42. EVOLUTION OF THE MOROCCAN OCEANIC BASIN AND ADJACENT CONTINENTAL MARGIN— A SYNTHESIS

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ABSTRACT

Although drilling in the Moroccan Basin failed to reach strata older than uppermost Jurassic, regional geology and geophysics combined with drilling results provide the basis for a reconstruction of the evolution of this basin and the adjacent margin since the Triassic. Rifting began around the Triassic/Jurassic boundary, and drifting probably started a little later, probably during the late Liassic (Domerian–Toarcian). Evaporites accumulated on the rifting margin prior to drifting, and possibly in the deepening adjacent oceanic basin during the late Liassic–earliest Dogger. Accumulation of thick turbidites in the basin characterized the Middle Jurassic–Neocomian interval, with a probable interruption during the early Late Jurassic "Atlantic" transgression at the time of widespread carbonate accumulation on all margins around the central Atlantic. The Upper Cretaceous through Cenozoic record reflects the predominant influences of oceanic circulation on sedimentation during that time. A major hiatus omits most of the Late Cretaceous, and the succeeding Cenozoic shows alternations of erosion and pelagic deposition.

INTRODUCTION

Direct access to older strata lying close to the foot of the Moroccan margin continues to elude all drilling attempts. The deepest level reached during Leg 50, at Site 416, lies at a sub-bottom depth of 1624 meters, within uppermost Jurassic strata (Figure 1).

Without direct examination of rock samples, we must infer the early evolution of the Moroccan Basin from geophysical data on the oceanic basin and from the geological record of the various sedimentary basins on the adjacent margin. This approach is valid for this area because of the detailed published results of years of geologic work in Morocco, where exploratory wells and outcrops of Mesozoic strata are abundant. For the deep basin itself, we had several good-quality multichannel seismic-reflection profiles — including parts of two commercial lines that could not be released for publication in this volume — to help complete the picture and tentatively correlate deep-water units with geological events recognized on land.

In assembling this synthesis, we have relied heavily on the record from sedimentary basins of western Morocco. We also tried to integrate data from various other basins surrounding the central Atlantic (Figure 2), and even from the North Atlantic (north of the Gibraltar–Azores and Newfoundland fracture zones). Our effort was greatly facilitated by the abundance and quality of syntheses that have been published on these various areas.

In Morocco itself, the western basins that border the Atlantic are the Essaouira Basin, and more to the east the Western High Atlas (Figure 3). Sometimes the two are grouped under the name of Southwestern Morocco Basin (Société Chérifienne des Pétroles, 1966). The westernmost part of that basin, south of Essaouira, is also called the Haha Basin (Choubert and Faure-Muret, 1962). This area was intensively studied for several years, and the results were included in a set of remarkable syntheses by Choubert and Faure-Muret (1962), the Société Chérifienne des Pétroles (1966), and later by Faure-Muret and Choubert (1971) and Ager (1974). Choubert and Faure-Muret (1962) clearly demonstrated that one cannot fully understand the record from these basins nor from the Central Atlantic itself without also considering the record from the Atlas (Middle Atlas and Central High Atlas).

For areas south of Morocco, we use for comparison the record from the Aaiun-Tarfaya Basin (Querol, 1966; Martinis and Visintin, 1966; Arthur et al., 1979; von Rad and Arthur, 1979) and from the Senegal Basin (Castelain, 1965).

Naturally, the record from the opposite side of the Atlantic, especially for the Jurassic and Early Cretaceous, is especially relevant, and several comparisons between the American and African margins have been attempted (see, for example, Bhat et al., 1975; Rona, 1970). The Canadian margin, off Nova Scotia and beneath the Grand Banks, has been studied in detail through numerous commercial wells, which have pro-

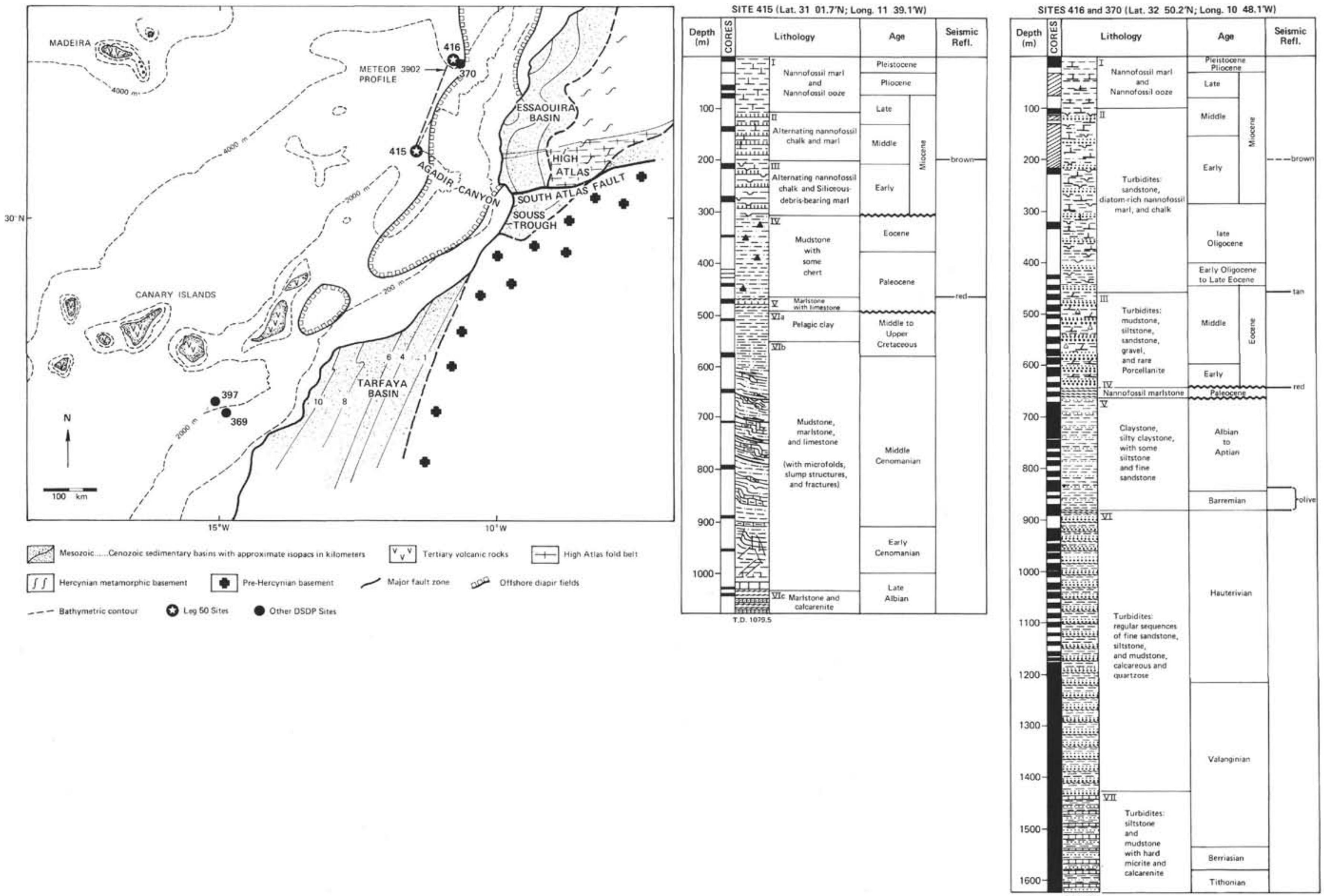

Figure 1. *Location of Sites 415 and 416 and stratigraphic summary.*

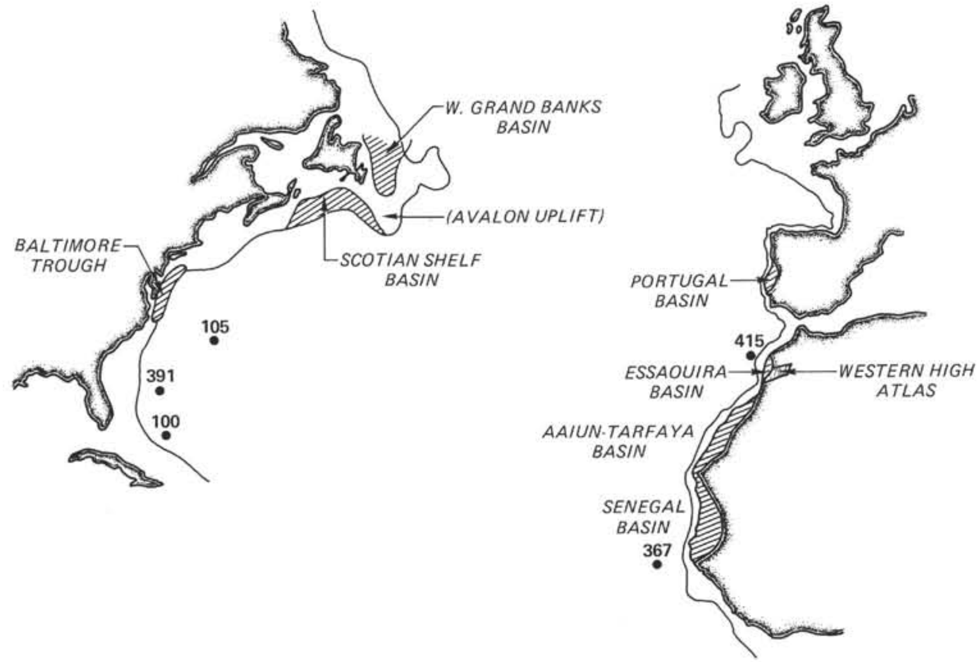

Figure 2. *Index map showing locations of various sedimentary basins of the Atlantic margin, cited in the text, and locations of DSDP sites that have reached Jurassic sediments in deep oceanic basins.*

vided the basis for excellent syntheses (McIver, 1972; Jansa and Wade, 1975).

Finally, in the North Atlantic, the Jurassic sequence in the Portugal Basin provides interesting additional data on the early history of the Central Atlantic (Faugères and Mouterde, 1979; Mouterde and Ruget, 1975).

REGIONAL SETTING OF SITES 415 AND 416

The two sites drilled in the Moroccan Basin during DSDP Leg 50 are close to the base of the continental slope and about 20 to 30 km seaward of the edge of a field of diapiric structures (presumably evaporites) that extends from the shelf down to the slope and deep basin areas (Figure 1). Both sites are well within the Jurassic magnetic quiet zone, about 300 km landward from the boundary.

The location of the boundary between oceanic and continental crust in that area remains unknown, and none of the data presently available uniquely solve the problem. Seismic profiles running eastward from the area of the quiet-zone boundary, where the crust is surely oceanic, do not show any change in the character of the acoustic basement, all the way to the area of Sites 415 and 416, and even beyond, until it disappears to the west beneath the diapiric evaporite field. The depth of the acoustic basement, computed from stacking velocity information based on multifold seismic profiles with correction for isostatic load, is approximately 5860 meters, a value quite comparable to the theoretical depth of 5320 meters computed from the classical cooling subsidence curves for oceanic crust. Both these observations suggest that the area is indeed underlain by oceanic crust, and that the acoustic basement represents the top of the basaltic layer 2. Since we really have no clear idea of what one ought to see in seismic profiles at the transition between oceanic and continental crust along passive margins, the possibility remains that such a transition would remain undetected on these profiles. Both the depth and the acoustic character of the basement might not exhibit major differences on either side of the boundary, or of any sort of transition zone. The boundary sometimes has been placed at the seaward edge of the diapir field that characterizes the continental slope area, east of Sites 415 and 416. To the north, however, the diapiric structures clearly extend into the deeper parts of the basin, all the way to the Seine Abyssal Plain (Beck and Lehner, 1974; Renz et al., 1975; Uchupi et al., 1977). On the basis of information presently available, there is no reason not to believe that some of the diapiric structures overlie oceanic crust.

