Geological Survey of Canada
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SSC File No. OSC93-01007-(031)
Contract No. 23420-3-0173/01-OSC
Financial Code: 230-120-00000-720104-04

Open File No. 3156

December 31, 1993

Natural Resources Canada
Ressources Naturelles Canada

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ABSTRACT

The report provides a summary of the organic facies, source rock type and maturation of organic-carbon-rich sediments (black shale, nannofossil chalk, and limestone) of Middle Jurassic (Callovian) to Late Cretaceous (Coniacian) age from various DSDP and ODP Sites of central North Atlantic. Major anoxic events occurred during the Callovian, Aptian-Albian, and Cenomanian-Turonian which resulted in abundant organic-rich shale and limestone on both sides of the central North Atlantic. Potential oil-prone (Kerogen Type IIA-IIB), condensate-prone (Kerogen Type IIB), and gas-prone (Kerogen Type III) source rocks are common on both sides of the Atlantic. Proportionately, the eastern North Atlantic has more oil-prone source rocks (Kerogen Type IIA-IIB). Sites 603, 635, 367, 547, 398, 400 have abundant oil-prone source rocks. About 10-15% of the organic-rich claystone and nannofossil chalks are nonsource (Kerogen Type IV) for hydrocarbons. The presence of several horizons of better source rocks in Callovian and Cenomanian-Turonian age sediments, and higher maturity levels, suggest that there is good potential for crude oil, condensate, and gas reservoirs to be found within 3000m (sediment depth from the sea floor) (for crude oil) to 3500m (condensate) depth in the continental margin of the central North Atlantic region.

INTRODUCTION

In the deep ocean basin, organic matter is being transported through a thick oxidizing water column. It is therefore believed that bathyal and abassal zone rocks retain only refractory organic matter. Contrary to the common belief, continental margin (slopes and rises) rocks can be productive source rocks (SR) to generate crude oil, condensate, and gas (Dow, 1978). Examples of older deep basin source rocks are the Mid-Cretaceous La Luna Formation of Venezuela, Miocene Monterrey Formation from southern California, and Permian Spraberry or Wolfcampian Formations from West Texas which are correlated to several crude oils from those basins.

Study of the nature and origin of organic matter from the continental margins of the central North Atlantic was initiated from the wells drilled by Glomar Challanger under the control of Deep Sea Drilling Project controlled by the Scripps Institution of Oceanography, La Jolla, California during 1968 to 1984. Some *COST* wells which were drilled prior to DSDP, also added more information. The Ocean Drilling Program (ODP) started drilling in 1985 in the deep basins of the world. However, with one exception, none of the ODP sites penetrated the Jurassic-Cretaceous sediments of the central North Atlantic.

The deep ocean sedimentary basins of the North Atlantic were developed as a result of the breakup of Pangea and formation of the North Atlantic ocean during the early Mesozoic. The oldest rock was possibly a Triassic shale in Site 547 of the eastern North Atlantic (Hinz et al., 1982). On both sides of the N. Atlantic, the amount and type of black shale and limestone (probable SR for oil and gas) change markedly with location and age. However, they are concentrated mainly in narrow geological age ranges: Mid to Late Jurassic (Callovian-Kimmeridgian); late Early Cretaceous (Aptian-Albian) or early Late Cretaceous (Cenomanian-Turonian) age. A wealth of data are available to define source rock type and maturation from various sediments of Jurassic-Cretaceous age from the central North Atlantic (Dow, 1978; Erdman and Schorno, 1978; Kendrick et al., 1978a, 1978b; Deroo et al., 1978a, 1978b, 1979a, 1979b, 1980a, 1980b; Habib, 1979, 1983; Tissot et al., 1979, 1980; Welte et al., 1979; Simoneit, 1979; Timofeev and Bogolyubova, 1979; Cornford, 1979, 1980; Boutefeu, 1980; Tissot and Pelet, 1981; Summerhayes, 1981, 1986; Herbin et al., 1983, 1986; Summerhayes and Masran, 1983; Hartung et al., 1984; Mukhopadhyay et al., 1984; Rullkotter et al., 1984a, 1984b, 1986, 1987; Rullkotter and Mukhopadhyay; 1984, 1986; Tyson, 1984; Stein, 1986, 1991). The objective of the present report is to synthesize various data from the DSDP wells (both sides of the central North Atlantic) in order to assess the source rock potential and maturation of Jurassic-Cretaceous sediments which may generate and migrate crude oil and gas to nearby structures.

DATA BASIS

The information used in this review of the amount, type, and maturation of various Jurassic-Cretaceous sediments are based on : (a) results of the writer's geochemical analyses and (b) data extracted from the published DSDP *Initial Report* volumes; various other articles published in a variety of journals; and one ODP *Scientific Results* volume. A series of organic-rich rocks from various DSDP Sites from both sides of the central North Atlantic were selected. Those DSDP Sites are: western Atlantic - 101, 105, 144, 386, 387, 390, 391, 392, 417, 418, 534, 603; eastern North Atlantic - 120, 135, 137, 138, 367, 368, 369, 370, 398, 400, 402, 415, 416, 545, 547, 549, 550, 551; ODP Leg 101 (Site 635) (Fig. 1).

ACCUMULATION OF ORGANIC MATTER IN CONTINENTAL MARGIN

Relating the types of organic matter (OM) found in deep ocean basin sediments to their origin requires a knowledge of sediment transport and depositional mechanisms. In a general sense, it is evident that the accumulation of organic carbon in the recent deep basin is related to the amount of suspended particulate OM and transformed particulate OM (from the degradation of dissolved OM by bacteria). Table 1 shows the distribution of particulate organic carbon (μg/l) and total particulate organic matter (μg/l) in the various basins of the world with an emphasis on the Atlantic Ocean. Accordingly, the average preserved total organic carbon in deep ocean sediment is 0.3 (wt. %). The discrepancy between the amount of total organic matter (μg/l) and total organic carbon (wt. %) in deep sea sediments is dependent on the settling velocity of the organic particles. Table 2 illustrates the settling velocities of quartz or calcite, vitrinite, inertinite (fusinite), and amorphous liptinite or alginite (organic aggregates). Amorphous liptinite, derived from the degradation of phytoplankton, in the form of fecal pellets would have similar or higher settling velocity to that of fusinite. This data suggest (a) typical pelagic or hemipelagic deep sea sediments contain too little OM (<0.5%) to be effective source rock, (b) the type of OM present is not likely to be good hydrocarbon source rock due to degradation of liptinite during distal transport or during settling through the water column where benthonic reworking leaves only the refractory and inert organic matter. Dow (1978), however, demonstrated that the total organic carbon content of recent bathyal and abyssal sediments from the Gulf of Mexico is as high as 0.6% (wt. %) which is 50% greater than threshold values (0.4%) for a source rock (Fig. 2).

Investigation of the deep marine basin sediments from Jurassic-Cretaceous (DSDP wells) of the central North Atlantic have indicated that some different mechanisms were being encountered by which the "normal case" of sedimentation in deep ocean basin is bypassed to yield potential hydrocarbon source rocks (Welte et al., 1979). In various DSDP wells, there are abundant Mid-Jurassic to Late Cretaceous black shales or limestone, on both sides of the present central North Atlantic ocean, with TOC content greater than 0.7%. These dark colored organic-carbon-rich rocks are possibly related to some form of sporadic or global anoxic events.

Two models are generally proposed for the development of those anoxia. Several authors favour ocean-wide stagnation in the deep ocean similar to the Black Sea (Thiede and van Andel, 1977; Demaison and Moore, 1980; Arthur et al., 1984). In this model, anoxic events with the development of good Type II or II-III (IIA and IIA-IIB) source rocks are formed in a silled basin where oxygen demand for oxidation of OM exceeds the already reduced oxygen supply (Fig. 3A). On the other hand, in the productivity model, which is being favoured by most scientists, anoxic events are formed by different mechanisms and generate excellent Type IIA, IIA-IIB, IIB (Classical Type II and II-III, Tissot and Welte, 1984) and III kerogens (Tissot et al., 1979; Welte et al., 1979; Habib, 1979, 1983; Rullkotter et al, 1984a, 1984b; Degens et al., 1986; Rullkotter and Mukhopadhyay, 1986). However, in the second model, nonsource refractory kerogens (Type IV) are common along with the better source rocks. The mechanism for the deposition and preservation of OM in deep ocean basins are (Fig. 3B):

- Eolian transport followed by settling through the water body (mainly sporinite and fusinite).
- Formation of mid-ocean anoxia by phytoplankton bloom in an upwelling region (mainly tal- and lamalginite with AOM 1 and 2).
- Sinking of autochthonous biomass (zoo and phytoplankton, terrestrial exinite, vitrinite and fusinite) produced in near surface waters (mainly oxidized AOM 1 and alginite).
- Turbidite flow or slumping - dumping the shallow marine sediments to deep ocean sites (mixture of terrestrial and marine macerals).
- Sinking of amorphous organic matter as fecal pellets formed in a shallow marine environment (mainly as AOM 2 and AOM 3).
- Settling of suspended organic matter transported by deep ocean bottom currents in the nepheloid layer.

ORGANIC CARBON, SOURCE ROCK TYPE, AND MATURATION

Organic Carbon

Organic-carbon-rich rocks of Mid-Jurassic (Callovian) age were observed on both sides of North Atlantic (Site 534A in the west and 547B in the east) (Fig. 4). Later deposition of black shale and limestone was concentrated mainly in the Early to Middle Cretaceous (Barremian to

Coniacian). Although the major concentration of black shale is restricted to Mid-Cretaceous, it is evident that the occurrences of black shale are not contemporaneous (Fig. 4).

In each Site, the distribution of average organic carbon content closely follows the distribution of dark-colored rocks (Fig. 5). An average of >1% TOC was observed in Mid-Jurassic (Callovian) and Barremian through Turonian age sediments on both sides of the North Atlantic. In Sites 603, 105, 144, 367 and 356, the average TOC content is greater than 3% within Cenomanian-Turonian rocks. Since black shales account for only 5-25% of the entire lithologic column, which contains abundant organic-lean (<0.3%) interbedded green and red claystones, the average TOC per stage varies between 1 and 3%. Some thin Cenomanian to Turonian age black shale layers in Sites 367, 144, 105, 603 contain more than 5% TOC (Stein, 1986). The highest TOC content of black shale was observed in Site 367 (33.3%) of the eastern North Atlantic (Summerhayes, 1981) and in Site 105 (13.6%) of the western North Atlantic (Deroo et al., 1978a). The organic carbon accumulation rate at the sediment-water interface, which controls the total organic carbon content in older deep marine rocks, is higher in the eastern basin (20 to 100 $gm/cm^{-2}/Ma^{-1}$) in Mid-Cretaceous compared to the western basins (18 to 50 $gm/cm^{-2}/Ma^{-1}$) (Stein, 1986).

Kerogen Type

The types of organic matter as seen in the continental margin sediments are quite similar to those in shallow marine and lacustrine facies (Jones, 1987; Mukhopadhyay and Wade, 1990) which form Kerogen Types IIA, IIA-IIB, IIB, III and IV source and nonsource rocks. However, the nature of the OM in some of the Kerogen Types (IIA, IIA-IIB, and IV) are different from their shallow marine counterpart. As an example, the maceral AOM 2 of Kerogen Type IIA source rock in the shallow marine environment, is highly fluffy and shows strong fluorescence. Compared to that, AOM 2 in the deep marine environment, is in the form of oval-shaped fecal pellets and shows much less fluorescence. Type IV nonsource rock in the deep basin is mainly derived from oxidized alginite, AOM, and fusinite.

For distal transport, marine organic matter (lamalginite [dinoflagellate, acritarch, and coccolith], AOM 2) has low resistance to oxidation compared to terrestrial exinite (sporinite, cutinite, and resinite). Therefore, Kerogen Type IIA, in a deep marine environment, is only preserved by an oxygen deficient regime caused either by upwelling or a high sedimentation rate (Muller and Suess, 1979; Arthur et al., 1984; Rullkotter and Mukhopadhyay, 1986).

