71. BATHYMETRIC RECONSTRUCTION METHOD: APPLICATION TO THE CENTRAL ATLANTIC BASIN BETWEEN 10°N AND 40°N[1]

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INTRODUCTION

It is well known that a general relationship exists between the age of the earth's crust at mid-ocean ridges and its depth (Menard, 1969; Sclater and Francheteau, 1970; Sclater et al., 1971). Depths increase from 2500 ±300 meters at a spreading center, to 5800 ±300 meters in oceanic crust of Early Cretaceous to Late Jurassic age (Figure 1; Sclater et al., 1971). The 3 km deepening of the oceanic crust can be satisfactorily explained by simple models involving the thermal structure of the oceanic lithosphere during its spreading from the axis of ridges to the adjacent oceanic basins (Sclater and Francheteau, 1970; Davis and Lister, 1974). It has also been suggested that structural highs like aseismic ridges, which have not come about by accretion, nevertheless follow the subsidence law of normal oceanic crust since they ride "piggy-back" on top of the oceanic lithosphere immediately after their creation at or close to spreading centers (Detrick et al., 1977).

The hypothesized relationship between the crust's age and depth, which postulates that the oceanic lithosphere has had a similar thermal structure — and consequently that oceanic crust subsidence has followed the same laws — throughout geological time, forms the basis of plate stratigraphy (Berger, 1973; Berger and Winterer, 1974) and studies of paleooceanography (van Andel et al., 1975). Several methods have been used for reconstructing the depth of a site (Berger, 1972; Berger and von Rad, 1972; Berger and Winterer, 1974; van Andel, 1975; Thiede, 1977). The purpose of this paper is to present a method of calculating the depth of any stratigraphic or lithologic marker found on the sea floor or within the drilling column of a DSDP site. First, the method will be applied to the depth reconstruction of the top of the sedimentary column at Hole 417D, Leg 51. We will then discuss the occurrence and evolution of the principal sedimentary facies in the Central Atlantic Basin between Africa and North America during four time episodes, focusing on the evolution of the carbonate line (Berger and Winterer, 1974). Finally, we shall discuss the implications of this depth reconstruction method for the evolution of the crestal depth of mid-ocean ridges.

PREVIOUS DEPTH RECONSTRUCTION METHODS

Berger (1972) was first in using the age-depth constancy hypothesis for reconstructing depths. The graphical method employed by Berger (1972), Berger and von Rad (1972), and Berger and Winterer (1974) leads to difficulties with the isostatic correction. van Andel et al. (1975) have modified the method to take into account the gradual accumulation of sediment with time. This has been used by van Andel (1975), but he made no allowance for density differences or hiatuses within the sedimentary column. Thiede (1977), who treated the depth of deposition of a site on the Rio Grande Rise, did take sedimentary hiatuses into account.

PROPOSED METHOD OF DEPTH RECONSTRUCTION

The method presented here provides depth estimates for all the holes for which basement age and depth are known. We believe it overcomes the shortcomings of previous methods. The following parameters are considered.

Basement Subsidence

We adopt the best-fit of Le Pichon et al. (1973) for the relationship between depth of the sea floor below sea level D and age of the crust T:

$$D\,(T) = 7100 - 3904 \exp\,(-T/78) - 606 \exp\,(-T/6)$$

where T is expressed in millions of years and D in meters (Figure 1). A different relationship could be introduced, such as the fit of Sclater and Detrick (1973), to the deep-sea drilling depth and age data. The method is not changed, although some results (crestal elevation), to be discussed later, would be affected.

Relief Correction

Any relief created at the axis of the mid-ocean ridge is conserved during subsequent subsidence of the crust. While the relief conservation hypothesis may be valid for small-scale bathymetric highs or lows, it is less likely to hold true for the large-scale undulations known to exist at the present axis of the Mid-Atlantic Ridge. For example, Sclater et al. (1975) have shown that, generally, any depth anomaly at the axis of the Mid-Atlantic Ridge is preserved as the crust moves toward the basins.

Isostatic Correction

If we assume local isostasy with compensation at the base of the lithosphere, then this permits us to compute the depth variation due to sediment loading.

If ρ_w, d_s, and ρ_a are, respectively, the densities of water, sediment, and asthenosphere, then the variation of water

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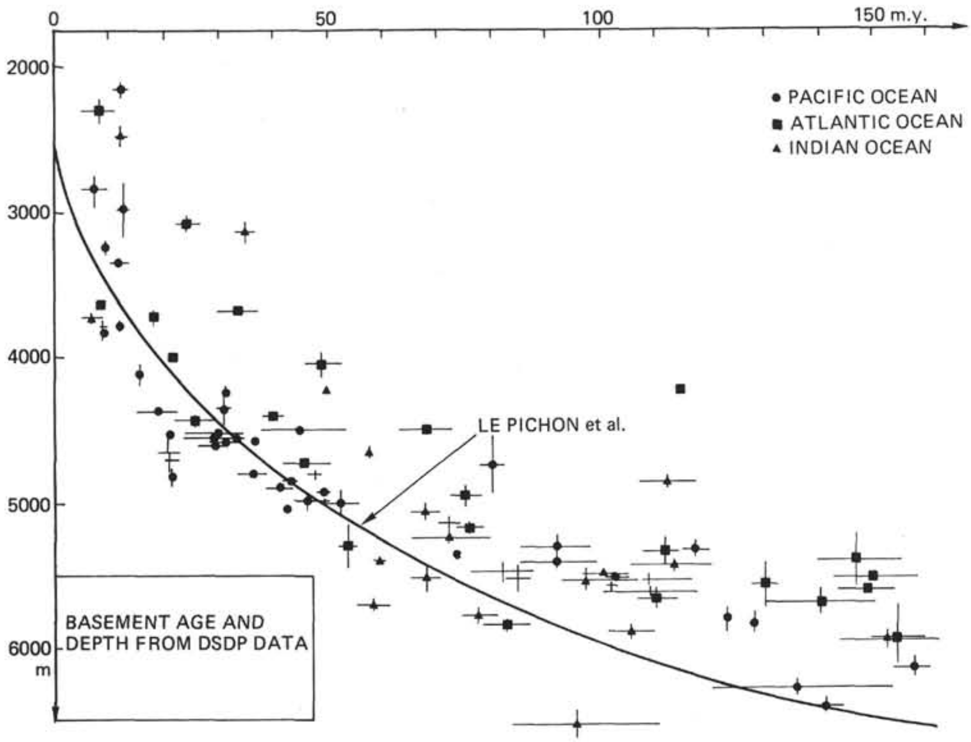

Figure 1. *Basement age and depth from deep-sea drilling data. The range in observed depths to basement and absolute ages inferred from fossil evidence are indicated by vertical and horizontal bars, respectively. The curve drawn through the data points is the empirical exponential fit of Le Pichon et al. (1973) and does not match well the depth flattening occurring around 80 m.y.*

depth ΔH_W on top of a sediment column whose thickness has varied by ΔH_s equals

$$\Delta H_w = \frac{d_s - \rho_a}{\rho_a - \rho_w} \Delta H_s; \rho_w < d_s < \rho_a$$

The equivalent variation of the basement depth is

$$\Delta H_c = \frac{d_s - \rho_w}{\rho_a - \rho_w} \Delta H_s$$

Thus, when sediment is added ($\Delta H_s > 0$), the water depth diminishes ($\Delta H_W < 0$), but the crust is depressed ($\Delta H_c > 0$).

For a given drill hole, the sedimentary column includes several sedimentary units separated by discontinuities or hiatuses. For each unit the density, thickness, and stratigraphy are known. We present the following definitions with respect to unit k (Figure 2):

T_{k-1}: age at end of sedimentation in the underlying unit number k-1,

ΔT_{k-1}: duration of a sedimentary hiatus placed at the bottom of unit k,

T_k: age at end of sedimentation for unit k,

d_k: sediment density of unit k,

H_k: depth in hole of the top of unit k,

τ_k: sedimentation rate in unit k.

