marsh environments. During highstand conditions, both outbuilding of deltas and presence of rocky headlands favoured compartmentalization of the shoreface to inner shelf area with respect to siliciclastic input. In compartments of low siliciclastic input, small carbonate shelves developed that consisted of: (a) an inner shelf belt with coral–rudist mounds topped by rudist biostromes, and with bioclastic sand bodies; (b) a dissipative shore zone of bioclastic sand bodies; (c) open lagoons/bays with radiolitid biostromes, calcareous green algae, skeletal sponges, nerineids, actaeonellids and benthic foraminifera, and (d) at the landward end, narrow micro-tidal flats or a narrow, mixed lithoclastic–bioclastic beach.

The carbonate successions are up to 100 m thick, and consist of stacked parasequence tracts that, up-section, become both thinner and record a shoaling of mean depositional water depth. Deposition of shallow-water carbonates was confined to the actual inner shelf to tidal flat/beach sector. At the down-dip end of the carbonate shelves, the coral–rudist mounds or the bioclastic sand bodies interfingered with and pinched out into inner shelf siliciclastics. Aside from local, laterally limited haloes of coarse bioclastic material, no carbonate slopes were individuated. Development of carbonate slopes was prevented by high input and effective dispersal of siliciclastics in a storm-dominated shelf environment. Carbonate shelf progradation over a distance of possibly up to a few kilometres was linked with aggradation of shelf siliciclastics ahead.

The facies and facies architecture of the carbonate shelves of the Lower Gosau Subgroup largely result from the combined effects of a steeply dipping substratum with a differentiated relief and a narrow shelf with an overall high siliciclastic input. Carbonate depositional systems similar with respect to physiographic setting, scale and facies are present in Holocene mixed siliciclastic–carbonate environments in convergent tectonic settings.

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