FACIES	41	81-110	Pl. 19-26	11 Figs.	1 Tab.	ERLANGEN 1999

Drowning of a Lower Jurassic Carbonate Platform: Jbel Bou Dahar, High Atlas, Morocco

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KEYWORDS: CARBONATE SEDIMENTOLOGY – PLATFORM DROWNING – MICROFACIES ANALYSIS – DEPOSITIONAL GEOMETRIES – MOROCCO (HIGH ATLAS) – LIASSIC

CONTENTS

SUMMARY

The high-plateau of the Jbel Bou Dahar, situated in the Central and Eastern High Atlas of Morocco, represents a Lower Jurassic carbonate platform that drowned at the beginning of the Toarcian. Three phases of platform evolution can be distinguished:

During the *pre-drowning phase* (upper Sinemurian - upper Pliensbachian) the platform interior facies reflects a restricted-marine lagoonal environment, protected by scattered buildups and cemented debris at the platform margin. Upper and mid-slope are dominated by coarse-grained, poorly sorted limestones, deposited through debris flows during sea-level lowstands. Sea-level highstand deposits occur at the toe of slope and are formed by an alternation of fine-grained litho- and bioclastic pack- to grainstones (turbidites), marls and mud- to wackestones (hemipelagic oozes).

A condensed section, reflecting an abrupt and fundamental environmental change along the entire platform, characterises the *drowning phase* (upper Pliensbachian - lower Toarcian). Within the platform interior densely packed biosparites represent the switch to high-energy environments, causing erosion of the former pre-drowning lagoonal sediments. These erosional products were redeposited on the platform slope, leading to the formation of coarse-grained non-skeletal sparites and micrites. Both platform interior and slope successions show a series of cyclic variations in sediment composition that could have been triggered by small-scale sea-level fluctuations.

In contrast to the abrupt facies change at the pre-drowning - drowning boundary, the transition to the *post-drowning phase* (lower Toarcian - Aalenian) is gradual. During this phase, biopelmicrites and pure micrites were deposited in all platform sections, followed by the deposition of calcisiltites. The facies point to quiet-water conditions below storm-wave base and display a uniform deep-marine sedimentation.

This analysis shows that the drowning of the Jbel Bou Dahar carbonate platform was caused by abrupt and fundamental changes in the shallow-water realm. After exposure of the platform, these changes prevented the carbonate factory from re-establishing itself and made it impossible for the platform to keep up with the subsequent rise in sea level. These local changes were probably triggered by high-frequency sea-level variations in combination with regional or even world-wide changes in ocean circulation patterns.

1 INTRODUCTION

1.1 Geological setting

The geology of Morocco is dominated by the structural elements of the Atlas System, comprising Rif-, Middle-, High- and Anti-Atlas (RICHTER, 1970; Fig. 1). The WSW - ENE trending mountain chain of the High Atlas represents an intracratonic rift that during the Triassic caved in along ancient fracture zones at the northern margin of the Sahara Craton. After a marine ingression at the beginning of the Jurassic (Sinemurian - Hettangian?) the High Atlas seaway separated the Sahara Craton from two smaller microplates (Moroccan and Oran Meseta) to the north. These plates were separated from each other by the NE - SW striking basin of the Middle Atlas (Figs. 1 and 2).

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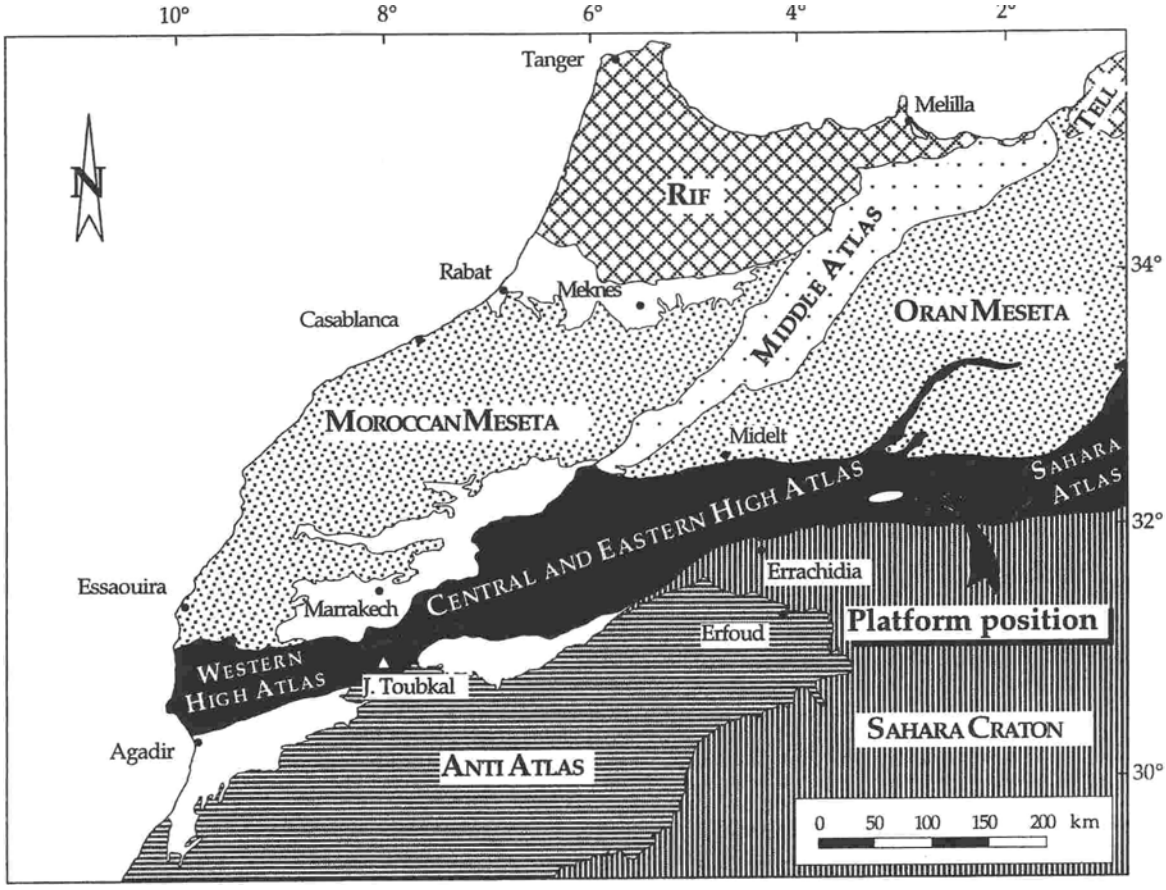


Fig. 1. Structural-geologic map, showing the major geologic provinces of Morocco (after WARME, 1988). White areas mark younger Cenozoic Basins. The Jbel Bou Dahar carbonate platform is shown in its original size and orientation.

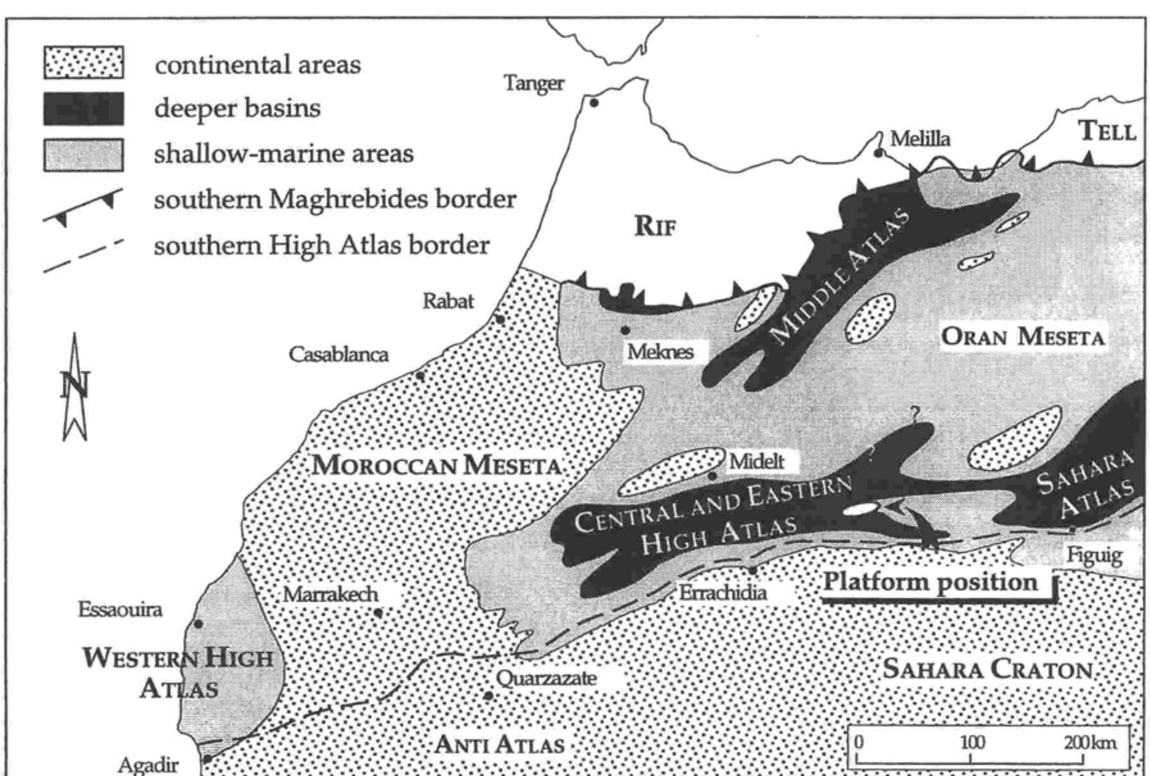


Fig. 2. Paleogeographic map of Morocco showing the major geologic provinces within the Middle Liassic (after DU DRESNAY, 1971).

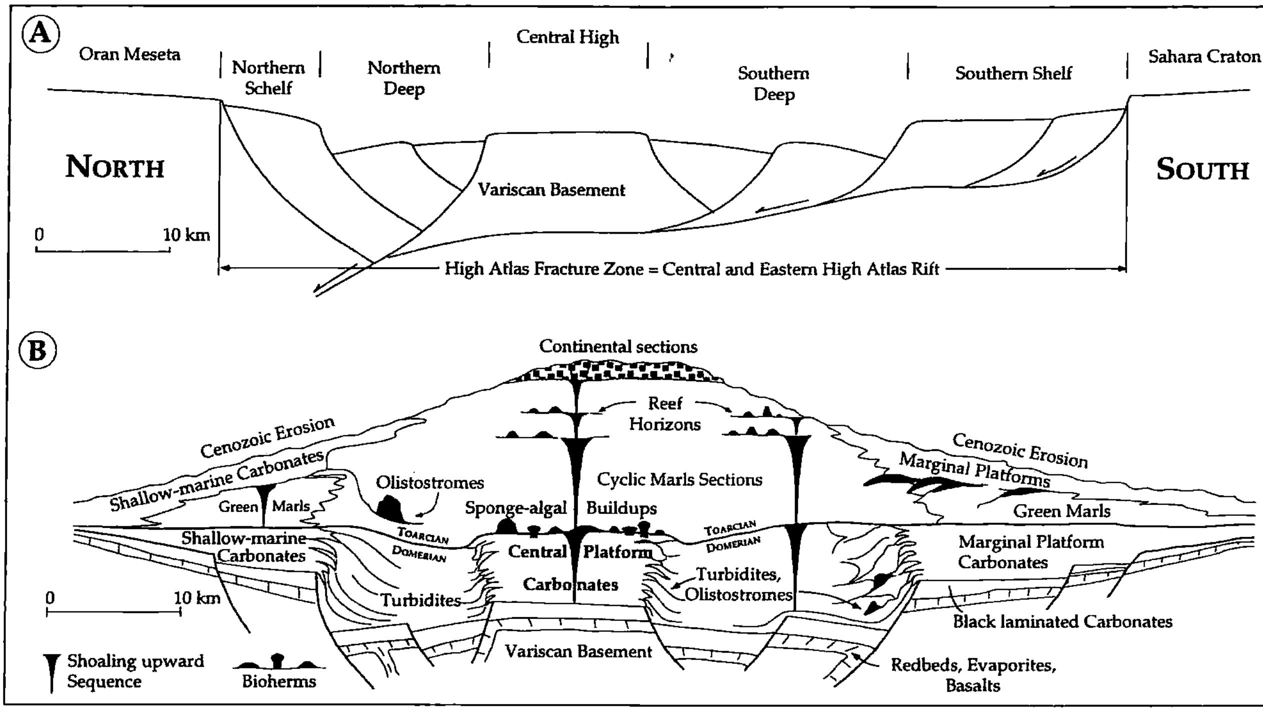


Fig. 3. Schematic cross-section of the entire Mesozoic succession of the Central and Eastern High Atlas between Errachidia and Midelt. A: Distribution of the major fault blocks. B: Depositional successions above the different paleogeographic segments (after WARME, 1988). The central platform carbonates (profile B) can be compared with the relative position of the Jbel Bou Dahar carbonate platform.

Continental (dry rift; WARME, 1988) and marine sedimentation (wet rift) within the Central and Eastern High Atlas Rift (CEHAR) and the tectonic deformation of the entire mountain range itself was controlled by an extensive fault pattern present within the basement. During the Sinemurian the renewed onset of tectonic movements along this horst-and-graben mosaic led to the fragmentation of extensive carbonate ramps (DUBAR, 1962; DU DRESNAY, 1979). Carbonate platforms like the Jbel Bou Dahar remained existent on topographic highs in the centre and along the margins of the rift basin (Fig. 3). These flat-topped, high-productive platforms were abruptly drowned at the beginning of the Toarcian and buried by fine-grained deep-marine carbonates and marls (DU DRESNAY, 1979; WARME, 1988).

1.2 The Jbel Bou Dahar carbonate platform

Jbel Bou Dahar is an oval shaped high plateau with a maximum height of nearly 500 m at approx. 1.000 m above sea level. The platform is about 36 km long and 8 km wide, with its longitudinal axis orientated in an ENE/WSW direction (Fig. 4). Complete exposure, minor tectonics and diagenetic overprints make the Jbel Bou Dahar an outstanding example of a totally preserved and intact Mesozoic carbonate platform.

Studies on the platform architecture were carried out by CREVELLO (1990), who compared the evolution of Jbel Bou Dahar with other carbonate platforms situated along the southern margin of the rift basin. In addition, he showed that the inner-platform deposits contained a facies-stacking pattern that could be linked to the interplay of orbital forcing and subsidence.

KENTER (1990) concentrated his investigations on the overall geometry of the platform slope. In his study the relationships between slope geometry and the dispersal and composition of the sediments are discussed (KENTER & CAMPBELL, 1991).

CAMPBELL (1992), CAMPBELL & STAFLEU (1992), and STAFLEU (1994) used the Jbel Bou Dahar as an example for modelling studies of carbonate platform geometries and drowning unconformities. The artificial seismic models generated through these studies that were then compared with other seismic structures (STAFLEU & SCHLAGER, 1995) and with the original findings at the Jbel Bou Dahar provided excellent correlations.

BLOMEIER (1997) focused his investigations on the drowning succession along the entire platform, but most of all on the facies patterns of the slope sediments and their sequence stratigraphic interpretation. Some of the results of that study form the base for this manuscript.

