Projects: Ba 675/9 „Evolution, Ökologie und Konstruktionsmorphologie der Mollusken und Algen des Rudistenriffes und der begleitenden Faziesbereiche", Project Leader: K. Bandel (Hamburg)
Wi 725/6 „Steuerungsfaktoren biogener Sedimentation an einem Rampen-Transekt im Abt-Alb der mittleren Süd-Pyrenäen", Project Leader: H. Willems (Bremen)
Ku 642/10 „Rekonstruktion intertethyaler Meeresspiegelschwankungen – die sequenzstratigraphische Entwicklung der kretazischen (Oberapt-Coniac) Karbonatplattform des nördlichen Sinai", Project Leader: J. Kuss (Bremen)

# Sedimentary Processes and Intertethyal Comparisons of Two Early/Late Cretaceous Carbonate Ramp Systems (NE-Africa and Spain)

*Martina Bachmann, Klaus Bandel, Jochen Kuss & Helmut Willems*

**Area of Study:** Sinai (NE-Egypt), Northern Jordan, Organyà Basin (SE-Pyrenees, Spain)
**Stratigraphy:** Aptian to Turonian
**Depositional Setting:** Carbonate ramp (Sinai and Jordan), carbonate ramp (Organyà)
**Facies:** Supratidal to subtidal inner ramp limestones with siliciclastic influence (Sinai and Jordan), subtidal shallow ramp facies (Organyà)
**Organisms:** Calcareous algae, benthic foraminifera, bivalves, gastropods
**Controlling Factors:** Low frequency eustatic sealevel changes due to orbital variations (precession and eccentricity)
**Research Topic:** Paleogeography, sequence stratigraphy, cyclostratigraphy, paleontology

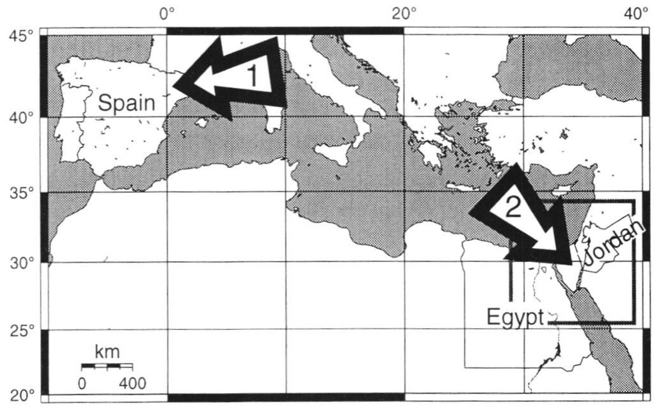


**Fig. 1:** Location of the two Aptian to Cenomanian ramp systems of the southern Pyrenees (arrow 1) and the northern Sinai and Jordan (arrow 2).

## Abstract

Regional studies on the Cretaceous carbonate shelves of Egypt and Jordan as well as of Spain, together with selected paleontological studies, form the basis of detailed investigations on sedimentary processes of two Late Aptian to Cenomanian carbonate ramps. The two ramps are situated on opposite shores of the Cretaceous Mediterranean Tethys and thus may allow to highlight the influence of various sedimentologic and biologic factors controlling the sedimentation patterns with respect to interpretations of sequence and cyclostratigraphy. The Tethyan comparison of the Late Aptian to Albian ramp of Organyà (S-Pyrenees) and the Late Aptian to Cenomanian ramp of the northern Sinai may act as examples to demonstrate the effect of different interacting parameters on carbonate ramp sedimentation and to filter superior, Tethyan-wide signals, which control age-equivalent sedimentation patterns, mainly induced by changing sealevels of different scales.

## 1 Aims and Methods

On the basis of detailed field work, the bio- and lithostratigraphic frameworks of different shallow shelf areas were established (Fig. 1). Macro- and micropaleontologic investigations of the following shelf inhabitants were carried out: Calcareous algae, benthic foraminifera, gastropods and rudists. Their distribution and paleoecologic relationships allow to describe different habitats of the Cretaceous shelves. Moreover, they typify various depositional systems which have been studied in detail on the basis of macro- and microfacies investigations. Within the first project (see 2. The Cretaceous Sediments in NE-Egypt and Jordan), these data were integrated and allow to estimate the regional paleogeographic relationships and some controlling factors for biogenous and sedimentary processes.

Variations of facies and depositional geometries reflect the dynamically changing environments which have been studied with respect to sequence stratigraphic interpretations (see 3. The Aptian/Albian Carbonate Ramp of Organyà, SE-Pyrenees, Spain). Additionally, a quantitative analysis of selected sections formed the basis of statistic analyses and interpretations of higher-frequency cycles. They will be compared with cyclic patterns of age-equivalent ramp deposits of the northern Sinai (see 4. The Late Aptian to Cenomanian Carbonate Ramp of the Northern Sinai) to filter superior signals of Cretaceous sealevel fluctuations and their controlling sedimentologic and biologic factors.

The studies began in different areas: NE-Egypt/Jordan (1990-1991: Bandel, Kuss), Spain (1990-1994: Willems, Bachmann). Within the course of a new project on Early to Middle Cretaceous ramp deposits in northern Sinai (started in 1994: Kuss, Bachmann) the regional results of the earlier facies studies on the Sinai were combined with new sedimentologic approaches, proved for the Spanish ramp before. The results of the first two projects have been published – the investigations for the new project are in progress.

The main aims of the studies were:

- Establishment of facies and stratigraphic frameworks within different paleoecologic positions of the Cretaceous successions to reconstruct specific depositional models along the Cretaceous shelf systems, especially ramps.
- Interpretation of biogenous and sedimentologic processes controlling Cretaceous ramp deposition in selected

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settings. Calculation of the carbonate and siliciclastic components affecting deposition on carbonate shelf systems, with respect to paleontologic and sedimentologic data.
- Studies on sequence stratigraphic and cyclostratigraphic patterns with respect to their controlling factors, especially the interaction between eustatic signals and regional processes (subsidence, biogenous growth, terrigenous input); these interpretations include calculations on the effects of the orbital parameters.
- Determination of superior signals controlling Cretaceous sealevel fluctuations of different duration, based on an N-S Tethyan comparison.

## 2 The Cretaceous Sediments in NE-Egypt and Jordan

### 2.1 Geologic and Tectonic Frame

The Cretaceous strata along the northern passive continental margin of Northeast Africa were formed on a broad extended shelf system, which was studied in the Sinai and Jordan. Here, the sedimentation was influenced by major tectonic events during the Mesozoic-Early Tertiary, linked with the formation and closure of the Neotethys Ocean. Its southern shores are represented by Sinai and Palestine areas, where two tectonic domains markedly influenced the sedimentary successions: the stable shelf in the south (not affected by rifting processes) with incomplete, mainly continental successions, and the unstable areas further north, where interdigitating continental-marine units occur (KUSS & BACHMANN 1996). The Early Cretaceous tectonic movements induced uplift within the unstable areas resulting in widespread continental deposition. The Aptian-Turonian period is characterized by a relative tectonic quiescence, while during Coniacian-Early Eocene times a new tectonic stress field developed, due to the convergence of the European and African plates. As a result, the northeast trending foldbelts of the Syrian Arc evolved, extending from Syria to the unstable shelf of the central Sinai (SHAHAR 1994) and across the Gulf of Suez area.

The deposition of the Cretaceous northdipping shelf in Sinai and Jordan was mainly influenced by the interplay of terrigenous input and carbonate production, regional structural movements and eustatic sealevel fluctuations. Based on biostratigraphic zonations (KUSS & MALCHUS 1989), the litho-/microfacies investigations enabled to reconstruct the facies interfingering between continental and nearshore/offshore shelf environments within the Cretaceous successions. Furthermore, the shifts of the shoreline were interpreted reflecting major onlap/offlap-patterns within the stratigraphic successions of the different areas (KUSS 1992a). They allow to estimate the $2^{nd}$-order relative sealevel fluctuations, forming the base of ongoing detailed interpretations on $3^{rd}$- and $4^{th}$-order sealevel oscillations (see 4.).

### 2.2 Stratigraphy and Facies

The major phases of the stratigraphic development of the Cretaceous shelf systems are briefly summarized for various timesteps. They indicate different depositional scenarios based on interpretations in KUSS (1992a, b) and recently compiled paleogeographic correlations (KUSS & BACHMANN 1996). Within this regional stratigraphic and lithofacies frame, detailed studies of selected shelf benthos were done (BANDEL & MUSTAFA in press, MUSTAFA & BANDEL 1992, KUSS & CONRAD 1991, SENOWBARI-DARYAN & KUSS 1992, KUSS 1994).

