Rudist biostromes on the margin of an isolated carbonate platform: The Upper Cretaceous of Montagna della Maiella, Italy

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ABSTRACT

In the Upper Cretaceous shallow-water platform succession of Montagna della Maiella, Italy, different types of bivalve biostromes (rudists, oysters) are present from the external to the internal platform. From Jurassic to Miocene times, Montagna della Maiella was part of the margin of the large, intraoceanic Apulian carbonate platform.

Two types of biostrome fabric were distinguished, (1) an open fabric (isolated rudists, supported by matrix) and (2) a packed fabric (densely packed, interlocking rudist clusters). An open biostrome fabric may have resulted from various factors, e.g. unstable substrate or environmental restriction. A packed biostrome fabric probably records favorable environmental conditions. In the Maiella, the following types of biostrome were recognized (1) caprinid biostrome, (2) hippuritid biostrome, (3) radiolitid biostrome and (4) oyster biostrome. The caprinid biostromes and hippuritid biostromes characterize the external platform environment. Coelenterates are subordinate or absent in these biostromes; encrusting organisms (red algae, bryozoans) are rare. The radiolitid biostromes and the oyster biostromes occupied the normal saline to restricted internal platform environment.

The Upper Cretaceous external platform succession contains 70–85% of cross-bedded rudist bioclastic grainstone; rudist biostromes, mostly 1–3 m thick, amount to between 8% to 18%. Here, the biostromes are commonly situated near the top of cycles that may be up to more than 10 m thick. The biostromes are present at or near the base of meter-scale cycles. The position of the biostromes within the cycles and the vertically-associated lithologies indicate that the requirements for both biostrome growth and preservation were met only in a narrow range of environmental conditions. The large lateral extent and the well-defined lower boundary of the biostromes suggest that the rudists could rapidly colonize lime sand and lime mud substrates. The rudist biostromes, however, were often buried by migrating carbonate sand bodies.

ZUSAMMENFASSUNG

Vom Jura bis zum Miozän war der Bereich der Montagna della Maiella (zentraler Apennin, Italien) ein Teil des Randes der grossen, intraozeanischen Apulischen Karbonatplattform. Die Oberkreide-Plattformabfolge enthält unterschiedliche Typen von Bivalvenbiostromen (Rudisten, Austern) von der externen zur internen Plattform.

Zwei Typen von Biostromgefügen wurden unterschieden, (1) ein offenes Gefüge (einzelstehende Rudisten, gestützt durch Matrix) und (2) ein gepacktes Gefüge (dichtgepackte Rudistenbüschel). Ein offenes Biostromgefüge kann durch instabiles Substrat oder durch ein ökologisch ungünstiges Milieu bedingt sein. Ein gepacktes Biostromgefüge zeigt wahrscheinlich ein günstiges Milieu an. Die folgenden Typen von Biostromen

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wurden unterschieden, (1) Capriniden-Biostrom, (2) Hippuritiden-Biostrom, (3) Radiolitiden-Biostrom und (4) Austern-Biostrom. Die Capriniden- und Hippuritiden-Biostrome charakterisieren die externe Plattform. Coelenteraten sind in diesen Biostromen nur untergeordnet vorhanden oder fehlen; inkrustierende Organismen (Rotalgen, Bryozoen) sind selten. Die Radiolitiden-Biostrome und die Austern-Biostrome wuchsen im normalsalinen bis eingeschränkten Milieu der internen Plattform.

Die oberkretazische Plattform-Abfolge besteht zu 70–85% aus kreuzgeschichteten rudisten-bioklastischen Grainstones. Die Rudistenbiostrome sind meist 1–3 m dick und machen 8–18% der Abfolge aus. In der externen Plattform liegen die Biostrome meist nahe dem Top von Zyklen, die bis über 10 m dick werden. In der internen Plattform dagegen kommen die Biostrome an oder nahe der Basis von ungefähr meter-dicken Zyklen vor. Die Position der Biostrome innerhalb der Zyklen und die vertikal assoziierten Lithologien zeigen, dass die Bedingungen für Wachstum und Erhaltung von Biostromen nur in einem engen Bereich von Milieubedingungen gegeben waren. Die Rudisten konnten Substrate aus Kalksand und Kalkschlamm sehr rasch besiedeln; dies wird durch die grosse seitliche Erstreckung und die deutliche Untergrenze der Biostrome nahegelegt. Die Rudistenbiostrome wurden jedoch häufig durch wandernde Karbonatsandkörper begraben.

RIASSUNTO

Dal Giurassico al Miocene l'area della Montagna della Maiella (Apennino centrale, Italia) faceva parte del margine dell' estesa piattaforma carbonatica apula intraoceanica. La successione di piattaforma del Cretacico Superiore presenta, dall' esterno all' interno, diversi tipi di biostromi a bivalvi (rudiste, ostreidi).

Sono stati individuati due tipi di strutture biostromali, (1) una aperta (rudiste isolate, sorrette da matrice) ed (2) una compatta (cespi compatti di rudiste). Una struttura biostromale aperta può essere condizionata da un substrato instabile o da un ambiente ecologico sfavorevole. Una struttura biostromale compatta, per contro, indica, probabilmente, un ambiente ecologico favorevole. Si possono distinguere i seguenti tipi di biostromi, (1) a caprinidi, (2) a hippuritidi, (3) a radiolitidi e (4) a ostreidi. I biostromi a caprinidi e hippuritidi caratterizzano la piattaforma esterna. I celenterati sono rappresentati solo secondariamente in questi tipi biostromali o mancano del tutto; organismi incrostanti (alghe rosse, briozoi) sono rari. I biostromi a radiolitidi e quelli ad ostreidi si sviluppano in un ambiente marino aperto fino a circolazione ristretta all' interno della piattaforma.

La successione della piattaforma del Cretaceo Superiore è costituita per il 70–85% da grainstones di bioclasti a rudisti con stratificazione incrociata. I biostromi a rudisti mostrano uno spessore da 1 a 3 metri e costituiscono dall' 8 a 18% della successione. I biostromi della piattaforma esterna si trovano per lo più al tetto di cicli che superano lo spessore di 10 metri. Nella piattaforma interna, invece, i biostromi sono situati in prossimità oppure direttamente alla base di cicli di uno spessore di circa un metro. La posizione dei biostromi all' interno di cicli e le litologie in associazione verticale, mostrano che lo sviluppo e la conservazione dei biostromi erano limitati a condizioni ambientali ristrette. I rudisti poterono colonizzare rapidamente substrati sia a sabbie che a fanghi calcarei; la forte estensione laterale dei biostromi ed il loro limite inferiore ben definito, avvalorano questa interpretazione. I biostromi a rudisti, tuttavia, spesso furono sepolti da corpi di sabbie carbonatiche migranti.

1. Introduction

Rudist bivalves are the most characteristic fossils of Cretaceous shallow-water platform successions. From Late Jurassic to Early Cretaceous times, the rudists occurred in buildups together with coelenterates, sponges and calcareous algae. In the Upper Cretaceous, by contrast, rudist limestones with densely packed elevator rudists are common (Vogel 1970; Kauffman & Sohl 1974; Kauffman & Johnson 1988; Scott 1988; Skelton & Gili 1991; Ross & Skelton 1993). At the same time, despite an overall increase in diversity, the importance of corals, hydrozoans and calcareous algae strongly diminished in the rudist accumulations (Fagerström 1987; Wood 1993; Heckel 1974; cf. Wray 1977). The rudists, however, were not bound by epibionts into a wave-resistant framework and they invariably formed biostromes and low mounds (Philip 1972; Longman 1981; Kauffman & Sohl 1974; Kauffman & Johnson 1988; Ross & Skelton 1993). Since the rudist biostromes were comparatively vulnerable to destruction, the Upper Cretaceous external platform
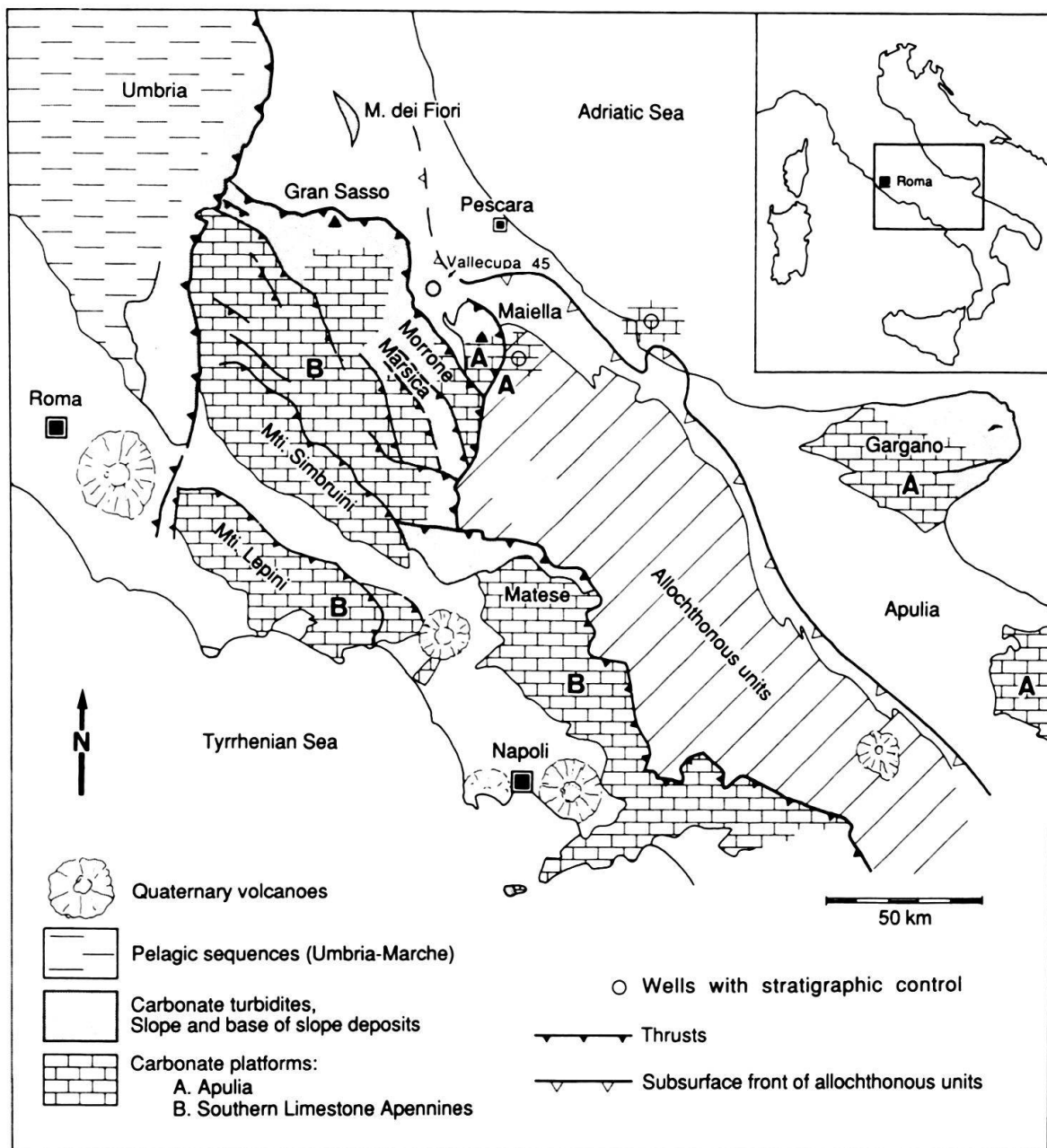
Fig. 1. Location of Montagna della Maiella in Italy. The Maiella was part of the margin of the Apulian Plat-
form (A), which is mainly autochthonous and is involved in Neogene thrusting only along its western part. The
Apulian Platform is partly covered by foreland deposits and the allochthonous units of the Southern Limestone
Apennines (B). From Eberli et al. (1993), reprinted by permission.