At this time, it is a matter of controversy as to how the terrestrial liptinites are well preserved in a deep marine environment. Summerhayes (1981) suggested that distance from the shore plays an important role in controlling the amount of terrestrial OM; better preserved OM is nearer to the coast. Others have suggested that terrestrial OM in distal marine environments is mainly controlled by turbidity flows and slumps (Degens et al., 1986; Rullkotter and Mukhopadhyay, 1984, 1986). The rapid burial of organic-rich sediments on the continental rise increases the ampunt of hydrogen and carbon compared to its decomposition to carbon dioxide and water. Under those circumstances, oxygen depletion starts which forms a temporary anoxia in the deep marine basin. This leads to the formation of organic-carbon-rich black shale with Kerogen Type IIA-IIB and IIB. Callovian black shales at Sites 534A and 547B are examples of this type. Habib (1983), on the other hand, suggested that terrestrial organic matter derived black shale originated mainly from the deposition of fecal pellets.

Comparing the source rock types at various Sites, it is observed that there is a distinct linear relationship between hydrogen index (in mg HC/g TOC) and the ratio of terrestrial and marine organic matter (Fig.6). Except for minor variations, it is evident that marine organic matter enhances the hydrogen content in a source rock.

Figures 7 and 8 clearly illustrate that marine OM is more abundant in the eastern Atlantic compared to the western Atlantic. Distinct differences in the Kerogen Type were observed in different parts of the north Atlantic Basin (Figs. 7, 8, and 9), although they contain similar types of organic matter. As an example, Callovian black shale from both sides of the Atlantic (534A and 547B) contain abundant AOM 2 as fecal pellets and have mixed macerals (Fig. 8; Tables 3 and 5). Samples from the west show less fluorescence compared to the east suggesting partial oxidation of AOM 2 (as fecal pellets) during transport forming dominant Kerogen Type IIB. Aptian to Turonian organic-carbon-rich rocks from eastern Sites 545, 416, 370, 367, 137 contain mixed terrestrial and marine macerals forming Kerogen Type IIA and IIA-IIB, whereas late Jurassic and Valanginian to Albian claystones from eastern Sites 549, 402, 400, 547, 416 contain mainly terrestrial liptinite and humic OM forming Kerogen Type IIB and III. Aptian to Turonian organic-rich rocks from western Sites 534, 105, 386, 387, are mainly Kerogen Type IIB and III with minor proportions of Kerogen Type IIA-IIB and IIA. On the other hand, western Sites 603, 415, and 416, of the same age, contain more Kerogen Type IIA-IIB.

Kerogen Types of various source/nonsource rocks were determined from various DSDP Sites using a pseudo-van Krevelen plot (H/C vs. O/C and hydrogen index vs. oxygen index) (Figs. 10 and 11). Sites 398, 367, 368 contain more AOM 2 forming Kerogen Type IIA-IIB compared to the black shales from Sites 400 and 402 (mainly Kerogen Types III and IV). Lower Barremian to lower Maestrichtian sediments from Sites 549, 550 and 551 contain mainly vitrinite and refractory macerals (fusinite, oxidized alginite of Kerogen Type III and IV (Hartung et al., 1984). In general, however, with the exception of Sites 400, 402, 550, and 551, Aptian to Turonian SR's in the eastern North Atlantic have more oil-prone Kerogen Type IIA-IIB SR than their western counterpart. Some organic-carbon-rich black shales (TOC = 1-3%) from both areas, however, contain Type IV Kerogen (having refractory macerals) which suggests that in the deep basin, TOC content is not the only decisive factor to form a better source rock. Figure 9 shows a comparable picture of organic matter types from both sides.

Detailed analyses of organic-rich rocks from specific sites show some sequential variability of organic-carbon and kerogen type (Figures 12-17); Figs. 12-15 are from three western Sites (105, 534, and 603) and Figs. 16-17 are from two eastern Sites (545 and 547). In Site 534, some peaks in TOC content are observed in Callovian and Barremian-Aptian age sediments. The comparable hydrogen index vs. oxygen index plot shows only a few samples with Kerogen Type IIA-IIB, most are Kerogen Type III (Fig. 13).

Table 3, 4, and 5 shows the organic facies and source rock potential of Callovian through Turonian rocks from Sites 534, 603, and 547. It shows that in Site 534, the best SR is in the Callovian and Berriasian to upper Barremian section (Fig. 13; Table 3). The organic matter in Site 603, on the continental rise off Cape Hatteras, shows peaks in organic carbon content and hydrogen index values in the Valanginian and Cenomanian-Coniacian forming Kerogen Type IIA-IIB and IIB which are derived mainly from mixed macerals (AOM 2, saprovitrinite, and lamalginite) (Fig. 14; Table 4). An organic-carbon-rich section, approximately 8 m thick, from the late Cenomanian in Site 105, also contains similar kerogen type and organic facies (Fig. 15). In comparison to Jurassic-Cretaceous sediments of the western Atlantic, organic matter in Sites 545 and 547 shows two peaks of better SR quality (one at Mid-Jurassic and one Albian) which forms Kerogen Type IIA-IIB (<5%), IIB (25%), and the rest Kerogen Type III. (Figs. 16 and 17). Table 5 shows that the best SR's in Site 547 occur in the Callovian and Albian. A comparison of organic facies, sedimentological and organic geochemical characteristics of the Callovian (Table 6) and the Albian (Table 7) SR's from Sites 534 (west) and 547 (east) suggest that the eastern source rocks are of better quality.

In ODP Site 635, the Albian-Cenomanian section is organic-carbon-rich (TOC: 0.55-4.05%); with the hydrogen indices of those sediments varying between 58 and 454 mg HC/g TOC (Katz, 1988). A plot of HI vs. OI shows most of the SR's lie between Kerogen Type II and III, suggesting abundance of Kerogen Type IIA-IIB an IIB (Katz, 1988).

The Pliocene to Pleistocene sections of Baffin Bay and Labrador Sea (ODP Sites 645, 646, and 647) and from Northwest Africa (ODP Sites 658, 657, and 659) are extremely organic-carbon-rich and have Kerogen Type IIA and IIA-IIB, and IIB which are partially formed in an upwelling zone (Stein, 1991). However, those sediments were not considered to be productive source rocks because of their extremely low maturation (T_{max}°C: 405 to 425°).

Maturation

Mean random reflectance (% R_o) and T_{max} (°C) are the two main parameters used for the study of maturation of these sediments. Figures 18, 19, and 20 showed the reflectance profile versus depth of sediments from Sites 391, 534A, 545, and 547A. A comparable maturation profile of sediments from the Angola Basin (Site 530A, Leg 75) was also demonstrated (Fig. 21).

The following shows the depths below the sea floor at which 0.5% R_o (minimum threshold for abundant generation of liquid hydrocarbons, Tissot and Welte, 1984) were reached at various Sites.

Sites	Depth of 0.5% R_o
Site 386	- 950 m (0.37% R_o) (Kendrik et al., 1978)
Site 391	~ 950 m (Dow, 1978)
Site 397	~ 1450 m (Kendrick et al., 1978a)
Site 398	~ 1700 m (Kendrick et al., 1978a)
Site 534A	~ 1500 m (Rullkotter et al., 1986)
Site 547A	~ 950 m (Rullkotter et al., 1984b)

Site 530A	~ 1150 m (Rullkotter et al, 1984a)
Site 545A	~ 950 m (from T_{mac}; Rullkotter et al., 1984b)
Site	0.45% R_o
415 and 416	~ 1600 m (Kendrick, 1978b)

All the above data suggest that Continental Margin Basins of the Atlantic Ocean have considerably higher temperatures compared to the shelf "basins" (example: Cohasset D-42 [Scotian Shelf] = 0.5% R_o at 2500 m). Figures 22 A and B show a plot of T_{max}(°C) versus depth from two eastern Atlantic DSDP Sites; both figures show an uniform increase of T_{max} values from 360 (equivalent R_o = 0.25%) to 430°C (equivalent R_o = 0.5%) (Tissot and Welte, 1984).

Considering the presence of a fair number of Kerogen Type IIA-IIB and abundant Kerogen Type IIB source rocks on both sides of North Atlantic during Callovian, Albian-Aptian, and Cenomanian-Turonian and a higher heat flow compared to shelf, oil, condensate, and gas should be common in reservoirs below 3500 m in the continental rise sediments.

CONCLUSION

* In contrast to general belief, deep ocean basins showed pulses of an anoxic environment during Mid-Late Jurassic (Callovian to Kimmeridgian) and Mid-Cretaceous (Barremian-Turonian with peaks at Albian and Cenomanian in the east and Cenomian to Turonian in the west). Those anoxic events are possibly caused by upwelling and turbidity current. Fresh AOM 2 and terrestrial exinites, mostly in the form of fecal pellets and alginite from shallow marine sediments, were transported to deeper basin by slumping and turbidity flow.

* Organic-carbon-rich black shales, nannofossil chalk and calcareous claystones are concentrated at four distinct geological times within the Mesozoic: (a) Callovian-Oxfordian - both sides; (b) Berriasian-Hauterivian: mainly to the west; (c) Albian-Aptian: mainly east; (d) Cenomanian-Turonian: both sides. Most source rocks have 1-5% TOC on both sides of the Atlantic. High TOC content is not always related to marine organic matter (lamalginite, AOM 1 and 2); some of them are derived from refractory nonsource macerals. Highest TOC content (33.3% was observed in Site 367 in the eastern Atlantic.

* In general, eastern Atlantic deep marine basins have a fair number of oil and condensate source rocks (Kerogen Type IIA-IIB and IIB) of Albian-Aptian and Cenomanian-Turonian age

whereas a majority of western Atlantic SR's in Cenomanian-Turonian are condensate and gas-prone. Sporadic good oil source rocks (Kerogen Type IIA-IIB) in Berriasian-Hauterivian, Albian-Aptian and especially Cenomanian-Turonian in the western Atlantic also observed (example: Sites 105, 391, and 534A). In Site 603 (continental rise off Cape Hatteras) several good Kerogen Type IIA-IIB SR's were observed. Typical Kerogen Type IIA SR's (HI = 550 to 750 mg HC/g TOC) are extremely rare in deep sea basins of the central North Atlantic. About 10-15% of organic-rich claystone and nannofossil chalks are nonsource (Kerogen Type IV).

* In the deep marine environment, most pelagic and hemipelagic sediments contain less than 1.0% TOC due to low diversity of organic species and degradation of organic carbon in the water column during their transport. The organic matter is mostly oxidized vitrinite and refractory inertinites, which are formed due to their high settling velocity compared to AOM 2 and alginite; those OM are gas-prone or nonsource. On the other hand, better quality source rocks (Kerogen Type IIA-IIB and IIB), in deep marine environments, are being formed in one of the following ways: (a) the presence of high sedimentation rate and transportation of OM by turbidity currents and slumping, (b) formation of a mid-oceanic anoxia caused by the high concentration of phytoplanktons in a nutient-rich upwelling zone, (c) AOM 2, formed in an anoxic environment within the shallow marine zone, is being transported as fecal pellets, and (d) the organic matter is formed in an anoxic enviroment within a silled basin (similar to deep sediments in the Black Sea).

* Continental margin SR's on both sides of the central North Atlantic have sustained considerably higher paleotemperatures (based on vitrinite reflectance) compared to the Shelf sediments which is possibly due to their closeness to the rifting centre. The presence of several horizons of good source rocks in Callovian and Cenomanian-Turonian age sediments, and higher heat flows, imply the possible existence of crude oil and condensate within 3000 m of the sediment water interface.

