PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Mesozoic--Cainozoic Subsidence History and Palaeobathymetry of the Northwest African Continental Margin (Aaiun Basin to D. S. D. P. Site 397)

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Mesozoic–Cainozoic subsidence history and palaeobathymetry of the northwest African continental margin (Aaiun Basin to D.S.D.P. Site 397)

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A well documented section across the continental margin at Cape Bojador is based on information of D.S.D.P. Sites 397 (uppermost continental rise) and 369 (slope), several on- and offshore commercial wells, and the interpretation of seismic profiles (figure 2). Within the Aaiun–Tarfaya coastal basin Mesozoic to Cainozoic sediments thicken from a hinge line to the present coast. Over a lateral distance of about 100 km under the present shelf, slope, and uppermost rise, a sedimentary sequence of nearly constant thickness (12–14 km) overlies continental to transitional basement. This uniformly subsiding part of the margin is termed 'Cape Bojador marginal basin'. Seaward of the upper rise the basement rises and the sediment cover thins.

For time intervals with unambiguous interpretation of palaeo-water depth, we inferred the subsidence rates of 'marginal basin' sites directly from sediment thickness and corrected them for compaction (figure 4). Since at the slope and rise sites the facies interpretation of the Late Cretaceous and Tertiary record does not allow an estimation of palaeo-water depth, this depth was found by 'backtracking' the present depth of stratigraphic boundaries below sealevel by using the subsidence rates from comparable shelf and coast sites. As a 'continental approach' to the margin this method infers the subsidence and palaeobathymetry of the poorly known continental slope and rise environments with the better established stratigraphic and facies information from the coastal basin and the shelf.

During the Jurassic, the subsidence rates in the 'Cape Bojador marginal basin' (table 1) were high (80–100 m/Ma); they increased slightly during the early Cretaceous (130–140 m/Ma). During the late Cretaceous and Cainozoic, subsidence slowed down more or less exponentially. During the (Triassic?–) Jurassic, we assume shallow-water conditions (possibly carbonate build-up) for the present slope and rise sites. The earliest Cretaceous is represented by a very thick Wealden-type deltaic sequence with shallow-marine deltaic sediments below Site 369 (?) and distal prodelta muds (about 500 m water depth) at Site 397. Subsequently, accumulation rates lagged behind the subsidence rates, causing a gradual deepening of the outer continental margin to its present depth. The continuous deepening of the sea floor has been accompanied by a landward facies migration until the Turonian.

A 1–2 km deep erosional scarp was formed by deep geostrophic currents during the Oligocene at the upper rise (Site 397), which was rapidly filled by early Miocene mass flows, until equilibrium conditions were gradually established.

1. Introduction

The increasing interest in the structure, evolution, and hydrocarbon potential of Atlantic-type continental margins is documented by a growing number of publications on the history of basin formation and subsidence. Multichannel seismic surveys, deep-sea drilling, and commercial on- and offshore wells have considerably improved our understanding of the structural and stratigraphic framework of these trailing edge margins.

By using the continental margin off Cape Bojador (northwest Africa) we hope to contribute to the knowledge on the development of mature passive margins. We are particularly interested in the geodynamic evolution of this rifted margin (approximately 200 Ma old) from the coastal basin down to the continental rise in the light of new geophysical and geological information. As a 'continental approach' to the margin, we propose a new 'continental margin backtracking method' to apply the better established stratigraphic and facies information from the coastal basin and inner shelf for the interpretation of the poorly known slope and upper rise environments.

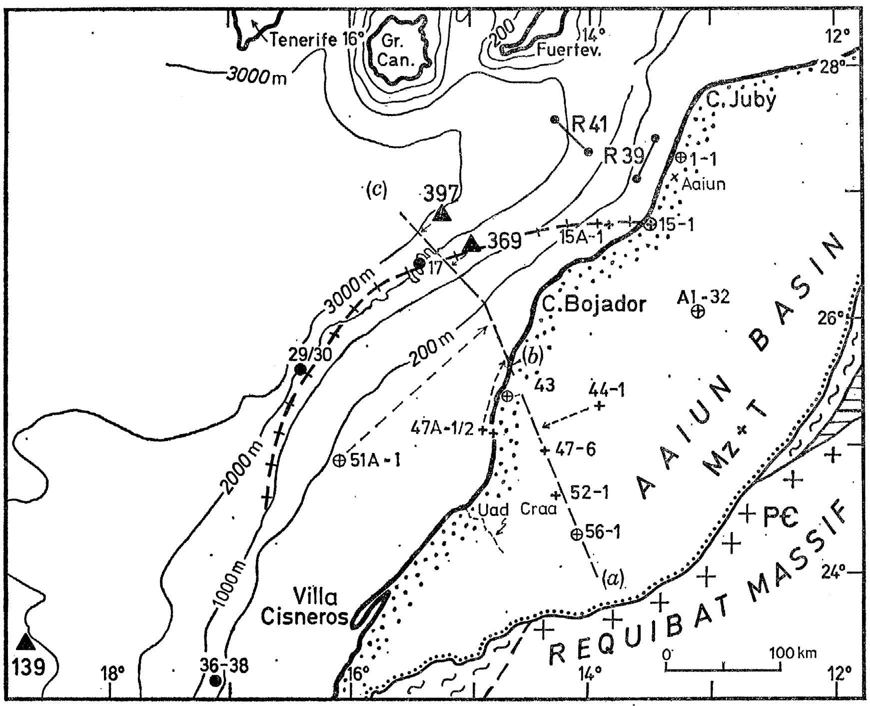

FIGURE 1. Area of investigation and location of on- and offshore exploration wells in the Aaiun Basin. ●, Valdivia 10 dredge stations with pre-Quaternary rocks (von Rad *et al.* 1979); ▲, D.S.D.P. sites; +, commercial wells; ⊕, exploration wells, shown in detail in figures 2 and 3; ●—●, seismic refraction profile (Roeser *et al.* 1971); + +, axis of 'slope anticline'; folded Palaeozoic rocks (Mauretanides); ⊟, unfolded Palaeozoic (Tindouf Basin). Profile *a–b–c*, see figure 2.

