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A SCHEMATIC MODEL OF THE EVOLUTION OF THE SOUTH ATLANTIC*

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ABSTRACT

– A schematic model of the evolution of the South Atlantic ocean is proposed to demonstrate the possibilities offered by the Deep Sea Drilling Project within the framework of Plate Tectonics to reconstruct a logical evolution of the history of the ocean basins and their paleoenvironment. The emphasis is put on the methodology available to reconstruct the ocean crust morphology and its sedimentary cover at all stages throughout the opening of the ocean. Paleobathymetric, deep paleo-water-circulation and paleo-sedimentary - facies maps at five different stages of the opening are presented and discussed. The last type of maps are in great part based on a new paleo - Carbonate Compensation Depth Curve for the South Atlantic which is tentatively proposed here.—

INTRODUCTION

It has long been known that the sedimentary record should be much more complete in the ocean basins than on the continents, because erosion is a more widespread phenomenon on land than it is on the deep sea floor. As it is the sedimentary record which contains most of the information available to reconstruct the paleoenvironment at the time the sediment was deposited, any paleoenvironment reconstruction relies heavily on its study. Accordingly, the deep holes made by the Drilling Vessel Glomar Challenger for the Deep Sea Drilling Project in the world ocean have provided a completely new basis to approach a paleoenvironmental study of our planet. This is specially so because Plate

Tectonics has given a coherent framework within which the various data collected from the ocean floor can be integrated to reconstruct a logical evolution of the history of the ocean basins and their paleoenvironment.

Paleoenvironmental oceanography is a new science which is progressing very rapidly. Any synthesis in this domain would be difficult to do and beyond the scope of this paper. We have attempted here to give a specific example of what can be done to reconstruct the evolution of a given ocean, limited ourselves to the ocean crust morphology and its sedimentary cover. We have chosen the South Atlantic Ocean because the age of its crust is known everywhere, through magnetic anomaly identification, and because the age distribution shows that it has been steadily widening since its early opening 125 to 130 M.y (millions years) ago. There are and there have been no deep sea trenches along its borders. As a consequence, there is a marked contrast in the sedimentary provinces, the deep basins being easily accessible to the products of erosion of the continents whereas the axial mid-Atlantic ridge only receives pelagic sedimentation.

Although it is theoretically possible to reconstruct, at least in a schematic way, the complete evolution of an ocean, the data we have are still quite limited and, for this reason, many of the conclusions are not yet firm and may even be erroneous. The emphasis is on the demonstration of a new methodology available to us to make such a reconstruction. 24 successful holes (figure 1) have been realized by the Glomar Challenger in the South Atlantic during different legs (3, 36, 39 40). Two of the Initial Reports are published (3, Maxwell et al., 1970; 36, Barker et al., 1974). Legs 39 and 40 Initial Reports (Perch-Nielsen et al., 1975; Bolli et al., 1975) are still in press but should be published soon. Only 4 of these drillings have been made in deep basins (Argentine, Brazil and Cape basins). It is consequently often risky to interpolate between holes over such a wide distance, although some reasonable guesses can be made.

In the first part, we will discuss some of the main features of the present South Atlantic environment, as it gives us one of the keys to interpret the sedimentary record. In the second part, we will present the methodology used to reconstruct the evolution of the ocean. In the last part, we will briefly comment paleogeographic and paleosedimentary maps of the South Atlantic ocean, from its birth to its present stage.

I. PRESENT ENVIRONMENT OF THE SOUTH ATLANTIC OCEAN

Physiography

In a geological sense, the South Atlantic Ocean can be considered to have been created by the drifting apart of the South American and the African continents. It should consequently extend northwards from the Falkland Plateau in the south. Thus its northern limit corresponds to the very large equatorial fracture zones, of which the Romanche fracture zone is the largest. Its southern limit is the Falkland - Agulhas fracture zone system (fig. 1). These fracture zones were flow lines of the relative continent motion during the opening (e.g. LE PICHON and HAYES, 1971a).

It is now known that the depth of the ocean is governed by the slow cooling of the plates as they move away from the ridge crest where they were produced by sea-floor spreading (LANGSETH et al., 1966; McKENZIE and SCLATER, 1969). At the accreting plate boundary, whose surface expression is the ridge crest, the plate, which has just been formed by rapid intrusion of hot material from below, is extremely hot throughout its thickness. From then on, its evolution will be essentially due to loss of heat through the sea-floor which results in thermal contraction. As isostatic equilibrium prevails, the sea-floor will deepen by roughly 30 % more than the amount corresponding to the contraction of the plate, to compensate for the increasing water load. Thus, the depth of the ocean only depends on its age, as is convincingly demonstrated by the empirical curve first compiled by SCLATER et al. (1971) (see fig. 6). The present 0 M.y. isochron follows the crest of the mid-Atlantic ridge and roughly corresponds to the 2600 m isobath. On each side, the sea-floor progressively deepens to reach depths larger than 5000 m under the basins.

However, two main volcanic rises, which run approximately east-west near 30°S, the Walvis Ridge and the Rio Grande Rise, are superposed on this general regular bathymetric trend (fig. 1). Together with the mid-Atlantic ridge, they divide the South Atlantic ocean into four main basins, the Brazil and Argentine basins to the west and the Angola and Cape basins to the east. In addition, as noted previously, the major fracture zones, which also run at cross-trend with the mid-Atlantic ridge, are large topographic features which provide east-west gaps through the ridge but prevent deep north-south flow.

Age of ocean floor

LADD (1976) has presented a synthesis of the VINE and MATTHEWS (1963) magnetic anomaly identifications in the South Atlantic ocean, from the Recent Gauss anomaly at the crest of the ridge to anomaly M 13, at the foot of the continental margin, in the Cape basin. Each of these anomalies corresponds to an isochron whose age is approximately known through correlation with D.S.D.P. results. We have used the time scales proposed by THIERSTEIN (1977) for the Cretaceous and TARLING and MITCHELL

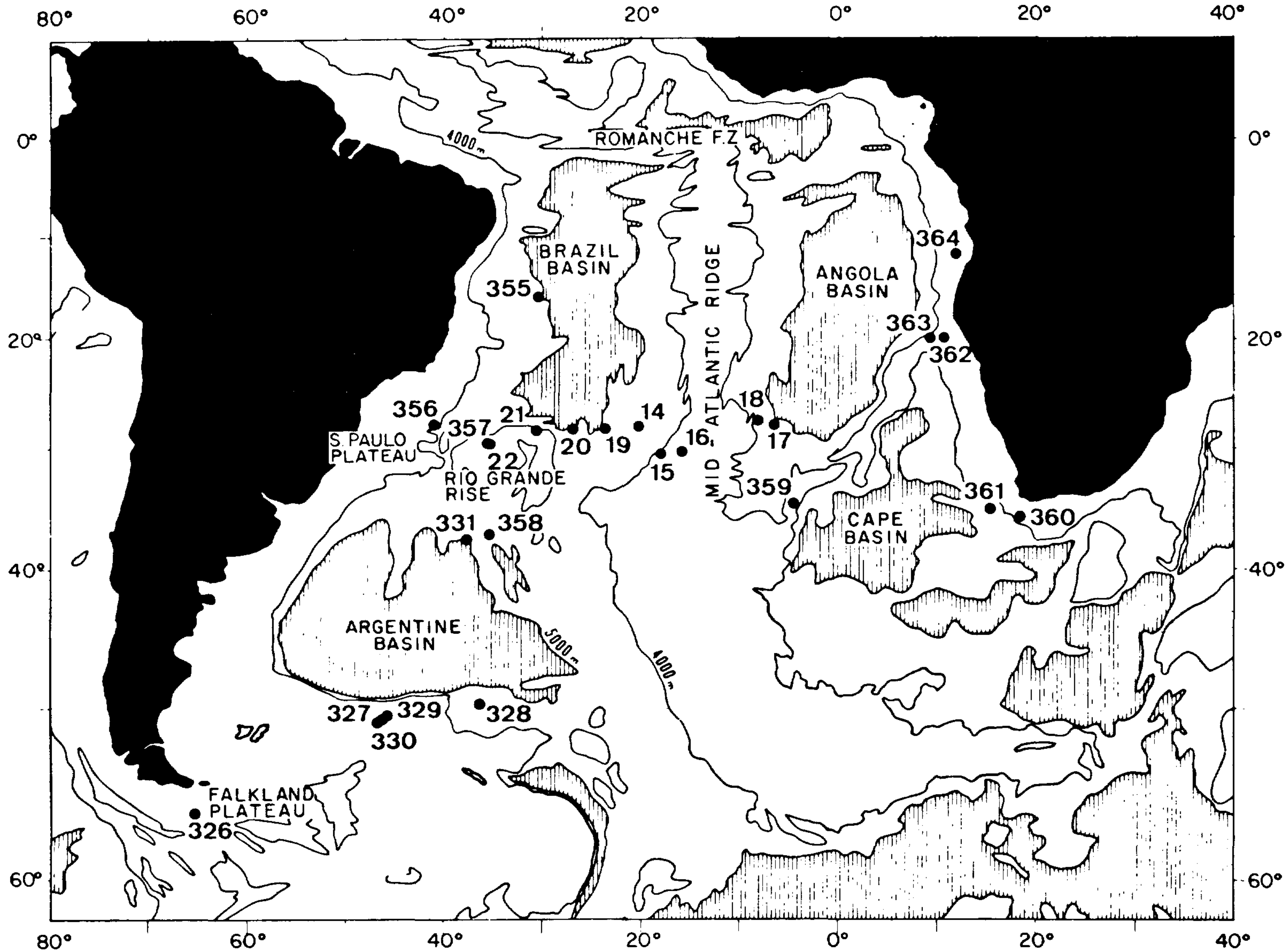

Figure 1. Topographic map of the South Atlantic ocean. DSDP drilling sites are identified by their numbers.

(1976) for the Cenozoic. The earliest anomaly identified corresponds to Valanginian, roughly 125 M.y. ago and it can be inferred that creation of oceanic crust started immediately before, sometime between 130 and 125 M.y. It is of course entirely possible that, prior to that time, a continental rifting stage was present for an extended period of time.

Sedimentary cover

It was previously mentioned that the depth of the sea-floor is directly related to its age. However this observation applies to the igneous oceanic crust as it has been produced at the ridge crest. As the plate moves away from the ridge crest, it is progressively covered by a layer of sediments which tends to increase with age. The thickness of the layer may reach several kilometers at the foot of the continental margin. It loads the crust which readjusts isostatically by sinking. If there were no isostatic adjustment, the water depth after sediment loading would be smaller than the ocean crust depth without sediment by a distance equal to the layer 1 thickness. As there is isostatic adjustment, the actual depth is decreased by 1/2 (using densities of 2.2 g/cm^3 for the sediments and 3.4 g/cm^3 for the mantle).

Figure 2 shows the isopach map of the sediment thickness modified after EWING et al. (1973) using some additional data from EMERY et al. (1975) off South Africa. It is obvious on this map that the thickness of sediments is negligible near the ridge crest, in the zone where the oceanic crust is very young. It is specially small between 30° and 10°S. It exceeds 1000 meters over most of the Argentine basin and part of the Brazil basin and over the continental margin area. Thus, except in the latter areas, the sea-floor depth is not significantly modified by the presence of sediments.

Water circulation

Since WUST (1939), it is known that a significant factor in the deep sea environment is the deep water circulation. As the deep basins of the South Atlantic ocean are open both to the north and south, they are swept by a vigorous deep water circulation which originates in high northern and southern latitudes. Figure 3 schematically shows the deep water circulation pattern. The bottom water is dominated by the spreading of the Antarctic Bottom Water (AABW) which is controlled by powerful western boundary currents. The resulting bottom water temperature is very low, less than 1.6°C in the three basins in which the Antarctic Bottom Current (AABC) enters, that is the Argentine and Brazil basins to the west and the Cape basin to the east. In contrast, the temperature is somewhat higher in the Angola basin (2.4°C).

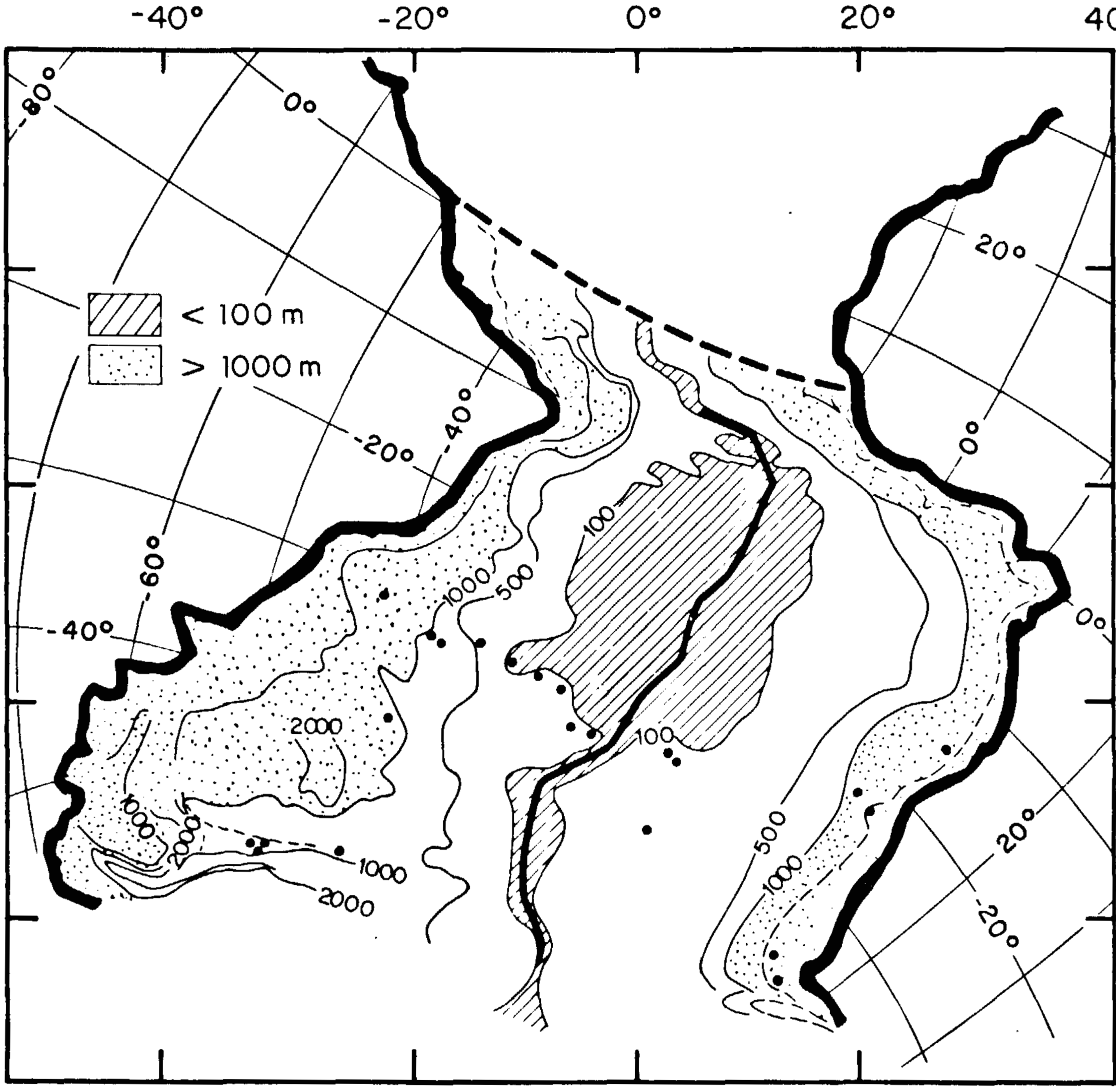

Figure 2. Oblique Mercator projection map of the South Atlantic showing the distribution of the thickness of the unconsolidated or semi-consolidated sediments after EWING et al. (1973). Isopachs are in meters. The pole of projection is at 30°N, 60°E. The equator of projection is vertical and is identified on the top of the figure to help in estimating the distortion. The same projection is used throughout this paper.