If one accepts the hypothesis that the crust in the area of Sites 415 and 416 is indeed oceanic, then its age still remains difficult to estimate directly. As will be discussed below, the geological record from the various basins surrounding the North and Central Atlantic suggests that oceanic crust appeared in the basin for the first time around 180 m.y. ago. An age estimate of about 170 to 175 m.y. for the basement beneath Sites 415 and 416 would be compatible with a spreading rate of slightly less than 2 cm/yr for the period between the early Liassic and the beginning of the Oxfordian.

The acoustic stratigraphy in the basin has been determined from multichannel seismic profiles from Geophysical Services International (lines AIP-AIQ-AIR, not released for publication), a Phillips line in the vicinity of Site 415 (see site chapter in this volume), and the

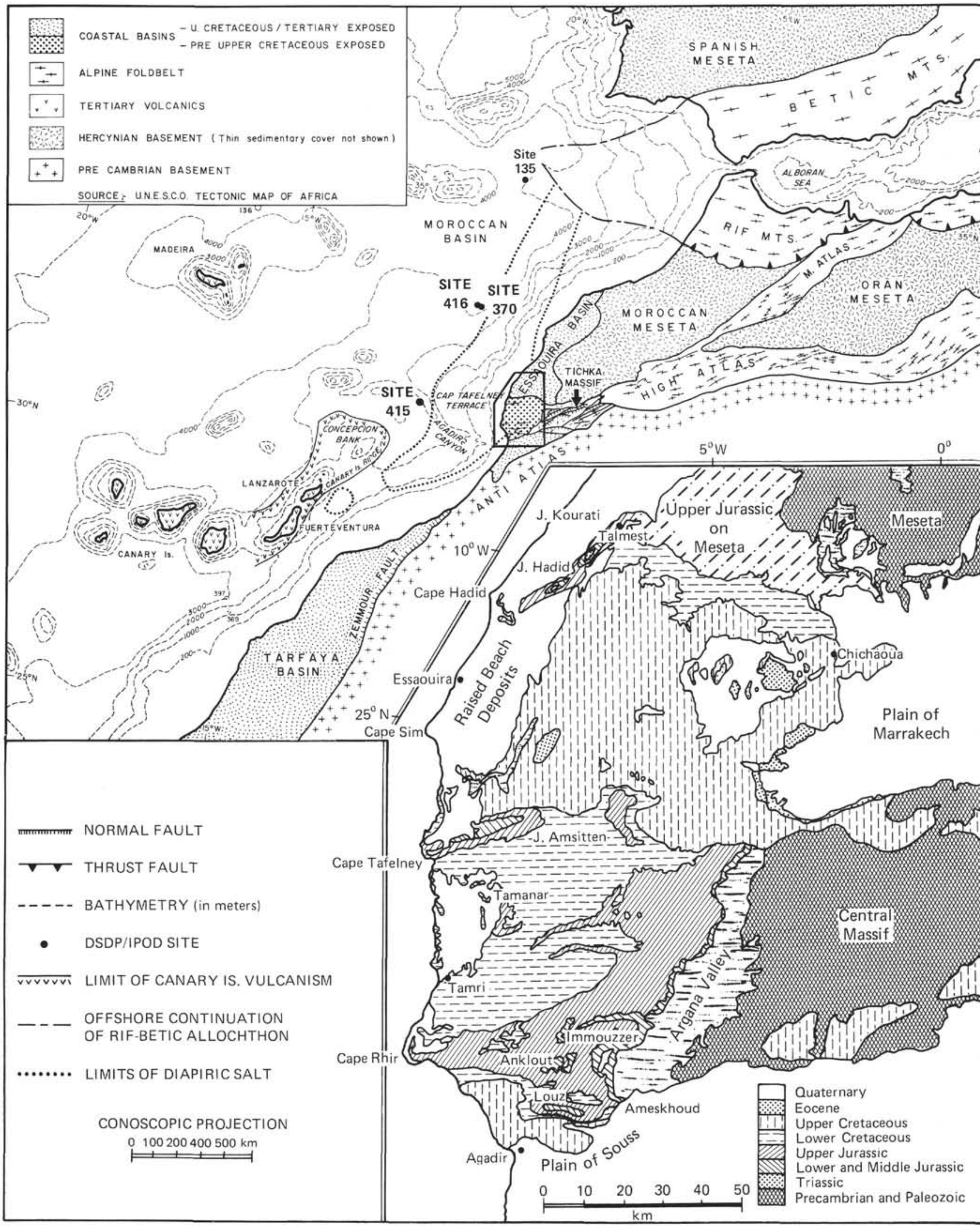

Figure 3. *Sedimentary basins of western Morocco (after Price, this volume; and Ager, 1974).*

Meteor 3902 profile (see Winterer et al., this volume). Of these profiles, the *Meteor* line, provided by K. Hinz of the Bundesanstalt für Geowissenschaften und Rohstoffe, is particularly useful to us, because it joins both drill sites (Figures 1 and 4). A detailed correlation between this acoustic stratigraphy and the drilling and logging results from Leg 50 appears in the two site chapters in this volume, and the regional significance of the main reflectors will be discussed below. Geophysical data, drilling results, and the geological record from land provide the basis for our interpretation of the evolution of the basin and adjacent margin.

THE EVOLUTION OF THE MOROCCAN BASIN AND MARGIN

The evolution of the Moroccan Basin and adjacent margin during the Triassic and Jurassic is schematically depicted on Figure 5, and correlations among various basins for that period appear on Figure 6.

Triassic Rifting (Phase I on Figure 5)

Pre-drift reconstructions of the central North Atlantic (e.g., Bullard et al., 1965; Le Pichon and Fox, 1971; Le Pichon et al., 1977; Klitgord and Schouten, 1977), although they differ slightly in details, commonly show the juxtaposition of Morocco and Nova Scotia and the striking parallelism of the Hercynian structures on both sides of what is now the Atlantic Ocean. Mesozoic rifting occurred essentially along a northeasterly trend roughly parallel to both the American Alleghenian-Acadian and the African Variscan orogens. Fracture zones apparently played a major role during the early history of the Atlantic rift, but their history for this period is still very poorly known.

The first fault grabens began forming along the Alleghenian-Acadian orogen, and later grabens formed to the east, at the site of the future Atlantic rift and on the adjacent African margin (van Houten, 1977). The eastward shift in the location of the main rift would account for the deposition of predominantly continental and lacustrine detrital sediment in North American grabens during the Late Triassic through the early late Liassic, while evaporites and red beds characterize the outer Canadian margin and North Africa. The similarity between the Canadian Euridyce Formation (Jansa and Wade, 1975) and correlative facies from Western Morocco (Société Chérifienne des Pétroles, 1966) is striking.

In Morocco, the Triassic history can be subdivided into two successive periods (Choubert and Faure-Muret, 1962). First, grabens were formed and filled with red detrital deposits while some relief resulting from the Hercynian tectonic phase still survived. Then, after erosion had reduced relief, clay sedimentation, commonly in lagoonal regimes, became predominant. It was during the second phase, during the latest Triassic and earliest Liassic, that basalt flows and dolerite sills were emplaced over wide areas. Most of the basaltic volcanic activity associated with the formation of the rift occurred more than 20 m.y. after the beginning of the earliest basin-filling phase.

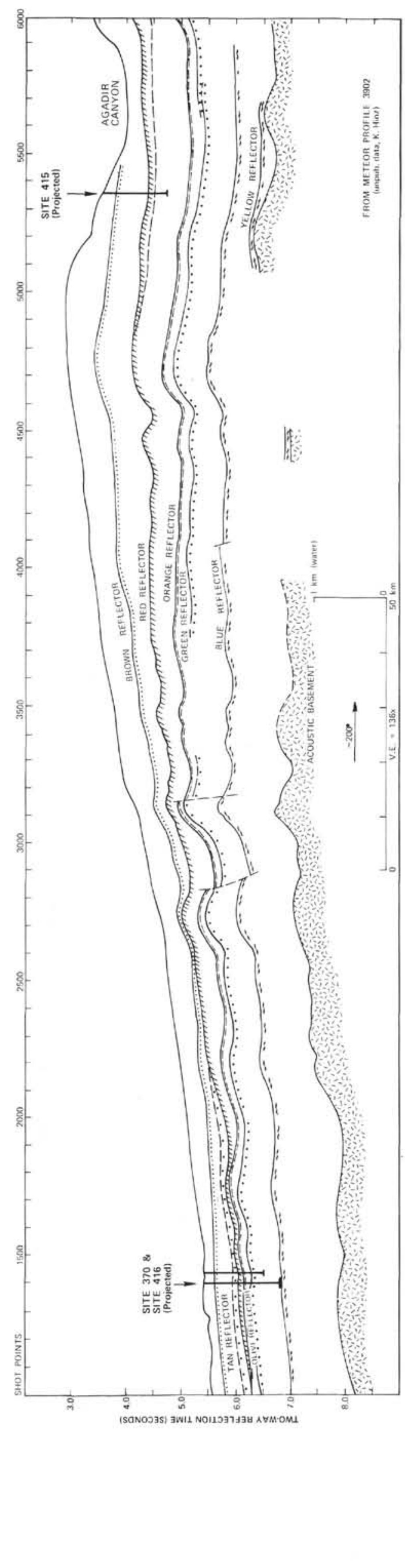

Figure 4. *Line-drawing interpretation of* Meteor *3902 multichannel seismic profile between Sites 415 and 416 (see original profile in chapter on underway geophysics in this volume). Location of profile appears on Figure 1.*