2. Structure and stratigraphy of the Cape Bojador margin

2.1. *Geological setting and drill sites*

Fortunately, a pair of closely spaced, continuously cored D.S.D.P. sites, one hole 1453 m deep at the uppermost rise (397, Leg 47a) and one 489 m deep at the intermediate slope (369, Leg 41) have been drilled off Cape Bojador, in addition to several very deep commercial on- and off-shore wells in the Aaiun Basin (figure 1).

All these wells lie within or seaward of the Aaiun (–Tarfaya) coastal basin which is bounded to the east by the Palaeozoic fold belt of the Mauretanides and the Precambrian Requibat Massif, to the north by the Precambrian Antiatlas High, and to the south by the West African craton. Towards the west, the coastal basin is open to the sea. The maximum sediment thickness is under the present shelf and slope (figure 2). During early Neogene times, the uplift of the volcanic province of the Canary Islands considerably influenced the Neogene sedimentation between this Archipelago and Cape Bojador.

The generalized southeast–northwest section across the Aaiun Basin and its seaward extension into the continental margin (figure 2) is based on seismic reflexion and refraction data from the Aaiun Basin (Querol 1966) and from the continental margin (Roeser *et al.* 1971; Beck & Lehner 1974; Hinz *et al.* 1974; Uchupi *et al.* 1976; von Rad *et al.* 1979; Hinz 1979); the seismic interpretation is controlled by onshore commercial wells (56–1 to 43–1: Auxini 1969), by two offshore shelf wells (47*a*–1; 51*a*–1: Conoco 1969) and two D.S.D.P. sites (369 and 397). Dredged and cored sediments of Aptian–Albian to Palaeogene age, taken from outcrops in

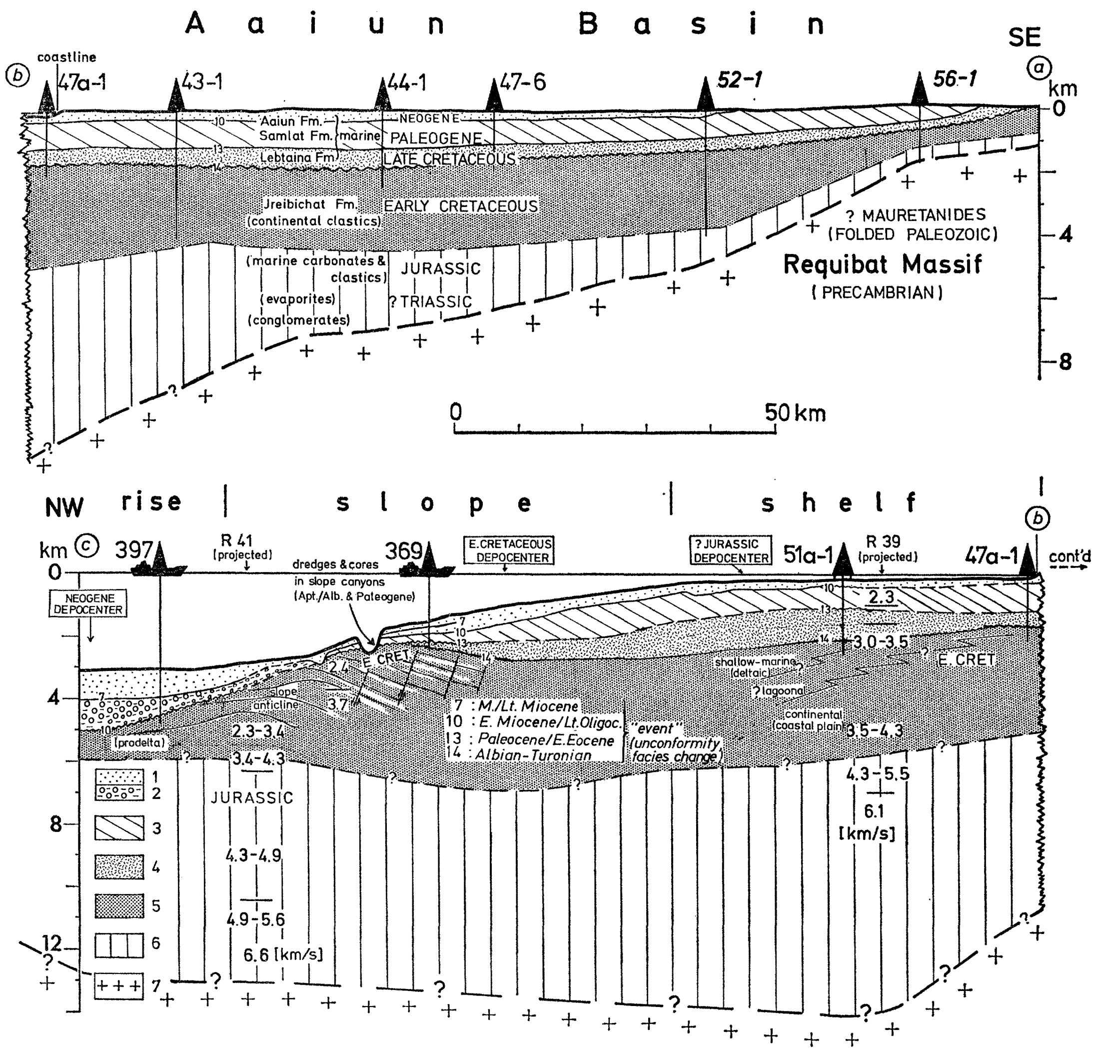

FIGURE 2. Highly generalized S.E.–N.W. cross-section of the Aaiun Basin, extended to the shelf, slope, and upper rise off Cape Bojador (after von Rad *et al.* 1979). For location of profile, seismic refraction profiles, commercial wells, and D.S.D.P. sites see figure 1. Basement depth and Jurassic/Cretaceous boundary are tentatively interpreted from refraction and multichannel seismic profiles (G. Wissmann, personal communication). 1, Neogene (on slope and rise mainly hemipelagic); 2, early Neogene, mostly 'allochthonous' (mass flows, etc.); 3, Palaeogene, 4, late Cretaceous; 5, early Cretaceous; 6, Jurassic (Aaiun Basin: + Triassic); 7, 'Basement' (Precambrian to Palaeozoic continental basement, possibly transitional to continental basement under slope and uppermost rise).

