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Stratigraphy, structure, paleoenvironment and subsidence history of the Mazagan Escarpment off central Morocco : a CYAMAZ synthesis

Synthesis
Paleoenvironment
Subsidence history
Mazagan Escarpment
Morocco

Synthèse
Paléoenvironnement
Subsidence
Escarpement de Mazagan
Maroc

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ABSTRACT

The stratigraphy and structure of the old, starved passive margin of the Mazagan Plateau and the adjacent Escarpment which extends from 1 000-3 000 m water depth was studied during the cofinanced French-German CYAMAZ deep diving campaign which obtained 130 in-situ samples, supplemented by direct sea floor observations during 18 dive traverses.

The facies evolution of the Mazagan carbonate platform between Kimmeridgian and Valanginian times was mainly influenced by blockfaulting and sea-level fluctuations. Regressive periods occurred during Kimmeridgian/Tithonian and Late Berriasian times, and are separated by a late Tithonian/early Berriasian transgression. The drowning of the main carbonate platform and the Early Cretaceous to Paleogene history of the hemipelagic to pelagic post-platform sediments was strongly influenced by vertical tectonics and sea level fluctuations.

?Upper Berriasian to ?Hauterivian quartz-bearing bioclastic wackestones document the transition from the carbonate platform to the hemipelagic deposition on the drowned platform margin. Well-bedded calcarenites in the El Jadida Canyon area are interpreted as turbidites, forming the missing link between a postulated Wealden-type delta and a major deep-sea fan. A conspicuous iron ooid- and belemnite rich, condensed horizon documents a fossil hardground near the Neocomian shelfbreak. Mid-Cretaceous, hemipelagic marlstones are overlain by Upper Cretaceous nannomicrites, limestone breccias and phosphorites. They document several upwelling and phosphatization events, followed by reworking and mass wasting.

During Jurassic to mid-Cretaceous block-faulting events, migrating in a landward direction, the carbonate platform was structured into a succession of blocks, controlled by old Hercynian faults trending 160° or 20° (Atlantic direction) or 90-

120° (Mediterranean direction). An important phase of vertical tectonism is marked by the Neocomian denudation of the escarpment. Downfaulting of blocks and mass wasting events were accentuated during Eocene and Miocene times, but continue until today. Subsidence was non-uniform with at least 3 periods of accelerated subsidence during major short-term block-faulting events. A precursor of the present steep Mazagan Escarpment is at least 120 Ma old ; the escarpment was mainly formed and maintained by vertical tectonics and only slightly influenced by non-depositional hardground formation (bypassing), gravitational mass wasting, defacing, and carbonate dissolution.

Oceanol. Acta, **1984.** Submersible Cyana studies of the Mazagan Escarpment (Moroccan continental margin), CYAMAZ cruise 1982, 161-182.

RÉSUMÉ

Stratigraphie, structure, paléoenvironnement et histoire de la subsidence de l'escarpement de Mazagan au large du Maroc central : synthèse des résultats de la campagne CYAMAZ

La stratigraphie et la structure de la marge passive du plateau de Mazagan et de l'escarpement adjacent (entre 1 000 et 3 000 m de profondeur) ont été étudiées durant la campagne de plongées CYAMAZ (cofinancée par la France et la RFA). A l'occasion de 18 plongées, on a prélevé 130 échantillons et observé directement le fond de la mer.

L'évolution des faciès de la plate-forme carbonatée de Mazagan entre le Kimméridgien et le Valanginien a été principalement influencée par des basculements de blocs et des fluctuations du fond marin. Des périodes régressives se situent au Kimméridgien/Tithonique, ainsi qu'au Berriasien supérieur. Elles sont séparées par une transgression datant du Tithonique supérieur au Berriasien inférieur. L'immersion de la plate-forme carbonatée et l'histoire Crétacé inférieur à Paléogène des sédiments post-plate-forme hémipélagiques à pélagiques, ont été fortement marquées par des fluctuations du niveau de la mer et par la tectonique verticale : en particulier une régression du Berriasien supérieur suivie d'une élévation rapide du niveau de la mer au Valanginien supérieur. Les « wackestones » bioclastiques à quartz du Berriasien supérieur à Hauterivien indiquent la transition depuis la plate-forme carbonatée jusqu'au dépôt hémipélagique sur la bordure immergée de la plate-forme. Les calcarénites bien litées dans la région du canyon de El Jadida sont interprétées comme des turbidites, formant le lien absent entre un delta de type « Wealdien » et un « deep-sea fan ». Un horizon très mince, condensé et bien en évidence, riche en ooïde de fer et en bélemnites, annonce un « hardground » fossile à proximité de la rupture de pente au Néocomien. Des marnes hémipélagiques datant du Crétacé moyen sont recouvertes de micrites pélagiques à nannoplancton du Crétacé supérieur, de brêches calcaires et d'une succession hétérogène de phosphorites et de brêches phosphoritiques. Ces dépôts confirment l'existence de plusieurs « upwellings » et phosphatisations suivies de remaniements et de glissements en masse.

Le basculement des blocs pendant le Jurassique supérieur et le Crétacé moyen provoque un recul de la plate-forme en direction du continent. Ces blocs sont contrôlés par des directions tardi-hercyniennes N160 et N20 (directions atlantiques), N90 et N120 (directions méditerranéennes). Une importante phase de tectonique verticale est marquée par la dénudation de l'escarpement au Néocomien. L'effondrement des blocs et des glissements en masse se situent en particulier au cours de l'Éocène et du Miocène. Ils continuent cependant jusqu'à aujourd'hui. Nous en déduisons une histoire de la subsidence complexe et hétérogène, avec au moins trois périodes de subsidence accélérée (non compensée par les dépôts) accompagnées d'effondrements importants. Un précurseur de l'actuel escarpement de Mazagan date de 120 Ma au moins. L'escarpement a été créé et entretenu principalement par la tectonique verticale. Le non-dépôt (hardgrounds), les glissements en masse, l'érosion et la dissolution des carbonates n'ont eu dans sa structuration qu'un effet limité.

Oceanol. Acta, **1984.** Études par le submersible Cyana de l'escarpement de Mazagan (marge continentale marocaine), campagne CYAMAZ 1982, 161-182.

INTRODUCTION

The Mazagan Plateau area represents the oldest Mesozoic, well exposed, sediment-starved continental margin of the Atlantic Ocean (Fig. 1). Here we can study the entire margin evolution from the Triassic to mid-Jurassic early-rift and Callovian continental break-up to the history of the Jurassic construction, destruction and drowning of the outer margin of a carbonate platform and to the Cretaceous-Tertiary post-platform sedimentation and tectonics. The Mazagan Plateau belongs to the group of Mesozoic carbonate platforms constructed at the margins of the circum-global Tethys (James, Mountjoy, 1983). The Mazagan paleo-shelf-edge lies well landward of the supposed ocean-continent boundary (Fig. 1). Vertical tectonics and sea-level fluctuations cause dramatic effects — drowning or exposure — at the shelf-slope break of such carbonate platforms (Pitman, Golovchenko, 1983).

During the French-German CYAMAZ cruise we concentrated our efforts on the study of the superbly exposed central and southern parts of the Mazagan Escarpment, of El Jadida Canyon, and of a small fault scarp on the Mazagan Plateau proper (Auzende *et al*, this vol. ; *see* Fig. 2). These data helped to supplement the wealth of new information gained by the four DSDP Sites 544-547 during IPOD Leg 79 (Hinz *et al.*, 1982 ; Winterer, Hinz, 1984) and by previous geophysical and dredging surveys (Renz *et al.*, 1975 ; Wissmann, von Rad, 1979 ; Hinz *et al.*, 1982).

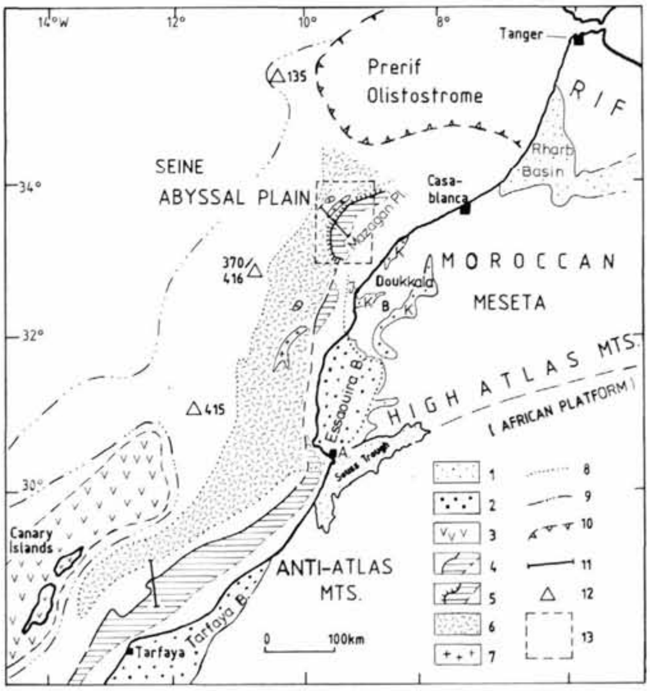

Figure 1

Geological and structural map of the Moroccan continental margin and adjacent Northwest Africa (modified from Hinz, et al., *1982, their Fig. 9). Legend : 1 = coastal basins with mainly Cenozoic fill ; 2 = coastal basins with mainly Paleozoic Mesozoic fill ; 3 = volcanic mass of Canary Island archipelago ; 4 = subcrop of edge of buried upper Jurassic carbonate platform (offshore) ; 5 = outcrop of Upper Jurassic carbonate platform edge ; 6 = ?Triassic salt diapir zone (not shown landward of 4, e.g. in Essaouira Basin) ; 7 = outcrops or subcrops of Precambrian to Paleozoic sialic basement ; 8 = limit of diapiric structures (oceanward limit = magnetic anomaly S-3 of Roeser, 1982, assumed to coincide more or less with the ocean/continent boundary) ; 9 = 2 sec. TWT sediment isopach ; 10 = seaward extent of Miocene nappes or olistostromes of the Rif and Betic Mountains ; 11 = location of profiles (Fig. 16.1, 16.2) : 12 = DSDP sites ; 13 =* see *Figures 2 and 3 for detail. A = Agadir, B = Basin, K = Cretaceous.*

The main objectives of the CYAMAZ cruise (*see* also Auzende *et al.*, this vol.) were the study of :

a) the stratigraphy, facies evolution and termination of the Late Jurassic carbonate buildup ;

b) the stratigraphy, nature and development of the starved post-platform sedimentation ;

c) the Mesozoic paleoenvironment and paleo-oceanography ;

d) the temporal and spatial development of the structural features of the Mazagan Escarpment ; and

e) the subsidence history, as modified by vertical tectonics, sediment accumulation, erosion and sea-level fluctuations.

The main prerequisites for the solution of these problems are a) a large set of representative samples across different parts of the carbonate platform and its Cretaceous-Tertiary cover ; b) good in-situ observations of the (micro-)structure of the plateau ; and c) a good biostratigraphic control.

Unfortunately, there were major shortcomings of these conditions : First, we were able to collect " only " 130 rock samples, mostly taken from outcrops (*in situ*) or very close to them. Although the sampling intervals were not statistically representative and although we might have missed important lithotypes and stratigraphic levels, our data base is an order of magnitude better and more exact than that of conventional dredging and coring surveys.

The second major problem of the CYAMAZ cruise was the lack of reliable biostratigraphic control, especially for the platform carbonates. Although the limestones are generally not diagenetically altered, they commonly contain only facies-diagnostic fossils, allowing only a rough age estimation (*e.g.* " Late Jurassic to early Neocomian "). The biostratigraphic control is better in the post-platform series, although also there the lack or poor preservation of calcareous nannoplankton or foraminifera often prevented determinations to the stage level (*cf.* Jaffrezo ; Jaffrezo *et al.* ; Čepek, Hagn ; Steiger, Cousin ; all in this vol.).

A wealth of data and interpretations was produced during and after the SEAZAGAN and CYAMAZ cruises. This information ranges from the fields of morphology and geophysics (based on multibeam echosounder and seismic reflection profiles) to biostratigraphy, facies analysis, sedimentology and geochemistry. In this paper we attempt to synthesize the most important results of the previous nine chapters, and to compare the geological development of the Mazagan Plateau with similar carbonate platforms around the central Atlantic Ocean.

We will also address four major problems of the development of passive continental margins enclosing old carbonate platform sequences :

1) What causes the abrupt termination or drowning of carbonate platforms and the stratigraphic turning point towards hemipelagic conditions ?

2) In what ways do global sea level fluctuations and vertical tectonics influence the evolution of the post-platform sequence ?

3) What shapes the steep escarpment of carbonate platforms ?

4) What are the tectonic controls on the subsidence history of this margin ?

GEOLOGICAL AND PHYSIOGRAPHICAL SETTING

The central Moroccan continental margin is one of the best studied examples of a very old, sediment-starved passive margin (Fig. 1). The Northwest African marginal or coastal basins with their thick Mesozoic-Cenozoic sedimentary fill (Tarfaya, Essaouira/south Atlas and Rharb Basins) are separated by the old Paleozoic shields of the Anti-Atlas Mountains and the Moroccan Meseta. The front of the Jurassic carbonate platform occurs near the present shelf edge and seaward of this front, we see a zone of seismically detected diapiric structures which represent the deposits of an early-rift evaporite basin. Paleozoic granite was cored, dredged and drilled (DSDP site 544) on a subsided fault block in front of the Mazagan Plateau (Wissmann, von Rad, 1979 ; Kreuzer *et al.*, 1984). The outer limit of the diapiric zone probably coincides roughly with the ocean/continent boundary (Hinz *et al.*, 1982 ; Roeser, 1982).