successions are often strongly dominated by grainstones composed of rudist debris (cf.
Carbone & Sirna 1981; Carannante et al. 1993; Sanders 1994).

Rudists were of wider environmental tolerance than corals and hydrozoans (cf. Wilk-
son 1975; Kauffman & Johnson 1988; Ross & Skelton 1993; Wood 1993), and most prob-
ably also were able to rapidly colonize different substrates (Ross & Skelton 1993;

Fig. 2. Late Cretaceous (84 Ma) palaeogeography and position of the Maiella (M) in the Cretaceous Tethys ocean. Position and shape of continents from Scotese et al. (1989). A: Adria, B: Bahamas, CA: Central Atlantic, D: Dinarids, EM: Eastern Mediterranean, PL: Piemonte-Liguria Ocean, Y: Yucatan. From Eberli et al. (1993), reprinted by permission.

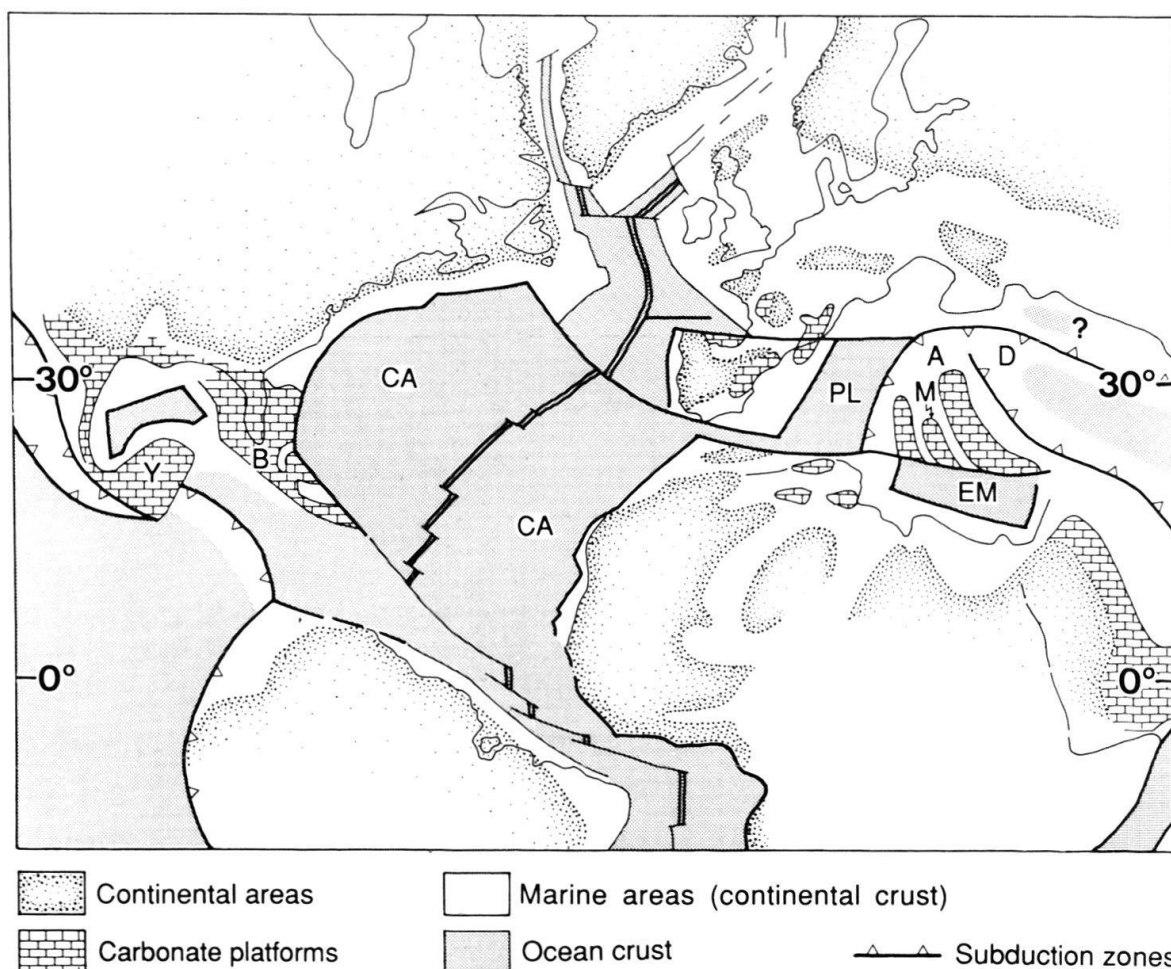Sanders 1994). In situ accumulations of rudists thus were distributed over entire shallow-water platform tops. This is different from Cenozoic carbonate platforms, where coralgal buildups are confined to the platform margins.

The possible controls over rudist accumulations may be deduced from their sedimentological context with respect to morphology, composition, fabric and associated lithologies (e.g. Kühn 1967; Masse 1979; Philip 1972, 1980; Masse & Philip 1981; Carbone & Sirna 1981; Accordi et al. 1982; Scott 1979, 1981; Scott et al. 1990; Caranannte et al. 1993; Gili 1993; Ross & Skelton 1993; Wood 1993; Sanders 1994). In the Upper Cretaceous platform succession of Montagna della Maiella, Italy, extensive outcrops allow for a good documentation of the rudist biostromes. Along an approximately 10 kilometer-long transect, the successions of both the external platform and part of the internal platform are well exposed. In this paper, the factors that controlled rudist biostrome growth and preservation are inferred from a description of biostrome types and fabrics, their distribution on the platform and the associated lithologies.

A

B

N

Lettomanopello

Pretoro

Valle Santo Spirito

Valle dell' Orfento

Valle delle Tre Grotte

Penna-piedimonte

Mucchia di Caramanico

Monte Cavallo

Valle dell' Inferno

Cima delle Murelle

Pesco Falcone

Acquaviva Gemello

M. Rotondo

Ravone della Vespa

V. S. Spirito

Fara San Martino

MONTE AMARO

Cima dell' Altare

Valle di Macchia Lunga

Fondo di Maiella

Valle di Taranta

Valle di Izzo

Lettopalena

0   5 km

Tertiary

Orfento Formation, Maastrichtian-U.Campanian

Upper Cretaceous basinal sediments

Upper Cretaceous carbonate platform deposits
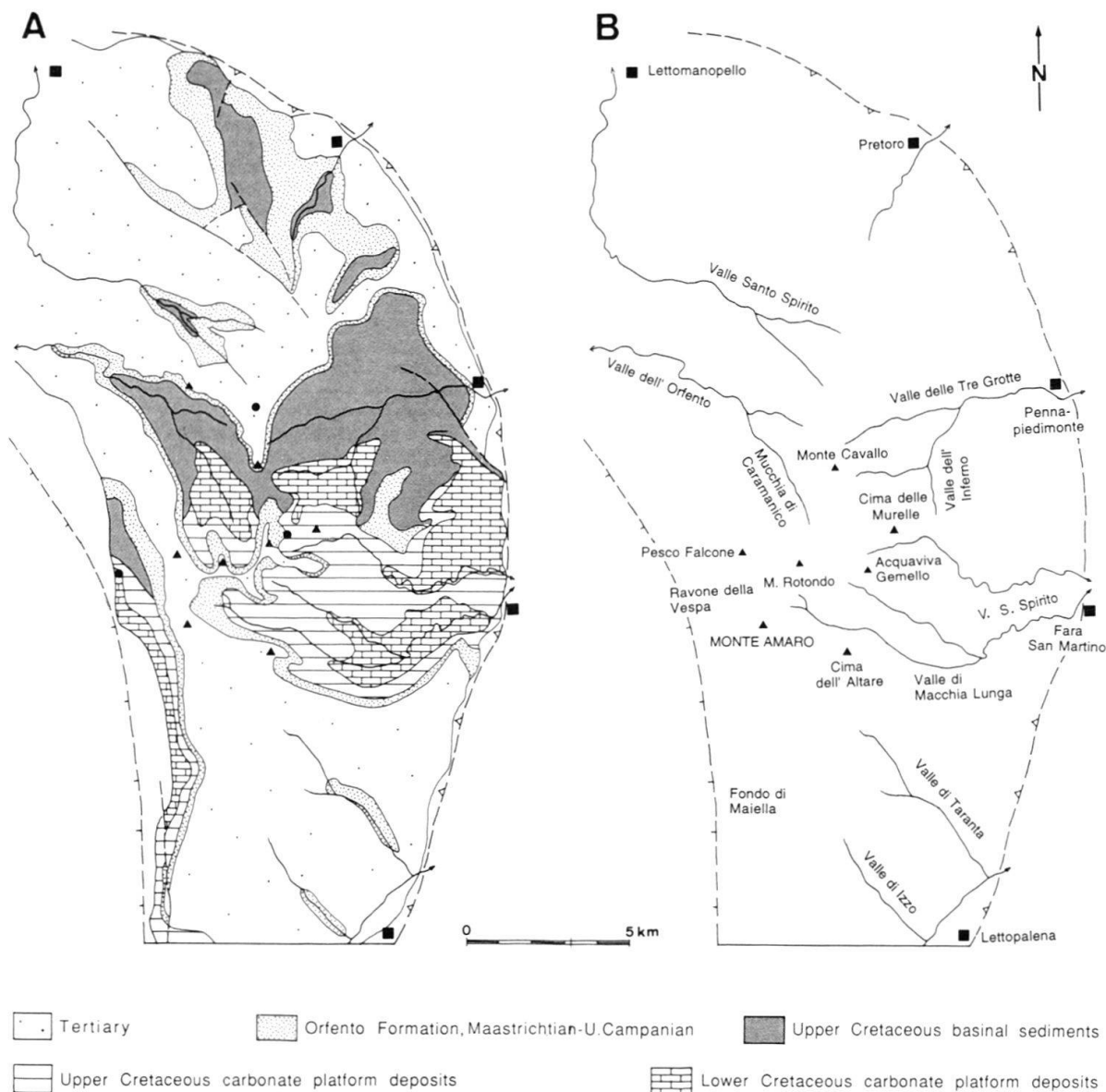
Lower Cretaceous carbonate platform deposits