If arbitrary unit n is the youngest unit and T_1 is the basement age, the relief conservation hypothesis signifies that the difference between the "observed" basement depth after removal of the sediments

$$H_n + \sum_{i=2}^{n} \frac{\rho_a - d_i}{\rho_a - \rho_w} (H_{i-1} - H_i)$$

and the theoretical (or empirical) depth for the age of the crust T_1

$$D(T_1)$$

or the quantity

$$C = H_n + \sum_{i=2}^{n} \frac{\rho_a - d_i}{\rho_a - \rho_w} (H_{i-1} - H_i) - D(T_1)$$

must be added to all depths computed on the basis of the empirical subsidence curve Equation (1). This statement is tantamount to saying that the original basement depth for zero age at the crest of the ridge is the true datum to be adopted for depth calculation rather than the 2590 meter empirical depth of Equation 1.

When one adds to the basement a layer of sediment of age greater than T, the isostatic correction corresponds to the depth variation at a point of age T within this sedimentary column. Although the crust will be deeper, the water depth

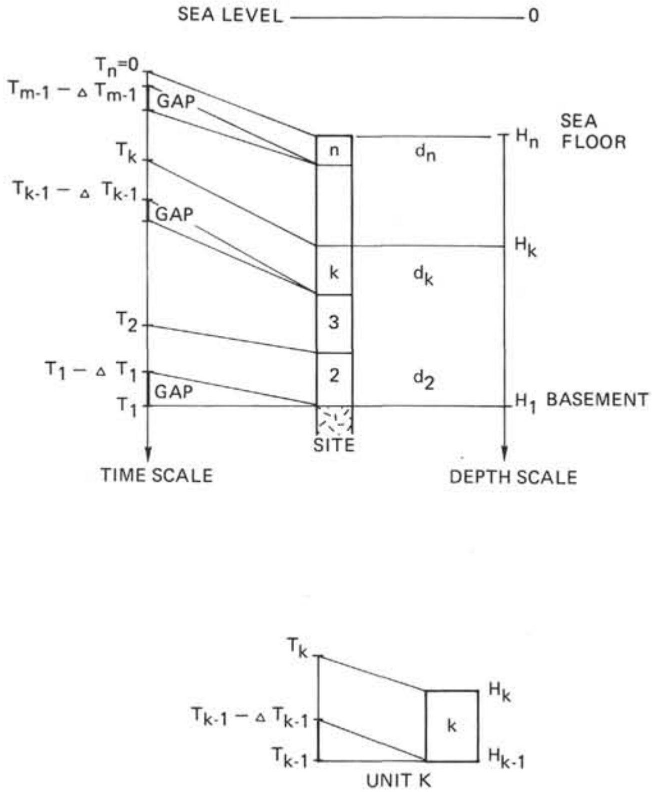

Figure 2. *Depth-time treatment of a drill site. The density of sedimentary unit is d_k.*

for the point of age T will be smaller and therefore the correction must be negative.

$$I(T) = \sum_{i=2}^{k-1} \frac{d_i-\rho_a}{\rho_a-\rho_w} (H_{i-1}-H_i)$$

for

$$T \epsilon (T_{k-1} - \Delta T_{k-1}, T_{k-1})$$

and

$$I(T) = \sum_{i=2}^{k-1} \frac{d_i-\rho_a}{\rho_a-\rho_w} (H_{i-1}-H_i) +$$

$$\frac{d_k-\rho_a}{\rho_a-\rho_w} \tau_k [T-(T_{k-1}-\Delta T_{k-1})]$$

for

$$T \epsilon (T_k, T_{k-1} - \Delta T_{k-1})$$

The depth of a point of age T within the sedimentary column composed of $n-1$ sedimentary layers of density d_2 to d_n overlying oceanic crust of age T_1 at a site of water depth H_n is:

Depth (T) = Theoretical depth at T + Inherited (positive or negative) topography + Isostatic (negative) correction.

$$\text{Depth } (T) = D(T_1-T) + C + I(T)$$

If

$$T \epsilon (T_{k-1}-\Delta T_{k-1}, T_{k-1})$$

$$\text{Depth } (T) = D(T_1-T) + H_n + \sum_{i=2}^{n} \frac{\rho_a-d_i}{\rho_a-\rho_w} (H_{i-1}-H_i) - D(T_1)$$

$$+ \sum_{i=2}^{k-1} \frac{d_i-\rho_a}{\rho_a-\rho_w} (H_{i-1}-H_i)$$

or

$$\text{Depth } (T) = D(T_1-T) - D(T_1) + H_n$$

$$+ \sum_{i=k}^{n} \frac{\rho_a-d_i}{\rho_a-\rho_w} (H_{i-1}-H_i)$$

If

$$T \epsilon (T_k, T_{k-1}-\Delta T_{k-1})$$

$$\text{Depth } (T) = D(T_1-T) + H_n + \sum_{i=2}^{n} \frac{\rho_a-d_i}{\rho_a-\rho_w} (H_{i-1}-H_i) - D(T_1)$$

$$+ \sum_{i=2}^{k-1} \frac{d_i-\rho_a}{\rho_a-\rho_w} (H_{i-1}-H_n) + \frac{d_k-\rho_a}{\rho_a-\rho_w} \tau_k [T-(T_{k-1}-\Delta T_{k-1})]$$

or

$$\text{Depth } (T) = D(T_1-T)-D(T_1) + H_n + \sum_{i=k}^{n} \frac{\rho_a-d_i}{\rho_a-\rho_w} (H_{i-1}-H_i)$$

$$+ \tau_k \frac{d_k-\rho_a}{\rho_a-\rho_w} [T-(T_{k-1} - T_{k-1})]$$

Equations 5 and 6 form the basis of the method and are easily programmed for a digital computer. The depth (T) curves are drawn automatically on an incremental plotter. The input data are the following: age and depth of basement below sea floor and a set of ages for the various sedimentary markers of interest; depth below sea floor; density of the underlying sediments; and duration of any sedimentary hiatus following deposition of the marker. The last card which is read gives the age of the top of the hole and its depth below sea level.

The model can be applied to any piece of ocean floor that obeys a known law of vertical motion $D\ (T)$, but is restricted at present to crust emplaced at a mid-ocean ridge and follows the well-known subsidence curve due to the evolution of the lithosphere. The method cannot be applied directly to continental margins in the earliest stages of continental rifting.

APPLICATION TO THE CENTRAL ATLANTIC BASIN

The depth reconstruction method is applied to deep-sea drilling sites located in the Central Atlantic Basin between the Newfoundland and Bahamas-Guinea fracture zones. We have selected those sites only whose age and basement depth are known, and these have been occupied during DSDP or IPOD Legs 2, 11, 14, 37, 41, 43, 44, 45, 49, and 51 through 53. Table 1 gives the general characteristics of each site: geographic location, structural position, sea-floor depth, and basement depth and age. The ages are usually derived from fossil evidence for the oldest sediments, using the time scales of Berggren and van Couvering (1974) for the Cenozoic and of van Hinte (1976) for the Mesozoic. In some cases, the basement ages were inferred from the age of the magnetic anomaly over the site. The age uncertainties are estimated to be ±1 m.y. for Neogene, ±3 m.y. for Paleogene, ±4 m.y. for Late Cretaceous, ±6 m.y. for Early Cretaceous, and ±10 m.y. for Jurassic (van Andel and Bukry, 1973; van Andel et al., 1975).

To make correlations between sites, a homogeneous sedimentary facies classification must be established. The different sediment types found in the studied area may be grouped in eight main facies. These facies are partly characteristic of geological periods and partly reflect the depth of deposition. Plotting facies information on a depth-age diagram permits detection of the influence of these two variables upon facies repartition.