The Mazagan Escarpment is located about 200 km west of Casablanca and constitutes an almost 3 000 m high submarine cliff, located between the seaward edge of the Mazagan Plateau and the Seine Abyssal Plain. Reconstructions of the central Atlantic at the end of the Liassic show the location of the Mazagan Escarpment between the African continent and a structural high in the northern part of the Nova Scotian margin ; both margins were separated by a narrow early-rift graben, filled by evaporitic sediments (Jansa, Wiedmann, 1982 ; Wissmann, Roeser, 1982 ; Olivet *et al.*, 1983). Because of its steepness, the Mazagan Escarpment provides an exceptional opportunity to study the Mesozoic to Tertiary stratigraphy, paleoenvironment, and subsidence history of a nearly sediment-free external carbonate platform. Because the Upper Jurassic to Paleogene continental margin sediments of the Atlantic Ocean are exposed at this escarpment, they can be directly observed and sampled from a submersible.

Figure 2 shows the bathymetry of the Mazagan Plateau (Auzende *et al.*, 1983) and the location of the 18 CYANA dives. Figure 3 represents a structural map of the area (*see* Ruellan *et al.*, this vol.). Our Cyana dives supplemented the information of four DSDP/IPOD sites from Leg 79 : site 545 on the slope, sites 544 and 547 on and near a subsided basement high, and site 546 on a salt diapir (Hinz *et al.*, 1982 ; and in press). Eighteen dives enabled us to take 130 rock samples between 3 000 m (lower diving limit of CYANA) and about 1 000 m and more than 6 000 color photos during 73 hours of observation. 8 dives (No. 84-90, 101) were made in the southern part of the steep escarpment (Fig. 5), and 5 dives at its central part (91, 94-98). Three dives were devoted to the upper series of the geological section : one on the top of the Mazagan Plateau (92) and two in the vicinity of El Jadida Canyon (99, 100) which strongly erodes the southern scarp.

STRATIGRAPHY, FACIES AND PALEOENVIRONMENT EVOLUTION

The order to describe the heterogeneous suite of CYAMAZ samples, we applied the methods of microfacies analysis (Flügel, 1978). 17 main microfacies (MF) types and several subtypes were distinguished on the basis of paleontological and sedimentological properties (*see* the Table) and are described and interpreted in detail by two previous papers (Steiger, Cousin ; von Rad, this vol.). Figure 6 summarizes the stratigraphic results of the CYAMAZ expedition, showing sediment facies, thickness and approximate age of six different parts of the Mazagan margin which all had a different development during the past 160 Ma : Moroccan Basin (sites 370/416), lower Mazagan slope (including site 545), central and southern Mazagan Escarpment, El Jadida Canyon area, and southeastern Mazagan Plateau horst.

The Upper Jurassic to Berriasian shallow-water platform carbonates have a thickness of a few hundred to about 800 m (Ruellan *et al.*, this vol.). They are partly overlain by Neocomian deeper-water, hemipelagic, clastic limestones and ?turbidites (usually 0 to 10 m, to a maximum of 300 m). Hemipelagic mid-Cretaceous (late Aptian to Cenomanian) nanno-marlstones (250-300 m) are restricted to the lower Mazagan slope. Pelagic Upper Cretaceous sediments (nannomicrite, phosphorites, limestone breccias) are discontinuous and only a few tens of meters thick and separated by unconformities from the overlying Paleogene pelagic foraminiferal wacke- and packstones and Neogene nanno chalks to oozes.

Renard (this vol.) describes the geochemistry (major and trace elements) of the platform and post-platform sediments, correlates this information with the microfacies types, and attempts a " chemostratigraphy ".

Evolution of the Late Jurassic to Berriasian carbonate platform

According to Leg 79 results (Jansa *et al.* ; Steiger, Jansa, 1984), the Late Jurassic shallow-water carbonate deposition started with a basal sandy and oolitic unit (" carbonate ramp stage ") during a mid-Jurassic regression. After the breakup of Pangaea, approximately 155-165 Ma ago, a series of Bathonian to Oxfordian transgressions started the evolution of the carbonate ramp with fault-controlled high subsidence rates. The yellowish-brown ammonite-rich quartz-bearing deeper-water limestones (" ammonitico rosso " facies) from the Vema dredge V30-RD 38 (Renz *et al.*, 1975) are the only paleontologically well identified (middle) Oxfordian rocks from the Mazagan Escarpment (3 300-3 150 m present water depth). Site 545, located on the Mazagan slope, has the facies of a downfaulted platform edge with periplatform talus in front

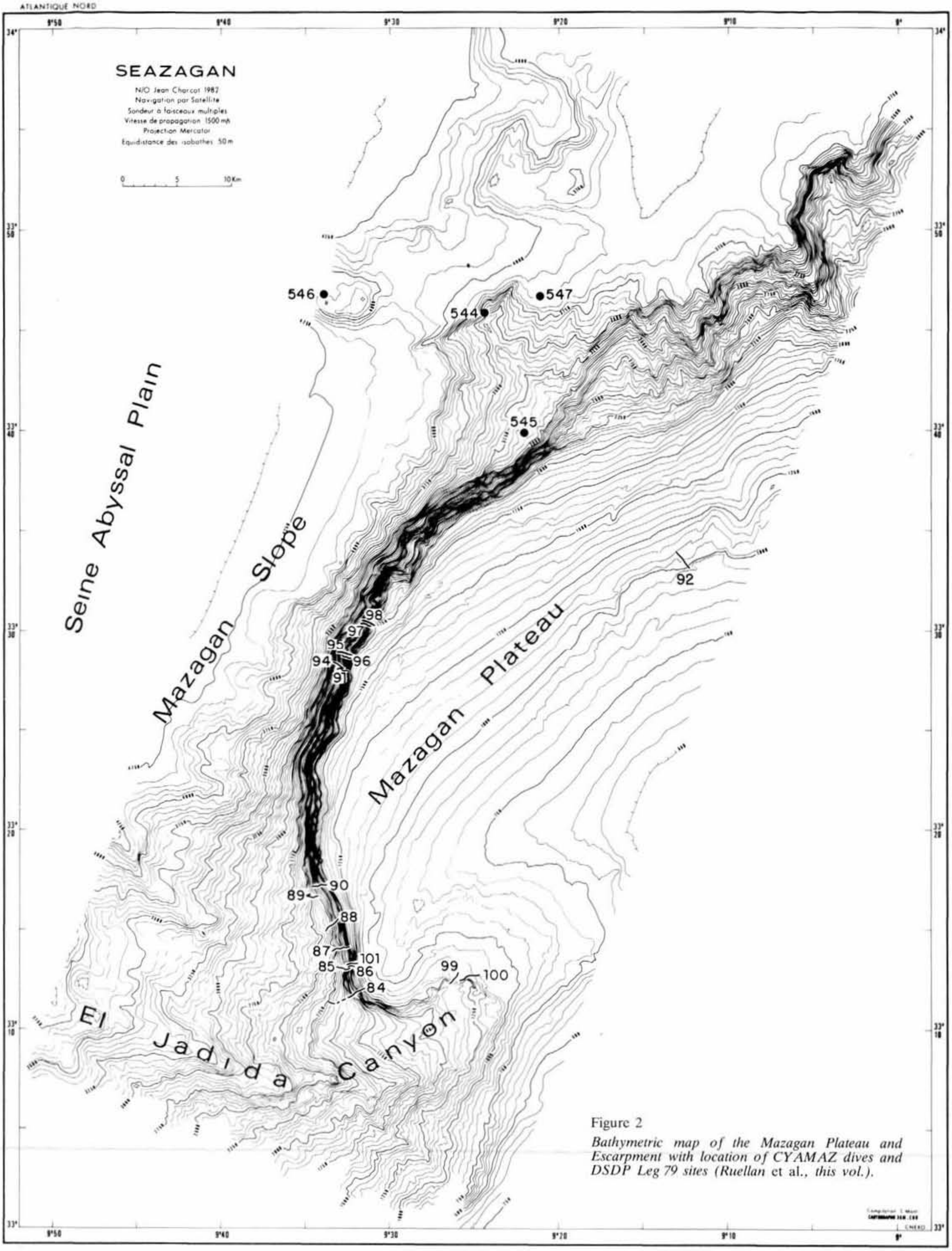

Figure 2

Bathymetric map of the Mazagan Plateau and Escarpment with location of CYAMAZ dives and DSDP Leg 79 sites (Ruellan et al., *this vol.).*

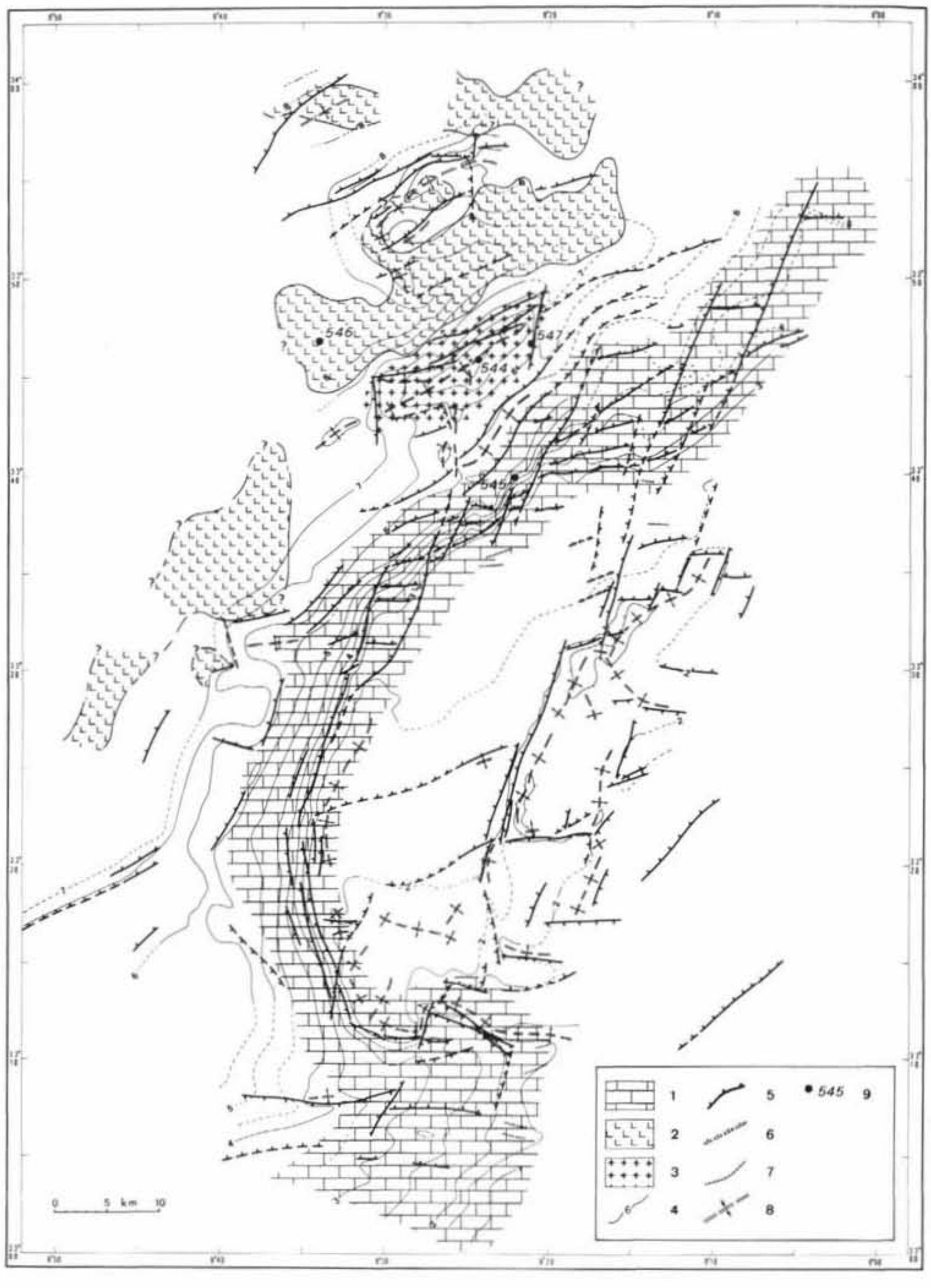

Figure 3

Structural map of the Mazagan Plateau and Escarpment. Isochrones = depth of acoustic basement in sec. TWT, 1 = faults only observed in the platform, 2 = faults only observed in the platform cover, 3 = major faults (platform + cover), 4 = acoustic basement highs, 5 = presumed faults, 6 = presumed salt diapirs, 7 = sialic basement (Paleozoic granodiorite, etc.*).*

of the developing paleo-escarpment (Steiger, Jansa, in press). In the deeper foreslope area (site 547), we find proximal resediments interbedded with nodular limestones and pelagic wackestones (for a more detailed comparison of CYAMAZ results with those from Leg 79 *see* Steiger, Cousin, this vol.).