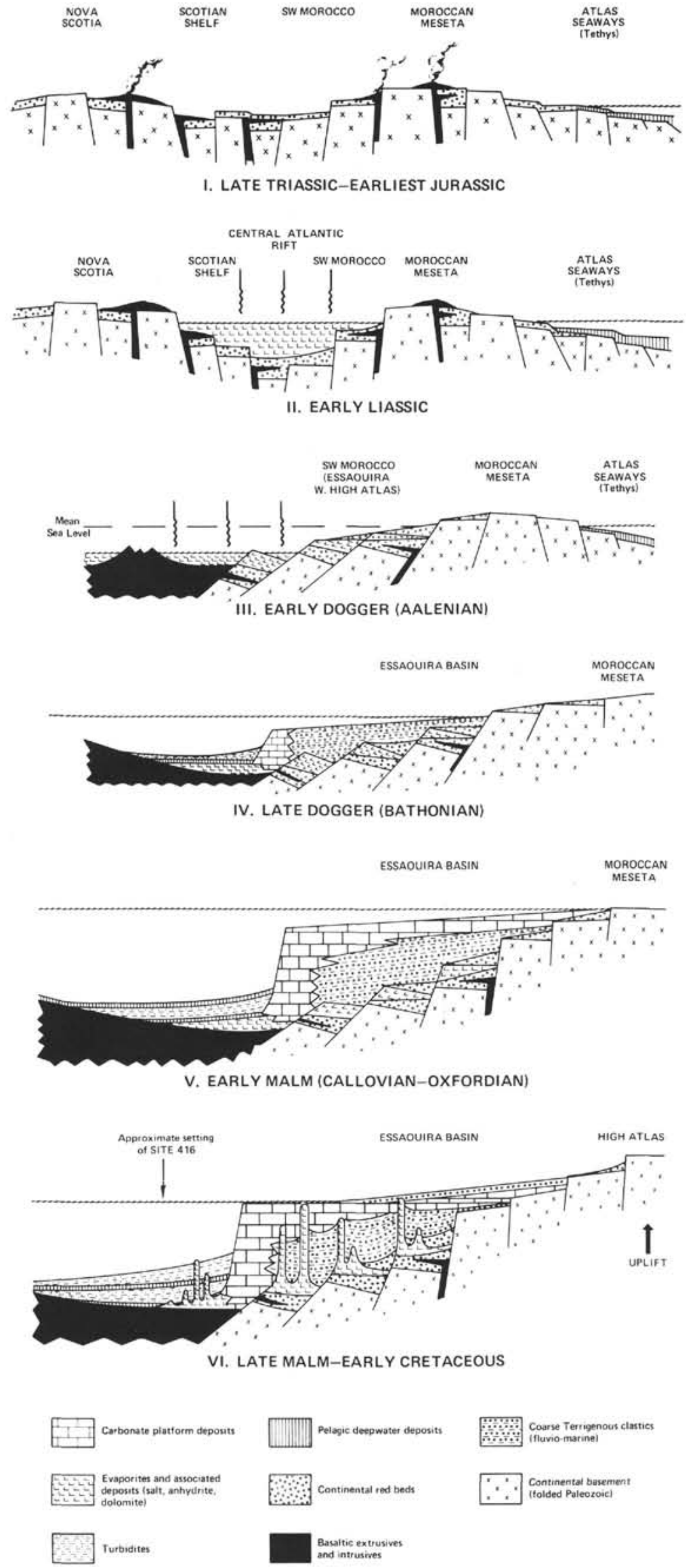

Figure 5. *Schematic interpretation of the evolution of the continental margin off Morocco during the Triassic and Jurassic.*

MAJOR PHASES	SCOTIAN SHELF	WEST GRAND BANKS BASIN	CENTRAL ATLANTIC	PORTUGAL BASIN	S. W. MOROCCO BASINS (ESSAOUIRA-W. HIGH ATLAS)	AAIUN-TARFAYA BASINS
LATE MALM (late Kimmeridgian–Tithonian)	MISSISAUGA FM. TERRIGENOUS CLASTICS	TECTONICS (AVALON UPLIFT)	COMPOSITE (CALC. AND TERR.) FLYSCH	TECTONICS (GRAND BANKS–IBERIA RIFT)	EO-CRETACEOUS ? TECTONICS (REGRESSION)	TAN TAN SANDS
EARLY–MIDDLE MALM (Callovian–Oxfordian–early Kimmeridgian)	MIC-MAC FM. (Neritic) / ABENAKI FM. (Carbonate platforms) / SHALES / VERRILL CANYON FM. (Deep water)	?	DEEP SEA ?–PELAGIC SEDIMENTS (Shale, siliceous or calcareous ooze)	?	HADID LIMESTONE; ANKLOUT LIMESTONE AND MARL	OPEN MARINE CARBONATES
LATE DOGGER (Bathonian)	MOHAWK FM: TERRIGENOUS COARSE CLASTICS	?	?–FLYSCH	?	(REGRESSION)	↑ DOLOMITES; LIMESTONES AND SANDSTONES ↓ ? ↑ alteration of NERITIC EVAPORITIC LAGOONAL AND CONTINENTAL Facies
MIDDLE DOGGER (Bajocian)		?	?–EVAPORITES AND PELAGIC OOZES	?	AMSITENE DOLOMITE ↑	
EARLY DOGGER (Aalenian)	REGRESSION (?Tectonics)	?	?–EVAPORITES	? (?–TECTONICS)	AMESKHOUD RED BEDS	
LATE LIASSIC (Domerian–Toarcian)	IROQUOIS FM: DOLOMITES ↑ EVAPORITES	WHALE UNIT: SHALES AND LIMESTONES (often bituminous with pyritized ammonites)	BASALT (OCEANIC CRUST)	SHALES AND LIMESTONES (often bituminous, w. pyritized ammonites) mixed subboreal and Tethys faunas	ANKLOUT DOLOMITE	
EARLY LIASSIC		MURRE FM: transgressive) LIMESTONES ↑ DOLOMITES ↑ EVAPORITES	(hatched)	(transgressive) LIMESTONES (w. subboreal ammonites and brachio.) ↑ DOLOMITES ↑ EVAPORITES	AMSITENE REEF LIMESTONES with Subboreal faunas	
EARLIEST LIASSIC – LATE TRIASSIC	CONTINENTAL RED BEDS (Graben filling) AND BASALTS (EXTRUSIVES AND INTRUSIVES)	? ?-EVAPORITES	(hatched)	? (?–EVAPORITES)	CONTINENTAL RED BEDS BASALTS (EXTR. AND INTR.) EVAPORITES	? (?–CONTINETAL RED BEDS)
EARLY TRIASSIC	CONTINENTAL RED BEDS (Graben filling)	?	(hatched)	CONTINENTAL RED BEDS (Graben filling)	CONTINENTAL RED BEDS (Graben filling)	?

Figure 6. *Correlation of Triassic and Jurassic sedimentary units among various basins surrounding the Central Atlantic and southern North Atlantic.*

The Triassic graben trends do not prefigure the evolution that is observed during the rest of the Mesozoic. In fact, the pattern of these Early Triassic grabens suggests that they may record the last chapter of Hercynian tectonics. However, during Liassic times facies patterns generally ignore these early trends (Choubert and Faure-Muret, 1962), except perhaps in certain offshore areas where downfaulting purportedly follows Hercynian lineaments (Robb, 1971). Probably toward the end of the Triassic, deposition of marine evaporites (commonly intercalated with basaltic rocks) began, thus marking the first marine influences in the incipient rift system. The beginning of this phase correlates with the eastward shift in the location of the main Atlantic rift.

The development of evaporite facies mainly on the eastern side of the rift might result from the proximity of the Tethys. Little is known about the early evolution of transform faults and fracture zones connecting the Tethys with the shallow Late Triassic Atlantic basins. There is little doubt, however, that hypersaline waters concentrated in these basins came from occasional spilling of Tethyan waters over sills located between the Moroccan Meseta to the south and the Outer Grand Banks–Iberian block to the north (Figure 7). On the other hand, the earliest evolution of the Grand Banks

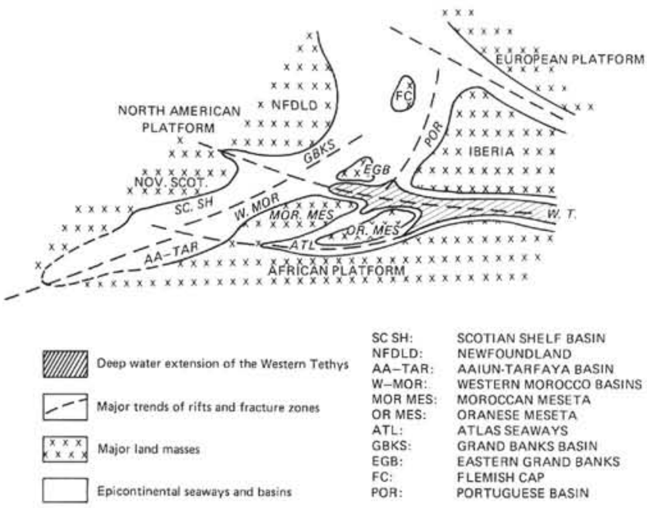

Figure 7. *Tentative schematic reconstruction of the distribution of seaways, rifts, and land masses around the northern Central Atlantic before the Domerian–Toarcian (after Lancelot, in press).*

and Portugal Basins apparently precludes an open direct connection between the Tethys and these basins during the Late Triassic.

Several interpretations have been proposed to account for the tectonic evolution of the fracture zones that have supposedly connected the Tethys and the early Atlantic rift. If the separation between Iberia and the Moroccan Meseta can be easily inferred from sediment data, these data still do not support any open connection between the Late Triassic–earliest Jurassic rift and the Tethys. Therefore, the Gibraltar and Atlas fault zones apparently had mainly strike-slip motion (Mattauer et al., 1972; Evans et al., 1974; Michard et al., 1975) and were not the sites of spreading and subduction as proposed by Dewey et al. (1973).

The southern limit of marine incursions from the Tethys appears to lie around the Southern Atlas–New England Seamount fracture zone, and evaporites, if present beneath the margins South of the Atlas zone, are much less extensive than in the northern part of the Atlantic rift. In these southern areas, Triassic sediments generally consist of continental to fluviatile deposits intercalated with basaltic–doleritic intrusions.

Early Liassic (pre-Domerian) Transgression (Phase II on Figure 5)

The first marine transgression in the basins surrounding the Central Atlantic rift zone is apparently of Early Jurassic age. It must be noted, however, that on both margins (Essaouira–western High Atlas to the east, Scotian shelf to the west), these earliest marine deposits are very poorly dated. It is therefore useful to look into the record of other nearby basins to try to understand the paleogeography of Atlantic flooding.

The most striking observation is that the marine incursion into the Atlantic rift zone did not come from the east: on the contrary, ample evidence shows that flooding was from the north (Choubert and Faure-Muret, 1962; Ambroggi, 1963; Faure-Muret and Choubert, 1971; Ager, 1974). The lateral succession of Liassic facies along the central High Atlas, from the east to the west, shows a transition from marine to intertidal and finally to continental deposits (Ager, 1974), thus precluding any gateway here for Tethyan waters to spill into the Atlantic. Although the evidence for marine lower Liassic rocks in the Essaouira and Scotian shelf basins is not well documented, well-dated marine Sinemurian–Domerian rocks occur in the Lusitanian Basin of Portugal, and can be contrasted with correlative marine beds in the Rif, Central High Atlas, and Middle Atlas. There is a striking difference between faunas from the carbonate layers of these basins: in Portugal, ammonites and brachipods are clearly subboreal (Mouterde and Ruget, 1975), whereas in the Rif and in the Central High Atlas and Middle Atlas they are definitely Tethyan (Choubert and Faure-Muret, 1962; Faugères and Mouterde, 1979). Thus, while the Atlas seaways were westward extensions of Tethys, the Lusitanian Basin to the north was separated from Tethys at least by a shallow sill, and probably by land joining the southwestern portion of the Iberian Meseta with the outer (eastern) part of the Grand Banks. West of the Grand Banks margin, lower Liassic deposits (Murre Formation), which are over 1300 meters thick in some places (Jansa and Wade, 1975), indicate a transgression. Because these layers are known only from subsurface data, and no ammonites have been recovered to compare with those of Portugal, a connection between the two basins is not documented. Both basins do show comparable transgressive sections, starting with dolomite and evaporite at the base and grading upward into limestone, but the succession of facies in the Rif and Atlas areas is also similar to this.