Fig. 3. Simplified geological map of Montagna della Maiella. Note the sharp contact between Lower to Upper Cretaceous platform deposits (to the south) and Upper Cretaceous basinal sediments (to the north) in the central part of the massif. This sharp contact results from a steeply northward dipping escarpment. After Catenacci (1970). Slightly modified from Eberli et al. (1993), reprinted by permission.

2. Geological framework

Montagna della Maiella comprises a N-S trending frontal anticline in the south-central Apennines (Fig. 1) (De Giuli et al. 1987; Ghisetti & Vezzani 1983; Roure et al. 1991). From Early Jurassic to Miocene times, the Maiella was situated at the northwestern corner of the large, isolated Apulian carbonate platform (Fig. 2) (Accordi & Carbone 1992). The Apulian platform came into existence during Early Jurassic rifting along the southern margin of the Tethys ocean, when a huge carbonate shelf was segmented into several

isolated shallow-water platforms (peri-Adriatic platforms; Bernoulli & Jenkyns 1974). These platforms were sheltered from terrigenous influx by deep-water troughs and plateaus (Bernoulli & Jenkyns 1974). During the Jurassic to Early Cretaceous, oolite shoals and organic buildups developed along the margins of the Apulian platform, whereas the internal platform succession records protected to restricted lagoonal environments (Accordi et al. 1988a). At the passage from the Early to the Late Cretaceous large parts of the Apulian platform, including the Maiella, became emergent. The resulting "mid"-Cretaceous unconformity is marked by deep karstification and the widespread occurrence of bauxite (D'Argenio & Mindszenty 1986; D'Argenio et al. 1986).

During Cenomanian times, the exposed banktop of the Maiella was re-flooded. In the Cenomanian to Upper Campanian succession of the Maiella platform margin, three different environments can be recognized (Fig. 3, 4) (Crescenti et al. 1969; Catenacci 1974). In the southern part of the Maiella, an internal platform environment is recorded by peritidal cycles. In the central part, cross-bedded bioclastic limestones and rudist biostromes indicate an external platform environment. Towards the north, the external platform was separated from a proximal basin by a steep, non-depositional escarpment (Fig. 3). In the proximal basin, a thick succession of deep-water limestones was deposited that onlaps the external shallow-water platform along the escarpment (Crescenti et al. 1969; Catenacci 1974; Accarie 1988; Vecsei 1991; Eberli et al. 1993). The escarpment probably was formed already during the Early Jurassic rifting, but was subsequently shaped by erosion (Eberli et al. 1993; Vecsei et al. in press).

From Cenomanian to Late Campanian times, both the shallow-water platform and the proximal basin showed an aggradational evolution. During this time interval, an approximately 250 m thick succession aggraded on the platform, whereas in the proximal basin at least 950 m of deep-water limestones were deposited. Due to the overall higher rate of aggradation in the proximal basin, the escarpment gradually became buried and was nearly levelled by Late Campanian times (Accarie 1988; Vecsei 1991; Eberli et al. 1993). The rudist biostromes described in this paper are present in the Cenomanian to Upper Campanian shallow-water platform succession. The top of this platform succession is a deeply-incised truncation surface that marks a turning point in the evolution of the Maiella (Sanders 1994).

3. Stratigraphy

3.1 Physical Stratigraphy

The base of the investigated platform succession is the "mid"-Cretaceous unconformity, noted above, which corresponds to the "lacuna con bauxite" of Crescenti et al. (1969). The Cenomanian to Upper Campanian external platform succession of the Maiella corresponds to the platform portion of the formal "Formazione Monte Acquaviva" of Crescenti et al. (1969). The internal platform succession comprises the "Formazione Monte Acquaviva equivalente" of Crescenti et al. (1969) (synonym: informal "Calcari a rudiste"; Catenacci & Chiocchini 1967). The "Formazione Monte Acquaviva" was formally redefined as "Cima delle Murelle Formation" (Vecsei 1991); the "Formazione Monte Acquaviva equivalente" was redefined as "Fondo di Maiella Formation" (Sanders 1994).
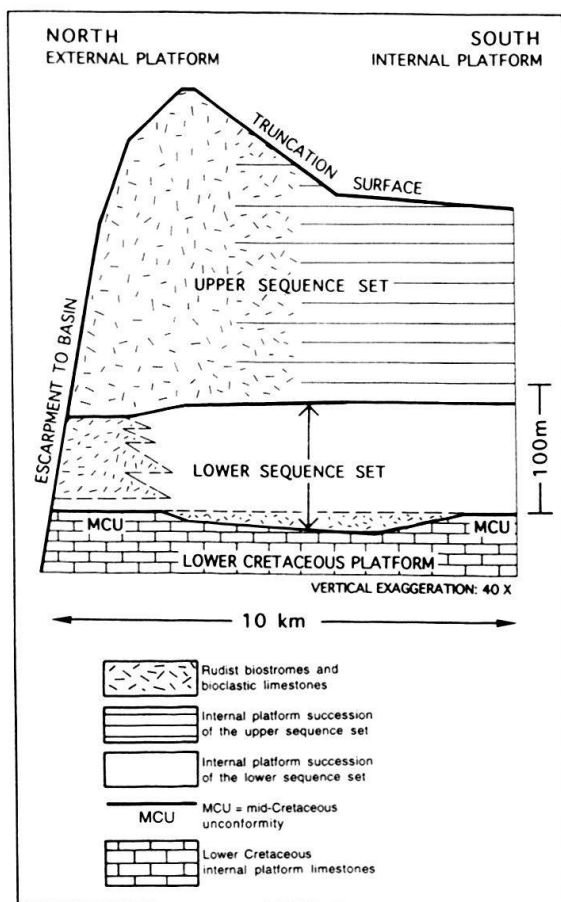
Fig. 4. Simplified north-south cross-section across the Cenomanian to Upper Campanian shallow-water platform succession of the Maiella, vertically exaggerated. The substratum is a Lower Cretaceous internal platform succession (brickwork pattern). The top of the Lower Cretaceous is the "mid"-Cretaceous unconformity (MCU). Above the "mid"-Cretaceous unconformity, two sequence sets were distinguished. In the lower sequence set (Cenomanian-?Turonian), rudist biostromes occur only in the external platform succession (hatched pattern); the internal platform succession (white) consists of limestones deposited in a protected lagoonal to tidal flat environment. In the upper sequence set, the preserved external platform belt (hatched) is much wider, while the internal platform succession (horizontal lines) records an open lagoonal environment. These two environments grade laterally into each other (horizontal lines and hatching). In the upper sequence set, biostromes occur both on the external and the internal platform. The platform is separated from the onlapping proximal basin succession (not shown in the figure) by an escarpment, and is topped by a deeply incised truncation surface.

In the sequence stratigraphic subdivision of the Maiella (Eberli et al. 1993), the Cenomanian to Upper Campanian platform succession forms a supersequence (in the sense of Van Wagoner et al. 1988). It is subdivided into two sequence sets (Fig. 4). The lower sequence set is of Early Cenomanian to ?Turonian age, and is separated from the overlying sequence set by a distinct deepening of facies. The upper sequence set is of ?Turonian to Late Campanian age (Sanders 1994).

3.2 Biostratigraphy

In the lower sequence set, an Early Cenomanian to ?Turonian age is indicated by the association of *Trocholina* sp., *Praealveolina* sp., *Pseudorhipidionina casertana*, *Chrysalidina* cf. *gradata*, *Pseudorhapydionina dubia*, *Orbitolina* sen. str., *Cisalveolina fraasi*, *Cisalveolina fallax*, *Chrysalidina* cf. *gradata*, *Vidalina* sp., *Nezzazata* sp., *Pseudorhapydionina* ex gr. *dubia*, *Dicyclina schlumbergeri*, *Nummofallotia ?apula* and *Praturlonella hammudai* (cf. Catenacci 1974; Accarie 1988; Sanders 1994). The rudist species *Caprina carinata*, *C. schiosensis*, *C. leptoteca*, *Caprinula boissyi*, *Ichthyosarcolites bicarinatus* and, higher up in the succession, *Distefanella bassanii*, *D. raricostata*, *D. lombricalis*, *D. spadai* and *D. douvillei*

(Accordi et al. 1988a; Pons & Sirna 1992) together indicate a Cenomanian to ?Late Turonian age. The upper chronostratigraphic limit of the lower sequence set is poorly constrained.