Fortunately, the carbonates were not secondarily dolomitized, as in so many outcrops of the Moroccan coastal basins. The study of the microfacies of the platform carbonates of the CYAMAZ expedition allowed a more detailed reconstruction of the evolution of the carbonate platform between Kimmeridgian and Valanginian times (Fig. 7 and 8).

Steiger and Cousin (this vol.) differentiated three facies caused by the formation of the Mazagan Escarpment facies during Kimmeridgian times :

a) a neritic platform margin facies of massive, stromatolitic, peloidal limestones with rapid, bacterial lithification, high accumulation rates, sponge growth (about 50 m water depth) and shallow coraliferous environments (facies A) ;

b) a seaward hemipelagic, subtidal to upper-bathyal periplatform facies of micritic calpionellid limestones and bioclastic, oolitic limestones with calpionellid-bearing lithoclasts (facies B) ; and

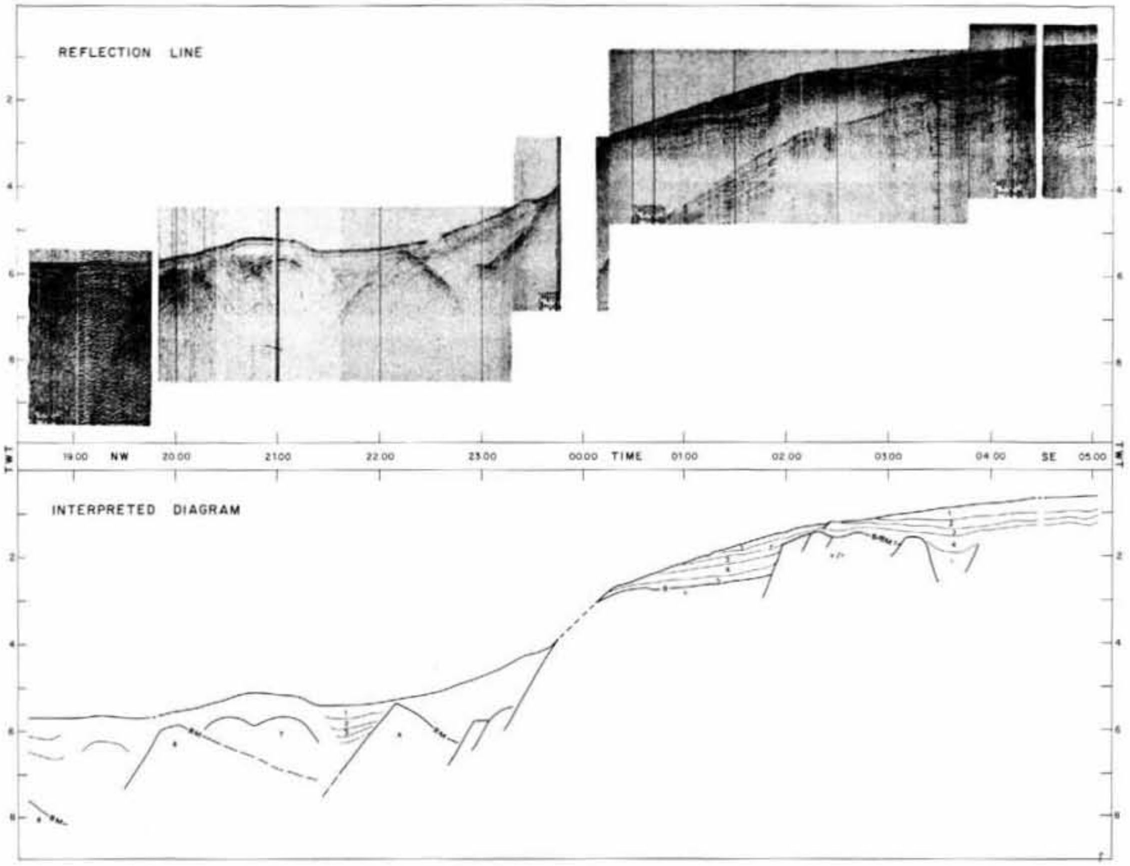

Figure 4

Seazagan seismic profile A across Mazagan Plateau and Escarpment.
A : original profile, B : line drawing.
1 = Neogene-Quaternary, 2 = ? Oligocene (-Early Miocene), 3 = Upper Cretaceous to Eocene, 4 = Upper Cretaceous, 5 = Lower Cretaceous deeper-water deposits, 6 = Upper Jurassic to Berriasian carbonate platform, 7 = Triassic-Liassic evaporites, redbeds, etc., *8 = Precambrian to Paleozoic sialic basement.*

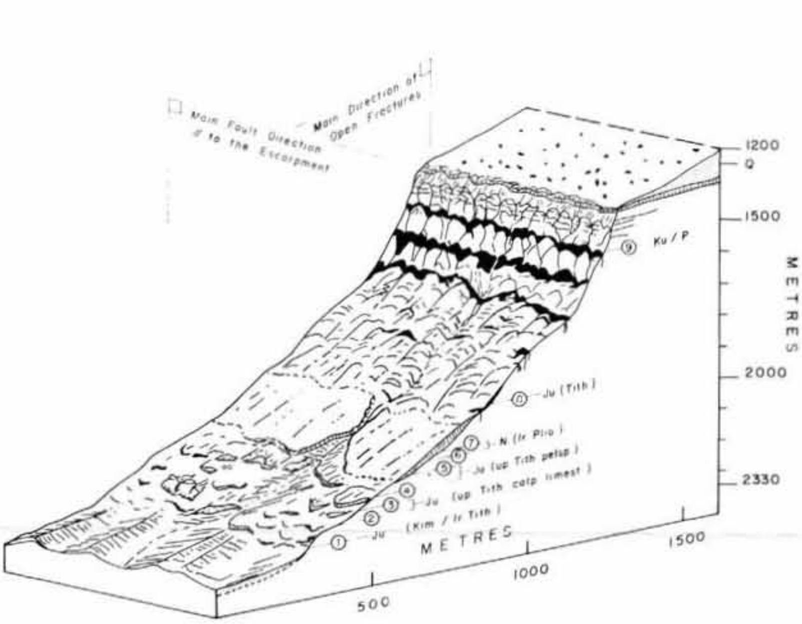

Figure 5

Schematic diagram of morphologic and structure of the southern Mazagan Escarpment (example of dive 87, Y. Lancelot). Numbers designate samples. Ju = Upper Jurassic, Ku = Upper Cretaceous, P = Paleogene, N = Neogene.

Table

Definition of microfacies (MF) types 1-18 of CYAMAZ samples (lithofacies description, paleoenvironment and age). Modified after von Rad (this vol., Tab. 1).

MF no	*Lithofacies description*	*Paleoenvironment*	*Age*
18	soft to semiconsolid, pelagic foram nanno ooze/chalk	pelagic-bathyal	M. Mioc.-Pliocene
18.1	green plastic calcar. clay		(-Quat.)
17	pelagic foraminiferal (globigerinid) pack-/wackest. consolidated (micrite)	pelagic-bathyal slope deposit	Paleocene-Eoc.
17.1	-dito-, glauconite-rich variety	outer shelf/upper slope	(-E. Oligocene) Eocene, Neogene
16	± silicified radiolarian chalk with porcellanite/quartz chert nodules	upper slope — ?upwelling pelagic-bathyal	(?Paleogene)
15	nannomicrite/nanno chalk to-marlstone	pelagic slope deposit	Late Cretac.
15.1	± recrystallized chalk		(?Late Cretac.)
15.2	± phosphatized calcareous clay-/marlstone		Oligo-Miocene
14	limestone breccias (mainly micritic intraclasts)	reworking in deeper water ?	(Tur.-) Maastr.)
13	phosphorite breccia/conglomerate with components of MF 8, 11, 12	slope with slump breccias and/or debris flow deposits (soft sediment deformation) and slump balls (100-3)	mid-to Late Cretac. (Lt. Apt.-Sant.)
12	laminated (micrograded), ± dolomitized phosphorite (= phosphatized micrite/calcarenite)	upper slope — hemipelagic ? (microlamination — ? O_2-minimum layer?)	Late Cretaceous (Lt. Turon.-Camp.)
11	phosphorites = ± phosphatized, massive echinoderm-mollusk micrites	clastic slope sediments (as MF 9)-phosphatized in Late Cretac. times (?upwelling event)	Late Cretaceous (Campan.-Maastr.)
10	quartz-bearing nanno marl-/claystone	hemipelagic-bathyal (?upper slope)	Lt. Apt.-E. Alb.
9	belemnite- (and quartz-) bearing, Fe oolite rich echinoderm micrite (partly oolitic ironstone)	hardground on slope/outer shelf ? (condensation horizon) w. reworking/bypassing/dissolution — ferruginization, Fe oolite formation	?Valanginian-Hauterivian (-E. Aptian)
8 *8.1	Quartz-bearing (echinoderm-mollusk) micrites micritic qtz-bearing intraclastic packstone with *Clypeina jurassica*	bathyal (outer shelf to slope) terrig. influx, restricted (?intratidal) environment with terrigenous influx (regressive phase)	Lt. Malm to Barremian
8.2	micritic qtz-bearing echinoderm-mollusk debris packstone/wackestone	bioclastic-terrigenous slope sediments: ?turbidites/slumps (canyon/upper fan facies ?)	(Berr.-) Valang.-Haut. (-E. Apt.)
8.3	micritic qtz-bearing glauconite/phosphorite-rich echinoderm-mollusk debris packstone/wackestone	outer shelf/upper slope, "transgressive" breccia (shelf edge)	(?E.) Cretac.
8.4	micritic echin.-mollusk debris packstone/wackest.	more hemipelagic (calcareous), slope deposit	Oxf.-Maastr. (?mid-Cret.)
7	Interclastic wackestone	intra-to supratidal lagoon	(?Early) Cretaceous
7.1	intraclastic pack — to wackestone	(nearshore, ?sabkha)	
7.2	dolomicrite, slightly laminated, qtz-bearing	restricted circulation, evaporitic	
6	Neritic fenestral limestones	shallow subtidal to intertidal (algal mats ~ loferites)	?Tithonian to Berriasian
6.1	neritic fenestral algal bindstone		
6.2	neritic fenestral peloidal packstone		
6.3	neritic fenestral bioclastic packstone		
6.4	laminated fenestral peloidal packstone		
*5	Neritic oolitic grainst./bindst./wackest.	oolite shoal or reworked into nearby lagoon (different settings)	?Tithonian to ?Berriasian
5.1	neritic oolitic algal bindstone		
5.2	neritic oolitic grainstone		
5.3	neritic oolitic bioclastic wackestone		
*4	Neritic bioclastic peloidal grainstone	lagoonal debris, very shallow water	Lt. Malm-Berriasian
4.1	neritic bioclastic grainstone	high-energy lagoon	
4.2	neritic bioclastic wackestone/grainstone	?low-energy lagoon	
4.3	neritic bioclastic peloidal packstone	high-energy lagoon, ?perireefal	
4.4	neritic algal bindstone w. coral debris	?near-reef debris, ?algal patch reefs	
4.5	neritic intraclastic packstone	lagoon, ?intertidal	
*3	Columnar stromatolitic peloidal packstone (= massive crustal pelsparite), including neritic algal bindstone w. coral debris and patches of microbioclastic grainstone (± sil. spong.)	high-energy lagoon with cyanobacterian stromatolitic pelmicritic crusts (fast buildup of platform margin ?)	Lt. Malm
*2	Fore-slope bioclastic oolitic grainstone with Calpionellid lithoclasts	fore-slope breccia (hemipelagic)	Lt. Tithon.-Berrias.
*1	Hemipelagic bioclastic packstone with calpionellids (and siliceous sponge remains)	deeper fore-reef slope (?20-100 m), small sponge bioherms	Lt. Tithon.-(E.) Berrias.