The development of the Jbel Bou Dahar carbonate platform started with the renewed onset of tectonic movements along an extended horst-and-graben mosaic in the upper Sinemurian. After this process, causing the fragmentation of broad shallow-marine carbonate ramps (CREVELLO, 1990), Jbel Bou Dahar remained as an isolated platform on a horst structure in the axial part of the rift basin (LAVILLE, 1988). Based on biostratigraphic ammonite zonations, the evolution of the Jbel Bou Dahar can be divided into three successive stages. The following data were used to establish these zonations: (A) direct determinations of ammonite assemblages, (B) calibrations of the shallow-marine fauna (mainly foraminifers and calcareous algae) with the ammonite zonations, and (C) lithostratigraphic correlations of the

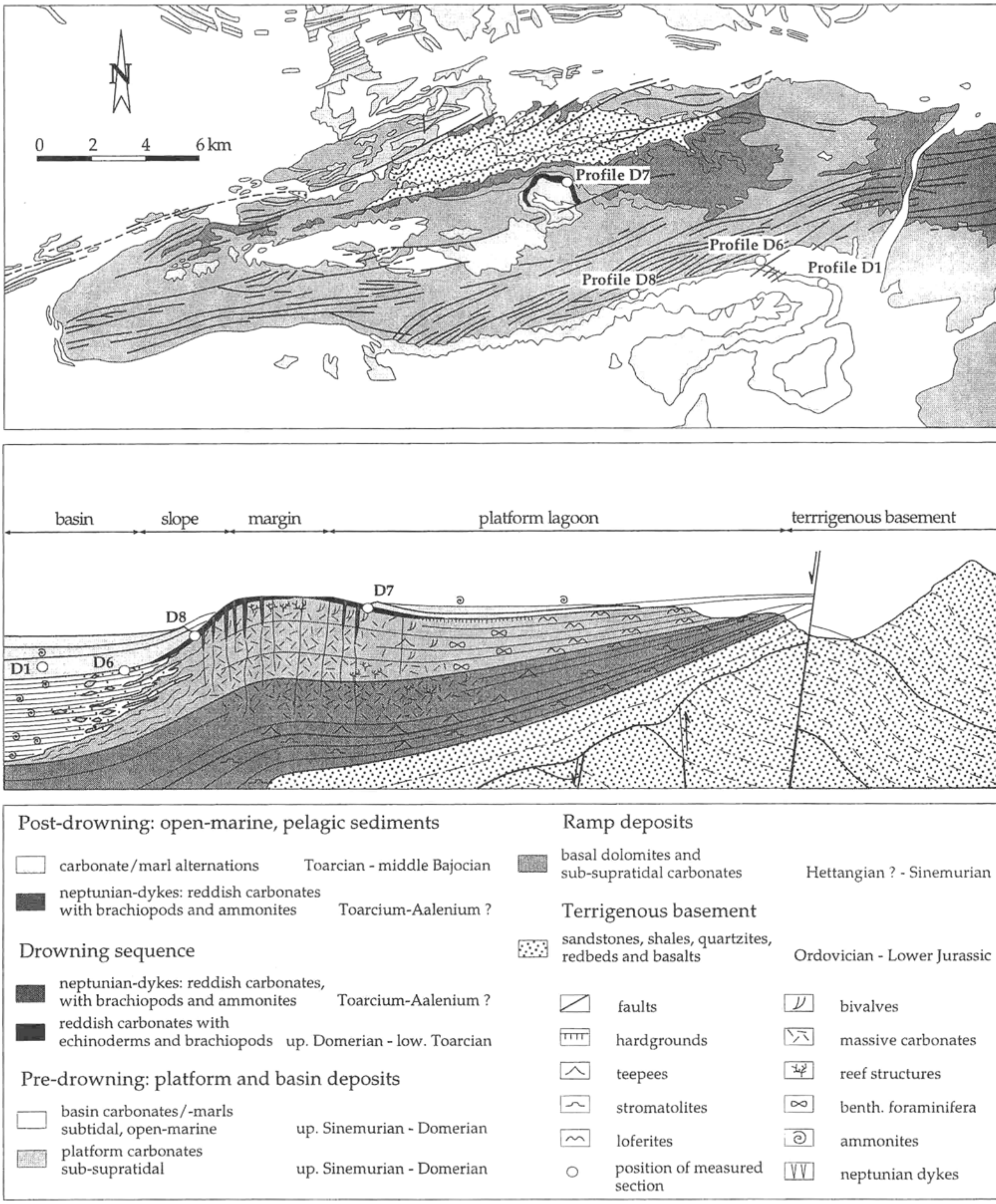


Fig. 4. Simplified geologic map and schematic cross-section of the Jbel Bou Dahar carbonate platform. (after Ghissassi et al., 1976).

shallow-marine platform strata and the deep-marine sediments within the basin (Dubar, 1948, 1950; Agard & Du Dresnay, 1965; Crevello, 1990).

The first stage, or pre-drowning phase, lasted from the upper Sinemurian to the upper Pliensbachian (Domerian). During this period aggradation and progradation of the platform was observed (Crevello, 1990). A variety of distinct facies zones developed, ranging from a lagoonal interior on the flat platform top to a deep marine environment at the toe of slope. Platform growth and sedimentation was controlled by the evolution of shallow-marine, carbonate-producing organisms in response to sea-level variations,

Nr.	Group	Categories			
1.	Matrix	Micrite	Cements		
2.	Shallow-marine platform biota	Corals	Bivalves	Gastropods	Foraminifers
		Encrusters	Calcareous algae	Recrystallized skeletal fragments	
3.	Suspension feeders & grazers	Echinoderms	Brachiopods		
4.	Open-marine biota	Ammonites	Siliceous sponges	Filaments	Calcispheres
5.	Encrusted grains	Oncoids	Micro-oncoids	Aggregate grains	
6.	Non-skeletal grains	Ooids	Lithoclasts		
7.	Peloids	Fecal pellets	Algal peloids	Pseudo-peloids	Bahamite peloids
8.	Terrigenous input	Quartz clasts			

Tab. 1. The point-count groups and -categories used in this study.

which periodically led to exposure of the platform top (Crevello, 1990). The platform margin consists of cemented debris with scattered build-ups, like bivalve mudmounds, some coralgal patch-reefs and sponge biostromes (Scheibner & Reijmer, this volume). The zone separates the coarse-grained upper slope deposits, rich in platform margin debris, from ooid shoals and micritic sediments on the platform top.

During the upper Domerian to the lower Toarcian the platform drowned and a thin, condensed section, containing a characteristic bio- and lithofacies, was deposited on the former platform surface.

Within the subsequent post-drowning phase deep-marine sediments, consisting of carbonate/marl alterations, form a distinct drowning unconformity on the steep flanks of the carbonate platform (Schlager, 1989). On the platform top a single bed, rich in partly dissolved ammonites, marks the beginning of this phase. Ammonite assemblages in the upper part of the succession verify the continuation of the hemi-pelagic depositional environment into the Bajocian (Warme, 1988).

The aim of this study is to document the actual drowning of the platform through a combination of detailed field studies and microfacies analysis. Based on these results a comparison will be made between the depositional environments that occurred before, during and after the drowning of the carbonate platform.

2 METHODS

To document the environmental changes during the entire platform evolution, four vertical profiles were studied, situated within different facies zones along the platform (Fig. 4). The profiles comprise all phases of platform growth (pre-drowning, drowning and post-drowning) and allow for a precise correlation of the sediments deposited within each phase. Large-scale platform geometries, depositional features (sediment stacking and dispersal patterns) and sedimentary structures were studied within the surrounding areas of the vertical sections. All successions were sampled bed by bed for thin section analysis, comprising qualitative and quantitative investigations of the sedimentary content. Quantitative analyses were made by point counting the thin-sections. In every slide 200 points were counted using the grain solid method (Dunham, 1962). In total 25 different categories were distinguished and subsequently grouped into 8 point-count groups (Tab. 1). Authigenic minerals like dolomite, quartz, glauconite, Fe-, Mn-enrichments or phosphate-impregnations were discarded from the counting procedure.

Based on frequency distributions of the different types of matrix and components, the sediments were classified after Dunham (1962) and Folk (1962). Furthermore nearly all types of microfacies (MF) could be classified according to the standard microfacies types (SMF) and facies zones (FZ) of Wilson (1975).

3 MICROFACIES ANALYSIS

3.1 Matrix and component descriptions

Group 1: Matrix

This group comprises the material deposited between sand-sized grains and mainly consists of microsparite and various types of cements.

1a: Micrite, mainly preserved as microsparite (Folk, 1959) forms a microcrystalline, very fine-grained, light-to dark-grey or reddish matrix. The average grain size of the single crystals varies between 4 and 10 µm. Maximum sizes of around 40 µm were mainly reached within marginal areas close to cement-filled pore spaces.

Microsparite is present in all sections and all phases of the platform evolution. Especially in the pre-drowning phase microsparite is frequently encountered within platform interior sediments (pelmicrites, micrites, loferites; SMF 19, 21, 22) and sediments deposited at the toe of slope (biopelmicrites; SMF 3). During the drowning phase a general increase in primary mud can be observed leading to the deposition of pure micrites (SMF 3) within the post-drowning phase.

1b: Various types of cements were precipitated within primary voids and secondary cavities.

Micrite cements (Pl. 19/1)

This cement type usually forms marginal, irregular, up to 250 µm thick rims within primary cavities. According to the red-brownish or light-grey colours, subsequent cementation generations can be distinguished.

The occurrence of this cement type is limited to the pelmicrites and micrites (SMF 19, 21) deposited within the platform interior during the pre-drowning phase.

Fibrous cements (Pl. 19/2, 7, 8, Pl. 21/2)

Radial-fibrous cements form isopachous, up to 800 µm thick crusts on various bioclasts and non-skeletal grains. The sub- to euhedral crystals occur in primary cavities as well as in secondary pore spaces like dissolved bioclasts.
This cement type occurs exclusively within the platform interior and slope sediments of the pre- and drowning phase (SMF 17, 12, 5, 4; MF 1).

Syntaxial cements (Pl. 19/3, 4)

This cement type is restricted to echinoderm fragments and forms irregular, clear, up to 1mm thick rims enclosing the bioclasts.

The cements were present in all sections and platform phases. Remarkable is the increased occurrence within the echinoderm-rich biosparites (SMF 12), deposited on the platform top during the drowning phase.

Dripstone cements (Pl. 19/5, 6, Pl. 24/6)

This cement type forms irregular thick, incomplete outer rims that partly surround ooids and echinoderm fragments. The clear crystals grow perpendicular to the substrate surface and are characterised by dissolution marks at the base. The occurrence of these gravitational cements is limited to sediments (biomicrites, SMF 3) deposited on the platform top at the beginning of the post-drowning phase. The cement rims are mainly found on ooids and echinoderm fragments that are partly dissolved, strongly impregnated or phosphatized. Nucleus and rim of the clasts point to the shallow-marine depositional realm as their source area. This type of environment did not exist anymore during the post-drowning phase. Thus, we assume that the components were formed either at the end of the pre-drowning phase or within the early stage of the drowning. Subsequently they were removed out of their original environment and redeposited within the post-drowning sediments. This transport might also explain the different directions of the cement lobes on the grains.

Dogtooth cements (Pl. 19/2, 8)

This cement type is characterised by single sub- to euhedral crystals with a maximum length of 800 µm. It was found as a primary cement generation on various components or as a second generation on previously precipitated fibrous cements. The crystals show different growth directions more or less perpendicular to the substrate. They form irregular or incomplete palisade-like rims that grow into primary cavities or secondary pore spaces such as dissolved skeletal fragments.

The occurrence of this cement type is mainly limited to sparites (SMF 5, 4) deposited on the slope during the pre-drowning phase.

Blocky cements (Pl. 19/1-4, 7, 8)

The clear anhedral to subhedral crystals, up to 1mm in size, always form the last cement generation found within the sediments. They grow directly on the substrate or on former precipitated cements and infill remaining pore spaces totally.
Blocky cements are the most common cement-type that occurs in all platform sections within all phases.

Group 2: Shallow- marine biota

This group comprises bioclasts of all sessile shallow-water organisms that originate on the platform top and within the margin. At the margin these organisms form distinct *in situ* build-ups like bivalve mud-mounds, coralgal patch-reefs and sponge biostromes (Crevello, 1990; Kenter,

Plate 19 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Cements

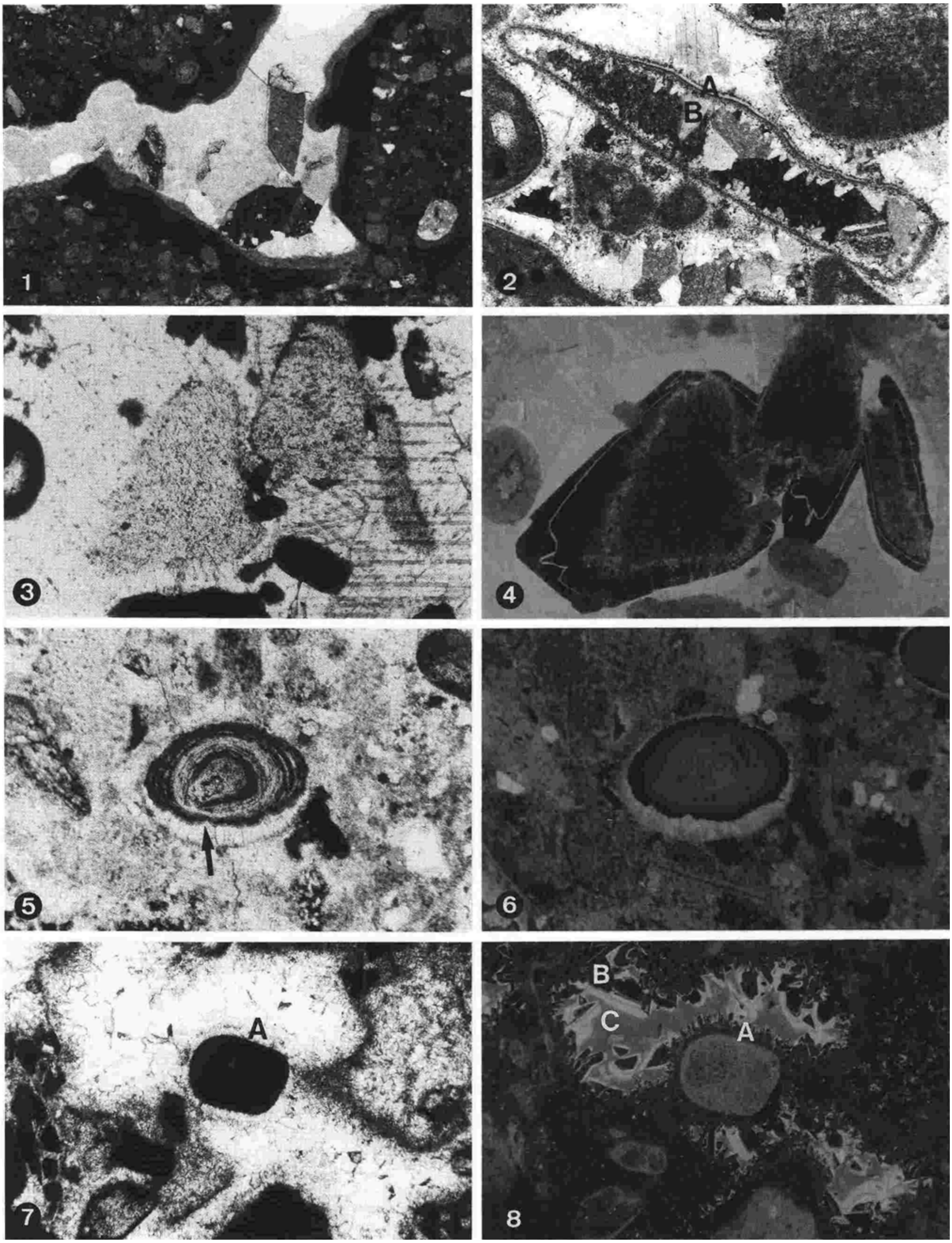
Fig. 1. Pre-drowning phase, platform interior (SMF 22): Primary cavity within a densely packed pelmicrite. The cemented rim consists of subsequent generations of irregular micrite cements with various reddish-brown and grey colours. Within the centre of the intergranular pore-space blocky cements were precipitated. x 24

Fig. 2. Pre-drowning phase, upper slope section: Recrystallized skeletal fragment under crossed nicols. The secondary cavity is cemented by a sequence consisting of three different cement types, a) Thin, isopachous rim of radial-fibrous cements, b) scalenohedric crystals, c) blocky cements. x 24

Figs. 3-4. Pre-drowning phase, middle slope section: Irregular overgrowth of syntaxial, banded-luminescent cements on echinoderm fragments in transmitted-light and under cathodoluminescence. x 12

Figs. 5-6. Post-drowning phase, platform top section: Single, mineralized ooid with an outer rim consisting of dripstone cements in transmitted-light and under cathodoluminescence. Note the dissolution features at the base of the dull-luminescent outer cement rim (arrow) and purple luminescence of the ooid. x 24

Figs. 7-8. Pre-drowning phase, middle slope section: Primary, interparticulary vug in transmitted-light and under cathodoluminescence. The cementation succession visible consists of (a) light-brown luminescent, radial-fibrous cements, (b) non-luminescent, dog-tooth cements and (c) banded, yellow to brown luminescent, blocky cements. x 12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1990; BLOMEIER, 1997; SCHEIBNER & REIJMER, this volume)

2a: Corals (Pl. 20/1)

In this group bioclasts are combined of solitary and colonial Scleractinia that usually are poorly preserved and completely recrystallized.
The occurrence of Scleractinian corals is limited exclusively to the sediments of the pre-drowning phase. During this period the frame-building organisms form irregulary scattered, isolated coralgal patch-reefs along the platform margin (CREVELLO, 1990; KENTER & CAMPBELL, 1991; SCHEIBNER, 1995; BLOMEIER, 1997). After erosion the skeletal fragments were deposited onto the platform slope. The highest amounts were found within coarse-grained biosparites (SFM 5, 4) of the mid-slope.