The Iroquois formation from the Scotian shelf consists of evaporites and dolomites and is considered to be of Hettangian–Pliensbachian age (McIver, 1972; Jansa and Wade, 1975). This marine incursion cannot yet be attributed directly to either of the two plausible sources (northern seas or Tethys), but the lithologic similarity of the Iroquois Formation and the lower-Liassic rocks of the Essaouira Basin area of Morocco (''Amsitène reef'' formation) is worth mentioning. In Morocco, Ager (1974) notes that the faunas (and those from younger strata in the eastern parts of the Essaouira Basin) show affinities with those from Portugal. The available evidence thus points toward a limited extension of the Tethys facies during the early Liassic toward the west, but only as far as the Atlas and the Rif. The evidence suggests that the first marine transgression in the Atlantic rift came from the north and not from the east, and that no good connection existed between the Tethys and the Atlantic prior to the Domerian. This implies the presence of barriers connecting the eastern Grand Banks area with both southwestern Iberia and the northwestern tip of the Moroccan Meseta. During all this time, evaporites may have continued to accumulate in the central grabens of the rift, as suggested by their wide extension seaward from both the American and African margins.

Transition From Rift to Drift: Domerian–Toarcian (middle late Liassic)

It is difficult to determine precisely the date of the first appearance of oceanic crust in the central Atlantic on the basis of geophysical data. The age of the oceanic crust adjacent to both the Moroccan and the Canadian margins cannot be estimated from magnetic data because of the absence of magnetic reversals during the Early and Middle Jurassic. In fact, even the location of the boundary between oceanic and continental crust remains uncertain at this time. Because no direct evidence has yet come from drilling in the deep basins, we can try to estimate the date of the onset of continental drift and associated generation of oceanic crust by indirect means, through the inferred evolution of the basins along the margins of the nascent Atlantic Ocean.

With the Domerian appears the first mixing of subboreal and Tethyan faunas both in the Rif and in the Portugal Basin (Faugères and Mouterde, 1979; Mouterde and Ruget, 1975). This indicates that for the first time Tethys waters invaded the Atlantic rift, probably flowing across the now-subsided sill joining the eastern edge of the Grand Banks and the southwest part of the Iberian Meseta. Although little is known about faunas from the Grand Banks Basin, they are much like those in the Portugal Basin. In Portugal, Domerian strata consist of limestone and shale, commonly bituminous and rich in pyritized ammonites (Mouterde and Ruget, 1975). On the Grand Banks, correlative deposits constitute most of the lithologically similar Whale Unit (Jansa and Wade, 1975), although the base might be slightly older than Domerian. The general uniformity of paleoenvironmental conditions in the Atlantic rift can be followed to the south into the Essaouira–Western High Atlas Basin, where Ager (1974) comments on the similarity of the brachiopods of probable Toarcian age near the top of the Anklout dolomites (Société Chérifienne des Pétroles, 1966; Ambroggi, 1963) to those described from the Toarcian of Portugal by Choffat (1947).

The Toarcian is characterized by a continuation of the same environmental conditions in the Grand Banks Basin, the Portugal Basin and the Rif area, but a major change is observed at this time on both the western and eastern flanks of the Moroccan Meseta, and possibly also in the Scotian shelf region. The Toarcian is marked in the Moroccan Meseta area by a major regression ascribed to a tectonic origin (Choubert and Faure-Muret, 1962). In the Atlas basins and in the Essaouira Basin, the Ameskhoud red sandstones overlie the Domerian–Toarcian Anklout dolomites. The distribution of detrital facies around the Meseta suggests a period of tectonic instability that contrasts with the preceding steady transgression in relatively calm tectonic environments.

The combined evidence for tectonic activity producing uplift and erosion and the general deepening or widening of various sills and straights allowing faunal exchanges between basins suggests that this period (about 180 m.y. ago) likely witnessed the beginning of the stage of continental drifting, accompanied by the formation of the first oceanic crust in the Atlantic Basin. Therefore, geological evidence shows good agreement with previous interpretations of geophysical data suggesting that drifting between Africa and North America began around that very time (Klitgord and Schouten, 1977). This event would also coincide with the major foundering of middle Liassic carbonate platforms and their replacement by deeper-water pelagic environments over much of the western part of the Mediterranean Tethys, which is dated as Domerian to Toarcian in a number of places (Bernoulli and Jenkyns, 1974). The Ligurian ocean basin also began to open about that time (Winterer and Bosellini, in press), suggesting a linkage, possibly via a transform fault through the Betic region of southern Spain, between the new Mid-Atlantic Ridge and nascent western Tethys oceanic basins.

A final remark about the nature of Liassic rocks in the basins bordering the Atlantic to the south: in Spanish Sahara (Aaiun–Tarfaya Basin), Liassic rocks do not crop out, but they are known from oil-company drilling to consist of an alternation of continental, lagoonal, or evaporitic layers with neritic facies (Querol, 1966; Martinis and Visintin, 1966). They are apparently comparable to the correlative facies in western Morocco, although no detailed stratigraphic information is available.

Latest Liassic and Early Dogger Regression and Possible Desiccation (Phase III on Figure 5)

In the Scotian shelf basin, no Aalenian strata are recorded, and the sharp transition between the Iroquois Formation, which reaches up to the Toarcian, and the overlying coarsely detrital Mohawk Formation (Jansa and Wade, 1975) might reflect tectonic activity along the western side of the Atlantic Rift like that on the east side, in Morocco. On the other hand, on that western flank of the Atlantic detrital sedimentation lasted until the beginning of the Late Jurassic, while by contrast the most likely correlative strata in the Essaouira Basin are undated dolomites (Amsitène dolomites). It is possible that during the Aalenian a combination of deepening of the Atlantic Rift Basin and limited marine incursions could have allowed the precipitation of evaporites near the edge of the Essaouira Basin.

If our inference of the beginning of drifting near the end of the Liassic is correct, a corollary is that at least some of the evaporites that are observed in the deep sedimentary basins off Morocco and Nova Scotia (Beck and Lehner, 1974; Jansa and Wade, 1975; Renz et al., 1975; Sherwin, 1972), and that extend well offshore in both areas, lie over Middle Jurassic oceanic crust.

It must be stressed that the Middle Jurassic is a period very poorly known in northwestern Africa. No datable fossils of Bajocian or Bathonian age have been found (Ager, 1974). Although the dolomites overlying the Ameskhoud red sandstones in the Jebel Amsitène region, south of Essaouira, have been interpreted previously as Middle Jurassic (Société Chérifienne des Pétroles, 1966), the beds are unfossiliferous, and this age is inferred from their situation beneath the well-dated Callovian–Oxfordian Anklout limestone. In the

Aaiun–Tarfaya Basin, dolomite and limestone together with sandstone occur near the base of a thick series of Upper Jurassic limestones in the Puerto Cansado 1 well (Martinis and Visintin, 1966), but their approximate Dogger–Lias age is very poorly documented. In sum, the presence of Dogger strata anywhere in the basins bordering northwest Africa remains very questionable, and if present their marine nature would be everywhere doubtful. In the Scotian shelf area, Dogger strata, if present, are part of the clastic Mohawk Formation.

In the Atlas area, although the Aalenian and Bajocian are characterized by marl and limestone, the Bathonian is marked by a major regression, which is well documented by clastics everywhere in the region. The sea disappeared from both the Meseta and the High Atlas and remained only in the northernmost areas. This regression would easily explain the absence or continental nature of most of the Dogger in the sedimentary basins bordering the Atlantic. Therefore, if any record of that period is present in the Atlantic, it lies in the deeper parts of the continental margin and in the oceanic basin that had begun to open during the Domerian–Toarcian. Such a record is probably present, buried beneath Sites 415 and 416 off the Moroccan margin, but could not be reached during Leg 50.

The long-recognized occurrence of evaporites, not only beneath the Moroccan continental shelf and slope, but also in the deep Moroccan Basin (Beck and Lehner, 1974; Renz et al., 1975), suggests a possible solution to the problem. If indeed some of these evaporites do overlie oceanic crust, and if this superposition is not the result of seaward gravitational creep of the salt, then they might be interpreted as post-Toarcian. The absence of marine Dogger deposits on the continental margins and the continental nature of what Dogger strata may be inferred suggest a large regression, which, at least during the Aalenian, may have led to partial or total desiccation of the northern part of the still-small Atlantic Basin, in a manner first informally suggested by W. B. F. Ryan (pers. comm.).

In this interpretation, Triassic–Liassic evaporites would have been deposited on continental crust during the formation of the major grabens of the rift; next followed the late Liassic transgression, and then the Aalenian regression, causing a recurrence of the evaporites within the central part of the basin soon after the first formation of oceanic crust. In the Moroccan Basin, the seaward edge of diapiric salt lies only about 20 km shoreward of Sites 415 and 416. It is likely that the section corresponding to the interval between the basement and the "yellow" reflector on seismic profiles contains evaporites, although their thickness and proportion would not have been sufficient to induce substantial diapirism.

Incipient diapirism may be evidenced in the reflection profile records (see *Meteor* 3902 profile, at shot points 3100–3200, in Winterer et al, this volume). The exact timing of deposition of evaporites in the deep part of the basin is difficult to determine. One can argue plausibly either for a direct correlation with transgressive/regressive cycles outside this area, or for an inverse correlation. That is, the Central Atlantic may have been isolated by a general eustatic fall and refilled by a general eustatic rise of sea level, or the isolation of the Atlantic may have resulted in a eustatic rise elsewhere, and the refilling may have resulted in a corresponding fall elsewhere. Lacking age data on the Middle Jurassic in the Atlantic Basin, we cannot choose between the possibilities.

Under the first hypothesis, it would have begun in the Aalenian, when there was a general worldwide tendency for regression between the transgressive Toarcian below and the Bajocian above (Hallam, 1978). An Aalenian regression would have permitted the first isolation of the new Atlantic Ocean Basin, which was probably still only a few hundred kilometers wide (Klitgord and Schouten, 1977). Given a sufficient isolation of the basin, evaporites could precipitate near the base of the margins. Isolation might have been enhanced by continuing marginal uplift around the edges of the newly formed ocean basin (Jansa and Wade, 1975). As mentioned earlier, the regressive Toarcian on both the eastern and western flanks of the Moroccan Meseta suggests that the rapid subsidence in the Atlantic was accompanied by uplift of the Meseta.

Intermittent or slow supply of sea water to the evaporite basin was required to build up salt deposits to a thickness sufficient to generate diapirs later. Repeated marine incursions might have occurred during the Aalenian and may account, for example, for the deposition higher up on the margin of the Amsitène dolomite, intercalated between two red-bed units. Passageways were available for Tethyan sea water flowing along troughs in the transform-fault system through the Betic region of southern Spain, and over sills linking the central Atlantic with epicontinental seas of the North Atlantic. To the south, similar restricted connections between the Pacific and the nascent Gulf of Mexico might have permitted the deposition of the Louann salt in the Gulf during the Middle Jurassic. It is tempting to imagine a scheme comparable to the Messinian events, but in reverse, with Tethyan Mediterranean waters spilling westward across the Gibraltar–Betic passage to the desiccated basinal salt flats of the Central Atlantic. Indeed, the logic of the Jurassic Atlantic desiccation argument echoes the logic of the Messinian Mediterranean (Ryan, Hsü, et al., 1973). The general eustatic rise of sea level during the Bajocian (Hallam, 1978) would have continued to bring waters to the desiccated Central Atlantic and ultimately would have completely flooded the basin, thus ending the deposition of evaporites.