The marine Cretaceous succession starts with Late Aptian nearshore deposits proved from the northernmost outcrops of the Sinai (KUSS & SCHLAGINTWEIT 1989). A rapid progradation of shallow-water carbonates during Albian times caused a southward shift of the coastline resulting in marine deposits of Middle-Late Albian age, reported also from central Jordan (WEIDICH & AL-HARITHI 1990). The maximum southward extension of peritidal carbonates during Late Cenomanian times documents the first Cretaceous maximum of the $2^{nd}$ order sealevel rise, followed by the gradual northward retreat of the carbonate shelf during Late Turonian times, which is due to the Turonian-Santonian drop of the sealevel (LEWY 1990). During latest Turonian-Coniacian times, the breakup of the Mid-Cretaceous carbonate shelf started as a consequence of the Syrian Arc tectonics. The resulting local subsidence and uplift of the unstable shelf are reflected by regionally differentiated sedimentation patterns. The continuing synsedimentary tectonic influence was overprinted by the again rising $2^{nd}$-order sealevel during Santonian to Maastrichtian times, resulting in the deposition of deeper shelf lithologies (chalk-marl units and shales) within the region.

### 2.3 Paleontologic Results

Studies on shallow water and "reefal" carbonates were carried out within the Albian to Turonian units with respect to their fossil content, and the characteristics of the Cretaceous biogenous sedimentation were reconstructed: Within protected shallow water environments rudist biostromes and bioherms evolved locally. The absence of large wave-resistant bioconstructions reflects the gently dipping shelf geometry resulting in a carbonate ramp system.

A Cenomanian rudistid biostrome was investigated in detail (Jordan) consisting of radiolitids forming brushlike growths, caprinulids with two almost equal cowhorn like valves and accompanying mytilid and heterodont bivalves and neritid and neritinid gastropods. The organisms compose an about 2 m thick unit which is overlain by shallow water limestones formed in lagoonal and intertidal environments. These limestones were formed during Turonian time as is indicated by *Hippurites* growths which settled on cemented and drowned beach rock surfaces. The rudistids were constructionally-functionally interpreted and described (BANDEL & MUSTAFA in press); furthermore, the accompanying gastropods were determined and ecologically interpreted (BANDEL & MUSTAFA in press). Actaeonellidae have close affiliation with those of the Gosau facies in the Alps, the nerineids lived partly together with them in the lagoon, partly among the rudists. The radiolitids had partly transparent opercular valves that aided in the culturing of unicellular algal symbionts held within the tissue of the mantle. The opercular lid moved only little, tightly locked by the large hinge teeth. The caprinulids stored much of their mantle tissue within the shell in canals. This prevented boring organisms to penetrate the shell and provided space for algal symbionts in the mantle tentacles, illuminated through the shell surface. The hippuritids had reduced their ligament to an elastic band that no longer induced the valves to a gape, when no muscle pulled them to a close. The opercular have here acted as container of mantle tissue protected in radial canals by a spongeous outer layer.

The close associations of rudists with lagoonal sediments and specialized nerineid and actaeonellid gastropods indicate that they were living in shallow, warm bank environment in clear water. Feeding, in contrast to the corals, was aided by symbionts and needed little plankton, and of the later only phytoplankton was necessary. This type of environment ceased to exist in the Late Maastrichtian and was not taken over by oysters, since these lived alongside in Jordan (and other places like the Gosau or Southern

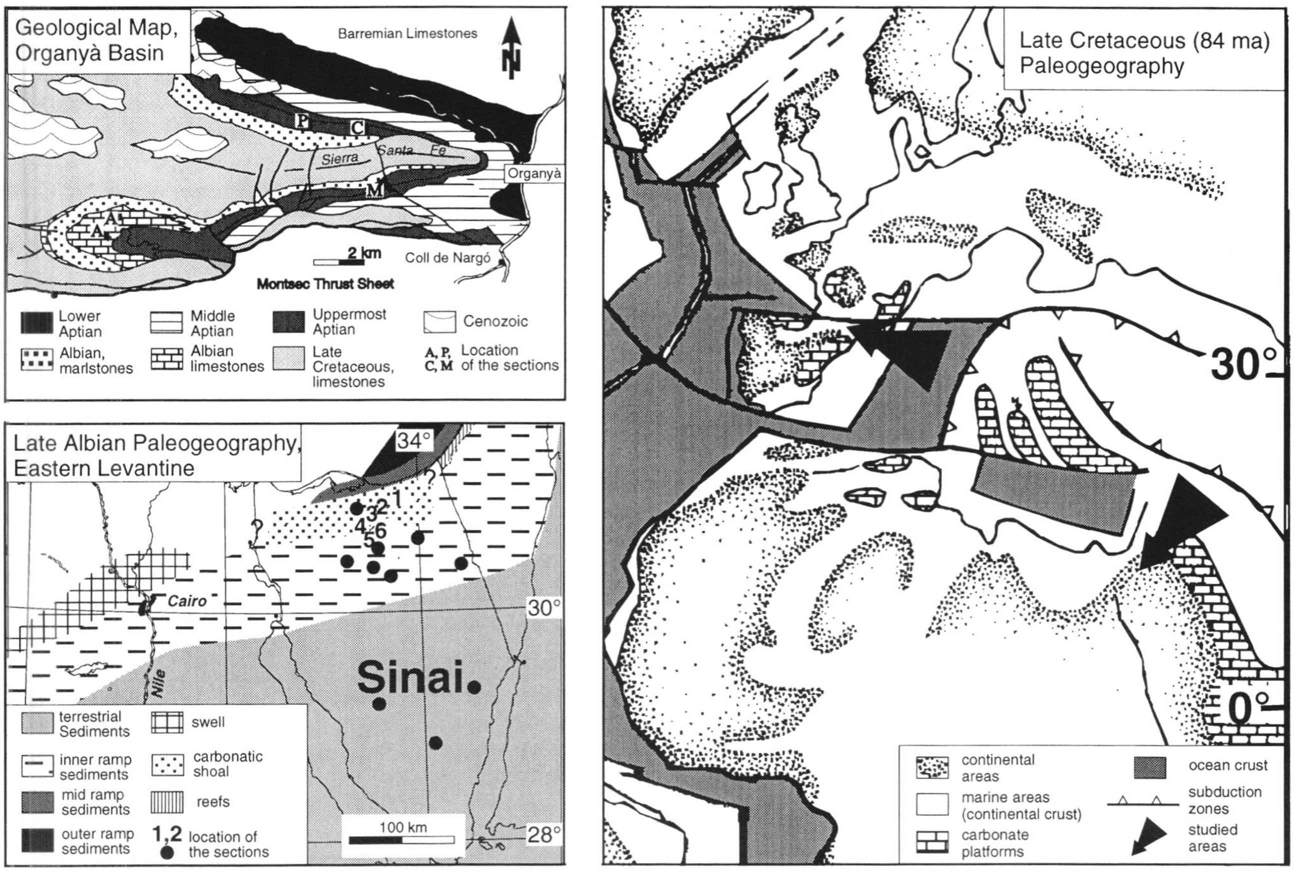



**Fig. 2:** Paleogeographic map of the Mediterranean Tethys (right, according to EBERLI et al. 1993). The arrows within this map indicate the position of the two Aptian to Cenomanian ramp systems of the Organyà Basin, southern Pyrenees (top left – sections P, C, M see Fig. 3) and the northern Sinai (bottom left – sections 1 to 6, see Fig. 5).

Pyrenees) and did not change much in the Cretaceous/ Tertiary transition.

Within the shallow carbonate ramp areas, the distribution of calcareous algae was investigated (KUSS 1994): first to improve the regional stratigraphic frame and second to support the paleoecologic interpretations, mainly based on micro- and macrofacies characteristics. Algae of Aptian-Albian carbonates occur in both calm and agitated waters of the shallow shelf, often concentrated in layers of winnowed ramp sediments and oolitic shoals. The Cenomanian taxa of the innershelf environments are mainly found within miliolid-bearing limestones together with oolitic, oncolitic sediments indicating bankmargin or slightly protected areas. Turonian algae were proved from shallow restricted lagoonal environments. Furthermore, several algal taxa can be used for paleogeographic correlations of the Albian-Cenomanian and Turonian-Coniacian strata (KUSS & CONRAD 1991).

The results of these studies concerning regional aspects of stratigraphic correlation, facies development, and investigations of selected shelf inhabitants of the Cretaceous shelf deposits in Sinai and Jordan formed the basis for detailed investigations on a smaller segment of the Early/Middle Cretaceous ramp (see 4.).