2b: Bivalves (Pl. 20/2)

This group incorporates the recrystallized bioclasts of bivalves with a primary aragonitic shell and oyster valves with primary low-Mg-calcite mineralogy.
The composition and distribution of these components show large differences when comparing the pre-drowning and drowning phase. Within the pre-drowning phase extended, autochthonous banks are formed within the shallow-marine facies belts of the platform top and margin by primary aragonitic bivalves e.g. *Lithiotis*, *Cochlearites*, *Opisoma*, *Lithoperna* (CREVELLO, 1990; SCHEIBNER, 1995; SCHEIBNER & REIJMER, this volume). After erosion these bioclasts were transported and redeposited on the platform slope (SMF 5, 4). During the drowning phase, however, oysters dominate this point-count group. They form low-diverse lumachelles (MF 3) on the mid-slope with well-preserved shells and fragments.

2c: Encrusting organisms (Pl. 20/3-9, Pl. 21/1-3)

This group comprises various species of microproblematica, sessile foraminifers, porostromate algae (e.g. *Girvanella*), bryozoans and serpulids. The bioclasts occur as isolated fragments or attached on shallow-water organisms, mainly associated within the build-ups of the platform margin.

Microproblematica are the most frequently encountered encrusters and comprise the species *Thaumatoporella parvovesiculifera*, *Tubiphytes obscurus*, *Radiomura cautica* and *Bacinella* sp. Sessile foraminifers present belong to the Cornuspiridae, Nubeculariidae and Polymorphinidae.

Bioclasts of this group mainly occur within the slope sediments (SMF 5, 4) of the pre-drowning phase. During this period they occur within the build-ups of the platform margin and form important sediment-binder and –baffler within this environment (CREVELLO, 1990). Within the drowning phase nubeculariid foraminifers occur attached to oysters and brachiopods (MF 3) within the coquinas of the mid-slope.

2d: Calcareous algae (Pl. 21/4, 5, 7-10)

This group comprises skeletal fragments of Dasycladaceae, Solenoporaceae and *Cayeuxia* species. The components show well preserved internal structures (tubes, pores or filaments) and usually are encrusted by foraminifers or spongiostromate algae.

In general, the occurrence of these algae is limited to the pre-drowning phase. They show a specific distribution pattern along the platform. Within the platform interior (SMF 22) mainly *Cayeuxia* fragments occur, while *Dasycladaceae* and *Solenoporaceae* fragments predominantly are found on

Plate 20 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Skeletal fragments: corals, bivalves, encrusting organisms

Fig. 1. Pre-drowning phase, middle slope section: Scleractinian coral fragment, showing radial orientated septae and a central columella. The bioclast is partially encrusted by sessile foraminifers (arrow). x 6

Fig. 2. Pre-drowning phase, platform margin: Bivalve-bioherm consisting of densely packed *Lithiotis* specimens. The organisms form low-diverse, autochthonous build-ups within the shallow sub- to inter-tidal environment of the platform margin. Hammer for scale.

Fig. 3. Pre-drowning phase, lower slope section: The microproblematicum *Thaumatoporella parvovesiculifera* RAINERI forms a suspension bridge-like encrustation within a vug of a nearly completely recrystallized coral fragment. x 12

Fig. 4. Pre-drowning phase, lower slope section: The attached microproblematicum *Bacinella ordinata* PANTIC is characterised by a layered structure, consisting of single lines of bubble-like cells. x 24

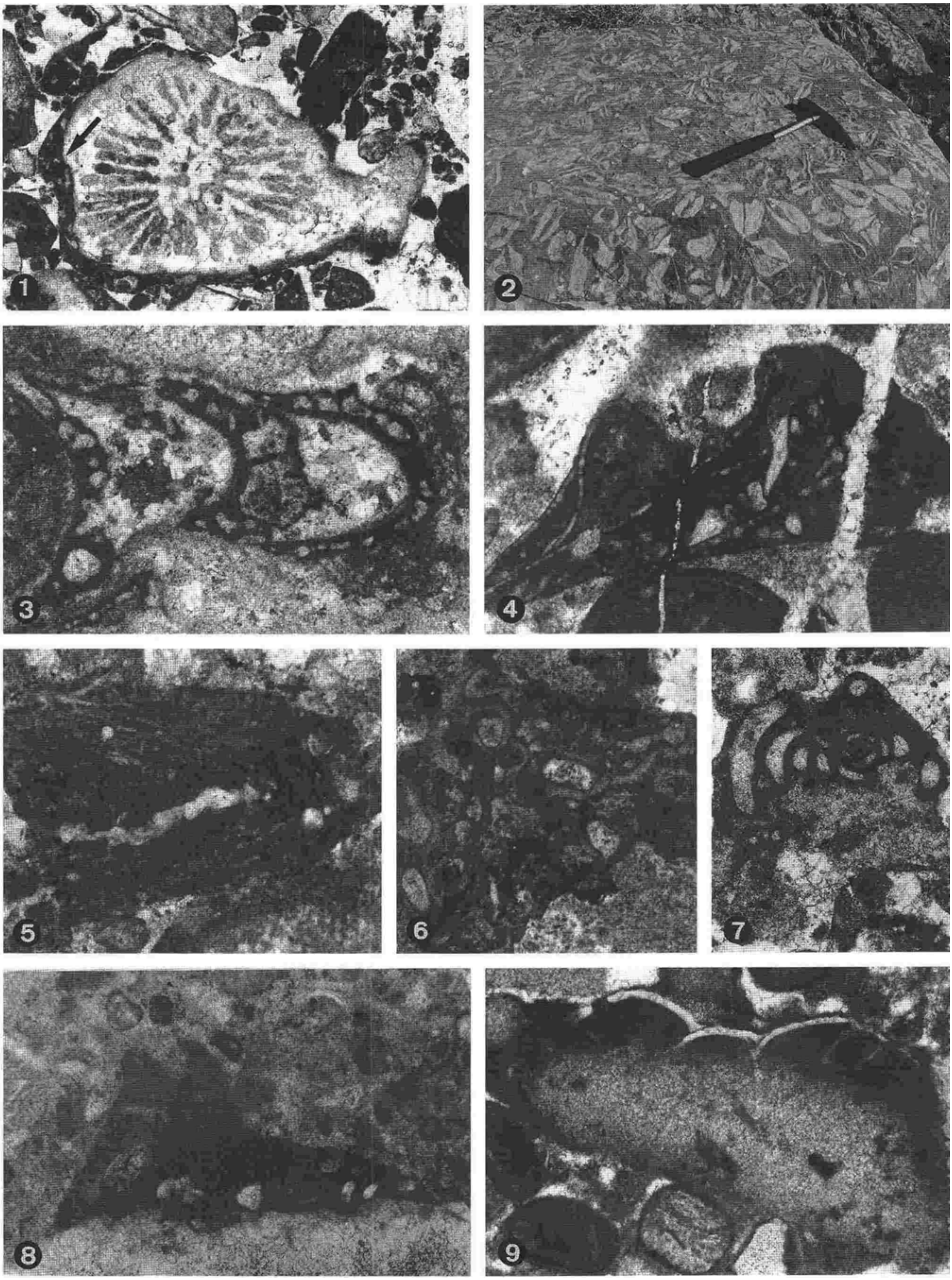
Fig. 5. Pre-drowning phase, lower slope section: Different views of the microproblematicum *Tubiphytes obscurus* MASLOV. The aggregates, shown in cross- and longitudinal-section, are characterised by micrite laminae with a central, chambered axial tube. x 24

Fig. 6. Pre-drowning phase, middle slope section: Irregulary chambered fragment of the microproblematicum *Radiomura cautica* SENOWBARI-DARYAN & SCHÄFER. The cell walls are characterised by a micro-crystalline, radial-fibrous structure. x 6

Fig. 7. Pre-drowning phase, lower slope section: Fine-agglutinated, sessile miliolid foraminifer, encrusting a recrystallized skeletal fragment. x 24

Fig. 8. Pre-drowning phase, middle slope section: Fine-agglutinated nubeculariid foraminifer encrusting a recrystallized skeletal fragment. x 24

Fig. 9. Pre-drowning phase, lower slope section: Simply convex-bounded shells of the polymorphinid foraminifer *Bullopora* sp., encrusting an echinoderm fragment. x 24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the slope. The latter are probably associated with the sessile organisms found within the build-ups at the platform margin.

2e: Gastropods (Pl. 21/6)

The shells of gastropods are usually completely recrystallized. They are present in all facies zones of the pre-drowning phase. During the drowning phase the components occur mainly on the platform top, forming an important category of low-diverse biosparites (SMF 12).

2f: Foraminifers (Pl. 22/1-14)

A wide-range of benthic-vagile foraminifers can be encountered throughout nearly all facies types. Using the taxonomic classification of LOEBLICH & TAPPAN (1988) the following groups were identified: Ammodiscidae REUSS, 1862; Ataxophragmiidae SCHWAGER, 1877; Cyclamminidae MARIE, 1941;

Endothyridae BRADY, 1884; Hormosinidae HAECKEL, 1894; Involutinidae BÜTSCHLI, 1880; Lituolidae DE BLAINVILLE, 1827; Mesoendothyridae VOLOSHINOVA, 1958; Nodosariidae EHRENBERG, 1838; Ophtalmidiidae WIESNER, 1920; Orbitopsellidae HOTTINGER & CLAUS, 1982; Pseudoaxidae MAMET, 1974; Spirocyclinidae MUNIER-CHALMAS, 1887; Tetrataxidae GALLOWAY, 1933; Textulariidae EHRENBERG, 1838; Trochamninidae SCHWAGER, 1877; Vaginulinidae REUSS, 1860.

The occurrence of most forms is limited to the pre-drowning phase. Here, fine-agglutinated Ammodiscidae, Trochaminidae, Tetrataxidae and Pseudotaxidae mainly occur within the platform interior (SMF 22), whereas large (e.g. Spirocyclinidae) and coarse-agglutinated species (Cyclamminidae, Lituolidae) are mainly found within the slope sediments (SMF 5). Vaginulinidae and Nodosariidae foraminifers, however, show a widespread distribution and are common in all sections and within all platform-drowning phases.

2g: Recrystallized fragments (Pl. 19/2)

This category comprises all shallow-water skeletal fragments whose primary aragonitic skeleton is partly or totally replaced and thus not could be classified properly. Most likely these components originate from shallow-marine platform organisms like molluscs, corals or calcareous algae.

The fragments mainly occur within the slope sediments of the pre-drowning phase (SMF 5, 4) and within the biosparites and -micrites (SMF 12, MF 2) of the drowning phase on the platform-top.

Group 3: Suspension feeders and grazers

This group comprises echinoderm and brachiopod fragments that appear in large quantities within the sediments of the drowning phase and thus characterise this specific depositional environment.

3a: Echinoderms (Pl. 23/1-3)

The category comprises spines and plate-fragments of crinoids and echinoids that occasionally show borings, small-scale micritizations and phosphatizations. Sometimes they are encrusted by sessile foraminifers or spongiostromate algae.

Within the pre-drowning phase, the fragments show a widespread distribution that ranges from the platform interior to the toe of slope, where the highest amounts are found. Within the drowning sequence, the massive occurrence of echinoderm bioclasts together with recrystallized skeletal fragments led to the formation of characteristic biosparites

Plate 21 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Skeletal fragments: encrusting organisms, calcareous algae and gastropods

Fig. 1. Pre-drowning phase, lower slope section: Serpulid worm tubes in various orientations infilled with microsparite. x 6

Fig. 2. Pre-drowning phase, upper slope section: Longitudinal section of a microsparite-infilled bryozoan zoarium, on top of a recrystallized bioclast. Note the radial-fibrous cement rim enclosing the component (arrows). x 24

Fig. 3. Pre-drowning phase, lower slope section: Longitudinal section of a fan-shaped bryozoan partly displaced by authigenous quartz crystals (right photo-section). x 12

Figs. 4-5. Pre-drowning phase, middle slope section: Longitudinal and horizontal cross-section of a stem-fragment of the dasycladacean algae *Dissocladella ebroensis* DRAGASTAN & TRAPPE. Central pore space and wall pores are encrusted by sessile foraminifers. x 6

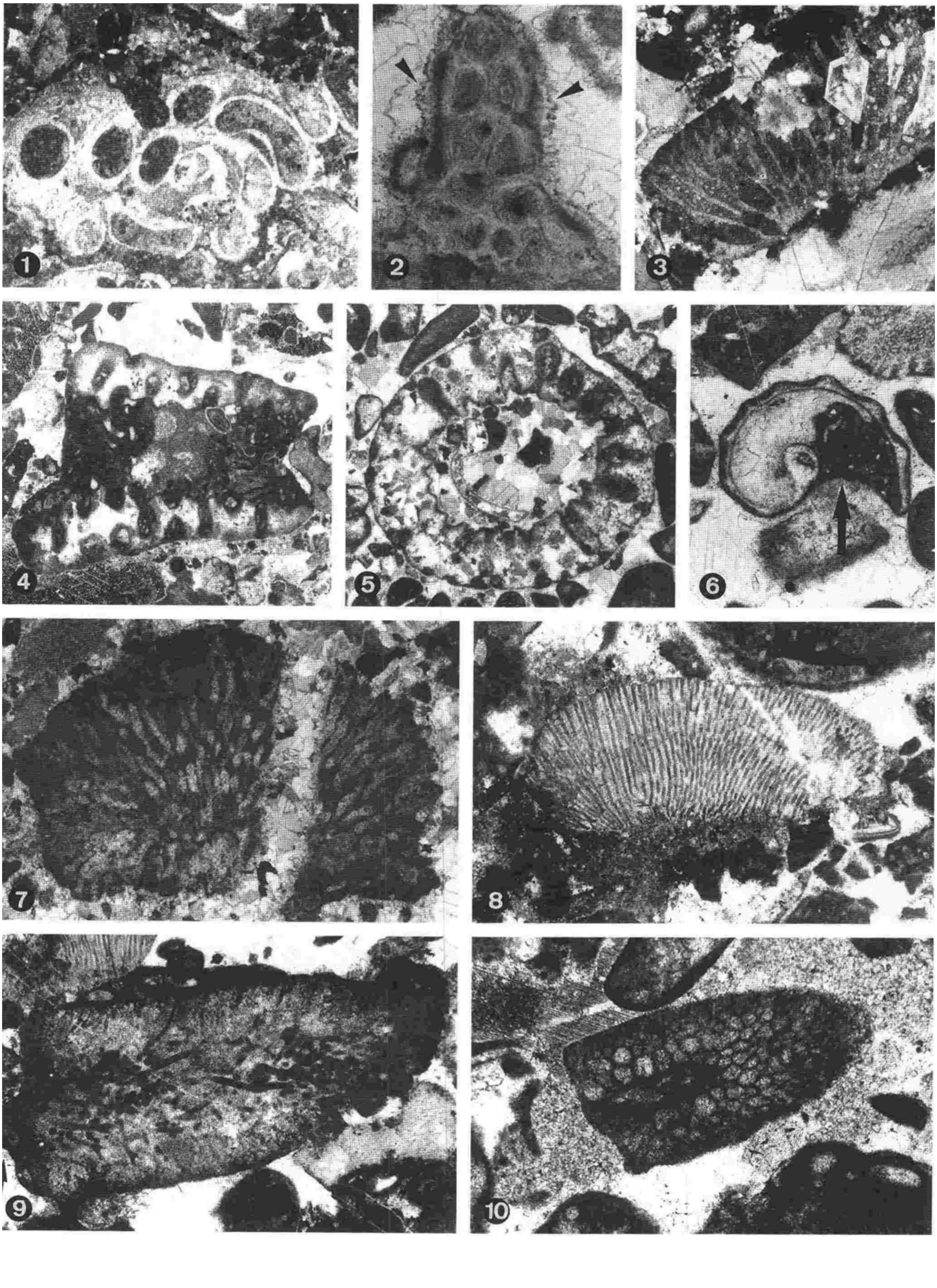
Fig. 6. Pre-drowning phase, lower slope section: Cross-section of a recrystallized gastropod. The micrite-filled intra-granular pore is partly encrusted by algae (arrow). x 12

Fig. 7. Pre-drowning phase, upper slope section: Phylloid thallus of the cyanophyceen algae *Cayeuxia*, showing thick, acute-branched, radial orientated filament tubes. x 12

Fig. 8. Pre-drowning phase, lower slope section: *Cayeuxia*-thallus showing basal-branched and distal parallel orientated filaments. x 12

Fig. 9. Pre-drowning phase, lower slope section: Thallus fragment of the udoteacean algae *Halimeda*, encrusted by sessile foraminifers (arrow). Within the central medulla-region the filament tubes show a parallel orientation to the longitudinal axis. Within the peripheral cortex they split up radial to the outlining of the thallus. x 12

Fig. 10. Pre-drowning phase, middle slope section: Unknown algal fragment, with a stem-like medulla region and a polygonal-chambered cortex area, x 24.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(SMF 12) on the platform top. During the post-drowning phase small amounts of crinoid fragments are present within the biopelmicrites (SMF 3) of all depositional areas of the platform.