Our interpretation of course remains hypothetical until the time of cessation of precipitation of evaporites has been successfully documented, both on the continent and in the Moroccan Basin. We want to point out, however, that if salt has indeed been deposited both on continental and adjacent oceanic crust, the very nature of tectonics associated with the initiation of sea-floor spreading suggests that deposition of evaporites is not necessarily entirely synchronous across the continent/ocean boundary region. Oscillations of sea level, together with creation of isolated depressions at the time of foundering of the edge of the continent, would allow deposition of evaporites on oceanic crust immediately after continental drift had begun, while the correlative record at the edge of the marine basins, on continental crust, would consist of an alternation of dolomites, deposited when the basin was flooded, and red beds, deposited when the basin partially desiccated.

An alternate explanation is to consider that the evaporites on oceanic crust are not younger than those on continental crust, and that they all were deposited at the time of the first marine incursions into the young Atlantic during the early Liassic. Under this alternative, the Sinemurian–Bajocian record from the Essaouira Basin would reflect only partial isolation of the young Atlantic Ocean from the Tethys, but without precipitation of evaporites. An implication of this latter model is that, if the area of Site 416 is indeed underlain by oceanic crust, then the age of this crust is approximately Sinemurian (whereas it is inferred to be late Liassic under the first interpretation), and that the onset of drifting would have been as early as the Hettangian–early Sinemurian (about 190 m.y. ago), that is, almost contemporaneous with the first basaltic intrusions and extrusions on both margins of the Atlantic.

The succeeding Bathonian regression could have led to renewed or continued deposition of evaporites in the deeper part of the basin, but the Bathonian probably was characterized by deposition of massive clastics (flysch type), as suggested by seismic profiles from the Moroccan Basin in the area of Sites 415 and 416. First, a thick interval of remarkably parallel and well-stratified reflectors overlies the "yellow" reflector, which itself corresponds to a strong angular unconformity. The acoustic character of this interval, between the "yellow" and the "blue" reflectors, is very comparable to that of the overlying interval (above "blue"), in which a massive flysch section was actually sampled at Site 416. The lack of "ponding," characteristic of deep sea turbidites, can easily be explained by incipient salt diapirism and by Tertiary tectonics that uplifted the area south of Site 416.

Thus, if indeed evaporite deposition ceased during the Bajocian when waters of Tethyan origin flooded the basin, a new cycle of sedimentation started during the Bajocian. During the transgressive Bajocian, there may have been a relatively short period of pelagic sediment deposition in an interval corresponding to layers at or just above the "yellow" reflector on seismic profiles. Then, immediately afterward, during most or all of the Bathonian, a thick wedge of terrigenous turbidites would have rapidly accumulated at the base of the margin (Phase IV on Figure 5). The effects of the general worldwide eustatic fall of sea level during the Bathonian were accentuated in the Moroccan region by the continued emergence and gentle folding of the Meseta and parts of the Western High Atlas (Faure-Muret and Choubert, 1971). Indeed, the sea abandoned most of that marginal high until some time in the mid-Cretaceous. It could therefore have acted as a persistent source for most of the terrigenous clastics of the turbidites in the deep Moroccan Basin.

The "Atlantic" Transgression: Late Jurassic (Phase V on Figure 5)

The widespread Callovian–Oxfordian transgression is the most striking general event on all the margins surrounding the young Atlantic Ocean. It represents the decisive major invasion of the basin by Tethys waters and thus marks the "maturation" of the Atlantic into a real ocean for the first time of its history. This event can be recognized from Morocco to the Senegal Basin on the African margin, and from the Grand Banks to the Gulf Coast on the American margin.

In Morocco, the transgression is particularly well recorded in the Essaouira Basin and Western High Atlas "central high" by the Anklout limestone and marl, followed upward by the Hadid limestone (Société Chérifienne des Pétroles, 1966). These strata crop out in the Jebel Amsitène area and all along the southern part of the Western High Atlas Basin from the coast, near Cape Rhir, through the Anklout and Imouzzer regions, to the western flank of the Argana Basin (Ager, 1974). They are also recorded to the north, on the Meseta itself, west-northwest of Marrakesh. In several places, as near Cape Rhir, abrupt transgression is attested by the occurrence of thick-shelled faunas representative of a high-energy marine environment, immediately above non-marine strata (Ager, 1974; Ryan, pers. comm.). The sea was clearly transgressing from the west (Ambroggi, 1963; Ager, 1974). The building of algal and coral reefs marks the peak of the transgressive phase during the Oxfordian and early Kimmeridgian. These reefs are responsible for the morphology of the steep continental slope off Mazagan, where ammonite-rich peri-reef Oxfordian limestone crops out at a present-day depth of around 3000 meters (Renz et al., 1975). Therefore, the reefs likely mark the position of the edge of the subsiding continental margin during this time.

In the Aaiun–Tarfaya Basin, the transgression is recorded (in subsurface data only) by the occurrence of good open-water marine facies (Querol, 1966). The maximum transgression occurs in the *Pseudocylammina jaccardi* zone (Oxfordian–early Kimmeridgian), whereas toward the south and the east overlying Tithonian sediments show an interfingering of neritic and littoral facies that are the first indication of the widespread uppermost Jurassic–early Cretaceous regression. Thicknesses of 1 to over 2 km of Middle to Upper Jurassic shallow-water limestone, marlstone, and dolomite are reported in the basin by Einsele and von Rad (1979), who postulate a thick sequence of shallow-water carbonates extending from the Aaiun–Tarfaya Basin north to at least the Mazagan Escarpment, where the edge of the Jurassic carbonate platform is clearly visible (Renz et al., 1975). The thickness of the calcareous layers implies a rate of subsidence of about 110 m/m.y. (Arthur et al., 1979).

Farther south, in the Senegal Basin, the Upper Jurassic is represented by a thick sequence (at least 760 m) of pure carbonates, devoid of any sandstone or siltstone (N'Diass 1 well; Castelain, 1965).

On the other side of the ocean, the Late Jurassic was also characterized by a major transgression, documented (in subsurface) from Nova Scotia to the Gulf Coast. Beneath the Scotian shelf (Jansa and Wade, 1975), this interval consists of (1) the shale and sandstone with intercalated limestone of the Mic Mac Formation, which represents a near-shore facies; (2) the predominantly carbonate Abenaki Formation (shallow-water carbonate bank); and (3) a deep-water equivalent, the shaly Verrill Canyon Formation (McIver, 1972). The total thickness of these sediments approaches 2000 meters.

Farther south, in the Baltimore trough area, lower Upper Jurassic carbonates are inferred from seismic data but were not reached in the COST B2 well (Scholle, 1977); still farther south, if the oldest reef carbonates sampled from the Blake Escarpment by dredging and drilling are of Early Cretaceous age (Heezen and Sheridan, 1966; Benson, Sheridan, et al., 1978), there is good evidence for a thick Jurassic carbonate platform beneath the Blake Plateau (Dillon et al., 1979; Folger et al., 1979).

In the Gulf Coast region, the Late Jurassic transgression is recorded by the limestone of the Smackover Formation, which generally overlies red beds of the Middle Jurassic Eagle Mills Formation. Finally, comparable facies of Late Jurassic age are found in Cuba (Viñales limestones; Khudoley and Meyerhoff, 1971).

The deep-water equivalents of these formations in the deep basins of the Central Atlantic are only partly documented. The base of the upper Jurassic has probably not been sampled in any of the Deep Sea Drilling Project sites. The oldest sediments ever recovered from the deep basins come from Sites 100 and 105, on the American side (Hollister, Ewing, et al., 1972), and from Site 367 (Lancelot, Seibold, et al., 1978), on the African side. In each place, the strata are Oxfordian and consist of pelagic, more or less argillaceous, reddish limestone, commonly with aptychi and rare ammonite phragmocones, comparable to the "Ammonitico Rosso" facies of the Mediterranean Alpine fold belts. At these drill sites, the limestones rests directly on oceanic crust. Oxfordian reddish limestones were also sampled at Site 391, in the Blake Basin (Benson, Sheridan, et al., 1978), but were located more than 200 meters above the basement believed to be oceanic.

In the Moroccan Basin, at Site 416, because the oldest sediments reached by the drill are only uppermost Jurassic, we have no direct evidence of the exact nature of the Upper Jurassic layers correlative with the transgressive open-water marine deposits observed on the margins. However, it is likely that a result of the generalized transgression would have been to interrupt or slow the accumulation of the voluminous terrigenous clastics, so that during Callovian, Oxfordian, and early Kimmeridgian times more-pelagic facies were deposited in the Basin — calcareous if the sea floor was above the CCD, shaly or siliceous if it was not. Clearly the uppermost Jurassic sediments sampled by the drill at Site 416 were deposited below the CCD, and the calcareous layers there were all redeposited from shallower waters.

The comparable site on the other side of the ocean, Site 391 (Blake–Bahamas Basin), is in a situation comparable to Site 416 with respect to the magnetic-quiet-zone boundary, but the Upper Jurassic as well as the Neocomian sediments are *in situ* sediments deposited above the level of the CCD. The difference between the two areas might be explained by tectonism associated with accumulation of the thick wedge of Middle Jurassic clastics at Site 416, depressing the sea floor so as to leave it below the CCD during the latest Jurassic and Early Cretaceous.

On the other hand, to try to use data from Site 391 to fix the depth of the CCD at Site 416 is inappropriate, because there is no reason to believe that the CCD was at the same level everywhere in the young Central Atlantic, in particular as close to the margin as is Site 416. It would be normal to expect coastal upwelling effects (hence the vertical structure of the water column would be different on the two sides of the ocean and there would be variation in the CCD). In any case, at Site 416 the sea floor must have crossed the CCD sometime between the beginning of the Middle Jurassic and the latest Jurassic; this still leaves the possibility that the Callovian–Oxfordian–lower Kimmeridgian sediments from the Moroccan Basin include pelagic carbonates.

The preceding discussion leads us to the question of the significance of the "blue" reflector which lies at most only tens of meters below the lowest level reached by drilling at Site 416. Assuming that the strata underlying the reflector belong to a thick flysch unit of Middle Jurassic age, and knowing that the overlying interval corresponds also to a flysch, the very strong "blue" reflector would mark an important break in sedimentation between those two major clastic episodes. Since a major Callovian–Oxfordian transgression is well documented on the margins of the Central Atlantic, one logical interpretation is that the reflector results from an Upper Jurassic pelagic interval sandwiched between the two flysch units. In this interpretation, the strata consist of shales, possibly with some cherts or limestones, depending on the depth of the sea floor with respect to the CCD at the time, and the interval could thus be comparable to the Scotian shelf sections.

Alternatively, the "blue" reflector may correspond to very calcareous turbidites of the latest Jurassic, similar to those at the bottom of the hole at Site 416, and any pelagic sediments would be just below the reflector, masked by the high reflectivity of the hard resedimented limestones.

Latest Jurassic-Early Cretaceous Regression (Phase VI on Figure 5)

After the "Atlantic" transgression, which began in Callovian time and reached its peak during the Oxfordian, a very long time of regression, lasting until at least the end of the Hauterivian, characterized both the Moroccan and Nova Scotia margins. The regressive facies have been recognized in western Morocco (Société Chérifienne des Pétroles, 1966), in the Scotian shelf area

(Jansa and Wade, 1975), and, for the first time, in the deep-water environments of the Moroccan Basin at Site 416.

In Morocco, open-shelf limestone and marl of the Callovian–Oxfordian Anklout and Hadid formations are followed upward by about 600 meters of alternating dolomite, anhydrite, and red mudstone of Kimmeridgian–Portlandian (Tithonian) age, representing lagoonal and sabkha environments.