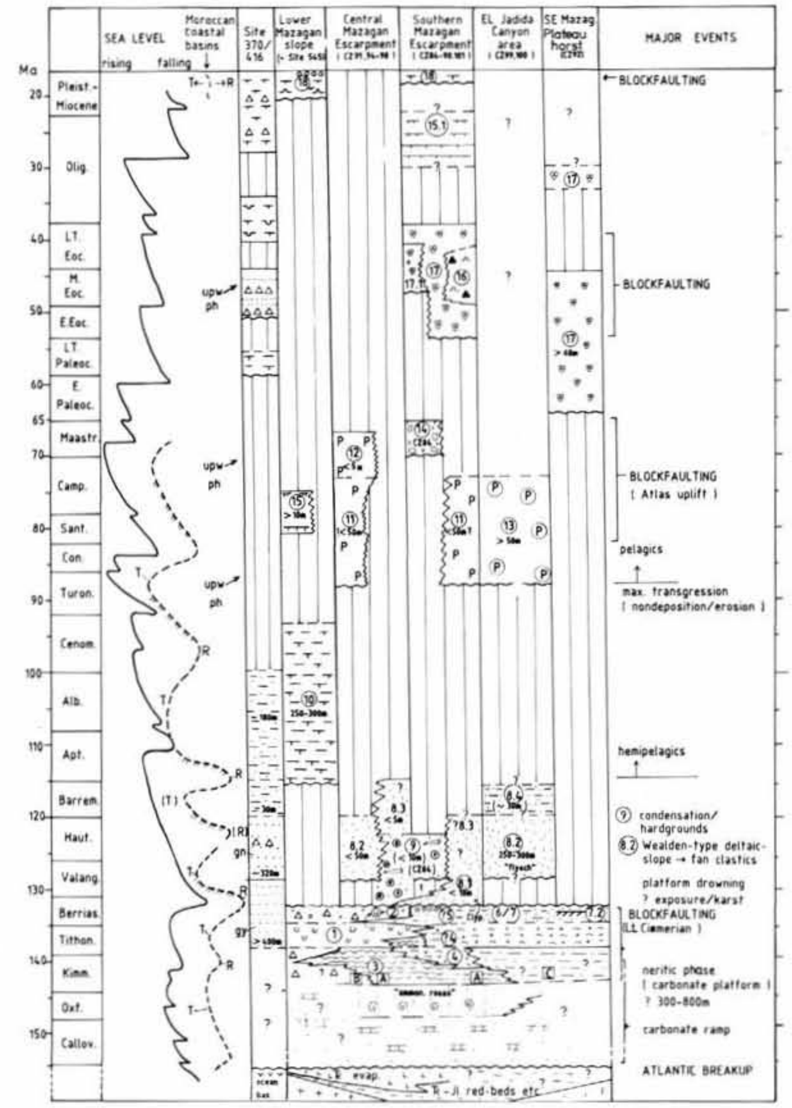

Figure 6

Time-stratigraphic summary of CYAMAZ results, correlated with sea level fluctuations and major tectonic or sedimentological events. Sea-level curve after Vail et al. *(1977) and Vail* et al. *(in press). Transgression (T)/regression (R) curve of Moroccan coastal basins refers to relative sea level changes, also influenced by vertical tectonics, subsidence, accumulation and erosion rates and is compiled from Wiedmann* et al. *(1978), Behrens* et al. *(1978), Behrens and Siehl (1982) and other sources. Hatched areas during transgressions : potential condensed sections. Stratigraphic columns show sediment facies, thickness (m), and microfacies number* (see *Tab. 1, and von Rad, this vol., Fig. 3 for symbols). Abbreviations : p = phosphorite, Ⓟ = phosphorite conglomerate, ph = phosphatization event, upw = upwelling event, gy = gray, gn = green.*

c) a landward shallow platform facies of intertidal to shallow-subtidal calcareous micritic and dolomitic deposits (fenestral limestones, dolomites ; facies C).

According to evidence discussed by Steiger and Cousin (this vol.), facies A is restricted to the Kimmeridgian to (middle) Tithonian, facies B to the late Tithonian to (early) Berriasian, whereas the age of facies C might range from Tithonian to Berriasian.

The facies model for the Kimmeridgian to (middle) Tithonian (Steiger and Cousin, this volume) shows a very broad shallow-water carbonate bank with a rather steep, probably fault-controlled platform slope (Fig. 8.1). The sea level was more or less stationary, and because the high growth rate of carbonate accumulation equalled the tectonic subsidence rate, the water depth remained very shallow.

The peloidal packstones (MF 3) were biologically lithified by fast-growing stromatolitic crusts (possibly cyanobacterians) into rigid small-scale stromatolitic domes and columns, and later cemented by sparite. This helped to stabilize the platform margin (Steiger and Cousin, this vol.). Siliceous sponges which helped to date this facies as pre-Tithonian grew on the substrate of early-diagenetically lithified, stromatolitic peloidal packstone forming a knobby seafloor. Lang and Steiger (this vol.) discuss also the diagenetic evolution of the sponges, such as the dissolution of opaline silica, calcification of the sponges, and their burial by peloidal sediment.

The presence of a periplatform talus facies in front of a faulted bank margin and of a pelsparitic low-energy backreef facies, typical for the interior Bahama Bank, is hypothetical (*see* Fig. 8.1 and Jansa *et al.*, 1984). According to Steiger and Cousin (this vol.) and Hüssner (1985), a more or less continuous, hummocky " pelsparite ramp " with carbonate sand bars but no indication of genuine reef buildings developed during

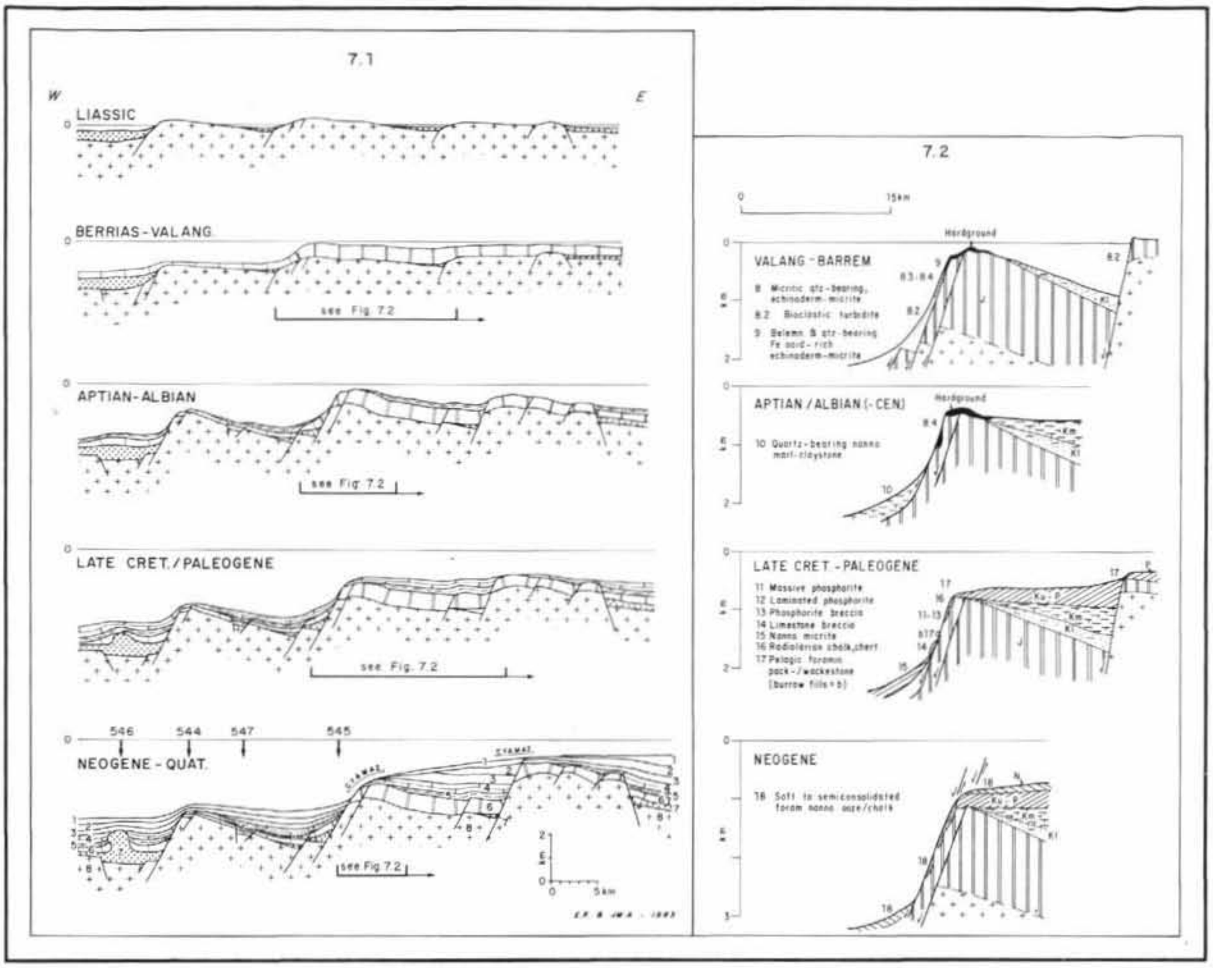

Figure 7

Palimspastic profiles across the Mazagan Plateau area showing the Liassic to Quaternary structural evolution (Fig. 7.1) and the Valanginian to Neogene facies evolution (Fig. 7.2). Numbers designate microfacies (MF) numbers (Tab. 1).

Kimmeridgian times between the coastline and the Mazagan Plateau area.

The late Tithonian to (early) Berriasian transgression caused a first change towards a deeper-water facies (Steiger, Cousin, this vol. ; Fig. 8.2). This transgression was mainly due to rapid tectonic subsidence not compensated by carbonate accumulation, and to a lesser degree to a global sea level rise. Therefore, fault blocks with stromatolitic packstones were covered by hemipelagic, calpionellid-bearing bioclastic wackestones (MF 1) with redeposited talus from exposed older Jurassic platform outcrops. Siliceous sponges were redeposited as periplatform talus into comparatively deep (?50-100 m) water, where calpionellids were deposited in a subtidal to upper bathyal environment (*see* Lang, Steiger, this vol.). According to Steiger and Cousin (this vol.), a landward lagoonal grainstone facies developed for the first time during the period.

During a global (late) Berriasian to (early) Valanginian sea level lowstand (Fig. 8.3) calpionellid wackestone deposits were locally eroded and redeposited into the periplatform talus (MF 2). A low-energy facies is indicated by peloidal wackestones. The most landward facies is documented by intra- to supratidal, more-or-less dolomitic packstones, rich in intraclasts or bioclasts (MF 6/7). Steiger and Cousin (this vol.) report sedimentological evidence (vadose diagenesis) for a partial emergence of the carbonate platform during this late Berriasian to (early) Valanginian regression. Terrigenous quartz grains, especially in a quartz-bearing, dolomitized, intraclastic packstone with reworked *Clypeina jurassica* (MF 8.1) might document a regression and the vicinity of a continent. Another explanation of the sudden quartz input and calpionellid limestone intraclasts would be a submarine erosional event due to local tectonics (Schlager, pers. commun., 1984). This facies indicates a transition from the platform to the post-platform phase. In most localities (*e.g.*, site 545), however, there is a major unconformity between the platform carbonates and the overlying Cretaceous deeper-water micrites (Fig. 6).

Figure 9 shows a paleogeographic map of the Late Jurassic. This sketch map does not differentiate between the three different stages, shown in Figure 8.1-8.3. The Mazagan Plateau is today characterized by a series of fault blocks with systems of faults striking about 20° and 150-180°. We believe that the main Late Jurassic platform margin developed along a major fault zone which formed on an old, rejuvenated margin-parallel Hercynian lineament. Especially

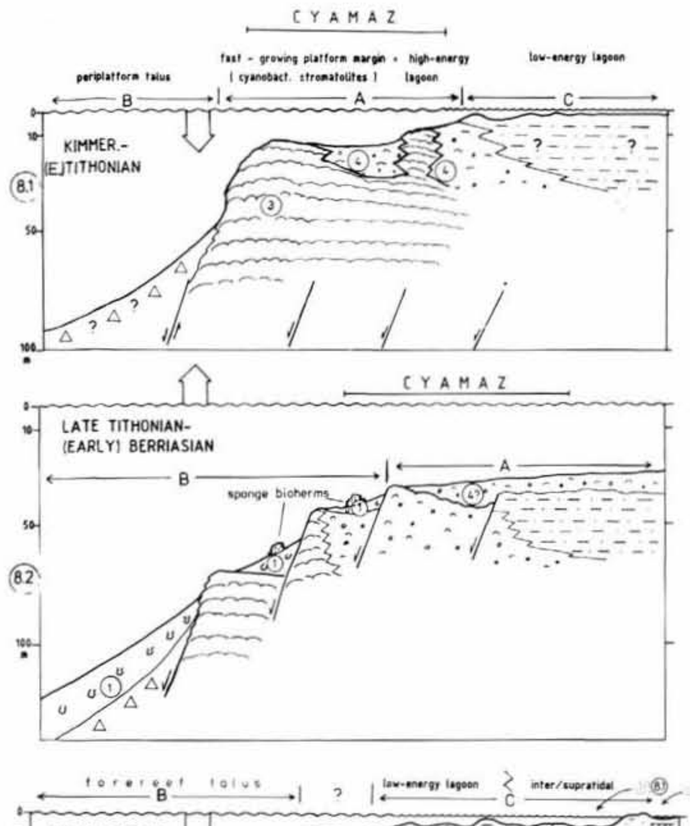

Figure 8.1

Kimmeridgian to Tithonian (regression). The faults, the periplatform talus facies B and the backreef facies C are entirely hypothetical. According to Steiger and Cousin (this vol.) a continuous, hummocky " pelsparite ramp " (MF 3 with minor intercalations of MF 4) might have existed during that time.

Figure 8.2

Late Tithonian to (early) Berriasian (transgression).

Figure 8.3

(Late) Berriasian to Valanginian (regression).

Figure 8

Evolution of the Mazagan carbonate platform between Kimmeridgian and Valanginian times. Numbers designate MF (microfacies) numbers (see *Tab. 1*).

A = neritic shallow-water facies (MF 3, 4.1, 4.4, 5.1).
B = hemipelagic facies e.g. *with calpionellids (MF 1,2).*
C = neritic micritic and sandy facies (MF 5.3, 6.2, 6.4, 7.1, 7.2, 8.1).

during the late Tithonian to Berriasian transgression peri-platform talus was shed downslope from an exposed escarpment to the area of Site 545. Site 544 is located at the lowermost fault block which was also capped by platform carbonates, whereas at Site 547 pelagic nodular limestone was deposited, mixed with proximal foreslope talus which was probably derived from the " Site 544 horst " (Steiger, Jansa, 1984). Presence of a very wide, shallow backreef facies of banks and lagoons is indicated in Figure 9 by the dashed pattern (*see* also Fig. 10).