3b: Brachiopods (Pl. 23/4-6)

Articulate brachiopods were found either as complete preserved specimens, valve fragments or individual spines. The internal microstructures and shell layering are usually well preserved. Punctate - (Terebratulida, Spiriferida), pseudopunctate - (Strophomenida) and impunctate shells (Rhynchonellida, Spiriferida) are often encrusted by sessile foraminifers, cyanobacteria or microproblematica.
Brachiopods are present in varying quantities within all phases of platform evolution. During the pre-drowning phase the occurrence of thick-shelled brachiopod fragments is mainly restricted to the slope sediments (SMF 5, 4). Within the drowning phase, low-diversity coquinas are present consisting of maximum 3 cm large, complete preserved spiriferid shells and their bioclasts (MF 3). In the post-drowning phase fragments of thin impunctate brachiopods remain important.

Group 4: Open-marine biota

This group comprises all marine organisms that characterise deep-marine environments.

4a: Ammonites (Pl. 23/7)

The primary aragonitic skeleton of the shells and its bioclasts are always replaced by blocky sparite.
Except for a single, dm-thick, ammonite-rich bed that marks the beginning of the post-drowning phase on the platform top, ammonites are very rare in all platform sections and phases.

4b: Siliceous sponges (Pl. 23/8)

Demospongia or Hexactinellida are represented by isolated micro- and megascleres, whose primary siliceous skeleton is replaced by blocky calcite. Megascleres show tri- or tetraxons with a maximum length of 1 cm and a maximum diameter of 0,15 mm. Dark, micritic crusts occasionally enclose the fragments, suggesting an association with encrusting algae or cyanobacteria.

The fragments are mostly found in pre-drowning sediments in which they form characteristic spiculites at the toe-of-slope (biopelmicrites, SMF 3).

4c: Filaments (Pl. 23/9)

These components, interpreted as mollusc fragments (Conti & Monari, 1992), are characterised by very thin (10 to 30 µm), relatively long (max. 1,5 cm) shells with a slightly curved shape. They show a lamellar microstructure and may be partly overgrown by scalenohedral cement rims.

Plate 22 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Skeletal fragments: benthic foraminifers

Fig. 1. Pre-drowning phase, lower slope section: Sagital section of the ophthalmidiid foraminifer *Ophthalmidium carinatum* Kübler & Zwingli. x 48

Fig. 2. Pre-drowning phase, lower slope section: Axial section of the ophthalmidiid foraminifer *Ophthalmidium leischneri* Kristan-Tollmann. x 48

Fig. 3. Pre-drowning phase, middle slope section: Axial section of the ammodiscid foraminifer *Glomospirella* sp. x 48

Fig. 4. Pre-drowning phase, lower slope section: Equatorial section of the mesoendothyrid foraminifer *Mesoendothyra croatica* Gusic. x 24

Fig. 5. Pre-drowning phase, lower slope section: Equatorial section of the endothyrid foraminifer *Endothyra* sp. Note the calcisphere above a siliceous sponge spicula on the left side. x 24

Fig. 6. Pre-drowning phase, lower slope section: Longitudinal section of the coarse-agglutinated lituolid foraminifer *Ammobaculites* sp. x 24

Fig. 7. Pre-drowning phase, lower slope section: Transversal section of the spirocyclinid foraminifer *Haurania deserta* Henson. x 12

Fig. 8. Drowning phase, platform top: Sagital section of the vaginulinid foraminifer *Lenticulina.* sp. x 12

Fig. 9. Pre-drowning phase, lower slope section: Axial section of the involutinid foraminifer *Aulotortus communis* Kristan. x 48

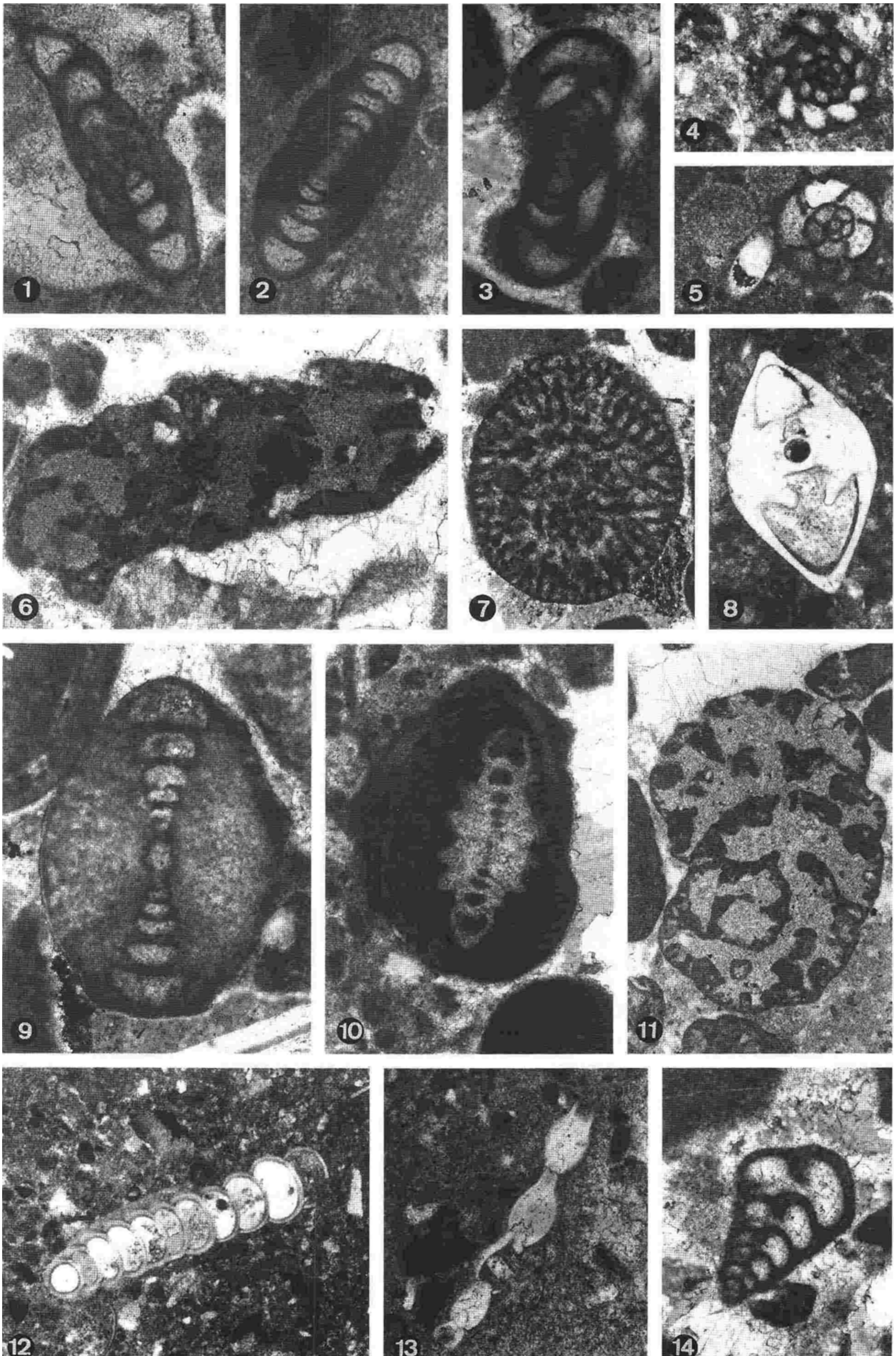
Fig. 10. Pre-drowning phase, middle slope section: Axial section of the involutinid foraminifer *Involutina liassica* Jones forming the nucleus of a micro-oncoid. x 24

Fig. 11. Pre-drowning phase, lower slope section: Equatorial section of the cyclamminid foraminifer *Pseudocyclammina liassica* Hottinger. x 12

Fig. 12. Pre-drowning phase, middle slope section: Longitudinal section of the nodosarid foraminifer *Nodosaria* sp. x 12

Fig. 13. Pre-drowning phase, upper slope section: Longitudinal section of the nodosarid foraminifer *Dentalina* sp. x 24

Fig. 14. Pre-drowning phase, middle slope section: Longitudinal section of the tetrataxid foraminifer *Tetrataxis inflata* Kristan. x 24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While filaments are relatively rare within pre-drowning and drowning sediments, they are locally concentrated in lenses on the slope (biomicrites, SMF 3) of the post-drowning phase.

4d: Calcispheres (Pl. 22/5, Pl. 25/8)

Components counted as calcispheres are characterised by a thin spherical ring-structure with a maximum diameter of 0.03 mm.

These components are only present in minor quantities in all platform phases. Highest amounts were found within the post-drowning biomicrites (SMF 3) deposited on the platform top.

Group 5: Encrusted grains

This group comprises all grains that show the encrusting activity of sessile organisms like foraminifers or cyanobacteria.

5a: Zoogenic oncoids (Pl. 24/1, 2)

The shape of these up to several cm large components is spherical to ellipsoidal or even irregular. They all show a nucleus that consists of one or more skeletal fragments (e.g. ooids or lithoclasts) which are enclosed by an accretionary micritic layer. Sometimes lutitic carbonate or terrigenous grains are incorporated within the laminated envelope. Frequent inter-growth of serpulids (serpulid-algal oncoids) or sessile foraminifers was found (*Bullopora* sp.; foraminiferal-algal oncoids, FLÜGEL, 1982).

The occurrence of these components is restricted to the pre-drowning phase. They can be found on the platform top (SMF 17, 22), where they originate and partly were redeposited on the platform slope (SMF 4).

5b: Micro-oncoids (Pl. 22/10)

All oncoids with a diameter less than 2 mm were classified as micro-oncoids. The nucleus usually consists of a single peloid, benthic foraminifer, recrystallized bioclast, echinoderm-, microproblematica- or calcareous algae fragment. A fine laminated, dark-grey up to 300 µm thick micritic envelope encloses these components.

Micro-oncoids are found exclusively within the sediments of the pre-drowning phase. During this period they were primarily produced within the platform interior environment and subsequently redeposited on the slope (SMF 4, 3).

5c: Aggregate grains (Pl. 24/3)

These components consist of at least two different grain-types (e.g. peloids, intraclasts, recrystallized bioclasts, micro-oncoids, benthic foraminifers, echinoderm fragments) that are cemented by encrusting algae or sessile foraminifers. The occurrence of aggregate grains is restricted to the sediments of the pre-drowning phase. Like zoogenic - and micro-oncoids they find their origin within the lagoon on the platform top. In a later stage they were redeposited on the platform slope (SMF 5, 4, 3).

Group 6: Non-skeletal grains

This group consists of ooids and lithoclasts, produced within the shallow-marine facies belts of the platform top, margin and slope.

6a: Ooids (Pl. 19/5-6, Pl. 24/4-6, Pl. 26/5)

Two types of ooids could be distinguished in the sediments of the Jbel Bou Dahar:

A) Radial-structured ooids (Pl. 24/4, 5) are characterised by a few laminae consisting of cryptocrystalline layers that alternate with laminae formed by radial orientated fibrous crystals. The nuclei of these grains with a maximum size of 1 mm, consist of peloids, small benthic foraminifers or other skeletal debris.

The components only occur associated with micro-oncoids and aggregate grains in the fine-grained biopel-

Plate 23 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Skeletal fragments: suspension feeders and grazers, open-marine biota

Fig. 1. Pre-drowning phase, lower slope section: Fragment of an echinoid plate, encrusted by dome-shaped spongiostromate algae. x 6

Fig. 2. Pre-drowning phase, lower slope section: Cross-section of an echinoid spine displaying the central porous channel and a radial meshwork. x 12

Fig. 3. Post-drowning phase, adjacent basin: Cross-section of a crinoid columnal characterised by a central lumen and a pentagonal-radial pattern. x 12

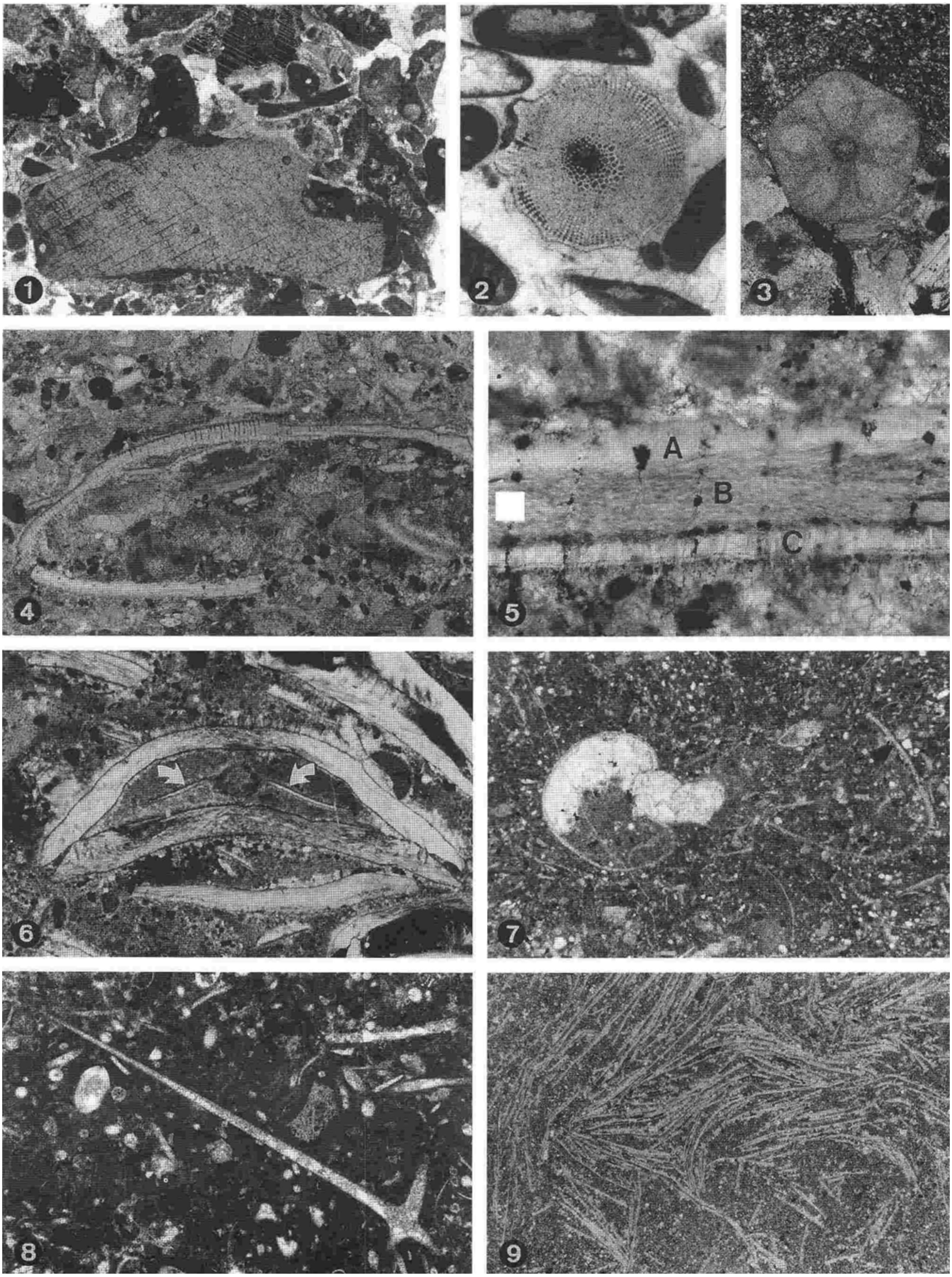
Fig. 4-5. Drowning phase, middle slope section: Cross-section of a thin, punctate brachiopod shell. The fragment is characterised by distinct microstructural units: (A) an outer radial-fibrous layer, (B) second foliated layer, and (C) inner prismatic layer. Note the trumpet-like extensions of the outer layer pores. Fig. 8 x 6; Fig. 9 x 48

Fig. 6. Drowning phase, upper slope section: Different cross-sections of completely preserved bi-convex, impunctate brachiopod shell. Note the individual brachida (arrows) and the well-preserved foliated microstructure, 6x.