In the Scotian Basin, the limestones of the Abenaki Formation are succeeded upward by the shallow-water terrigenous coarse clastics of the Lower Cretaceous Missisauga Formation. The age of the base of this formation is attributed to the Berriasian, but, regionally, clastic facies extend down at least into the Tithonian (Jansa and Wade, 1975).

In the Moroccan Basin (Site 416), the lowest part of the drilled section consists of coarse detrital sediments deposited by turbidity currents in deep water at the foot of the margin. The age of the base of this facies is unknown, but from the preceding discussion it appears reasonable to locate the lower boundary of this interval some tens of meters below the total depth reached at Site 416 ("blue" reflector). Considering the rates of accumulation of the uppermost Jurassic sediments at this site, this age is probably not much older than late Kimmeridgian.

The regression apparently reflects at least mild tectonic activity in both Morocco and Nova Scotia. In Morocco, this "Eo-Cretaceous" phase is characterized by several unconformities within the lagoonal and continental strata of the Atlas area (Choubert and Faure-Muret, 1962). In the Essaouira Basin, salt diapirs rose to the surface during Late Jurassic time, as shown by the unconformable superposition of uppermost Jurassic strata over diapiric salt (Société Chérifienne des Pétroles, 1966), but it is not clear that any real orogenic movement affecting basement took place here at that time, because the structures may be due entirely to diapirism. In any case, it was during the latest Jurassic that the Atlas chain generally began its uplift, judging by isopach maps drawn for the Kimmeridgian of Western Morocco by the Société Chérifienne des Pétroles (1966).

In Canada, a very comparable evolution took place with the development south of the Grand Banks of the Avalon uplift, which was elevated and eroded during the Early Cretaceous, after a major rejuvenation of clastic-sediment source areas and the development of drainage systems during the latest Jurassic (Jansa and Wade, 1975). This tectonic phase may be directly related to the rifting of the North Atlantic between the Grand Banks and Iberia, a phase which is rather well-documented along the Iberian margin (Boillot et al., 1979).

The evolution of the onshore and shallow parts of the Western Moroccan margin bears further discussion, to understand its influence on sedimentation in the basin near Site 416. During the Jurassic, certain patterns of facies and isopachs persist in the southwest basin of the Moroccan margin: in addition to the normal westward (seaward) trends toward finer-grained or more-marine facies, the maps of the Société Chérifienne des Pétroles (1966) show a structural high trending west-southwest across the Cape Tafelney area, bordered on the north by a structural low. Over the high, sediments are relatively thin, and reefs cluster there. In the low, between Cape Tafelney and the town of Essaouira, sediments are relatively thick. The Essaouira low is further defined by a persistent high — also the site of reef building — north of Essaouira. Still another high can be discerned trending west across Cape Rhir, slightly north of Agadir. In essence, the Western High Atlas chain extends westward beneath the Mesozoic cover as a basement high that intersects the coastline between Capes Tafelney and Rhir and extends westward across the shelf between the modern Agadir Canyon and the unnamed submarine-canyon system that heads into the coast between Cape Tafelney and Essaouira. This west-trending basement high can indeed be identified on seismic profiles from the shelf and slope off that part of the Moroccan margin (Robb, 1971; Summerhayes et al., 1971). Structural and sedimentary troughs flank the ridge on both sides, one near Essaouira and one near Agadir. Subsidence rates have been different on the high and in the troughs since at least as long ago as the early Jurassic. We consider it likely that the two troughs acted as important avenues for sediment transport from land to the deep turbidite basins at the foot of the continental slope, not only during Middle and Late Jurassic times, but also into the Early Cretaceous.

Putting the regional picture together, we see during the late Jurassic and earliest Cretaceous (when the core record at Site 416 begins):

1. Continuing emergence of the High Atlas, and retreat of the seaways that extended into that region from the east.

2. Continuing subsidence of the Essaouira coastal basin of southwest Morocco, but in an uneven way, with fairly well-defined, more or less rapidly subsiding troughs paralleling the high that extends from the High Atlas basement westward onto the continental margin. Salt diapirs accentuate the structural relief locally and some break through to the surface.

3. The subsidence rate on the shelf increased in the Late Jurassic compared to the Middle Jurassic, but sedimentation kept the shoreline mainly seaward of the present coast until Berriasian time. Kimmeridgian and Portlandian strata indicate restricted lagoonal and sabkha environments. Farther seaward, carbonate banks flourished and supplied abundant detritus to Late Jurassic turbidity currents that flowed down to Site 416. Passageways through the carbonate banks, perhaps along the trough north of Cape Tafelney, allowed at least some terrigenous detritus eroded from the High Atlas and western Meseta to spill down the continental slope onto the continental rise in turbidity currents (Price, this volume). Material from both bank and continental sources arrived both separately and mixed. On the shelf, and perhaps on the continental slope between the carbonate banks and Site 416, hemipelagic aragonitic lime muds (Schlager, this volume) with calpionellids were deposited and then partly eroded by turbidity cur-

rents that carried the mud pellets and calpionellids to Site 416. Net accumulation rates were relatively slow — only 10 m/m.y. in the Berriasian — according to the biostratigraphy. The relatively slow accumulation rate for turbidites at Site 416 implies very infrequent turbidity currents. The supply rate from the carbonate banks was probably much slower than the potential rate from terrigenous sources, a rate that was achieved later, during the Hauterivian.

Early Cretaceous Drowning of Carbonate Banks and Valanginian–Hauterivian Flysch

Environments during the earliest Cretaceous were a continuation of those of the Late Jurassic, with gradual transgression of the shoreline eastward. Marine carbonates with ammonites appear in the Berriasian landward of the present coastline (Société Chérifienne des Pétroles, 1966), and at Site 416 the ratio of carbonate to terrigenous detritus in the turbidites began to decrease (Schlager, this volume), indicating better access for the terrigenous debris to the basin, or perhaps the onset of drowning of the offshore carbonate banks. In the coastal region, the Valanginian is represented by only about 20 meters of marly limestone with ammonites. The transgression had reached its peak, and terrigenous supply rates were still fairly low.

At Site 416, the water depth may have increased during this time, because sedimentation rates slowed while normal "tectonic" subsidence continued. If we assume normally subsiding oceanic crust beneath Site 416, the "tectonic" subsidence should be about 25 m/m.y. at the beginning of the Valanginian.[3] Isostatic subsidence will permit about 2 meters of new sediment (porosity 60%) for every 1 meter of tectonic subsidence. Any rate of accumulation less than 50 m/m.y. thus would result in a net deepening of the sea floor. The accumulation rates during Berriasian time were below this value, allowing for compaction.

Beginning sometime in the early Valanginian (Core 416A-38), conditions changed suddenly. Carbonate turbidite layers at Site 416 became much less important, and phosphorite grains appeared for the first time, suggesting that some of the carbonate banks had drowned. The increase in the proportion of terrigenous turbidite beds at Site 416 occurs at a time when sedimentation rates still may have been fairly low, as suggested by the thinness (average 4 cm) of beds compared to those above (average 9 cm in the upper part of the Hauterivian).

Biostratigraphic data suggest a rate of about 55 m/m.y. for the lower Valanginian (Cores 416A-32 to 48), but this figure also represents some of the underlying calcareous turbidites. However, from the time of Core 416A-38, terrigenous sediments poured onto the continental rise off Morocco in increasing quantities, reaching an average accumulation rate of about 65 m/m.y. according to the biostratigraphic data. The sediments are completely dominated by terrigenous debris, doubtless derived from the Atlas and the Meseta, and include abundant macerated plant debris.

The fairly regular upward increase in average bedding thickness of the Valanginian and Hauterivian turbidites suggests a prograding fan, but Site 416 was certainly in a very distal position on any fan system, as indicated by the small average bed thickness, by the prevalence of Bouma C and D units, and by the apparent lack of any trace of fining- or coarsening-upward sequences that would indicate a position on a part of the fan subject to rapid shifting of channels.

The depth of the water in the basin during this time of rapid accumulation of turbidites is difficult to estimate. The estimated depth to basement is about 7900 meters, but this estimate might be in error by several hundreds of meters, because it is based on stacking velocities from multichannel seismic-reflection profiles. Without refraction data, the velocities from the lower part of a thick sedimentary section cannot be determined with certainty. After correction for isostatic loading from the total column of sediments, basement depth is about 5860 meters (assuming average densities of 2.1 for the sediment column and 3.3 for the mantle), a depth which is not much in excess of the theoretical depth of 5320 meters derived from the subsidence curve of normal oceanic crust. After restoring the thickness of sediment accumulated prior to the Cretaceous and correcting again for isostatic loading, the depth of the Early Cretaceous sea floor is estimated at 4500 meters. This figure is compatible with independent estimates based on benthic foraminifers (Sliter, this volume).

This depth estimate implies rapid subsidence of the sea floor during post-Oxfordian Jurassic times, if one considers that the actual depth difference between the "blue" reflector in the basin and the middle-Oxfordian shallow-water, ammonite-rich carbonate rocks dredged by Renz et al. (1975) on the flank of the nearby Mazagan Escarpment is about 2850 meters. Of course, the exact depth of a dredge sample is rather difficult to estimate, and this figure of 2850 meters remains a minimum water depth for Site 416 during the Oxfordian. Subsidence of more than 1000 meters during the Oxfordian and Kimmeridgian would correspond to a rate of slightly more than 100 m/m.y., a figure very similar to that (110 m/m.y.) calculated by Arthur et al. (1979) for the subsidence of the Middle–Upper Jurassic carbonates beneath the Aaiun–Tarfaya Basin.

In any case, the water at Site 416 was deeper than the CCD during the accumulation of the distal flysch. The evidence from foraminifers (Sliter, this volume) shows that only the arenaceous faunas in the uppermost parts of the turbidite cycles were indigenous; all other foraminifers — and calpionellids — were resedimented from shallower water.

On the shelf, phosphorite continued to accumulate, and carbonate banks nearly disappeared, at least as significant contributors to turbidites during the Valanginian. On the other hand, a thin shelly facies occurs over parts of the present-day onshore area of exposure of the Valanginian, especially around the trough between Cape Tafelney and Essaouira (Société Chérifienne des

[3] If depth $= D_0 + K\sqrt{\text{age}}$ and $dD/dt = K/(2\sqrt{\text{age}})$, using $K =$ 360, and age $= 180 - 131 = 49$, $dD/dt = 26$ m/m.y.

Pétroles, 1966). The succeeding outcropping Hauterivian includes a wide band of reefs having their eastern limit some 100 km east of the present coast. The reefs pass westward into marlstone along a line that skirts the edge of the clearly defined Essaouira Trough, but reefs also surmount diapiric structures within the trough (Société Chérifienne des Pétroles, 1966). The strata of the Hauterivian are thick (500–1000 m) in both troughs that flank the Atlas high, and are thin (< 400 m) over the high.

The source area for the quartz-rich terrigenous sands and silts in the turbidites at Site 416 lay east of the reefs, in the High Atlas and Meseta. A continental facies of the Hauterivian crops out along the eastern edges of the coastal basin, but it is only about 300 meters thick at most (Société Chérifienne des Pétroles, 1966). To account for the huge quantities of terrigenous Hauterivian sediments on the continental rise at Site 416, we visualize passageways through the reef area, especially along the axis of the Essaouira Trough, which may actually have been a submarine canyon, partly rimmed with active reefs nourished by upwelling water from the adjacent deep canyon. Another sluiceway for terrigenous sediments may have existed along the Agadir Trough, feeding the part of the continental rise around Site 415 (see Price, this volume).

