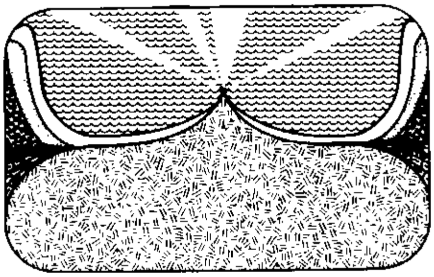
Articles



Stratigraphy and Hydrocarbon Potential of the Central North Atlantic Basin

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Abstract

The Central North Atlantic Basin, including most of the lower continental rise areas, should not be regarded as being prospective for hydrocarbons, because of lack of reservoirs, pervasive cementation, insufficient burial, generally low geothermal gradient, and adequate organic matter in only one of the units of the sedimentary fill. The upper parts of the continental rises and the continental slopes in the front of major Lower Cretaceous deltas appear to be prospective. The deeply buried pre-Lage Jurassic succession of shallow- water carbonates beneath the continental slopes and rises appears to offer promise, but until the Deep Sea Drilling Project provides us with better data from the lower parts of the continental margins it is not possible to assess the hydrocarbon potential of these areas.

Introduction

Although a very substantial part of the world's petroleum production already comes from accumulations beneath the ocean floor, almost all is from the near shore shelf areas. We still know little from actual drilling about the hydrocarbon prospects of sedimentary strata beneath the deeper waters adjacent to the continental shelves or those of the continental slopes, rises and deep ocean basins. This paper will examine the hydrocarbon potential of the deep North Atlantic Basin and the surrounding rise areas, based on what is known to date. In broad terms, this is the area of the North Atlantic which is underlain by oceanic crust. The area under discussion extends from the latitude of Grand Banks off Newfoundland in the north to the Sierra Leone Rise in the south (Fig. 1) and is referred to herein as the Central North Atlantic Basin. The data and interpretations presented here are

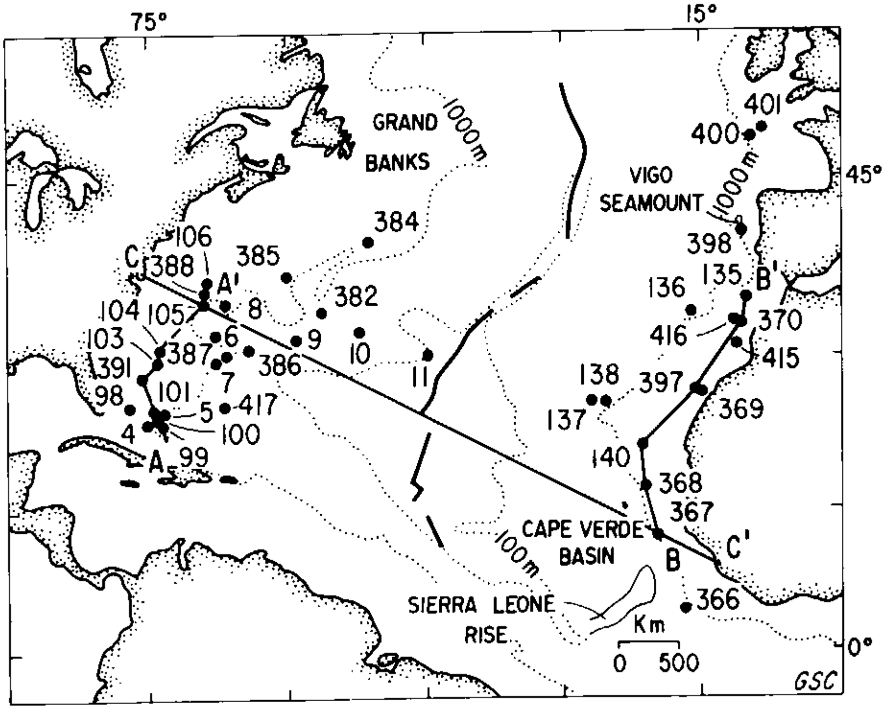

Figure 1
Location map, Central North Atlantic Basin, AA', BB', CC' are lines of cross-section shown on Figures 4, 5, and 6. Numbered solid circles are DSDP drilling sites. Contours indicated sediment thickness in metres.

based on results from the JOIDES Deep Sea Drilling Project (DSDP) work carried out in the Central North Atlantic (Jansa *et al.*, 1977). Location of the DSDP sites and of three schematic stratigraphic cross-sections (parallel to the American continental margin, across the Central North Atlantic, and parallel to the African continental margin) are shown in Figure 1.

Figure 2 gives an idealized cross-section from the continent to the ocean basin and shows the major constituents of the margin. The average depth of the floor of the ocean basin is four km. The sediments in the basin are underlain by oceanic crust, with the transition between oceanic and continental crust occurring somewhere below the continental rise. The continental rise is formed by a relatively smooth wedge of sediments with a very low slope and a width ranging from 0 to 600 km. The rise is well developed and broad off North America, but very narrow in places off northwest Africa (Fig. 10).