In the upper sequence set, due to the absence of precise biomarkers, the lower and middle part are not well dated. The foraminifer *Cuneolina pavonia* marks a Late Albian to earliest Campanian age, *Montcharmontia* cf. *apenninica* indicates a Coniacian to „middle" Campanian age, but it may range with very rare specimens to the end of the Maastrichtian. In addition, cf. *Murgella* suggests a Santonian age (ranges according to Sartorio & Venturini 1988). The rudists *Milovanovicia dobrunensis, M. bosniaca, Jerinella klinae, Sauvagesia tenuicostata, Hippurites socialis, H. colliciatus* and *Vaccinites sulcatus* document the Coniacian to Early Campanian interval, but the biostratigraphic resolution of the rudist assemblages is generally poor (see Pons & Sirna 1992; Accordi et al. 1988a). A Late Campanian age of the upper part of the upper sequence set is indicated by the rudists *Sauvagesia tenuicostata, Joufia reticulata, Lapeirousia pervinqueri, Vaccinites atheniensis, V. gosaviensis* and *V. sulcatus* (cf. Accordi et al. 1988b; Accarie 1988).

In view of the absence of precise biomarkers, the internal platform succession is poorly dated. At the base of the Upper Cretaceous internal platform succession, an assemblage of *Cisalveolina fraasi, Pseudorhapydionina dubia, Cuneolina pavonia parva* and *Dicyclina* cf. *schlumbergeri* indicates a Middle Cenomanian age. In the overlying succession the foraminifera *Cuneolina ?laurentii, Montcharmontia* cf. *apenninica, Nezzazata-Valvulammina*, cf. *Valvulammina*, *Pseudorhapydionina* cf. *dubia* and cf. *Murgella* indicate a Cenomanian to, possibly, Campanian age.

The top of the platform succession is a deeply-incised truncation surface that can be recognized over the entire platform top of the Maiella (Fig. 4) (Sanders 1994). In the proximal basin, the hiatus associated with the truncation is situated within the Calcarata zone of the Late Campanian (Accarie 1988; Vecsei 1991). This fits with the Late Campanian age of the uppermost part of the external platform succession (see above) and indicates that the internal platform succession of the Maiella reaches up to the Late Campanian at most. The deposits of the internal platform are probably truncated at a deeper (?Lower Campanian) stratigraphic level (Sanders 1994).

4. Methods

The sequence sets of the platform succession were mapped on a scale of 1/ 10 000. Field mapping on large photomosaics provided the control on the lateral and vertical variations of lithologies, including the rudist biostromes. The biostromes and horizons of inter-to supratidal limestones were chosen as marker horizons. The mapping on photomosaics and the correlation of short sections allowed the reconstruction of subtle depositional geometries of the biostromes. In addition, nine stratigraphical sections up to 250 m long were measured along a transect from the external platform to the most internal preserved part of the platform. Over 600 polished rock slabs and more than 200 thin sections served for the documentation of the lithologies. For the description of the rudist morphotypes, the terminology of Skelton & Gili (1991) is applied.
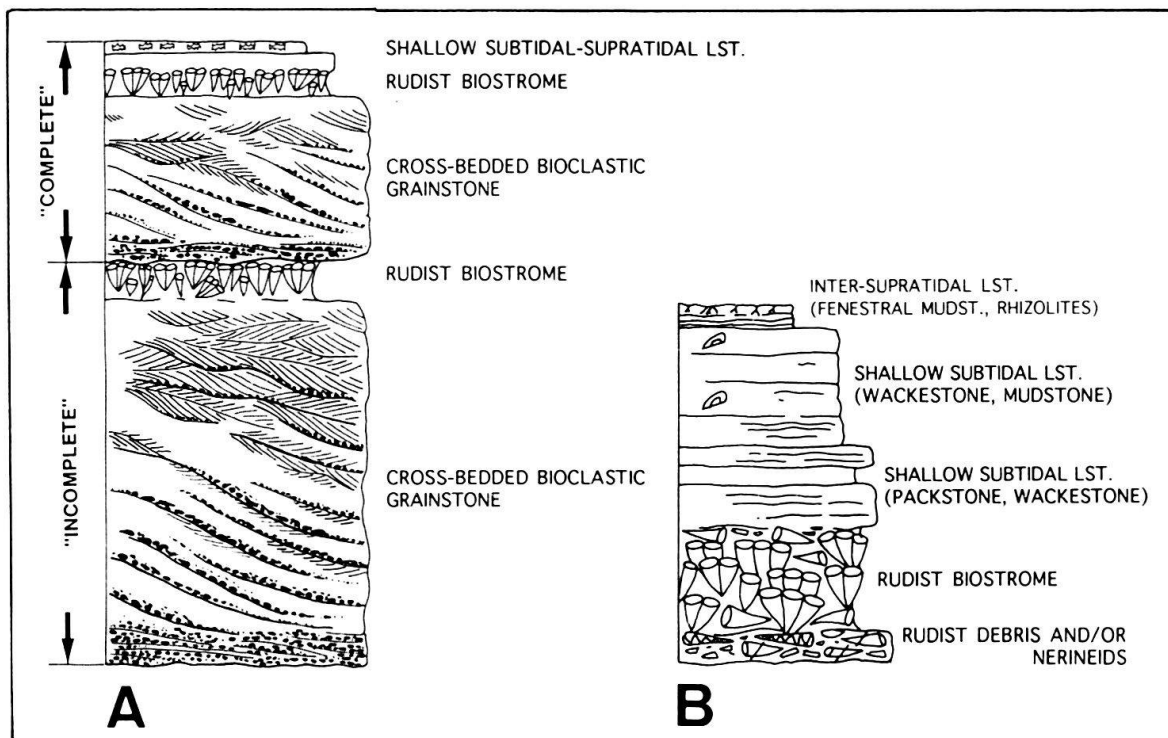
Fig. 5. Common cycle types of the Cenomanian–Upper Campanian platform succession of the Maiella. A: Grainstone cycle. The grainstone cycles consist mainly of horizons of cross-bedded bioclastic grainstone. The master bedding surfaces in the grainstone horizons dip from a few degrees to more than 20°. The grainstone horizons are between a few meters to more than 20 m thick, and are topped by a rudist biostrome. The rudist biostrome may be overlain by the grainstone horizon of the successive cycle ("incomplete grainstone cycle"), or by a relatively thin horizon of shallow-subtidal to supratidal limestones ("complete grainstone cycle"). B: Lagoonal cycle. The lagoonal cycles commonly have a basal layer of coarse bioclastic rudstone with rudist debris and/or abundant nerineids, which is overlain by a rudist biostrome. The rudist biostrome is followed up-section by shallow-subtidal limestones which, in turn, are topped by limestones from an inter-supratidal environment. The lagoonal cycles typically are several meters in thickness.

5. The platform succession

5.1 Overview

The lower, Cenomanian to ?Turonian sequence set shows a clear separation between an external platform environment to the north (Cima delle Murelle Formation) and a protected lagoonal-tidal flat environment to the south (Fondo di Maiella Formation) (Fig. 4). In the lower sequence set there are no biostromes in the internal platform succession. The lower sequence set is separated from the overlying sequence set by a distinct deepening of facies over the entire platform top.

In the upper, ?Turonian to Upper Campanian sequence set an approximately 2.5 to 3 km wide external platform environment and a more or less open, deeper subtidal lagoonal environment can be distinguished. These environments graded laterally into each other. In the upper sequence set the rudist biostromes are found from the external platform to the most internal preserved part of the carbonate shelf. The top of the upper sequence set is the mentioned, deeply-incised truncation surface (Fig. 4).
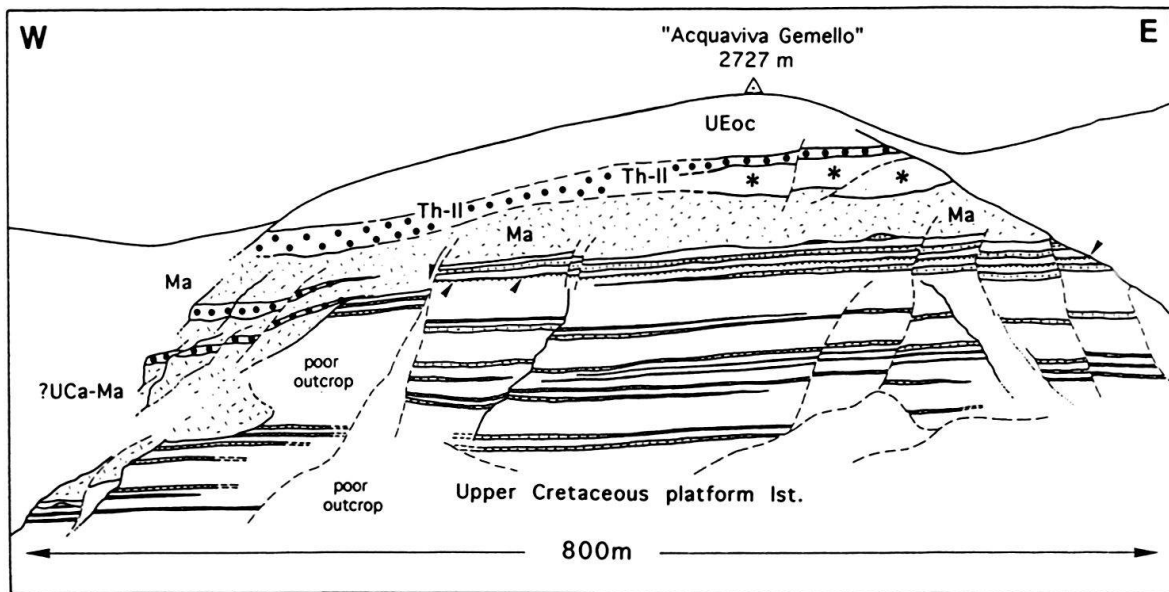
Fig. 6. Rudist biostromes (dotted horizons, slight vertical exaggeration) in the external platform succession, on the southern flank of "Acquaviva Gemello" in the central Maiella. Line drawing from photomosaic. Note the lateral persistence of the biostromes, accompanied by only small changes in thickness. The biostromes are vertically separated by thick successions of bioclastic grainstones (white). Near the top of the Upper Cretaceous platform succession, a laterally persistent radiolitid "meadow" occurs (marked by arrowtips) that is composed of a single layer of radiolitids in growth position. Towards the west, the Upper Cretaceous platform succession is truncated. The truncated platform is onlapped and overlain by an ?Upper Campanian-Maastrichtian (?Uca-Ma, Ma) succession of calcirudites (coarse dots) and bioclastic limestones (hatched). The calcirudites pinch out to nearly zero towards the east. The Maastrichtian deposits are overlain by a probable erosional remnant of Thanetian reefs (flower pattern), which is in turn truncated and overlain by coarse, lithoclastic calcirudites of latest Thanetian-early Ilerdian age (Th-Il, coarse dots). The calcirudites are overlain by an Upper Eocene succession of bioclastic limestones (UEoc).