deeply incised lower slope canyons (see figures 1 and 2), supplement the deep sea drilling results (von Rad *et al.* 1979).

2.2. *Stratigraphy and facies migration*

Continental basement consists of metamorphic rocks, possibly of the Requibat Massif, and was reached at well 56–1; it is estimated to be 12–14 km below the present shelf and slope (figure 2; see also §2.3).

The basement is overlain by Triassic (?) terrestrial sandstones and conglomerates (56–1), ? red beds, and possibly some (late Triassic to) early Jurassic evaporites, and then by thick Jurassic carbonates (and clastics) of shallow-water origin. The pre-Cretaceous sediments attain a tremendous thickness (up to 8 km), especially below the present shelf and upper slope; in part, they might be interpreted as platform carbonates deposited on a tectonically stable, steadily subsiding shelf.

The early Cretaceous is represented by a very thick, regressive Wealden-type deltaic sequence consisting of continental clastics to distal prodelta muds (D.S.D.P. 397) which 'drowned' the middle Jurassic carbonate platform (Vail *et al.* 1979). The maximum sediment thickness (4 km) is reached in the inferred 'delta front environment' below the present slope. Horizontal or slightly landward dipping strata are offset by antithetic growth faults below the lower slope. These relations suggest that the 'slope anticline', described from shallow-penetration seismic records by Hinz *et al.* (1974) is not a compressional feature, but is caused by subsidence due to differential loading or by isostatic rebound after the Oligocene erosion at the outer margin (Arthur *et al.* 1979). A seaward thinning of the individual layers is noted near the distal part of the delta (Hinz 1979).

Late Cretaceous sediments are much thinner and only preserved landward of the intermediate slope. Their thickness increases between D.S.D.P. 369 (60 m, with hiatuses) and 51a–1 (915 m), indicating a seaward decrease of subsidence and a seaward thinning and pinch-out of individual strata because of reduced terrigenous sediment supply (Hinz 1979). Only a few hundred meters of Palaeogene sediments were deposited without any progradation. They are also erosionally truncated seaward of the intermediate slope. The Neogene under shelf and upper slope (369 to 43–1) is extremely thin, because most sediment bypassed this area on its way to deeper areas. However, below the lower slope and uppermost rise, an oversteepened late Oligocene–early Miocene erosional surface (unconformity 10 in figure 2) is covered by 600 m of rapidly deposited, early Miocene mass-flow units (debris flows, grain flows, turbidites, etc.), in turn overlain by a thick drape of middle Miocene to Quaternary hemipelagic deposits (von Rad, Ryan *et al.* 1979).

FIGURE 3. Highly generalized Mesozoic and Cainozoic sedimentary stratigraphy of nine drill holes across the Aaiun Basin and Cape Bojador continental margin. Lithofacies of onshore wells (except Puerto Cansado) only according to small sketches in AUXINI (1969). 1, nanno ooze; 2, (nanno) chalk; 3, limestone; 4, sandy limestone; 5, dolomite; 6, marly dolomite; 7, marl; 8, marlstone; 9, siliceous (diatom/radiolarian) ooze/mud; 10, porcelanite (-chert); 11, silt(stone); 12, sand(stone); 13, conglomerate/gravel; 14, clay/mud; 15, pebbly mudstone (debris flow deposit); 16, claystone; 17, silty claystone; 18, ash layers; 19, volcaniclastic debris flows; 20, shell layers (coquina); 21, intertidal sandy channel fills; 22, limestone concretions; 23, lignite; 24, belemnites; 25, phosphates/phosphorite; 26, metamorphic basement; 27, slumping; 28, erosional unconformity with duration of hiatus and reworked lithologies; 29, evaporites; 30, upwelling conditions; 31–35, inferred environment of deposition: 31, hemipelagic sediments (upper slope to upper rise), 32, neritic, ± clastic sediments (shelf); 33, shallow-water carbonates (platform); 34, paralic (lagoonal to intertidal); 35, terrestrial (alluvial plain, etc.).