Stratigraphy, Central North Atlantic Basin

The oldest known sedimentary rocks in the Central North Atlantic Basin are reddish, argillaceous, pelagic limestones, marls and calcareous clays dated by microfossils as Oxfordian-early Tithonian (Fig. 3; Jansa *et al.*, 1977). The limestone is micritic with variable amounts of clay minerals and microfossils (pelagic pelecypods, crinoids, foraminifera and radiolarians). The reddish limestone grades upward into white pelagic nannofossil limestone and chalk, with abundant calcite replaced radiolarians, of Late Jurassic-Early Cretaceous age. In contrast, in front (seaward) of Early Cretaceous deltas, fine-grained hemipelagic sediments enclosing thin turbidite beds were deposited. Mid-Cretaceous deposits in the Basin consist of carbonaceous, dark grey hemipelagic shales. The shales are rich in organic matter, both of terrestrial and marine origin. Although there is a high concentration of lipids in some of these shales, in most of them terrestrial organic matter dominates. During the post-Cenomanian starved basin phase, variegated and reddish zeolitic clays

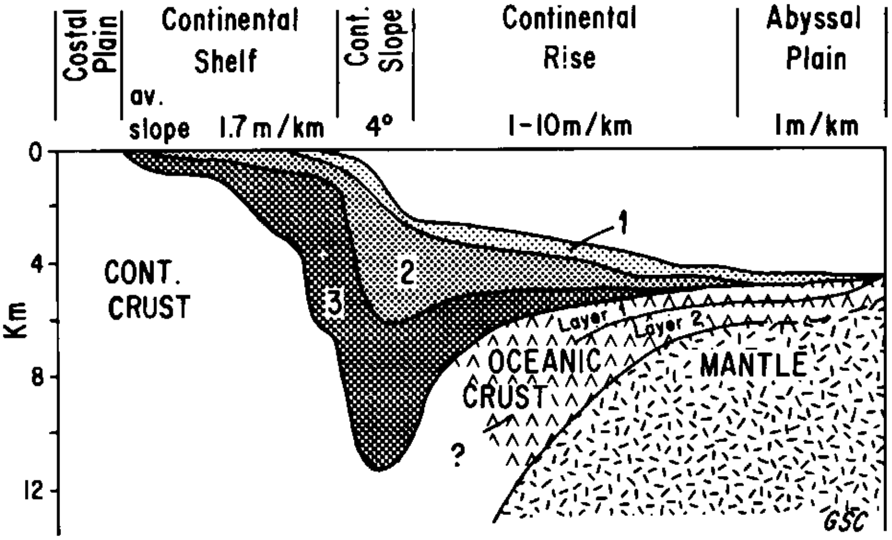

Figure 2
Principal elements of the Atlantic margin (drafted symbols depict sediments and sedimentary rock sequences of Recent to Cenozoic (1), Mesozoic (2), Paleozoic (3) age.

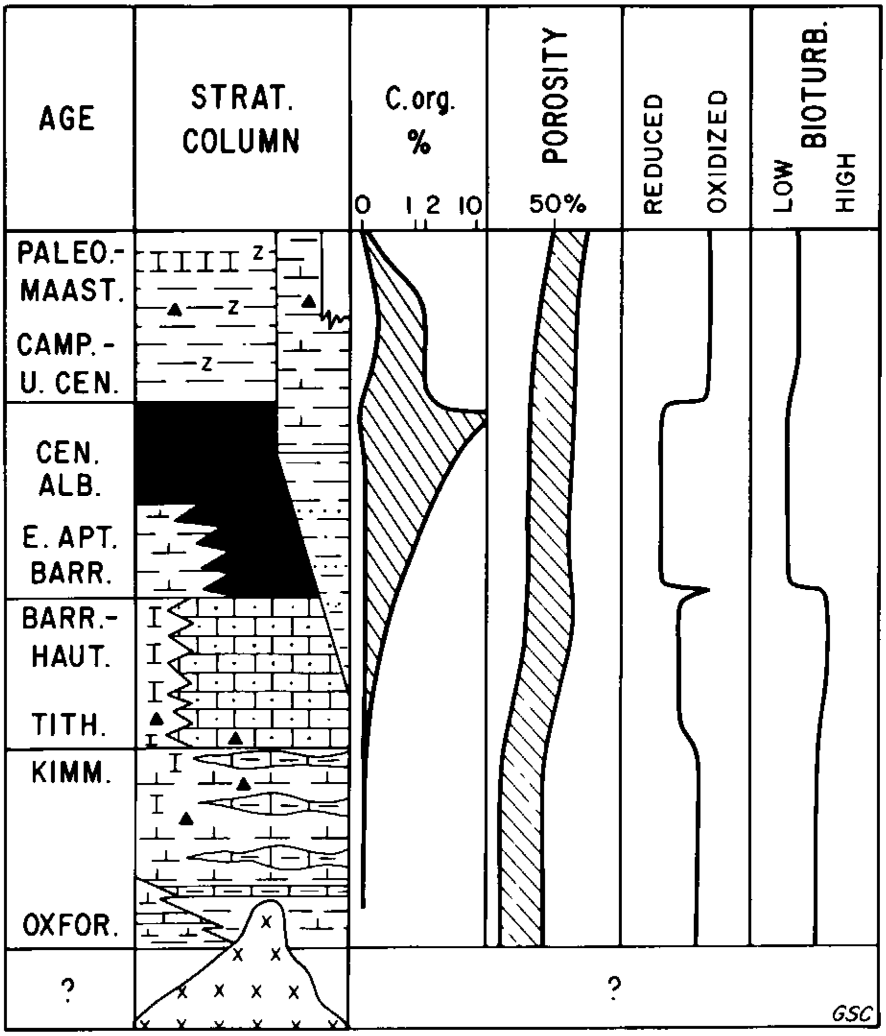

Figure 3
Schematic stratigraphic column and sediment characteristics, Central North Atlantic Basin. Symbols as for Figures 4, 5 and 6 except for diapiric salt at base of Figure 3. See text for discussion of organic carbon content, porosity, redox conditions and bioturbation.

were deposited in the basin. The clay deposition was interrupted by a brief period of nannofossil chalk and marl sedimentation during Maestrichtian time. A hiatus separates late Cretaceous deposits from Tertiary deposits in most of the Central North Atlantic Basin. Siliceous clays with chert were deposited during Eocene-Oligocene time, with mainly hemipelagic sediments and nannofossil oozes being deposited during the Miocene and Pliocene.