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FIGURES

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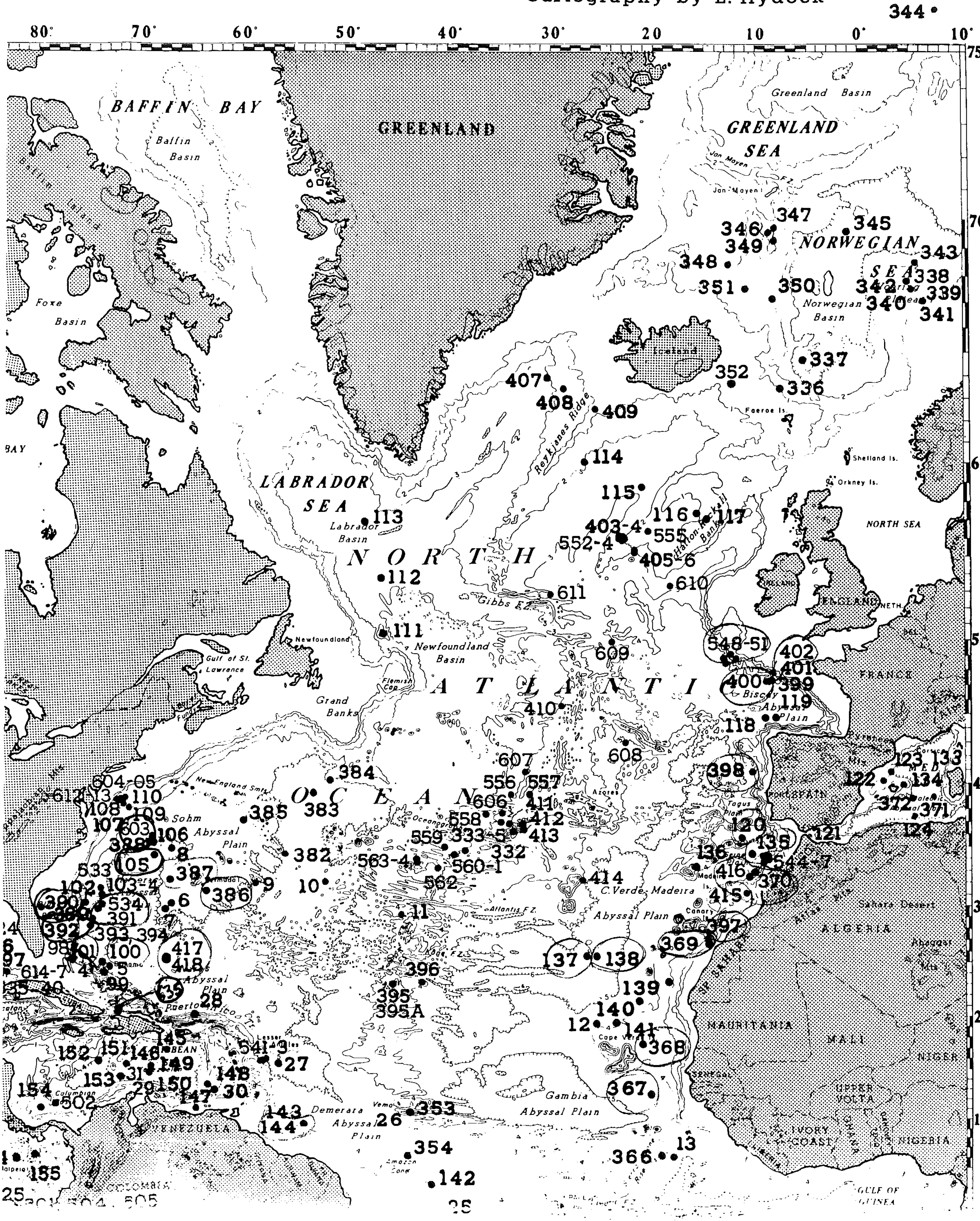


Cartography by L. Hydock

Figure 1

Total particulate matter and particulate organic carbon variation with depth: a compilation of literature data (bracketed values: ranges, unbracketed: means).

Sources:

a) Brewer et al. (Atlantic)[15]
b) Menzel and Ryther (Pacific + Atlantic)[18]
c) Biscaye and Eittreim (Atlantic)[11]
d) McMaster et al. (Atlantic, W. African coast)[16]
e) Milliman (Atlantic, W. African coast)[5]
f) Wenzel (world mean)[7]
g) Huntsman and Barber (Atlantic, W. African coast)[31]
h) Karl et al. (Cariaco Trench)[17]
j) Gordon (NW Atlantic)[32]
k) Parsons and Seki[22]
l) Riley (review, N. Atlantic)[20]
m) McIver (worldwide)[19]

	Particulate organic carbon (µg/l)		Total particulate matter (µg/l)
Surface waters, eg. 0 - 400 m	30(15-52)[d]	50[h]	20-80[a]
	(140-420)[e]	12(95-145)[j]	140(16-670)[d]
	(100-300)[g]	(100-250)[k]	(250-750)[e]
Mid and deep waters, e.g. >400 m	5-10[b]	4(0.5-33)[j]	20(12-25)[a]
	10(3-10)[f]	(20)[k]	3-5[c]
	60(50-75)[h]	(16-50)[l]	
Nepheloid layer, e.g. <1000 m from deep sea floor	(1.6-3.0)[j]		20-200[a]
			150[c]
			(320)[d]
	sediment accumulation and lithification		
Deep sea sediments		(0.3% C_{org})[m]	

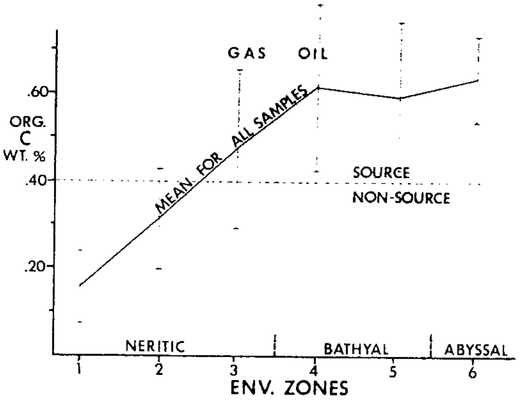
Table 1

Settling velocities of spheroidal particles of 10 μm diameter

a = calculated from Stokes law
b = experimental values[20]

	Settling velocity (m sec^{-1})	Time to settle through 4000 m of water (yrs)
10 μm quartz or calcite [a] (density 2,6 g/cc)	62×10^{-6}	2,0
10 μm fusinite [a] (density 1,6 g/cc)	23×10^{-6}	5,4
10 μm vitrinite [a] (density = 1,3 g/cc)	12×10^{-6}	10,9
5 - 15 μm organic aggregates [b]	3 to 6×10^{-6}	22,0

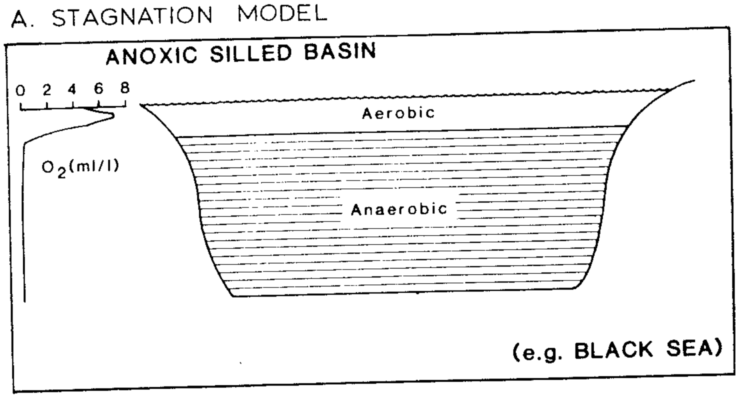
Table 2



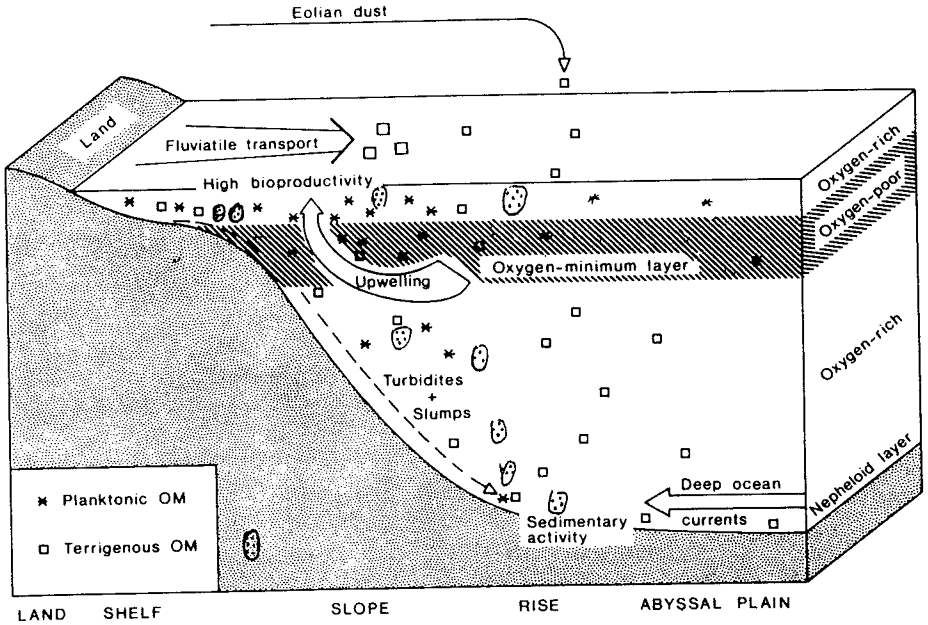
Mean organic-carbon values in various Gulf Coast environmental zones. Bars represent standard deviation of mean and approximate range in values.

Figure 2

A. STAGNATION MODEL



B. PRODUCTIVITY MODEL

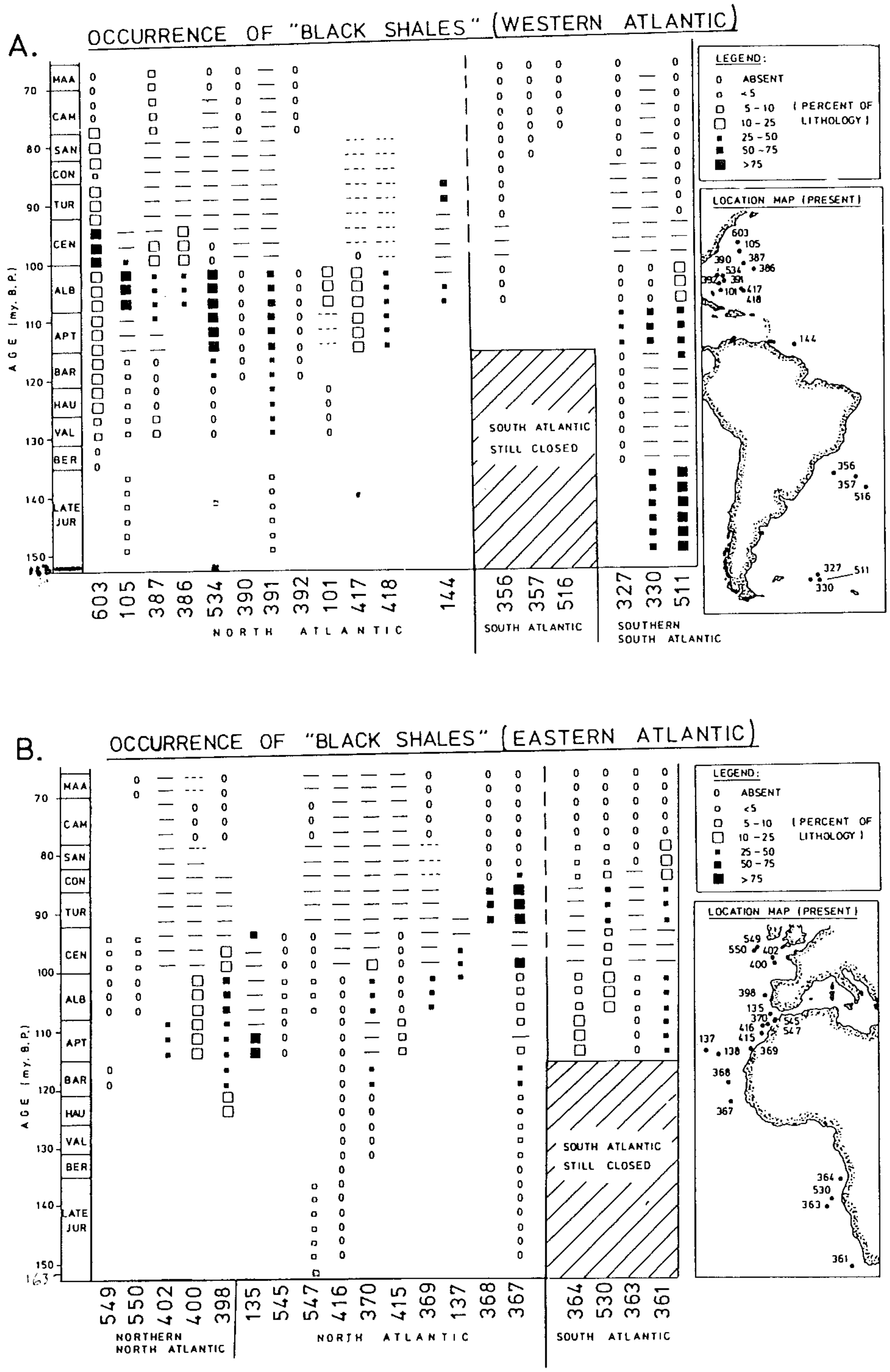


General models for the deposition of organic-carbon-rich sediments.