5.2 Platform cycles

In both sequence sets, the external platform succession is dominated by cycles up to more than 10 m thick, of bioclastic limestones and rudist biostromes ("grainstone cycles"; see Fig. 5A), whereas thin (some decimeters to approximately 1 m thick) peritidal cycles comprise only a very small fraction. The grainstone cycles consist in their lower and middle part of cross-bedded grainstone (Pl. 1/1). The grainstone is mainly composed of well-rounded rudist and other mollusc debris, whereas other components (peloids, echinoderm debris, benthic foraminifera, calcareous algae, bryozoans, coated grains) comprise less than 5% of the sediment (Pl. 1/2). The rudist biostrome is typically situated in the upper part of the grainstone cycles (Fig. 5A). The biostrome, in turn, is either sharply overlain by bioclastic limestone of the successive cycle (incomplete grainstone cycle), or by limestones deposited in a protected shallow subtidal to supratidal environment (complete grainstone cycle) (see Fig. 5A). The grainstone cycles fit the definition of parasequence of Van Wagoner et al. (1988).

The external platform succession consists of 70% to more than 85% of rudist bioclastic grainstone, whereas the rudist biostromes make up between 8% to 18%. In the grain-
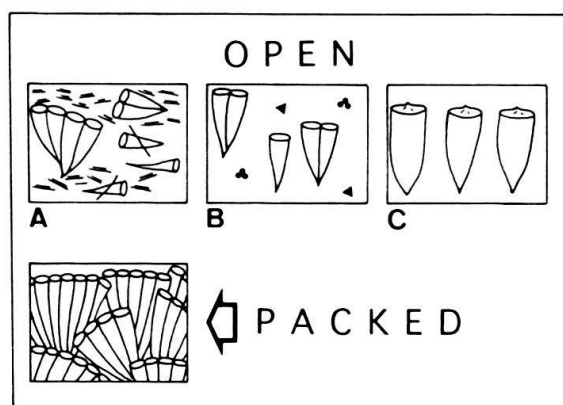
Fig. 7. Types of biostrome fabric. The open fabric is matrix-supported, and the rudists or rudist clusters are not in contact with each other. Three varieties of open fabric are distinguished. A: open fabric with a matrix of bioclastic grainstone to rudstone. B: open fabric with a matrix of wackestone to floatstone (with miliolids, blackened bioclasts, microbial lumps and ostracods). C: open fabric with a matrix of well-sorted, fine bioclastic grainstone to packstone between large radiolitids (*Durania, Joufia*). In the packed fabric, the rudist clusters are in contact with and support each other, and little space is left for matrix.

stone intervals, the common presence of master bedding surfaces and bi-directional megaripple laminasets indicates that the grainstone was deposited from subaqueous dunes. A subordinate portion of the grainstone intervals displays subparallel lamination, low-angle cross lamination and keystone vugs; these latter grainstone intervals probably were deposited in association with beaches (Sanders 1994). The rudist biostrome horizons dip with a few degrees at most, whereas the depositional dip of the master bedding surfaces in the underlying grainstone horizons commonly attains $10°$ to over $20°$ (Fig. 5A) (Sanders 1994). In the grainstones, toppled and overturned rudists with the upper (left) valve still in position are relatively common (Pl. 1/3). The strong prevalence of bioclastic grainstones over rudist biostromes gives rise to a characteristic facies architecture: some meters to more than 20 m thick horizons of bioclastic grainstones are separated by rudist biostromes or very thin, but laterally extensive rudist thickets (rudist "meadow"; Fig. 6).

In the internal platform succession, the biostromes occur either in the lower part of meter-scale upward-shallowing cycles (Fig. 5B), or they are intercalated in thicker successions of bioclastic packstones and grainstones. In the upward-shallowing cycles, the biostromes are commonly underlain by a thin horizon of coarse bioclastic floatstone with rudist debris and/or nerineid gastropods (Fig. 5B), or an up to one meter thick horizon of miliolid-bearing, bioclastic wackestone to packstone (see also Fig. 8). The biostromes are overlain by limestones deposited in protected, shallow subtidal to low intertidal environments (e.g. peloidal packstones, wackestones with miliolids and lituolids, wackestones with miliolids and ostracods).

In upward-thinning cycle sets, the biostrome types change vertically. In the external platform succession, the lower part of upward-thinning cycle sets contains biostromes dominated by caprinids or hippuritids, whereas in the upper part radiolitid-dominated biostromes occur. Similarly, on the internal platform, the lower part of upward thinning cycle sets typically contains radiolitid biostromes, whereas biostromes dominated by oysters occur in the upper part.

6. Biostrome fabrics

Two types of biostrome fabric are distinguished: (1) open fabric and (2) packed fabric (Fig. 7). In an open biostrome fabric, the rudists and other fossils (coelenterates, sponges,

gastropods, calcareous algae) float more or less isolated in a matrix of bioclastic wacke-stone to packstone; some rudist clusters may locally be interspersed. Three varieties of open fabric are distinguished (Fig. 7). (A) Open fabric with a matrix of bioclastic grain-stone to rudstone. This fabric characterizes biostromes built by a variable proportion of recumbent rudists, i.e. caprinids and *Ichthyosarcolites* (Pl. 1/4). (B) Open fabric with a matrix of wackestone to floatstone (with miliolids, lituolids, blackened biogens, microbial lumps and ostracods), typically in biostromes built by radiolitids and/or oysters. These bi-ostromes are dominated by elevator radiolitids, which are preserved in growth position or are toppled. Clinger radiolitids are subordinate. (C) Open fabric with a matrix of well-sorted, fine bioclastic grainstone between large elevator radiolitids. The radiolitids are commonly in life position, and often are arranged with an even spacing of 30 to 50 cm between the individuals (Pl. 1/5). The horizons with the large radiolitids often comprise a "gap" with open biostrome fabric within biostromes that both above and below are built by densely-packed thickets of different rudists (Pl. 1/6).

Packed biostrome fabric was observed in biostromes dominated by hippuritids or ele-vator radiolitids. In a packed biostrome fabric, the rudists comprise densely-packed ar-rays of clusters. The orientation of the clusters ranges from upright to gently inclined. The matrix of the packed biostromes is a poorly-sorted wackestone with angular rudist debris. Biostromes built by slender, gregarious hippuritids locally are so tightly packed that individual clusters can hardly be identified, and nearly no matrix occurs between the individuals (Plate 1/7). Both in the packed biostromes and the open biostromes, no dis-tinct encrustation by epibionts was observed on the rudists. The rudist shells are often perforated by *Trypanites*, which probably was produced by clionid sponges (Plate 1/8).

7. Biostrome types and distribution

7.1 External platform

The external platform succession of the lower sequence set (Cenomanian-?Turonian) is characterized by grainstone cycles with caprinid biostromes (Pl. 1/4; Fig. 8: column 1). The caprinid biostromes have an open fabric and consist of caprinids and, subordinately, corals, hydrozoans and some encrusting algae. The matrix is a poorly to moderately well-sorted bioclastic grainstone with up to some centimeter wide (?)crustacean burrows. The caprinid biostromes often develop gradually from the underlying lithology (bioclastic grainstone), and are up to more than 5 m thick. The thick biostromes contain crudely-stratified lenses of bioclastic rudstone.