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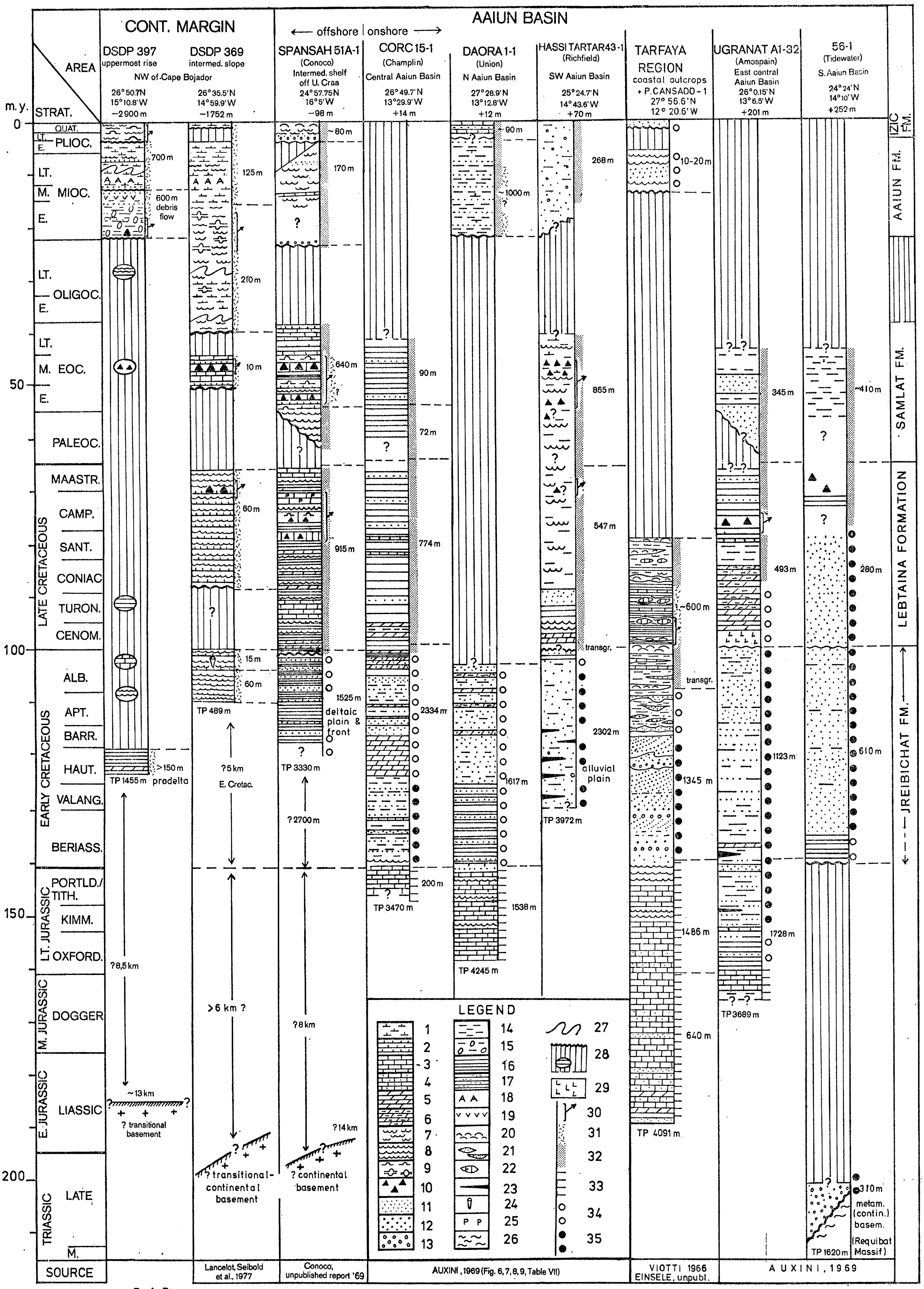

von Rad, Ryan *et al.* (1979)

FIGURE 3. For description see opposite.

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Figure 3 shows the highly generalized sedimentary stratigraphy of nine drill holes across the Aaiun Basin and the Cape Bojador continental margin. Here, only a few principal points of selected drill holes which are relevant for the discussion below can be mentioned: Hassi Tartar 43-1 and 47a-1 (Auxini 1969; see also Ratschiller 1970), as well as Puerto Cansado-1 (Viotti 1966; near Tarfaya) represent typical 'coastal sites' (see also figure 4).

The well Spansah 51a-1 (Conoco 1969) at the central shelf penetrated a similar, although slightly more marine facies. The 'Wealden-type' early Cretaceous is represented by more than 1500 m interbedded sandstones, shales and siltstones ('Jreibichat Formation'). Some dolomite and anhydrite layers indicate lagoonal conditions; lignite and carbonaceous material suggest a coastal swamp environment, whereas glauconite, echinids and local oolite beds point to shallow-marine incursions of the sea on a deltaic plain. The late Cenomanian transgression produced fully marine, multicoloured calcilutites, calcisiltites and marls which are partly dolomitic and cherty. Phosphatic limestones suggest upwelling conditions during the latest Cretaceous. Part of the Palaeocene is missing. The Eocene siliceous, fossiliferous limestones, marls, and cherts contain a characteristic radiolarian and benthonic foraminiferal (*Uvigerina*) fauna, which might indicate upwelling conditions during the late Palaeogene in an oxygen-depleted upper slope environment (see von Rad *et al.* 1979).

All sediments penetrated in D.S.D.P. site 369 (1752 m water depth) at the present intermediate slope are hemipelagic and were deposited above the CCD (Lancelot, Seibold *et al.* 1977). The oldest sediments are 75 m of late Aptian to Albian dark organic-rich nanno marls. Only 60 m of late Cretaceous (Coniacian–Maastrichtian) nanno marls and limestones with porcelanites are preserved and these are bounded by erosional hiatuses. They indicate an upper slope environment, similar to the environment indicated by 10 m of middle Eocene nanno limestone with porcelanites. A surprisingly complete latest Eocene to late Oligocene record of hemipelagic, ± siliceous nanno oozes is present at this site, whereas the Oligocene sediments were eroded both on the shelf and on the upper rise (D.S.D.P. Site 397).