Termination (drowning) of the Mazagan carbonate platform (Fig. 11-12)

One of the major problems of the evolution of passive continental margins is the cause of the termination of carbonate platform growth. Figure 13.2 shows a schematic facies sequence of neritic platform carbonates, overlain by condensed hardground sequences rich in ammonites, belemnites, iron ooids, ferromanganese or phosphoritic crusts, or by hemipelagic, quartz- and glauconite-rich, foraminiferal nanno chalks. Above another unconformity follows a sequence of pelagic nanno chalks. Such sequences are very typical for many Early Jurassic outcrops in the Alps or Late Jurassic exposures in Greece (Bernoulli, Jenkyns, 1974 ; Ogg *et al.*, 1983). From the Helvetic Alps, Bergner *et al.* (1982) described a Barremian to lower Aptian carbonate platform phase (Schrattenkalk) overlain by clastics during the early Aptian transgression (Brisisandstein), a mid-Aptian to Albian (Cenomanian) glauconitic-phosphoritic condensation horizon (Lochwaldschicht, etc.), and pelagic Turonian nanno limestones (Seewerkalk). They report a similar coeval sequence from the western High Atlas.

What is the cause of this conspicuous stratigraphic turning point which abruptly terminates the buildup of neritic carbonates ? Schlager (1981) speaks of " the paradox of drowned carbonate platforms ", because normally the growth rate of coral reefs is at least ten times as fast as the average rates of sea level rise or

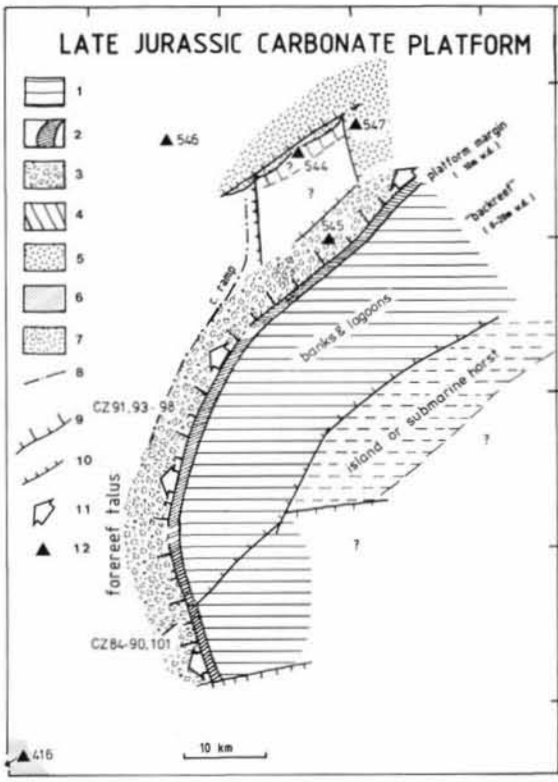

Figure 9

Paleogeographic sketch map of the upper Jurassic to Berriasian carbonate platform (partly modified after Steiger, Jansa, 1984 ; Winterer, Hinz, 1984). Legend : 1 = backreef (lagoonal facies, microfacies MF 6-7) ; 2 = shallow platform margin (stromatolitic peloidal packstone, MF 3) ; 3 = forereef talus (hemipelagic bioclastic packstone with calpionellids and siliceous sponge remains, MF 1) ; 4 = carbonate bank at NW lower Mazagan block (site 544, grainstone/cyanobacterian crusts) ; 5 = nodular deeper-water limestone, breccias and turbidites of Kimmeridgian age, pelagic sediments of Tithonian to Neocomian age (site 547) ; 6 = deep-water pelagic mudstone/limestone with distal turbidites (site 416) ; 7 = Paleozoic granite/gneiss (subaerial or submarine outcrops) ; 8 = outer limit of carbonate ramp in Oxfordian time ; 9 = paleoescarpment (major fault zone) ; 10 = major paleofault ; 11 = mass wasting from paleoescarpment ; 12 = DSDP Site.

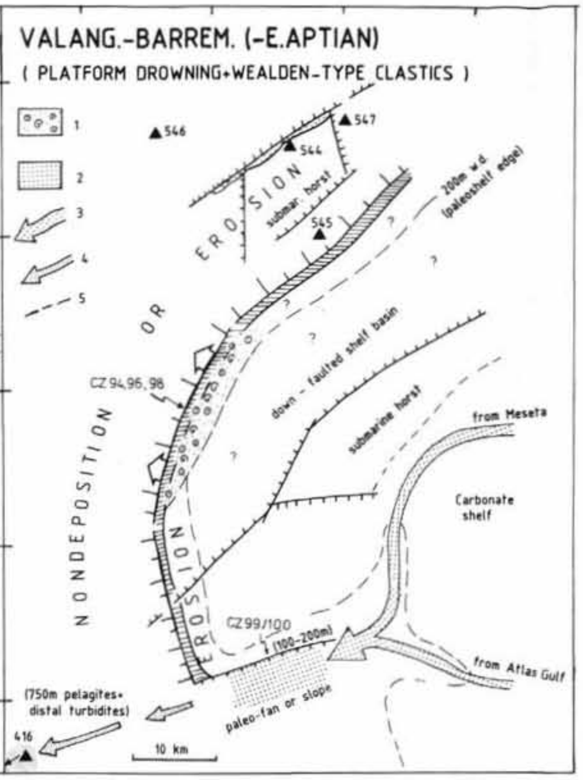

Figure 10

Paleogeographic sketch map of the Valanginian to Barremian (early Aptian) platform drowning and " Wealden-type " clastic deposition. Legend : 1 = thin hardground deposits (belemnite- and quartz-bearing, iron ooid-rich echinoderm micrite, MF 9) ; 2 = quartz-bearing echinoderm micrite (?turbidites or clastic slope deposits ; MF 8) ; 3 = proximal turbidity currents, slumps, debris flows ; 4 = distal turbidity currents ; 5 = paleo-shelf edge.

subsidence. According to Schlager (1981), the following causes or combination of causes can be responsible for the termination of carbonate platforms (in the order of importance for the Mazagan area ; *see* Fig. 13.1) : a) drowning by rapid (*i.e.* > 1 mm/yr.), short-term sea level rise ; especially a short regression might have exposed the carbonate bank, killed the reefs, and reduced the growth potential of the reef builders during the following rapid sea level rise ; b) drowning by pulses of rapid tectonic subsidence which surpassed the carbonate accumulation rate, for example by block-faulting during extensional tectonics (rifting) ; c) environmental stress and the small growth potential of the stromatolitic buildups, as compared to recent coral reefs. Other possible factors are regional massive terrestrial and freshwater input from deltas (drastic drop in salinity, murky waters) during regressive episodes, and plate-tectonic drift to higher latitudes. The latter might have been the main cause for the drowning of the northward drifting, diachronous carbonate platforms off eastern North America which lie now off New Jersey, New England, and Nova Scotia (Jansa, 1981). Off NW Africa, however, the latitudinal shift of the Mazagan Plateau between Late Jurassic and mid-Cretaceous times was insignificant.

The fact that in the Mazagan area the platform was successively drowned, as blockfaulting probably progressed from the ocean towards the continent (Bosellini, 1973 ; Ruellan *et al.* this vol. ; Steiger, Jansa, 1984 ; Winterer, Hinz, 1984), suggests that a tectonic subsidence pulse, coinciding with the late Berriasian/Valanginian onset of transgression, is the main cause for the drowning of the Mazagan platform. To us climatic changes or short-term rapid tectonic subsidence episodes (possibly associated with drifting events ?) are more attractive explanations for the platform drowning than global sea-level fluctuations and plate-tectonic movements which are too slow to become effective.

Unfortunately, the time of the " drowning event " can only be indirectly estimated as (mid)-Valanginian from the uninterrupted fossil record in the deep Moroccan Basin Site 416 (Schlager, 1980). The thick sequence of distal turbidites deposited there on a deep-sea fan shows a characteristic differentiation of

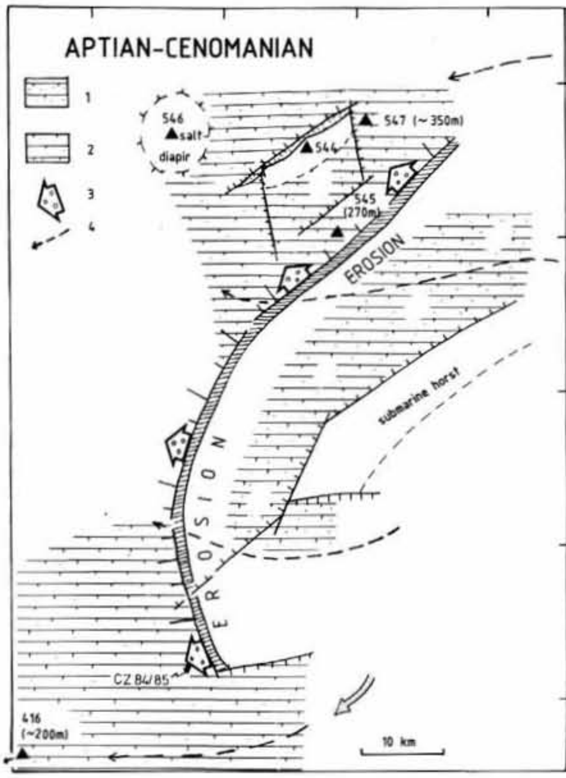

Figure 11

Paleogeographic sketch map (Aptian to Cenomanian). Legend : 1 = ? sandy nanno marl- to claystone (< 500 m water depth), 2 = quartz-bearing nanno marl (> 1 000 m water depth, MF 10) ; 3 = slumps and debris flows ; 4 = transport of clay and silt (in part after *Winterer, Hinz, 1984.*

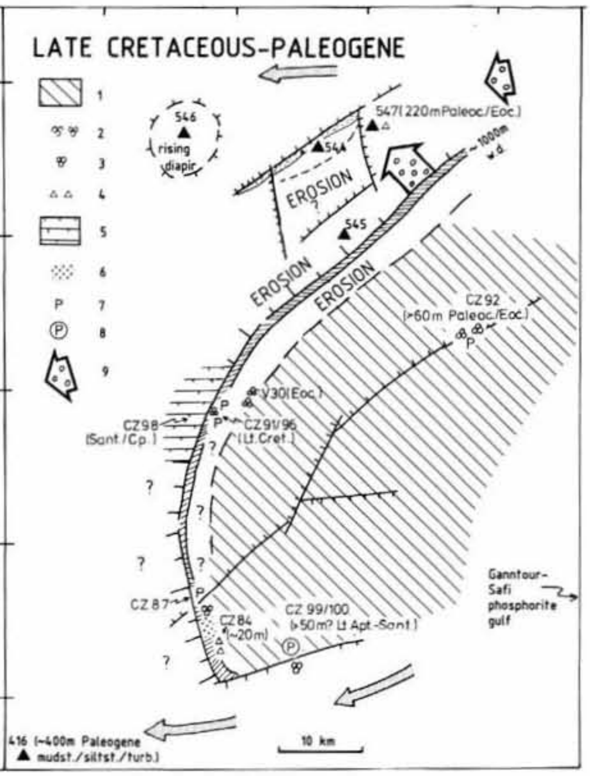

Figure 12

Paleogeographic sketch map of the Late Cretaceous/Paleogene. Legend : 1 = undifferentiated Upper Cretaceous to Paleogene sediments ; 2 = Paleogene pelagic foraminiferal micrite (MF 17) ; 3 = ? Eocene radiolarian mudstone/chert (MF 16) ; 4 = Chert ; 5 = Upper Cretaceous pelagic nannomicrite (MF 15) ; 6 = Upper Cretaceous limestone breccia (MF 14) ; 7 = Upper Cretaceous phosphorites (MF 11/12) ; 8 = Upper Cretaceous phosphorite breccia (MF 13) ; 9 = Late Cretaceous/Paleogene slumps and debris flows (partly modified from Jansa, 1981).

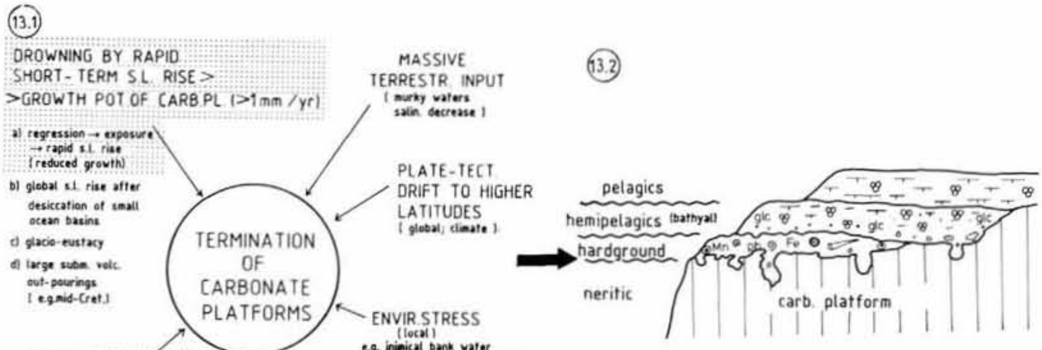

Figure 13

Potential causes for the termination (" drowning ") of fossil carbonate platforms (after *Schlager, 1981). The most likely causes for the termination of the Mazagan carbonate platform are emphasized by dotted pattern (13.1). Figure 13.2 : sketch showing typical vertical facies sequence overlying drowned carbonate platforms (ph = phosphorite, glc = glauconite).*

two facies (*see* also Fig. 6) : a) Tithonian to mid-Valanginian gray calci-turbidites with micrite, ooids and neritic skeletal grains, derived from the growing Mazagan carbonate platform ; b) late Valanginian to Hauterivian green to brown turbidites lacking micritic limestone and neritic fossils, but with an upward increasing content of reworked phosphorite and ooids with quartz nuclei. Schlager (1980) suggests that this documents the drowning of the carbonate platform, maybe by a slight intra-Valanginian sea level drop, followed by a rapid sea level rise (Vail and Mitchum, 1977). This date fits well to the rough age estimates for the drowning event, inferred from Leg 79 information (" post-Berriasian to pre-Aptian " : Jansa *et al.* ; Steiger, Jansa, 1984) and from our CYAMAZ data (" post-Berriasian, probably pre-Hauterivian " : Steiger, Cousin ; von Rad, this vol.).