The external platform succession of the upper (?Turonian–Upper Campanian) se-quence set consists of thick grainstone cycles with hippuritid biostromes (Fig. 6; Fig. 8: column 2). These biostromes commonly have a packed fabric and are 1 to 3 m thick, but locally reach a thickness of more than 6 m. The thick biostromes may contain up to 1 m thick intercalations of bioclastic rudstone, or sharply intercalated lenses of bioclastic grainstone with megaripple laminasets. The hippuritid biostromes locally show a core zone of very densely packed individuals of one type of gregarious, slender hippurites (Pl. 1/7). The core zone grades into a smaller marginal zone with an open fabric, with hip-purite clusters, corals, hydrozoans, nerineids and radiolitids. The matrix of the bio-stromes is a bioclastic floatstone to wackestone with angular rudist debris (Pl. 2/1).
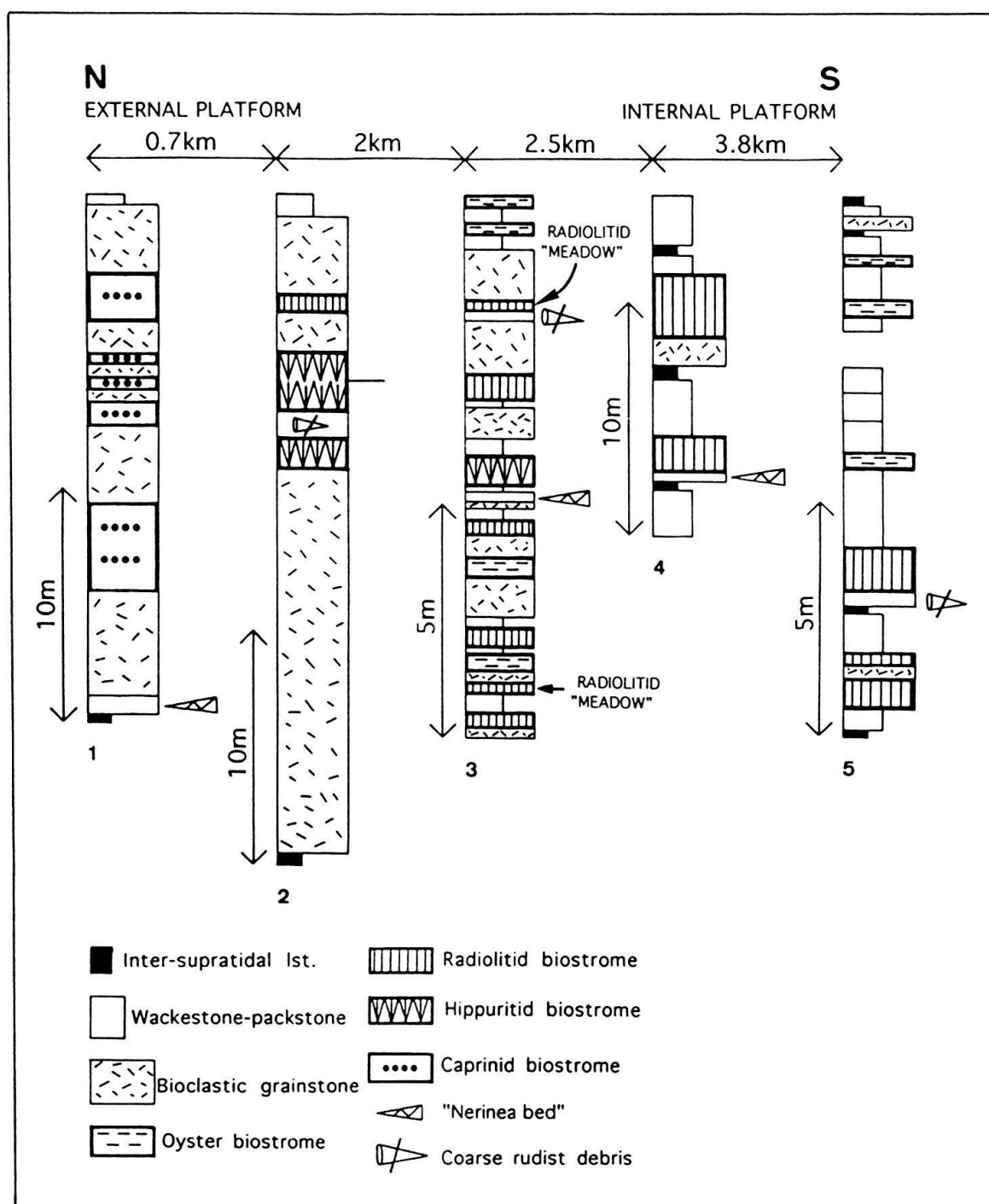
Fig. 8. Parts of sections from the external to the internal platform. 1: North side of Cima delle Murelle, lower sequence set. This section is situated at the most external investigated position on the platform. 2: West side of Cima delle Murelle, upper sequence set. Note the occurrence of a radiolitid biostrome in the upper part of the cycle set. 3: Ravone della Vespa, upper sequence set. This section is situated at the transition from the external to the internal platform environment. Note the occurrence of all biostrome types in this section, and the close vertical spacing of biostromes. In addition, laterally extensive "meadows" of radiolitids are relatively common. 4: Valle di Macchia Lunga. The two, comparatively thick cycles with radiolitid biostromes occur at the base of the upper sequence set of the platform succession. 5: Fondo di Maiella. This section is situated at the most internal investigated part of the platform.

Hippuritid biostromes with an open fabric that contain large corals and hydrozoans occur close to the Upper Cretaceous platform edge. The matrix of the open hippuritid biostromes is a coarse, poorly sorted bioclastic grainstone to rudstone.

Both the caprinid biostromes and the hippuritid biostromes can commonly be traced laterally over hundreds of meters to locally more than a kilometer. The rudists locally also comprise "meadows" that can be physically traced over hundreds of meters (Fig. 6). A "meadow" is a thin blanket of densely packed radiolitids that are of remarkably similar size (20–40 cm) and appear to be of the same genus.

The most common associates of the rudists are corals, nerineid and actaeonid gastropods and hydrozans. Bryozoan fronds and fragments of calcareous algae are rare. Among the corals mostly unbranched, massive types were observed; only in thin sections can rare fragments of branched corals be found. The massive corals are commonly some centimeters to 20 cm in diameter, but specimens up to 50 cm in size were found. The largest and most common corals were found together with hippuritid clusters in coarse bioclastic grainstone to rudstone. The hydrozoans are not always easy to distinguish in outcrop from corals, but they seem to be relatively common and are of similar size to the corals. Both nerineid and actaeonid gastropods are very common in the grainstone horizons beneath the biostromes, and they also occur in the marginal zone of biostromes. In some platform cycles, 20–40 cm thick beds with abundant nerineids ("nerineid beds") rest on the transgressive surface, or slightly above (Pl. 2/2). On the internal platform succession, such "nerineid beds" locally occur at the base of radiolitid biostromes (Fig. 8: columns 3, 4).

7.2 Internal platform

In the internal platform succession biostromes dominated by radiolitids or oysters are common (Fig. 8, columns 3, 4). The radiolitid biostromes are commonly between 40 cm–1 m thick and consist mainly of radiolitids and variable amounts of ostreids, requieniids, and nerineid and actaeonid gastropods. These biostromes range from packed biostromes composed exclusively of erect radiolitids to open biostromes. The matrix of the radiolitid biostromes typically is a bioclastic packstone to wackestone with smaller benthic foraminifera, *Thaumatoporella*, peloids, some blackened bioclasts and lumps of possible cyanobacterial origin. The radiolitid biostromes are underlain and covered by limestones of shallow subtidal to intertidal origin.

Oyster biostromes typically are 30 to 60 cm thick and consist mainly of thick-shelled, sculpted bivalves (oysters and cf. *Chondrodonta*), rudists (requieniids, monopleurids) and a variable amount of radiolitids, actaeonid gastropods, *Thaumatoporella*, green algal fragments and, locally, (?) spongiomorph stromatoporoids (Pl. 2/4). The fossils float in a wackestone to packstone matrix that commonly contains miliolid and lituolid foraminifera, blackened bioclasts and peloids. The oyster biostromes locally rest on a radiolitid biostrome.

7.3 Transitional zone

In the upper sequence set of the platform succession, the transition from the external to the internal platform environment is gradual. In the transitional zone, all types of biostromes are present, but they are typically thin and densely spaced in a vertical direction

(Fig. 8: column 3). Between the biostromes, comparatively thin horizons of cross-bedded bioclastic grainstones and limestones of protected shallow subtidal environments are present (mainly bioclastic packstones to wackestones, some mudstones) (Pl. 2/4). In the transitional zone, extensive "meadows" of radiolitids are relatively common.

8. Boundaries of the biostromes

The lower boundary of the biostromes most commonly is well defined or sharp. A gradual development of biostromes from an upward increasing proportion of intact and erect individuals is relatively rare. Both in the external and the internal platform succession, the biostromes often overlie an up to some decimeter thick, calcarenitic to calciruditic horizon that consists of poorly-sorted, coarse rudist debris, nerineid and actaeonid gastropods, blackened bioclasts and some intraclasts. Alternatively, the biostromes sharply overlie bioclastic grainstone, or bioclastic packstone to wackestone (Pl. 2/4).

Laterally, the biostromes commonly pinch out gradually over some tens of meters. The pinchout is associated with an increasing proportion of toppled rudists and coarse rudist debris. Some biostromes also show a relatively well-defined pinchout over some meters only. In the external platform succession, the upper boundary of the biostromes is commonly sharp where they are overlain by bioclastic grainstone (Pl. 2/5). Locally, the top of a biostrome is reworked to an up to some decimeters thick, coarse bioclastic horizon of well-rounded bioclastic debris (Pl. 2/6). In the internal platform succession, the top of one biostrome is visibly onlapped and buried by miliolid-bearing wackestones and packstones. Gradational upper boundaries occur, where the biostromes grade up-section into a progressively more open biostrome fabric with strongly bioeroded and fragmented specimens.

9. Interpretation and discussion

9.1 Biostrome fabrics

The two types of biostrome fabric (open fabric and packed fabric) bear a distinct environmental significance. Open biostrome fabrics are either related to the growth habit of recumbent rudists (caprinid biostromes, including *Ichthyosarcolites*) or to environmental conditions. The open hippuritid biostrome fabrics probably result from an episodically unstable bioclastic substrate close to the platform edge. An unstable substrate is suggested by the coarse bioclastic matrix and the common occurrence of overturned, large coral and hydrozoans heads and toppled hippuritid clusters.

The open biostrome fabrics built by large radiolitids might reflect a preference of these rudists for a substratum of clean, fine sand. The reasons for the more or less even spacing between the large radiolitids and the common paucity or absence of other rudists between, however, are unclear. The substratum that seems to be preferred by the large radiolitids may have been unfavourable for other rudists.