The regional distribution of lithostratigraphic units is shown in three cross-sections. Cross-section A-A' (Fig. 4) parallels the American continental margin from the Bahamas to Hatteras Abyssal Plain, and B-B' (Fig. 5) parallels the African continental margin from the Cape Verde Basin in the south to Vigo Seamount off the coast of Portugal in the north (note the presence of turbidites of Early Cretaceous age off Morocco, and greenish clays of Late Cretaceous age off the Spanish Sahara and Morocco). The third cross-section C-C' (Fig. 6) encompasses the entire North Atlantic Basin from Cape Hatteras to Senegal. Figure 6 shows that all sequences are present on both sides of the Mid-Atlantic Ridge.

Hydrocarbon Potential, Central North Atlantic Basin

Factors which control the occurrence of oil or gas fields include: presence of traps, reservoir, porosity, source, geothermal gradient, maturation of organic matter, and tectonism (Klemme, 1975, and others). The generalized stratigraphic column for the region (Fig. 3) also shows comparison with factors important for the consideration of hydrocarbon generation. The variation in the organic carbon content in the sediments is plotted on logarithmic scale from 0 to 10 per cent; next is porosity with 50 per cent at the centre of the column, followed by a column which shows the reduced or oxidized status of the deposited sediments. The last column shows intensity of bioturbation, which plays an important role in organic matter preservation particularly in the presence of oxygenated bottom waters. The individual factors as they apply to deep sea deposits of the area are discussed below.

LEGEND for Figs. 4,5,6

z	VARICOLORED ZEOLITIC CLAY
▨	GREENISH CLAYSTONE
■	BLACK CARBONACEOUS SHALE
░	GRAYISH-GREEN CLAYSTONE-INTRACLAST SANDSTONE (TURDIBITES)
▦	WHITE CHALKY LIMESTONE
▦	REDDISH-BROWN ARGILLACEOUS LIMESTONE
▦	GREENISH-GRAY LIMESTONE
∧ ∧ ∧	OCEANIC BASEMENT
∿	UNCONFORMITY

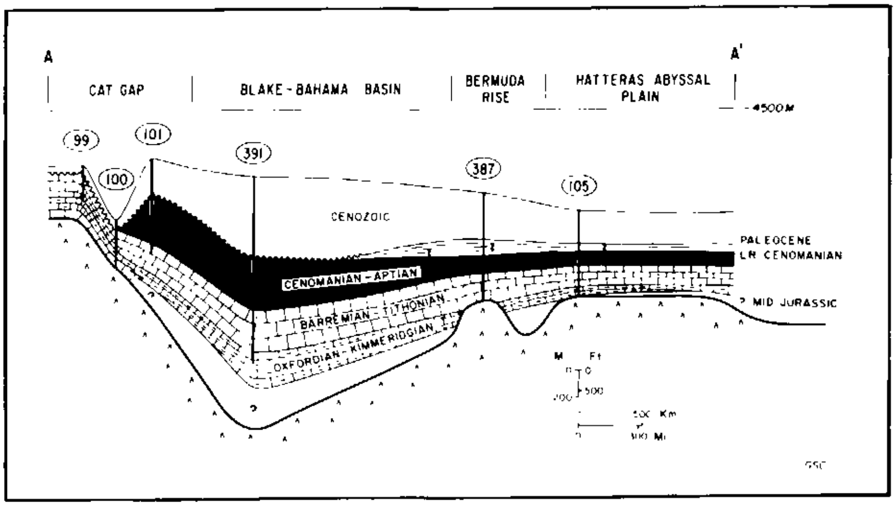

Figure 4
Schematic lithostratigraphic cross-section parallel to the North American continental margin (for location see Fig. 1).

Tectonism. Most of the Atlantic basin lacks tectonic deformation with the exception of broad regional uplifts related to the development of the volcanic islands such as the Cape Verde Archipelago, Canary Islands, Bermuda, and others. Most of these uplifts are Late Tertiary in age and too young to contribute significantly to the development of hydrocarbon traps. But in some cases, where uplift was accompanied by high sediment influx, it could lead to the development of hydrocarbon traps.

Reservoir rocks. Although some of the DSDP holes were located at the seaward extension of the major Mesozoic sedimentary basins, none of them encountered potential reservoir rocks. As outlined above, clays and marls dominate the sequence not only under the abyssal plains, but also beneath the rises and some of the slopes. The turbidite beds off Morocco and Portugal penetrated by Sites 370, 416 and 398 are only several centimetres thick and are not porous. Similar turbidite sequences can be expected to be present in front of the major Mesozoic deltaic systems off Nova Scotia, the Baltimore Canyon, Senegal and the Spanish Sahara.