Early Cretaceous hemipelagic clastic sedimentation

Figures 7 and 10 show the morphology and paleogeography during Valanginian to Barremian times. After the drowning of the platform, nondeposition, bypassing, or erosion predominated along most parts of the Mazagan Escarpment. The former platform margins became submarine horsts. Only along the central escarpment a thin sequence of hemipelagic, quartz-rich echinoderm micrites, and condensed iron ooid-ammonite-belemnite-rich beds (MF9) were deposited. In the present El Jadida Canyon area, however, we discovered a > 200 m thick sequence of well-bedded bioclastic turbidites which were probably derived from the Moroccan Meseta or the " Atlas Gulf " via a paleo-canyon system. Further downslope, at site 416, a 750 m thick sequence of distal turbidites interbedded with pelagites was deposited in an outer fan or abyssal plain environment (*see* also Fig. 6). Thus we think we have found the missing link in a huge " Wealden-type " delta system between the alluvial to nearshore clastics of the coastal basins (Behrens *et al.*, 1978) and the deep-sea fan of the Moroccan Basin (Lancelot, Winterer, 1980 ; Price, 1980 ; Schlager, 1980 ; von Rad, Sarti, in press).

The main results of a paleoenvironmental study of the heterogeneous Early Cretaceous lithofacies types (von Rad, this vol. ; *see* also Fig. 6 ; Tab. 1) are :

1) The lower Neocomian (probably Berriasian to Valanginian) quartz-bearing intraclastic, dolomite-rich packstones (MF 8.1) occur only locally and indicate a transition from the carbonate platform to a restricted inter-to supratidal shallow lagoon or sabkha setting, influenced by terrigenous quartz input.

2) The quartz-bearing echinoderm (crinoid)-mollusk pack-to wackestones of Berriasian to early Aptian age (MF 8.2) are (bio-)clastic, deeper-water shelf to slope sands. The 150-200 m thick, well bedded sequence, observed in the El Jadida Canyon area, was probably deposited by turbidity currents or mass flows in a canyon/intercanyon environment. We cannot, however, exclude the possibility that these sands are non-turbiditic, open-marine calcarenites, deposited on the drowned carbonate platform, similar to the thin glauconite-rich, conglomeratic variety MF 8.3, deposited near the paleo-shelf edge.

3) A conspicuous, very thin, quartz-bearing iron-ooid rich echinoderm micrite with concentrations of belemnites and ammonites (MF 9) is a condensed Berriasian to ?basal Hauterivian condensation horizon, formed near the old shelf-break. The iron ooids and the partly ferruginous matrix originated from direct, multi-stage precipitation of goethite around preexisting nuclei and in the matrix in a deeper-marine hardground (around 100 m ?) environment, interrupted by extended periods of nondeposition, dissolution, and erosion.

Mid-Cretaceous hemipelagic nannofossil marl deposition

The late Aptian onset of several global mid-Cretaceous transgressions marked a major stratigraphic turning point towards hemipelagic conditions. Figures 7 and 11 show a palinspastic profile and a paleogeographic sketch map of the Mazagan area during the Late Aptian to Cenomanian. The upper Aptian-Albian (-Cenomanian) hemipelagic, quartz-bearing nanno marlstones (MF 10), sampled during the CYAMAZ expedition and in DSDP Sites 545/547, were deposited only at and beyond the foot of the paleo-escarpment. From seismic evidence we infer a (?more sandy) nanno marl-/limestone sequence landward of the main paleo-escarpment. The paleoescarpment itself was an area of nondeposition or erosion and the source of major slumps and debris flows towards the Mazagan slope (*see* Fig. 10 ; Steiger, Jansa, 1984).

Late Cretaceous pelagic sedimentation

A major transgression with a peak during Turonian times marked the Late Cretaceous period, which is characterized by rather thin, intermittent sequences of pelagic sediments separated by unconformities. Sedimentation was restricted to the areas to the east (landward) and southwest (seaward) of the more or less nondepositional paleo-escarpment (Fig. 12). Figure 7, however, shows that overlapping Upper Cretaceous sediments cover extensive parts of the Mazagan area and level some of the old, blockfaulted horsts.

Tertiary evolution (Fig. 12)

In most places, there is a major hiatus between the Cretaceous and Tertiary rocks. Only at the SE Mazagan horst (dive 92), early Paleocene (Danian) pelagic foraminiferal packstones were recovered. The Paleogene (mostly Paleocene to Eocene) pelagic foraminiferal pack-to wackestones were deposited in a pelagic slope environment similar to the present one. Radiolarian chalks with chert nodules (?Eocene) indicate increased silico-plankton fertility. The Tertiary record is interrupted by several unconformities. The Neogene is represented by mid-Miocene to Quaternary soft to semiconsolidated, pelagic foraminiferal nannofossil oozes which cover the whole Mazagan area, except for the steepest slopes, with a thin veneer of autochthonous or slumped sediments.

STRUCTURAL EVOLUTION

Many seismic surveys have been conducted in this area, especially by BGR, Lamont-Doherty Geological Observatory, and lately by CNEXO (*see* Ruellan *et al.*, this vol.). A single-channel profile across the Mazagan Escarpment (Fig. 4) shows Upper Jurassic to lower Neocomian carbonates on tilted fault blocks, overlain by a thin Cretaceous and Tertiary cover. Owing to the steepness of the slope and the massive carbonates, there is very little seismic resolution along

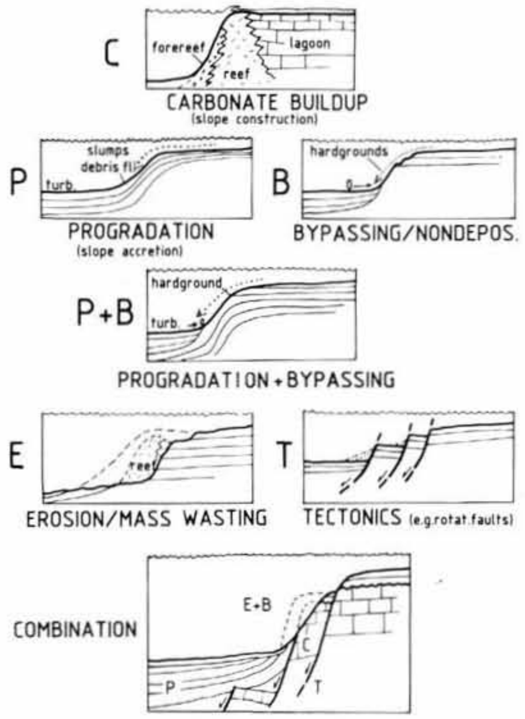

Figure 14

Constructional, destructional, and deformational processes shaping the steep slopes of passive margin-type carbonate platforms.

the escarpment. Except for this seismic information and a small number of widely spaced and poorly positioned dredge samples and cores, no information was available prior to the CYAMAZ cruise on the stratigraphy and structure of the Mazagan Escarpment between 3 000 and 1 000 m.

Figure 5 shows an unexaggerated block diagram of the southern Mazagan Escarpment, summarizing the stratigraphic and tectonic results of one dive (CZ 87). The slope of the escarpment ranges from 20° to subvertical near the edge of the plateau. Straight sediment ridges strike perpendicular to the depth contours at the foot of the slope. Small, straight canyons dissect the escarpment which is structured by vertical faults parallel to the escarpment and open fractures perpendicular to it. Only the upper scarp shows the influence of block tectonics, erosion and mass wasting. Neogene nanno oozes are onlapping or lie in protected pockets. They testify slumping or bypassing along the slope. In this area, a major unconformity separates the massive upper Jurassic to Berriasian shallow-water carbonates from the overlying bedded Late Cretaceous to Paleogene cover of pelagic micritic limestones.

The Mazagan carbonate platform which constitutes the seaward extension of the stable Moroccan Meseta is broken into a succession of downfaulted and slightly tilted blocks from the plateau to the foot of the escarpment (Fig. 3 and 4 ; *see* Ruellan *et al.*, this vol.). This faulting is controlled essentially by very old (?Hercynian) vertical (to listric ?) faults, trending mainly 20° (and 160°) (" Atlantic direction "), as well as 90° (and 120°) (" Mediterranean direction ").

Ruellan *et al.* (this vol.) subdivided the evolution of the Mazagan continental margin into five main stages (Fig. 7.1) :

1) *Late Triassic to Liassic* intracontinental rifting with the deposition of evaporites overlying a redbed environment (Winterer, Hinz, 1984). The subsiding epicontinental basin, filled by evaporites, lies essentially seaward of the Upper Jurassic carbonate platform. There were embayments into the Moroccan Meseta (*e.g.*, the " Atlas Gulf "/Essaouira Basin ; *see* Fig. 1). A Raetian to Hettangian phase of early rift-faulting and subsidence was inferred from Leg 79 evidence (Winterer, Hinz, 1984).

2) From *Late Jurassic to early Neocomian* — after a postulated mid-Jurassic tectonic reactivation (possibly block-faulting along listric faults) and onset of drifting — moderate subsidence and buildup of a 500-800 (?) m thick carbonate ramp and platform, especially on faulted basement highs. Much thinner, hemipelagic to pelagic sediments were deposited in the deeper areas to the west. Landward the platform carbonates became thinner and the depositional environment locally somewhat deeper.

3) During the *Early Cretaceous* (?Neocomian to Aptian) we note a very important block-faulting phase which resulted in the outcropping of platform carbonates along the outer edge of tilted blocks and the creation of small sediment-filled basins in the adjacent half-grabens. According to Huessner (1984) this block-faulting event was a response to different rates of subsidence, since the former western High Atlas rift became an " aborted rift " (after a mid-Jurassic compression) with slowed-down subsidence, whereas the Atlantic margin continued to subside strongly. This caused a landward retreat of the carbonate platform.

4) The *Upper Cretaceous* deposits are widely overlapping the existing relief and spread over much of the Mazagan Plateau and the adjacent Moroccan Meseta. The maximum transgression was during the tectonically quiet Turonian times.

5) Numerous unconformities (?lower Senonian, ?upper Eocene, ?mid-Miocene) separate the intermittent Upper Cretaceous to *Tertiary* sequence. Seismic evidence and the observations of « fresh » vertical faults at the present Mazagan Escarpment suggest that the faulting is still continuing.

The Triassic to Early Cretaceous evolution of the Moroccan margin is dominated by the rifting and early drifting stages of the opening of the Atlantic Ocean, whereas the Late Cretaceous to Tertiary evolution is influenced by African events, such as vertical epeirogenic movements of the High Atlas " inversion " and the Rif orogeny. Therefore the development of the contingent North American and Northwest African continental margins is very similar during the first phase and different during the second phase (Ruellan *et al.*, this vol. ; *cf.* also Stets, Wurster, 1982).