On the internal platform open biostromes indicate episodic storm destruction, or unfavorable environmental conditions. Storm destruction is suggested where coarse debris and toppled, gregarious radiolitids are associated with erect clusters and isolated individuals. Unfavorable environmental conditions, like muddy water and/or increasing salinity,
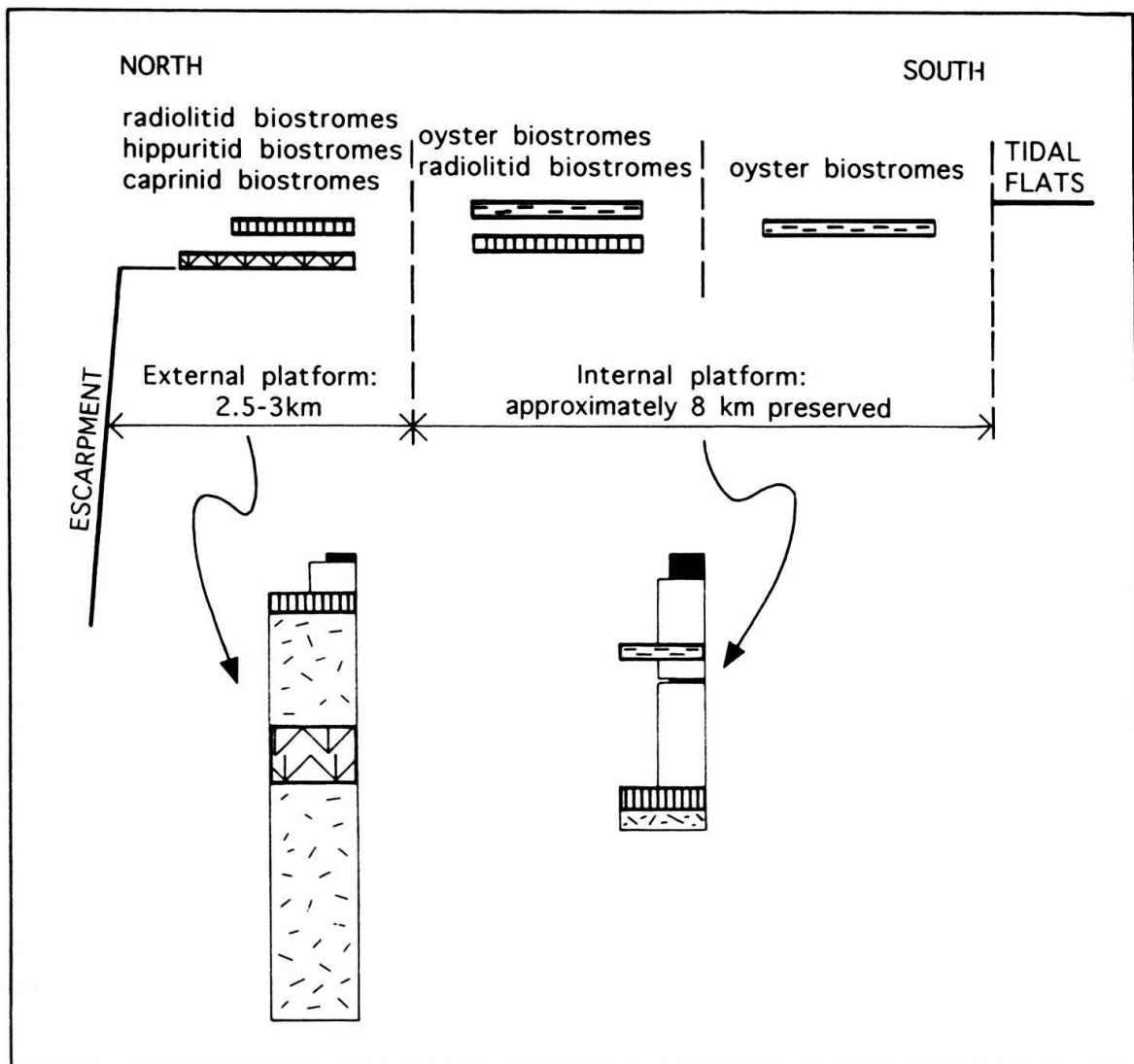
Fig. 9. Scheme of distribution of rudist biostromes from the external platform to the internal platform environment of the Maiella during the Late Cretaceous (for legend see Fig. 8). The external platform environment is characterized either by caprinid biostromes (Cenomanian), or by hippuritid biostromes and radiolitid biostromes (Turonian to Campanian). On the internal platform, both radiolitid biostromes and oyster biostromes flourish, but close to the tidal flats only oyster biostromes are present. In the lower part of the figure, two idealized upward thinning cycle sets are shown with the typical lithologies and the vertical position of the biostromes within the cycle sets.

are suggested where intact, but isolated rudists are embedded in a matrix of wackestone with miliolids, lituolids, ostracods, cryptmicrobial lumps and blackened bioclasts.

The packed biostrome fabrics probably record ecologic conditions that were favorable only for certain rudist genera. The arrays of upright rudist clusters most probably are a primary growth fabric. The inclined arrays of clusters may result from tilting due to storm washout of fine, supporting sediment (P. Skelton, written comm.), or it may also represent a primary fabric (Höfling 1985).

From its physiographic setting, the Upper Cretaceous rudist-rich Cima delle Murelle Formation of the Maiella would classify as a "steep margin complex" in the classification of Ross & Skelton (1993). By definition, steep margins had an original slope angle in excess of 10°, were situated in front of an oceanic or fault-bounded basin, and show an aggradational evolution (Ross & Skelton 1993). The described succession of the Maiella platform margin shows that a steep margin complex may internally be composed of stacked, progradational parasequences of up to some tens of meters in thickness.

9.2 Biostrome types and their stratigraphic position

From the external platform to the internal platform, different biostrome types occur (Fig. 9). The external platform succession is characterized by caprinid biostromes (lower sequence set; Cenomanian-?Turonian) or hippuritid biostromes (upper sequence set; ?Turonian–Upper Campanian). The internal platform succession contains radiolitid biostromes and oyster biostromes. A similar lateral and vertical stratigraphic distribution of rudists was observed in the Upper Cretaceous of other marginal segments of the Apulian platform (Accordi et al. 1987) and in the Upper Cretaceous of the Lazio-Abruzzi platform (Carbone & Sirna 1981; Accordi et al. 1982; Mariotti 1982). The change from Cenomanian caprinid communities to Turonian-Maastrichtian hippuritid communities is related to the extinction of most Caprinidae at the Cenomanian/Turonian transition (cf. Masse & Philip 1986; Philip & Airaud-Crumiere 1991).

In the external platform succession of the Maiella, (1) the large discrepancy between the amount of mollusc (rudist) bioclastic grainstone (70% to >85%) and the amount of rudist biostromes (8% to 18%), and (2), in the complete grainstone cycles, the close vertical association of the biostromes with the overlying shallow subtidal to supratidal limestones indicates that the biostromes were preserved only in a narrow range of water energy. The high amount of mollusc bioclastic grainstones also indicates that the rudists were mainly sediment producers, rather than "reef builders" (see also Carannante et al. 1993). The bioclastic dunes from which the grainstones were deposited (see above) most probably were intermittently colonized by rudists (Fig. 10). These thickets were repeatedly destroyed when the dunes migrated during episodic high-energy events. In the grainstone horizons, high-energy events are also suggested by the relatively common toppled and overturned rudists with the left valve still in place. During storms, rudist bioclastic material was also derived from biostromes that flourished in areas where the sand dunes were already inactive, whereas in other areas, the dunes remained active (cf. Sanders 1994). The crucial prerequisite for the preservation of the biostromes thus probably was dune aggradation accompanied by a local lowering of water energy. In the grainstone intervals below the biostromes, a lowering of water energy during sand-dune aggradation is suggested by the vertical succession from clinoforms of crudely-bedded, coarse bioclastic limestone at the base to very well-sorted and rounded, fine sand bioclastic limestone with megaripple laminasets at the top (Sanders 1994; see also Fig. 5).

In the internal platform succession, both the radiolitid biostromes and the oyster biostromes occur in the lower part or at the base of meter-scale lagoonal cycles. The biostromes thus occupy the part of the cycles that most probably corresponds to the bathymetrically deepest interval. This suggests that the biostromes grew soon after relative sea-level rise. Their growth was subsequently terminated by environmental restriction
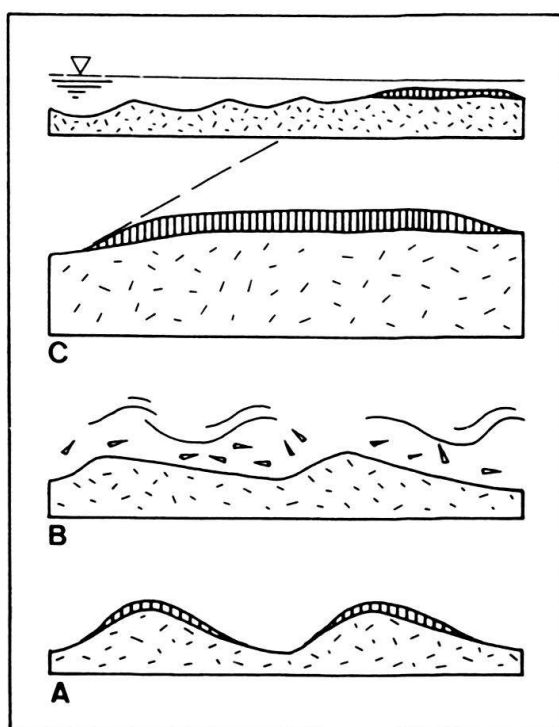
Fig. 10. Relation between the development of bioclastic sand dunes (hatched) and preservation of rudist biostromes (vertical lines). A: During calm periods, the surface of the sand dunes probably was covered by rudist thickets. Stage A represent a transient state that is not recorded. B: During storm-induced dune migration, the thickets were uprooted and destroyed. The shells of the dead rudists were turned to bioclastic sand. C: After prolonged sand dune aggradation and final abandonment, the local energy regime was lowered enough to allow both the spread and preservation of a rudist biostrome. Large, destructive waves were dissipated in areas where the sand dunes remained active. Stage C is preserved in the rock record.

(muddy water, increasing salinity). From their associated lithologies and their position near the top of upward-thinning cycle sets, the oyster biostromes would occupy the most internal position on the platform, close to the tidal flat environment. Farther offshore, the radiolitid biostromes flourished.

The biostromes of the external platform are typically in the upper part of the cycles, whereas the biostromes of the internal platform occur in the basal to lower part of the upward-shallowing cycles. This contrasting vertical position is probably controlled by the same environmental factors, i.e. water energy, sedimentation rate and environmental restriction (hypersalinity, water turbidity).

9.3 Growth of rudist biostromes

A rapid spread of the rudist biostromes is suggested by their large lateral extent, their commonly well-defined base, and by the laterally extensive rudist "meadows" that consist of rudists of very similar size and, most probably, the same species. Such "meadows" may occur both in an internal and external platform environment (cf. Grosheny & Philip 1989; Scott et al. 1990). By comparison with gregarious bivalves from recent continental shelves, the rudist meadows might have originated from "spatfalls" of larvae on to uncolonized substrata (cf. Barnes & Hughes 1988). Spatfalls typically lead to dense, monospecific biostromes of bivalves of the same age (larvae of following years are eaten by the existing colony; Barnes & Hughes 1988). If the rudists had a similar mode of colonization, this may provide at least a partial explanation for the large lateral extent of the biostromes, their well-defined base, and the extensive "meadows" of apparently one generation of the same genus. The rudists thus might have been able to colonize very large areas

of substrate within a year or a few years. The abundant gastropods at the base of some biostromes could provide a hard substrate for biostrome nucleation (cf. Vogel 1968; Herm & Schenk 1971). In general, however, the rudists were evidently able to spread directly on lime sand and lime mud substrates.