## 3 The Aptian/Albian Carbonate Ramp of Organyà, SE-Pyrenees, Spain

### 3.1 Introduction

The carbonate ramp of Organyà may serve as an Early Cretaceous case study, to interpret cyclic sedimentation patterns of a deeper ramp system, comprising a transect along the subtidal inner ramp, the mid ramp and the outer ramp. The about 700 m thick deposits of Latest Aptian and the Earliest Albian were studied with regard to sequence- and cyclostratigraphy and their various controlling factors, based on detailed interpretations of the sedimentation patterns.

**Geological setting:** The investigated sections represent the southern margin of the Organyà Basin (southeastern Pyrenees, Fig. 2), which is now situated in the Bóixols Thrust Sheet, the uppermost nappe of the South Central Pyrenean Unit (VERGÉS & MUÑOS 1990). During Early Cretaceous, the extensional Organyà Basin (VERGÉS 1993) was situated at the northern margin of the Ebro Continent. There, the sedimentation patterns were affected by tectonic movements of the opening Gulf of Biscay as well as by the geodynamic events derived from the Tethyan realm (compare BERÀSTEGUI et al. 1991).

Exclusively subtidal sediments were investigated in 4 sections, documenting a transect from the shallow, proximal ramp down to the deeper, distal areas (Pl. 1/1). A detailed facies analysis allows to establish sequence stratigraphic interpretation and to distinguish thickening- and coarsening-upward cycles of $4^{th}$- and $5^{th}$-order (Pl. 1/2,3), as well as cyclic changes of the facies distribution within the various sections (Fig. 3). Additionally, statistic methods recorded by a Late Aptian reference section (quantitative analysis, principal component analysis) give more detailed information about the cyclicity of the facies distribution (BACHMANN 1994).

### 3.2 Stratigraphic Frame and Ramp Model

The stratigraphic concept of the Uppermost Aptian (Font Bordonera Unit) and the Lowermost Albian (Lluça Unit) used here is based on the concept established by

BERÀSTEGUI et al. (1990). The biostratigraphic frame is based on planktic and benthic foraminifera and ammonites (PEYBERNÈS 1976, MARTINEZ 1982, SOUQUET & PEYBERNÈS 1991, SCHÖLLHORN 1992).

The integration of all sedimentologic data allows to concentrate on two major factors, which controlled the distribution of different facies types on the Late Aptian/Albian stormprotected ramp (BACHMANN 1994): water depth and

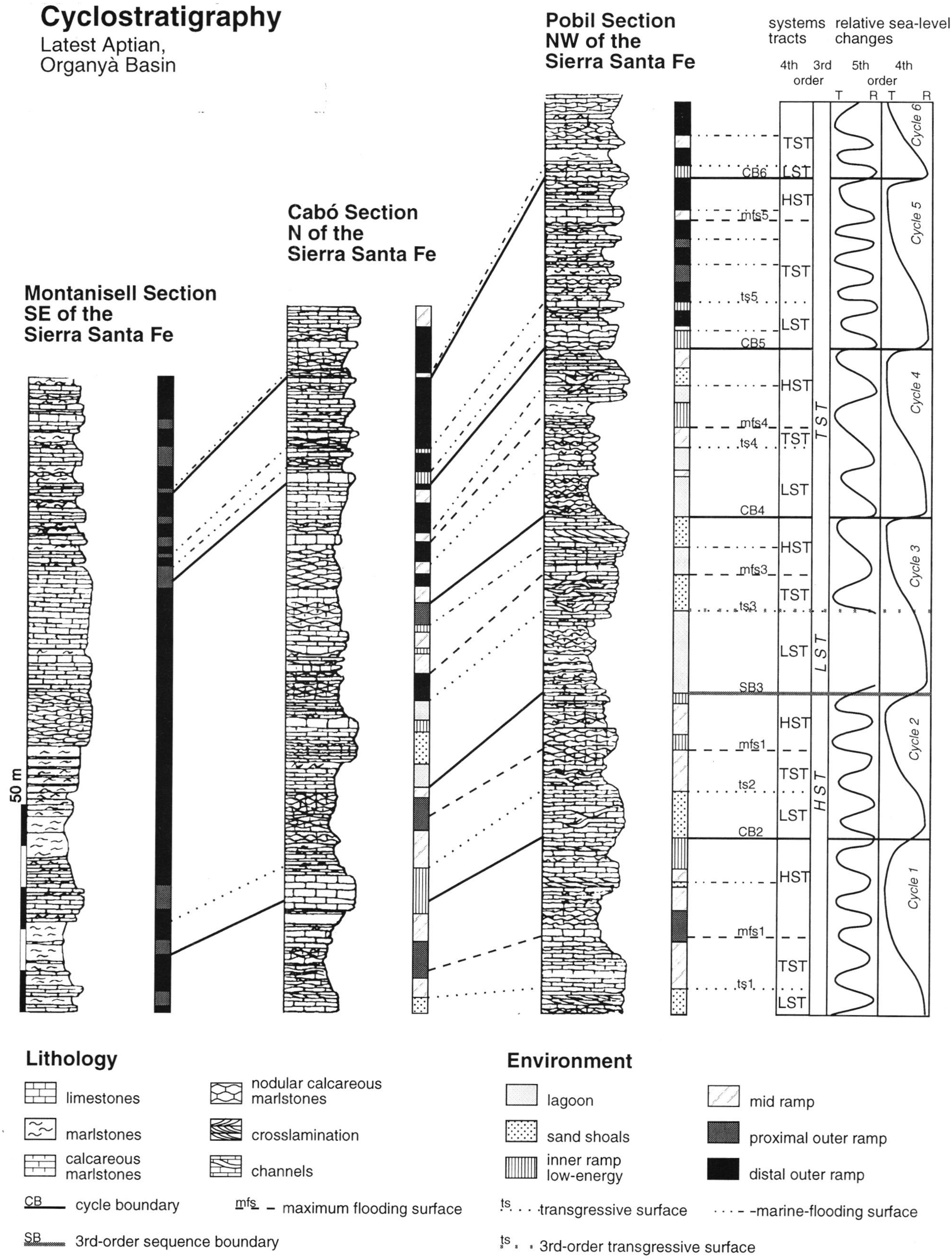



**Fig. 3:** Sequence and cyclostratigraphic interpretation of the latest Aptian strata of the Organyà Basin (location of sections see Fig. 2), based on facies and statistic analyses.

water currents, depending on bottom topography. Moreover, two different ramp scenarios were distinguished: The Latest Aptian ramp was subdivided into three major areas of deposition, characterized by the distribution of the biogenous and abiogenous components, sedimentary structures, and 20 individual microfacies types (BACHMANN 1994): The inner ramp (above the fairweather wavebase) with small scaled variations of sedimentary patterns comprise bioclastic carbonate shoals, lagoonal areas, and few small patch reefs of rudist and coral bioherms. The midramp area (between fairweather wavebase and storm wavebase) is dominated by thick marly and bioclastic packstones, whereas wackestones and marlstones with autochthonous bioclasts prevail in the outer ramp (below the storm wavebase). During lower Albian, a SW-directed coastal onlap took place, the inner ramp-bioherms disappeared entirely, and a steepening of the general ramp geometry can be derived from common turbidites in the outer ramp.

### 3.3 Sequence Stratigraphy and Cyclostratigraphy

Based on the results of both microfacies and statistics, several cycles of different orders can be distinguished within the three sections of the Upper Font Bordonera Unit: 3$^{rd}$-, 4$^{th}$- and 5$^{th}$-order cycles, characterized by paleoenvironmental changes (Fig. 3). Variations of the depositional environment are especially expressed by changes of the component composition (shallow/deeper marine ramp) and by variations of wave agitation. Facies changes within the succession reflect the shifting of the depositional environments up and down the ramp and are derived from relative sealevel changes (Fig. 3, right). These facies variations have been used for the definition of the systems tracts within the sequence stratigraphic interpretation, and for the determination of characteristic sedimentation patterns. Also, the point of offlap break (definition according to VAIL et al. 1991) was only determined by sedimentation patterns within the different sections. The correlation of the sections was supported by results of a detailed mapping campaign (SCHWENKE 1993, WITTMANN 1993), by a strong facies change in all sections, and by cyclic patterns (e.g. counting of 4$^{th}$-order cycles).