As the upper limit of the AABW is situated between 3500 and 4200 meters (LE PICHON et al., 1971 b; JOHNSON et al., 1975), the sea floor morphology controls its spreading. In particular, the passage of the AABW from one basin to the other often occurs through narrow passages or channels. It enters the Argentine basin from the south through a gap in the Falkland F.Z. (LE PICHON et al., 1971 a), follows the Argentine continental rise, enters the Brazil basin through a gap in the Rio Grande rise, called the Vema Channel (LE PICHON et al., 1971 b). It then continues to the north although a small branch enters the Angola basin through the Romanche F.Z. However, the sill depth in the Romanche F.Z. is only 3750 m (METCALF et al., 1964), so that the core of the AABW is prevented from entering the Angola basin.

Another branch of the AABC crosses the mid-Atlantic ridge and enters the Cape and Agulhas basins. Most of the water is prevented from entering the Angola basin by the Walvis ridge. There is only limited access near 6-7°W and 35-36°S (SHANNON and RIJSWIJCK, 1969; CONNARY, 1972; CONNARY and EWING, 1974).

Ewing et al. (1973) have shown that the AABC has controlled the distribution of sediments in the whole Argentine basin since the deposition of a major seismic reflector, called reflector A, which is now known to be quite probably Upper Oligocene ($\pm$ 30 M.y.) in age (Perch-Nielsen et al., 1975). This control includes non deposition or even erosion where the current flows and transport of large quantities of fine clay in suspension in what has been called the nepheloid layer. In addition, as we will see later, the deep cold water is highly corrosive and dissolves the carbonates. This has been clearly demonstrated by MELGUEN and THIEDE (1974, 1975) and CHAMLEY (1975) on the flanks of the Vema Channel and the adjacent Rio Grande Rise. Yet, it is quite clear that small changes in the morphology of the basins may deeply affect the circulation of the AABC. One should note further that, above the AABW, the North Atlantic Deep Water (NADW) flows from north to south. Its upper limit is near 1000 m.

Figure 3 also shows in a schematic fashion the main surface current pattern. This pattern controls the distribution of primary productivity in surface waters. It is specially high along the equatorial zone, off Angola and to the south.

Lysocline and CCD

A study of the preservation of the calcareous microfossils in recent sediments demonstrates that they suffer increasing dissolution with increasing depth, as has long been known. It is useful to characterize the degree of dissolution by two different levels, which have been called the lysocline and the Carbonate Compensation Depth (CCD).

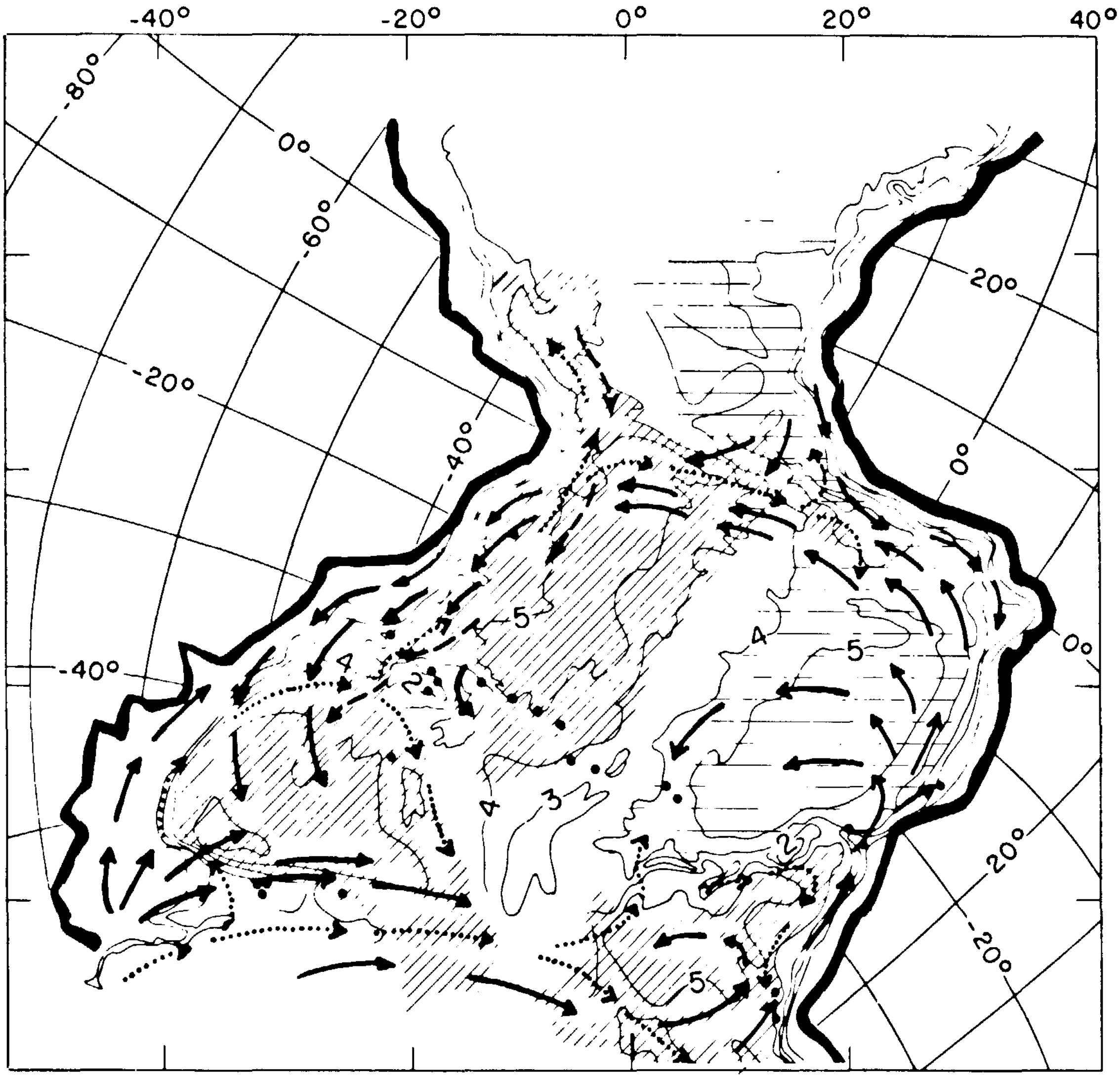

Figure 3. Bathymetric and paleocurrents map. Heavy arrows : surface currents; dashed arrows, NADC; dotted arrows, AABW. Horizontal hachures : bottom temperature greater than 1.6°C; oblique hachures, less than 1.6°C.

The lysocline has been defined by BERGER (1970 a) as the level at which the degree of dissolution of the calcareous microfossils shows a rapid increase. For example, in the case of planktonic foraminifera, the percentage of fragmentation of the tests of foraminifera passes at this level from 20 or less to more than 50% (MELGUEN and THIEDE, 1974). The lysocline is at different depths for different types of microfossils. It is for example deeper for the coccoliths than for the foraminifera (SCHNEIDERMANN, 1973; BERGER, 1973; BERGER and ROTH, 1975). Throughout this paper, the lysocline used will be the foraminiferal lysocline.

The lysocline is specially well defined in the Western South Atlantic where it coincides with the upper boundary of the AABW. In the Vema Channel and on the Rio Grande Rise, a detailed study by MELGUEN and THIEDE (1974) has shown that the lysocline sharply separates well preserved from poorly preserved calcareous assemblages. BERGER (1968) has shown that the lysocline is situated, as an average, 500 m. above the CCD and this has been verified in the South West Atlantic (MELGUEN and THIEDE, 1974).

The CCD was introduced by ARRHENIUS in 1952 to define the level at which the rate of supply of calcium carbonate is equal to the rate of dissolution, so that no more carbonate sediment is deposited (BRAMLETTE, 1961). Although the depth of the CCD is mainly controlled by the temperature of the water and the pressure, the rate of dissolution tending to increase as the temperature decreases and the pressure increases, many other factors are significant, such as the primary productivity (BRAMLETTE, 1965; TAPPAN, 1968; BROECKER, 1971; BERGER and ROTH, 1975), the carbonate supply from the continent and the distance to the continent (BERGER, 1970 a; BERGER and WINTERER, 1974), the succession of transgressions and regressions and the climate (SEIBOLD, 1970; BERGER and WINTERER, 1974) etc ... Therefore the CCD cannot be defined for the South Atlantic Ocean as a whole but it varies from basin to basin (fig. 4) and even within a basin.

According to ELLIS and MOORE (1973), the CCD varies from 5000 m. in the Argentine basin to 5200 m. in the Cape basin and to more than 5500 m. in the Angola Basin. For Berger (1968), the CCD varies from 5200 to 5800 m. from north to south in the Angola basin. BISCAYE et al. (1976) indicate a depth larger than 6000 m. in the Angola basin. Thus, there is still some disagreement among the different authors. We assume, for this paper, that the CCD in the Cape, Brazil and Angola basins is respectively 200, 500 and 1000 m. deeper than in the Argentine basin. These differences may be mainly explained by the AABC circulation previously discussed. In the Angola basin, where the input of AABC is minimum, the degree of saturation of the water in carbonate is higher at comparable depths than in the western basins, which results in a lower dissolving (TAKAHASHI, 1975). On the other

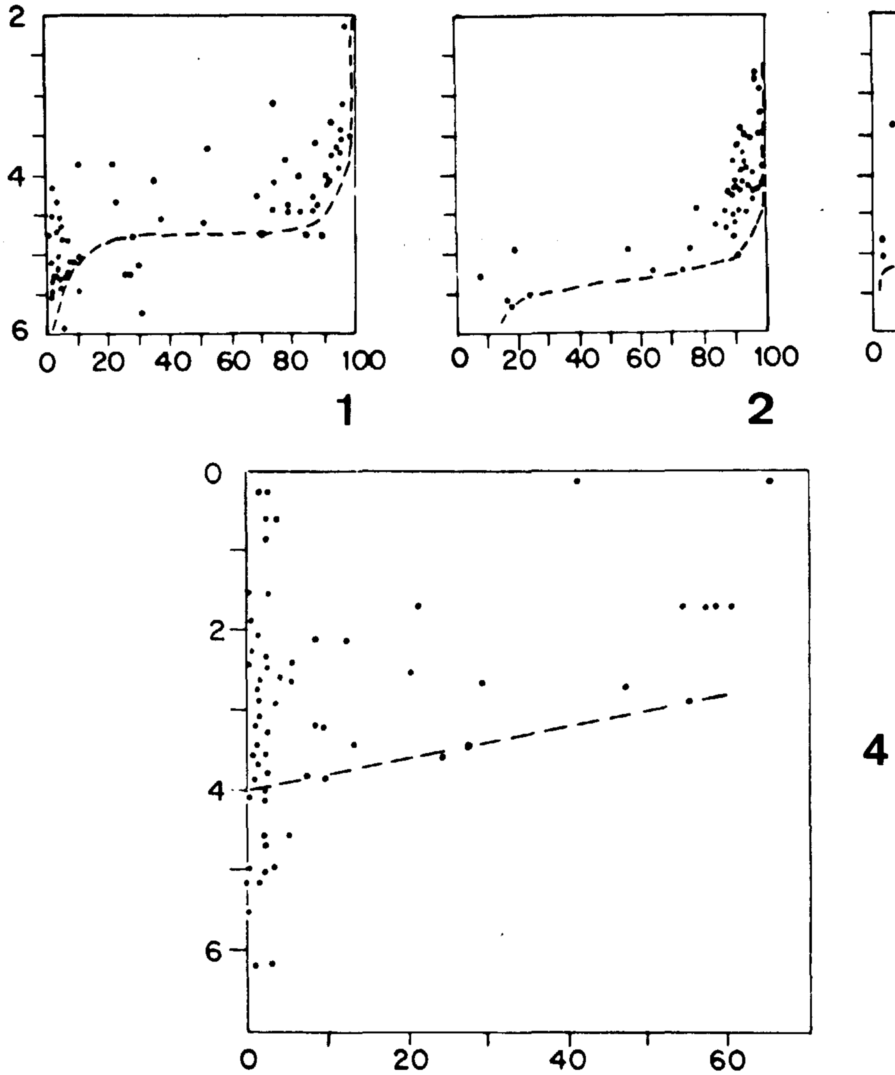

Figure 4. Calcium carbonate content in surface sediments of the South Atlantic Ocean in percent versus water depth in kilometers. 1,2,3, Argentine and Brazil basins, Angola basin and Cape basin respectively after ELLIS and MOORE (1973); 4, Falkland rise and 50°S after BISCAYE et al. (1976).

hand, the degree of under saturation (acidity) of the bottom water in the western basins is strongly affected by the AABC. This is demonstrated by the fact, mentioned previously, that the upper limit of the AABW coincides with the lysocline in the Vema Channel.