The facies selected are the following:

1) *Carbonate,* including ooze, chalk, marl, and limestone (eventually shallow-water limestone). All these sediments contain fossils with a carbonate shell. They must be deposited above the calcium carbonate compensation depth

TABLE 1
General Characteristics for Each Site

Leg-Site or Hole	Sources	Latitude (N)	Longitude (W)	Geographical Setting–Remarks	Depth of Sea Floor (m)	Sediment Thickness (m)	Basement Age (m.y.)
2-9	Peterson, Edgar, et al., 1970	32°46.4′	59°11.7′	Eastern flank of Bermuda Rise	4973	834	78
2-10		32°51.7′	52°12.9′	Lower flank of the Mid-Atlantic Ridge	4700	450	75
2-11		29°56.6′	44°44.8′	Upper flank of the Mid-Atlantic Ridge	3571	284	13
11-100	Ewing, Hollister, et al., 1972	24°41.3′	73°48.0′	Cat Gap (no cores after Neocomian carbonate ooze)	5325	320	155
11-101		25°11.9′	74°26.3′	Blake-Bahama Outer Ridge (basement estimated by geophysical data)	4868	740	145
11-105		34°53.7′	69°11.4′	Continental rise hills between New York and Bermuda	5251	623	145
14-135	Hayes, Pimm, et al., 1972	35°20.8′	10°25.5′	750 meters above abyssal plain southwest of Horseshoe Abyssal Plain (basement estimated)	4152	≅ 1000	148
14-136		34°10.1′	16°18.2′	Abyssal hills 160 km north of Madeira (oldest sediment anomalously young)	4169	308	113
14-137		25°55.5′	27°03.6′	Abyssal hills 1000 km west of Cap Blanc	5361	397	101
14-138		25°55.4′	25°33.8′	Foot of the continental rise 130 km east of Site 137	5288	437	92
37-332B	Melson, Aumento, et al., 1977	36°52.7′	33°38.5′	Deep drill valley FAMOUS area	1806	142	3.5
37-333		36°50.5′	33°40.1′	Deep drill valley FAMOUS area	1666	219	3.5
37-334		37°02.1′	34°24.9′	Middle of magnetic anomaly 5	2619	259	9.5
37-335		37°17.7′	35°11.9′	West end of FAMOUS traverse	3188	450	13
41-367	Lancelot, Seibold, et al., 1978	12°29.2′	20°02.0′	Cape Verde Basin, base of continental rise	4748	1140	143
41-368		17°30.4′	21°21.2′	Cape Verde Rise	3366	>985	
43-384	Tucholke, Vogt, et al., 1975	40°21.6′	51°39.8′	South of Grand Banks, "*J*-anomaly" ridge	3909	324	114
43-385		37°22.2′	60°09.5′	Flank of Vogel Seamount (Late Cretaceous volcanism)	4956	393	82
43-386		31°11.2′	64°14.9′	Central Bermuda Rise	4792	964	112
43-387		32°19.2′	67°40.0′	Western Bermuda Rise	5118	794	132
44-391C	Benson, Sheridan, et al., 1976	28°13.7′	75°36.8′	Blake-Bahama basin Basement estimated 250 meters below last core	4964	1660	155 (?)
45-396	Rabinowitz, Melson, et al., 1976	22°58.9′	43°30.9′	Anomaly 5, south of Kane fracture zone	4450	150	13
49-411	Luyendyk, Cann, et al., 1977	36°46.0′	33°23.3′	Rift valley, graben in western wall (FAMOUS Zone)	1935	95	1
49-413		36°32.6′	33°10.5′	Transform Valley B	2598	100	3.5
51-417A	This volume	25°06.6′	68°02.5′	Southernmost part of Bermuda –	5468	208	109
51-417D		25°06.7′	68°02.8′	Anomaly *M*0	5479	343	109
52-418A		25°02.1′	68°03.4′		5511	324	109
53-418B		25°02.1′	68°03.4′		5514	320	109

(CCD) (Bramlette, 1961; Berger and Winterer, 1974), except for reworked sediments which are rapidly covered.

2) *Red clay limestone* linked with specific sedimentation conditions in the Upper Jurassic and comparable to the red nodular limestone well known in the Alpine (Tethysian) pelagic series. In some cases, it may be regarded as a carbonate-dissolution facies.

3) *Black shales,* widely distributed throughout the Atlantic in Early and Middle Cretaceous times.

4) *Mud or clay with chert or radiolarians* linked with great depths, they are known at various periods.

5) *Zeolitic clay* and (6) *clay,* carbonate-free, are found in the deepest areas below the CCD.

7) *Multicolor clay* widely distributed in Late Cretaceous times.

8) *Silty mud* and *turbidites,* redeposited sediments, may be found at various depths.

BATHYMETRY OF HOLE 417D

For the purpose of illustration, the method has been applied to Hole 417D. The following stratigraphic control points have been used: Section 21-4 (343 m) nannofossil chalk, late Aptian 109 m.y.; Section 17-1 (295 m) organic claystone and chalk, late Cenomanian 93 m.y.; Section 5-1 (168 m) (washed interval), middle Eocene 47 m.y.; Section 1-1 (0 m), Quaternary 0 m.y. We assumed that the section contains no hiatus. Densities of 3 g/cm^3 were assigned to the asthenosphere, 2.1 g/cm^3 to the two lower sedimentary units, 1.8 g/cm^3 to Units IV, Va, Vc, and VI, 1.7 g/cm^3 to Unit III, and 1.6 g/cm^3 to Units I, II, and Vb.

Figure 3 is a plot of the top of the sedimentary column at Hole 417D, since the basaltic crust was emplaced in late Aptian 109 m.y. ago. A slight revision of basement age could be made, because Gartner (this volume) estimates this to be at least 112 m.y. or middle Aptian on the basis of *Lithastrinus floralis,* a distinctive calcareous nannofossil datum in the lowest sediments. We adopt the 109-m.y. age for the site, which agrees with the fission-track age of 108.3 $\pm$1.3 m.y. determined by Storzer and Selo (this volume). According to Figure 3, the basaltic crust was emplaced at a depth of about 2200 meters, about 400 to 500 meters higher than the average depth of the present Mid-Atlantic Ridge. The empirical depth-age model that we use (Equation 1) ignores the possible existence of a rift valley at the axis of the ancestral ridge. That a $\sim$1.5-km-deep rift valley was present is suggested by the calculated spreading rates, which are all less than 2 cm/y from the *Lynch* survey data (Hoskins and Groman, 1976). In the present mid-ocean ridge, the cut-off between rifted and non-rifted ridges occurs for spreading rates of about 2.5 cm/yr (Lonsdale, 1977). Thus it is possible that the crust was emplaced at a depth greater than 3000 meters on the rift valley floor and that the thin nannofossil chalk (Unit VIII) was deposited within this valley before the crust had even begun to subside. This difficulty of assigning a correct depth to the earliest deposits is a general one and has not been stressed in previous studies. However, it could be eliminated by using a different depth-age law $D(T)$. This would model an average rift valley/rift mountain province profile for young time and match the thermal subsidence for older time.

On the basis of the foregoing discussion and with a sedimentation rate in excess of 3 m/m.y., the cyclic radiolarian sandstone and claystone (Unit VII), which is less than 3 meters thick at Hole 417D, could also have been deposited in the rift valley (rift mountain) province, because commonly the crust resides about 1.5 m.y. in this valley (Needham and Francheteau, 1974). The first good age datum in the sedimentary sequence above the oldest sediments is Cenomanian to late Albian in Hole 417D (Section 17-1) and middle Albian (106 m.y.) in Hole 418B (Section 28-3; Gartner, this volume). This datum is found within the organic claystone and chalk or "black shale" unit (Unit VI). The Cenomanian to late Albian Section 17-1 of Hole 417D corresponds to the latest occurrence of calcareous sediments and to the disappearance of sediments rich in organic matter (Deroo et al., this volume). Thus, the organic unit (Unit VI) was probably sedimented in the rift mountain province of the Mid-Atlantic Ridge and the crust had started to subside normally away from the ridge axis when the carbonate line (Berger and Winterer, 1974) was crossed and the rhythmic organic sedimentation ceased. This event corresponds to a depth of 3450 meters in Figure 3. The multicolor clay unit (Unit V) started its deposition at a depth of 3800 meters, the radiolarian clay and ooze unit (Unit IV) at 4750 meters, and the pelagic clay (Unit II) at 5050 meters.