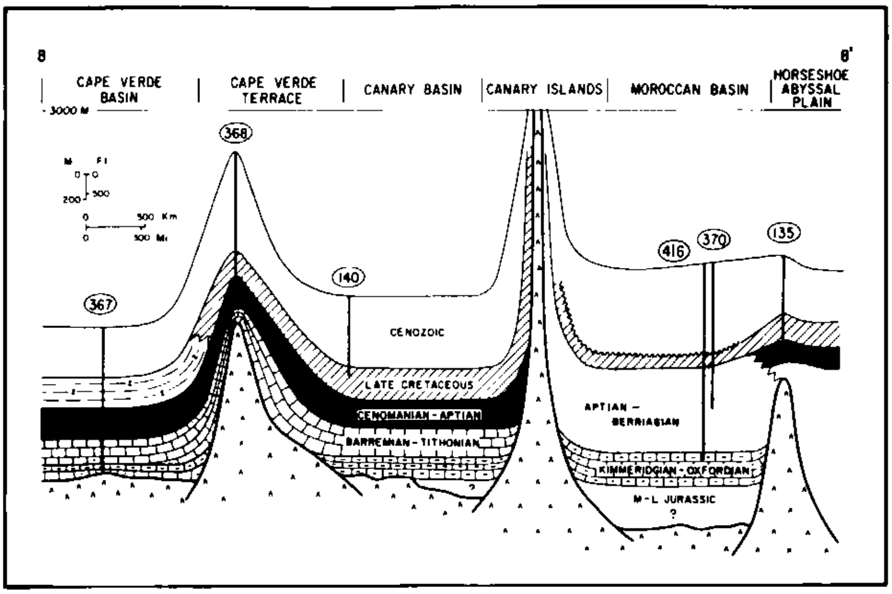

Figure 5
Schematic lithostratigraphic cross-section parallel with the northwestern African continental margin in the eastern North Atlantic (for location see Fig. 1).

Because of the supposed importance of turbidites as potential reservoirs in deep sea sequences, it is vital to point out one of the misconceptions about turbidites which dominates marine geology textbooks and literature. Development of thick, sandy turbidite sequences requires special conditions including the presence of a narrow shelf adjacent to a high-relief land region which provides a sizable local source. This situation is achieved on active continental margins, for example along the California coast and also in some epicontinental basin settings, such as the Caucasian coast of the Black Sea (Zenkovich *et al.*, 1976). In contrast, the passive Atlantic type continental margin generally is a much less favorable place for the development of thick sandy turbidite sequences, owing to generally low relief of the land areas and to broad shelves which trap most of the coarse debris. Probably the only periods favourable for widespread turbidite deposition were associated with major low stands of sea level when most of the shelves were subaerially exposed and coarser clastics accumulated

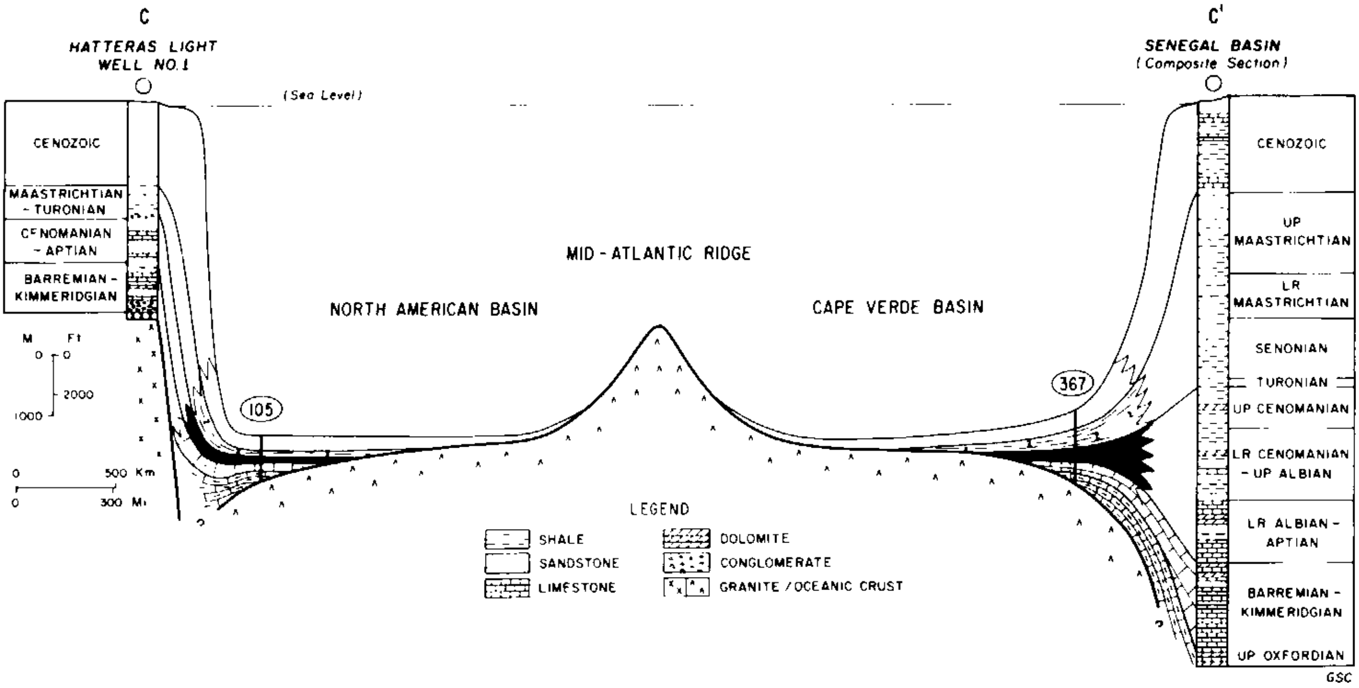

Figure 6
Schematic lithostratigraphic cross-section from Cape Hatteras light well No. 1 to Senegal across Central North Atlantic (for location see Fig. 1).