In the South Atlantic, the fertility of the surface waters is a significant factor in the control of the CCD. In areas of high productivity (e.g. equatorial zone and upwelling areas in general, STEEMAN-NEILSEN and JENSEN, 1957), two opposite processes affect the CCD. The increased supply of calcium carbonate tends to lower it whereas the additions of organic material tends to increase the acidity at the sediment-water interface and in the sediment itself, and thus to raise the CCD. This is why the CCD is shallower in the Falkland plateau area and along the Angola margin than in the adjacent basins.

Finally, the concentration of calcium carbonate in sediments is obviously affected by the input of non calcareous terrigenous material which dilutes it. Supply of terrigenous sediments is important along the continental margins, especially off large rivers, such as the Orange, the Congo, the Niger, the Amazon and the Parana. The dilution is maximum off the Congo and along northern part of the Argentine continental margin. In the Argentine basin, however, the main part of the terrigenous material comes from the south in suspension in the AABC (BISCAYE and DASCH, 1968; HOLLISTER and ELDER, 1969; EWING et al., 1973). Along the African margin, the terrigenous material derived from the Congo is transported by surface currents in the central part of the Angola basin and to the south of the Guinea basin along the coast of Gabon (Bornhold, 1973). South of the Walvis ridge, the terrigenous material derived from the Orange and Kunene rivers is transported by the Benguela current along the continental margin toward the southern part of the Angola basin. The Olifants and Berg rivers also supply terrigenous sediments to the Cape basin (SIESSER et al., 1974).

Surface sediment distribution

We have just seen that the surface sediment distribution on the sea-bottom is controlled by a multiplicity of complex factors among which the ocean basin morphology, the biogenic productivity, the terrigenous supply, the oceanic circulation and obviously the CCD play a major role. Figure 5 shows this distribution in a simplified manner, the major sedimentary facies being the only ones shown. This map is a compilation based on the numerous studies which have been made in the South Atlantic since the early work of MURRAY and RENARD (1891) during the Challenger expedition (1891). PRATJE, in 1939, taking into account the work of WUST (1936), pointed out the importance of the AABC in the distribution of the sedimentary facies. TUREKIAN (1964), GOLDBERG and GRIFFIN (1964), BISCAYE (1965), EWING (1965), LISITZIN (1971), EWING et al

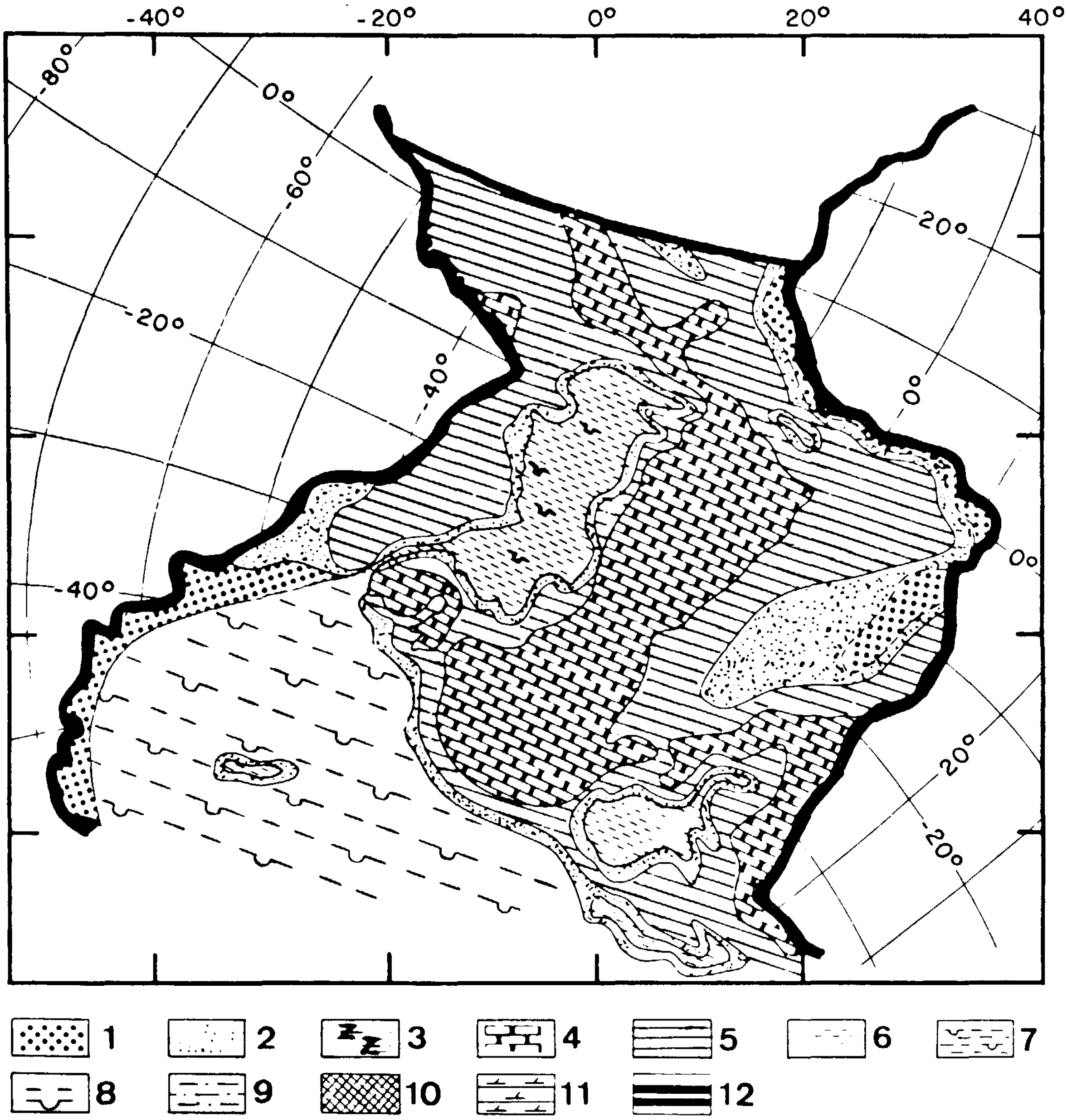

Figure 5. Map of present-day sedimentary facies distribution. 1, mud; 2, coccoliths and foraminifer-bearing mud; 3, zeolitic mud; 4, calcareous ooze or chalk; 5, marl; 6, pelagic clay; 7, diatom-bearing pelagic clay; 8, radiolarian and diatom-bearing mud; 9, shale and sandstone; 10, evaporites; 1, dolomitic limestone; 12, sapropel. The same symbols are used throughout this paper.

(1973), ELLIS and MOORE (1973), CALVERT and PRICE (1971), RAMSAY (1974), SIESSER et al.(1974), MELGUEN and THIEDE (1974), GARDNER (1975), BISCAYE et al.(1976), BURKE and STANTON (1976) have studied some of the major aspects of the sedimentation in the South Atlantic.

To define the major pelagic facies and their succession as a function of increasing water depth, we have used the common DSDP classification with modifications coming from the study of MELGUEN and THIEDE (1974) in the Vema Channel and on the Rio Grande rise. The continental margin sediment distribution is however more difficult to schematize in this way. We have been forced to adopt a highly simplified facies distribution which is in part based on our own observations in the Sao Paulo basin (CNEXO cruise, unpublished report), on the Niger Delta (THIDE et al., 1974), and on the Angola margin (MELGUEN et al., 1975).

The sedimentary facies adopted for this study are the following:

- mud consists essentially of silty clay with less than 10 % of calcareous or siliceous biogenic components. It is characteristic of parts of continental margins with large terrigenous input.
- coccolith and foraminifer bearing mud differs from the preceding by a greater abundance (10 - 30 %) of calcareous micro- and nannofossils as a result of a greater biogenic productivity or of a smaller supply of terrigenous material. It is characteristic of the base of the continental margin, the continental rise and the lower flanks of the mid-Atlantic ridge just above the CCD. In the latter case it depends not so much on the degree of dilution as on the degree of carbonate dissolution.
- radiolarian and diatomaceous bearing mud is similar to the previous one, but with siliceous instead of calcareous microfossils. It is, in general, characteristic of high productivity areas with high terrigenous material supply.
- marl contains 30 to 60 % of calcium carbonate, consisting essentially of microfossils and nannofossils. On the continental margin, however, marls may include terrigenous components.
- calcareous ooze or chalk contains more than 60 % of calcium carbonate (nannofossils and foraminifers). This facies, characteristic of oceanic ridges is also found along continental margins with little supply of terrigenous material.
- pelagic clay contains less than 2 % of calcium carbonate. It is found in deep basins, at or below the CCD and generally represents the residue of sediments heavily dissolved. Pelagic clays are often associated with zeolites, especially in areas influenced by volcanism.

MELGUEN and THIDE (1974) have determined the depth range of most of the pelagic facies with respect to the CCD in the area off Brazil. From bottom upward, pelagic clay is found below or at the CCD; coccolith and foraminifers bearing mud, from the CCD to 200 m. above it; then marl which extends up to approximately 1000 m above the CCD; and finally calcareous ooze and chalk above this 1000 m level. These considerations do not apply to the continental margin area where the major factor is not so much depth as the supply of terrigenous material. Thus, for example, the continental margin of Argentina is mostly covered by mud whereas the Cape basin continental margin is highly calcareous (fig. 5). In the same way, the distribution of biogenic siliceous mud is primarily related to the surface water productivity, and to the oceanic circulation. In the Argentine basin, for example; the distribution of displaced Antarctic diatoms, follows the flow of the Antarctic Bottom Water (BURCKLE and STANTON, 1976).

To conclude, we may point out the main characteristics of the map in figure 5. These are the wide area of calcareous facies over the mid-ocean ridge; the restriction of the terrigenous sedimentation to part of the Argentine and Angola basins; the restriction of siliceous mud to southwest, around the Falkland plateau and over the Argentine basin (small areas rich in siliceous debris, such as Walvis Bay are not represented); the variable extent of the pelagic clay area in the deep basins, reflecting changes in the CCD level. These changes are, as previously mentioned, strongly related to the flow of the AABC, which increases the carbonate dissolution and supplies the deep basins with suspended clay.

II. METHODS OF RECONSTRUCTION

Paleobathymetry

The preliminary basis for any reconstruction of the paleo-environment of an ocean is a paleobathymetric map. SCLATER and McKENZIE (1973) previously proposed a reconstruction of the paleo-bathymetry of the South Atlantic ocean. However, there are now much better magnetic data which allow us to obtain a more precise reconstruction.

The fit of the South American and African continents, as obtained by BULLARD et al. (1965), demonstrates that there has been no significant internal deformation as they moved apart and, consequently, that they have behaved as rigid plates throughout the opening. Consequently, we can obtain the past relative positions of the two continents at different stages during the opening by fitting together corresponding isochrons of the ocean crust. The linear magnetic anomalies associated with spreading of the sea-floor (Vine and Matthews lineations) were created at the accreting plate boundary (the ridge crest) and subsequently carried away on either side of the boundary. The finite rotation which will fit them together will also restore the plates to their proper positions with respect to the ridge crest, at the time the anomalies were created. It will also restore, of course, the older isochrons to their proper relative positions at the time, thus obtaining the corresponding distribution of sea-floor ages by subtracting from the rotated isochrons the age of the reconstruction. The process is equivalent to eliminating the portion of sea-floor younger than the age of the reconstruction.

LADD (1976) has obtained such fits by trial and error method for some of the most clearly identified anomalies. We have used his parameters and those of Sibuet and Mascle (in preparation) to reconstruct maps of the distribution of ocean crust isochrons at different geological stages, of which four are shown in this paper: the Albian (anomaly MO, 100 M.y.), the Coniacian-Santonian (anomaly 34, 86 M.y.), the Maastrichtian (anomaly 31, 68 M.y.) and the Lower Oligocene (anomaly 13, 34 M.y.). These maps are plotted on an oblique Mercator projection which avoids distortion. The corresponding parameters are given in table 1.

If, as discussed previously, a piece of ocean floor of a given age is associated with a given depth it is then trivial to convert these ocean floor paleo-isochrons maps into paleobathymetric maps. The empirical curve which relates depth to age is shown in figure 6. An empirical formula was obtained by least squares by LE PICHON et al., (1973) on the basis of data compiled by SCLATER et al. (1971). The curve may be 200 m too low between 80 and 120 M.y. on the basis of recently compiled North Atlantic basin data (TREHU et al., in press). However, this kind of error is probably well within the accuracy of this method.