Fig. 7. Post-drowning phase, middle slope section: Thin-shelled ammonite showing a geopetal structure. x 6

Fig. 8. Pre-drowning phase, middle slope section: Longitudinal section of a tetraxon megasclere of a siliceous sponge. Note the elliptic to spherical cross-sections of other sponge needles and ophthalmidiid foraminifers. x 12

Fig. 9. Post-drowning phase, adjacent basin: Biomicrite with local enrichment of thin, long-stretched, slightly curved filaments. x 6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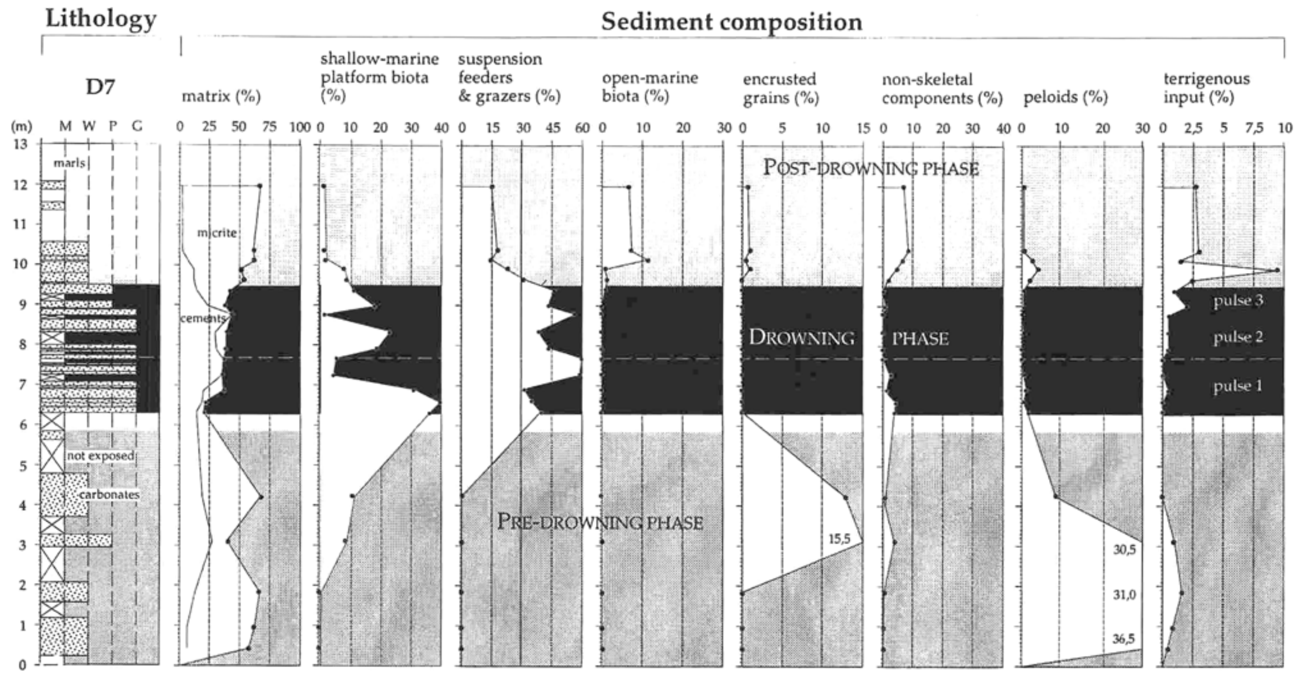


Fig. 5. Platform interior (Profil D7): Lithology (DUNHAM, 1962) and sediment composition during distinct platform phases. Point count groups are described in the text. M: mudstones; W: wackestones; P: packstones; G: grainstones.

micrites (SMF 9) of the platform slope within the pre-drowning phase. Based on the type of nuclei and the overall sediment composition we assume that the shallow sub- to intertidal facies zones of the platform interior formed the primary production area of these grains.

B) Tangential-structured ooids (Pl. 19/5-6, Pl. 24/6, Pl. 26/5) have a maximum size of 2 mm and show several lighter and darker, cryptocrystalline lamellae. The nuclei are often broken or abraded and mainly consist of echinoderm fragments. The components show phosphatization, dissolution features and an irregular overgrowth of dripstone cements which may point to a change in the diagenetic environment during the formation of the ooids. This could be related to a switch from phreatic to vadose conditions within the ooid sand shoals at the platform margin (SCHEIBNER & REIJMER, this volume).

Both types of ooids show a fundamentally different lateral and stratigraphical distribution. While radial-structured ooids occur within the slope sediments (SMF 9) of the

Plate 24 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Encrusted grains, ooids and lithoclasts

Fig. 1. Pre-drowning phase, platform interior: Zoogenic algal oncoid showing a fine-laminated micritic rim and a nucleus formed by an arenitic intraclast that possesses the same fabric as the surrounding sediment. x 12

Fig. 2. Pre-drowning phase, middle slope section: Zoogenic foraminiferal-algal oncoid with a recrystallized skeletal fragment (gastropod shell?) as nucleus. The micritic rim consists of irregular micritic layers, formed by spongiostromate algae and sessile foraminifers (*Bullopora* sp.), x 12

Fig. 3. Pre-drowning phase, lower slope section: Aggregate grain consisting of an echinoderm fragment (right side) and a rounded intraclast, cemented by a sessile foraminifer. x 12

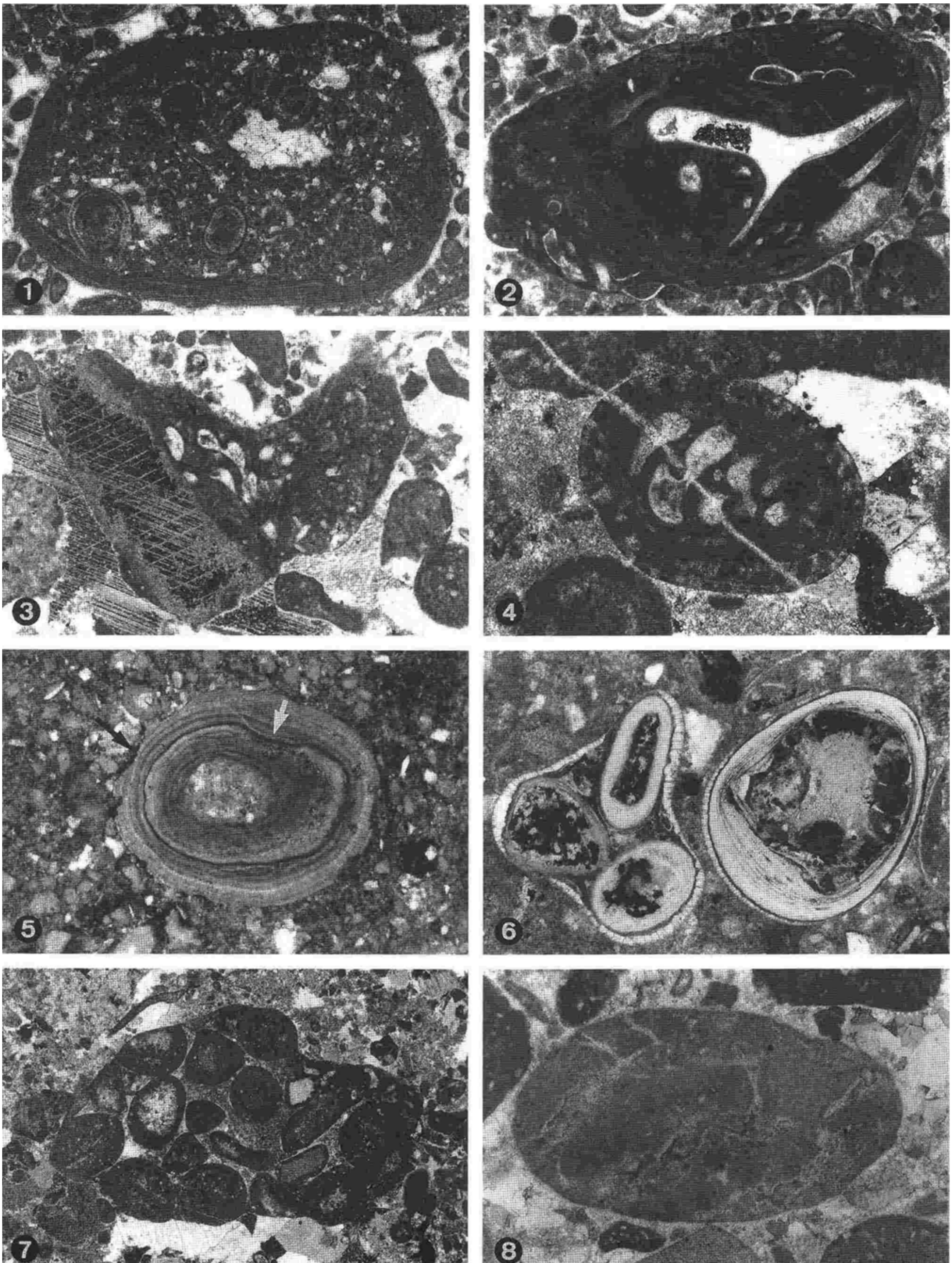
Fig. 4. Pre-drowning phase, lower slope section: The nucleus of the radial-structured ooid is formed by a small benthic foraminifer *Tetrataxis inflata*, indicating the platform interior as the primary source area of this grain. x 24

Fig. 5. Pre-drowning phase, platform interior: Radial-structured ooid, whose single layers are characterised by pressure solution (arrows). x 24

Fig. 6. Post-drowning phase, platform top: Tangential-structured ooids with an outermost, radial-structured gravitational cement layer, reflecting vadose diagenetic conditions. x 24

Fig. 7. Pre-drowning phase, middle slope section: Angular intraclast with truncated components at the edge. The arenitic components consist of peloids (bahamite peloids), well-rounded echinoderm fragments and recrystallized bioclasts. x 6

Fig. 8. Drowning phase, middle slope section: Well-rounded extraclast with a mudstone fabric. The clast contains a heterogenous, microsparitic matrix with irregular wispy seams. x 12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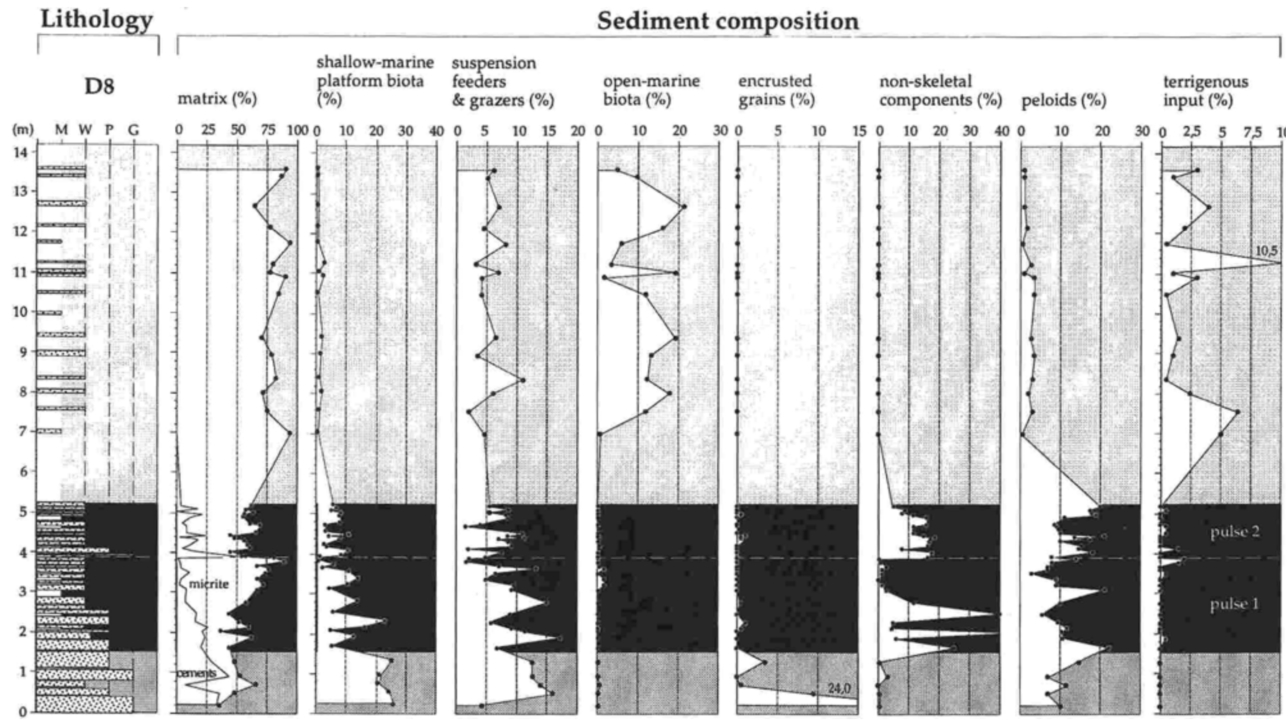


Fig. 6. Middle slope section (Profile D8): Lithology and sediment composition. For signatures see Fig. 5.

pre-drowning phase, tangential-structured ooids were exclusively found in the platform top sediments (SMF 3) of the post-drowning phase.

6b: Lithoclasts (Pl. 24/7, 8)

According to their occurrence and fabric lithoclasts are grouped into intra- or extraclasts. Their size varies from 0.3 mm to several centimetres. During the platform evolution a specific distribution of distinct types of lithoclasts from different source areas can be recognised.

During the pre-drowning phase (Pl. 24/7) mainly intraclasts, showing the same composition as the surrounding sediment, were deposited on the platform top (SMF 17) and on the slope (SMF 5, 4). The components are commonly overgrown by sessile foraminifers, algae, cyanobacteria or serpulids.

During the drowning phase (Pl. 24/8) mainly extraclasts were found on the platform slope, which resulted in the formation of characteristic extrasparites (MF 1). Fabric and composition of the clasts with fragments of ostracods or

Plate 25 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Outcrop and microfacies types (pre-drowning phase)

Fig. 1-2. Middle slope section and its structural-geologic interpretation. Note the onlapping sediments of the post-drowning phase, forming a distinct drowning unconformity (sensu Schlager, 1989) on the steep flanks of the Domerian carbonate platform.

Fig. 3. Pre-drowning phase, platform interior: Pelmicrite (SMF 22) showing horizontal component laminations and long-stretched intergranular pores. x 6

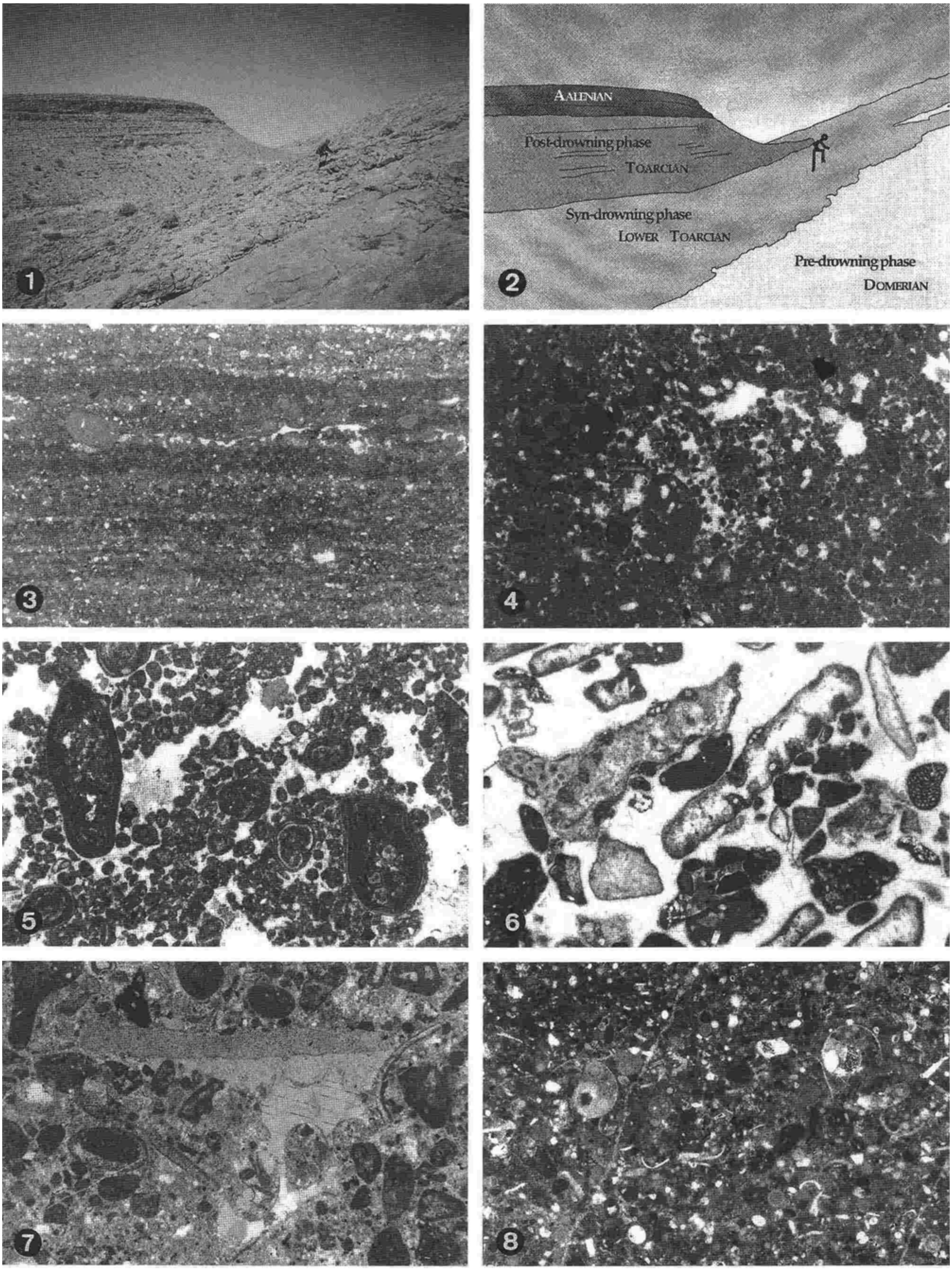
Fig. 4. Pre-drowning phase, platform interior: Burrowed pelmicrite with sparitic areas (SMF 22). Bioturbation partly destroyed the primary lamination and horizontal arrangement of the components. x 12