Bathymetry is a useful tool for reconstructing the evolution of the CCD with time. This evolution and the occurrence of the main sedimentary facies with time and depth will be discussed for the following periods: (a) Late Jurassic (Figure 4), (b) Early Cretaceous to Cenomanian (Figure 5), (c) Late Cretaceous (Figure 5), and (d) undifferentiated Cenozoic (Figure 6).

Late Jurassic

Sites that have reached Upper Jurassic basement frequently show the presence of red, clayey limestone (Facies 2) of late Kimmeridgian-Tithonian age underlain by marly sediments and overlain by white-gray limestones (Facies 1). In the deepest sites (Sites 391 and 100), red, clayey limestones are followed by argillaceous limestones with chert of Tithonian age. These facies relationships are well known in the Tethysian pelagic series, where red, clayey limestone is considered a dissolution facies and is related to sedimentation around a foraminiferal CCD (about 1000 m above the CCD at present; Bosellini and Winterer, 1975). This corresponds to a foraminiferal CCD of 2700 to 3000 meters (Figure 4). The red, clayey limestones seem to be specific to Late Jurassic sedimentation in the north Central Atlantic. All sites stay above the CCD level during this period (Figure 4).

The scarcity of sites where basement is older than lower Tithonian does not permit precise bathymetry, so that no geographic reconstruction has been made for the Late Jurassic. Site 367 on the African plate and Sites 100, 101, and 105 on the American plate are close to the mid-ocean ridge crest for an age of about 140 m.y. All these sites are deeper than 2000 meters and show red, clayey limestone deposits (Facies 2). Site 391 near the axis of the western Atlantic Basin (3200 m depth) also shows the same sediment facies.

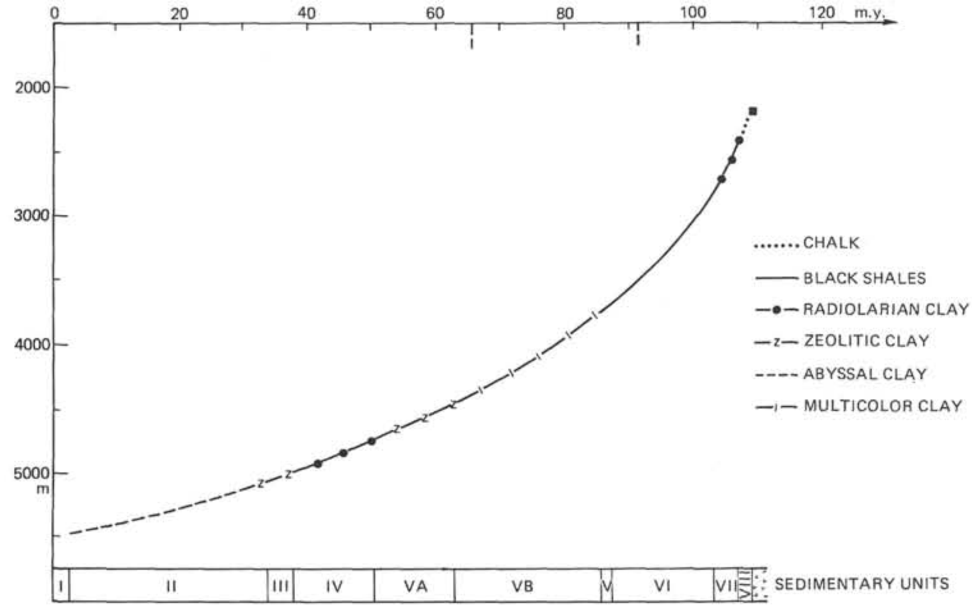

Figure 3. *Subsidence curve for Hole 417D, illustrating the depths of deposition of each sediment unit. The black square represents the initial depth at the ridge crest when the site was created.*

White limestones are deposited at the same time on the northern shallow site (1700 m depth), Site 135.

Early Cretaceous to Cenomanian

From Berriasian to Barremian times, all sites show limestones with various marl contents (Facies 1); therefore deposition was above the CCD (Figure 5). Then, starting anywhere from Aptian to Cenomanian, black shales (Facies 3) rich in organic matter appear, except for Sites 136, 137, and 384. The black shales are always devoid of carbonate for all the sites of the Central Atlantic; thus, the carbonate line is crossed at a depth close to that where black shales are deposited.

A reconstruction of the Central Atlantic between the Newfoundland fracture zone in the north and the Guinea-Bahama fracture zone in the south for magnetic anomaly *M*0 time (late Aptian, 110 m.y.) is shown in Figure 7, using the parameters of Schouten (*in* Rabinowitz et al., 1979) for Africa-North America, and Sibuet (personal communication) for Iberia. The depth of the 11 sites enables a bathymetric sketch to be made in the late Aptian geographic setting of the Central Atlantic. The bathymetric method illustrated here is similar to that of van Andel et al. (1975), but differs from the approach of Sclater and McKenzie (1973) and Sclater et al. (1977) in which the isobaths are derived from a theoretical (or empirical) model. Depth anomalies at the drilling sites are presented in the bathymetric maps; for example, the anomalous deep in the western Atlantic Basin (Figure 7) reaches a depth of about 4000 meters. The ridge crestal depth is about 2200 meters in the southern part of the domain as shown by the sites on the Bermuda Rise (Sites 417, 418, and 386). It becomes shallower to the north as shown independently by sites on the African (Site 136) and American (Site 384) plates, both above 1200 meters. The same general relationship prevails at the present crestal depth of the Mid-Atlantic Ridge.

The intersection between the carbonate compensation surface and the sea floor (Figure 7) defines two domains below the CCD: one far from the mid-ocean ridge in the deep basins below 3000 meters, and the other as a narrow and discontinuous region on the ridge crest at a depth of about 2000 meters. The map depicts two black shale facies covering the entire Central Atlantic (including continental margin sites not shown here, because their depths are unknown), except for the limestones which are restricted to the shallow areas in the north and occasional sites on the ridge (Hole 417D and Site 418).

Late Cretaceous

Many of the sites with a basaltic basement older than Late Cretaceous (Sites 137, 138, 417, 418, and Jurassic basement sites) reach a great depth (to 4600 m), and sediments typical of a very deep environment of deposition characterize the sedimentary column. All these sediments are carbonate free and were probably deposited below the CCD.

Multicolor clays (Facies 7) always occur above the black shales and only during the Late Cretaceous. The facies may correspond to the last term of a deepening Cretaceous sedimentary sequence with carbonate muds, black shales, and multicolor clays being sedimented successively. This deep, pelagic sequence prevails over a wide depth range; that is, it is deposited at depths between 2000 and 3800 meters at Site 386 and between 2500 and 4500 meters at Site 387.

The radiolarian clay and chert (Facies 4) and the zeolitic clay (Facies 5) occur during any period in the areas of the North Atlantic that lie below the CCD. The difference between the two facies may be diagenetic, because the zeolites of Facies 5 are commonly the result of radiolarian epigenesis.