We discussed earlier the effect of the sediment cover on the depth of the sea-floor. Given a sediment thickness of 1, the sea-floor depth will be smaller than the theoretical depth of 1/2. This correction will thus be significant only where the sediment thickness is larger than 500 meters, giving a correction larger than 250 m. In addition, it will get smaller with increasing age. As can be seen in figure 2, the correction will thus only be significant in the ocean basins. The estimate of the sediment thickness at the time of the reconstruction was made on the basis of figure 2 and of the different DSDP holes. We then obtained paleoisopach maps by successively peeling off the part of the sediment layer younger than the age of the reconstruction. Although the paleoisopach maps obtained (not shown for lack of space) are not very accurate, they are sufficient for correction purposes except over the continental margins where, anyway, the empirical law relating depth to age breaks down because of strong

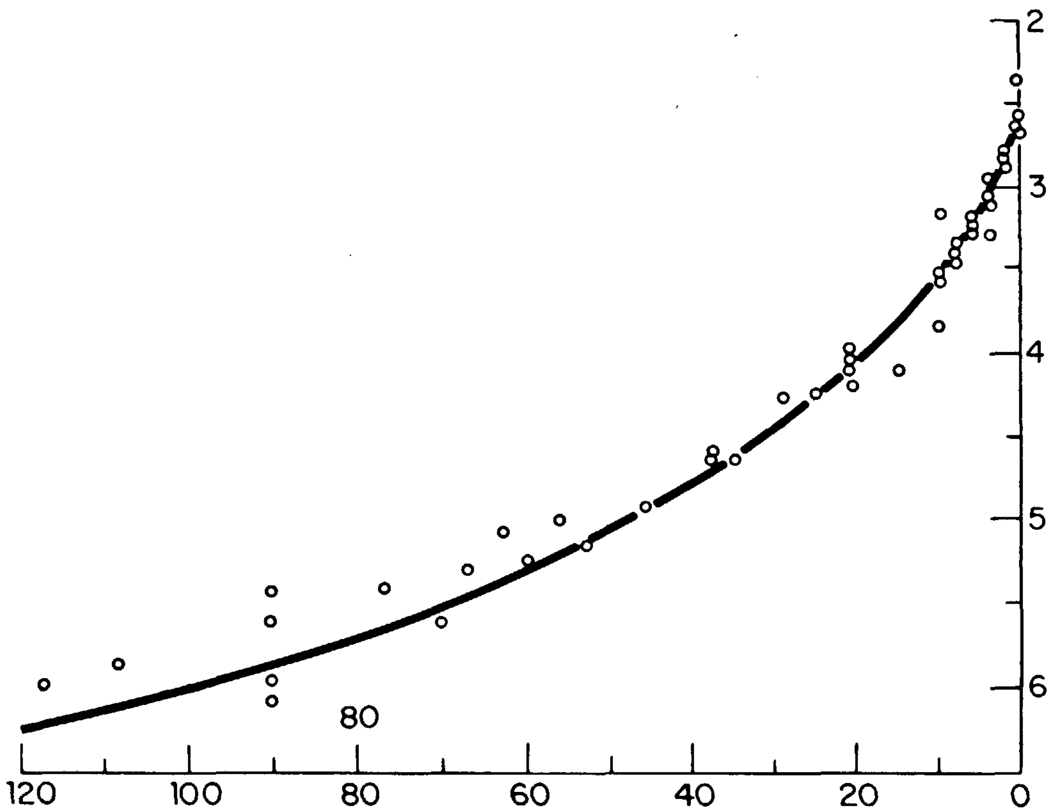

Figure 6. Empirical depth-age curve for the ocean bottom, for ages greater than 80 m.y. after LE PICHON et al. (1976) based on data of SCLATER et al. (1971) and TREHU et al. (in press). Continuous curve, D = 7 100 - 3 904 exp (A/78 - 606 exp (A/5.98) where D is the depth in meters and A is the age in m.y.

coupling between the continental lithosphere and the oceanic lithosphere.

However, even if the depth is anomalous with respect to the theoretical depth, available data suggest that the subsidence curve is not. It is then still possible to obtain an estimate of the paleodepth by proceeding backward from the present depth and removing the amount corresponding to the theoretical subsidence between the present and the age for which the reconstruction is made. This method can be applied not only to the lower continental margin area but also to other anomalous areas such as fracture zones and the Walvis and Rio Grande rises. It is thus implicitly assumed that these volcanic ridges have always maintained the same depth difference between their summit and the adjacent sea-floor. This hypothesis, which was already used by SCLATER and McKENZIE (1973) seems reasonable to us and leads to paleobathymetric reconstructions which seem to be in good agreement with drilling results.

To summarize, after applying the adequate sediment thickness correction, the depth of the transverse volcanic ridges and plateaus was obtained by assuming a constant depth difference between their summits and the adjacent sea-floor. The paleodepths are not correct in the continental margins areas due to insufficient data on sediment thickness.

This last restriction could be a very significant problem for the interpretation of the sedimentary record of the JOIDES drill holes, because we need an accurate reconstruction of the paleobathymetric evolution for this purpose. It can be seen in figure 1 that many of these holes are in so called "anomalous areas" where the use of the empirical curve of figure 6 may lead to errors larger than 1000 meters in the estimate of the present depth. Fortunately, for these holes, we have detailed information on the sediment thickness which enabled us to obtain with good accuracy the paleobathymetric evolution by proceeding backward from the present depth using the empirical curve as a subsidence curve and not as an absolute depth curve.

A final remark of technical nature should be made here. The empirical age-depth formula used here is based on the magnetic reversal time scale proposed by HEIRTZLER et al. (1968) which is slightly different from the TARLING and MITCHELL (1976) time scale used in this paper. This is not a major problem, however, as the empirical curve of SCLATER et al. (1971) relates depth to magnetic anomaly number. Thus, provided one uses the same time scale throughout the correction process, it is then possible to apply the new time scale to the corrected sea-floor paleobathymetry without error.

Paleo CCD

The discussion of the surface sediment distribution has demonstrated that the variation of level of the CCD is a crucial factor in the facies distribution. It is thus necessary to know its evolution through time as well as space in order to reconstruct maps of paleodistribution of sediments. Unfortunately, this is not an easy problem as was shown by the considerable differences in the estimates, made by recent papers, of the present CCD in the different basins of the South Atlantic. This is partly due to the fact that the CCD varies not only from basin to basin but also within the same basin, and partly to insufficient data.

With the present distribution of data, it is of course impossible to approach adequately the paleovariation of the CCD in space. It is necessary to make some simplifying assumptions in order to extrapolate data, from one to a few points at most, to the whole surface of the South Atlantic sea-floor. In this paper, we have tried to establish an average curve for the deep Argentine and Cape basins considering, by reference to present observations discussed earlier, that it is shallower than the CCD in the Brazil and Angola basins but deeper than the CCD over the high productivity areas of the Falkland plateau and the Angola continental margin. Thus our average curve provides a reference level from which we estimate by difference the CCD in the other locations.

This hypothesis seems to be confirmed by data available from the various drilled sites. If, for example, we compare the curves of evolution of paleodepth of the pelagic clay facies on the Falkland plateau to those in the Argentine and Cape basins, the former are generally situated 2 000 m shallower. A similar observation is made when we compare the paleodepths of the marls deposited at the lysocline level in the Cape basin (fig. 10) and in the area of high productivity of the easternmost Walvis ridge (sites 361 and 363). The lysocline, during middle Eocene and lower Oligocene, seems to have been from 1 000 to 2 000 m shallower in the latter area than in the Cape basin.

We base our estimate of this paleo CCD curve shown in figure 12 on an analysis of the facies of all JOIDES sediment cores recovered in the South Atlantic. For the periods where these data did not give us any reliable estimate of the paleo-CCD, we have used values previously proposed by other authors (RAMSAY, 1974); BERGER and ROTH, 1975; VAN ANDEL, 1975) based on data coming from other parts of the ocean.

The type of information coming from a description of the sedimentary facies at the different drilling sites is vividly illustrated by the 5 sites drilled on a transect of the mid-Atlantic ridge during leg 3 (fig. 7). Sites 16 to 19 are situated at increasing

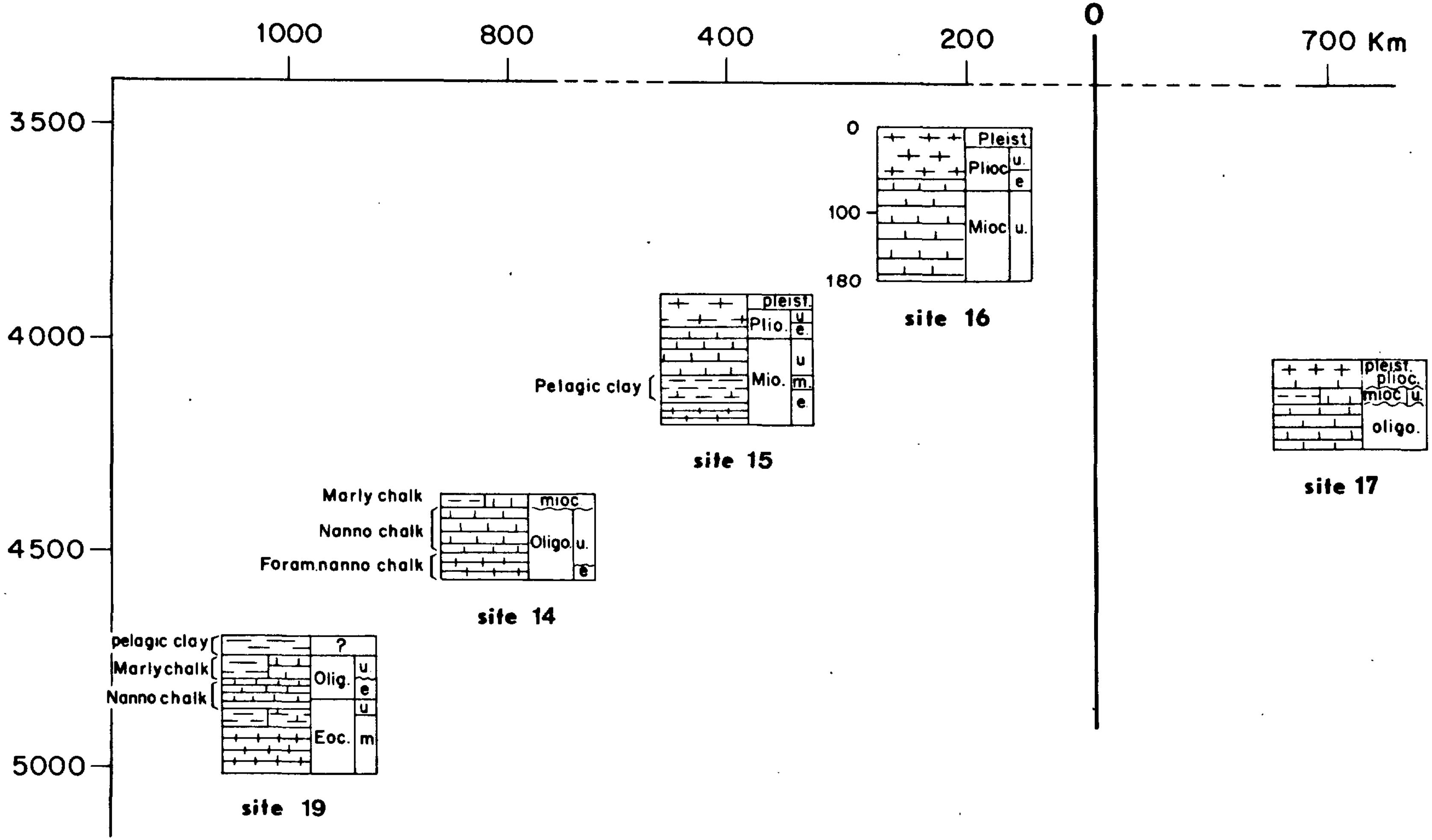

Figure 7. Sedimentary facies evolution as a function of the distance from the Mid-Atlantic Ridge axis. Sites 15 and 19, drilled by Glomar Challenger, leg 3 (MAXWELL et al., 1970) show a rise of CCD level in Eocene and Middle Miocene. Water depth in meters.

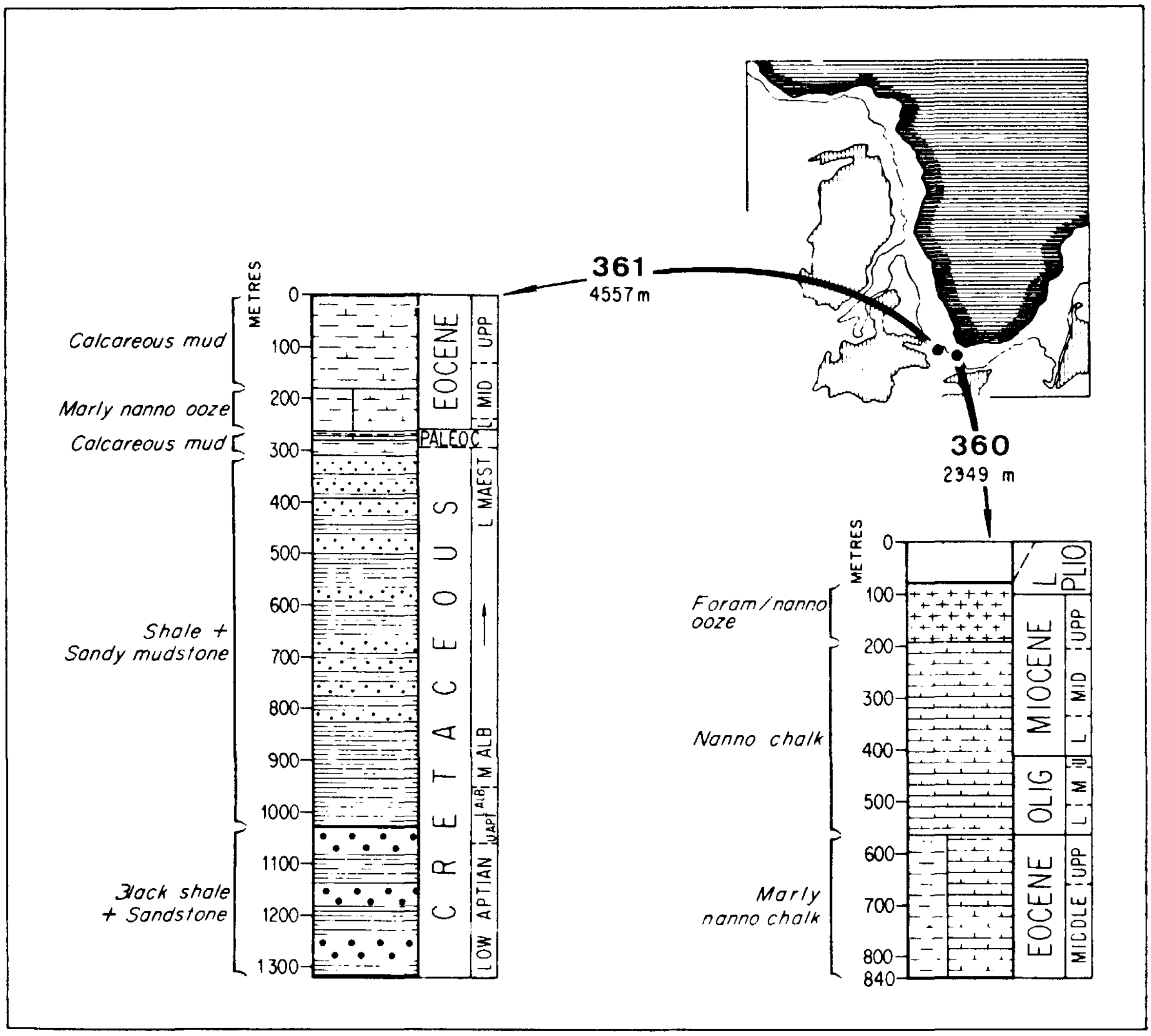

Figure 8. Evolution of sedimentary facies at sites 360 and 361 drilled on the Cape continental margin and in the Cape basin (DSDP leg 40; BOLLI et al., 1975).

distances from the ridge crest, and consequently increasing depths and ages. First, we note that the surface sediments pass from chalk to marly chalk to pelagic clay with increasing depth, indicating that the present CCD is situated between 4 300 and 4 700 meters here. Second, we know that, as the oceanic crust operates like a conveyor belt, progressively moving down the flanks of the ridge, the calcareous mud from the crest area will be transgressively covered by sediments more affected by dissolution. Thus, at site 19, the earliest Eocene sediments are Eocene chalk which changes to marly chalk in upper Oligocene and finally to pelagic clay after a hiatus. Third, the vertical succession of facies does not only reflect the deepening of the ocean crust but also the variations of the CCD. This is shown in site 15 where pelagic clay is present in middle Miocene between two chalk intervals, thus indicating a shallowing of the CCD at the time. Similarlv, in site 19, marly chalk appears in Upper Eocene between two chalk intervals indicating that the lysocline reached site 19 in upper Eocene due to a shallowing of the CCD.