Fig. 5. Pre-drowning phase, platform interior: Pelsparite (SMF 17), characterised by a bimodal grain-size distribution. The components mainly consist of lutitic peloids and ruditic oncoids that are concentrated in "nests", surrounded by fibrous cements. x 6

Fig. 6. Pre-drowning phase, upper slope section: Coarse, densely packed biosparite (SMF 5), with poorly sorted, arenitic to ruditic components. Note the various encrusting organisms (bryozoan, foraminifers) on the recrystallized bioclasts. x 6

Fig. 7. Pre-drowning phase, lower slope section: Poorly sorted, densely packed biopelmicrite (SMF 4), with various non-skeletal components and bioclasts. Note the shelter pore below the long-shaped echinoderm fragment, filled by syntaxial cement. x 6

Fig. 8. Pre-drowning phase, lower slope section: Fine-grained, well-sorted biopelmicrite (SMF 9), composed of lutitic to arenitic components. Besides siliceous sponge spiculae, peloids and terrigenous quartz clasts, calcispheres and thin-shelled mollusc fragments (arrows) are present. x 6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Post-drowning phase
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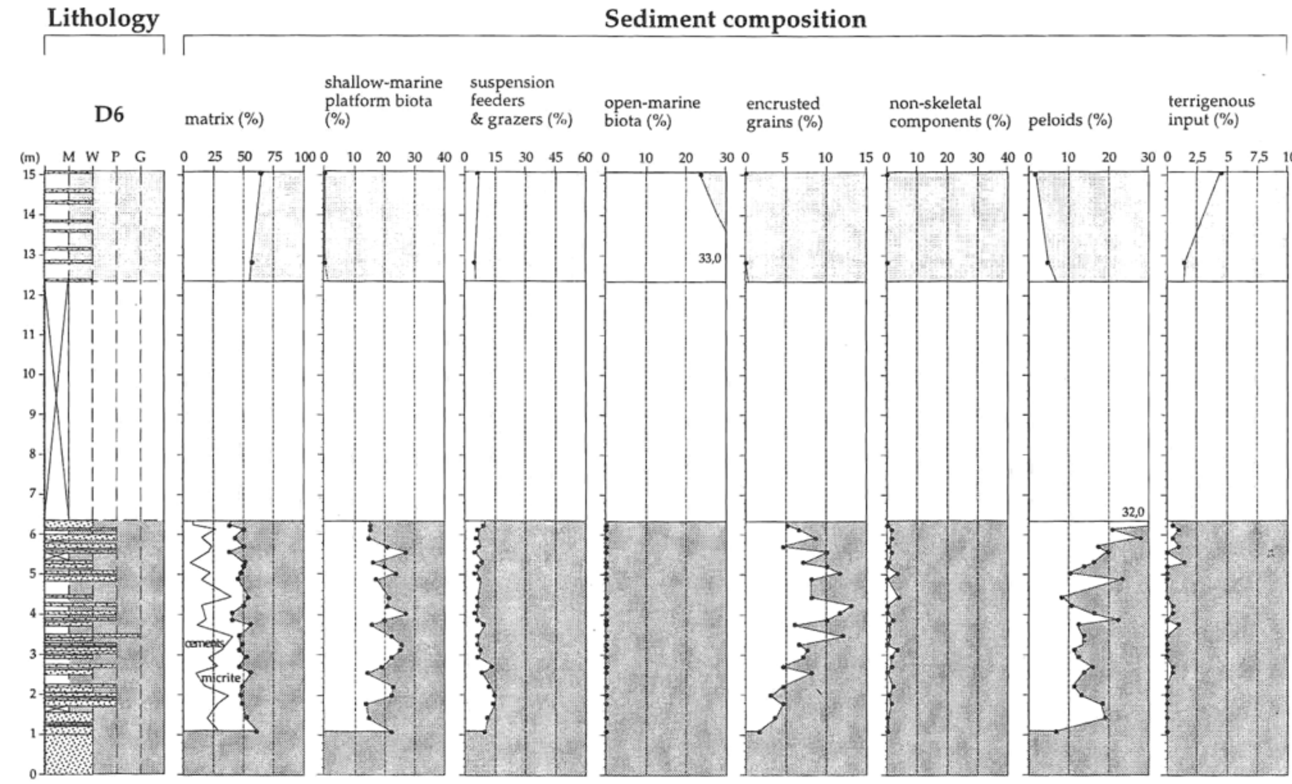


Fig. 7. Toe of slope section (Profile D6): Lithology and sediment composition. For signatures see Fig. 5.

small benthic foraminifers embedded in a heterogeneous green to red-brownish micritic matrix, suggests the mud-rich lagoonal environment of the pre-drowning phase as a primary source area.

Group 7: Peloids

All components consisting completely of micrite or microsparite are combined within this group. Colour, intragranular structure, shape and grain size were used to

Plate 26 The Jbel Bou Dahar, a Lower Jurassic carbonate platform (High Atlas, Morocco): Microfacies types (drowning and post-drowning phase)

Fig. 1. Drowning phase, platform top: Densely packed biosparites (SMF 12), rich in echinoderms and recrystallized skeletal fragments mark the drowning succession on the platform top. x 6

Fig. 2. Drowning phase, middle slope section: Coarse-grained, poorly sorted rudstones consisting of rounded extraclasts and pseudo-peloids (extrasparites, MF 1) mark the onset of the drowning phase on the platform slope. x 6

Fig. 3. Drowning phase, middle slope section: Brachiopod-coquina (MF 3) containing a monotypic association of almost complete preserved, bi-convex bioclasts, occasionally showing equally orientated geopetals (arrow).

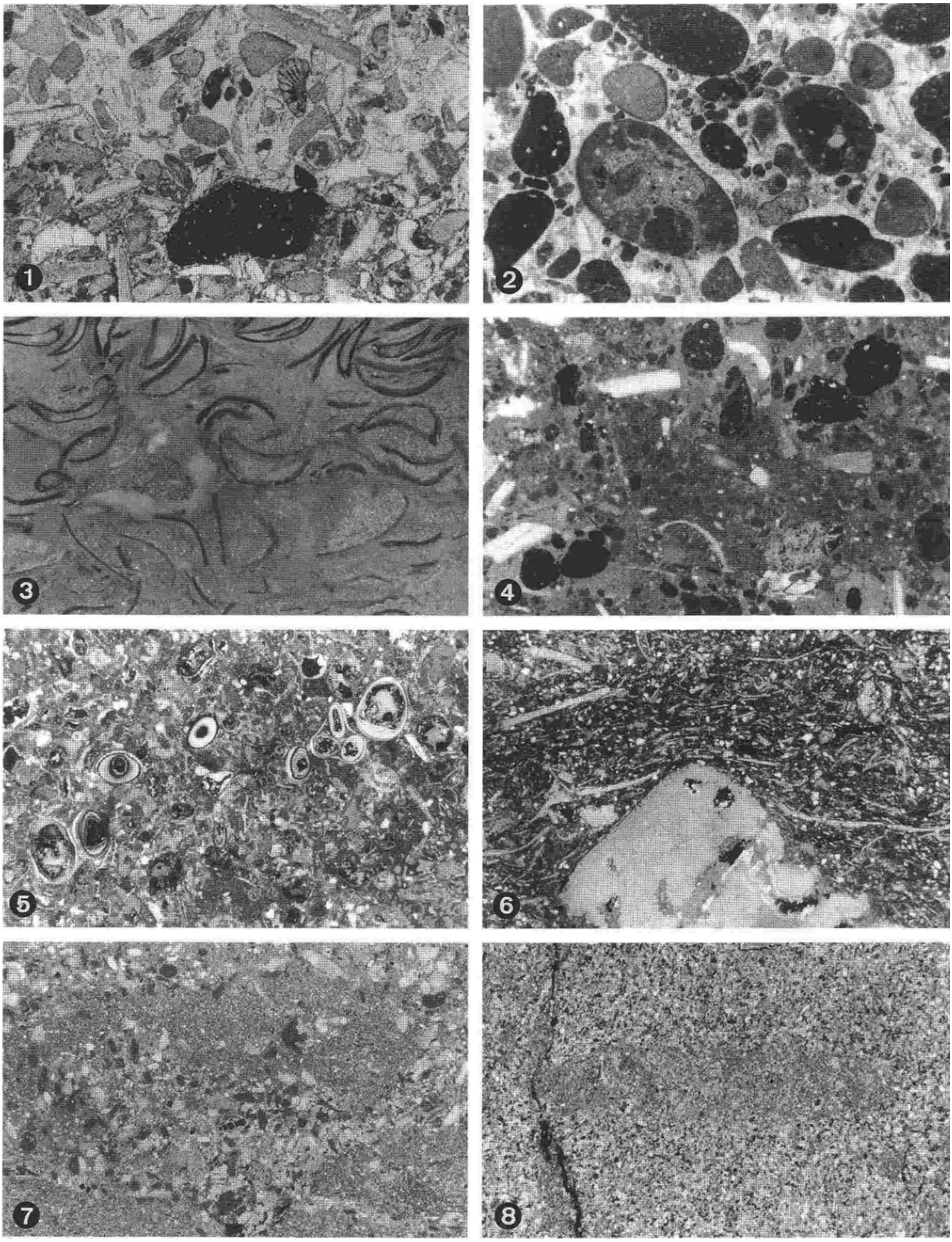
Fig. 4. Drowning phase, middle slope section: At the end of the drowning phase mainly biopelmicrites (MF 2) were deposited on the slope. The sediments show a mixed facies consisting of peloids, micritic extra-clasts and echinoderm fragments embedded within a heterogeneous microsparitic matrix. x 6

Fig. 5. Post-drowning phase, platform top: Echinoderm-rich biomicrites (SMF 3) were deposited at the beginning of the drowning period within all platform successions. On the platform top they are characterised by ooids, which are partly dissolved and strongly phosphatized. x 6

Fig. 6. Post-drowning phase, middle slope section: Filament-rich biomicrite (SMF 3) showing a sub-parallel orientation of the long-stretched components. Note the strongly bored and phosphatized echinoderm fragment. x 6

Fig. 7. Post-drowning phase, adjacent basin: The micrite (SMF 3) is characterised by thin horizons consisting of well sorted, lutitic components (e.g. peloids, filaments, echinoderm- and brachiopod fragments). The mm- thin layers are frequently disturbed by bioturbation. x 6

Fig. 8. Post-drowning phase, adjacent basin: The youngest sediments are marked by high amounts of terrigenous material (detrital quartz). This ultimately leads to the deposition of densely packed, well-sorted calcisiltites (SMF 2). Within this facies type bioturbation structures are frequently observed (centre of picture). x 6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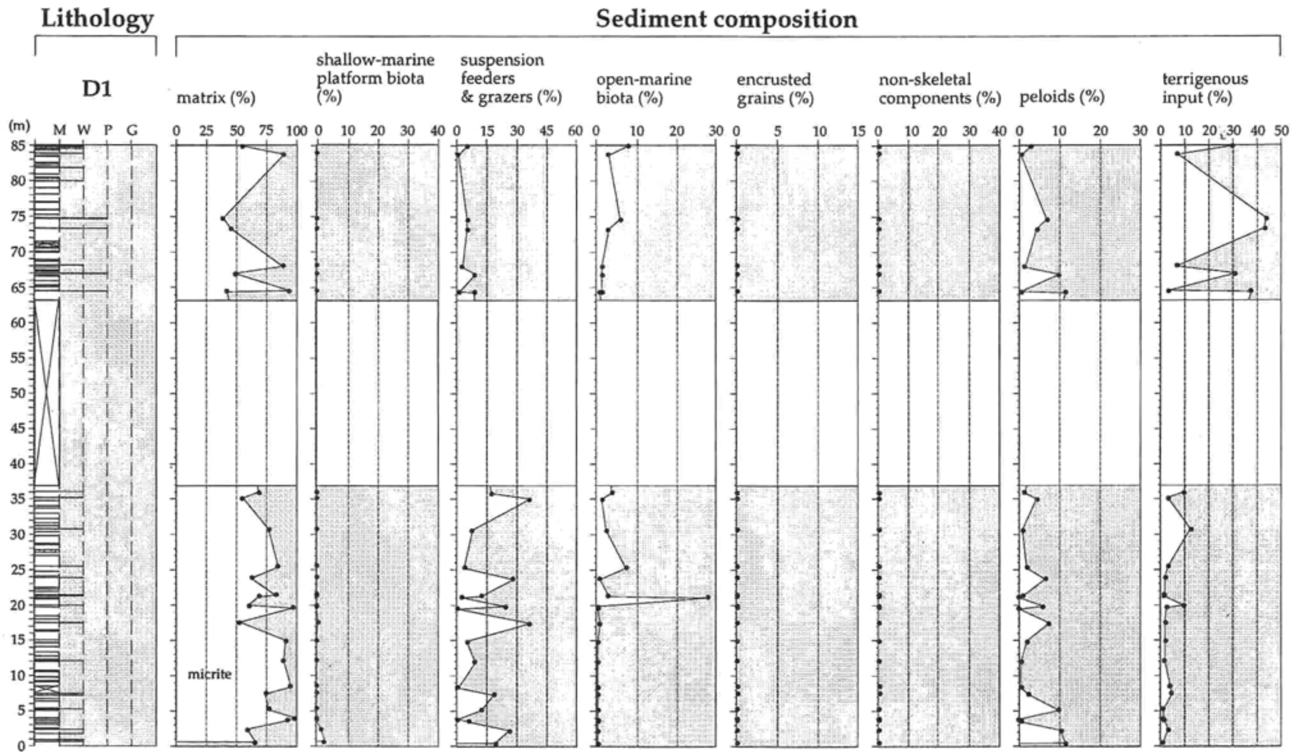

Fig. 8. Adjacent basin (Profile D1): Lithology and sediment composition. For signatures see Fig. 5.

differentiate distinct types of peloids like algal peloids bahamite peloids, pseudo-peloids or fecal pellets.

Algal peloids (FLÜGEL, 1982), which are the disintegration products of different algae, show dark-grey colours and occasionally tube-like filaments. These components mainly occur within the pre-drowning phase (SMF 22, 17, 4, 3). They are predominantly associated with spongio- and porostromate algae, oncoids, micro-oncoids and aggregate grains suggesting the lagoon as their primary source area. Bahamite peloids or pelletoids are formed by the micritization of different skeletal fragments (FLÜGEL, 1982). Partial transformed components often have a micritized border, while their nucleus still shows the original microstructure or blocky sparite. The components are common within the platform interior and slope sediments of the pre-drowning phase (SMF 5).

Pseudopeloids are the reworked products of a muddy seafloor with a size below 0.3 mm. They mainly occur during the drowning phase within characteristic extrasparites (MF 1) deposited on the platform slope. These peloids show the same mud- to wackestone fabric as larger extraclasts. Fecal pellets are well rounded and sorted, dark-grey peloids. The components were found in small amounts in all environments and platform drowning phases.

Group 8: Terrigenous input

This group comprises all non-carbonate grains. The components mainly consist of angular quartz clasts that are very well sorted and have an average grain size of 0.03 mm. Because of their size and sorting we assume that these grains were transported by wind into the depositional area of the Jbel Bou Dahar carbonate platform.

Within the pre-drowning sediments only minor quantities of terrigenous components are present in all platform sections. During the drowning phase a slight increase can be observed within all successions. The highest amounts were reached in the post-drowning phase. At the end of this phase an abrupt increase lead to the deposition of typical calcisiltites (SMF 2; Fig. 8).