A. Stagnation model of the type "Black Sea"

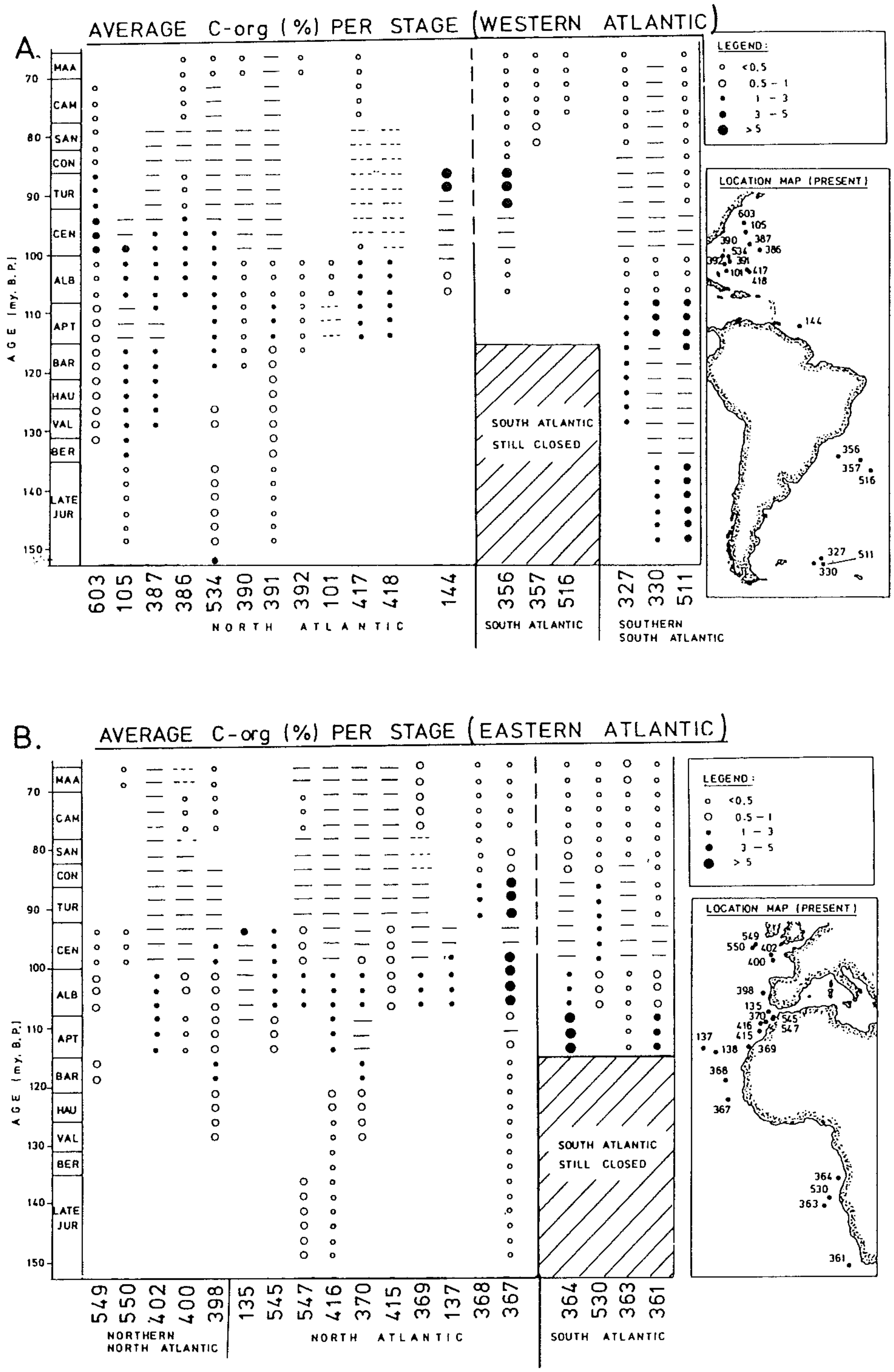
B. Productivity model, including influences of oxygen-minimum layer, terrigenous input and turbidity currents (modified after Cornford, 1979).

Figure 3



Occurrence of black shales in the Late Jurassic—Cretaceous Atlantic Ocean, based on the lithology descriptions published in the *Initial Reports of the Deep Sea Drilling Project* *Dashes* indicate hiatuses.

Figure 4



Distribution of weighted average organic carbon percentages per stage in Late Jurassic—Cretaceous Atlantic Ocean sediments *Dashes* indicate hiatuses.

Figure 5

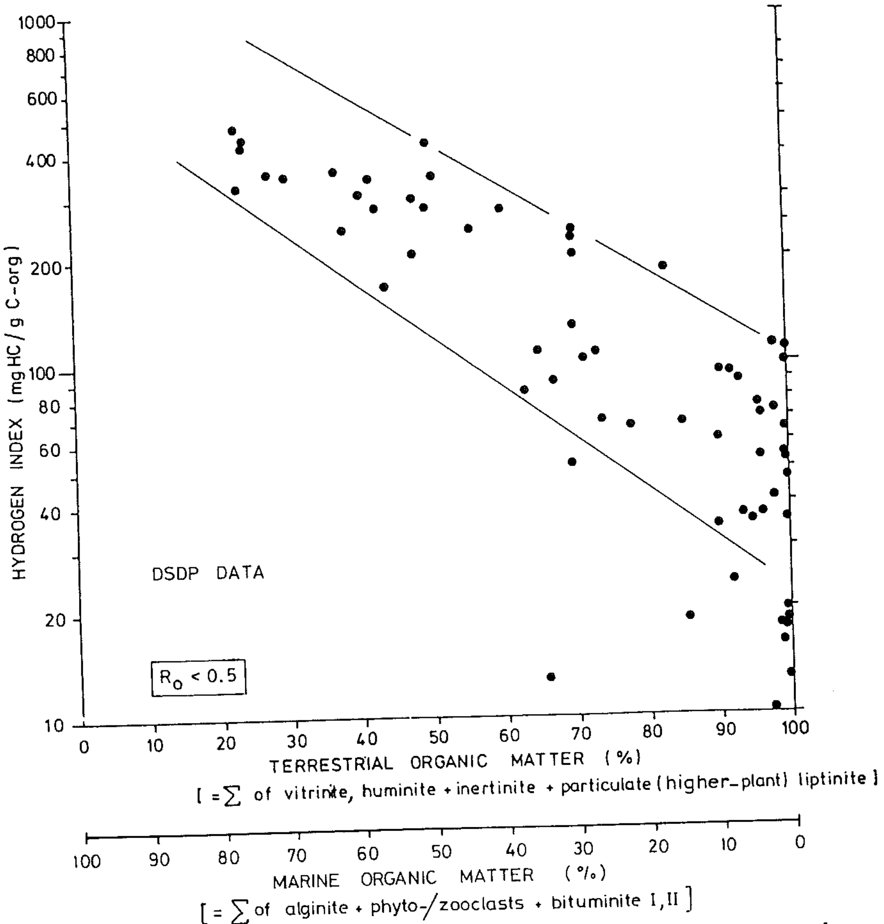
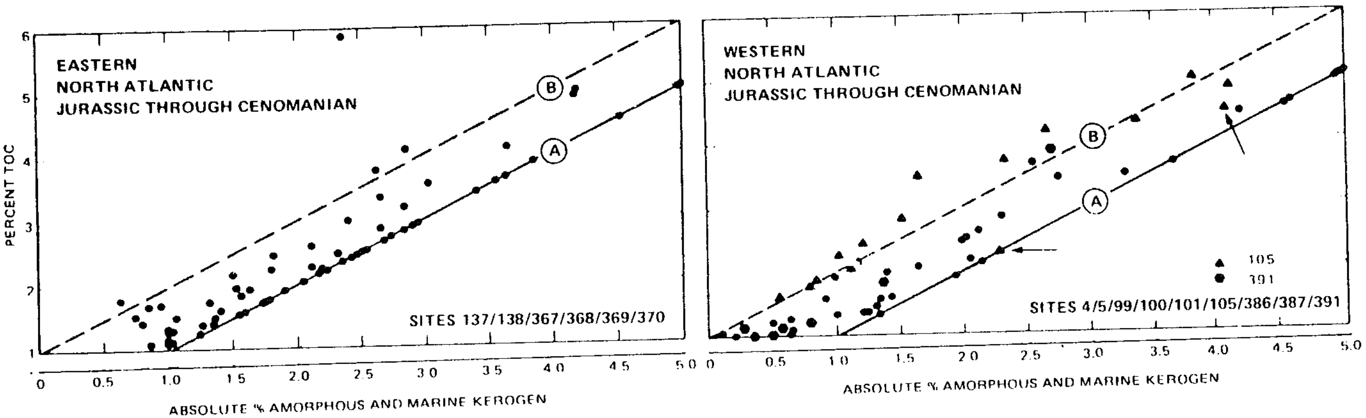


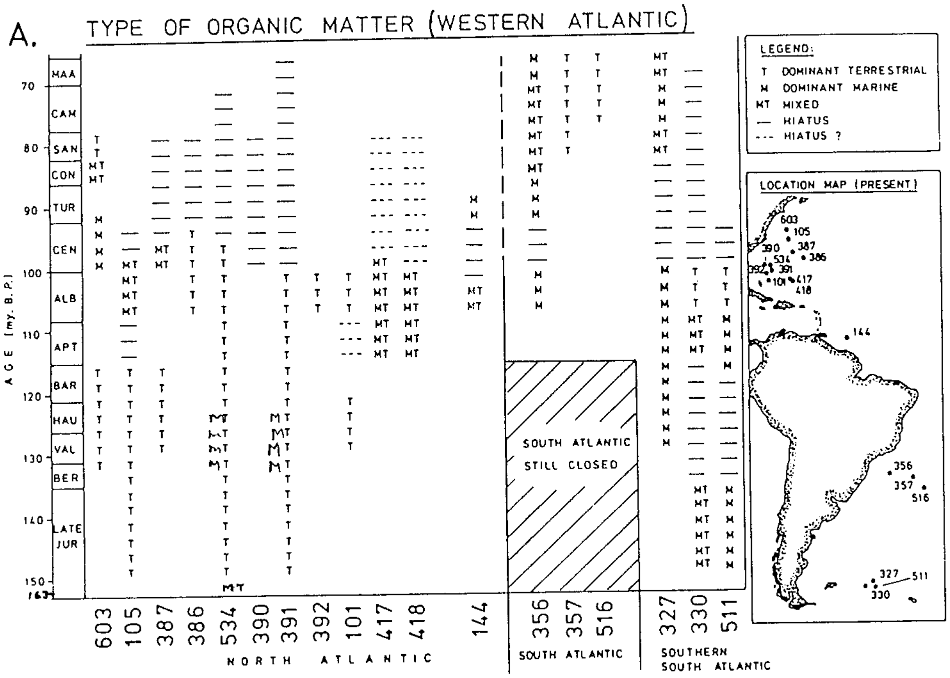
Figure 6

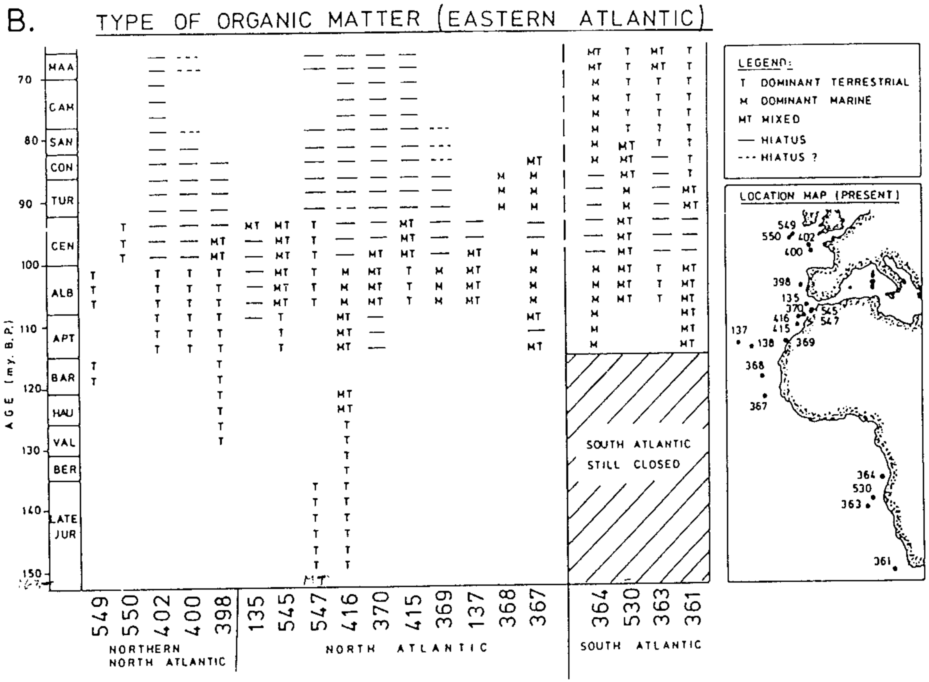
Correlation between hydrogen index values from Rock-Eval® pyrolysis and maceral components from kerogen microscopy. Determinations were performed on immature DSDP samples ($R_0 < 0.5\%$).