A reconstruction of the Central Atlantic for magnetic anomaly 34 time (Santonian, 80 m.y.) is given in Figure 8,

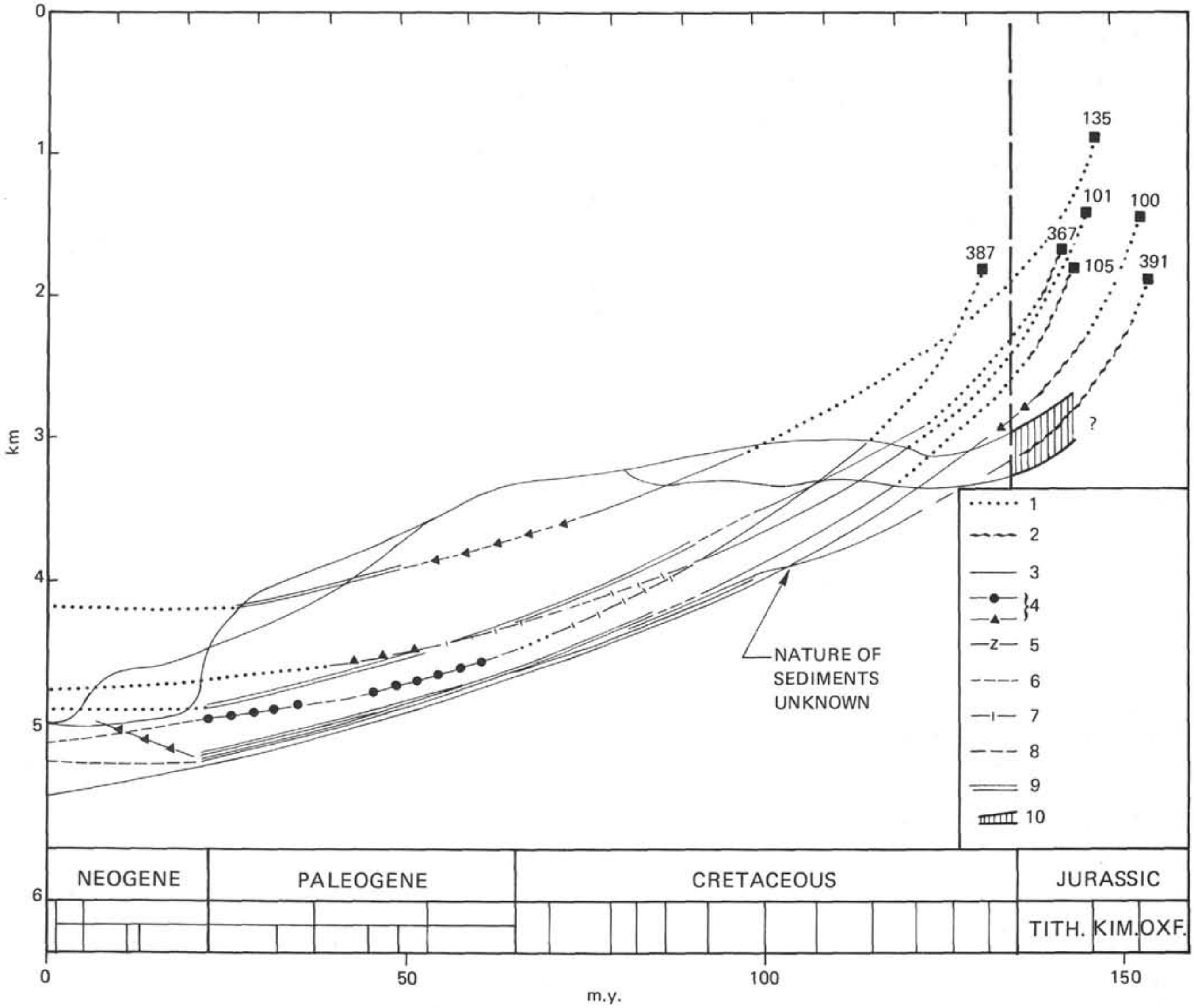

Figure 4. *Subsidence curves of central Atlantic sites emphasizing Jurassic sites. 1: limestone; 2: red clayey limestone; 3: black shales; 4: radiolarian clay and cherty clay; 5: zeolitic clay; 6: abyssal clay; 7: multicolor clay: 8: redeposited sediments; 9: hiatus; 10: range of CCD levels. The black square with site number is the crestal depth.*

using the parameters of Le Pichon and Fox (1971) for Africa-North America and those of Sibuet (personal communication) for Iberia. All sites in the deep basins show deep-water facies as discussed here. The occurrence of hiatuses at sites of the eastern continental margin of North America (Sites 391, 105, and 384) showing differing depths is probably due to bottom contour currents with their origin in the South Atlantic. The shallow depth of Site 385 located on the flank of Vogel Seamount is probably only meaningful locally. Thus the isobaths near this site are drawn very tentatively.

Tertiary

This period will not be discussed here, except for some trends of the CCD (Figure 10). From the Paleocene, the average CCD deepens steadily until the Oligocene, where it reaches 4200 to 4500 meters. The depth evolution is bracketed by Site 10 which shows carbonate sediments while the deeper Site 385 shows abyssal clays. The flysch occurrence at Site 135 fits this model, because Berger and von Rad (1972) consider the sediments to have been deposited below the CCD. The significant deepening of the carbonate line may be caused by influx of Antarctic bottom water and its effect on fertility, or by the very low eustatic sea-level position during the Oligocene following the extensive late Mesozoic transgression and the resulting carbonate partitioning between shallow and deep seas (van Andel, 1975).

After the Miocene, the results do not fit from site to site. Thus, Site 386 gives a CCD above 4700 meters, while it must be 4900 meters to satisfy the data of Sites 101 and 105. The pronounced CCD shoaling inferred for the Miocene by Berger and von Rad (1972) for the Atlantic Ocean and van Andel (1975) for the Indian Ocean has not been shown by our analysis. Instead, we observe a lull in the evolution of the CCD until it drops to 5000 meters from the end of Miocene to Quaternary.