D.S.D.P. Site 397, on the uppermost rise, has an extremely thick (1300 m) Neogene sequence overlying directly early Cretaceous strata (von Rad, Ryan *et al.* 1979). The late Hauterivian dark, laminated silty claystones with siderite layers are probably distal prodelta muds deposited at high rates of deposition in a water depth of 500–1000 m (Einsele & von Rad 1979). 1–2 km of Barremian to Oligocene sediments are missing in a large 100 Ma hiatus, but partly preserved in reworked pebbled within the rapidly deposited early Miocene debris flows, grain flows, turbidites, and slumps. The upper part of the Neogene consists of a 700 m thick undisturbed sequence of hemipelagic nanno marls and oozes, indicating nutrient-rich (upwelling) conditions and very little influx by coarse-grained terrigenous material. From this information we draw the following conclusions: The large Early Cretaceous Wealden-type delta system is characterized by the seaward transition from an alluvial plain (56-1) via a lagoonal (51a-1) and deltaic plain or forest environment (? below Site 369) to a distal prodelta facies (397). The facies migrated landward obliquely through space and time, as, for example, indicated by the migration of the terrestrial–paralic boundary from the earliest Cretaceous in 51a-1 to Cenomanian–Turonian in Ugranat. The trend to a 'fining-upward facies sequence' is caused by a transgressive sea and an upward decrease of the terrigenous and a relative increase of the biogenic input (Einsele & von Rad 1979). There was an expanded oxygen-minimum zone and/or regional upwelling during late Cenomanian to Turonian times (Einsele & Wiedmann 1975).

During the earliest Cretaceous, the shelf-slope transition was situated about 50 km seaward of the present shelfbreak (i.e. between sites 369 and 397, see also Lehner & De Ruiter 1977, their figure 3). The present outer shelf edge and slope as distinct morphological features were developed during the Cenomanian and they remained at this position between sites 369 and 51*a*–1 for the past 90 Ma. The present coastline lies between the early and 'middle' Cretaceous strandlines.

2.3. *Basin configuration*

On top of continental basement the sediment thickness of the Aaiun–Tarfaya coastal basin increases in a wedgelike form from a 'hinge line' or tilt axis at its southeastern flank separating areas of uplift (Requibat Massif) from the subsiding basin. Under the central shelf at Spansah 51*a*–1 the sediment cover amounts to about 14 km.

Owing to collapse tectonics (Querol 1966) this rapid down-warping of the basement is probably effected by stepwise downfaulting, not shown in figure 2. Rona (1973) and Pitman (1978) use this well known phenomenon as model in their hypothetical treatment on the relations between seafloor spreading, eustatic sealevel changes, subsidence, and sediment accumulation. However, this conception is valid only for part of the continental margin deposits.

The outer Cape Bojador continental margin has a different basin configuration (see figure 2). For a lateral distance of about 100 km under the outer shelf and the slope, the basement depth remains more or less constant at about 12–14 km. Then it rises slowly under Site 397 (about 12 km: G. Wissmann, personal communication) towards the oceanic basement below the central and western Canary Islands (7.8 km: Dash & Boshard 1969; Grunau *et al.* 1975). We describe the sediment accumulation on this continental margin with deeply depressed basement as the filling of a very broad 'marginal basin' (Lehner & De Ruiter 1977), the 'Cape Bojador marginal basin'. This basin configuration is not only different from regularly seaward thickening sediment wedges, but also from marked trough-like depressions, described from other parts of the Atlantic continental margin (Schlee *et al.* 1976; Sheridan 1976).

A similar situation to that off Cape Bojador has been reported, e.g. from the continental margin off Angola and southern Morocco (Beck & Lehner 1974, figures 7 and 12), or from sections off eastern North America (Schlee *et al.* 1976, figures 6 and 11; Sheridan 1976).

3. Methodology

3.1. *Backtracking of stratigraphic boundaries in continental margin sites*

We define *subsidence* as the change of depth which a certain stratigraphic level undergoes during a given time owing to crustal downwarping of its basement relative to the present sea level. The accuracy of determining subsidence depends on the precision of biostratigraphic boundaries and their position in the absolute time scale, as well as on the interpretation of palaeo-water depth. Since these data are often uncertain, only general trends in subsidence can be delineated.

If the basement age of oceanic sites is known, the palaeodepth of a certain stratigraphic level can be generally inferred from the present water depth and the basement age, by using the well known empirical age–depth relation (Sclater *et al.* 1971; Berger & von Rad 1972). In this case, subsidence is mostly attributed to the contraction of the cooling lithosphere.

To determine the palaeodepth of sediments in continental margin sites, a different approach is necessary. Wells (47a–1, 43–1, 51a–1) near the present coastline and on the shelf indicate that the water depth probably never exceeded shelf (or rarely uppermost slope) depths during the past 200 Ma; hence we can directly deduce the subsidence rates during a given time (table 1) from the thickness of sediment accumulated at that time. However, for the rise and slope sites, we know that the subsidence rates during the past 100 Ma have not equalled the accumulation rates, because the water depth has increased to the present 2–3 km. On the other side, we can assume that from about 200 Ma B.P. until earliest Cretaceous times, the basin floor remained close to sea level (§4.1). For this time interval the subsidence rates can be equated with sedimentation rates. To learn more about the subsidence history since the earliest Cretaceous, we