Dependence of TOC on absolute content of amorphous and marine kerogen (which is TOC × sum of amorphous, gray amorphous, round bodies, and structured marine kerogen types). Values greater than 5% have been divided by appropriate factors to bring them onto plot. Line A samples are totally controlled by amorphous and marine kerogen; line B samples have TOC controlled by amorphous and marine kerogen above background of 1% TOC that is not amorphous or marine. Arrows point to two samples from site 105 (western North Atlantic) from rich unit at top of Cenomanian.

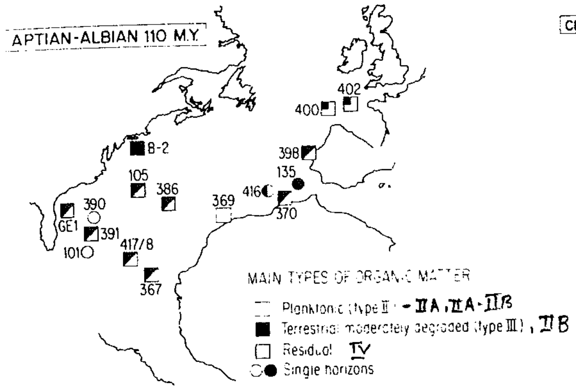
Figure 7



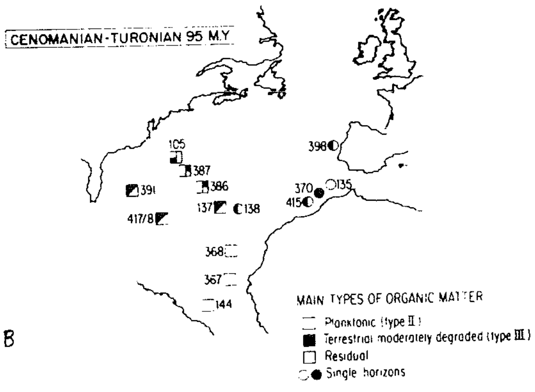


Type of organic matter in the Late Jurassic—Cretaceous Atlantic Ocean sediments. Classification is based on data derived from Rock-Eval® pyrolysis and kerogen microscopy T = dominantly terrigenous (i.e. > 60%); MT = mixed (40—60%, terrestrial/marine); M = dominantly marine (> 60%) organic matter. *Dashes* indicate hiatuses.

Figure 8

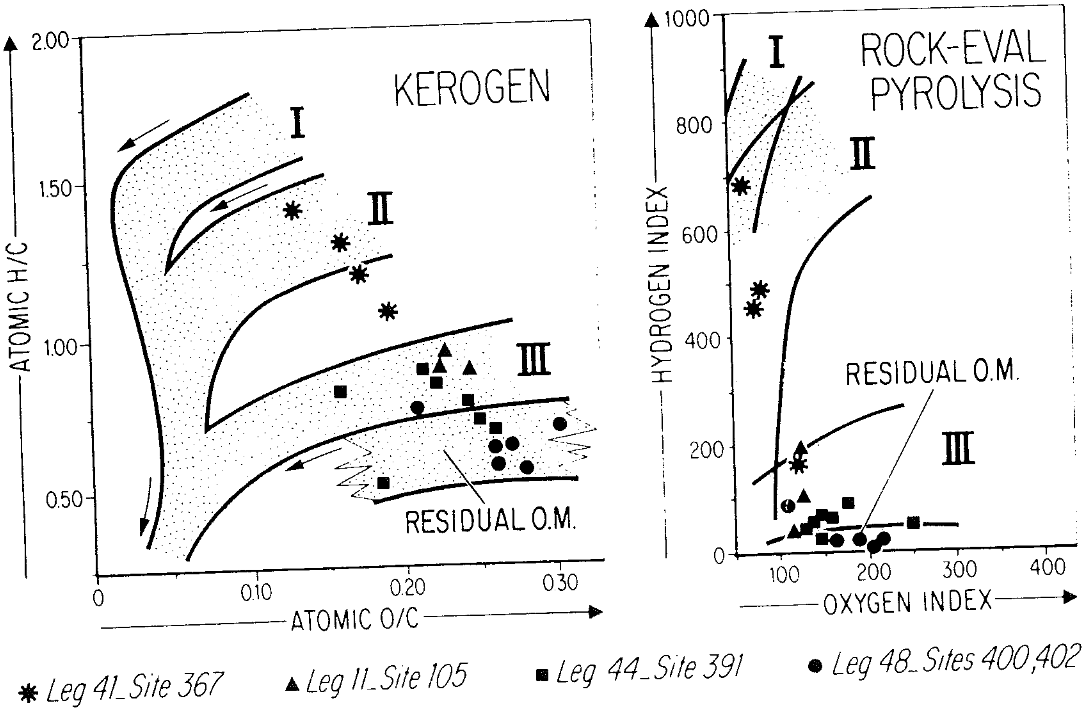


Main types of organic matter observed in Aptian and/or Albian beds of North Atlantic (position of continents is only approximate at 110 m.y.). From Tissot et al (1979), with additions.



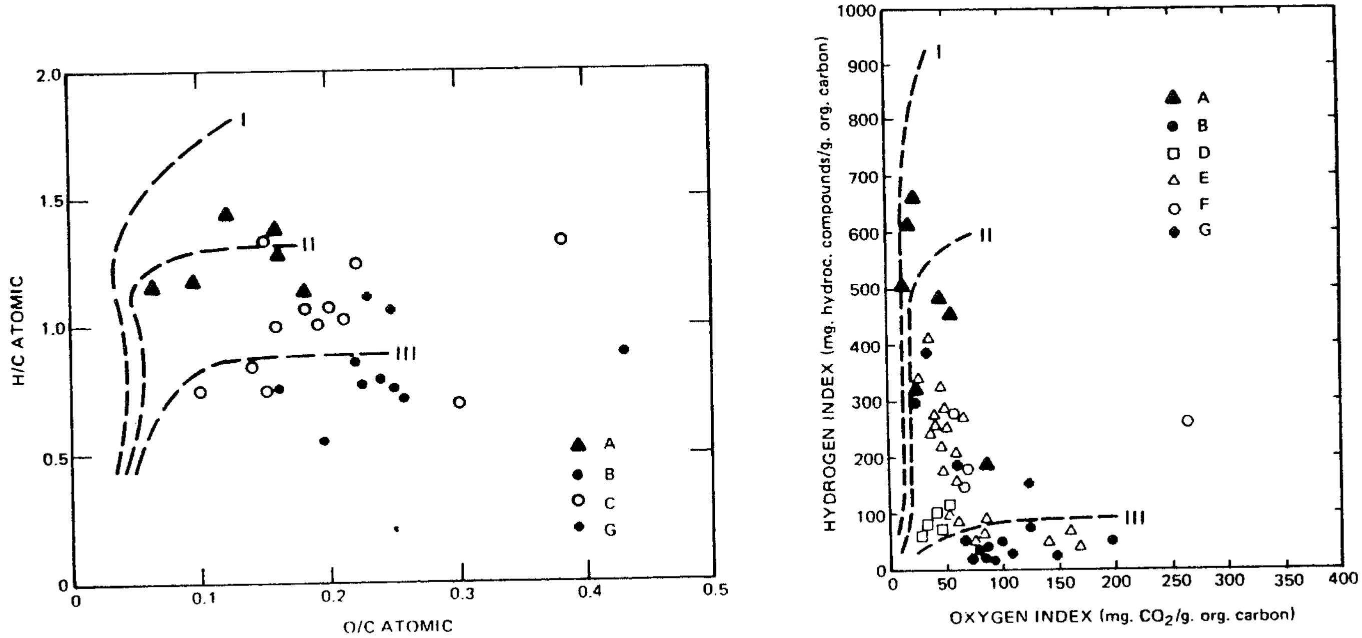
Main types of organic matter observed in Cenomanian and/or Turonian beds of North Atlantic (position of continents is only approximate at 95 m.y.). From Tissot et al (1979) with minor changes.

Figure 9



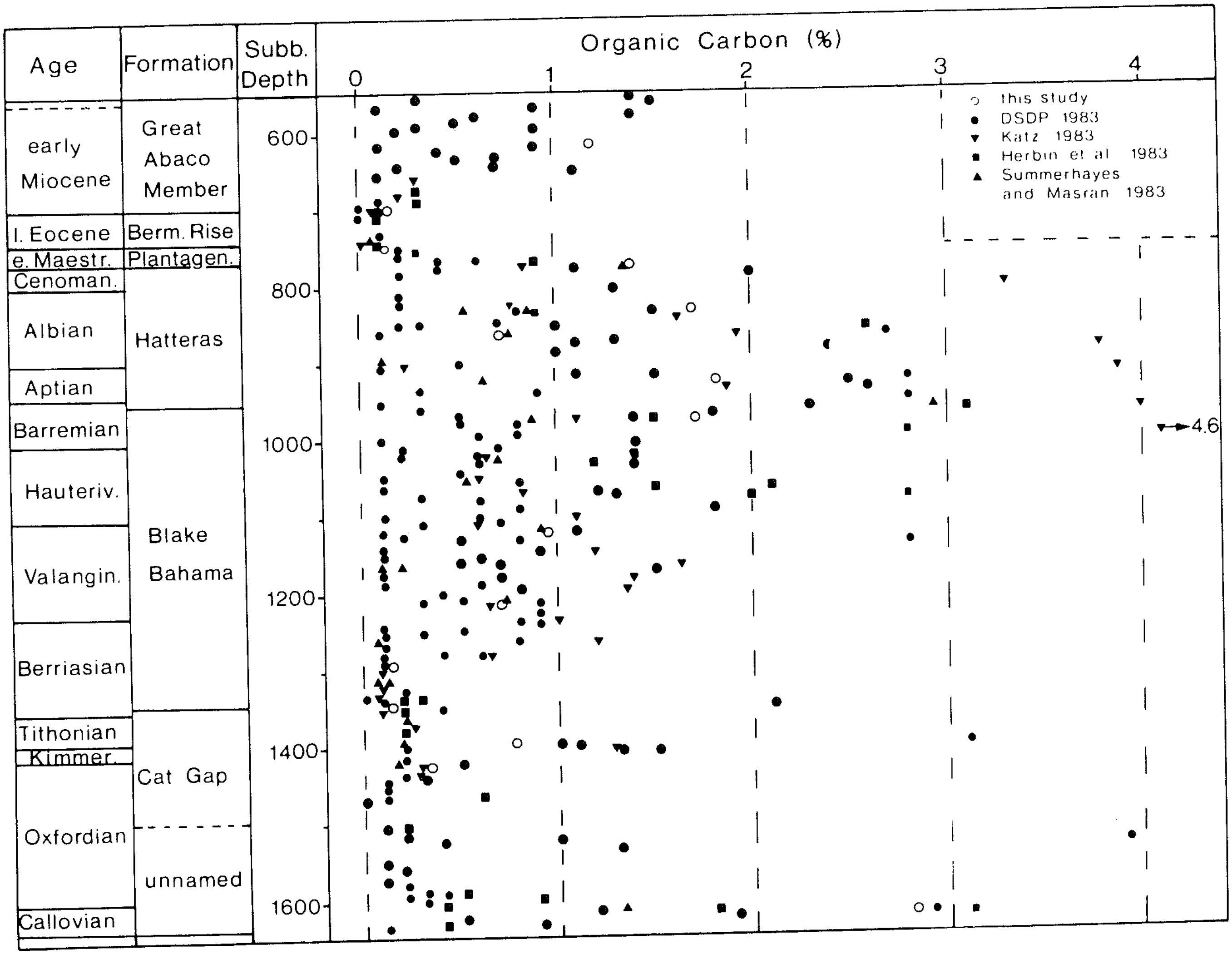
Principal methods for characterization of kerogen. On left, elementary composition is plotted on Van Krevelen diagram for samples from five sites in Atlantic. On right, Rock-Eval pyrolysis data are shown on same set of samples. *I*, *II*, *III*, types of kerogen.