near the shelf edge and on the upper part of the continental slope. Perhaps then, as a result of overloading, oversteepening or other factors, sediment could have been redeposited into a deeper basin by turbidity currents. In the history of the Central North Atlantic Basin, only two such time intervals appear to have been favourable for development of coarse-grained turbidites. One was during the early Cretaceous; the second during late Tertiary to Pleistocene time.

This does not mean that turbidites are lacking in other stages of the Atlantic Basin development. On the contrary, they are very common, but are represented by clayey turbidites which consist of silty clay beds several mm to a few cm thick probably originated as spill-over from shelves or from fine-grained sediments of the upper slope.

If some reservoir rocks are present in the deep ocean basin sequence preservation of porosity should be considered. Diagenetic cementation is found to be pervasive in the deep sea rocks of the area. The porosity column (Fig. 3) shows high total porosity of the deep sea sediments, and its reduction with increasing depth of burial and age of the sediments. In terms of petroleum geology this porosity is ineffective, because of low permeability. Data from Deep Sea Drilling Project cores indicate that the first well-cemented sediments in the deep water basin occur about 800 m below sea bottom, in contrast to 2,500m below sea bottom on the Scotian Shelf (Jansa and Wade, 1975). Cementation in the deep sea is selective: sediment with the highest initial porosity is cemented first. This is an important observation because if reservoir rocks are present in clastic sediments beneath the lower part of the continental rises of the circum-North Atlantic, the pores in these rocks would have to be filled early by hydrocarbons to escape destruction through widespread development of diagenetic cement.

Pelagic carbonates also are present within the Central North Atlantic, as noted above. What are their prospects as reservoir rocks? Because they were initially composed of low-magnesium calcite and have low permeability, and because of their deep-water setting, they are not susceptible to freshwater-type alteration processes which normally affect shallow-water carbonates (Scholle, 1977). Their cementation history appears to be similar to that of clastic rocks, with depth of burial a critical factor. Apparently overburden stresses within the carbonate sequences set up mechanical and chemical compaction (solution-precipitation), which markedly reduces the relatively low initial effective porosity. Effective porosity within the carbonate appears preservable only through early overpressuring, early oil migration, or by lack of burial.

The other negative factor for preservation of reservoir properties may be the presence of megaslumps on the continental margins. These were recognized on the Spanish Sahara slope, off Morocco by Lancelot, Seibold *et al.* (1977: DSDP Site 369), Ryan, Sibuet *et al.* (1976, DSDP Site 397) and on the continental slope of Nova Scotia (Jansa and Wade, 1975). The slumps can be up to 300 km long, with the vertical thickness of sedimentary sequence involved in a mass wasting mechanism being from a few hundred to a few thousand metres thick. The mass movement in smaller scale slumps results in brecciation and destruction of reservoir beds. In the larger ones, breaching of reservoirs may occur through fracturing. The topographic relief on the slump surface, however, provides a favorable structural setting for development of reservoirs in overlying turbidite beds.

Source rocks. In terms of hydrocarbon prospects, the most encouraging property of deep sea sediments of the Central North Atlantic is the high content of organic matter in Aptian-Cenomanian carbonaceous shales (Fig. 3). The organic matter is comprised of a mixture of terrestrial material derived from higher land plants and lipids apparently derived from marine plankton. Near the continental margins terrestrial organic matter is more common in the shales, which thus are likely to be a gas and condensate rather than an oil source. Organic rich mid-Cretaceous shales are known to be involved in oil generation in Venezuela (Miller *et al.*, 1958) and Columbia (Morales *et al.*, 1958). These shales may be correlative with the black shales of the Atlantic Basin.

The source rock potential of other sequences is poor to very poor as can be seen from the $C_{org.}$ values in Figure 3. The distribution and potential of source rock in ancient basins is indicated by the distribution and potential of Recent marine deposits. Concentrations higher than 0.5 per cent which is considered as a minimum for potential petroleum source rock, are observed in Recent sediments located along the present continental margin. Highest concentrations are found on shelves (where $C_{org.}$ exceeds 2%) and in the semiclosed epicontinental and small ocean basins (where $C_{org.}$ averages 5%; Romankevic, 1977). The low values of organic carbon content in the Mesozoic-Cenozoic Central North Atlantic Basin sediments correspond well to the known distribution of organic carbon in Recent pelagic sediments.

Another factor shown in Figure 3 is the variation of redox conditions. Organic matter was destroyed by oxidation during or after deposition in most of the deep sea late Jurassic carbonates and late Cretaceous-early Tertiary zeolitic clays. Organic matter was only preserved in the Lower to Middle Cretaceous sequences and (in some areas) within early Tertiary sequences, due to reducing conditions or to a less oxygenated environment.