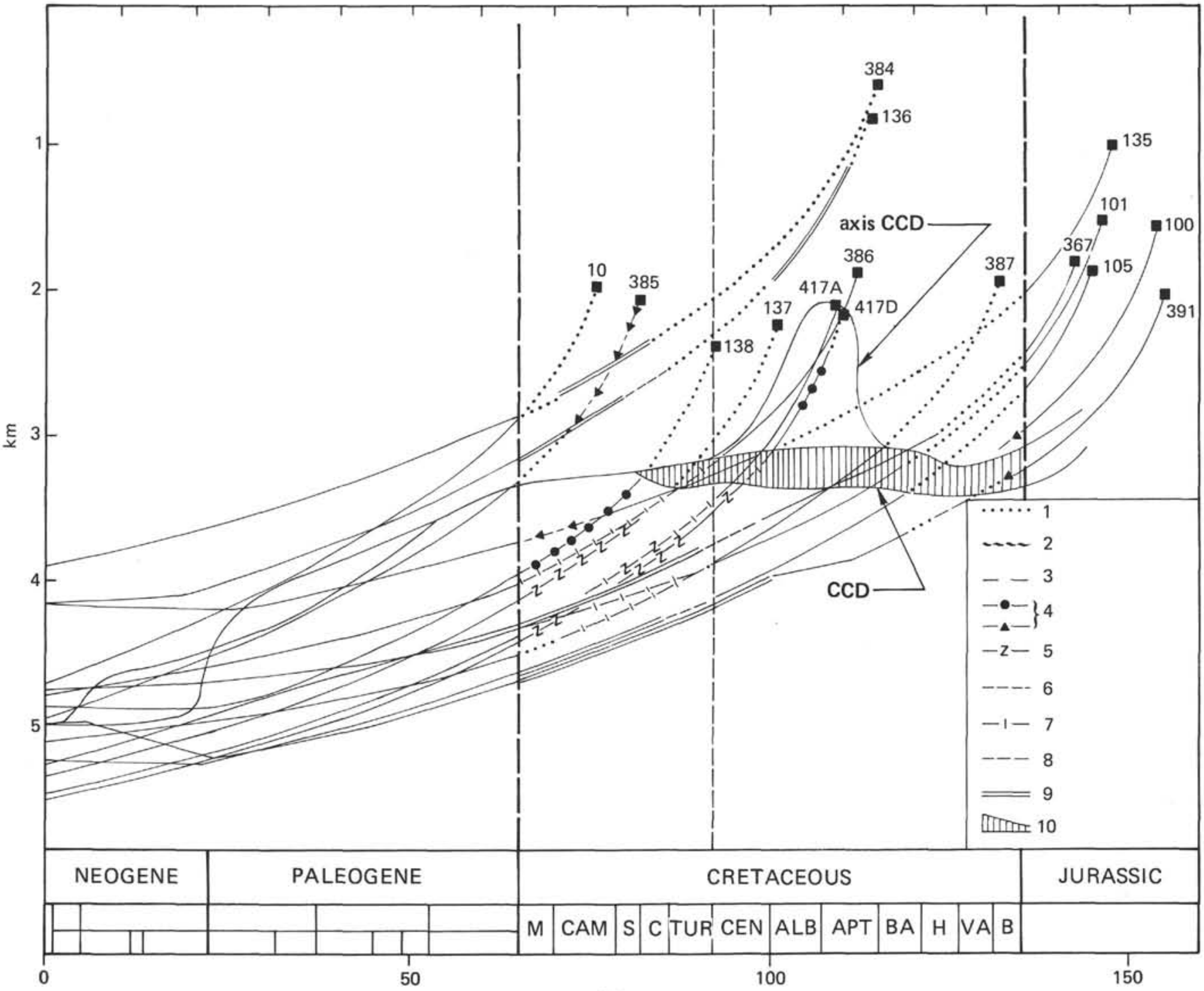

Figure 5. *Subsidence curves of Central Atlantic sites emphasizing facies distribution in the Cretaceous. Key to symbols is the same as in Figure 4.*

The Tertiary sites below the CCD display all the deep-water facies previously discussed for the Late Cretaceous, except the multicolor clays.

Crestal Elevation

The starting point for the subsidence at each site represents the crestal elevation when the site was created according to the *D(T)* subsidence law. The crestal depths of all the sites considered in this paper are shown in Figure 9. Excluding sites located on topographic highs (Sites 136 and 384) or sites that have a poorly defined basement (Sites 136 and 391), the crestal depths increase with time between 155 and 80 m.y. There is a serious gap in the data between 80 and 15 m.y. and a large scatter in the crestal depths of the young sites. In fact, this scatter masks a grouping of depths in the FAMOUS area near 36°N (Sites 332 through 335, 411, and 413) and the Leg 45 Site 396, near the Kane fracture zone at 22°N. Thus, the data reflect the along-strike variation in the crestal depth of the Mid-Atlantic Ridge shown by many authors (e.g., Anderson et al., 1973). The trend of crestal depth with age shown in Figure 9, which is a consequence of the *D(T)* subsidence law, is similar to the empirical law of Veevers (1977) relating crestal depth and age of the ocean basin for sites at the crest of ridges. Whereas Veevers is limited in his approach by the small number of oceans with different ages extant on today's earth, the advantage of our method is that it can derive a crestal depth law for each ocean and can also include a large number of data points. Therefore, the statistics should be improved. The linear relationship between crestal depth and age suggested by the data in the Central Atlantic between 155 m.y. and 80 m.y. (depth = 2040-13.2T, where depth is in m and age T in m.y.) is shown in Figure 9, together with the law of Veevers (1977) for an initial opening age of 180 m.y. for the Central Atlantic Ocean. The fit with Veevers is reasonable, although all sites (except Site 391) are shallower. Part of the scatter in crestal depths may be due to depth variations along the strike of the ridge similar to that found today. In

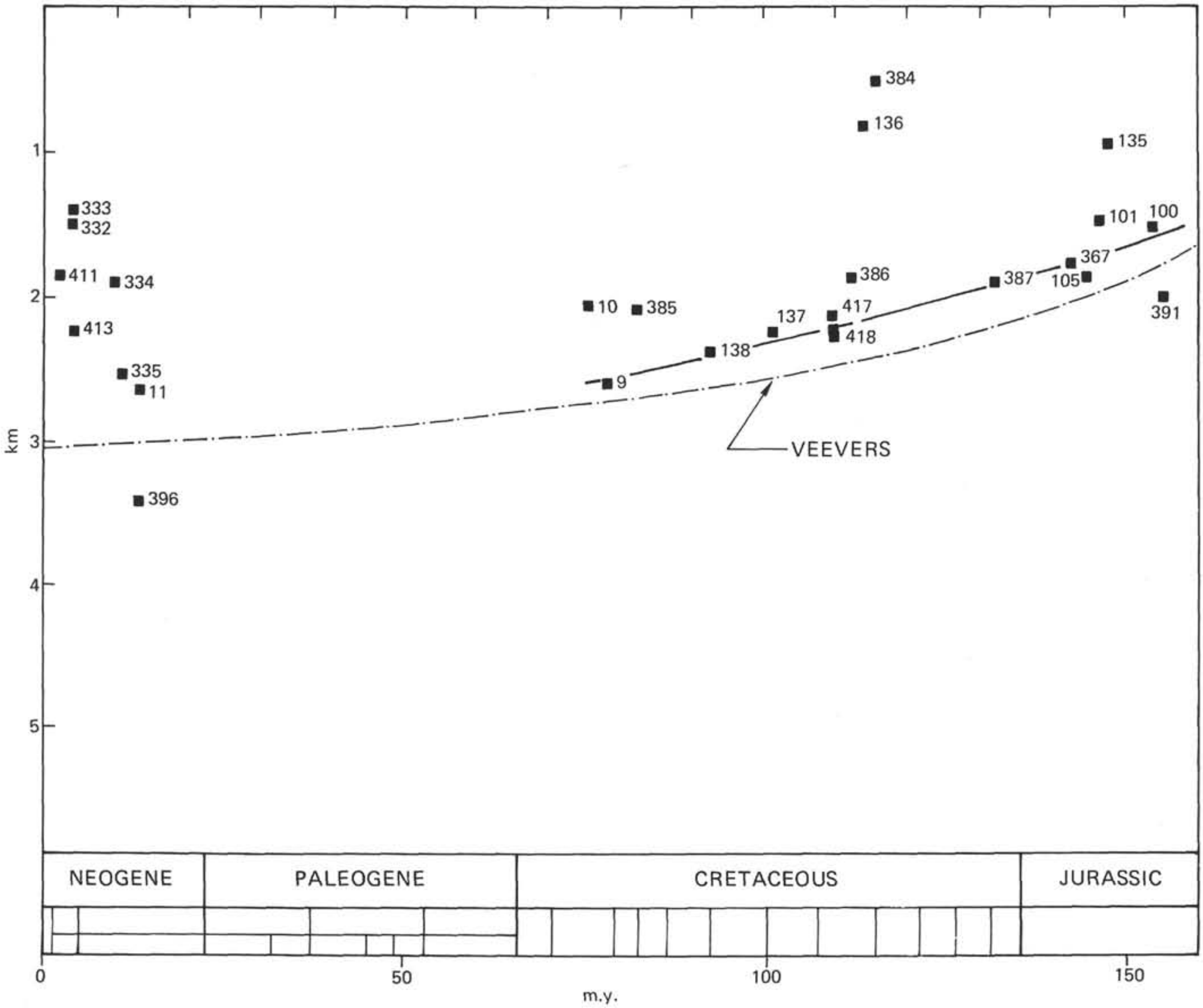

Figure 6. *Subsidence curves of Central Atlantic sites emphasizing evolution of facies distribution in the Cenozoic. Key to symbols is the same as in Figure 4.*

addition, the method does not distinguish among sites created within a rift valley or at the axis of non-rifted ridge. A similar analysis conducted by van Andel et al. (1975) in the equatorial Pacific produced a much greater scatter in the crestal depths. Finally, the Mid-Atlantic Ridge has gradually widened from a rather narrow feature in the Jurassic to the broader one of today. A similar evolution, but starting in the Eocene, was inferred for the equatorial East Pacific Rise (van Andel et al., 1975).

The crestal elevation pattern is, of course, a direct function of the subsidence law $D(T)$. If a fit had been made to account for the flattening of ocean crust with age (Figure 1), the crestal depth would be uniform with the age of the basin. The observed flattening of the depth-age curve for ages older then about 80 m.y. is assumed to be due to processes affecting the older lithosphere. Alternatively, it could reflect a secular variation of crestal elevation with age.