**3$^{rd}$-Order Cycles (Sequences):** Six 3$^{rd}$-order sequences were observed within the Late Aptian to Albian strata (BACHMANN 1994). Sequence boundaries are marked only by changes in facies, because of subtidal depositional conditions throughout (Pl. 1/3). The sealevel dropped only a few times below the point of offlap break. The LSTs are characterized by basinward shifts of the shallow facies belts: Carbonates of the lagoonal, shoal and sometimes midramp facies, overly the midramp or outer ramp respectively. In general, only minor amounts of sediment were accumulated during the LST. The TSTs are characterized by landward shifts of the facies belts (interrupted by high-frequency sealevel changes); furthermore, an increasing transgression during the late TST resulted in stronger landward shifts of the facies belts within the latest Aptian strata (Fig. 3). Midramp to outer ramp sediments covered the former inner ramp area. The HSTs are characterized by progradational, or aggradational facies patterns, indicating sealevel stillstand. Variations of the depositional environments within the sections are due to higher-frequency sealevel changes.

**4$^{th}$-Order Cycles:** 4$^{th}$-order cycles were equally recognized by variations of the depositional environments within all Aptian (Fig. 3) and Albian sections (Pl. 1/3). Furthermore, they became evident by variations of the statistic parameters within the Late Aptian reference section, where six 4$^{th}$-order cycles were shown in detail (Fig. 3): The thickness of the 4$^{th}$-order cycles varies between 35 to 40 m in the shallowest section to less than 30 m in the deepest section, reflecting different accumulation rates within different depths of the carbonate ramp. Again, facies changes define the 4$^{th}$-order sequence boundary as well as the systems tracts.

**5$^{th}$-Order Cycles (Parasequences):** The 5$^{th}$-order cycles are well expressed by facies variations in the upper parts of the Late Aptian sections (Fig. 3, Pl. 1/2). Each cycle reflects a transgressive-regressive change of the relative sealevel, as indicated by facies changes from outer-ramp to inner-ramp sediments (proximal ramp area) and from distal outer-ramp to proximal outer-ramp sediments (distal ramp area, Pl. 1/1). These facies variations are masked by the lower frequency cycles within the lower parts of the sections. Here, the 5$^{th}$-order cyclicity is reflected by the variations of the statistic parameters (BACHMANN & WILLEMS 1996). In both cases, the thickness of the 5$^{th}$-order cycles is about 5 m in the outer ramp and up to 9 m in the inner ramp.

### 3.4 Discussion of the Controlling Factors

On a regional scale, the laterally continuous cyclicity patterns as well as the homogenous shifting of facies patterns and the constant ratio of the 4$^{th}$- and 5$^{th}$-order cycles (1:4 to 1:5) indicate that allocyclic sedimentary processes are a major control on the deposition of the Late Aptian and Early Albian strata (BACHMANN 1994). The cycles are clearly controlled by sealevel fluctuations, with the 3$^{rd}$-order amplitudes being higher than those of 4$^{th}$-/5$^{th}$-order. Thus, the eustatic signal is assumed as a major controlling factor. Cyclicity ratios of 1:4 to 1:5 are typical of the Milankovitch frequency band, related to orbital variations (precession during the Cretaceous: 18.6/22.5 kyrs according to BERGER & LOUTRE 1994; eccentricity 100/400 kyrs). The discussed strata comprise a period between 300 and 700 kyrs (according to timescales of HAQ et al. 1988 or CARON 1985); at least 30 cycles of 5$^{th}$-order (30x21 kyrs=630 kyrs) were distinguished. This best fits in the timescale of CARON as well as in the new timescale of GRADSTEIN et al. (1994), which gives a longer period for the Aptian than HAQ et al. 1988. Thus, the interpretation of the 5$^{th}$- and 4$^{th}$-order cycles as controlled by precession (21 kyrs) and eccentricity (about 100 kyrs) corresponds fairly well with the given biostratigraphic frame of 700 kyrs. Obliquity cycles could not be identified.

Uncommon are the high sedimentation rates of the Organyà Basin compared to other areas (e.g. DRUMMOND & WILKINSON 1992, PRATT & SMEWING 1993). The 5 to 9 m thick cycles of ca 21 kyrs (BERGER & LOUTRE 1994) result from average accumulation rates of 22 cm/1000 yrs to 40 cm/1000 yrs (without decompaction), which were interpreted as a result of high subsidence rates in connection with extensional tectonic movements in the SE Pyrenees (VERGÉS 1993). Furthermore, the latter are interpreted to induce a 3$^{rd}$-order sealevel rise. However, there is no time-equivalent sequence boundary compared with the global sealevel curve (HAQ et al. 1988) or compared with sequence stratigraphic interpretations of adjacent areas (GARCÍA-MONDÉJAR 1990, GARCÍA-MONDÉJAR & FERNÁNDEZ-MENDIOLA 1993, GRÄFE 1994, LENOBLE & CANÉROT 1993). Thus, local events seem to be the major controlling factors of the 3$^{rd}$-order sealevel changes (BACHMANN 1994).

## 4 The Late Aptian to Cenomanian Carbonate Ramp of the Northern Sinai

### 4.1 Introduction

The aim of the ongoing studies on the northern Sinai carbonate shelf is to analyze the sequence stratigraphic patterns and the interplay between low- and high-frequency

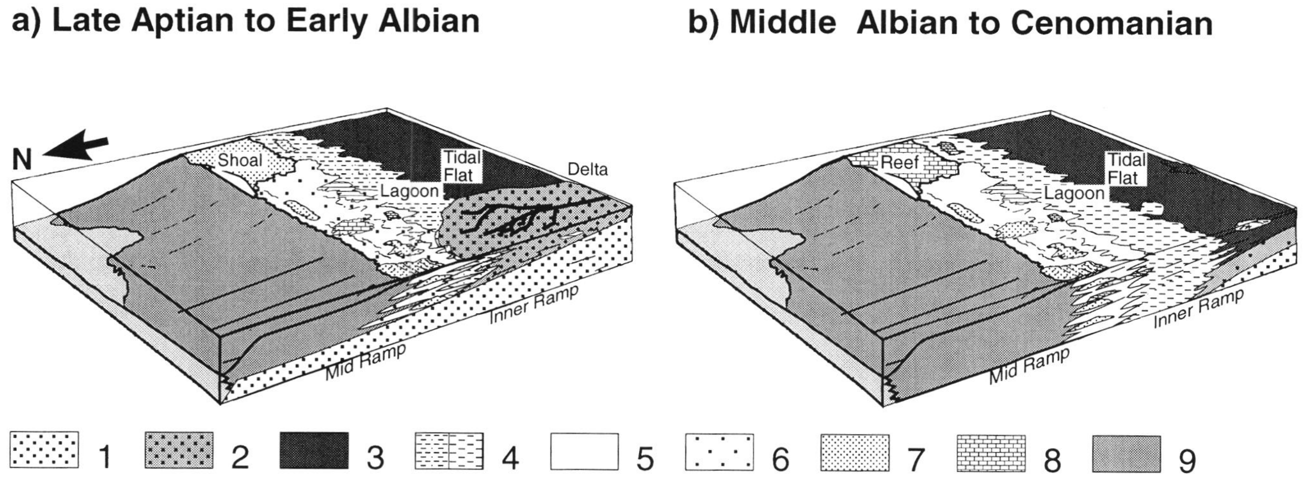



**Fig. 4:** Late Aptian to Cenomanian ramp geometry and facies distribution of the northern Sinai. 1) Terrestrial sediments, 2) deltaic sediments, 3) tidal flats, 4) lagoon with siliciclastic input, 5) open marine shallow ramp, 6) open marine with siliciclastic input, 7) oolitic and bioclastic shoals, 8) rudist bioherms and biostromes, 9) distal ramp.

cycles mainly caused by sealevel changes with respect to regional and global controlling factors; among them the influence of climatic variations will be tested and compared with the results of the Organyà Basin. The Late Aptian to Cenomanian carbonates of the northern Sinai were formed at the southern passive margin of the Tethyan Ocean, which is characterized by the absence of major tectonic movement during this time. The strata were studied by means of 21 sections, reflecting a transect from the continent to shallow marine environments, whereas deeper marine sediments are not present in surface outcrops. The sections cover a nearly 100 km N-S running shelf segment perpendicular to the Cretaceous shoreline. Here, detailed correlations are demonstrated along the northernmost exposed transect of about 40 km N-S distance (Figs. 2 bottom left, 4, 5). Within this frame, a detailed bed-by-bed analysis allows to reconstruct lateral and vertical shifts of sedimentation patterns, with respect to gradual changes of the ramp paleoenvironments. The change from a mixed carbonatic-siliciclastic environment to a carbonate ramp system during Early/Middle Albian times is evident in most sections.