Geothermal gradient and heat flow. The next factors to be discussed are geothermal gradient and heat flow and their bearing on organic matter maturation. Surprising data were published recently by Herman *et al.* (1977), who pointed out that the heat flow and the geothermal gradient near the Mid-Atlantic Ridge is lower than it should be according to Sclater and Francheteau's theoretical calculations (1970). Figure 7 shows the theoretical curve of heat flow from the Mid-Atlantic Ridge toward the African margin, along with actual heat flow measurements. In areas south and north of the equator, heat flow remains approximately at the world average heat flow level for all portions of the

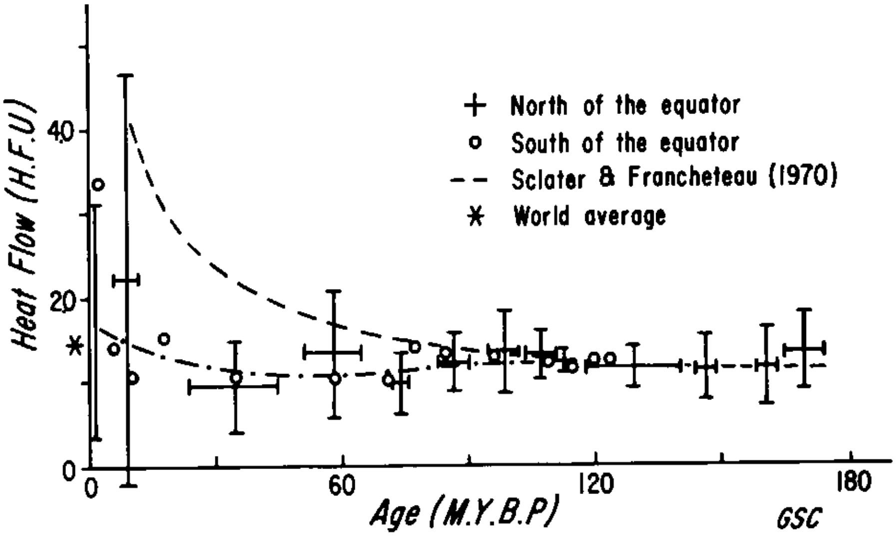

Figure 7
Heat flow data from the Atlantic portion of the African Plate in North Atlantic (the standard deviation about the mean of heat flow and age are shown by bars; adapted from Herman et al., *1977).*

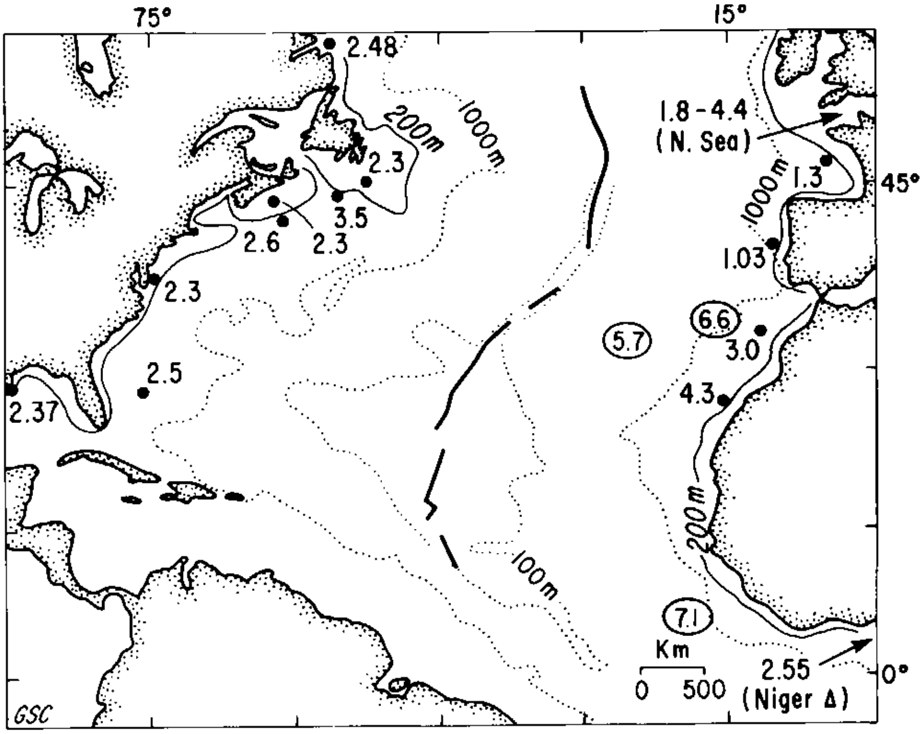

Figure 8
Temperature gradients in the Central North Atlantic Basin. Numbers inside circles represent average geothermal gradient of the region recalculated from Herman et al. *(1977).*

ocean floor underlain by oceanic crust that is 80 million years or more in age. The geothermal gradient shows a range of values mostly between 4.8 to 6.8°C/100m. The average geothermal gradient for the oceanic African plate of the North Atlantic is 6.5°C/100m.

The limited data on geothermal gradients at the continental margin and in deep sea boreholes on the continental rises indicate that here the geothermal gradient is considerably lower. On the African slope and rise it is at least 4°C/100m locally but on the North American continental rise the gradient is about 2.5°C/100m and 3.5°C/100m locally (Fig. 8). An even lower gradient of 2.3°C/100m is characteristic of the Scotian Shelf and Baltimore Canyon COST B-2 well (Robbins, 1977). No data are yet available from the oil exploratory wells on the northwest African shelf.