Calcium Carbonate Compensation Depth

The age of the basement is of primary importance for the position of the CCD. Sites with Jurassic basement show that the CCD lay at 3000 to 3300 meters during the Early Cretaceous (Figure 5). The sites with Aptian basement (Sites 417, 418, and 386) have black shales appearing at about 2200 meters, shortly after creation of the crust, and the very low carbonate content shows that the CCD may have been crossed at about this depth (Figure 5). Finally, computing the continental margin CCD versus time and assuming that the thermal subsidence of the basement is valid during the spreading period (after initial "rifting"), the CCD lies at about 2300 ±200 meters for Hole 398D and Sites 400 and 402 of the European margin at Aptian to Cenomanian time (Montadert, Roberts, et al., 1977; Sibuet, Ryan, et al., in press).

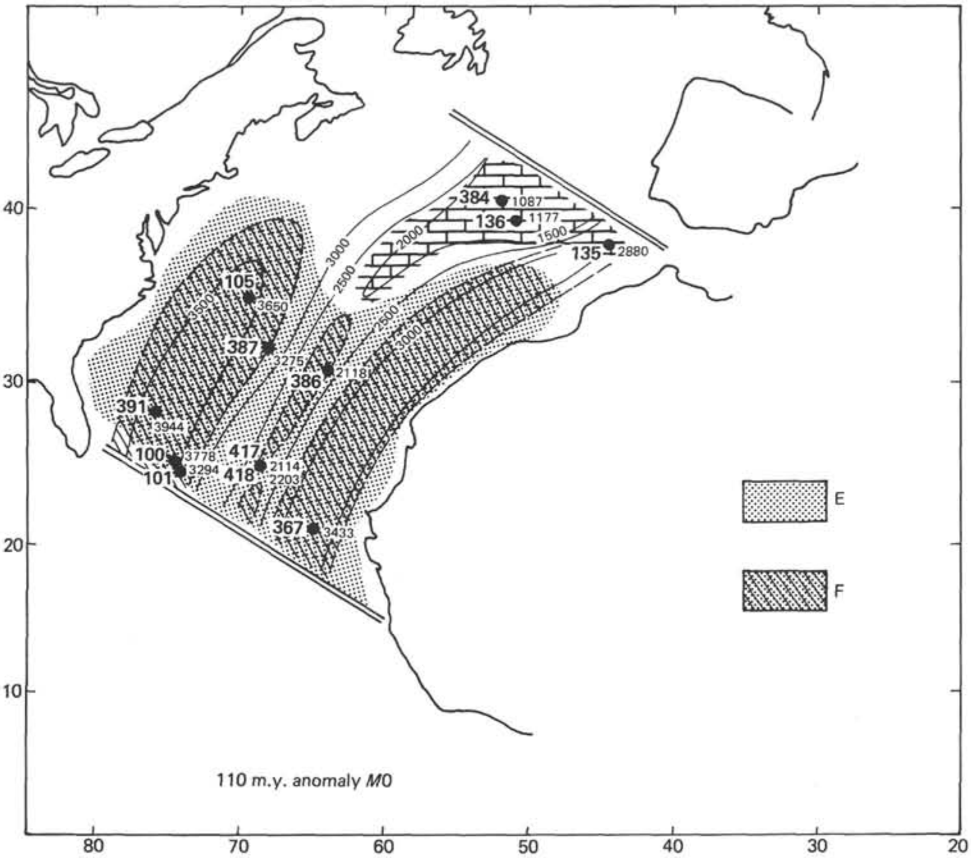

Figure 7. *Bathymetric and geographic map for magnetic anomaly* MO *time (110 m.y.). The black dots mark the position of the site. The number to the right is the depth. E: black shales (Facies 3); F: carbonate-free black shales. The chalk pattern indicates limestone (Facies 1). The rotation applied to Africa and its sites is 65°.6N 20°.2W (-55°). North America and its sites are held fixed. The Newfoundland and Guinea-Bahama fracture zones are shown by parallel lines.*

The wide range of calcite compensation depths in various structural settings at Aptian to Cenomanian times may be explained in two ways. First, the CCD level during this period displays strong variations, and uncertainties in the measured ages of the sites and the depth reconstruction method do not permit description of these variations. Second, the CCD level may be dependent upon the structural setting, with shallower CCD close to the mid-ocean ridge axis and to the continental margin and deeper CCD in the basins. With this model one is led to consider an "axis CCD" (a) defined over a zone of about 400 km, centered on the ridge crest, an "off-axis CCD" (b) in the deep ocean basin, and a "margin CCD" (c) in the continental margin environment. During the Aptian to Cenomanian period (a) is about 2200 $\pm$100 meters, (b) 3150 $\pm$150 meters, and (c) 2300 $\pm$200 meters (Figure 10). In the Jurassic and the Upper Cretaceous one cannot distinguish the three CCD levels, but in the Upper Cretaceous the carbonate line abuts the mid-ocean ridge closer to the crestal zone mainly because the ridge crest has subsided to deeper levels. The model is shown in Figure 10.

We would like to emphasize the influence of the tectonic setting of the CCD level as well as the close association between deposition of black shales and CCD. The causal link between the compensation depth and the sedimentation and preservation of sediments rich in organic matter is still unclear and must await a determination of the relative importance of variables such as ridge-crest elevation and volcanism and also a genetic model for the Cretaceous anoxic events (Schlager and Jenkyns, 1976).

CONCLUSION

This study has shown the importance of the setting of each site in order to make significant correlations. Only two factors, depth and age, have been considered although many others are important, such as deep-water circulation and climatic events. Bathymetric and geographic reconstructions are useful to evaluate the influence of sedimentation at various ages; for example, the effect of current circulation in Santonian time. The bathymetry derived is still of a preliminary character, because of the small number of sites; however, it may be more meaningful for understanding sedimentation than bathymetry predicted from one smooth empirical subsidence curve. Some sites cannot be included in these reconstructions, such as continental margin sites, for lack of subsidence laws.

A gradual change in the depth of the crest of the ancestral Mid-Atlantic Ridge is suggested by the depth data from