### 4.2 Biostratigraphic Frame

Pre-Aptian deposits are delivered by continental sandstones. Due to a general southward transgression, Late Aptian sediments occur only in the northern Sinai, whereas Albian to Turonian strata cover the northern and the central region. Only the Late Aptian to Cenomanian part will be shown here in detail.

Because of the shallow marine Aptian-Turonian deposition, the biostratigraphic interpretation results mainly from benthic organisms. The ongoing analysis of ostracode assemblages in comparison with Israelian charts – studied by A. Bassiouni – allows to subdivide the Late Aptian to Turonian succession; equivalent ages are indicated by a few planktic foraminifera in the upper part of the sections of the eastern area. The studies on several Albian ammonites (by F. Geyer) from the northern area is not finished yet. In the northern part, orbitolines and dasycladacean algae were used for the biostratigraphic subdivision of the Late Aptian to Cenomanian sediments (Kuss & Schlagintweit 1989, Kuss 1994, Simmons et al. in prep.). Furthermore, the assemblages of pollen and spores will be used for stratigraphic correlations (studied by Salah El-Din).

### 4.3 Lithostratigraphic Correlation, Ramp Model, Description of Facies Patterns

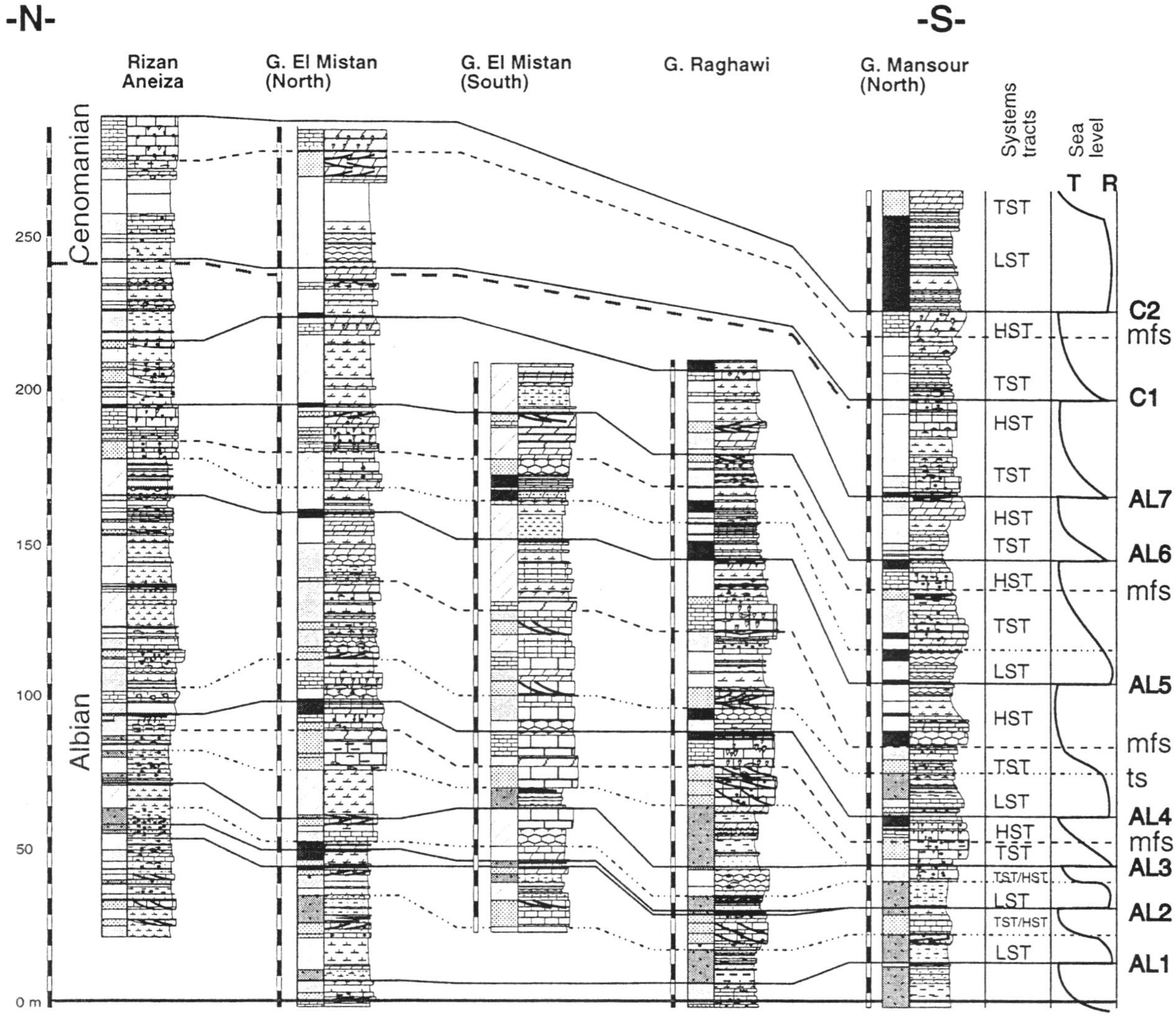
Various facies types were distinguished within the sections, reflecting different environments of deposition (Figs. 4, 5). The imprints of biosedimentary discontinuities are visible in several horizons of all sections and are used for correlation (Fig. 5). Within the Aptian/Early Albian succession they are characterized by burrows and ferruginous crusts; during Middle Albian to Cenomanian, rhizolitic layers (Pl. 2/7), carstifications (Pl. 2/6), teepee structures (Pl. 2/4) as well as some kaolinitic sandstone intercalations (during the Lower Albian) reflect emersion of the shallow shelf. Based on biostratigraphic data and short-distance lithostratigraphy, very detailed correlations of the sections allow to reconstruct extended emersion horizons (Fig. 4) and to illustrate the lateral facies changes. Their stratigraphic distribution reflects the rapid N-S shifting facies belts within the different sections along the ramp transect. In general, two depositional models can be distinguished: a siliciclastic-influenced shallow shelf during the Aptian/Early Albian, and a carbonate-dominated regime during the Middle Albian to Turonian

**The Late Aptian to Early Albian Ramp:** During Late Aptian-Early Albian, the northern Sinai shallow shelf is characterized by a gently north-dipping ramp geometry – there is no sign of a shelf break in any section. The inner ramp facies belt is superimposed by a northward prograding delta system with multiple intercalations of prodelta claystones, sandstones, marls, all of them with various amounts of iron ooids. Towards the north, the delta facies interfingers with lagoonal mixed siliciclastics and shallow marine carbonates, markedly influenced by siliciclastic input (Fig. 4). Rare and even small rudist bioherms developed in backshoal areas with lateral extensions of about a few meters. Several minor marine transgressions are indicated by southward encroaching, bioclastic carbonate shoals, formed under open marine highenergy conditions. They interdigitate or overly deltaic sediments. The sections studied here represent deposition within the inner ramp (sensu Burchette & Wright 1992); the midramp and outer ramp facies below the wavebase do not occur within the sections (Fig. 4).

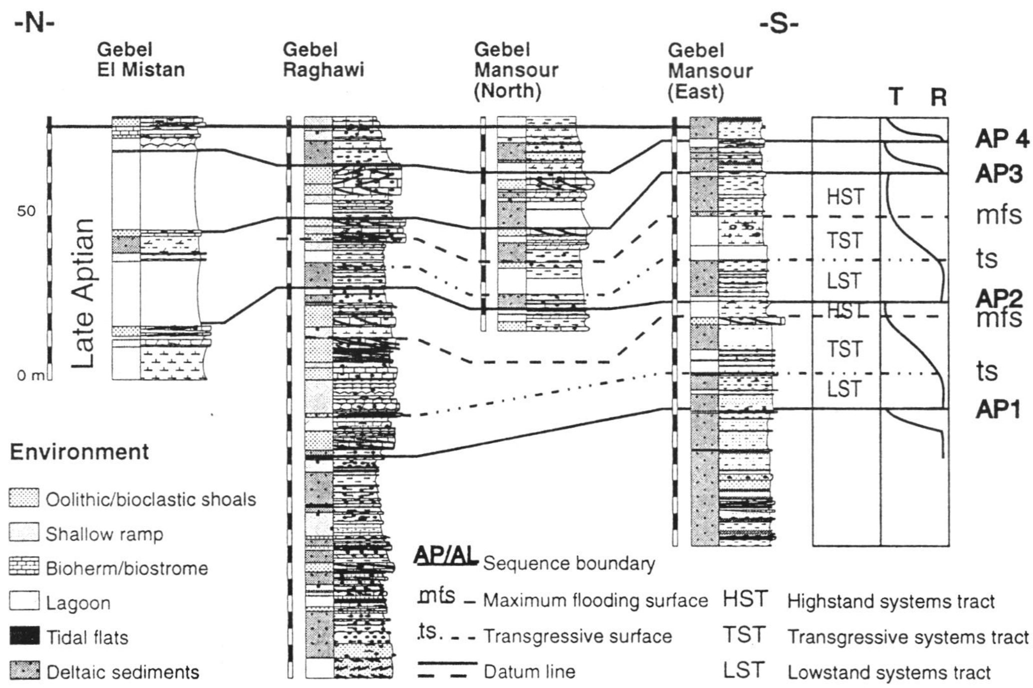
**The Middle Albian to Cenomanian Ramp:** During Middle Albian and Cenomanian times, only subordinate changes affected the ramp geometry. The delta system dis

**Fig. 5:** Sequence stratigraphic interpretation of the Late Aptian to Cenomanian ramp deposits of the Northern Sinai (location of sections see Fig. 2).