It is obviously not possible in this paper to describe in detail the information given by the 24 drill sites, and which permits us to estimate the paleo-CCD. We just give as an example in figures 8 and 9 the analysis of site 360 drilled in Cape basin in 2 949 m water depth. The sediments at this site have clearly recovered CCD variations in their facies (fig. 8), in the proportion of carbonate (fig. 9), in the sand fraction, its relative abundance, its composition and the preservation of the foraminifera tests that it contains (fig. 9).

The nature of the sediment facies was determined on smear slides. It is a more or less marly nanno chalk. The Eocene sediments are richer in clay and less calcareous than the Oligo-Pliocene sediments. This could result either from increased dilution by terrigenous material or by increased dissolution. It is the purpose of the study of the sand fraction (63 to 2 000 microns) (MELGUEN and THIEDE, 1974) to discriminate between the two possibilities. We know for example that marls deposited at the lysocline level are characterized by a degree of fragmentation of planktonic foraminifera close to or greater than 50 %. Figure 9 illustrates that the fragmentation was greater than 50 % in middle Eocene. Note also the relative abundance of dissolution resistant components such as benthic foraminifera and fish debris. Thus we can conclude that this site was close to the lysocline during the Eocene. Note also in figure 9 the indications of another level close to the lysocline during middle Miocene.

In practice, we have considered three types of facies as being specially significant in estimating the position of the CCD: pelagic clay deposited at or below the level of the CCD, marls

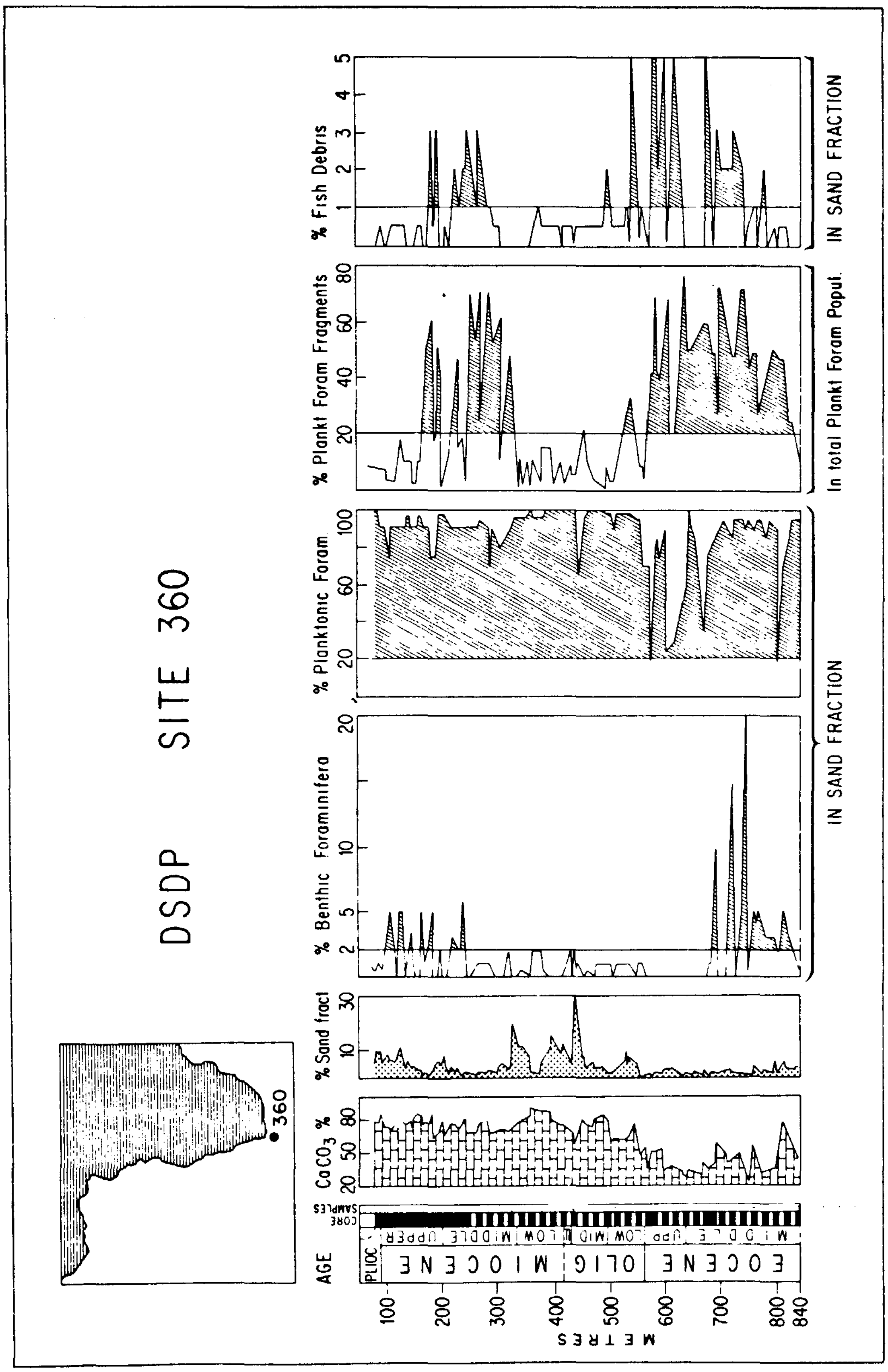

Figure 9. Carbonate content, coarse fraction abundance (63 - 2 000 µ) and composition in sediment.

deposited at the lysocline level, roughly 500 m above the CCD and chalk deposited at least 1 000 m above the CCD. We have then summarized the paleofacies information for each of the drill sites on a curve which gives the evolution of the paleodepth with time. Figures 10 and 11 give the two most important sets of such curves. Figure 12 shows the paleo-CCD curve that we have adopted. For comparison purposes, we have also shown this paleo-CCD curve on figures 10 and 11.

Below, we will discuss this paleo-CCD curve that has to be still considered as quite hypothetical and is only considered as an average curve for the deep Argentine and Cape basins.

- Aptian-Albian (see fig. 12 for corresponding age in M.y.)

The value of 1 500 m chosen, which is very shallow, is related to the period of deposition of black shales with intensive carbonate dissolution (MELGUEN, in preparation). Although part of the dissolution occurred after sedimentation, as shown by the existence of numerous moulds of coccoliths now dissolved (NOEL and MELGUEN, in press), and although there was abundant terrigenous supply at the time, we still consider the lack of calcium carbonate as reflecting a very high CCD (site 361), see fig. 10 for paleodepth). Black shales were also deposited during Albian on the Falkland plateau at a paleodepth close to 1 500 m.

- Coniacian - Santonian

4 000 m after RAMSAY (1974)

- Santonian - Campanian

The value of 3 200 m is based on site 361 in the Cape basin which contains very rare and highly dissolved calcareous nannofossils. The paleodepth is 3 000 m and we have chosen 3 200 m for the paleo CCD to agree with the value proposed by VAN ANDEL (1975).

- Campanian - Maastrichtian

The value of 4 500 m chosen is the one proposed by RAMSAY (1974) as we have only indirect evidence, that is the presence of chalk during the Maastrichtian and the Campanian-Maastrichtian respectively in the Argentine (site 358) and Brazil (site 355) basins. The paleodepths of 2 700 and 3 100 m respectively suggest a CCD deeper than 3 700 and 4 100 m.

- Maastrichtian - Paleocene

The estimate of 3 000 m is based on the presence of pelagic clay at a paleodepth of 3 000 m at site 328 in the Argentine basin. This value is confirmed by the presence of pelagic clay at sites 361 and 355 at the Maastrichtian/Paleocene boundary, at paleodepths of 3 200 - 3 400 m. It agrees with the estimate of RAMSAY (1974).

- Upper Paleocene

The estimate of 3 600 m is made on the basis of the presence of pelagic clays at a paleodepth of 3 600 m in the Brazil basin (site 355). This is in agreement with the 3 500 m proposed by VAN ANDEL (1975) and close to the 4 000 m proposed by RAMSAY (1974). However, there is chalk at a paleodepth of 3 600 m in the Cape basin (site 361) at that time which suggests a much deeper CCD. The chalk deposition is only a short event as the Paleocene/Eocene boundary is already marked by the presence of marls deposited close

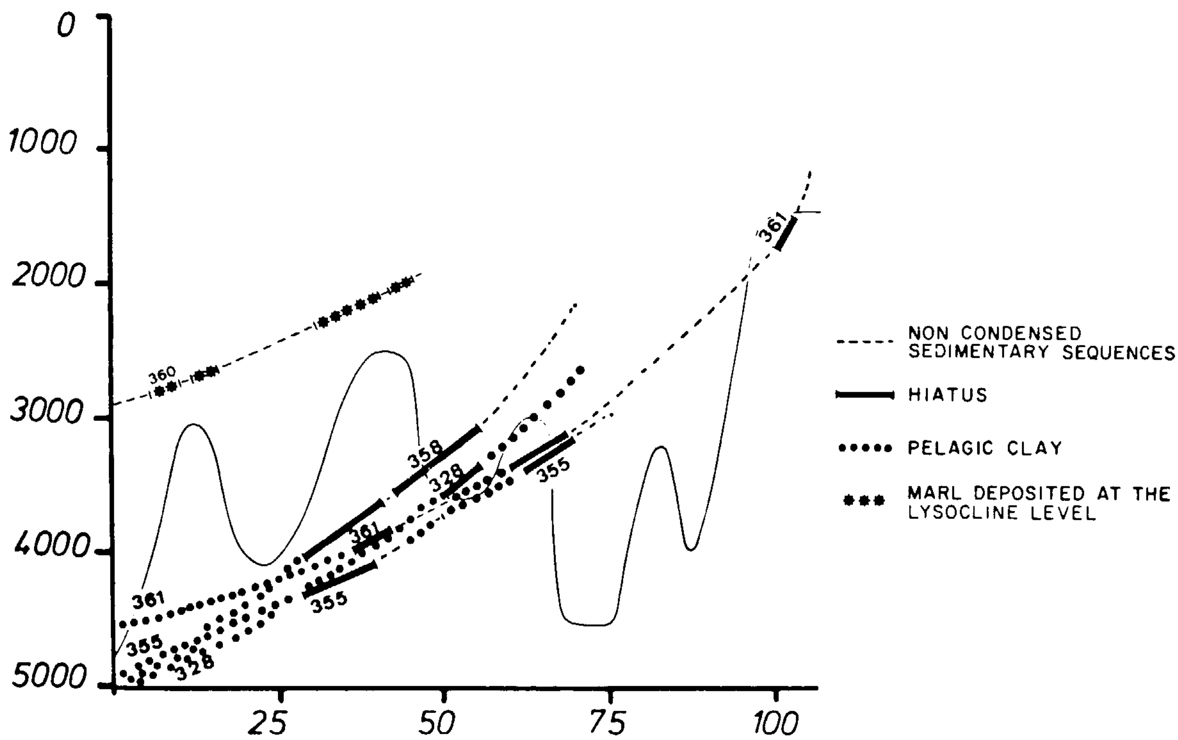

Figure 10. Paleobathymetric evolution of sites 355 (Brazil basin; leg 39), 360 and 361 (Cape basin, leg 40), 328 and 358 (Argentine basin, legs 36 and 39). Hiatuses indicate changes in oceanic paleocirculation. The CCD curve of figure 12 has been drawn in accordance with the paleobathymetry of representative facies, such as pelagic clay, marl deposited at the lysocline level and chalk (average values from Argentine and Cape basins). Water depths in meters, age in m.y.

to the lysocline. Unless the chalk is not in place, this suggests a very large difference in CCD between the Cape and Brazil basin which seems unlikely to us.

- Middle Eocene

The estimate of 2 500 m is based on good data from site 360 in the Cape basin, where marls were deposited at a paleodepth of 2 000 m close to the lysocline level (fig. 10). This is confirmed by the apparition of pelagic clay at a paleodepth of 3 700 m at site 361. BERGER and ROTH (1975) have proposed a paleo-CCD of 3 000 m which is in reasonable agreement considering that its level is generally deeper in the Cape and Argentine basins than to the north.

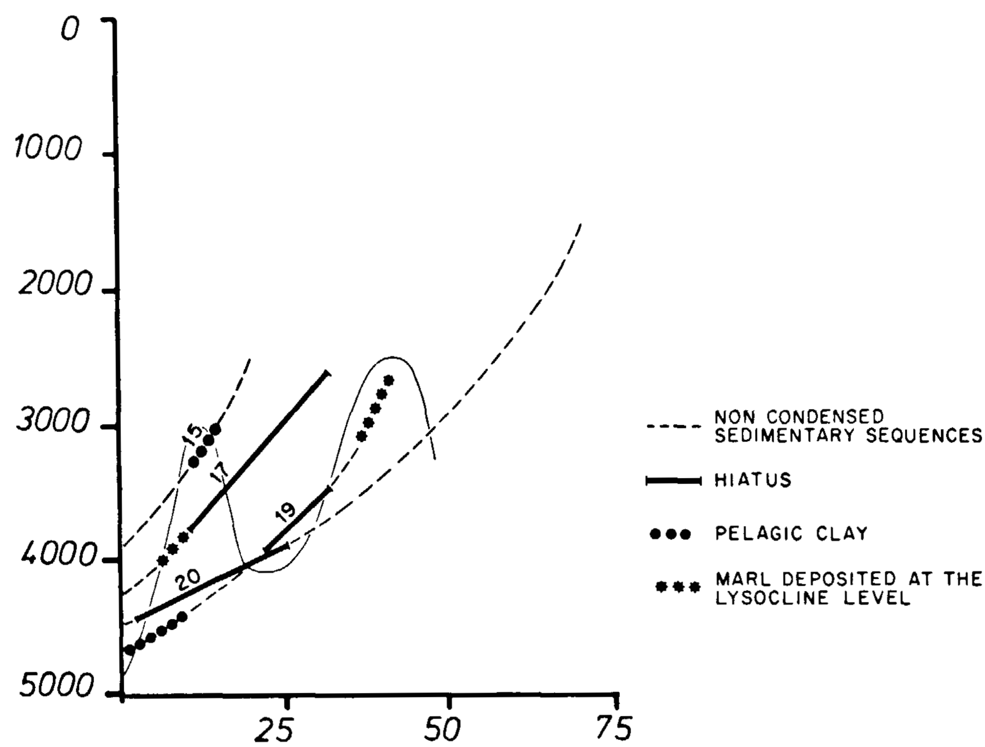

Figure 11. Paleobathymetric evolution of sites 15, 19, 20, drilled on the flanks of the Mid-Atlantic Ridge (DSDP, leg 3, MAXWELL et al., 1970). The CCD curve is shallower than the lysocline level of sites 17 and 19. Both sites are situated in the Angola basin, where the CCD is much deeper than in the Argentine and Cape basins. Water depths in meters, age in m.y.