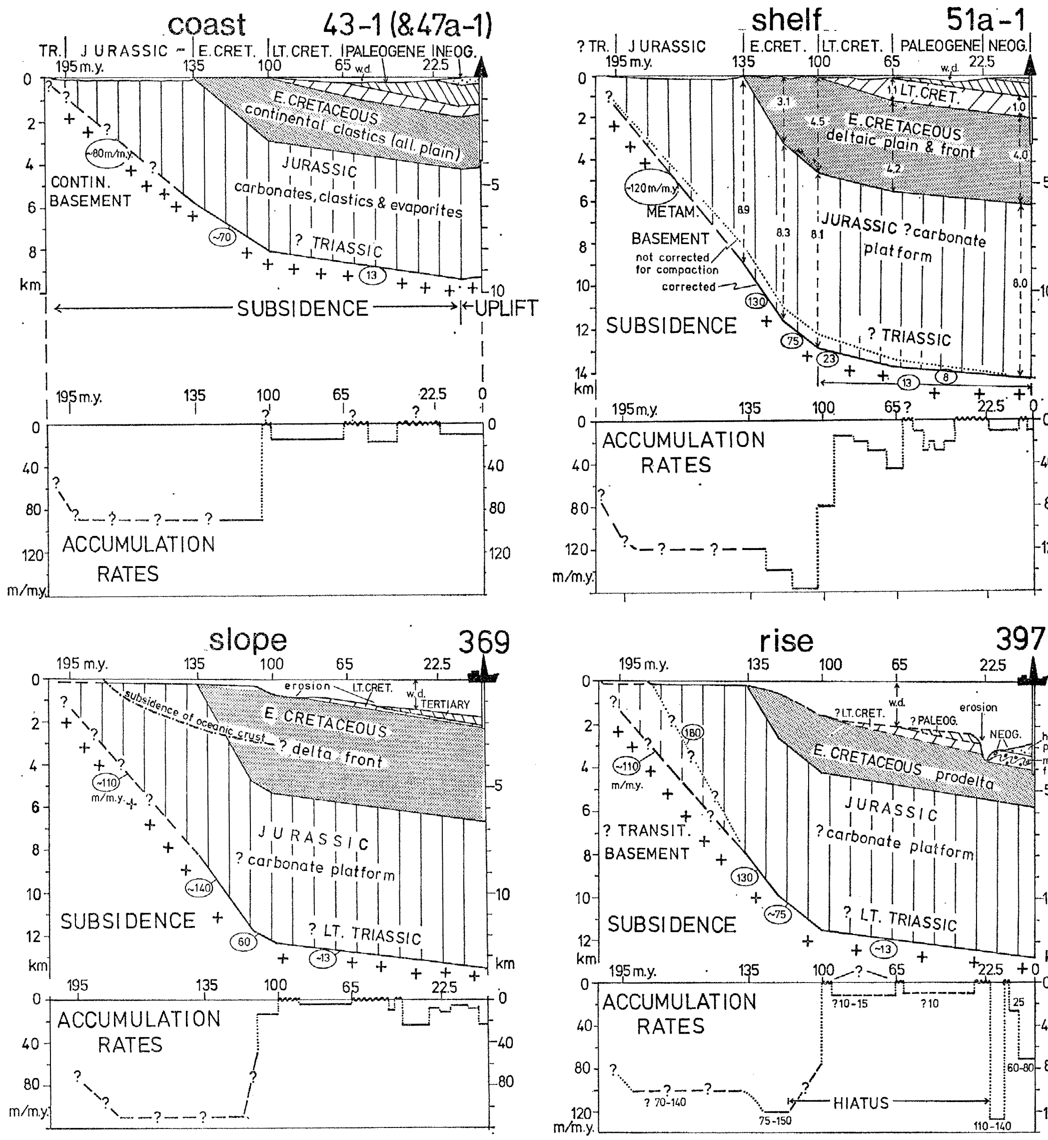

FIGURE 4. Mesozoic and Cainozoic subsidence history and changes in water depth (w.d.) as well as accumulation rates at four sites across the Cape Bojador continental margin. The right-hand margin of each subsidence diagram shows the present thickness and depth below sealevel of the different stratigraphic units (see figures 2 and 3). Rates of subsidence (in m/Ma). Unburied sediment thicknesses and subsidence rates are corrected for compaction (see §3.2). The uncorrected subsidence curve (stippled) is shown only for well 51a–1. The data between 200 and 120 Ma are highly speculative. For comparison, the empirical thermal subsidence curve of oceanic crust ('Sclater curve') is shown in one diagram.

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Table 1. Subsidence rates (m/Ma) at the Cape Bojador continental margin

If Triassic (or older) sediments overlie basement, the 'Jurassic' rates become smaller. Bold numbers signify reliable data, because sediment thickness, stratigraphic boundaries and palaeo-water depth (continental to shallow-water marine) are sufficiently well known. For numbers with normal types, the palaeo-water depth is less well known. Rates in brackets are transferred from the coast and central shelf ('back-tracking'). Values shown in italics are found by the connection of depth points inferred from sediment thickness and facies interpretation with points found by 'back-tracking' (see § 3.1).

<table>
<tr><th rowspan="2">area (site)</th><th rowspan="2">Jurassic</th><th colspan="3">early Cretaceous</th><th rowspan="2">late Cretaceous</th><th colspan="2">Tertiary</th></tr>
<tr><th>Valang.–Hauteriv.</th><th>Barrem.–lt. Aptian</th><th>lt. Aptian–Albian</th><th>Palaeogene</th><th>Neogene</th></tr>
<tr><td>present coast (47a–1, 43–1)</td><td>80</td><td colspan="3">70</td><td colspan="2">13</td><td>uplift</td></tr>
<tr><td rowspan="2">central shelf (51a–1)</td><td></td><td>130</td><td colspan="2">75</td><td>23</td><td colspan="2">8</td></tr>
<tr><td>120</td><td colspan="3">110</td><td colspan="3">13</td></tr>
<tr><td rowspan="2">slope (D.S.D.P. 369)</td><td></td><td colspan="2">140</td><td>60</td><td colspan="3"></td></tr>
<tr><td>110</td><td colspan="3">120</td><td colspan="3">(13)</td></tr>
<tr><td rowspan="2">upper rise (D.S.D.P. 397)</td><td></td><td>130</td><td colspan="2">75</td><td colspan="3"></td></tr>
<tr><td>110</td><td colspan="3">100</td><td colspan="3">(13)</td></tr>
</table>

have to apply the results from comparable shallow-water sites. For Spansah 51*a*–1 and Hassi Tartar 43–1 we calculated average subsidence rates of 13 m/Ma for the shallow-water sediments deposited during the past 100 Ma (table 1). If we 'backtrack' a certain stratigraphic level (e.g. the base of the Cretaceous) in Site 397 parallel to the Late Cretaceous to Tertiary subsidence curve of the shelf well from 0 to 100 Ma B.P. (figure 4), we get an additional depth point in our subsidence diagram (at 100 Ma B.P.). By connecting this point with that found on the basis of 'reliable' palaeodepth data at 120 Ma B.P. (late Hauterivian), the subsidence curve is completed.