Favorable environmental conditions, at least for certain rudist genera, are suggested by the thick, packed hippuritid- or radiolitid biostromes with many successive generations of rudists. Such dense, paucispecific populations were probably sustained for a prolonged interval of time only if the overall ecologic conditions remained at or near maximum for the given rudist genera (compare Walker & Alberstadt 1975; Fagerström 1987). On the Maiella platform margin, the thickest packed hippuritid- or radiolitid biostromes occur on the external platform, i.e. in an environment of overall good aeration and water agitation, and without terrigenous input. The intercalations of bioclastic rudstone in many of the thicker biostromes of the external platform succession suggest that the biostromes, or parts of them, were episodically destroyed during high energy events (Sanders 1994). If the overall environmental conditions of the location remained within the zone suited for biostrome growth, the bioclastic material was soon re-colonized by the rudists. The intercalated horizons of foreset-laminated grainstone, and the sharp upper transition of many biostromes into the overlying grainstone horizons also indicate that the biostromes could be easily choked by migrating sandbodies. Thus, while the rudists probably were very efficient substrate colonizers (see also Ross & Skelton 1993), because of their inability to construct more or less wave-resistant bioherms, the rudist biostromes were highly vulnerable to destruction by high energy events and/or to choking by migrating sand bodies.

10. Conclusions

In the Cenomanian to Upper Campanian platform succession of the Montagna della Maiella, different types of biostromes are present from the external to the internal platform. Two types of biostrome fabric are distinguished: (1) open fabric and (2) packed fabric. Open fabric results either from an unstable substrate or from environmental restriction; this does not hold for recumbent rudists like caprinids, including *Ichthyosarcolites*. Packed biostrome fabric indicates optimum environmental conditions during biostrome growth, at least for a given group of rudists. The following types of mollusc biostromes were recognized (1) caprinid biostrome, (2) hippuritid biostrome, (3) radiolitid biostrome and (4) oyster biostrome. The external platform succession is characterized by caprinid biostromes (Cenomanian-?Turonian) and hippuritid biostromes (?Turonian–Upper Campanian). The ?Turonian-Campanian p.p. internal platform succession contains radiolitid biostromes and oyster biostromes.

Rudist biostrome growth and preservation were possible only in a relatively narrow range of environmental conditions (water energy, sedimentation rate, salinity). In the external platform succession, the discrepancy in the amount of rudist bioclastic grainstone (70% to >85%) to rudist biostromes (8% to 18%) indicates that the rudists served mainly as sediment producers. The facies architecture of the Upper Cretaceous external platform succession is characterized by up to more than 20 m thick horizons of bioclastic grainstone (deposited from bioclastic sand bodies) with intercalated, comparatively thin rudist biostromes. The rudist biostromes were vulnerable to choking by shifting sandbod-

ies, and were locally destroyed by storms. The rudists most probably were highly effective colonizers that could cover large areas of substrate within a very short interval of time.

Acknowledgements

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Plate 1 and 2

Plate 1

1. Topmost part of cross-bedded bioclastic grainstone. Two dune laminasets with opposite dip are separated by a reactivation surface. The upper dune laminaset is overlain by a rudist biostrome. Hammer is 35 cm long. Cima delle Murelle Formation. South side of Monte Acquaviva.

2. Thin section of cross-bedded bioclastic grainstone. The sediment is a moderately well to well sorted bioclastic grainstone composed of well-rounded rudist and other mollusc fragments and a minor amount of peloids and calcareous algae. Scale bar = 0.5 cm. Cima delle Murelle Formation. West side of Cima delle Murelle.

3. Small cluster of radiolitids in bioclastic grainstone. The right rudist is preserved with the upper (left) valve. Hand lens for scale. Cima delle Murelle Formation. Colle Daniele near Cima delle Murelle.

4. Biostrome that consists mainly of large *Ichthyosarcolites* embedded in a matrix of moderately sorted bioclastic grainstone-rudstone. Hammer is 33 cm long. Cima delle Murelle Formation. West side of Cima delle Murelle.

5. Part of rudist biostrome in the external platform succession. In the lower part of the picture, the biostrome is built by clusters of medium-size hippuritids and radiolitids. The backweathering "holes" in the middle part are the tests of large radiolitids, which form a horizon in the middle part of the biostrome. The upper part of the biostrome has an open fabric and is composed of erect radiolitids and some recumbent rudists. Hammer is 33 cm long. Cima delle Murelle Formation. South side of Acquaviva Gemello.

6. Detail of photo no. 5. Test of a large radiolitid in the middle part of the biostrome. Altimeter is 6 x 6 cm in size. Cima delle Murelle Formation. South side of Acquaviva Gemello.

7. Hippuritid biostrome with a packed fabric. Slender, gregarious hippuritids of one or a few species are arranged in a tightly interlocked fabric. Hammer is 33 cm long. Cima delle Murelle Formation. Eastern flank of Monte Sant'Angelo.

8. Internal mould of hippuritid bivalve with the preserved infills of borings. The borings are 0.5–1 mm wide. Borings of similar width and branching pattern are produced by clionid sponges and myzostomid worms. Scale bar = 1 cm. Cima delle Murelle Formation. South side of Acquaviva Gemello.
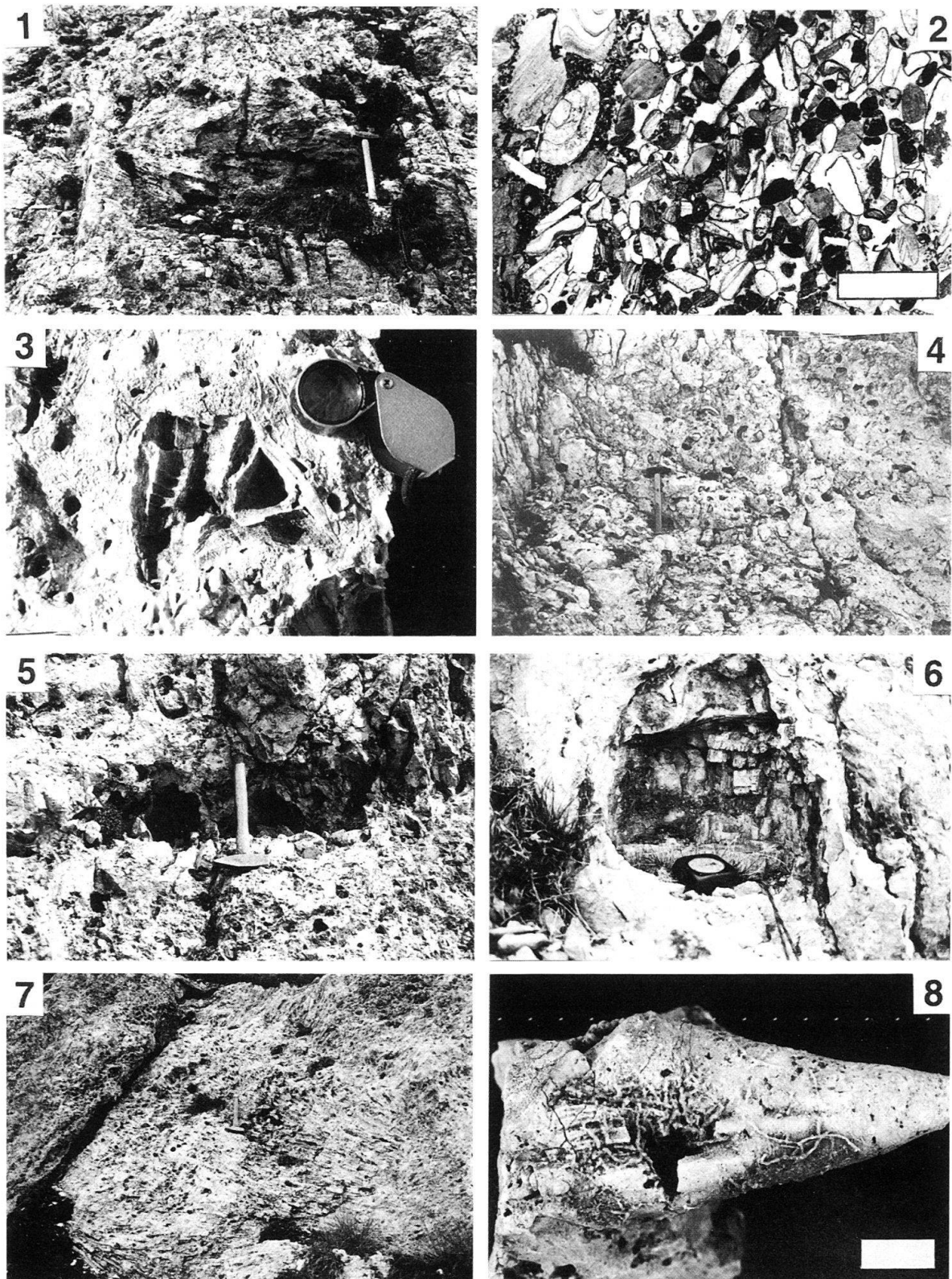
PLATE 1

Plate 2

1. Thin section of rudist biostrome matrix. Debris from radiolitids and other rudists is embedded in a micritic matrix. The rudist debris typically is angular. Micritization is minor to absent, whereas borings of the *Trypanites* type are common. Scale bar = 0.5 cm. Cima delle Murelle Formation. South side of Acquaviva Gemello.

2. Horizon rich in nerineid and actaeonid gastropods. Width of view approximately 1.1 m. Cima delle Murelle Formation. Eastern flank of Monte Sant'Angelo.

3. Biostrome of (?)stromatoporoids (dark specks on photograph) and oysters. The (?)stromatoporoids are elongate, often slightly branched, reticulated knolls up to 8 cm in diameter. The fossils are embedded in a matrix of bioclastic packstone-wackestone with scattered smaller benthic foraminifera. Hammer is 33 cm long. Fondo di Maiella Formation. Upper part of Valle di Macchia Lunga.

4. Evenly bedded bioclastic wackestones and packstones are overlain by an approximately 60 cm thick radiolitid biostrome with a packed fabric. Hammer is 33 cm long. Fondo di Maiella Formation. Ravone della Vespa.

5. Upper boundary of a rudist biostrome. In the lower part of the picture, the rudist clusters are sharply overlain by bioclastic grainstones. Hammer is 33 cm long. Cima delle Murelle Formation. South side of Acquaviva Gemello.

6. Horizon of well-sorted and very well-rounded bioclastic debris (mainly debris from rudist shells) above a rudist biostrome. Note the thick cement fringes (white) between the components. Hand lens for scale. Cima delle Murelle Formation. West side of Cima delle Murelle.

PLATE 2