Many studies have shown that most commercial hydrocarbons appear to have been generated by thermal transformation of kerogen during burial of suitable source rocks (Philippi, 1965). Figure 9 shows the "liquid window" as a function of temperature and depth of burial. If the geothermal gradient of the Scotian Shelf and Baltimore Canyon is plotted on this graph, then the top of the liquid window should occur at 2000m. This is in agreement with geochemical data from these areas (Purcell *et al.*, 1978; Smith *et al.*, 1976) which are interpreted here to indicate that the maturation of organic matter begins at depth of 2.2 to 3.7 km of overburden

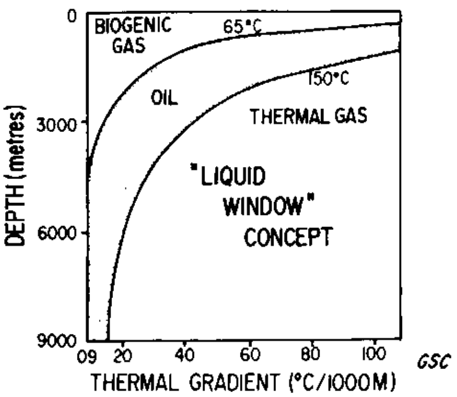

Figure 9
"Liquid window" concept after Pusey 1973.

However, even at a depth of four km, the organic matter is still only marginally mature (Purcell *et al.*, 1978). Generalizing this observation, and using a geothermal gradient on the American continental rise as low as that on the Scotian Shelf, allows us to predict that the prospective areas for liquid hydrocarbons at the American Basin margin will be limited to the areas where sediments are at least four km in thickness, and in the deep basin to the areas covered by more than two km of sediments.

Sediment thickness. The sediment thickness of the Central North Atlantic Basin is shown diagrammatically in Figure 10. The majority of the basinal deep Atlantic has sedimentary cover less than one km in thickness. Two to three km of sediments occur beneath the lower American rise and sediments exceed five km in thickness beneath the upper rise and slope (Fig. 10). Similar thickness in excess of five km of sediments probably occurs in local areas off the Spanish Sahara and Senegal on the northwestern African slope; but beneath the continental rise the sediments are three km or less thick. According to Klemme (1975), 90 per cent of the world's hydrocarbon reservoirs are located below two to three km of overburden. Almost 30 per cent thicker overburden is required for hydrocarbon generation on the American margin, however, because of the low average geothermal gradient as noted above.

Considering the sedimentary thickness parameter, prospective areas for hydrocarbons are limited to the slope off Africa and the slope and upper rise of the American Basin, particularly in front of major Mesozoic depocenters such as the Scotian Shelf, Baltimore Canyon and Blake Plateau.

Conclusions

Similar sequences of Late Jurassic and younger pelagic carbonates and hemipelagic clays occur on both sides of the deep Central North Atlantic Basin. For a variety of reasons discussed in the text, the hydrocarbon prospects of these sequences are regarded as unpromising. In the Central North Atlantic Basin (excluding upper continental rise areas) the sediments are too thin to generate hydrocarbons in commercial accumulations. Although Late Jurassic and younger rocks of the upper continental rise and continental slope environment appear more favourable, the probably lack of reservoir rocks, in combination with Jurassic cementation of relatively coarse-grained rocks and a low geothermal gradient, suggest a very low probability for the occurrence of major hydrocarbon accumulations over most or all of the deeper parts of the American continental margin. An exception may exist seaward (basinward) of the Scotian Shelf, Baltimore Canyon and Blake Plateau areas where during Early Cretaceous time, conditions may have been favourable for development of sandy turbidite reservoirs. These potential reservoirs probably would interfinger with Mid-Cretaceous carbonaceous shales, which are considered to be good source rocks, mainly for wet gas. Theoretically, another potential reservoir could be developed in Tertiary turbidite sediments on the margin, but the seismic data seems to indicate that the Tertiary on the continental rise and slope is generally too thin for adequate maturation. The northwest African margin may have slightly better overall hydrocarbon potential because of locally higher geothermal gradients, tectonic and volcanic activity together with requisite thickness of sediments necessary for oil generation located higher up on the slope.

Thus most of the Central North Atlantic Basin, including the lower continental rise areas, should not be regarded as prospective of hydrocarbons. Beneath the upper rise another exploration target may occur in buried successions, i.e., pre-upper Jurassic shallow-water carbonates which would appear to offer the most promise. Unfortunately, we know little about these rocks. Until the Deep Sea Drilling Project provides us with better data from the deeper parts of the continental margins it will not be possible to assess the hydrocarbon potential of these areas with any degree of certainty.