Thus our 'continental margin backtracking method' is based on the assumption that the subsidence curves of comparable shelf and coast sites can be also applied to slope and rise sites. Whether this is reasonable, can be checked by comparing the subsidence curves found by this method with those of shelf and coastal sites, where palaeo-water depth never exceeded shelf conditions. In their general trend the different curves should be consistent (see figure 4).

3.2. *Correction for compaction*

To account for the decrease of thickness due to postdepositional compaction, the unburied thickness of the Meso- and Cainozoic sediments was calculated by assuming an average porosity: depth relationship from McCulloh (1967). His curve lies between the porosity curves of Dickinson (1953) and Ham (1966), both shown in Rieke & Chilingarian (1974). We also checked the results of these calculations by the average-porosity-depth-curve method of Perrier & Quiblier (1974) for predominantly shaly series. The data obtained by both methods are in good agreement. They also include the effects of chemical–mineralogical diagenesis of limestones.

In figure 4 the uncorrected subsidence curve is indicated only for well Spansah 51a–1 (stippled), whereas the other diagrams show only compaction-corrected subsidence rates. By considering compaction, the uncorrected subsidence rates of the Jurassic sediments were slightly increased, and those of the Cretaceous and Tertiary slightly decreased. In general, however, the difference between the corrected and uncorrected curves is surprisingly small.

4. Subsidence history and palaeobathymetry of the continental margin off Cape Bojador

4.1. *Relation between subsidence, sedimentation rate and palaeo-water depth*

The subsidence graphs of figure 4 contain three types of information: (1) the thickness of sediments deposited during a certain time interval (see figure 2); (2) the change of subsidence for different stratigraphic horizons (see also table 1); (3) the palaeo-water depth for a given site and time found by facies interpretation or 'backtracking' (see §3.1).

For the Jurassic, the rates of subsidence (80–120 m/Ma) are not well established. At three of the four sites the values depend entirely on the geophysical interpretation to trace the base of this sequence. If Triassic or even Late Palaeozoic sediments are included in this sequence, the rates become considerably smaller than shown in table 1 (P. Lehner, personal communication); if sedimentation (e.g. at Site 397) started not before the late Liassic onset of spreading (170–180 Ma ago), they become greater. The high Jurassic subsidence was compensated by carbonate buildup (like at the Mazagan Plateau, Renz *et al.* 1975) after a rapid initial deposition of continental clastics, red beds, and possibly some evaporites. The great thickness of Wealden-type deltaic early Cretaceous sediments, inferred from seismic data below Site 369, requires an increase of subsidence. Therefore, it is unlikely that this area deepened essentially before mid-Cretaceous times. Otherwise, an abnormal subsidence rate had to be inferred for this time interval.

A similar case is Site 397, for which we estimated a palaeo-water depth of 500–1000 m (see §2.2). Under these assumptions we get subsidence rates of 130–140 m/Ma for the Early Cretaceous (Valanginian to Hauterivian). These rates agree reasonably well with the value of the shelf site Spansah 51a–1 (table 1), for which the facies interpretation is unambiguous. Then, the subsidence rates slowed down more or less exponentially for the past 100 Ma. Only at the present coast and inland did some Neogene uplift take place.

The subsidence rates from the shelf, slope, and upper rise agree fairly well (table 1) and confirm the picture of a uniformly subsiding 'Cape Bojador marginal basin' during the past 200 Ma. Farther east, in the area of the coastal 'sediment wedge', the subsidence rates decrease considerably. During the Late Cretaceous and Tertiary, however, the subsidence rate at the present shelf and coast were about equal (*ca.* 13 m/Ma). This indicates that the uniformly subsiding 'marginal basin' expanded landward during that time. This simplified interpretation of subsidence cannot resolve small post-middle Cretaceous transgressions or regressions on the shelf including the coastal basin. They may have been controlled by superimposed eustatic sealevel changes (see Pitman 1978), or by changes in the quantity of sediment input from the continents.

If the inferred subsidence history of the Aaiun Basin is generally correct, then the deductions for the palaeo-water depth on the slope and upper rise should also be in the right order of magnitude. Since the Jurassic, the sedimentation rates under the slope and upper rise have lagged behind the subsidence rates, so that the water depth increased gradually. Especially during middle Cretaceous to Palaeogene times, the subsidence rates at the slope and upper rise exceeded the accumulation rates (figure 4). At times, e.g. during the early–late Cretaceous and Cretaceous–Tertiary boundary, subsidence was discontinuous and sedimentation alternated with erosion or stopped completely (figure 3). Therefore, the sea floor continued to deepen, especially at Site 369, where most of the sediment material bypassed the slope on its way to the rise and abyssal plain.

Probably during the middle to late Oligocene, geostrophic bottom currents cut extremely deep (1–2 km) into the lower part of the continental margin at Site 397 (Arthur *et al.* 1979) to erode all sediments down to the Hauterivian (figures 2 and 4). Aptian, Albian, Turonian, possibly Eocene, and Oligocene pebbles which were occasionally found within the overlying debris flows (figure 3) testify to the former existence of middle Cretaceous to Palaeogene strata before the erosion of a pre-early Miocene slope. The sedimentation rates of the early Miocene mass flow deposits were so rapid that the oversteepened erosional scarp was buried, and the water depth reduced.

Though it is missing under the shelf and rise, the Oligocene section is completely preserved under the slope (Site 369). Apparently geostrophic currents, responsible for the submarine erosion at Site 397, were restricted to water depths below 2000 m along the base of the slope. The synchronous erosion of Oligocene sediments on the shelf was caused by the drastic lowering of sea level (more than 200 m, Vail *et al.* 1978) during a widespread regression (Pitman 1978).