Albian to Cenomanian




Late Aptian



appeared and the siliciclastic input thus decreased. Evidence of wave activity is documented by massive oolitic and bioclastic grainstones with large scale crossbedding (Pl. 2/3). These carbonate shoals covered large parts of the region and interfingered towards the south with bioclastic packstones and wackestones often with orbitolines, dasycladacean algae and coarse agglutinated foraminifera, indicating a shallow ramp facies without major influences of wave activity. Lagoonal sediments are characterized by marls or miliolid wackestones. In contrast to the older ramp system, rudist bioherms and biostromes show large extensions and alternate with lagoonal sediments and tidal flat deposits, and in a few cases also with oolitic shoal facies (Fig. 4). Tidal flats with algal laminates and birdseyes became more prominent during Late Albian and Cenomanian (Pl. 2/5).

### 4.4 Sequence stratigraphic interpretations: 3rd-Order Sequences and their Geometries

A sequence stratigraphic interpretation is given for the Late Aptian to Early Cenomanian succession, and local relative sealevel curves were reconstructed (Fig. 5); a global correlation is not given yet, because detailed biostratigraphic interpretations are still in progress. Owing to the different major depositional environments, sequence stratigraphic patterns vary during Late Aptian/Early Albian and Middle Albian/Cenomanian times.

**Late Aptian:** The major depositional characteristics of the Late Aptian succession are summarized on the basis of four sections (Fig. 5). They reflect a 30 km wide segment of the shallow, deltaic-influenced inner ramp, comprising four sequences (AP1-AP4). The sequence boundaries are marked by progradation of the facies belts, in some cases also by emersion and by hardgrounds. Increasing siliciclastic input and northward progradation of the delta system (Pl. 1/4) is typical of the lowstand systems tracts (LST). A gradual transition to more lagoonal conditions is observed within the late LST. The sealevel normally rises slowly during the early transgressive systems tracts (TST) and open marine, shallow inner ramp facies established in the late TSTs. The most important feature is the retrogradation of facies belts and the decreasing siliciclastic input (e.g. Gebel Mansour E Section, Fig. 5). Similar depositional environments prevailed during the highstand systems tracts (HST), which is reflected only in minor progradations of the facies belts.

**Albian/Cenomanian:** Within the Albian/Early Cenomanian strata, 9 sequences can be distinguished (AL1-C2), which are demonstrated along a shallow ramp transect of 40 km lateral extension comprising 5 sections (Fig. 5).

All sequence boundaries are characterized by emersion horizons indicated by carstifications, teepee structures, and kaolinitic sandstone intercalations (Pl. 2/4,6,7).

Early Albian lowstand deposits are again characterized by deltaic facies with sandstone intercalations, most prominently exposed in the southern sections (Pl. 1/4,6). The Middle to Late Albian decrease of deltaic siliciclastics, simultaneously resulted in a declining amount of lowstand deposits, thus often missing in the inner ramp area. In Early Cenomanian times, the 3rd-order cycles (sequences) are superimposed by a 2nd-order sealevel rise, and additional accommodation space was created. As a consequence, the LSTs are now characterized by thick intertidal deposits.

Because of the frequent absence of Albian to Cenomanian LST sediments, the transgressive surface often coincides with the sequence boundary, but is always marked by coastal onlap. The TSTs are always characterized by open marine carbonates documenting a retrogradation of facies belts, expressed by oolitic and bioclastic shoals frequently covering wide areas of the ramp (Pl. 1/6). The maximum flooding surface coincides with the transition from open marine high-energy to low-energy (lagoonal) environments. The retrogradational facies patterns terminated in the late TSTs, and the gradual progradation characterizes the following HSTs, resulting in the filling of the distal inner ramp areas during times of stable sealevel. Moreover, larger rudist bioherms established, and extended carbonate lagoons, sometimes tidal flats, developed.

### 4.5 Cyclostratigraphic Interpretation

The 3rd-order sequences are superimposed by different types of higher frequency cycles, as indicated by characteristic stacking patterns of 4th- and 5th-order cyclicities. Macroscopically, these cycles stand out by thickness variations of the single beds confined with characteristic facies variations from deeper to shallow environments of deposition (Pl. 2/5). Differences of the cyclic stacking patterns are due to the respective position on the ramp, the 3rd-order sealevel fluctuations (controlling the accommodation space), and the general depositional conditions during Late Aptian to Cenomanian times (decreasing siliciclastic input).

During Aptian/Albian times, 4th-order cycles are well developed within different areas of the ramp. They are about a few meters in thickness with characteristic facies changes, interpreted as being due to higher frequency sealevel changes. These cycles can be described by sequence stratigraphic terms:

4th-order cycle boundaries are often marked by emersion, karstification or teepee structures, when they occur within a 3rd-order HST or near a 3rd-order sequence boundary, re spectively. Within the TST or early HST of a 3rd-order sequence, the 4th-order cycle boundaries are reflected by changes in facies only. During 3rd-order LST, the 4th-order

**Plate 1:** Stratigraphic sections of the Cretaceous ramps of the Organyà Basin (Figs. 1-3) and the northern Sinai (Figs. 4-6).

**Fig. 1:** Montanisell section (Late Aptian): The northward dipping limestones and marls were formed within the outer ramp. The upper part of the section is characterized by 5th-order thickening-upward cycles (Total thickness of section is about 400 m).

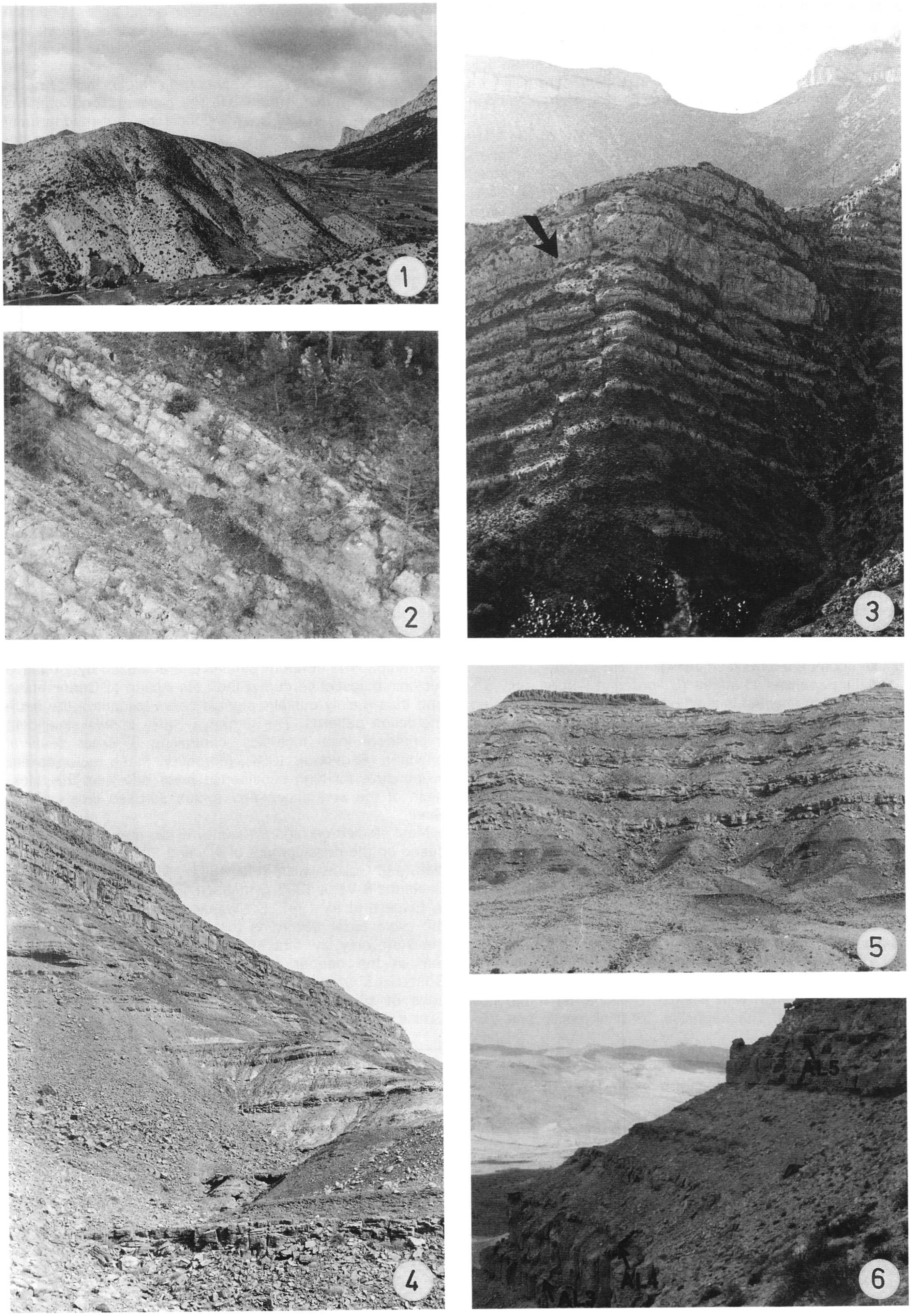
**Fig. 2:** Pobil section (Late Aptian): Two 5th-order cycles of the upper part of the section are reflected by alternations of inner ramp limestones and midramp marls (Total thickness is about 15 m).