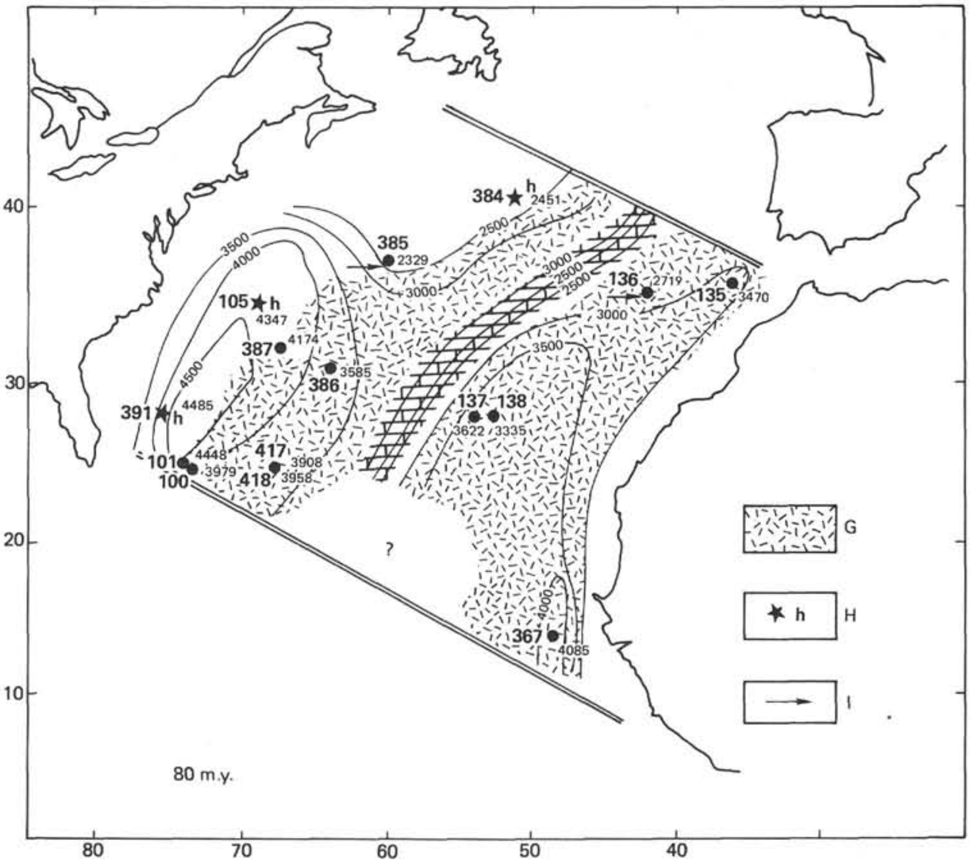

Figure 8. *Bathymetric and geographic map for magnetic anomaly 34 time (80 m.y.). G: Undifferentiated clays including zeolitic clay (Facies 5), radiolarian clay (Facies 4), and multicolor clay (Facies 7); H: hiatus; I: reworked sediments (silt, turbidites) (Facies 8). A carbonate belt has been placed along the axis of the Mid-Atlantic Ridge. The rotation applied to Africa is 79°.1N, 15°.7W (-30.4°). North America is held fixed.*

Jurassic (155 m.y.) to Santonian (80 m.y.). This trend reflects the flattening of ocean floor depths for crustal ages greater than 80 m.y. It is not entirely clear whether a secular crestal depth change is a real feature or whether the flattening is due to processes affecting the older lithosphere.

The CCD evolution-with-time curve is smoother than in previous reconstructions. We introduce the concept of an "axis CCD" associated with the crestal region of the Mid-Atlantic Ridge. The smoothness of our CCD curve may result from the small number of sites or from a different interpretation of the sediment column.

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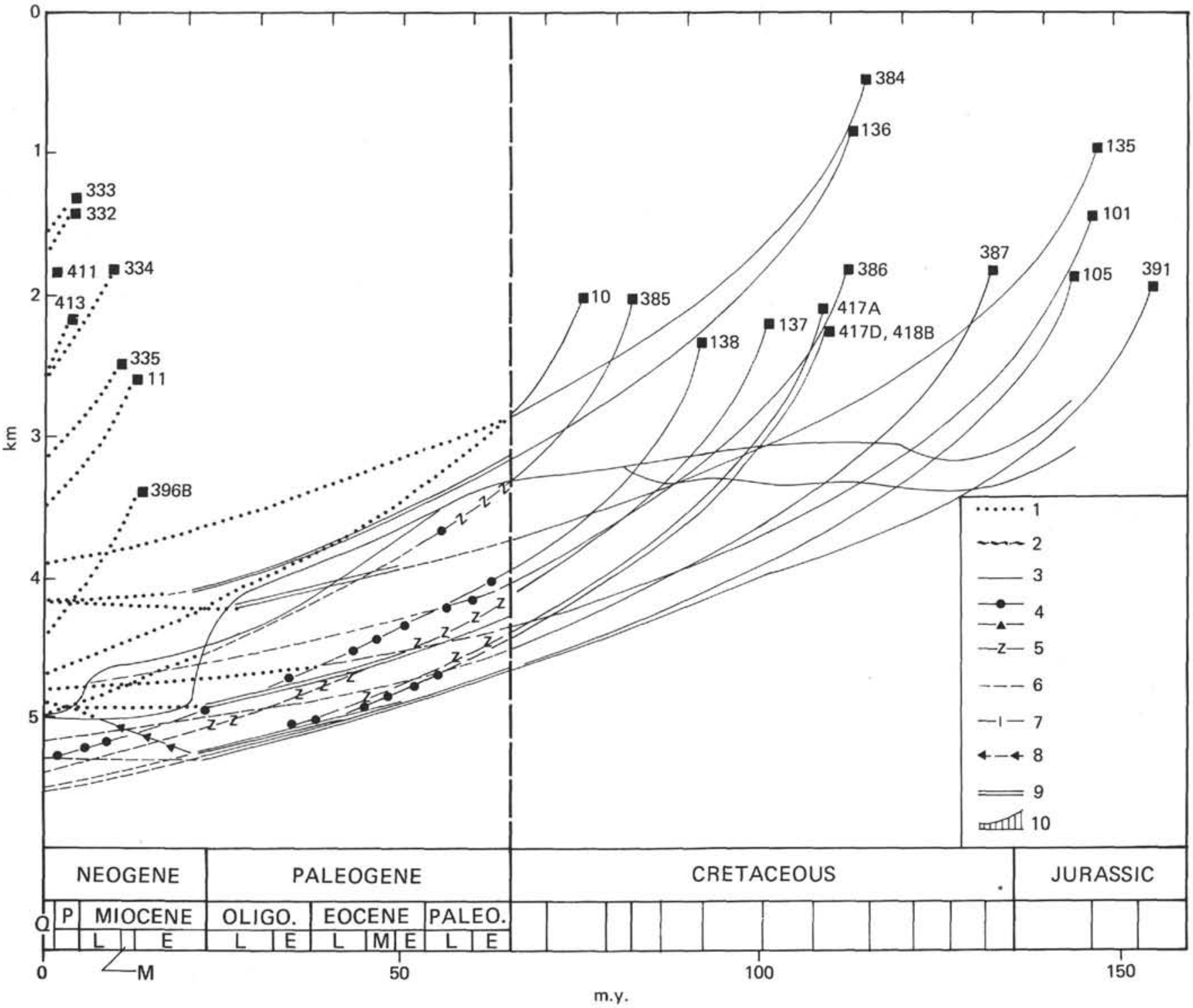

Figure 9. *Plot of crestal depths as a function of age. The numbers indicate the sites. A linear fit (continuous line) has been drawn for the 80 to 155 m.y. time span. The dash-dot curve is Veevers (1977) law with a 180 m.y. age of opening.*

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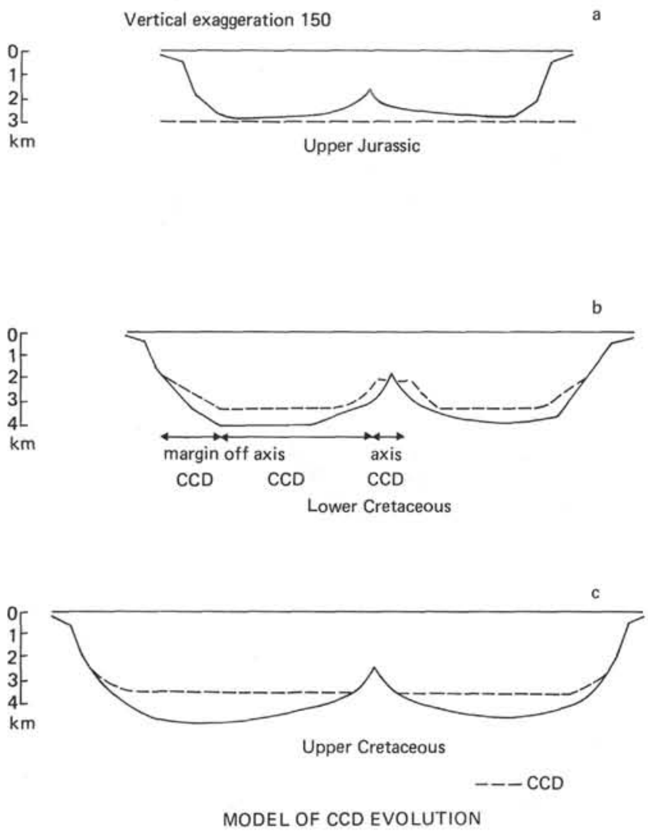

Figure 10. *Model of CCD evolution at three different periods. The CCD level is marked by a dashed line. The Lower Cretaceous diagrammatic section shows the postulated axis CCD.*

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