3.2 Microfacies types and point-count results

Every drowning phase is represented by an association of characteristic carbonate microfacies types (MF) that were classified using the standard microfacies types (SMF) of WILSON (1975).

3.2.1 Pre-drowning phase

Platform interior (Pl. 25/3-5)

The successions deposited on the platform top are characterised by limestone/marl alternations, which are separated by distinct exposure surfaces. The marls are usually badly exposed (section D7; Fig. 5).

The lateral varying limestones consist of pel- and biopelmicrites (wackestones, SMF 22), pure micrites or dismicrites (mudstones, SMF 21) and algal mats (loferites, SMF 19). Horizontal laminations are frequent and are formed by lateral component enrichments or the occurrence of interlamellar, long-stretched cavities. These primary patterns are frequently destroyed by bioturbation, resulting in an irregular arrangement of the components and the formation of stromatactis-like structures that are filled with micrite and/or blocky cements. Occasionally pelsparites (grain- to

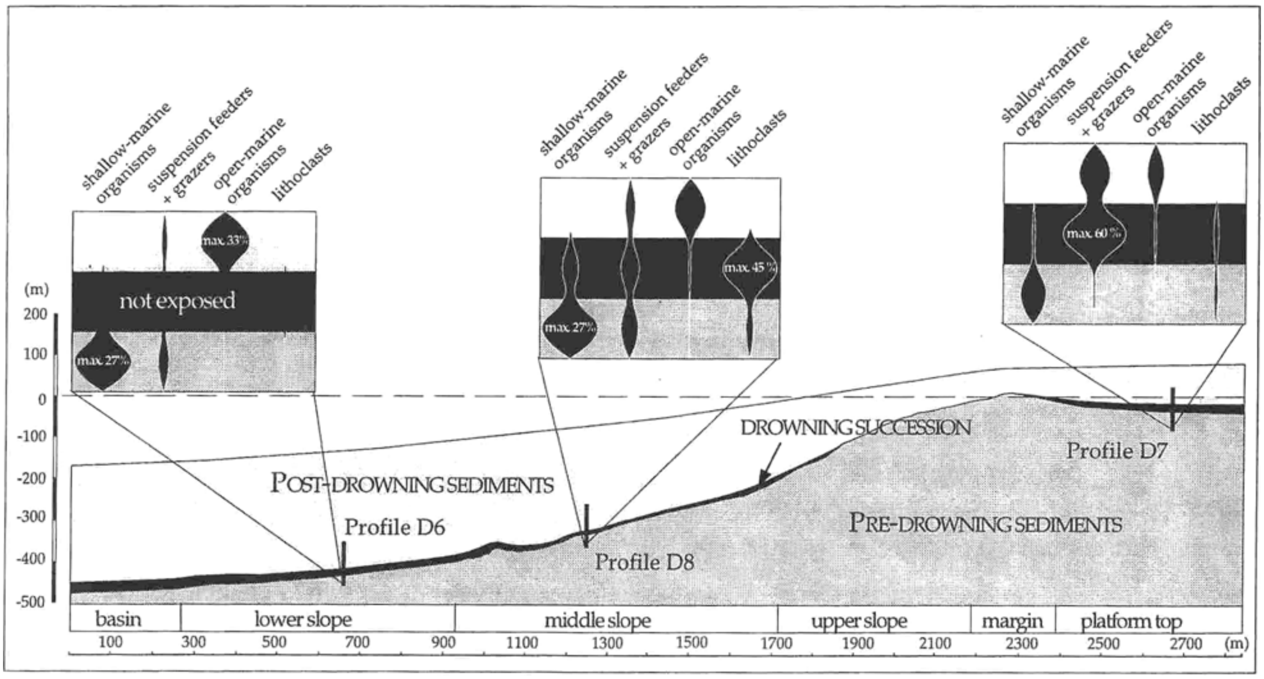

Fig. 9. Sediment composition within different platform sections and drowning stages.

packstones, SMF 17), cemented by radial-fibrous and blocky cements, are interbedded within the successions. They are characterised by an irregular, nest-like distribution of poorly sorted components with a bimodal grain-size distribution. The facies types are characterised by high amounts of peloids (max. 36.5 vol.-%) and encrusted grains (max. 15.5 vol.-%), minor amounts of fragments of shallow-marine biota (mainly calcareous algae; max. 10.0 vol.-%) and terrigenous clasts (max. 2.0 vol.-%; Fig. 5).

Platform slope (Pl. 25/6-8)

The pre-drowning succession of the middle slope section is characterised by thick-bedded, coarse-grained and poorly sorted limestones, separated by stylolites or very thin marl horizons (section D8; Fig. 6).

The carbonates (mainly bio-, biopelsparites and -micrites) all can be assigned to SMF 5 (grain- to wackestones, rudstones, floatstones). They possess a heterogeneous matrix with strongly varying amounts of microsparite (2.0 – 58.5 vol.-%) and orthosparite (6.0 – 43.5 vol.-%). The arenitic to ruditic components are dominated by shallow-marine bioclasts (max. 27.0 vol.-%; Fig. 9), mainly encrusting organisms (microproblematica), corals and recrystallized skeletal fragments. Peloids (mainly bahamite peloids; max. 14.5 vol.-%) and encrusted grains (max. 24.0 vol.-%) are also frequently encountered. Lithoclasts are almost completely absent.

At the toe of slope (section D6; Fig. 7) the succession consist of medium-bedded marls and limestones with two different microfacies types.

Type 1 limestones consist of fine-grained bio- and biopelsparites (grain- to packstones) that can be classified as SMF 4 carbonates. The sediments are highly diverse with abundant shallow-marine skeletal fragments (max. 27.0 vol.-%; Fig. 9) and peloids (max. 28.5 vol.-%). The well sorted, arenitic components are cemented by radial-, syntaxial-, dogtooth- or blocky cements.

Type 2 limestones are formed by biopelmicrites (wackestones, SMF 9) with predominantly lutitic to fine-arenitic components embedded in a homogenous microsparitic matrix texturally homogenised by bioturbation. In comparison with the other facies type, the amount of bioclasts of shallow marine biota is slightly decreased (15.0 – 22.0 vol.-%) while peloids show a small increase in (max. 32.0 vol.-%). Characteristic is a low, but constant amount of terrigenous input (< 5.0 vol.-%).

3.2.2 Drowning phase

Platform interior (Pl. 26/1)

The base of the drowning succession on the platform top is marked by the abrupt occurrence of red-brownish carbonate beds, which unconformably (low-angle angular discontinuities) overly the sediments of the pre-drowning phase and show a totally different microfacies.

In these pure biosparites (grainstones, SMF 12), with blocky and syntaxial cements, encrusted grains are absent and peloids only occur in small amounts (max. 4.0 vol.-%). They are characterised by large quantities of suspension feeder and grazer fragments (mainly echinoderms, max. 59.5 vol.-%; Fig. 9) and bioclasts of other shallow-marine platform biota (mainly recrystallized bioclasts, max. 39.0 vol.-%). Both groups were deposited in three anticyclic pulses with decreasing absolute amounts (Fig. 5). During the entire phase the occurrence of terrigenous input can also be observed. It shows a slight, stepwise increase towards the top of the succession. The continuous increase of the amount of microsparite within the matrix, results in the deposition of packstones that mark the transition to the post-drowning phase.

Platform slope (Pl. 26/2-4)

The drowning succession within the mid-slope is formed by an alternation of thin- to medium-bedded, red-brownish carbonates and marls that with a low angle unconformably onlap the thick-bedded carbonates of the pre-drowning phase.

The most common facies types are bio- and biopelmicrites (pack- to wackestones, MF 2), showing a general increase in the amount of micrite across the entire succession. Characteristic is also the intercalation of some coquinas, showing a monotype association of brachiopods or oysters (MF 3). Just like on the platform top the composition of the carbonates changes drastically. Instead of a wide range of skeletal and non-skeletal grains, high amounts of non-skeletal grains, e.g. lithoclasts (extraclasts, max. 45.0 vol.-%; Fig. 9) and peloids (pseudo-peloids, max. 22.0 vol.-%), are deposited at the beginning of the drowning sequence. The input of these grains shows two successive pulses (Fig. 6) and results in the formation of characteristic extrasparites (grain- to packstones, MF 1). The biofacies mainly contains fragments of shallow-marine biota (max. 22.0 vol.-%) and suspension feeders (max. 18.0 vol.-%). Towards the top of the drowning sequence their absolute amounts decrease. In contrast to the pre-drowning-phase encrusted grains are nearly completely missing within the slope succession. In addition, a first occurrence of terrigenous clasts and open-marine biota can be observed.

3.2.3 Post-drowning phase (Pl. 26/5-8)

This period is represented in all sections by uniform, monotonous alternations of thick-bedded marls and thin-bedded limestones. In contrast to the pre- to drowning transition that is marked by minor unconformities and abrupt facies changes, the drowning to post-drowning boundary is conformable and gradual. The infill of the basin with aforementioned marl/limestone alternations ultimately produces a clear drowning unconformity with a distinct onlap pattern that is very pronounced at the steep upper and mid-slope (Pl. 25/1, 2).

All sediments can be classified as SMF 3 and consist of biomicrites, biopelmicrites and pure micrites (wacke- to mudstones). They display a continuous increase of the fine-grained matrix (max. 95.0 vol.-%) from the end of the drowning succession towards the post-drowning phase. The components mainly consist of skeletal fragments of suspension feeders and grazers (max. 36.5 vol.-%, profile D1) and other open-marine biota (max. 33.0 vol.-%, profile D6; Figs. 7, 9). Fragments of shallow-water biota and non-skeletal components are almost completely absent. The carbonates deposited within all sections don´t show any distinct facies change. The biopelmicrites of the platform top, however, are characterised by the occurrence of arenitic, strongly impregnated and phosphatized ooids and echinoderm fragments, that frequently show vadose cement rims (dripstone cements).

Within the upper part of profile D1 (Fig. 8) a major increase in terrigenous input led to the deposition of an additional carbonate microfacies type. These calcisiltites (pack- to wackestones, SMF 2), with some burrowing structures, are characterised by high amounts of very well sorted, detrital quartz silt (max. 43.5 vol.-%).

4 DEPOSITIONAL ENVIRONMENTS

4.1 Pre-drowning phase

Platform top

Following Wilson (1975) the carbonates present on the platform top can be classified as SMF 22, 21 and 19 (FZ 7, 8). They reflect a sheltered lagoon, characterised by distinct inter- to shallow sub-marine environments under restricted marine conditions (Fig. 10). Vast amounts of mud, mainly preserved as microsparite within most facies types, points to quiet-water environments, with low wave- and current activity. Local enrichments of shallow-water components and small-scale occurrences of pelsparites (SMF 17) reflect areas with moderate water energy like tidal channels or bars (Crevello, 1990).

Within the various lagoonal environments, low-diverse biotic associations are preserved, mainly consisting of small benthic foraminifers, molluscs (mainly gastropods), echinoderms and calcareous algae. Bioturbation, destroying primary laminated fabrics, is frequently observed and reflects the activity of various burrowing organisms under well-oxygenated bottom-water conditions. Loferites (SMF 19), algal stromatolites and components like oncoids, micro-oncoids and aggregate lumps point to a widespread distribution of encrusting and sediment-binding organisms.

Lateral discontinuities, polygonal mud cracks and teepee structures mark periodical subaerial exposure of the entire platform top and have been related to climate induced sea-level changes (Crevello, 1990).

Platform margin

The margin consists of an up to 100-m wide zone, containing facies belts 6 and 5 of Wilson (1975). It forms the transition from the lagoon to the upper slope, and shows a gradual change in dip direction from the lagoonal centre (inner margin, max. 5°) to the adjacent basin (outer margin, max. 10°). The transition to the steep upper slope is marked by a sharp increase in dip from 10° to max. 35° (Kenter, 1990; Crevello, 1990; Scheibner & Reijmer, this volume).

The inner margin is characterised by a variety of partly interfingering, dolomitized micritic and sparitic carbonates (SMF 11 – 15). The sediments were deposited in supratidal to shallow submarine environments with low to moderate wave energy and current activity. Cross lamination, horizontal bedding and other small-scale sedimentary structures are common. Teepee structures and mud cracks occur at the most elevated parts (Fig. 10). Intensive reworking and redeposition of skeletal and non-skeletal components occurred, forming well-sorted carbonate sandbars with ooids. Together with the cemented debris and the build-ups of the outer margin these bars acted as natural barriers protecting the lagoon.

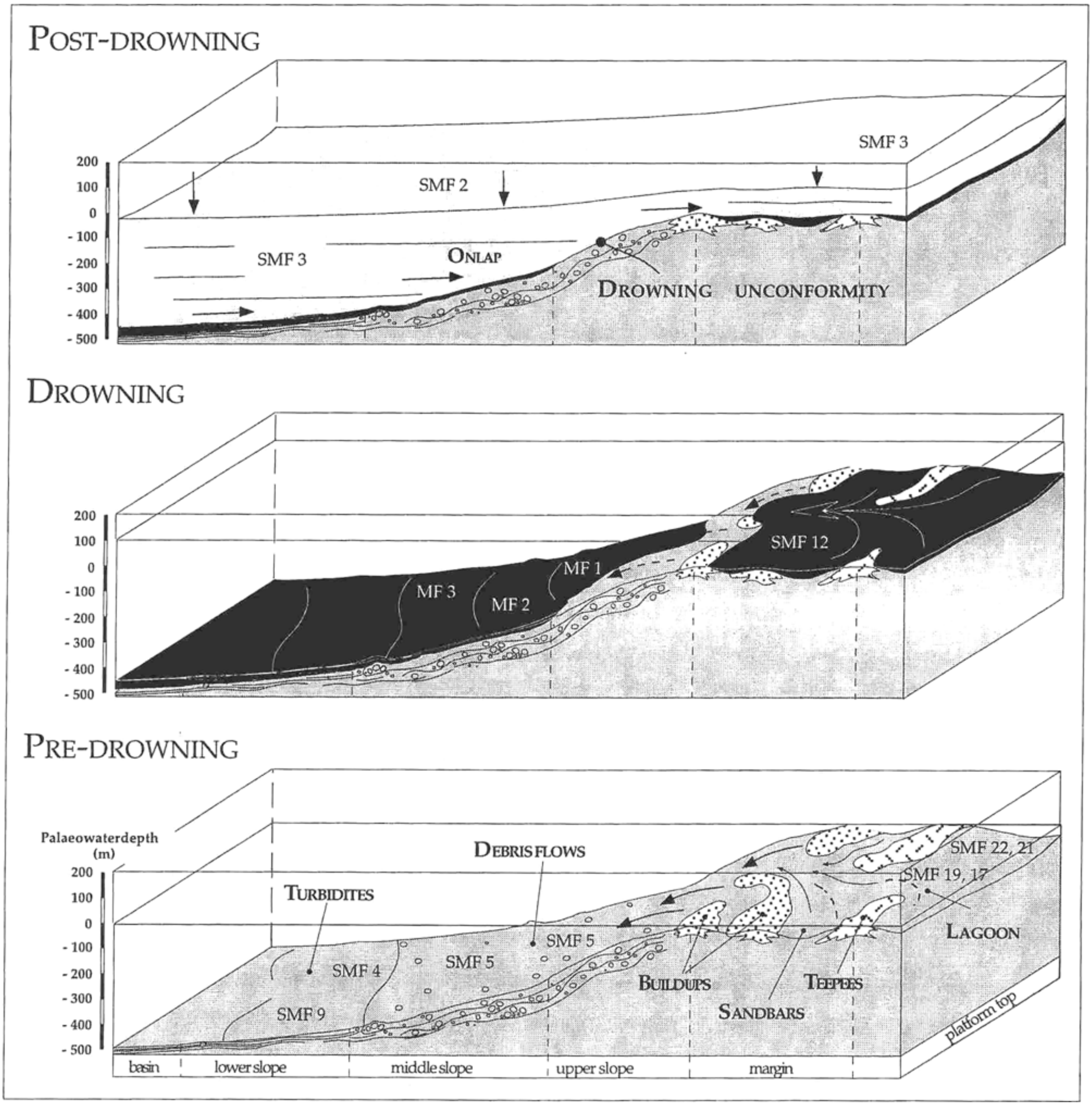

Fig. 10. Platform morphology and distribution of microfacies types (MF and SMF, after WILSON, 1975) within different sections and phases of the platform evolution. Arrows mark the main direction of sediment transport.

The outer margin predominantly consists of poorly sorted, coarse-grained debris forming massive talus fans and boulder trains (SMF 5, 6). Build-ups (SMF 7), up to several meters thick, occur in this zone surrounded by cemented debris (Fig. 10). Within the intertidal to shallow subtidal zone bivalve mud-mounds developed under moderate to strong current and wave activity (SCHEIBNER & REIJMER, this volume). With increasing water depth some dispersed coralgal patch-reefs can be found (scleractinian corals associated with microproblematica and other encrusters). At some places sponge mounds mark the transition to the steep upper slope (KENTER & CAMPBELL, 1991).