**Fig. 3:** Abella section (Early Albian): Several 4th-order sealevel fluctuations are expressed by alternations of carbonate shoal deposits (massive beds) with midramp to outer ramp marls. The arrow indicates a massive limestone (30 m) near the top interpreted as LST of a 3rd-order sequence.

**Fig. 4:** Gebel Mansour South section: 200 m thick deltaic marls, siltstones and sandstones, intercalated with crossbedded bioclastic carbonates of Late Aptian / Early Albian age. The top is formed by Middle Albian cyclic carbonates.

**Fig. 5:** Gebel Mansour North section (Late Aptian to Early Cenomanian): The lower part is mainly composed of deltaic siliciclastics, whereas the limestone units above (Middle to Late Albian) reflect several 3rd-order sequences (detail in Fig. 6). The top is covered by cyclic dolomitic limestones (detail see Pl. 2/5) of Early Cenomanian tidal flats. (Total thickness of the section spans about 350 m).

**Fig. 6:** Detail of Fig. 5 illustrating three Early Albian 3rd-order sequences (SBs are indicated by arrows): SBs AL3 and AL4 are characterized by carstifications (compare Pl. 2/6). The lowstand deposits of AL3 are missing, thick sandstone intercalations reflect the LST of the AL4 sequence. TSTs are composed of carbonate shoal deposits. Thin rudist biostromes interfinger with lagoonal marls within the HSTs. (Total thickness is about 80 m).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AL5
AL4
AL3
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LSTs are either absent or characterized by siliciclastic deposition (with subordinate deltaic influences) – the 4th-order HST and TST are poorly developed. Within 3rd-order TST, the 4th-order cycles are well developed, whereas during 3rd-order HST, the higher frequency cycles are delivered by facies changes from tidal flat, restricted lagoon to open marine backshoal areas with rudist bioherms.

Within the nearshore deltaic environments of the Late Aptian/Early Albian ramp, at least two periods of higher-frequency cyclicity occur: 5th-order cycles may be reflected by variations from supratidal (caliche, ferruginous crusts and rhizolitic layer), to intertidal and shallow subtidal environments of deposition (well bioturbated sandstones, marlstones and limestones). These cycles are often bundled to 4th-order cycles. This pattern is obvious within the Cenomanian ramp deposits, where two periodicities of superimposing cycles are well developed within the extended supratidal to lagoonal areas. Here, multiple small-scale alternations (10 cm to 1.5 m) of stromatolitic tidal flats to massive or bioturbated dolomites reflect 5th-order cycles (Pl. 2/5), which are bundled in thickening- and thinning-upward 4th-order cycles, respectively. Furthermore, 4th-order cycles composed of bioturbated limestones, marls (locally with oysters) and dolomitic limestones often occur during late Cenomanian times. They are 0.5 to 2 m thick and may be characterized by a thickening- or thinning of the marly units, reflecting imprints of superimposed 3rd-order sealevel changes.

### 4.6 Discussion of the controlling factors

The 3rd-order sealevel fluctuations are the most important controlling factor of the sedimentation patterns and geometries. But still, the higher-frequency signals markedly influenced the ramp sedimentation, whereas distinguishing between 4th-order and 3rd-order sequence boundaries may be difficult (compare STRASSER 1994).

Relative sealevel changes (3rd-order, 4th-order, and 5th-order) are documented in simple shifts of the facies belts up or down the ramp. Because of the uniform ramp geometry, the "carbonate factory" shifts with the sealevel change (HANDFORD & LOUCKS 1993). Moreover, the decreasing siliciclastic influence from Aptian to Cenomanian times (including the termination of the delta-development) is interpreted as a consequence of the southward retrograding shoreline due to a 2nd-order sealevel rise. The strong siliciclastic influence during Late Aptian to Early Albian LSTs and its gradual to abrupt decrease at the mfs may be a result of the prograding or retreating shoreline, respectively, resulting in a greater isolation from the siliciclastic input (compare LOUTIT et al. 1988). The Middle Albian to Cenomanian LST sediments (if they occur) are very similar to those of the overlying HST. The lagoonal sediments deposited during TST in Late Aptian time may reflect a moderate deepening combined with a small shelf barrier formed by siliciclastic shoals. The deposition of thick oolitic and bioclastic shoals reflects a strongly increasing accommodation space during TST, creating moderate deepening of the depositional environment over wide areas together with an increase in wave activity. However, lagoonal sediments (open marine and restricted) as well as rudist bioherms are much more common during the HST. The progradational patterns during HST, favor low energy conditions and muddy environments within the shallow ramp area, which favor the development of rudist bioherms.

## 5 Comparison of the Factors Controlling the Sedimentation on the Two Ramps

Both studied areas (Pyrenees and Sinai) reflect homoclinal ramp morphologies, characterized by cyclic sedimentation patterns which allow to distinguish 3rd-, 4th-, and 5th-order sealevel changes. They are mainly responsible for shifting facies belts up and down the ramps, resulting in similar sequence stratigraphic patterns within the two different areas. The following major differences were observed: Varying amounts of siliciclastic input (much higher within Sinai area), different depths of deposition (controlling e.g. the types of sequence boundaries) and differences in the types and dominance of bioconstructions (influenced e.g. by different regional morphologies, current systems).

A clear 3rd-order sealevel signal controlled the sedimentation patterns within both successions (Tab. 1). The amplitudes of these 3rd-order sealevel fluctuations surpass those of the higher frequencies, typical of greenhouse periods when the eustatic low frequency signal is more dominant compared to the higher frequency climatic signal (not intensified by the growing of polar ice caps, compare TUCKER et al. 1990). However, we assume different controlling factors on the 3rd-order sealevel changes at the respective ramps: The northern Sinai is characterized by a relative tectonic quiescence during the Late Aptian to Cenomanian and thus mainly eustatic signals seem to control the sedimentation patterns. The Organyà Basin shows significant imprints of local tectonics, controlling 3rd-order sealevel changes (BACHMANN 1994). Moreover, these tectonics are responsible for high subsidence rates and thus the thickness of the sequences and cycles surpass those of the Sinai.

Most studies on high frequency cyclic carbonates are focused on the development of 4th- and 5th-order peritidal cycles (e.g. GOLDHAMMER et al. 1987, 1990, 1993, JIMENEZ DE CISNEROS & VERA 1993, STRASSER 1988, 1994, summarized in EINSELE et al. 1991, SCHWARZACHER 1994) (definition of the cycle order according to VAIL et al. 1991). However, there are only few studies on interpretations of cyclic pattern in the deeper parts of carbonate platforms (e.g. BOSELLINI & STEFANI 1990). The same is true for investigations of cyclic sedimentation on carbonate ramps (e.g. ELRICK & READ 1991). They are often concentrated on the

**Plate 2:** Sedimentary structures illustrating characteristics of 3rd-order sequences and higher frequency cycles of the Albian/ Cenomanian ramp (north Sinai).