The climate of the time was probably humid and warm. One can imagine a landscape with abundant vegetation — including trees producing sap that survived as amber grains in turbidite sediments at Site 416 — growing along the banks of streams flowing off the Atlas and Meseta. Weathering may have produced some red soils, suggested by red-coated quartz grains in the turbidites (if these grains are not simply reworked from older Mesozoic and Permian red beds).

The Meseta and High Atlas remained emergent, and probably continued to rise, at least isostatically, during the erosion that produced the flood of clastics into the Morocco Basin. Intermontane basins accumulated red sandstones (Choubert and Faure-Muret, 1962). The increased rates of sedimentation in the Hauterivian at Site 416 may be related to increased uplift in the source area, or to a change to a climate with higher erosion rates. The abundance of plant debris suggests a change to more-humid conditions, but erosion rates do not necessarily follow rainfall rates: semiarid climates prevail today in some regions with very rapid erosion. We have no data to decide this question from Leg 50 cores.

On a regional scale, as pointed out by many authors (e.g., von Rad and Arthur, 1979), early Cretaceous "Wealdean" deltas were built out onto the continental margin at many places around the North and Central Atlantic, and almost parallel sequences of facies are known from the Aaiun–Tarfaya Basin (Tan-Tan sands), from Nova Scotia (Jansa and Wade, 1975), and from the Senegal Basin (Castelain, 1965). In some areas, this may be related to tectonics, but the very extent of the facies on both sides of the Atlantic suggests that climate may also have played a role.

The results of Leg 50 point up one feature of the "Wealdean" facies that needs underlining — namely, that this is not simply a deltaic facies, but is a prograding terrigenous clastic facies, which may be expressed in deeper water by turbidite fans or even abyssal plains. In Morocco, the turbidites on the continental rise may have been connected with their sources by submarine canyons, and there may have been no substantial deltas at all. The local physiography of the clastic facies will depend on local conditions of shelf width, river size, etc. In fact, Wealdean turbidites (flysch) are common in the nearby Mediterranean Tethys basins; in North Africa; in the French, Italian, and Swiss Alps; in Yugoslavia; and in Greece. Some of these reflect tectonism (e.g. the closing of the Vardar Ocean at the end of the Jurassic) and a tendency to begin closing the Ligurian oceanic basin. These events, connected by changes in direction and rates of plate motions, may well have been reflected in the Atlas and on the Meseta.

Barremian–Albian Distal Turbidites and Hemipelagic Sedimentation

With the Barremian, the sedimentation regime in the Moroccan Basin changed markedly. Deposition of the Hauterivian flysch stopped rather abruptly and was replaced by slower accumulation of very distal turbidites and hemipelagic muds. These sediments, which were recovered from Hole 416A and possibly from the very base of Hole 415A, record diminishing terrigenous influences and correlative increasing oceanic influences. The base of the interval may correlate with the "olive" reflector on the seismic profiles, although this reflector might also correspond to a more subtle change of facies around the Barremian/Aptian boundary.

Barremian to Albian time was marked by several relatively small scale transgressions and regressions on the adjacent margin. The abrupt end of the flysch facies might be related to the beginning of a transgression recorded in the Essaouira (Haha) Basin (Choubert and Faure-Muret, 1962). After another regressive episode, the late Aptian is characterized by a renewed transgression that lasted until the beginning of the Albian. The Albian and the early Cenomanian were again regressive and, to the east, are expressed as the "Infracenomanian," an extensive continental facies that still further east, in the Sahara, is well known under the name "continental intercalaire" (Choubert and Faure-Muret, 1962).

All data suggest that Barremian–Albian time was marked by greater stability than the preceding phases — both in sedimentation and tectonics. The isopach maps of the Société Chérifienne des Pétroles(1966) for the Essaouira Basin underline this stability.

This stratigraphic interval is well known elsewhere in the Central Atlantic, where it includes organic-rich "black shales," but in the Moroccan Basin, because of the predominance of clastic facies, organic matter of marine origin is almost undetected. The bulk of the organic matter is terrestrial, and its distribution within the sediment is strongly influenced by depositional processes. Variations within turbidites sequences are generally greater than overall variations in the entire column. Values for organic carbon in any case are low and rarely reach 1 per cent, except in some layers near the bases of individual turbidite units, where they are more than 2 per cent.

Late Cretaceous: Eustatic Transgression and Tectonic Regression on the Margin, Tectonics and Hiatus in the Basin

Late Cenomanian and Turonian times witnessed the major "Cenomanian" transgression that invaded Africa all the way to the Sahara platform. The transgression established marine conditions that persisted throughout the Late Cretaceous in all major sedimentary basins in Morocco except the Essaouira Basin–Western High Atlas region, where the central high that characterizes the westward extension of the High Atlas emerged just after the Cenomanian.

The Turonian apparently is missing just west of the Argana Valley (Choubert and Faure-Muret, 1962; Société Chérifienne des Pétroles, 1966), and the Senonian is completely absent from the Essaouira Basin except for the narrow troughs on both sides of the central high. This emergence is also well documented by reworked Cenomanian fossils (*Cuneolina*) in Coniacian sediments from the southern trough (Souss Trough), east of Agadir.

A result of the transgression was to reduce the amount of terrigenous clastic sediments delivered to the basin during most of the Late Cretaceous, thus keeping rates of accumulation relatively low. At the same time, uplift of the Western High Atlas might have helped oversteepen the continental slope, causing nondeposition or erosion there.

At Site 416, no record exists of the Upper Cretaceous between poorly-dated Albian–Cenomanian sediments and the Paleocene. The only record of Upper Cretaceous sediments in the deep Moroccan Basin comes from Site 415, where Maestrichtian chalk was found interbedded within lower-Paleocene strata. If the coring interval for this chalk is correctly identified, the chalk is obviously reworked from nearby slopes. Although tectonic activity may have played a role in denuding the slope, as for example in the deep basin at Site 415, where middle Cenomanian sediments have been deformed and repeated on low-angle faults, erosion by bottom currents was probably the main cause for the hiatus. In that case, tectonic stacking of the Cenomanian layers indeed might have been the reason for the preservation of that part of the record near Site 415. Such stacking might have helped these sediments escape erosion that removed all deposits down to the lower Cenomanian over most of the basin.

The deformation and piling up of sheets of Cenomanian sediments observed at Site 415 and on seismic profiles in the area (see site chapter and Price, this volume) might have resulted from tectonic activity associated with the uplift and gentle deformation of the Western High Atlas during Turonian–Senonian times. The general direction of folding suggests that the sea floor sloped toward the north — that is, away from the Agadir Canyon area. Seismic profiles show that folds which affect the upper part of the interval between the "orange" and "red" reflectors are steepest and highest in the south and die out gradually toward the north. The folding affects beds from the "red" reflector down to the basement, but Paleogene beds above the red reflector are much less deformed and seem to seal the structures. They are thicker in synclines and thinner over anticlines, and gradually smooth the topography of the "red" reflector.

On the *Meteor* 3902 seismic profile (Figure 4), two faults cut the strata slightly more than half way between Sites 415 and 416. The faults extend from below the "blue" reflector (possibly down to the basement) upward to just below the "red" reflector, but they do not affect strata above that surface. The layering in the entire interval from the "red" reflector down to the basement parallels the underlying basement topography. Since at least the upper part of this acoustically well-stratified interval corresponds to turbidites, postdepositional (post-Cenomanian) deformation appears highly probable. Such deformation would also explain the difference in depth for the basement at Site 416 — where it is close to isostatic balance — and at Site 415 where it probably has been uplifted during the tectonic deformation that occurred around the Agadir–Canary Island zone. Our analysis implies that some deformation must have taken place as early as the Late Cretaceous and that it predates formation of the Canary Islands.

The occurrence and wide areal extent of a major hiatus, spanning the Upper Cretaceous and lower Tertiary, is among the major characteristics of sedimentation in the North Atlantic: it has been observed in the western basins (Hollister, Ewing, et al., 1972; Tucholke, Vogt et al., 1979), as well as in the basins and slopes of the eastern margins (Lancelot, Seibold, et al., 1978; von Rad, Ryan et al., 1979). By definition a hiatus is negative evidence, and obviously we could be dealing with a series of erosional events spanning a wide range of ages, so that if the latest one happened to be the most violent it may have destroyed all record of the preceding ones. A comparison of the extension of various hiatuses in several regions of the North Atlantic shows that this is indeed the case. Therefore, it is only by looking at the least-disturbed record, in areas where erosion has been minimal, that one can try to estimate the timing of these successive erosional events.

The Moroccan Basin, and the eastern North Atlantic in general, do not provide data reliable enough for this approach. Our results demonstrate, however, that although erosional events in both the western and eastern North Atlantic often might have resulted in a similar record, they were not caused by the same event and did not occur at the same time. A review of this problem (western North Atlantic) shows that in the North American Basin major erosion did not occur prior to the early Eocene (Tucholke and Vogt, 1979), whereas results from Sites 415 and 416 show that in the Moroccan Basin the major phase of sediment removal occurred at some time between the late Cenomanian and the Paleocene; this was followed by several erosion phases during the early Tertiary.

The evidence for major Late Cretaceous erosion comes from both drilling results and seismic profiles. At Site 415, lower Paleocene pelagic sediments were recovered about 25 meters above poorly dated Cenomanian–Coniacian(?) sediments. The contact was not cored. One could argue for redeposition of these Paleocene materials, because they contain at least one layer of probably reworked Maestrichtian chalk and generally appear to be bounded by very sharp contacts, although these might also result from artificial layering produced by the coring technique.

Since a major reflector ("red") has been identified with a smaller hiatus at the Paleocene/Eocene boundary, it can be used to trace the lower Tertiary beds, slightly above the major unconformity over large areas of the Moroccan Basin. The *Meteor* 3902 profile (Figure 4) shows that these layers blanket the time-transgressive erosion surface, and it therefore confirms the pre-Paleocene removal of Upper Cretaceous sediments.

Prior to Leg 50, it had been widely assumed that the major erosion that caused extensive hiatuses in the deep basins of the Central Atlantic was of early Tertiary age. This appears to be true for the northwestern basins, where the rather sudden flow of Arctic bottom water beginning with the early Eocene (Berggren and Hollister, 1974) has caused more or less pronounced erosion, depending on the physiographic setting of a given site (see discussion in Tucholke and Vogt, 1979). On the other hand, our data from the eastern Atlantic, together with those of von Rad, Arthur, et al. (1979) and Montadert, Roberts, et al. (1979) suggest a different timing in this region.

Arthur et al. (1979) proposed that the 100 m.y. hiatus observed near the foot of the Spanish Sahara margin resulted from several superimposed erosional events, among which the widespread Oligocene hiatus observed both in the North and South Atlantic would have been the most important. If we admit that such hiatuses result from erosion and not simply from nondeposition, an interpretation firmly documented by the time-transgressive nature of the unconformities on a regional scale, then there is no reason to expect that sediment removal would have happened at the same time in both the western and eastern basins of the North Atlantic.

In the western Atlantic, bottom currents capable of eroding the sea floor along the North American continental margin came from the high latitudes of the North Atlantic, after subsidence of sills in the Iceland–Faroe Ridge area related to opening of the Norwegian Sea. This event is believed to have taken place around the early Eocene (Berggren and Hollister, 1974). Erosion in the eastern basins is more difficult to explain and in any case cannot be the result of the same oceanographic regime. Bottom waters hugging the North African margin must have flowed northward, as they do today in a relatively subdued manner. Antarctic bottom waters are not believed to have flooded the deep northeast Atlantic prior to the Paleogene.