Figure 10



Elemental kerogen data (left) and pyrolysis data (right) from middle Cretaceous black shale samples with >1% TOC: A = sites 367, 368 (Deroo et al, 1978a); B = site 391 (Deroo et al, 1978b); C = sites 386, 387 (Kendrick, 1979); D = site 400 (Deroo et al, 1979b); E = sites 417, 418 (Deroo et al, 1980); F = sites 415, 416 (Boutefeu, 1980); G = site 398 (Deroo et al, 1979a). Dashed lines refer to kerogen types I, II, and III, as explained by Tissot et al (1980).

Figure 11



Organic carbon data for deep sea sediments from DSDP Site 534 in the Blake-Bahama Basin.

Figure 12

DSDP Site 534 organofacies types

Stratigraphic age	Lithology	C_{org} (%)	HI (mg hc/g C_{org})	Dominant macerals
Valanginian-Cenomanian	Grey limestone; calcareous claystone; carbonaceous claystone	0.7 1.8	55	Vitrinite; amorphous marine OM (fecal pellets); inertinite; recycled oxidized spores
Callovian	Black nannofossil claystone	2.8	238	Amorphous marine OM; amorphous humic OM; vitrinite; spores, pollen

Table 3

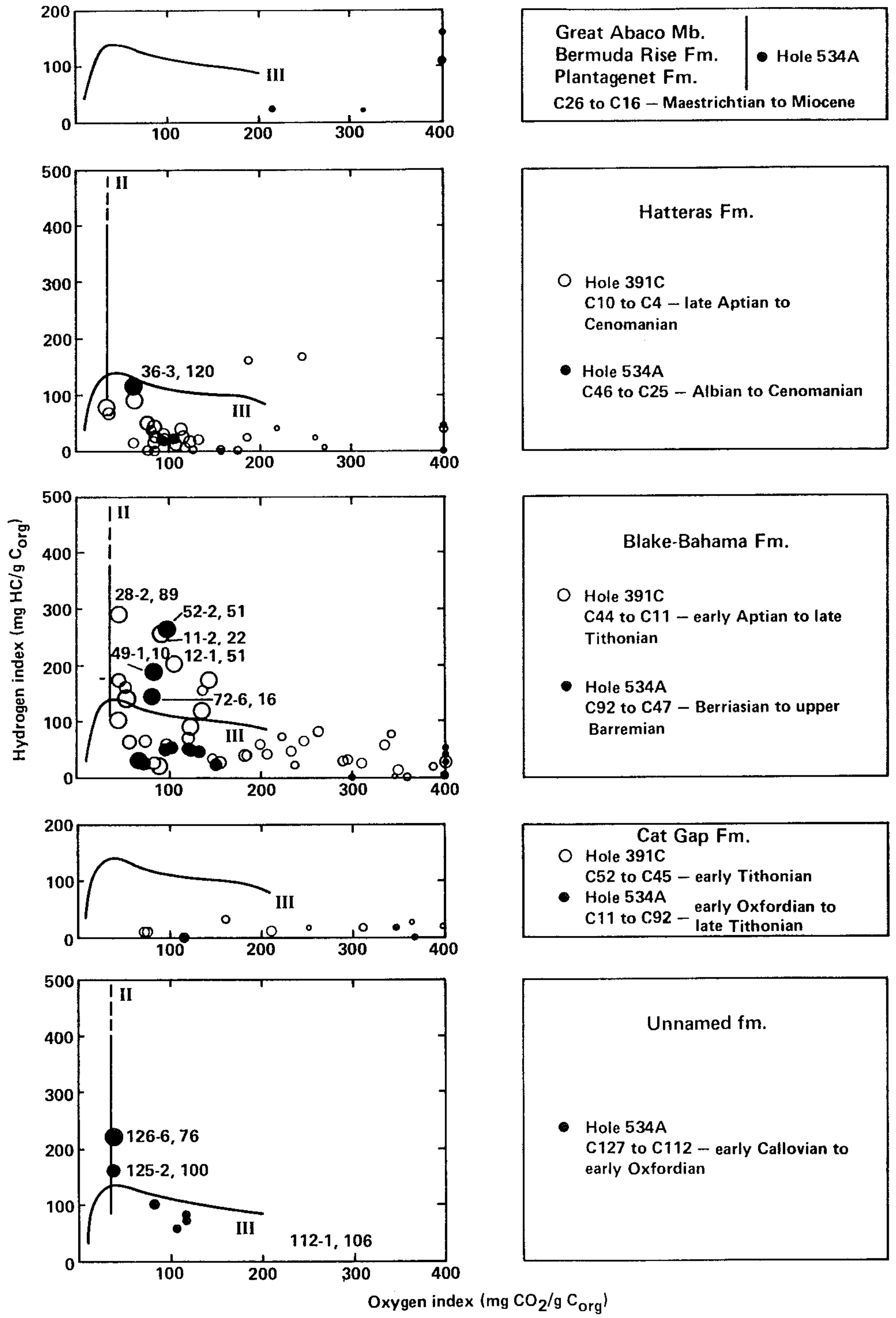


Figure 13

Diagrams of pyrolyses of the different formations for Holes 391C and 534A (the radii of the circles are proportional to the total organic carbon content). (C26 = Core 26.)

DSDP Site 603 organofacies types

Stratigraphic age	Lithology	C_{org} (%)	HI (mc hc/g C_{org})	Dominant macerals
Santonian	Variegated claystone	1.55	18	78% recycled vitrinite
Coniacian –late Turonian	Variegated claystone	8.5	346	> 50% sapropelinite (fecal pellets)
Turonian –Cenomanian	Black carbonaceous claystone	6–14.5	>400	50% degraded liptinite (fecal pellets?), phytoclasts
Barremian	Dark grey carbonaceous claystone	1–38	50–75	primary vitrinite with pyrite (unusual association)
Berriasian- –Valanginian	Nannofossil limestone	1.5–60	≈300	saprovitrinite (coal)

Table 4

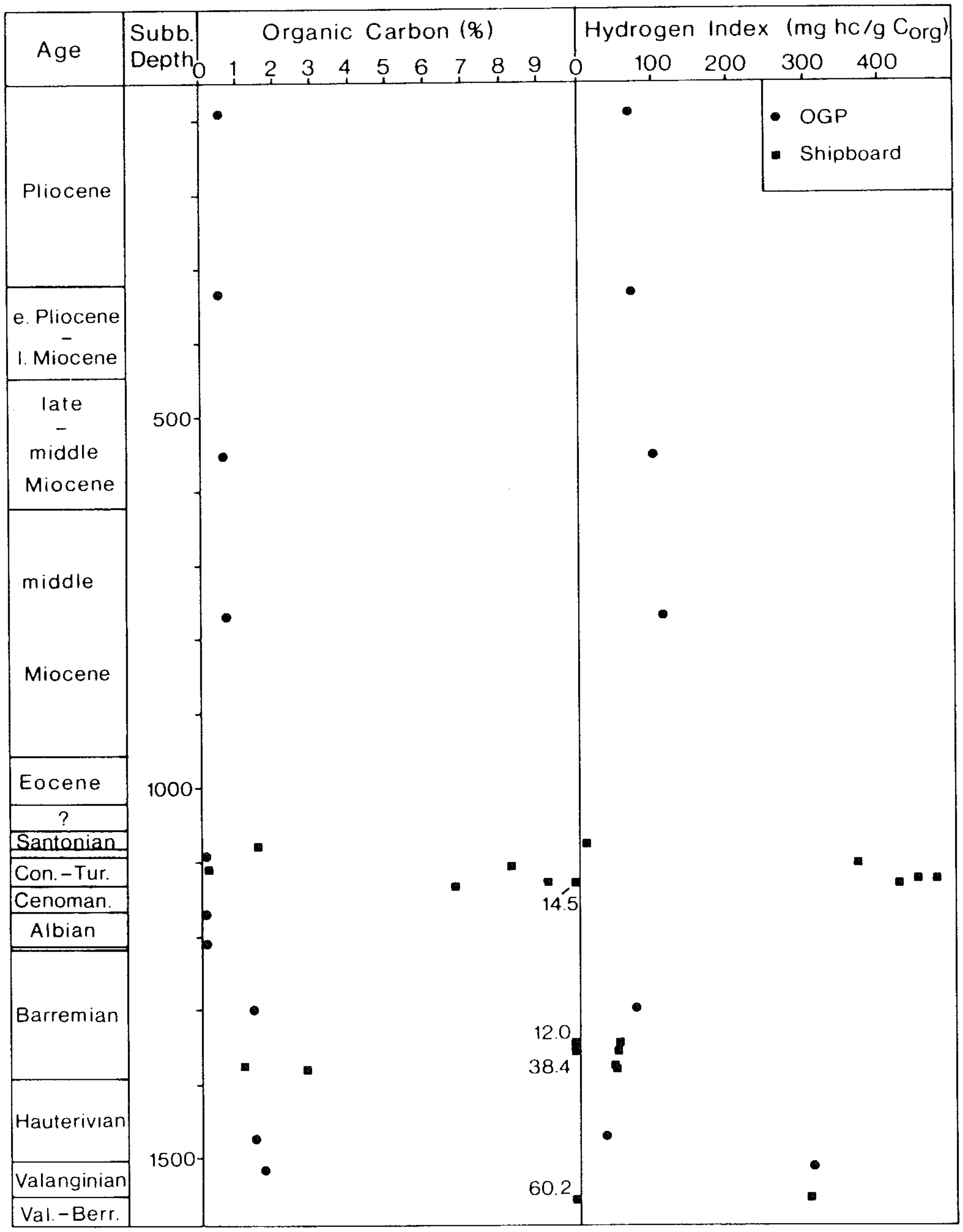
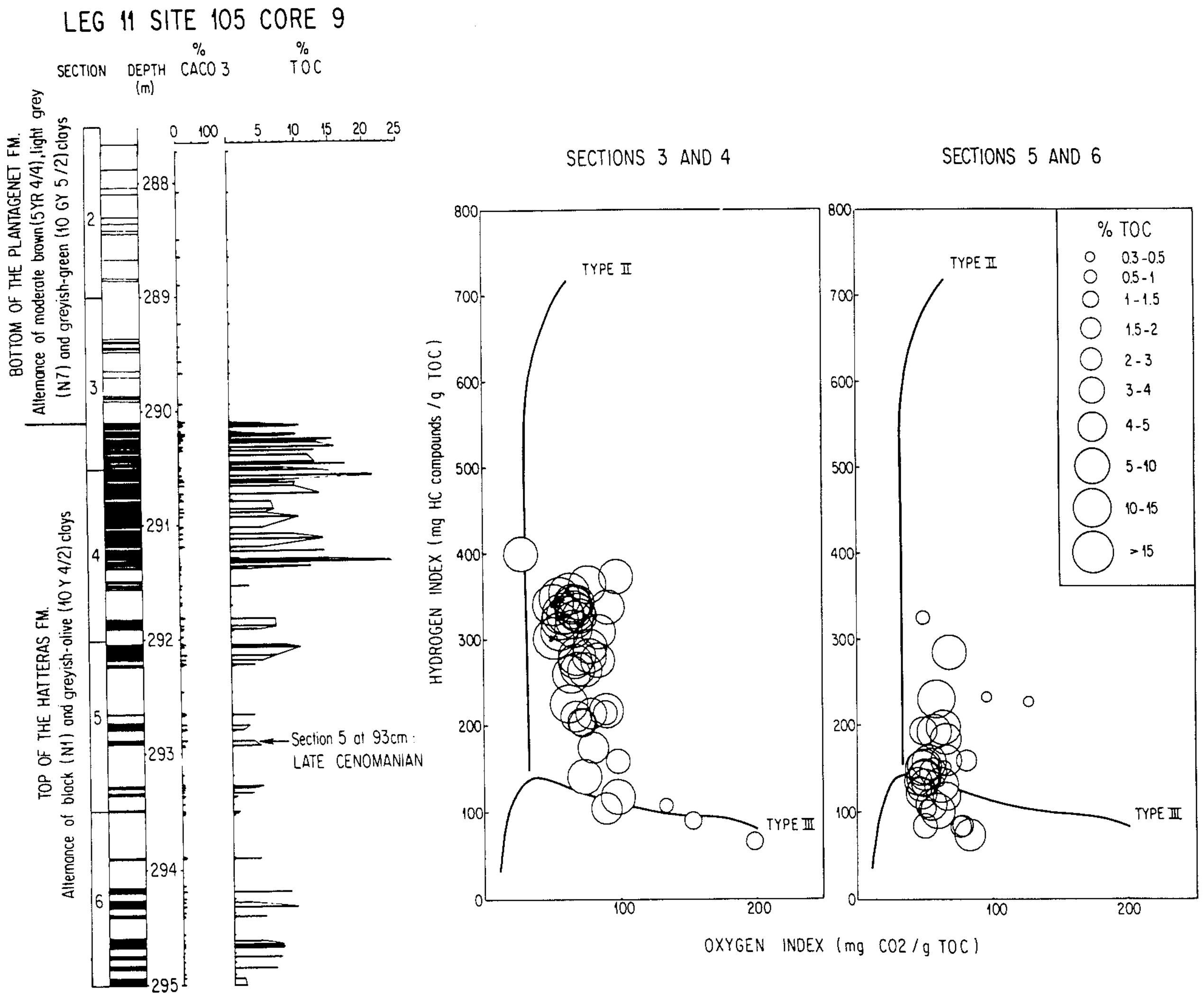


Figure 14

Organic carbon and hydrogen index values (from Rock-Eval pyrolysis) for deep sea sediments from DSDP Site 603 off Cape Hatteras. Circles indicate frozen organic geochemistry panel samples taken at regular intervals, squares represent small-size samples picked from organic-carbon-rich strata onboard DV *Glomar Challenger*.