Figure 15 shows that the subsidence of the major tilted fault blocks migrated progressively landwards : mainly from sedimentological evidence, we postulate that the westernmost low sialic block (site 544, not shown in Fig. 15) had probably already been downfaulted to bathyal water depth during Tithonian times (Steiger, Jansa, 1985), the main Mazagan Escarpment block during Berriasian to Valanginian (-Hauterivian) times, and the southeastern Mazagan Plateau horst

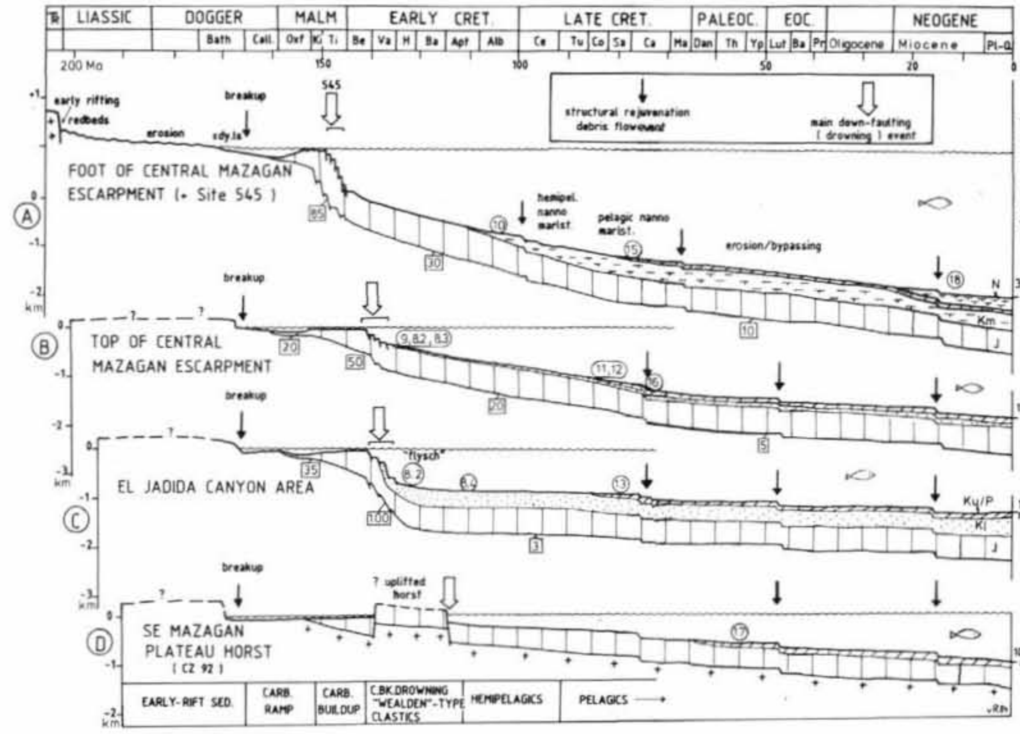

Figure 15

Non-uniform subsidence history and paleobathymetric evolution of the Mazagan Escarpment (" geohistory diagrams " with geological age plotted against depth below or above sea level). Four different areas of the present Mazagan Slope Escarpment and Plateau (present water depths : A = 3 000 m, B = 1 900 m, C = 1 200 m, D = 1 000 m) have been backtracked from 0-200 Ma to show their structural, facies and paleodepth evolution. Boxed numbers under " basement " = total subsidence rates (m/Ma), uncorrected for compaction etc. *Encircled numbers = microfacies (MF) types* (see *Tab. 1*). *J = (Upper) Jurassic platform carbonates, Kl = Lower Cretaceous, Km = mid-Cretaceous, Ku/P = Upper Cretaceous/Paleogene, N = Neogene. Figure 15 A modified after Winterer and Hinz (1984).*

(CZ dive 92) probably not before Barremian to Aptian times.

It is also noteworthy that the Mazagan Escarpment is at least 120 Ma old and was since that time only slightly deformed by erosion, biogenic or chemical dissolution, and gravitative processes (Fig. 7). Pockets or burrows in the Upper Jurassic platform limestones are filled or overlain by Lower Cretaceous, Upper Cretaceous, Paleogene or Neogene sediments, often demonstrated by a hand specimen or thin-section (von Rad, this vol.).

SUMMARY AND COMPARISON WITH SIMILAR CARBONATE PLATFORMS

Stratigraphic and structural evolution of the Mazagan margin

Figure 6 summarizes the *stratigraphic and tectonic results* of the CYAMAZ campaign and attempts to answer in which way *global sea level fluctuations* and *vertical tectonics* influenced the evolution of the post-platform sequence. In addition to VAIL's global sea level curve (Todd, Mitchum, 1977 ; Vail *et al.*, in press), we show a transgression-regression curve which is based on the published evidence from the Moroccan coastal basins and which fits better to our sedimentary data. This figure demonstrates the major tectonic events and unconformities, like the breakup-unconformity and the major blockfaulting episodes, as well as the facies evolution at the Mazagan Plateau between mid-Jurassic and Paleogene times. The evolution starts with the (Kimmeridgian-) Tithonian neritic carbonate platform phase, possibly preceded by an mid-Jurassic to Oxfordian (-Kimmeridgian) " carbonate ramp phase ". It is followed by the bioclastic " flysch " facies, which was found only in the paleocanyon-fan system to the south of the plateau. At about the same time we find at the paleo-escarpment (near the shelfbreak) condensed hardground series (MF 9, MF 8.3-8.4 and part of MF 8.2). From late Aptian to Cenomanian times hemipelagic nanno marls (MF 10) where deposited at the foot of the escarpment. The upper Late Cretaceous is characterized by pelagic nanno chalks (MF 15), phosphorites (MF 11, 12), phosphorite breccias (MF 13), and limestone breccias (MF 14). The phosphorites indicate increased plankton fertility, caused by upwelling events, and slow starved-sedimentation conditions in an upper slope/outer shelf setting. After another hiatus at the Cretaceous/Tertiary boundary, pelagic foraminiferal chalks, breccias, and radiolarian cherts of Paleocene to Eocene age set in. The Neogene is characterized by pelagic foraminiferal nanno ooze deposition, interrupted by several unconformities, in an environment which was very similar to the present one.

The " stratigraphic turning points " (Schlager, 1981) are clearly influenced by vertical tectonics, sea level fluctuations, and possibly also by climate, a very poorly known variable. A late Berriasian regression might have exposed the platform which might have been subsequently karstified (Steiger, Cousin, this vol. ; Vail, pers. comm.). The rapid Valanginian transgression drowned the platform below the euphotic zone and beyond recovery. The condensed iron ooid- and belemnite-rich horizon might correlate with the Valanginian-early Hauterivian transgression. The Wealden-type deltas and their submarine extension to a prodelta-canyon-deep-sea fan system were built forward mainly during the Hauterivian regression (von Rad, Sarti, in press). The thick hemipelagic Late Aptian-Albian (-Cenomanian) nanno marls at the lower slope coincide with the Late Aptian to Albian transgression. On the other hand, the early Neocomian, Aptian, Senonian and Paleogene breccias are in our interpretation caused by major blockfaulting episodes which increased the relief of the old escarpments and triggered local slumps and mass flows.

The shaping of steep escarpments at carbonate platforms

One of our major objectives was to find out what processes formed the steep escarpment of this old passive-margin type carbonate platform. Figure 14 shows several possible constructional and destructional processes of carbonate platform development, independant of their applicability to the case of the Mazagan Plateau (*cf.* Jansa, 1981) :

a) slope construction by reef growth or carbonate buildup ;

b) slope accretion by progradation (upbuilding and outbuilding) with slumps and debris flows at the slope and turbidites at the apron ;

c) bypassing of sediments or nondeposition with hardgrounds along the steep sediment-starverd slope ;

d) progradation and bypassing with turbidites onlapping in an upslope direction, a common combination of (b) and (c) ;

e) erosion (defacing) and/or mass wasting might have truncated the outer part of prograded sediments and actually all or most of the outer high-energy reef section of a carbonate platform, causing a landward retreat of the platform slope (Freeman-Lynde *et al.*, 1981, Schlager *et al.*, 1984) ; and

f) vertical tectonics (*e.g.*, rotational block-faulting) might have transformed the rifted margin into a staircase of progressively down-faulted fault blocks.

Schlager and Ginsburg (1981) have predicted a succession of steps a→b→c→e : platform slopes steepen as they grow higher ; then they shift from accretion to bypassing, and finally to erosion.

In the case of the Mazagan Escarpment we see evidence of *all* these processes : Carbonate buildup (cyanobacterian crusts etc.) can be only responsible for part of the relief during the Late Jurassic-early Neocomian construction of the platform ; progradation is only seen locally in the apron of the slope ; vertical tectonics is apparently the most important factor ; and post-early Neocomian erosion, nondeposition and bypassing is evident by the hardgrounds and pocket fillings overlying the platform carbonates. Defacing and backcutting of the cliff, however, were of minor importance, since the fully cemented, massive pelsparites have been very resistant to erosion (Steiger, Cousin, this vol.). However, local erosion and biogenic or chemical dissolution is indicated by the rounded and pitted surfaces of the Jurassic limestone outcrops along the escarpment, and episodic defacing of the paleo-escarpment is indicated by the limestone breccias in the Miocene-Pliocene debris flows of site 545 (Steiger, Jansa, 1984).

Paleobathymetry and subsidence history

Another problem of general interest is the tectonic control of the subsidence history of starved, passive continental margins. Figure 15 shows schematic sketches of the paleobathymetric and subsidence evolution of four blocks across the Mazagan slope, Escarpment and Plateau which all had an individual subsidence and facies history. The subsidence curves are very different from curves for " fat " passive continental margins (*e.g.*, Watts, Steckler, 1979 ; von Rad, Einsele, 1980) or for the exponentially decreasing subsidence of the cooling oceanic crust (Parsons, Sclater, 1978). For the Mazagan Plateau with its starved-sediment conditions we invoke a complex history with at least 3 times of structuration and accelerated subsidence.

1) Rifting during late Triassic-Liassic times occured along rejuvenated Variscan faults and produced rotational fault blocks trending more or less parallel to the present escarpment.

2) After the mid-Jurassic onset of drift, we have moderate subsidence (about 30-50 m/Ma) during the 15-20 Ma of carbonate buildup under shallow-water conditions.

3) About 120-130 Ma ago termination of carbonate buildup (a) by a rapid regression followed by a major Valanginian transgression, and (b) by a new structuration by block-faulting. The subsidence rates increased to up to 85 m/Ma for the lower blocks (Fig. 15A) and up to 100 m/Ma for the El Jadida Canyon area (Fig. 15C), where Lower Cretaceous deeper water sediments were deposited. They were not compensated by sedimentation. On higher blocks (Fig. 15B), we observed condensed hardground formations, followed by nondeposition and erosion. Thus a precursor of the present Mazagan Escarpment is at least 120 Ma old. Only thin, pelagic, deep-water sediments were intermittently deposited on the slowly subsiding plateau and slope.

4) During the Campanian/Maastrichtian, Eocene, and possibly also the Miocene, we had other structural rejuvenations of the slope after periods of long tectonic quiescence and very reduced subsidence rates (3-20 m/Ma).

Comparison of the Mazagan Plateau with other parts of the Jurassic-Early Cretaceous carbonate platform off Northwest Africa

The seaward edge of the Upper Jurassic carbonate platform forms a conspicuous structural feature off the Northwest African continental margin (Fig. 1) which is almost continuous for about 800 km from the

(16.1)

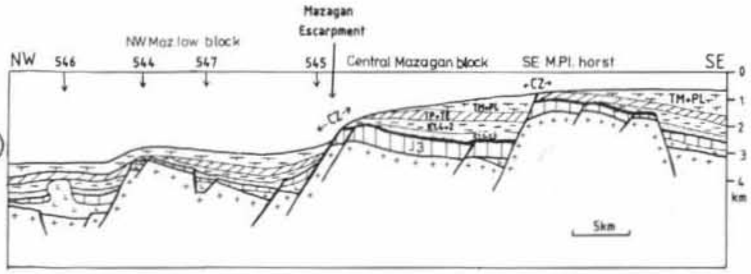

Figure 16.1

Schematic cross-section of the Mazagan area (modified after Ruellan et al., *this vol., their Fig. 6). Numbers designate DSDP sites ; CZ = area explored by CYAMAZ dives.* See *Figure 1 for location. + = granitic basement (Paleozoic), L = Triassic/Liassic evaporites, redbeds,* etc.

(16.2)

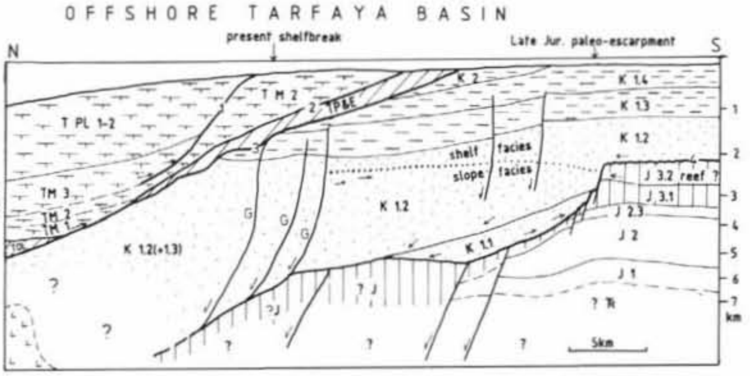

Figure 16.2

Schematic cross-section of the offshore part of the northern Tarfaya Basin NE of Cape Juby (for approximate location see *Fig. 1). Modified after Mitchum and Vail (1977) and Todd and Mitchum (1977). Major unconformities and the buried carbonate platform are outlined by heavy lines. Note seaward thickening wedge of (1 to more than 3 km thick) Lower Cretaceous clastic series burying the block-faulted, steep paleo-escarpment of the Upper Jurassic carbonate platform. J3.2 = Upper Jurassic Puerto Cansado Formation, K1.1 + 1.2 = Lower Cretaceous Tan-Tan Formation (prodelta* etc.*), K1.3 + 1.4 = mid-Cretaceous Aguidir Formation.* See *also Hinz* et al. *(1982, Fig. 2).*

(16.3)

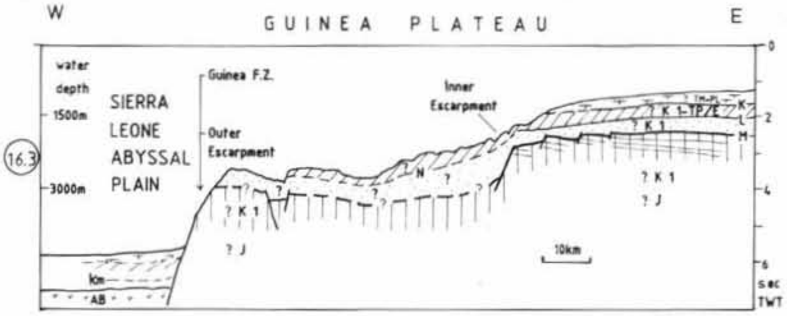

Figure 16.3

Line drawing after airgun seismic profile (RRS Shackleton) across the Guinea Plateau and Escarpment off Guinée (West Africa). Modified after Jones and Mgbatogu (1982, Fig. 5). K, L, M, N = reflectors ; Km = mid-Cretaceous (black shale) reflector, AB = acoustic basement. Stratigraphic correlation very tentative.