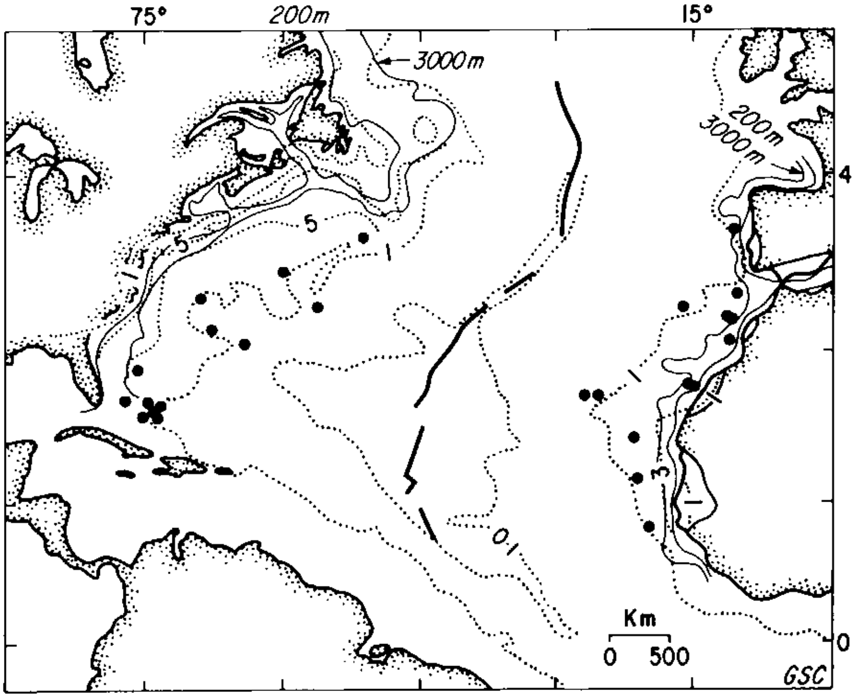

Figure 10
Sediment thickness in km (dotted lines) in Central North Atlantic Basin. Bathymetry in metres, shown by solid lines.

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References

Herman, B.M., M.G. Langseth, and M.S. Hobart, 1977, Heat flow in the oceanic crust bounding western Africa: Tectonophysics, v. 41, p. 62-77.

Jansa, L.F. and J.A. Wade, 1975, Geology of the continental margin off Nova Scotia and Newfoundland: *in* Offshore Geology of Eastern Canada: Geol. Survey Canada Paper

Jansa, L.F., J.V. Gardner, and W.E. Dean, 1977, Mesozoic sequences of the central North Atlantic: *in* Y. Lancelot, E. Seibold *et al.*, 1977 Initial Reports of the Deep Sea Drilling Project, v. 41, Washington, p. 991-1031.

Klemme, H.D., 1975, Giant oil fields related to their geologic setting: A possible guide to exploration: Can. Petrol. Geol. Bull., v. 23, p. 30-66.

Lancelot, Y. and E. Seibold, *et al.*, 1977, Initial Reports of the Deep Sea Drilling Project, v. XLI, Washington.

Miller, J.B., K.L. Edwards, P.P. Wolcott, H.W. Anisgard, R. Martin and H. Anderegg, 1958, Habitat of oil in the Maracaibo Basin, Venezuela: *in* L.G. Weeks, ed., Habitat of Oil, Amer. Assoc. Petrol. Geol., Tulsa, Oklahoma, p. 601-640.

Morales, L.G. and the Columbian Petroleum Industry, 1958, General geology and oil occurrences of Middle Magdalena Valley, Columbia: *in* L.G. Weeks, ed., Habitat of Oil: Amer. Assoc. Petrol. Geol., Tulsa, Oklahoma, p. 601-640.

Phillippi, G.T., 1965, On the depth, time and mechanism of petroleum generation: Geochim. Cosmochim. Acta. v. 29, p. 1021-1049.

Purcell, L.P., M.A. Rashid, and I.A. Hardy, 1978, Hydrocarbon Geochemistry of the Scotian Basin: Offshore Technology Conference, Houston, p. 87-92.

Pusey, W.C. III, 1973, The ESR-Kerogen method, a new technique of estimating the organic maturity of sedimentary rocks; Petroleum Times, v. 77, no. 1952, p. 21-26.

Robbins, E.I., 1977, Geothermal gradients: *in* P.A. Scholle, ed., Geological Studies on the COST No. B-2 Well, U.S. Mid-Atlantic Outer Continental Shelf Area, U.S. Geological Survey Circular 750, p. 44-45.

Romankevic, E.A., 1977, Geochemia organiceskovo vescestva v okeane, NAUKA, Moscow, 1977, p. 256 (in Russian).

Ryan, W.B.F. and J.C. Sibuet *et al.*, 1976, Passive Continental Margin: Geotimes, October 1976, p. 21-24.

Scholle, P., 1977, Deep-water carbonate sedimentology, diagenesis and petroleum potential: Amer. Assoc. Petrol. Geologists, Program and Abstracts, 1977, p. 50-51.

Sclater, J.G. and J. Francheteau, 1970, The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth: Geophys., Jour. Royal Astronom. Soc., v. 20, p. 509-542.

Smith, M.A., R.V. Amato, M.A. Furbush, D.M. Pert, M.E. Nelson, J.S. Hendrix, L.C. Tamm, G. Wood Jr., and D.R. Shaw, 1976, Geological and operational summary, COST No. B-2 well, Baltimore Canyon Trough area, Mid-Atlantic OCS: Open-File Report 76-774, U.S. Geol. Survey, p. 79.

Zenkovich, V.P., D.M. Doobman, A.G. Kiknadze, V.L. Menshikov, and G.A. Orlova, 1975, Geomorphological Observations on the Continental Slope and in Underwater Canyons: Communications of Academy of Sciences of Georgian SSR, v. 78, no. 1.

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