Hills of the lower continental rise off Cape Hatteras. Site 105, Core 9, Section 3, 4, 5 and 6. Log of total organic carbon and carbonate contents; characterization of the type of organic carbon content.

Figure 15

Table 6

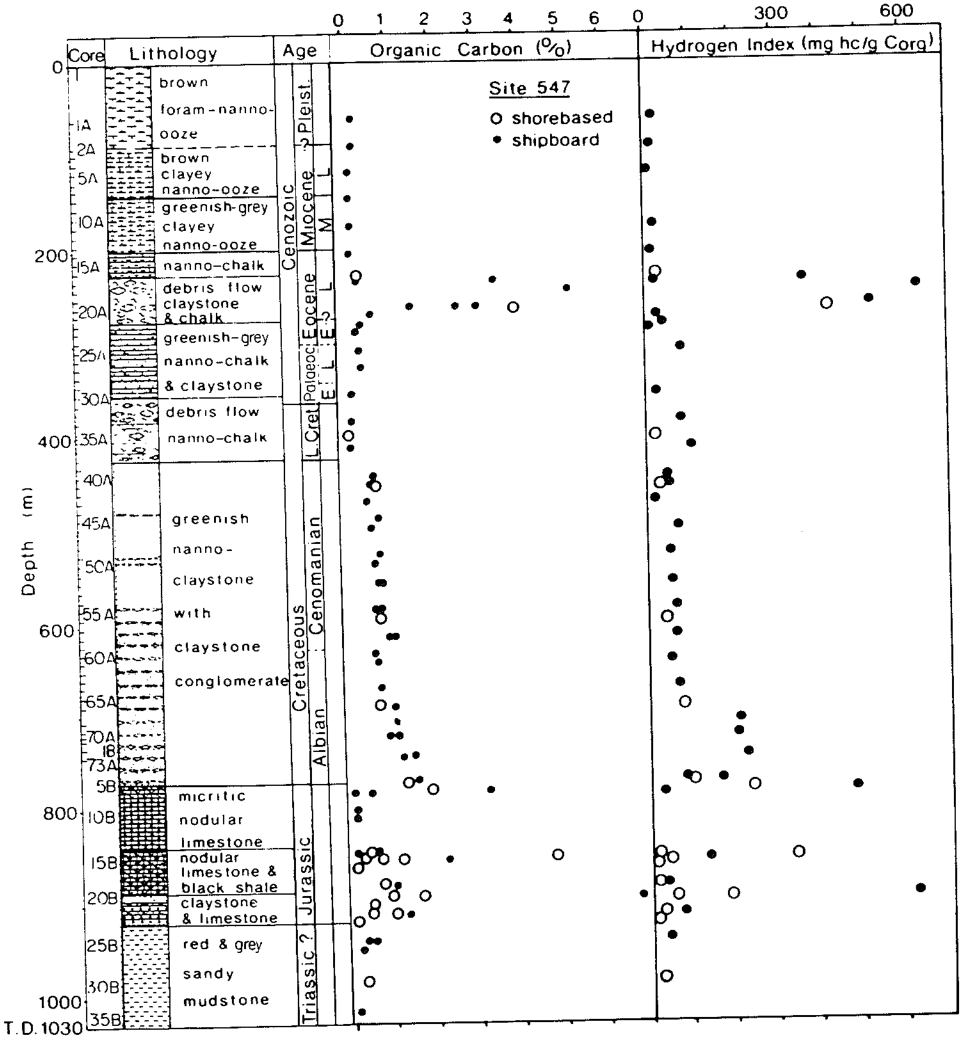
Sedimentological, organic petrographic and organic geochemical characteristics of two Callovian (tentative at Site 547) black shales from DSDP Sites 534 (Blake Bahama Basin) and 547 (Mazagan Escarpment); sedimentology data from Sheridan *et al.* (1983) and Hinz *et al.* (1984)

	Sample Site-Core-Section (Interval)	
	534A-125-5 (127–131 cm)	547B-15-2 (8–12 cm)
Sub-bottom depth	1619.8 m	847.6 m
Sedimentology	Black nannofossil claystone, partly laminated, partly massive or with graded texture; laminae are discontinuous concentrations of fine organic material and pyrite/Fe oxide particles and/or nannofossil micrite; common pyrite nodules, minor bioturbation; synsedimentary slumping, folds, shear planes; abundant flattened elongate claystone intraclasts with phosphate concretions, fish debris, plant debris; slope deposition likely (10–15°C inclination of beds); Callovian–Oxfordian sediment topography (seismic reflection) shows ridges and troughs with 100 m relief (i.e. local oxygen depletion possible)	Grayish black fissile claystone within nodular micrite matrix; upward gradation from pale yellowish brown micrite nodules in darker yellowish brown claystone matrix followed by darkening matrix with fewer and smaller nodules with olive gray claystone underlying organic-matter-rich black shale on top; black shale nonbioturbated, bioturbation increasing downwards, common pyrite; similar intervals below Core 547B-17 are severely disturbed tectonically indicating occasional downslope shifting of still moderately soft sediment
C_{org}	2.81%	4.75%
Hydrogen index	238 mg hc g C_{org}^{-1}	345 mg hc g C_{org}^{-1}
Maceral composition	Amorphous unstructured liptinite (sapropelinite II) with small liptodetrinite, unicellular algae (minor), spores, vitrinite, minor inertinite	Biodegraded phyto- and zooclasts mixed with exinite (sapropelinite II), spores, vitrinite, minor inertinite
Nonaromatic hydrocarbon composition	Dominant pristane and C_{16}-isoprenoid, abundant hopenes and diasterenes, *n*-alkane maximum at *n*-C_{15}, minor long chain *n*-alkanes, significant concentrations of short chain isoprenoids (C_{13}–C_{15}, C_{18}), phytane ($\ll$ pri), 17β(H) hopanes and 17α(H) hopanes	Dominant long chain *n*-alkanes (maximum at *n*-C_{27}), abundant shortchain *n*-alkanes (maximum at *n*-C_{17}), phytane, pristane (phy/pri$>$1), hopenes and 17β(H) hopanes

Table 7

Sedimentalogical, organic petrographic and organic geochemical characteristics of two Albian claystones from DSDP Sites 534 (Blake Bahama Basin) and 547 (Mazagan Escarpment); sedimentology information from Sheridan *et al.* (1983) and Hinz *et al.* (1984)

	Sample Site-Core-Section (Interval)	
	534A-34-1 (141–150 cm)	547B-6-1 (77–84 cm)
Sub-bottom depth	832.5 m	772.8 m
Sedimentology	Greenish black carbonaceous claystone, common pyrite, silty stringers in background sediment, abundant quartz, smectite + kaolinite in clay minerals (terrigenous); indications for downslope transport (e.g. calciturbidites)	Dark greenish clay mudstone/claystone with conglomeratic intervals, mudstone indistinctly laminated with flattened burrows containing pyrite, conglomeratic intervals contain highly flattened and stretched mudstone/claystone clasts with locally associated slump folds; hemipelagic sedimentation on slope with abundant resedimentation
C_{org}	1.70%	1.87%
Hydrogen index	35 mg hc g C_{org}^{-1}	244 mg hc g C_{org}^{-1}
Maceral composition	Amorphous humic matter (major portion converted to micrinite), recycled spores; minor phytoclasts, sapropelinite II and vitrinite	Large phytoclasts, unicellular algae (minor), spores, sapropelinite II, vitrinite (minor)
Nonaromatic hydrocarbon composition	Long chain *n*-alkanes dominant (maximum at *n*-C_{29}), strong odd-over-even predominance, pristane and phytane minor (pri $\hat{=}$ phy), significant concentrations of 17β(H) hopanes and hopenes	Sterenes and steradienes dominant, abundant pristane and phytane (pri $<$ phy), intermediate concentration of *n*-alkanes (maxima at *n*-C_{17} and *n*-C_{29}), significant concentrations of diasterenes, 17β(H) hopanes and hopenes



Organic carbon and hydrogen index values (from Rock-Eval pyrolysis) for deep sea sediments from DSDP Site 547 off the Mazagan Escarpment (after Rullkötter *et al.* 1984).

Figure 16

DSDP Site 547 organofacies types

Stratigraphic age	Lithology	C_{org} (%)	HI (mg hc g C_{org})		Dominant macerals
Eocene	Clayey nannofossil chalk (slump)	4	431		Phyto-, zooclasts; exinite; amorphous marine OM
Cenomanian	Clayey nannofossil chalk (with slumps)	0.7	30 50		Exinite, resinite; amorphous humic matter; vitrinite
Albian	Nannofossil-bearing claystone (frequent slumps)	0.7-3	80 450		Exinite, resinite; amorphous humic matter, vitrinite; amorphous marine OM; phyto- and zooclasts
Jurassic	Claystone/black shale	0.4 10 (gradational)	20 600	Top:	amorphous marine OM; terrigenous liptinite; vitrinite
				Middle:	inertinite; recycled terrigenous liptinite
				Bottom:	inertinite