- Lower Oligocene

We have adopted a value of 3 000 m close to the 3 200 m of BERGER and ROTH (1975). The only available data is a slightly higher degree of fragmentation of planktonic foraminifera (30 %) at site 360 at a paleodepth of 2 250 m (fig. 10). This suggests a level slightly above the lysocline, hence our choice.

- Middle Miocene

The estimate of 3 000 m is based on the presence of marls deposited at the lysocline level at a paleodepth of 2 500 m at site 360 in the Cape basin and on the presence of pelagic clays at a paleodepth of 3 000 m at site 15 on the Brazil basin flank of the mid-Atlantic ridge (fig. 7 and 11). Our estimate is 500 m deeper than the one proposed by BERGER and ROTH (1975).

From the Middle Miocene to present time, the CCD has dropped to 4 500 - 4 800 m and more depending on the different basins (fig. 4).

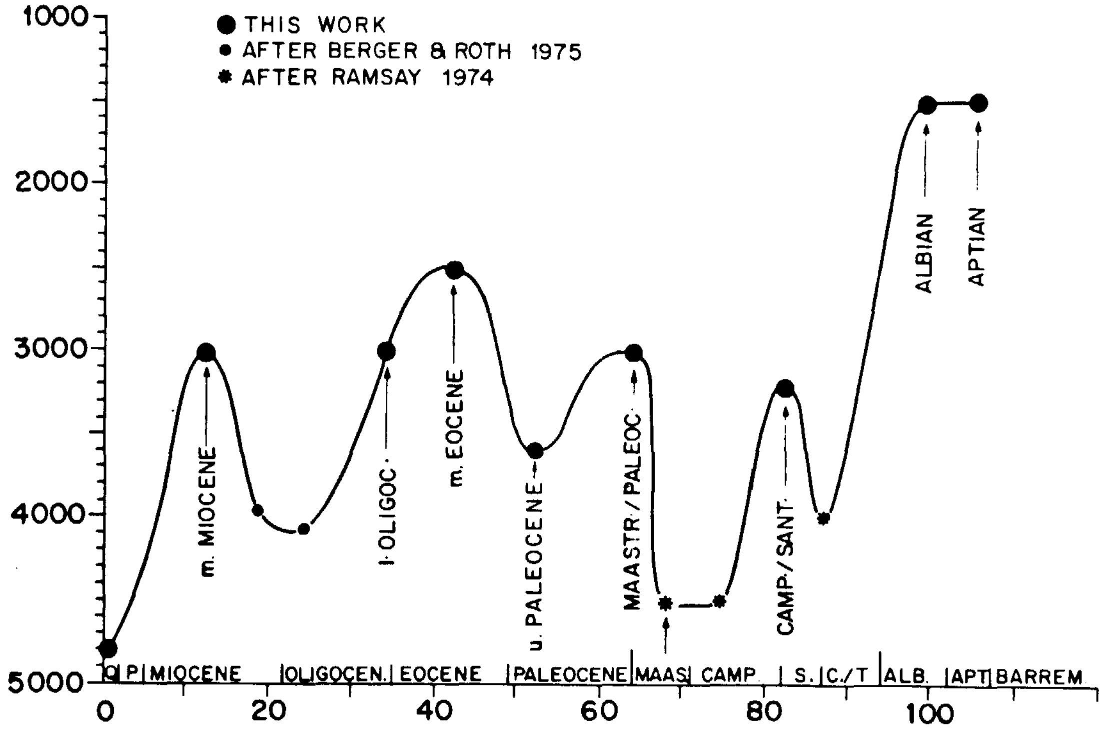

Figure 12. CCD fluctuations since Aptian time in the South Atlantic ocean (average values from Argentine and Cape basins). Water depths in meters, age in m.y.

The paleo-CCD curve of figure 12, which tries to give a rough approximation of the general evolution of the CCD in the Argentine and Cape basins, will thus be the basis of our attempt at reconstructing the paleofacies maps. Although this curve will undoubtedly be modified, it will allow us to demonstrate the basic methodology of reconstruction.

Deep water circulation

We have seen the importance of the water circulation in the present deep sea floor of the South Atlantic ocean, and especially of the AABC which plays a major role in the processes of transport of sediment, erosion and sedimentation control and dissolution. It is consequently essential to be able to reconstruct, at least in a general way, the paleocirculation of the deep sea floor. A first approach, which was followed by EWING et al. (1971), is to use the information given by seismic reflection data on the relationship of seismic reflector characters to the AABW circulation. These authors showed that all over the Argentine basin a new type of sedimentation clearly related to the AABC was installed at the age of a major seismic reflector, called reflector A, which is now known to date from the Upper Oligocene (PERCH-NIELSEN and SUPKO, 1975). A second approach is related to the fact that bottom currents result in dissolution and erosion which appear as hiatuses in the sedimentary column. Thus a study of the distribution of hiatuses on the ocean gives some basic information for a reconstruction of paleocurrents.

Hiatuses become widespread during the Maastrichtian and most specially at the limit Upper Cretaceous/Cenozoic over the Falkland plateau, the Rio Grande Rise and the Sao Paulo plateau. They suggest the presence of strong bottom water circulation at depths ranging between 1 000 and 3 000 m. Over the Walvis Ridge, hiatuses are frequent at the Coniacian-Santonian limit, but not in Maastrichtian (site 363).

In Early Cenozoic, hiatuses appear in the Argentine and Brazil basins, during the Paleocene/Eocene at sites 358 and 328 and especially during the Eocene/Oligocene at sites 329, 327, 358, 22 and 355. They suggest the installation of deep water circulation at that time. It seems that the AABC first appears in the Cape basin in Eocene but it probably only becomes a strong well-defined current in Oligocene.

These observations agree with the conclusions of MARGOLIS and KENNETT (1970), KENNETT et al. (1974), SHACKLETON and KENNETT (1975 a and b) that the AABW circulation begins in Eocene/Oligocene and that the AABC becomes well established in Upper Oligocene. M ajor fluctuations of the AABC occurred in Miocene, Pliocene and Pleistocene during peaks of the Antarctic glaciation (BERGER, 1973;

1974; WATKINS and KENNETT, 1971).

We have no direct information either on the first passage of the AABC through the Romanche Fracture Zone or on the installation of the NADC. SCLATER and McKENZIE (1973) have proposed an Oligocene age for the former (35 M.y.) whereas BERGGREN and HOLLISTER (1974) proposed a later age between Oligocene and Upper Miocene. The NADC seems to be well established in the North Atlantic by lower/middle Eocene (BERGGREN and HOLLISTER, 1974).

The major point is that in the first stage of opening of the ocean, in Lower Cretaceous, there is no evidence for any significant deep or intermediate water circulation in the South Atlantic.

Facies distribution map

Knowing the paleobathymetry and the approximate paleo-CCD, it is possible to reconstruct a paleofacies distribution map, on the basis of the present distribution of facies with respect to CCD and of the probable relative abundance of the terrigenous sedimentation, especially on the Argentine and Angola continental margins.

It is necessary, of course, to try to account for the spatial variation of the CCD at any given time. This is mostly related to the influence of the AABC after its establishment as discussed for the present situation. Prior to its establishment, we have supposed that the CCD is at the same depth in the Brazil and Angola basins, roughly 500 m deeper than in the Cape and Argentine basins to take into account the easier access to cold water there.

There is however an exception which concerns the early periods of stagnation during which the CCD was very shallow. This was for example the case during the Coniacian north of the Rio Grande-Walvis topographic barrier. The CCD, there, seems to have been intermittently close to the photic zone whereas it was at a paleodepth of 3 200 m in the Cape and Argentine basins.

III. SCHEMATIC MODEL OF EVOLUTION

Figures 13 to 22 present a series of paleobathymetric, paleocurrent and paleofacies maps constructed according to the methodology previously discussed and which schematize the evolution of the south Atlantic ocean, as it widens, deepens and as a vigourous deep thermohaline circulation progressively gets established. Three main periods can be recognized: from Valanginian to Santonian, this is the early opening stage which goes from the continental rift to the narrow confined basin stage; from Campanian to early Oligocene, the ocean progressively opens to the north and to the south as the topographic barriers formed by the large fracture zones and the Walvis-Rio Grande ridges break; the deep water circulation is initiated; from upper Oligocene to the present, the modern pattern of deep-sea circulation and sedimentation is established and is mostly modulated by the climatic fluctuations associated with the Antarctic glaciation, which control, in a great part, the CCD variations and the AABC circulation.

Early opening: Valanginian-Santonian (127 - 82 M.y.)

Fig. 13, 14, 15, 16.

Figures 13 and 15 illustrate that we are dealing with two narrow basins, closed to the north and south, but fairly deep as they are already deeper than 3 km 100 M.y. ago and they are deeper than 4 km 80 M.y. ago when the first breaks in the topographic barriers appear, first to the south, then to the north 'Equatorial Fracture Zone) and in the center (Walvis - Rio Grande).

Figure 14 shows the distribution of sediment 100 M.y. ago; figure 16 shows it just prior to the break (roughly 85 M.y. ago) whereas figure 17 shows it immediately after the break (80 M.y. ago). The South Atlantic consists now of two narrow confined basins, characterized by a frequent stagnant environment where black shales and sapropels (black deposits very rich in organic matter) are sedimented. To the South of the Walvis-Rio Grande barrier, these black shales are deposited during Aptian Albian at depths greater than 3 000 m (fig. 13, 14) over a thickness of several hundred meters. They are very fine, very homogeneous and very poor in microfossils. Intermittent layers of coarse sandstones, often rich in plant debris, have been deposited by turbidity currents.

To the north, evaporites (products of evaporation of salt water which include anhydrite and halite, associated with dolomite) are deposited within salt basins whose limits are outlined in fig. 14 (LEYDEN et al., 1976). Seismic reflection data suggest that the evaporite thickness exceeds several hundred meters. However, we have no direct information on these evaporites. The evaporites seem to be overlain by dolomitic marls which have been reached in site 364 on the Angola margin (BOLLI et al., 1975).

To the south, the sapropelitic sedimentation ends during Albian time, which confirms the paleobathymetric information of an earlier opening across the Falkland-Agulhas barrier than across the Equatorial Fracture Zone barrier. Thus the oceanic sedimentation regime progressively gets established to the south and is reflected on the mid-Atlantic flanks by the deposition of pelagic calcareous sediments and on the southern border where siliceous mud is deposited under a high productivity zone. To the north, the sapropelitic sedimentation intermittently continues and the corresponding deposits have been cored on the Angola margin, on the northern flank of the Walvis Ridge and on the Sao Paulo plateau (BOLLI et al., 1975; PERCH-NIELSEN et al., 1975). Marls and

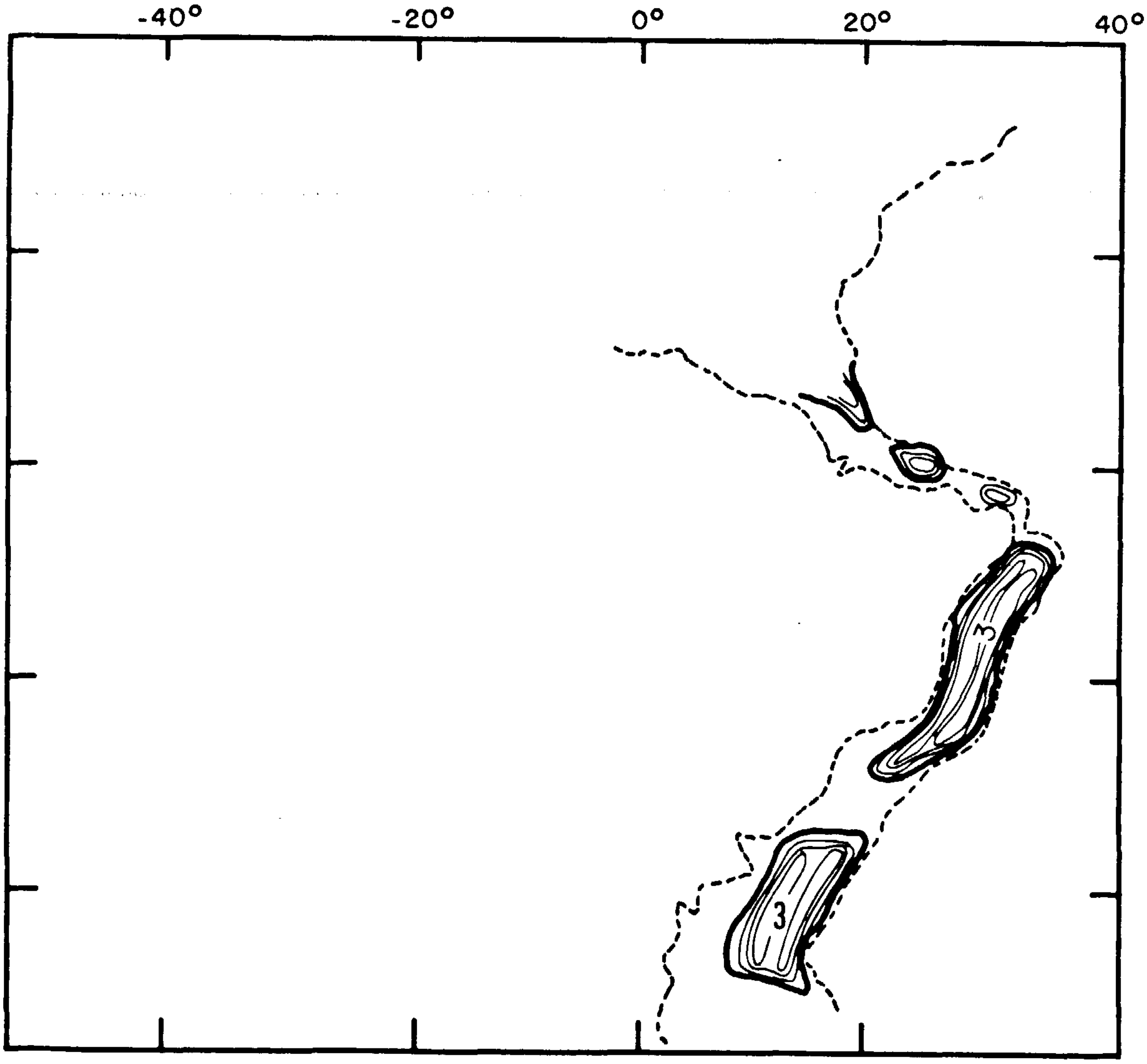

Figure 13. Paleobathymetry of the South Atlantic Ocean at Albian time (anomaly MO = 100 m.y.). Two major basins are well differentiated north and south of the Rio Grande Rise and Walvis Ridge. Water depths in km.