**Fig. 1:** Sequence boundary AL 4 at the Gebel Rhaghawi section: The rudist biostrome of the AL3 is overlain by well bedded dolomites with birdseyes of late HST. The SB (arrow) is marked by rhizolitic layers – the following LST starts with wackestones.

**Fig. 2:** Cycle boundary of a higher frequency cycle at the Gebel Rhaghawi section within the 3rd-order HST of AL4: A sharp erosive contact marks the top of the rudist biostrome ("*Sellaea* facies", MASSE pers. comm.) overlain by oolitic grainstones.

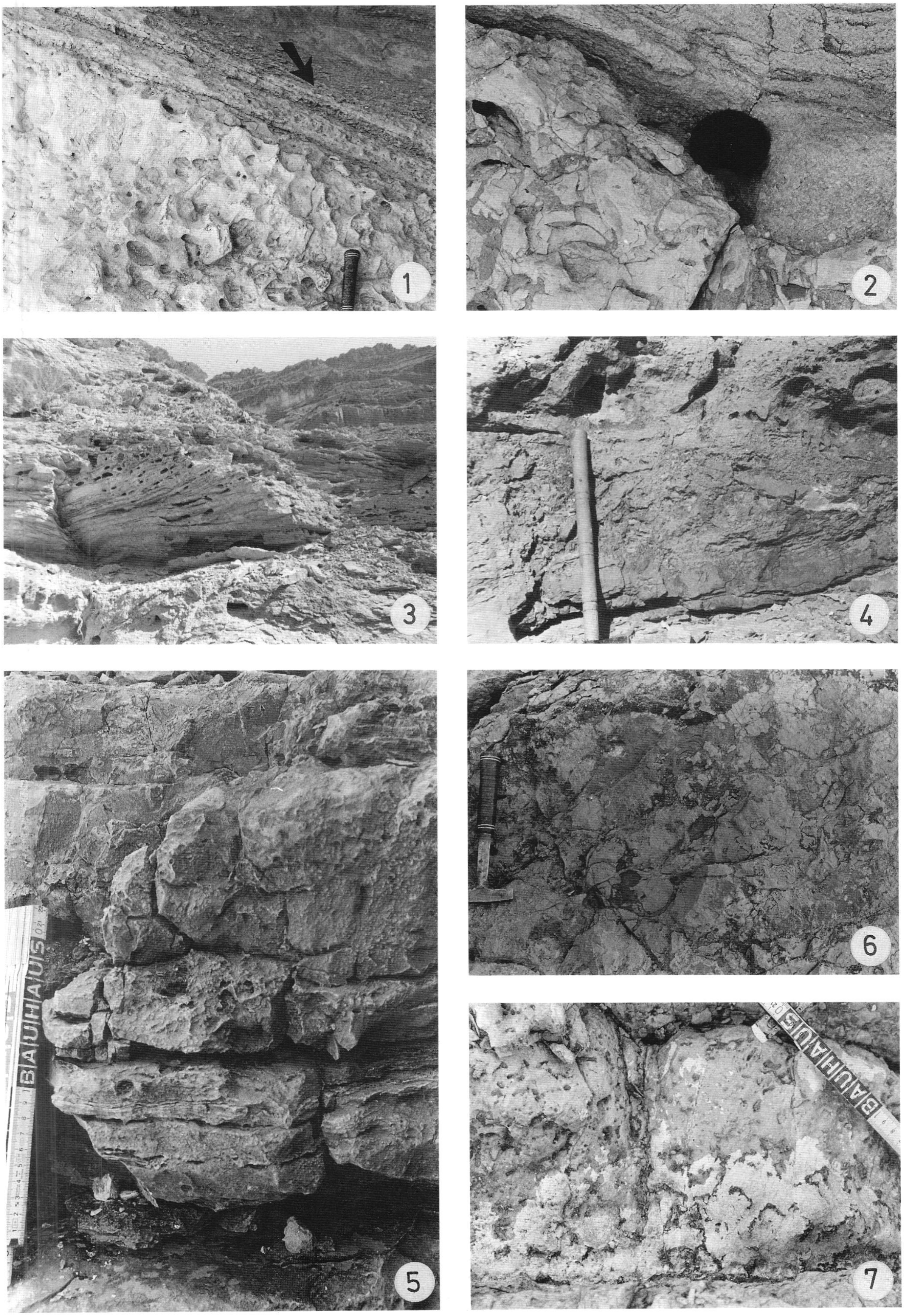
**Fig. 3:** Detail of the section Gebel Mansour North (uppermost part of the TST AL5): The Middle Albian oolitic shoal is characterized by large crossbedding foresets. (Thickness of the shoal is about 2 m).

**Fig. 4:** Teepee structure characterizing a sequence boundary within the southerly exposed Late Albian carbonates of Gebel Araif el Naqa.

**Fig. 5:** Tidal flat deposits of the Cenomanian sequence C2 at the Mansoura North section. Algal laminites and massive dolomites are arranged in higher frequency cyclic stacking patterns forming parts of the 3rd-order LST.

**Fig. 6:** Mottling, due to carstification reflects emersion during the sealevel lowstand AL 3 (compare Pl. 1/5).

**Fig. 7:** Rhizolithes within mudstones characterize the sequence boundary AL 7 (Late Albian) at the Gebel Mistan section.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BAUHAUS

| | | **Organyà, Spain** (Wi 725/6) | **Sinai, Egypt** (Ku 642/10-1) |
|---|---|---|---|
| **3rd-order cycles** | **Facies** | Inner ramp (shallow subtidal) to Mid ramp | Inner ramp: supratidal to shallow subtidal |
| | **Thickness** | 100 to 300 m | 20 to 80 m |
| | **Siliciclastic Input** | Clay during LST and TST | during LST: clay, silt and sand<br>during HST: Clay |
| | **Sequence Boundaries** | mainly type 2:: change in facies | mainly type 1: omission and emersion surfaces |
| | **Systems tracts** | **LST**: shallow marine carbonates of the inner ramp<br>**TST**: limestones and marls of the mid- and outer ramp with retrogradational sedimentation patterns<br>**HST**: aggradation and slow progradation of the parasequences | **LST:** Deltaprogradation (alternation of clay, sandstones, siltstones) and intertidal to lagoonal carbonates<br>**TST**: retrogradation of the high energy-facies belt, deposition of bioclastic and oolithic shoals<br>**HST**: slow progradation, development of broad backshoal areas, evolution of rudist bioherms |
| | **Estimated duration** | ca. 1 ma | 1 to 3 ma ? |
| | **Controlling factors** | regional tectonics and global | predominantly eustatic |
| **4th-order cycles** | **Thickness** | 30 to 40 m | 5 to 9 m |
| | **Siliciclastic Input** | subordinated | mainly during LST |
| | **Cycle Boundaries** | facies changes | emersion or facies changes |
| | **Systems tracts** | LST; TST, HST | mainly TST and HST |
| | **Estimated duration** | 100 ka | ? |
| | **Controlling factors** | eustasy, climatic changes due to orbital parameters | ? |
| **5th-order cycles** | **Thickness** | 5 to 9 m | 0,4 to 1,5 m |
| | **Cycle Boundaries** | facies changes | facies changes |
| | **Systems tracts** | transgressive-regressive cycles | transgressive-regressive cycles |
| | **Estimated duration** | 21 ka | ? |
| | **Controlling factors** | eustasy, climatic changes due to orbital parameters | ? |

**Tab. 1:** Comparison of the major characteristics defining the $3^{rd}$-, $4^{th}$-, and $5^{th}$-order cycles of northern Sinai and the Organyà Basin.

lower-frequency $3^{rd}$-order sequences (e.g. TUCKER et al. 1993, CALVET et al. 1990).

The $4^{th}$- and $5^{th}$-order cyclicities of the Organyà Basin have been interpreted with respect to duration and causing factors (BACHMANN 1994, see also Tab. 1). The sedimentation patterns reflecting the higher frequency cycles vary in both areas, caused by different depositional depths and ramp facies belts. The thickness of the cycles may differ according to the individual accommodation space. While the study in Spain is already completed and the results are published (BACHMANN 1994, BACHMANN & WILLEMS 1996), the ongoing Sinai-study shall prove the evidence of comparable data and thus of superior controlling parameters.

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