Table 5

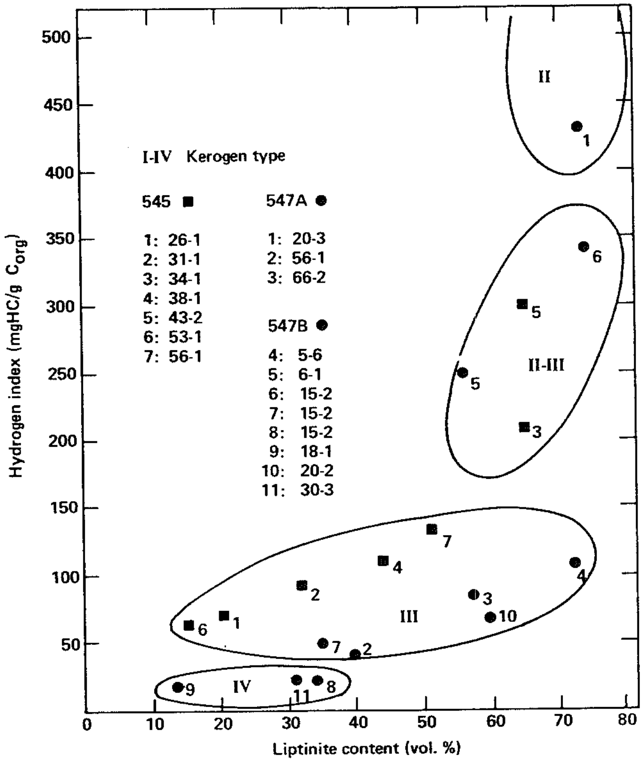
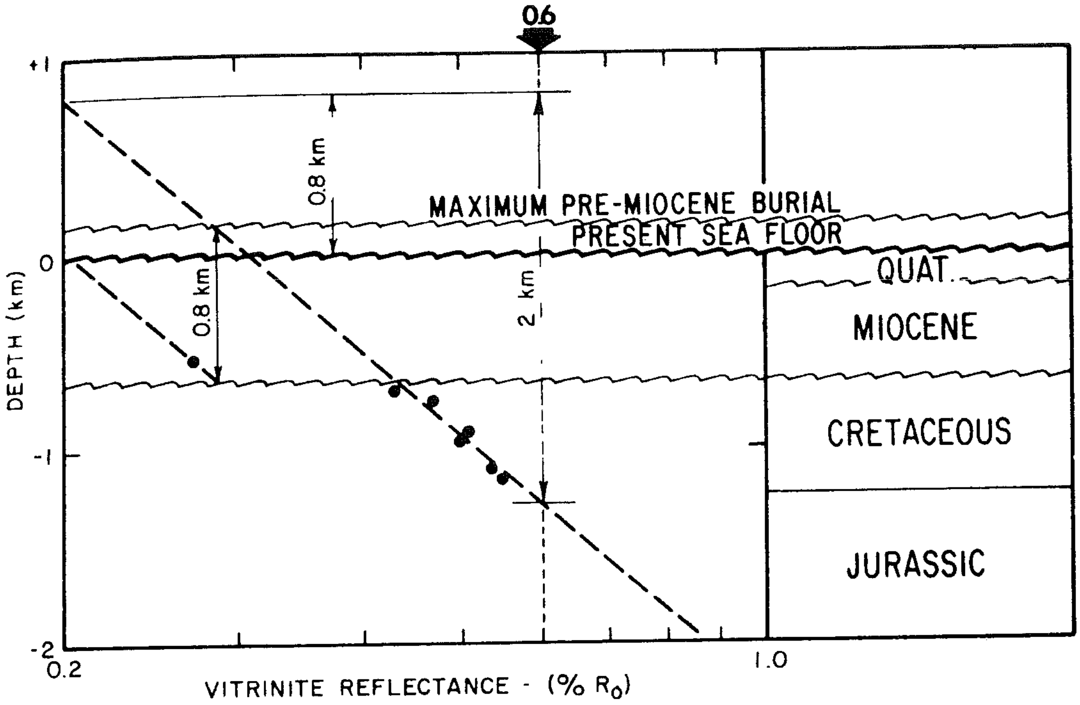


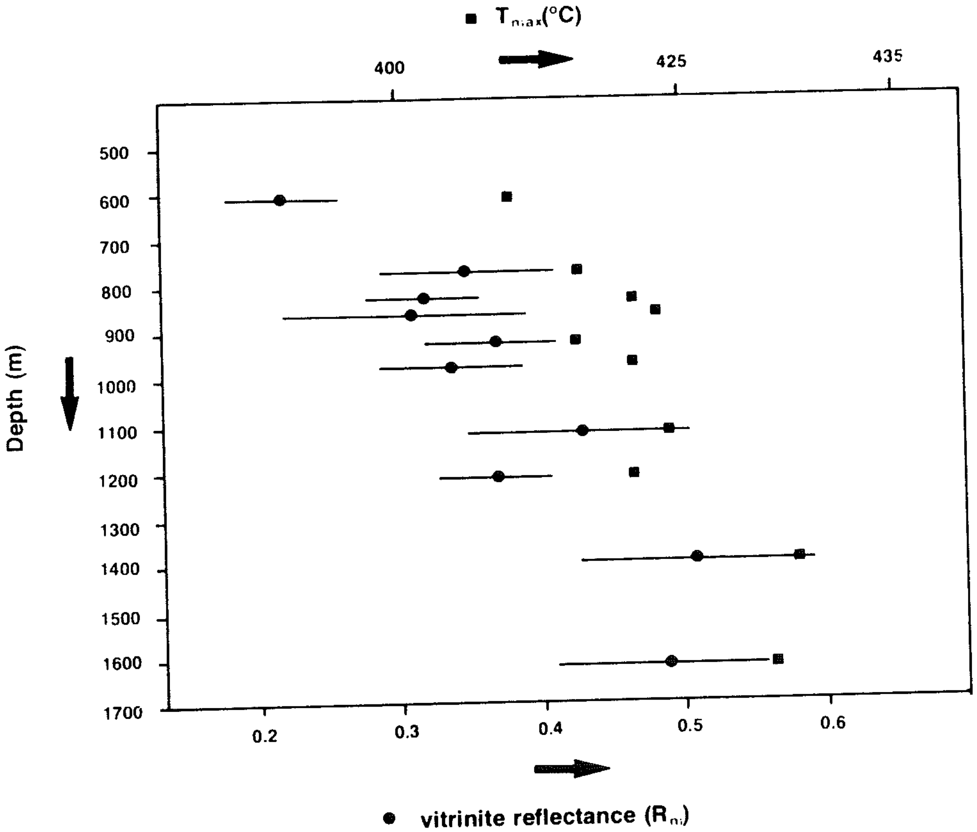
Figure 17

Hydrogen index (from Rock-Eval pyrolysis) versus liptinite content (from maceral analysis) diagram for DSDP Leg 79 sediments.



Kerogen-maturation profile for DSDP Site 391, continental rise, western North Atlantic.

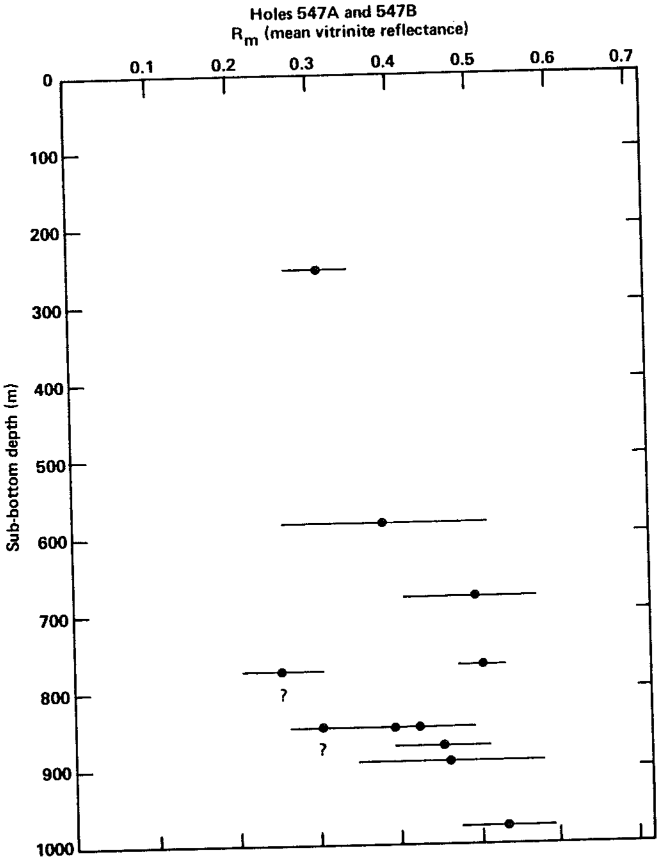
Figure 18



Plot of mean vitrinite reflectance (R_m) and T_{max} (°C) *versus* depth.

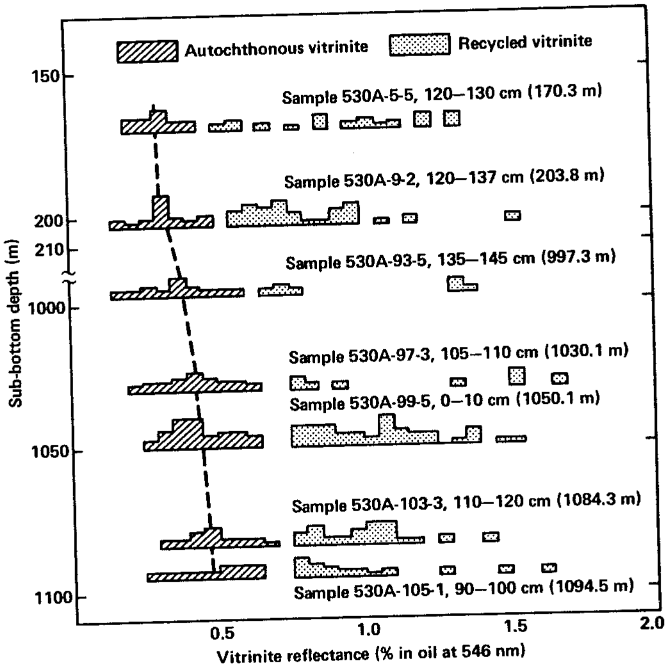
Figure 19

Figure 20

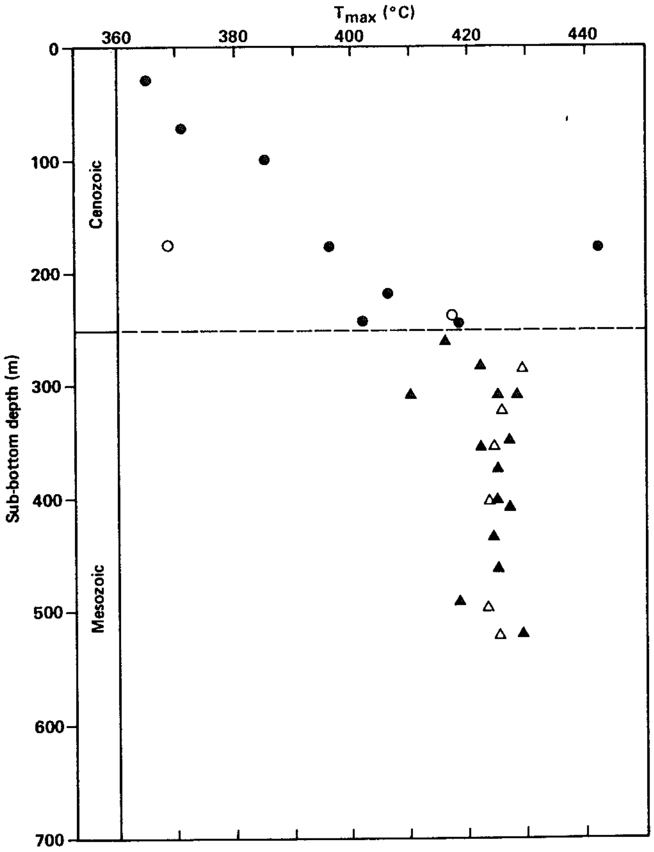


Vitrinite reflectance versus depth for DSDP Site 547 sediments.

Figure 21



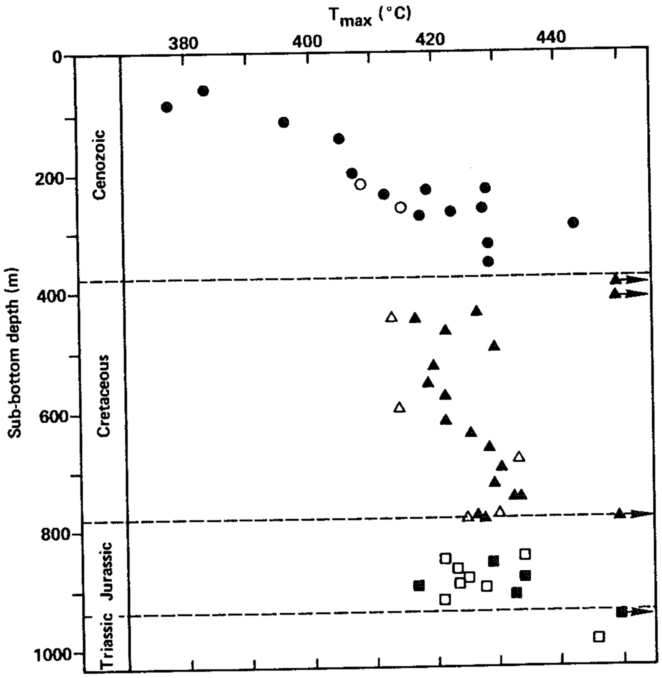
Reflectance histograms of autochthonous (primary) and recycled vitrinite/huminite for sediment samples from DSDP Hole 530A (Angola Basin).



Temperatures of maximum pyrolysis yield (T_{max} from Rock-Eval pyrolysis) versus depth for DSDP Site 545 sediments. Closed symbols indicate shipboard data, open symbols are from shore-based studies.

A

Figure 22



Temperatures of maximum pyrolysis yield (T_{max} from Rock-Eval pyrolysis) versus depth for DSDP Site 547 sediments. Closed symbols indicate shipboard data, open symbols are from shore-based studies. Arrows indicate values in excess of 450°C.

B