Drilling results from the entire North Atlantic, however, show that the Late Cretaceous was a time of at least some circulation of oxygenated bottom waters, contrasting abruptly with the anoxic conditions that prevailed during the late Early and early Late Cretaceous. Because in the deep basins the rate of accumulation of these well oxygenated sediments was everywhere extremely low, (the result of a high CCD and a lack of detrital terrigenous influx), even a rather moderate circulation on the bottom would have produced nondeposition in the deeper flat areas, and erosion along tectonically oversteepened slopes.

The exact origin and path of these late Cretaceous bottom waters remains unknown, but they probably originated from the southern hemisphere and reached the North Atlantic via the widening and deepening South Atlantic. The large Upper Cretaceous hiatus observed in the southernmost Atlantic and Indian Ocean lends support to this interpretation.

Cenozoic: Pelagic Sedimentation in the Basin

Pelagic sedimentation (calcareous marl and chalk) begins with the earliest Tertiary in the Moroccan Basin. Coring in this part of the section was so discontinuous that no definite conclusions can be reached from Leg 50 results. What is worse, the paleontological results (Vincent et al., this volume) show that the exact depths from which sediment samples were actually recovered remain very uncertain. Nevertheless, even this framentary record shows a striking contrast between pelagic Cenozoic and terrigenous or hemipelagic Mesozoic sediments. It should be remembered, on the other hand, that nothing is known of the sediments that may have been eroded away during the Late Cretaceous. Drilling results from the continental slope of Africa (Lancelot, Seibold, et al., 1978) and the occurrence at Site 415 of redeposited Maestrichtian chalk within Paleocene sediments suggest that pelagic sedimentation prevailed in the area since at least the latest Cretaceous.

Lower-Paleocene pelagic sediments accumulated very slowly in the Moroccan basin. They consist of marl and calcareous clay, suggesting that for the first time since at least the latest Jurassic the sea floor in the basin was above the CCD. In the absence of Upper Cretaceous sediments, we have no way to document the timing of any lowering of the CCD or of shoaling of the sea floor prior to the Paleocene. For the rest of the Cenozoic, the spotty record from both Sites 415 and 416 does not permit reconstruction of the evolution of the CCD with time, but it shows relatively good agreement with general trends that have been documented from previous drilling in the eastern North Atlantic (Berger and von Rad, 1972).

Paleocene marls may reflect the beginning of shoaling of the CCD following the general deepening during the Maestrichtian observed over most of the North Atlantic (Tucholke, Vogt, et al., 1979). The very low rate of accumulation of the Paleocene sediments (about 1 m/m.y.) leaves open the possibility of occasional erosion or nondeposition. A hiatus, for example, separates the lower from the upper Paleocene at Site 415, whereas this interval is complete at Site 370/416. This difference may reflect different conditions of bottom-water movement at the two sites, Site 415 being in an area that probably was uplifted already during the Paleocene, while Site 370/416 was in a deeper setting. Alternatively, the hiatus at Site 415 may be but an artifact of the coring technique.

The upper Paleocene differs strongly at the two sites. While pelagic sediments accumulated at a rate of about 1 m/m.y. at Site 370/416, they accumulated at 15.5 m/m.y. at Site 415 during the same time interval. This high rate of accumulation at Site 415 correlates with an influx of coarse detritus (gravel and conglomerate), which suggests that Agadir Canyon became active around this time.

A short hiatus spans the Paleocene/Eocene boundary at Site 370/416. A comparable hiatus may occur at Site 415, but the boundary falls in an uncored interval. The hiatus at Site 370/416 corresponds to the prominent "red" reflector on seismic profiles.

The early Eocene was a time of renewed detrital turbidite sedimentation at both sites. The main pelagic contribution is the abundant radiolarians, commonly transformed into chert. The low abundance and dissolution of calcareous microfossils suggest continued shoaling of the CCD. Middle- and upper-Eocene sediments were cored only at Site 370/416. They show a gradual decrease of terrigenous sediments (turbidites), which still dominate this interval, and a concomitant increase in pelagic elements, beginning with mainly siliceous microfossils and gradually giving way to calcareous fossils. The Eocene succession along the African margin thus parallels the Eocene around most of the North Atlantic, recording a time of marked increase in the productivity of surface waters. This increase reflects a major change in oceanographic conditions, resulting in the onset of circulation of North Atlantic deep water in the deep western basin and in greater upwelling along the African margins, a scheme comparable to that we observe at present.

The early Oligocene was the time of another hiatus at Site 370/416, so that uppermost lower-Oligocene sediments rest directly on middle- to upper-Eocene sediments. The equivalent interval is very poorly known at Site 415, where a very large hiatus, inferred from the rate-of-accumulation curve and from logging results, is believed to span the middle and late Eocene, the entire Oligocene, and part of the early Miocene (see discussion in site chapter and in Vincent et al., this volume). An Oligocene hiatus is commonly observed in various basins of both the North and South Atlantic (Arthur et al., 1979, and references therein), especially in the eastern North Atlantic (Berger and von Rad, 1972; Lancelot, Seibold, et al., 1978).

Although our data do not add any conclusive new evidence, they are in line with previous results and confirm the widespread occurrence of this hiatus that probably resulted from the onset of circulation of Antarctic bottom waters in the deep Atlantic. On the other hand, we have insufficient core material to assess the influence of more-local paleoenvironmental conditions associated with the evolution of the adjacent margin.

The uppermost part of the stratigraphic column at both sites is so sparsely sampled that no conclusions can be reached about the evolution of oceanographic conditions in this area during the Neogene. The major difference between the Neogene and the Paleogene record in the Morocco Basin is the general occurrence in the former of calcareous microfossils, in various stages of preservation in various intervals. Because of both the hiatuses and the discontinuous coring record, our data do not document in detail the conditions of the gradual regional deepening of the CCD during the Neogene and its oscillations during the middle and late Miocene. The reader is referred to detailed studies of Neogene stratigraphy appearing in von Rad, Ryan, et al. (1979), and also to Cita and Vismara Schilling (this volume) for a more thorough discussion of Neogene paleoceanography.

A final word about the evolution of the Canary Islands: although Site 415 is very close to this prominent feature, no evidence was found in Leg 50 cores that would help document its evolution, except for Late Cretaceous tectonic activity. Such activity must have predated the volcanic eruptions which may have begun only around the Eocene/Oligocene boundary (Grunau et al., 1975).

A summary of the stratigraphy of the Moroccan Basin sediment near Site 416, obtained from a combination of Leg 50 results and of our interpretation of the regional geology and geophysics appears on Figure 8.

CONCLUSIONS

Although our ultimate objectives were not met by drilling, Leg 50 results when placed in the context of the regional geological framework of the North African margin help us to understand the evolution of this

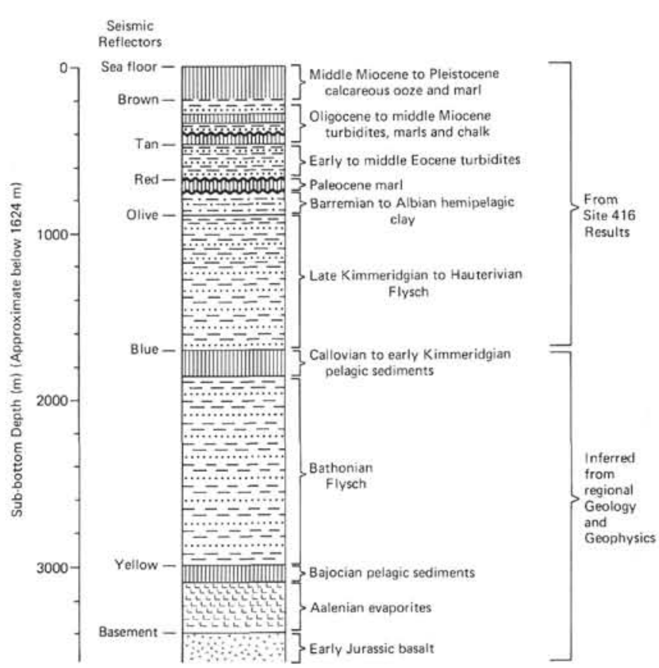

Figure 8. *Stratigraphy of sediments of the Moroccan Basin in the area of Site 416, from a combination of Leg 50 results and interpretations of the regional geology and geophysics. (Depth below 1624 meters is approximate.)*

margin and its relations with the adjacent oceanic basins during early phases of their history. The results demonstrate to us that major problems regarding the evolution of passive margins can be solved by drilling in regions where more-landward facies of the deeper-margin formations have been studied in great detail — on the adjacent continent or in wells drilled on the shelf.

There are basically two approaches to the study of the evolution of a margin. One is to synthesize data from many present-day margins of different ages around the world, which are assumed to represent various stages in the evolution of an "ideal" margin. Another approach is to concentrate the work on a given "mature" margin that can be considered very close to the "ideal" model. Such a margin should not only be representative as a model, but also should have a wealth of existing geologic data and a sedimentary section that permits reaching the missing parts of the record with the drill.

Leg 50, which used the second approach, shows that the North African margin offers great potential for future investigations. The especially favorable conditions there are the following:

1. The North African margin is bordered by sedimentary basins that record the history of the ocean before, during, and after the major phases of opening of the North Atlantic.

2. Sedimentary layers from these basins crop out in southwest Morocco, where they can be (and have been) studied in great detail. By establishing comparisons with the exceptional quantity of high-quality subsurface data from other basins surrounding the North Atlantic, one can use the Moroccan strata as an essential data base for a general interpretation of the early stages of opening of the Atlantic.

3. The continental margin off Morocco displays all the features presently believed to be characteristic of a rifted margin: the edge of the margin corresponds to an old foundered carbonate platform; salt basins existed both landward and seaward of this feature and can be used as exceptional recorders of sea-level changes associated with early rifting and early drifting; and terrigenous clastics make up most of the (much reduced) continental rise at the foot of the slope.

4. Because this margin is among the "starved" margins that characterize the eastern Atlantic, all these characteristic features are within reach of the drill in the deep basin. Some (e.g., the carbonate bank) have been also studied by dredging, and can be studied in great detail through direct observation by submersibles. The northwest African margin is unique in being the oldest starved margin of the Atlantic, so that its entire evolution can be studied in a single area.

5. The North African margin is close to younger rifted margins to the north, so that direct comparisons can be established through the study of lateral facies changes from basin to basin.

6. The margin is located in a key area at the western end of the Tethys, and the Mesozoic outcrops of tectonized margins from the Alpine fold belts provide exceptional opportunities to extend correlations and results over large distances.

7. This margin also offers, with the Blake Basin, the only opportunity to study Early to Middle Jurassic paleoenvironments of the Atlantic in a deep-water setting and to compare them with the marginal Tethyan environments (Alpine outcrops) on the one hand, and the Jurassic world ocean (yet to be drilled in the Pacific) on the other.

8. Finally, the combination of geophysical, deep-sea-drilling, and geological data already gathered in the area now makes it possible to propose crucial tests for a model of evolution.

Each new piece of information, including the Leg 50 results, has helped reduce the number of missing pieces in the puzzle. Among the various approaches that can help us complete the study of this margin, deeper drilling into the Moroccan Basin can be considered a necessary step. Even though this proved to be beyond the capability of *Glomar Challenger* during Leg 50, improvements in drilling techniques should lead to exceptionally rewarding results along this margin.

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