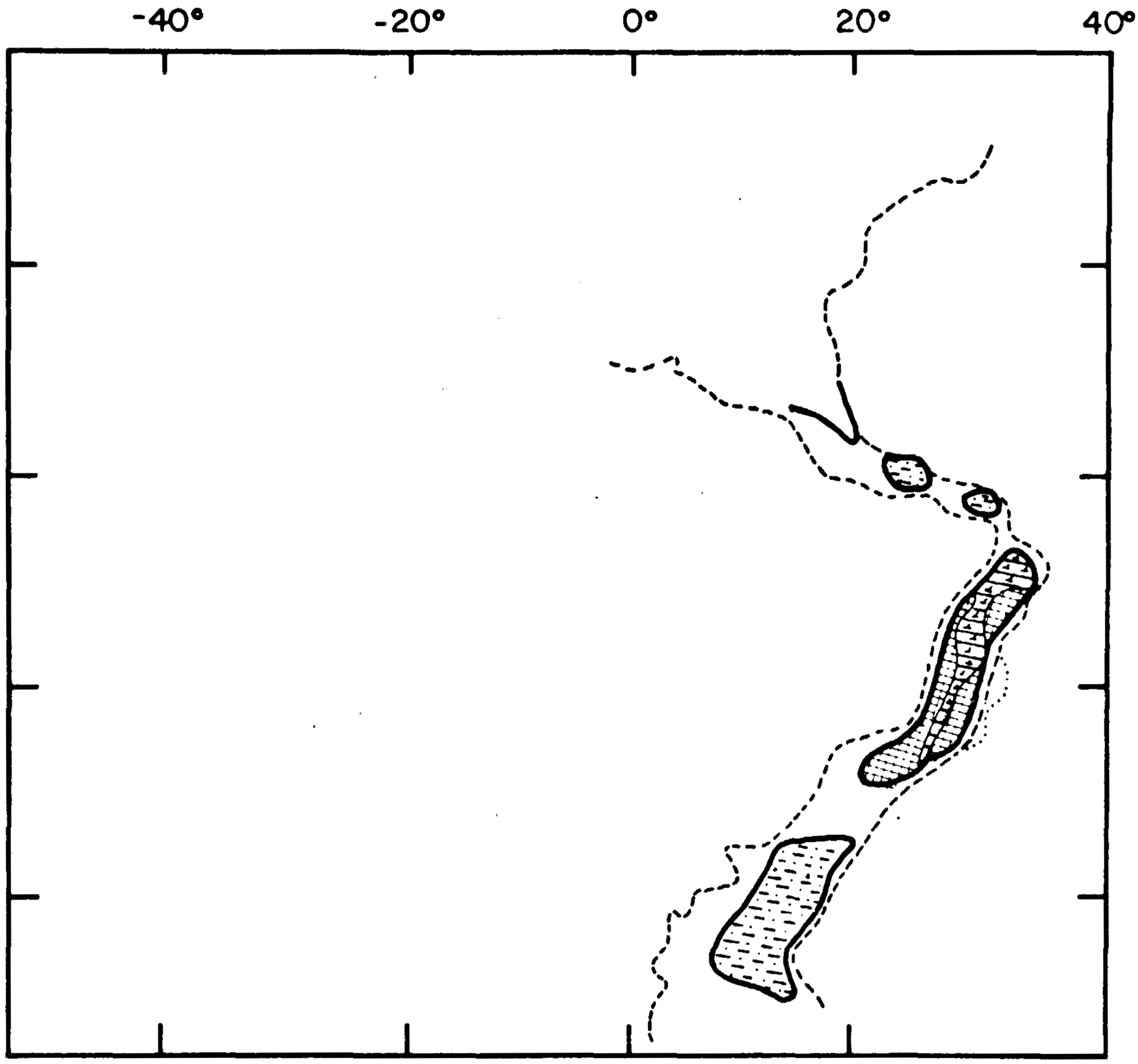

Figure 14. Albian (anomaly m O = 100 m.y.) sedimentary facies distribution based essentially on DSDP legs 36 and 40 (BARKER, DALZIEL et al., 1974; BOLLI, RYAN et al., in press). Limits of the salt basins are from LEYDEN et al. (1976). The CCD in the southern basin is around 1 500 m.

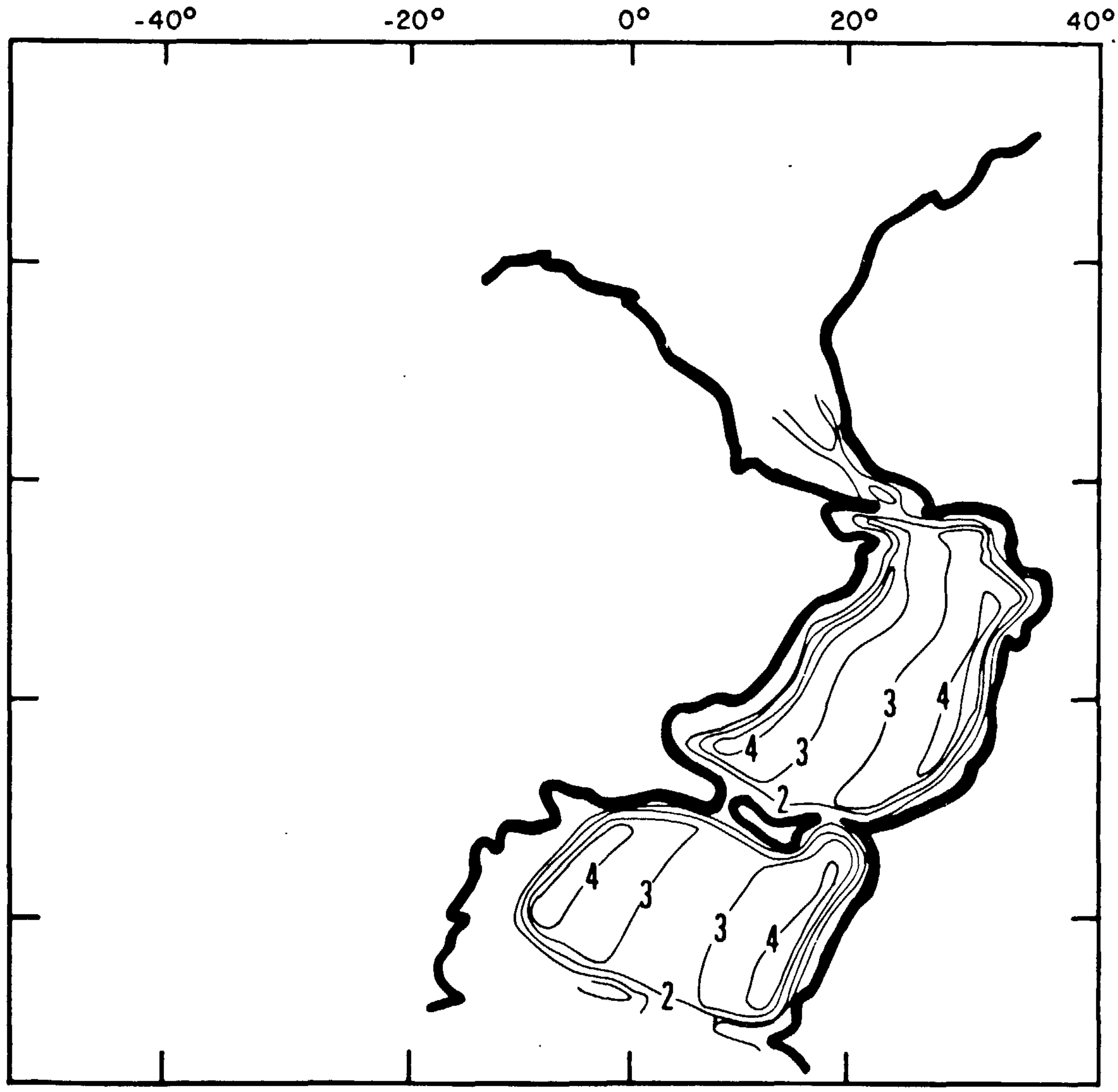

Figure 15. Paleobathymetry of the South Atlantic Ocean during Coniacian/Santonian time (anomaly 34 : 86 m.y.) Water depth in km.

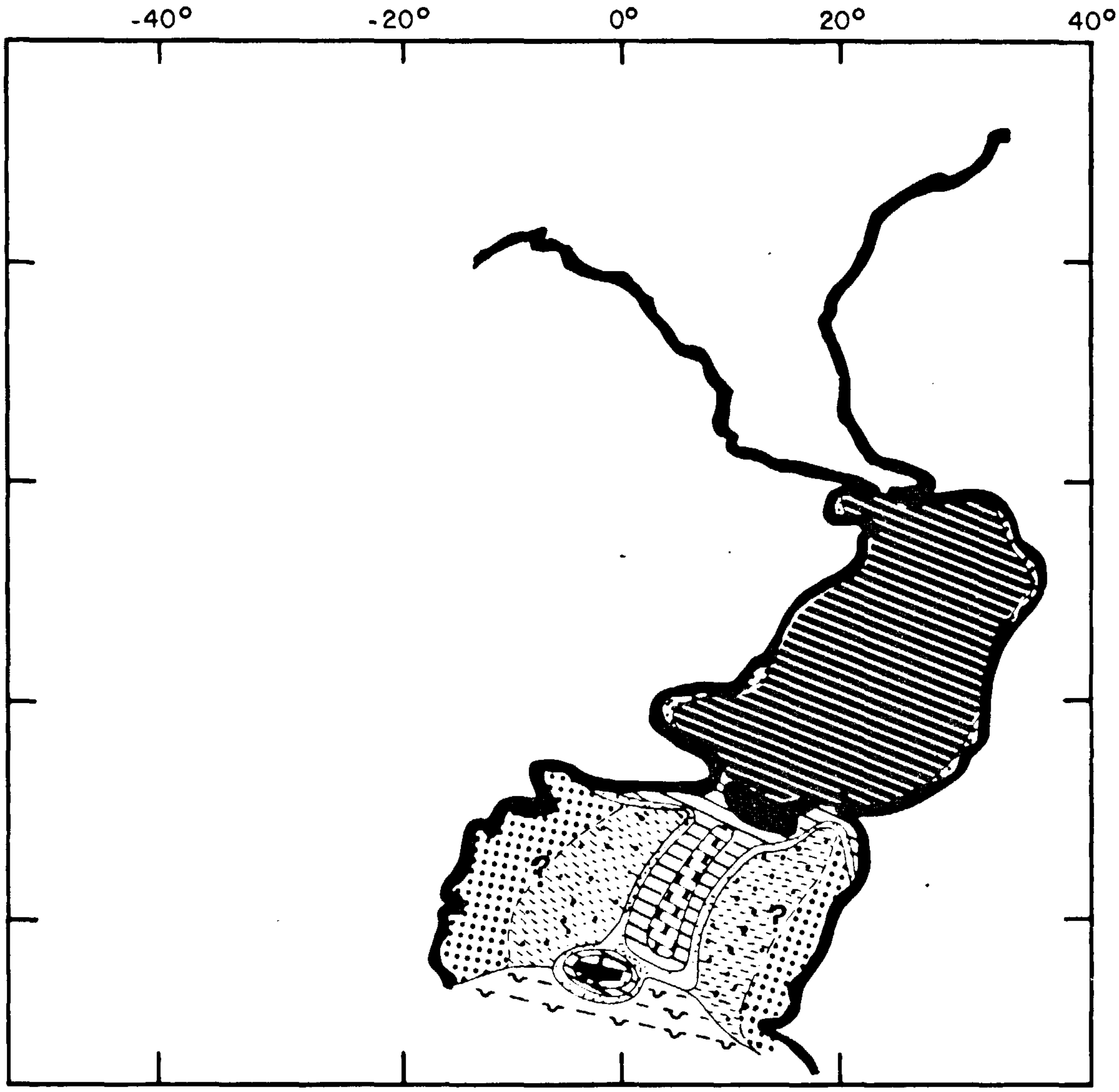

Figure 16. Coniacian/Santonian (anomaly 34 : 86 m.y.) sedimentary facies distribution based on data from DSDP legs 36, 39, 40 (BARKER, DALZIEL et al., 1974; PERCH-NIELSEN, SUPKO et al., in press; BOLLI, RYAN et al., in press). CCD level around 3 200 m in the Cape and Argentine basins, and around 2 000 m in the Brazil and Angola basins. For facies symbols see figure 5.

marly limestones alternate with the sapropels. They contain microfaunas which are quite similar to those living in the Tethys (the ocean situated between Eurasia and Africa) at the time (BOLLI et al., 1975).

Progressive establishment of oceanic circulation:

Campanian-Early Oligocene (82 - 35 M.y.) Fig. 17, 18, 19, 20.