Platform slope

The slope carbonates studied all can be assigned to SMF 9, 5 and 4, representing an open-marine environment below storm wave base (FZ 4 to 2). Depending on their paleobathymetric position the sediments studied were deposited at about 300 m (mid-slope, section D8), respectively 450m (lower slope, section D6) below the platform margin on a steep granular slope, showing inclinations of up to 29° (KENTER, 1990; KENTER & CAMPBELL, 1991).

Within the steep mid-slope coarse grained, poorly sorted carbonates (SMF 5, FZ 4) dominate. The successions are characterised by small-scale scours and angular unconformities. They contain components that originated within the shallow-marine facies zones of the platform (FZ 8-5) and are mainly derived from the platform margin. Transport by debris flows that are characterised by turbulent high-energy regimes, explains the poor sorting, irregular orientation and heterogeneous distribution of the components and matrix (EINSELE, 1991).

The sediments of the successions (alternations of medium-bedded marls, SMF 5 and SMF 9 carbonates) present on the gentler dipping lower slope, point to a fundamentally different transport mechanism. Arenitic, well sorted SMF 4 carbonates were interpreted as the depositional products of turbidity currents transporting sediments from the shallow marine facies belts into the adjacent basin (Fig. 10). In contrast the carbonates of SMF 9 can be interpreted as hemipelagic oozes that were formed through the deposition of carbonate muds and a mixture of fine-grained shallow- and open-marine grains.

4.2 Drowning phase

Platform top

The drowning succession reflects an abrupt and fundamental change of the depositional environment within the platform interior. The shift from a mud-dominated facies (pre-drowning) to densely packed biosparites (SMF 12) reflects a change from prevailing quiet-water conditions to an open-marine environment with high-energy waves and current activity above the storm-wave base.

While the platform sediments of the pre-drowning phase contain various non-skeletal and skeletal grains, the drowning sediments show characteristic biotic assemblages. Encrusted grains, peloids and ooids are completely missing and low-diversity populations with echinoderms, brachiopods or molluscs dominate (Fig. 9). Sub-sequences, shown by contrary pulses of suspension feeders and grazers (echinoderms, brachiopods) versus other shallow-marine organisms (mainly molluscs) mark a cyclic sedimentation during the entire drowning succession. It is likely that these small-scale variations that were also found within the slope sediments, were triggered by high-frequency sea-level fluctuations (Fig. 11). These could have been responsible for periodic changes of the environmental conditions (e.g. energy level, water depth, nutrient content) and could have shifted the balance among the different organism groups. Near the top of the drowning sequence an increase in micrite (Fig. 5) marks the transition of the entire platform below storm wave base, in which quiet water conditions allowed for the deposition of muddy, fine-grained material.

Platform slope

The drowning sediments deposited on the mid-slope also reflect a fundamental modification of the depositional environment of the carbonate platform.

While the pre-drowning sediments show a high diversity of non-skeletal and skeletal grains, the sediments of the drowning sequence are characterised by the deposition of specific, non-skeletal grains and a low-diversity biofacies. Extraclasts and peloids that represent erosional products of mud-rich lagoonal sediments were deposited during the pre-drowning phase and point to extensive erosion of the lithified substrate within high-energy environments. After erosion, these components were transported across the platform margin and deposited, under decreasing transport energies, on the platform slope (Fig. 10). The absence of skeletal fragments of corals, microproblematica, calcareous algae and other sessile carbonate-producing organisms, point to a deterioration of the build-ups situated at the platform margin. Instead of these skeletal fragments, bioclasts of echinoderms, brachiopods and molluscs dominate leading to the deposition of thin coquinas that occur scattered along the slope.

Analogous to the platform top sequence, the drowning succession on the slope is characterised by a cyclic sedimentation pattern displayed by the repeated shedding of non-skeletal grains (Fig. 6). This cyclic input could also have been caused by high frequency sea-level fluctuations.

4.3 Post-drowning phase

Entire platform area

Within all successions the sediment fabric and microfacies reflect a uniform depositional environment across the entire platform. Fine-grained limestones (SMF 3), containing fragments of pelagic organisms point to sedimentation within an open-marine, deeper-water environment below storm-wave base. Extensive bioturbation of all sediments reflects oxic bottom-waters as well as continuous pore-water circulation within the sediments.

At this point of time the independent sediment production on the carbonate platform stopped and the platform remained as a submerged plateau. Relative high amounts of strongly impregnated and phosphatized ooids as well as skeletal echinoderm fragments were deposited on the flattened platform top. They form the relics that mark the former presence of shallow-marine facies belts. Hemipelagic oozes that onlap the steep flanks of the carbonate platform ultimately form a distinct drowning unconformity (SCHLAGER & CAMBER, 1986; SCHLAGER, 1989; CAMPBELL & STAFLEU, 1992; Pl. 25/1, 2; Fig. 10).

At the beginning of the Aalenian, increased input of detrital quartz led to the deposition of well-sorted calcisiltites (SMF 2). We suggest that the terrigenous material originated on the Sahara Craton and was transported by wind into the depositional area of the Jbel Bou Dahar carbonate platform.

5 DISCUSSION AND CONCLUSIONS

A distinct picture of the carbonate platform history evolves when the results of the field studies and microfacies analyses are combined (Fig. 9, 10).

During the pre-drowning phase platform sedimentation was steered by an interplay of sea-level fluctuations and the growth of carbonate-producing organisms within the shallow-water realm (CREVELLO, 1990). Distinct facies belts formed along the carbonate platform, ranging from a sheltered lagoon (FZ 8, 7) on the flat platform top to a margin (FZ 6, 5) characterised by sand shoals and build-ups, and a steep sandy slope (FZ 4, 3) with its distinct sea-level related sedimentation patterns (CREVELLO, 1990; KENTER, 1990; BLOMEIER, 1997; SCHEIBNER & REIJMER, this volume).

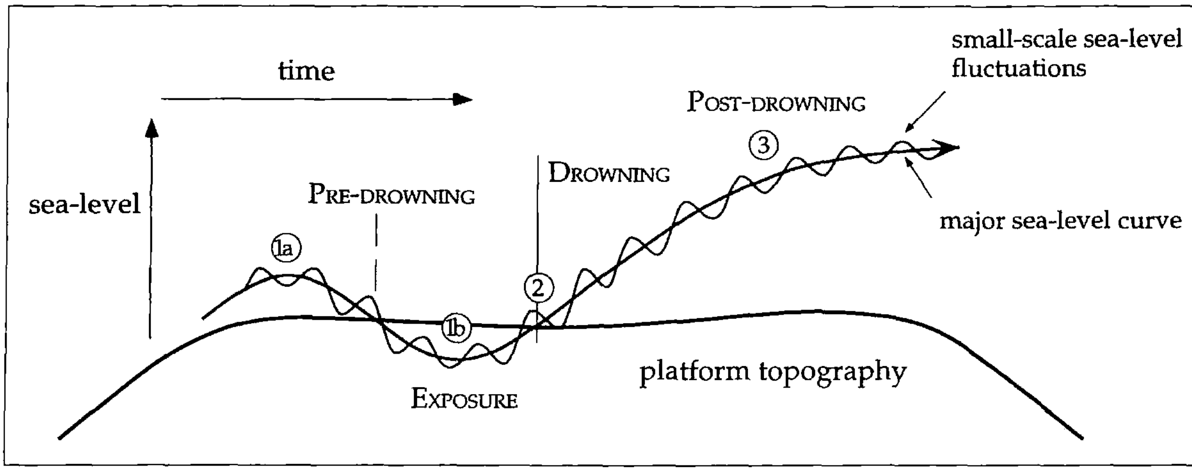

Fig. 11. Sea-level variations and drowning stages. 1a) Pre-drowning phase and sea-level highstand: carbonate production within the flooded platform interior. 1b) Pre-drowning phase and sea-level lowstand: subaerial exposure of the platform top and shift of the carbonate production area to the margin and upper slope. 2) Renewed flooding of the platform top at the beginning of the drowning phase. 3) gradual transition to a deep-marine sedimentation during the post-drowning phase.

On the platform top sea-level lowstands produced distinct exposure horizons (CREVELLO, 1990). During these periods sediment production ceased within the emerged areas of the platform interior and the carbonate factory shifted to the margin and upper slope section of the platform (Fig. 11). Transport and deposition of eroded material through debris flows formed distinctive sediment packages, bounded by erosional surfaces on the upper and mid-slope. Based on their sediment composition BLOMEIER (1997) interpreted these sediment packages as lowstand system tracts.

During sea-level highstands restricted-marine conditions were restored on the platform top, resulting in the production of mud-rich sediments (Profile D7; Fig. 5). The muds were transported to the adjacent basin and partly deposited on the gently dipping lower slope forming onlapping highstand system tracts (BLOMEIER, 1997). These sediment packages (Section D6; Fig. 7) consist of two types of carbonates that alternate with marls: (1) hemipelagic oozes (mud- to wackestones, SMF 9), and (2) medium-coarse grained pack- to grainstones (turbidity currents, SMF 4).

At the mid- to lower slope the alternation of highstand and lowstand system tracts forms a typical interfingering depositional pattern (BLOMEIER, 1997). Modelling studies by BOSSCHER & SOUTHAM (1992) using a light-dependent platform growth model in response to sea-level fluctuations came up with the same type of stacking pattern.

To answer the question what actually caused the platform drowning we need to evaluate various processes that may have played a role during this event.

Drowning resulting exclusively from a rapid eustatic sea-level rise is not very likely within this period of the earth history, seen as a greenhouse era (FRAKES et al., 1992). Without distinct glaciations of the polar ice caps the amplitudes of eustatic sea-level fluctuations would have been far too small to cause the drowning of a healthy carbonate platform. SCHLAGER (1981) already demonstrated that the growth potential of healthy carbonate platforms is orders of magnitude higher than the rates of long-term eustatic rises in sea level.

Burial by prograding siliciclastics (SCHLAGER, 1989) can also be excluded as the sediments deposited at the beginning of the post-drowning phase only contain small amounts of terrigenous material. An increased input of probably wind-driven quartz grains does not occur before the Aalenian, at a time when the platform was already drowned.

Drowning in the sense of "death by emergence-and-submergence" (SCHLAGER, 1998; WILSON et al., 1998) requires subaerial exposure, causing complete deterioration of the entire shallow-marine environment before renewed flooding whereby marine conditions are re-established. CREVELLO (1990) proposes a large-scale exposure event at the end of the pre-drowning phase and estimates the duration of the subaerial exposure between several 100.000's of years and perhaps more than 1 Ma. Based on the microfacies analysis, which shows some indications for vadose environments on the platform top, we agree that subaerial exposure might have happened at the end of the pre-drowning phase. However, no evidence for such a long-time event proposed by CREVELLO (1990) could be observed. No large-scale features like calcrete soils or karsted surfaces were found on the platform top and no subaerial-altered erosional products were deposited at the toe-of-slope. In addition, the global sea-level curve of HAQ et al. (1988) does not indicate such a major sea level drop for the beginning of the Toarcian. It seems that the duration of the subaerial exposure, preceding the drowning was only a small "normal" event within a series of high frequency sea-level variations superimposed on a large-scale sea-level rise (Fig. 11). These small-scale events caused cyclic variations in sediment composition during the pre-drowning and drowning stages. At the pre-drowning – drowning boundary, however, they were, in combination with fundamental environmental changes, sufficient enough to hamper the renewed start of carbonate production on the platform. While the pre-drowning - drowning transition occurs as a major event, the drowning to post-drowning boundary is gradual, and only shows a series of small-scale events that led to the deposition of a similar deep-water facies on the slope and the former platform interior.

The question still remains why small-scale sea-level variations caused the complete deterioration of the carbonate reef-system and the subsequent drowning of the carbonate platform? We propose that some additional factors, as shown in our microfacies analysis, played a decisive role in the drowning of the platform.

An abrupt transition within the lagoon from wacke- to mudstones to grainstones at the beginning of the drowning sequence points to a change from a quiet-water environment to high-energy conditions. At the slope this transition is marked by the input of high amounts of non-skeletal grains (extraclasts, pseudo-peloids). These components, consisting of lithified lagoonal material of the pre-drowning phase, show that erosion took place on the platform top followed by the deposition of the eroded material on the platform slope. Severe deterioration of the build-ups at the platform margin must have taken place as is reflected in the composition of the slope sediments that suddenly lack this type of bioclasts. The platform margin must have lost its protective function and allowed for open-marine, high-energy conditions to establish themselves on the platform top.

The occurrence of low-diversity biota assemblages, mainly with echinoderms and molluscs, can be seen as a response of the carbonate platform community to this environmental change on the platform top. In literature, the occurrence of these type of communities often have been related to a change from oligotrophical to meso- or eutrophical conditions (ZEMPOLICH, 1993). This is also confirmed by the Fe-, Mn- and P- enrichments found in the drowning and post-drowning sediments. According to FÖLLMI et al. (1994) and DRZEWIECKI & SIMO (1997) these types of encrustations can also be related to a primary higher nutrient content in the water column.

The drowning process of the Jbel Bou Dhar shows a transition from a healthy carbonate platform to a deeper incipiently drowning stage just like the present-day Pedro Bank (GLASER & DROXLER, 1991) and Cat Island (DOMINGUEZ, et al., 1988). Instead of recovering form this semi-drowned state a subsequent rise in sea level led to the ultimate drowning of the entire platform.

In comparison with the succession of the entire rift basin that show equal drowning features and a subsequent, uniform deep-marine facies (WARME, 1988) within the Toarcian, these local processes seem to be triggered by a regional or even global change in ocean circulation patterns. JENKYNS et al. (1991) clearly showed the occurrence of an Early Toarcian anoxic event within the Alpine-Mediterranean domian. HALLOCK & SCHLAGER (1986), HALLOCK et al. (1988) and DRZEWIECKI & SIMO (1997) proposed upwelling of nutrient-rich depth-waters as a possible cause for the deterioration of oligotrophical reef communities. This theory agrees with the death-in-the-tropics scenario of WILSON et al. (1998), who made nutrient-rich surface waters of the equatorial upwelling zone responsible for the death of carbonate-producing, shallow-water organisms and the subsequent drowning of various Cretaceous platforms.

Besides the environmental and oceanographic causes the onset of local fault block tectonics, resulting in the decollement of the platform margin, could have formed an additional reason for the deterioration of the platform. These type of tectonic movements were frequently observed during the structural evolution of the rift basin (AGARD & DU DRESNAY, 1965; LEE & BURGESS, 1978; BRECHBÜHLER et al., 1988) and would also explain the large-scale down faulting in the Domerian of platform margin facies belts (CREVELLO, 1990) along the southern border of the platform.

In conclusion, we propose that a series of disadvantageous processes (SCHLAGER, 1998) led to the ultimate drowning of the carbonate platform:

• Subaerial exposure caused by high frequency sea-level variations destroyed the former reef communities at the end of pre-drowning phase.

• Local environmental effects (inimical bank waters, washed off soil and the release of nutrients and suspended material) during the renewed flooding of the platform top hampered the re-establishment of a flourishing carbonate-producing community.

• High-energy conditions prevailed during nearly the entire drowning phase and resulted in continuous transport of eroded platform-top substrate sediments across the margin to the slope.

• Competition by better-adapted organisms like echinoderms and molluscs with the oligotrophic carbonate-producing living communities may also have played a role.

• Regional or even global changes in ocean circulation patterns probably produced unfavourable environmental conditions for platform growth during the drowning phase.

ACKNOWLEDGEMENTS

We thank Jeroen Kenter (Vrije Universiteit, Amsterdam) for the introduction into the geology of the Jbel Bou Dahar and for discussion in the field. Florian Böhm (Geomar, Kiel) is thanked for reviewing a first draft of the manuscript and for numerous discussions. We acknowledge the constructive reviews by W. Schlager (Vrije Universiteit, Amsterdam) and J.W. Warme (Colorado School of Mines, Golden).

M. Dahmani of the Ministére de l'Energie et des Mines in Rabat provided the fieldwork permits. A. Milhi is acknowledged for his assistance in the field during the initial stages of our fieldwork.

Thin-sections were made by the thin-section department of the Vrije Universiteit (Amsterdam), A. Tim and W. Reimers (Christian-Albrechts-University, Kiel). T. Kuhlmann prepared part of the photo-prints.

This research has been supported by grants Re 1051/1-1, 1-2 and 1-3 of the Deutsche Forschungsgemeinschaft (German Science Foundation).

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Manuscript received January 29, 1999
Revised version accepted June 22, 1999