Figure 16

Comparison of the structure of the Northwest African Upper Jurassic (to lower Cretaceous) carbonate platform at 33°30′N (Mazagan Plateau), 29°N (offshore Tarfaya Basin) and 10°N (Guinea Plateau). Legend : Tr = Triassic ; J = Jurassic ; J1 = lower Jurassic (Liassic) ; J2 = middle Jurassic (Dogger) ; J3 = upper Jurassic (Malm) ; J3.1 = Oxfordian ; J3.2 = Kimmeridgian to Tithonian ; K = Cretaceous : K1 = lower Cretaceous ; K1.1 = Valanginian ; K1.2 = Hauterivian to Barremian, K1.3 = lower to middle Aptian ; K1.4 = upper Aptian to lower Cenomanian ; K2 = upper Cretaceous ; Tp & E = Paleocene/Eocene, T_{OL} *= Oligocene ;* T_M *= Miocene ;* $T_{M\,1,2,3}$ *= lower middle, upper Miocene ;* T_{PL} *= Pliocene ; G = Growth faults ; 1 = mid-Miocene unconformity ; 2 = mid-to Late Oligocene (" Styrian ") unconformity ; 3 = Paleogene (?E. Eocene) unconformity (" Pyrennean ") ; 4 = early Neocomian (" Late Cimmerian ") unconformity with ?karstified surface.*

Mazagan Plateau in the north to the northern Tarfaya Basin in the south (Hinz *et al.*, 1982). Further south, off the Western Sahara (Ranke *et al.*, 1982), Mauretania and northern Senegal the carbonate platform is deeply buried and less evident. It becomes again a prominent morphologic unit off southern Senegal and Guinea (Wissmann, 1982 ; Jones, Mgbatogu, 1982). The present water depth of the top of the outer edge of the carbonate platform increases southward, from about 2 km at the Mazagan Plateau to 2-3 km off the northern Tarfaya Basin, to 4-7 km off Western Sahara, Mauretania and northern Senegal. Only in two regions along the West African margin is the escarpment of the Mesozoic carbonate platform exposed at the present sea floor : at the Mazagan Plateau off the Moroccan Meseta in the north (Fig. 16.1) and at the Guinea Plateau off the Casamance in the south (Fig. 16.3). Apparently, these two very stable Paleozoic-Mesozoic platforms formed south of the Azores Fracture Zone and north of the Guinea Fracture zone at the northeastern and southeastern boundary of the Jurassic Atlantic Ocean (Wissmann, pers. comm.). Both plateaus were characterized by highly reduced subsidence rates and starved sedimentation or erosion during the past 125 Ma, and hence remained exposed or nearly exposed high-standing basement blocks at the West African margin. These structural highs are also associated with promontories of the West African Paleozoic fold belt and correlate with the contingent Avalon Uplift (?) north of the Scotian margin, and the Peninsular Arch/South Floridan margin, respectively (Wissmann, Roeser, 1982).

The structure of the *offshore Tarfaya Basin* (Fig. 16.2) is an excellent example for an impressive Late Jurassic carbonate shelf margin with a well developed Kimmeridgian to Tithonian " reef " and a steep (10-20° !) Tithonian/Berriasian paleo-escarpment. The Mesozoic carbonate platform is buried by a thick wedge of Lower Cretaceous, clastic deeper-water sediments (Todd, Mitchum, 1977 ; Mitchum, Vail, 1977 ; Hinz *et al.*, 1982). The profile (Fig. 16.2) is based on an industrial multichannel seismic line, interpreted by Mitchum and Vail (1977), using data from surface geology and commercial on- and offshore wells. Valanginian deep-marine clastics (K 1.1) are restricted to a small slope basin in front of the escarpment with both deep-marine downlap and onlap against the paleoslope. The Hauterivian regressive sandstones overly directly an eroded surface of the old carbonate platform which was probably subaerially exposed and karstified during a major late Berriasian to mid-Valanginian sea-level lowstand (Vail, pers. comm.). The overlying Hauterivian to Barremian (K 1.2) sediments (Tan-Tan Formation) are a seaward thickening (1 to more than 3 km) sequence of deltaic sandstones and prodeltaic silty mudstones, characterized by syndepositional growth faults. A major regression is indicated by the shelf facies overriding the slope facies, after the basin was filled to sea level. The overlying Aptian to lower Cenomanian Aguidir Formation (K 1.3 + 1.4) is a several 100 m thick sequence of marine shales and marls, deposited during the mid-Cretaceous transgressions. Late Cretaceous sediments are thin or eroded by a major Late Cretaceous/Paleogene (" Laramide ") unconformity. The Tertiary sedimentation is interrupted by several major unconformities, especially during mid-Oligocene and upper mid-Miocene times.

If we compare the evolution of the northern Tarfaya Basin with that of the Mazagan Plateau, we note the following similarities and differences : a) the evolution, structuration and drowning of the Upper Jurassic carbonate platform is very similar, as is the Late Jurassic subsidence history (although the platform carbonates are much thinner at the Mazagan Plateau) ; b) similar as at the Mazagan Plateau, the relief between the Late Jurassic shallow-water platform and the adjacent deep-sea plain or continental rise was about 2.5-3 km (Hinz *et al.*, 1982) ; c) although the Wealden-type deltaic clastics of the Lower Cretaceous (K 1.2 + 1.3) are similar to the bioclastic turbidites of the El Jadida Canyon area (MF 8.2), the sedimentation rates are about 10 times as high in the Tarfaya Basin as on the sediment-starved Mazagan Plateau ; d) also the mid-Cretaceous transgressive marls and shales (K 1.4) are much thicker than the comparable hemipelagic late Aptian to Cenomanian nanno marls from the Mazagan slope.

A very similar, thick Cretaceous Wealden-type deltaic sequence with an upward and seaward facies transition from continental clastics to lagoonal/intertidal deposits → delta front sediments → laminated prodelta muds was described from the West Saharan (Cape Bojador) marginal basin (von Rad, Einsele, 1980 ; von Rad, Arthur, 1979 ; Ranke *et al.*, 1982). Distal turbidites reached the deep-sea fan, now uplifted and exposed at the island of Fuerteventura (Robertson, Bernoulli, 1982).

The Guinea marginal platform (Lehner, de Ruiter, 1977 ; Jones, Mgbatogu, 1982) is very similar to the Mazagan area, although much less well studied (Fig. 16.3). A large part of the platform has hardly been buried by post-platform sediments since the early stages of separation from the contingent Blake Plateau/Florida margin. The Upper Jurassic to Cenomanian carbonate platform is up to 3 km thick and has a relief of about 3 000 m with an inner and an outer escarpment. The plateau has a steep southward-facing scarp, formed by the left-lateral transform fault of the Guinea Fracture Zone. Thus the Guinea Plateau and its plate-tectonic neighbour, the Blake Plateau/S Florida margin (Fig. 17), had a very similar evolution as the Mazagan Plateau.

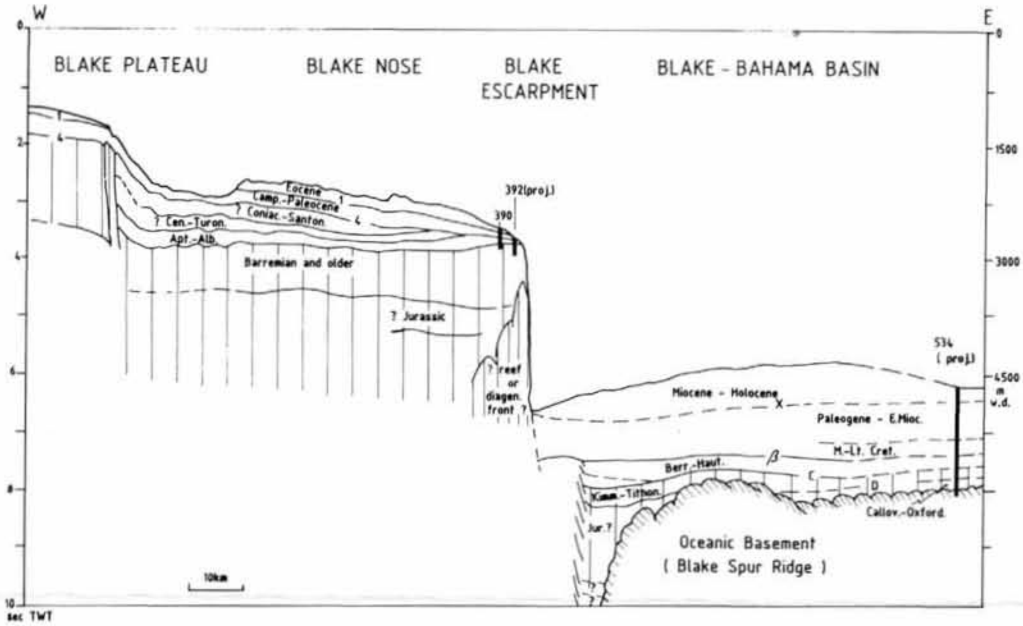

Figure 17

Section across Blake Plateau, Blake Escarpment and adjacent Blake-Bahama Basin (approximately 10°N). Line drawing of CONRAD seismic profile MC 2 through DSDP site 390 with sites 392 and 534 projected. Modified after Sheridan and Enos (1979, Fig. 2 ; see also Sheridan, Gradstein et al., *1983). Note carbonate bank margin facies (reefal or other massive or diagenetically altere carbonates ?), identified as hyperbolic reflectors overlying an opaque, reflectionless zone.*

Comparison of Blake and Bahama Plateau with Mazagan Plateau

Figure 17 shows a schematic section across the *Blake Plateau,* Blake Escarpment and adjacent Blake-Bahama Basin, an area which has also been studied in great detail by seismic surveys (Shipley *et al.*, 1978 ; Folger *et al.*, 1979), dredging, coring, scientific ocean drilling (Benson, Sheridan *et al.*, 1978 ; Sheridan, Enos, 1979 ; Sheridan *et al.*, 1983), and submersible surveys (USGS dives with Alvin, 1981, unpublished). After the breakup of Pangaea at 155-165 Ma, active sea floor spreading began, followed by a major Callovian transgression, rapid subsidence, and carbonate buildup starting in Oxfordian/early Kimmeridgian times (Ogg *et al.*, 1982). At Blake Nose an indurated, Neocomian, upward-shoaling sequence of open-shelf muds, oolites and peritidal sediments overlies a several kilometres thick Jurassic carbonate platform sequence. Reef growth and carbonate buildup at Blake Nose ended with emergence and freshwater diagenesis (karst development) during a middle to late Barremian sea-level lowstand, followed by subsidence to greater water depths during the following sea level rise. A condensed sequence of red goethitic crusts with pisolites (very similar to the iron ooid-rich facies MF 9 of CYAMAZ) and nannofossil oozes overlies erosional surfaces of intertidal limestones. During the Aptian the water depth at site 392 had already increased to several 100 m (Sheridan, Enos, 1979). According to Leg 101 results, a large Jurassic/Lower Cretaceous " megabank " in the area between the northern straits of Florida and the southern Blake Plateau was drowned by a rising sea level about 100 Ma ago (Schlager, Austin, press release for ODP Leg 101, April 1985).

As at Mazagan Plateau, a major hiatus spans the late Albian through early Campanian, suggesting submarine erosion and bypassing by strong ?Santonian bottom-following contour currents. From the Santonian/Campanian on, water depth increased and the shelf margin shifted landward towards the locus of Tertiary to Recent carbonate bank accretion (Sheridan, Enos, 1979).

Site 534 in the *Blake-Bahama Basin* documented a complete record of Callovian to Cenomanian deep-sea sediments (Sheridan *et al.*, 1983). The Berriasian to Barremian Blake-Bahama Formation contains redeposited clastics from the Blake Plateau, especially Hauterivian to Barremian turbidites and debris flows (Robertson, Bliefnick, 1983). This environment is comparable, although of much minor importance, to the deep-sea fan environment recorded in DSDP site 416 of the Moroccan Basin (Lancelot, Winterer, 1980). A much thicker, Wealden-type Early Cretaceous deep-sea fan facies was discovered in site 603, 800 km NNE of site 534 on the " Hatteras Deep-Sea Fan " (von Rad *et al.*, 1984 ; Sarti, von Rad, in press).

A similar, 2 km thick Early Cretaceous to Eocene section of the *Bahama Escarpment* was studied and sampled by the US submersible Alvin (Freeman-Lynde *et al.*, 1981). Similar to the Blake Plateau, it consists of a lower and middle Cretaceous sequence of peritidal, lagoonal, patch-reef and back-reef limestones, unconformably overlain by an intermittent cover of Maastrichtian and Eocene pelagic limestone. These authors and Schlager *et al.* (1984) assume that a 1-5 km wide zone of reef and fore-reef deposits was removed by erosional backcutting of the cliff, helped by spallation of joint blocks. For the Mazagan area, we assume that block-faulting was the main factor shaping the steep paleo-escarpment and that there was no major backcutting of the well-cemented massive Upper Jurassic peloidal pack- and grainstones.

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