4.2. *Driving forces of the subsidence at the continental margin*

For the continental margin off southern Morocco, Beck & Lehner (1974) have pointed out that the fractured continental basement has subsided to about the same depth as the oceanic basement (about 6 km). Off Cape Bojador, the basement below the continental margin probably lies about 12–14 km below sea level (figure 2), similar to that below the Blake Plateau Basin (Sheridan 1976) and the Baltimore Canyon Trough (Schlee *et al.* 1976). According to a somewhat modified 'Sclater curve' (Veevers 1976), the unloaded oceanic crust at the continent–ocean boundary can be expected at about 6 km below sea floor, if the ocean basin is 150–180 Ma old. The fact that the continental (to transitional) basement below the 'Cape Bojador marginal basin' is about twice as deep cannot be explained unambiguously by any one of the existing theories (see, for example, Bott, this volume). It is, however, certain that, before gravity loading became active, additional 'driving forces' have to be invoked, such as thermal, stress-, and metamorphism-related mechanisms (see, for example, Watts & Ryan 1976).

Even long after the graben-like early rifting and early spreading stage of the North Atlantic, e.g. during the Early Cretaceous, flexural subsidence was still very rapid and amounted to 4 or 5 km (see figure 4 and table 1). According to the calculations by Watts & Ryan (1976) on the subsidence of the mature east coast margin of the U.S.A., about 40–55 %, i.e. 6–7.5 km, of the total basement depression off Cape Bojador (13–14 km) might be due to the loading effect of the 10–14 km thick pile of Cainozoic and Mesozoic sediments plus the weight of the water column. Thus, during the Cretaceous alone, roughly 2 km of basement subsidence appears to have been caused by other forces. Even during the last 65 Ma, when subsidence rates had decreased considerably, the basement subsided a further 0.8 km, whereas the sediment cover amounted only to 0.3 km (Site 369) or to 1.3 km (Site 397) during that period.

The poor correlation between sediment load and subsidence supports the hypothesis that, in addition to isostatic adjustment, other mechanisms strongly influenced the vertical movement on the continental margin.

5. Comparison with other continental margins of the North Atlantic

5.1. *Jurassic–early Cretaceous shallow-water deposits at the shelf edge*

The Jurassic, as well as the earliest Cretaceous, sediments at the slope and upper rise off Cape Bojador are assumed to have been deposited in a shallow-marine (to prodelta) environment. This view is supported by other evidence: off Morocco, Late Jurassic (Oxfordian) reefal and shallow-water subtidal carbonates were dredged from the base of the Mazagan Escarpment between 3500 and 4000 m water depth (Renz *et al.* 1975; Wissmann & von Rad 1980). Similar Jurassic carbonate platforms were reported from the shelf edge off Senegal (Lehner & De Ruiter 1977) and off Southern Morocco (Vail *et al.* 1978). Middle Cretaceous sapropelic shales with calcareous concretions and belemnites reflect an oxygen-depleted (possibly upper slope) environment and mollusc-phosphate rich limestone breccias, possibly from the outer shelf to upper slope, were dredged from 2800 m water depth in a canyon at the lower Cape Bojador slope (figure 1, no. 29/30: von Rad *et al.* 1979).

Late Jurassic to early Cretaceous shallow-marine platform carbonates and reefs occur also on the West Atlantic continental margin, e.g. at the Blake Plateau, in the Baltimore Canyon

Trough off New Jersey, or at the edge of the Scotian shelf and Grand Banks (Emery & Uchupi 1972; Sheridan 1976; Gradstein *et al.* 1975; Schlee *et al.* 1976). Since the middle Cretaceous, these reef barriers at the shelf edge have subsided several kilometers.

5.2. *Subsidence history*

During the late Jurassic, Cape Bojador was only about 1000 km away from Cape Cod (Le Pichon *et al.* 1977). Therefore, structural and stratigraphic data from the formerly conjugate central North American Atlantic margin – i.e. Baltimore Canyon Trough to Scotian Shelf Basin – are of particular interest for the area investigated. Gradstein *et al.* (1975) derived the subsidence history from a study of eighteen exploratory wells drilled on the Scotian shelf, the Grand Banks and the Labrador shelf. In general, the rates of subsidence during the Jurassic and/or Early Cretaceous were also very high (up to about 100 m/Ma) and decreased gradually afterwards (Late Cretaceous: less than 30 m/Ma.). However, the subsidence curves differ considerably from well to well. Better agreement of the curves could be found if wells of similar position with respect to the shelf edge are compared.

It is also interesting to note that several wells from the central and outer East Canadian shelf show increasing subsidence rates in the Aptian–Albian period, before the vertical movement slows down. Similarly, Whitten (1976) emphasized the spasmodic increase of late Aptian to early Albian subsidence at the continental shelf between Florida and New York. His view that a global process may be responsible for this phenomenon is supported by work in the coastal basins of Morocco, where Wiedmann *et al.* (1978) observed similarly accelerated Albian subsidence rates. Because of the uncertain ages of the stratigraphic boundaries and the hiatuses in the Cape Bojador sites, it is impossible to decide whether here, too, an increased rate of subsidence took place during the Aptian–Albian.

There is also a good correlation between the 'Cape Bojador marginal basin' and the contiguous Baltimore Canyon Trough off New Jersey. At the Cost B–2 well (150 m water depth) the early Cretaceous to recent facies sequence (Scholle 1977) is strikingly similar to the development of the shelf well Spansah 51a–1 off Cape Bojador. Also the subsidence history of the Cape Bojador shelf and the Baltimore Canyon Trough at and below the Cost B–2 well are comparable: the high Jurassic (and possibly Triassic) rates (130 m/Ma) decrease slightly during the deltaic to littoral early Cretaceous (100 m/Ma). Gradually, subsidence decreases to about 40 m/Ma during the Aptian and Albian and finally to 10 m/Ma during the latest Cretaceous and Paleogene.

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