Figure 18 shows that this is the stage of complete disruption of the different east-west topographic barriers. At anomaly 34 time (82 M.y., fig. 15), there is already a 200 km gap between the well defined marginal fracture zones of the equatorial fracture zones. Similarly, to the south, the long Falkland-Agulhas fracture zone has already been broken and the opening enters into a new stage where it is not constrained any more by this strong Africa-South America coupling (LE PICHON and HAYES, 1971). The Walvis-Rio Grande barrier is still nearly continuous but the first gaps appear.

This opening of the Brazil and Angola basins to the north is clearly reflected in the sedimentary records from the Santonian/ Campanian limit upward, as marls have been drilled, for example, on the flank of the Walvis ridge (site 363), on the Angola margin (site 364), on the Sao Paulo plateau (site 356) and on the Rio Grande rise (site 357). These marls are overlain by chalks (BOLLI et al., 1975; PERCH-NIELSEN et al., 1975). Campanian chalk has also been drilled in the Brazil basin (site 355). Figure 17 shows that, to the south, in the Cape and Argentine basins, there is no striking sedimentation change from the Santonian to the Campanian.

During the Maastrichtian, over the whole South Atlantic, there is an extensive sedimentation of chalk, which is related to a deepening of the CCD (4 500 m, fig. 12). These chalk deposits are especially widespread north of Walvis-Rio Grande, where the terrigenous supply seems less abundant than to the south.

It is probably during Maastrichtian, as previously mentioned, than an intermediate depth circulation (1 000 - 3 000m) progressively gets established, as numerous hiatuses appear at this paleodepth on the Rio Grande rise and Falkland plateau. This paleocirculation is tentatively sketched on fig. 18, although the arrows are highly hypothetical.

At the beginning of Paleocene (fig. 20). the CCD gets much shallower (3 000 m in the Cape and Argentine basins and this is reflected in a regression of the chalk facies and an extension of the pelagic clay facies. This shallowing of the CCD seems to be part of a worldwide phenomenon described by WORSLEY (1974). Thus, the Paleocene is characterized by highly condensed sedimentary series, strongly affected by dissolution.

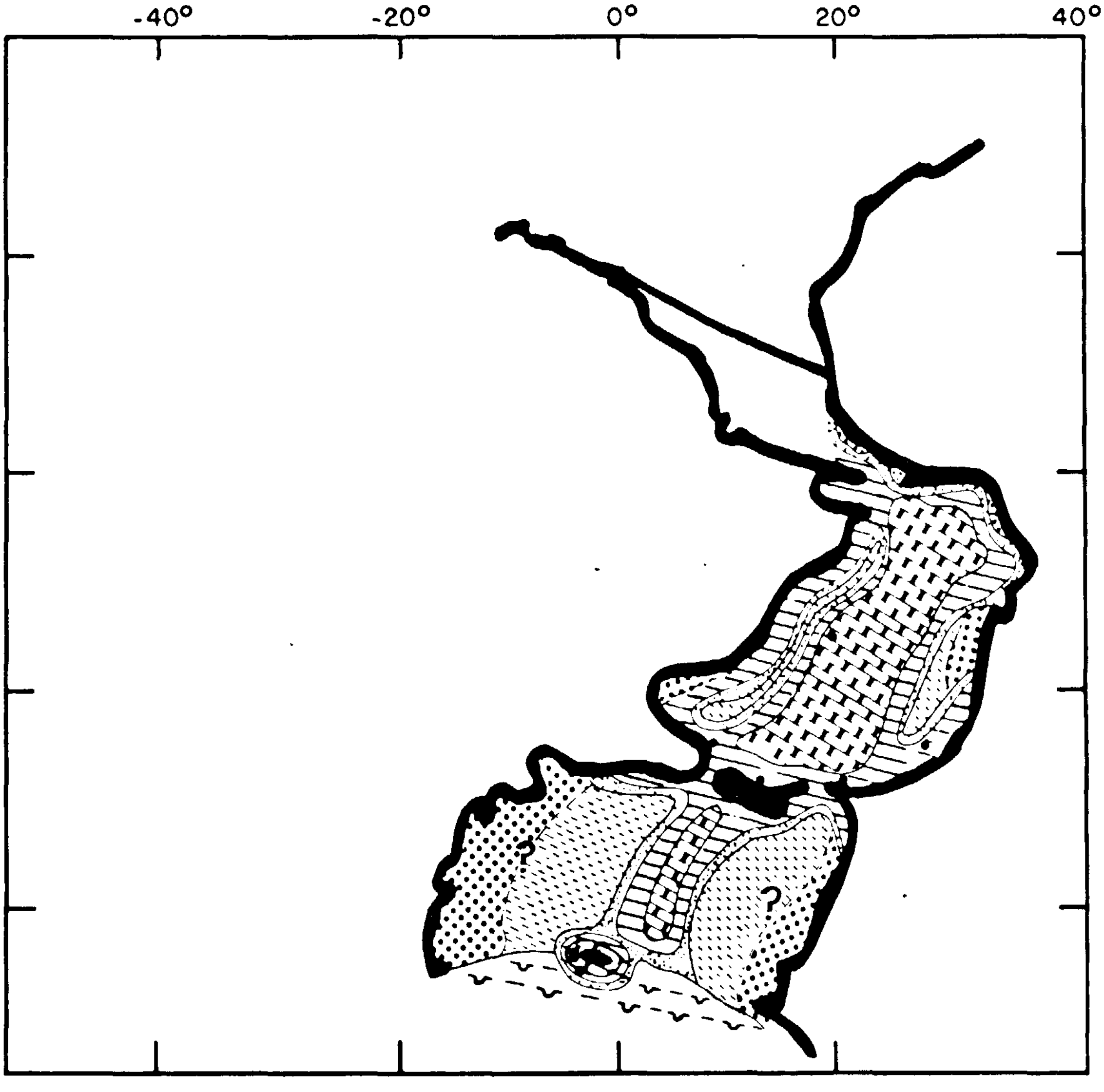

Figure 17. Santonian/Campanian (anomaly 34 : 82 m.y.) sedimentary facies distribution based on DSDP legs 36, 39, 40 (BARKER, DALZIEL et al., 1974; PERCH-NIELSEN, SUPKO et al., in press; BOLLI, RYAN et al., in press). CCD level around 3 200 m in the Cape and Argentine basins, and 3 700 m in the Brazil and Angola basins.

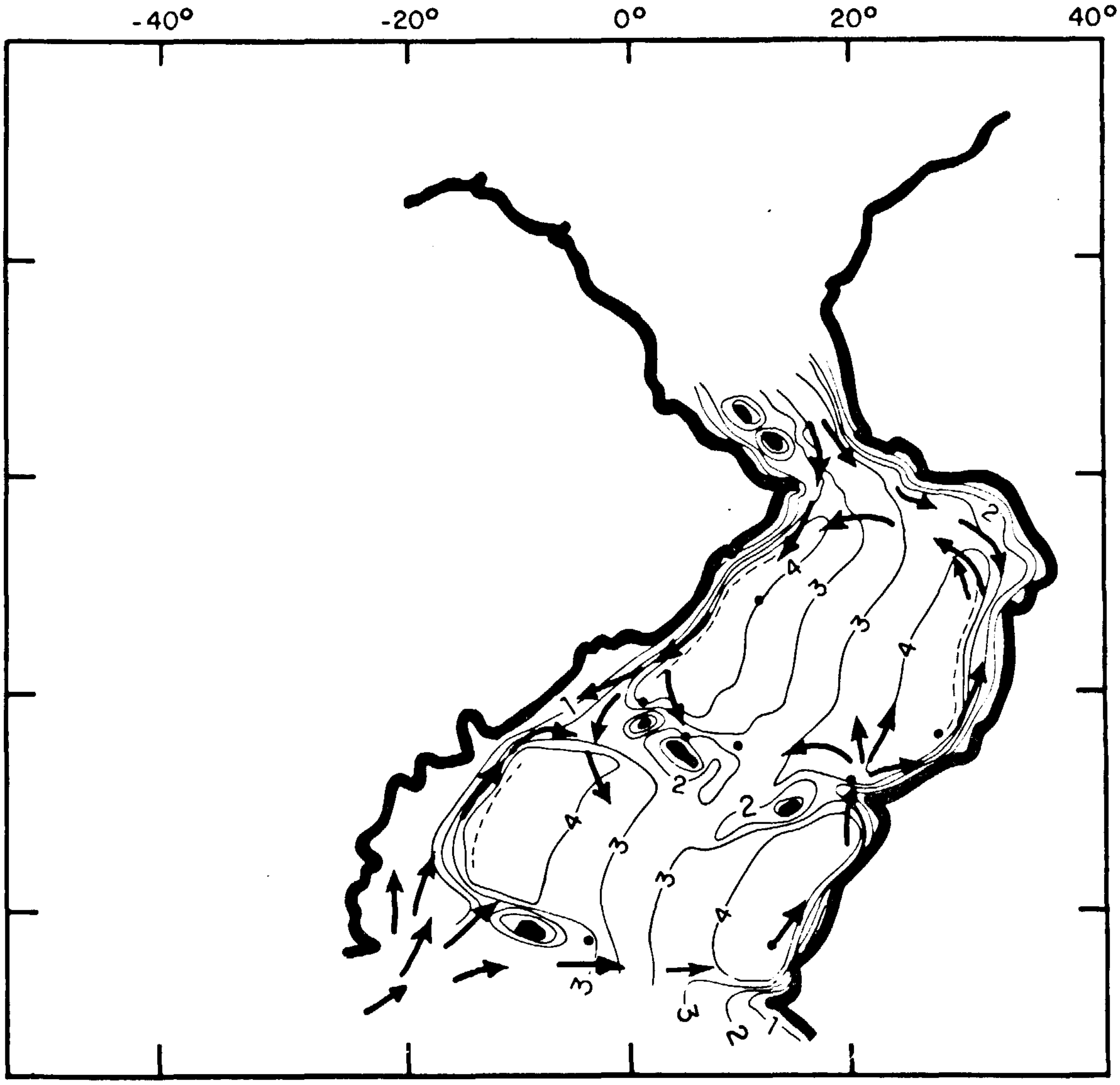

Figure 18. Paleobathymetry and paleocirculation of the South Atlantic Ocean during Maastrichtian time (anomaly 31 : 68 m.y.). Water depths in kilometers.

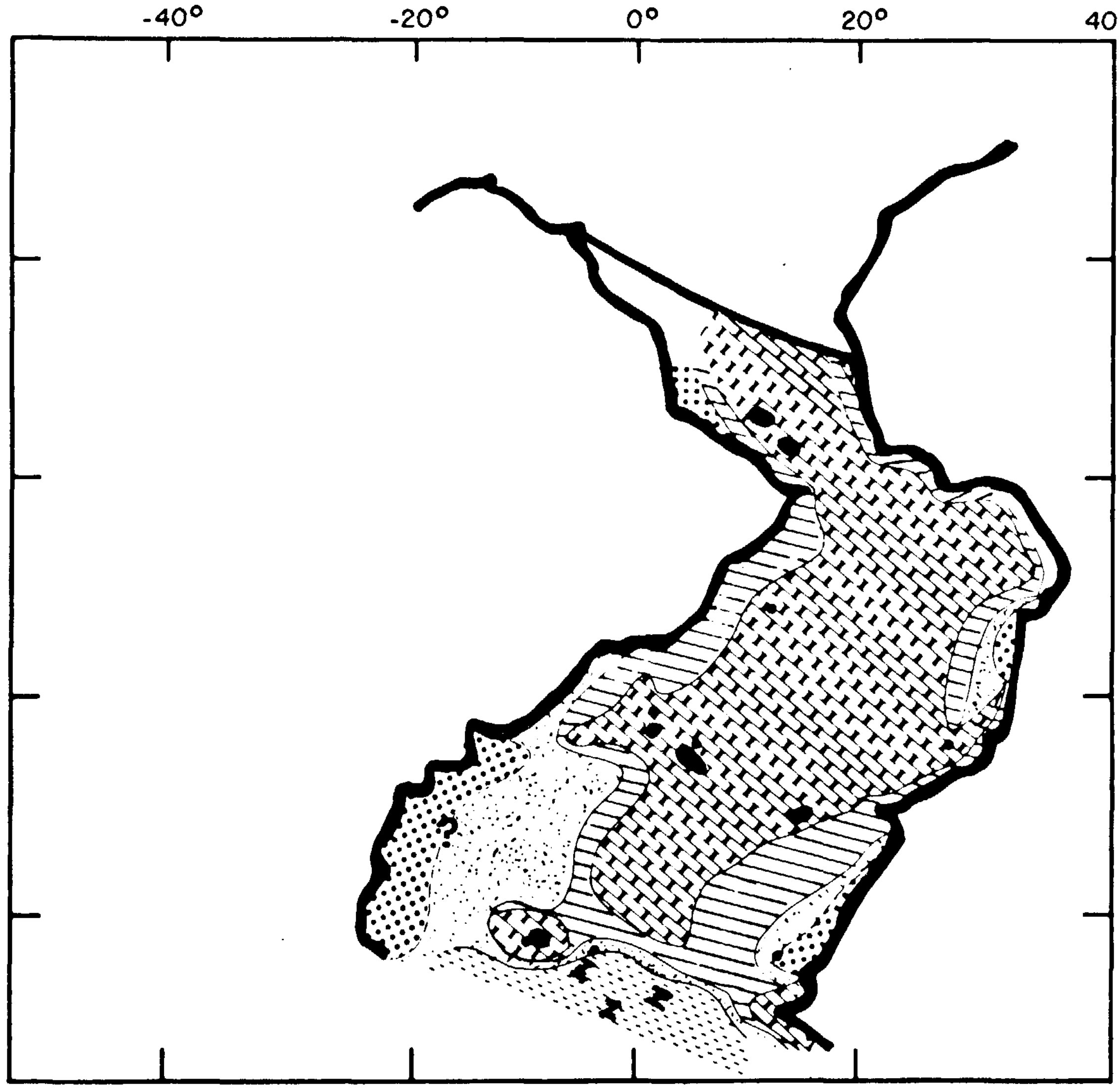

Figure 19. Maastrichtian (anomaly 31 : 68 m.y.) sedimentary facies distribution based on DSDP legs 36, 39, 40 (BARKER, DALZIEL et al., 1974; PERCH-NIELSEN, SUPKO et al., in press; BOLLI, RYAN et al., in press). CCD level around 4 500 m according to RAMSAY (1974). For facies symbols see figure 5.

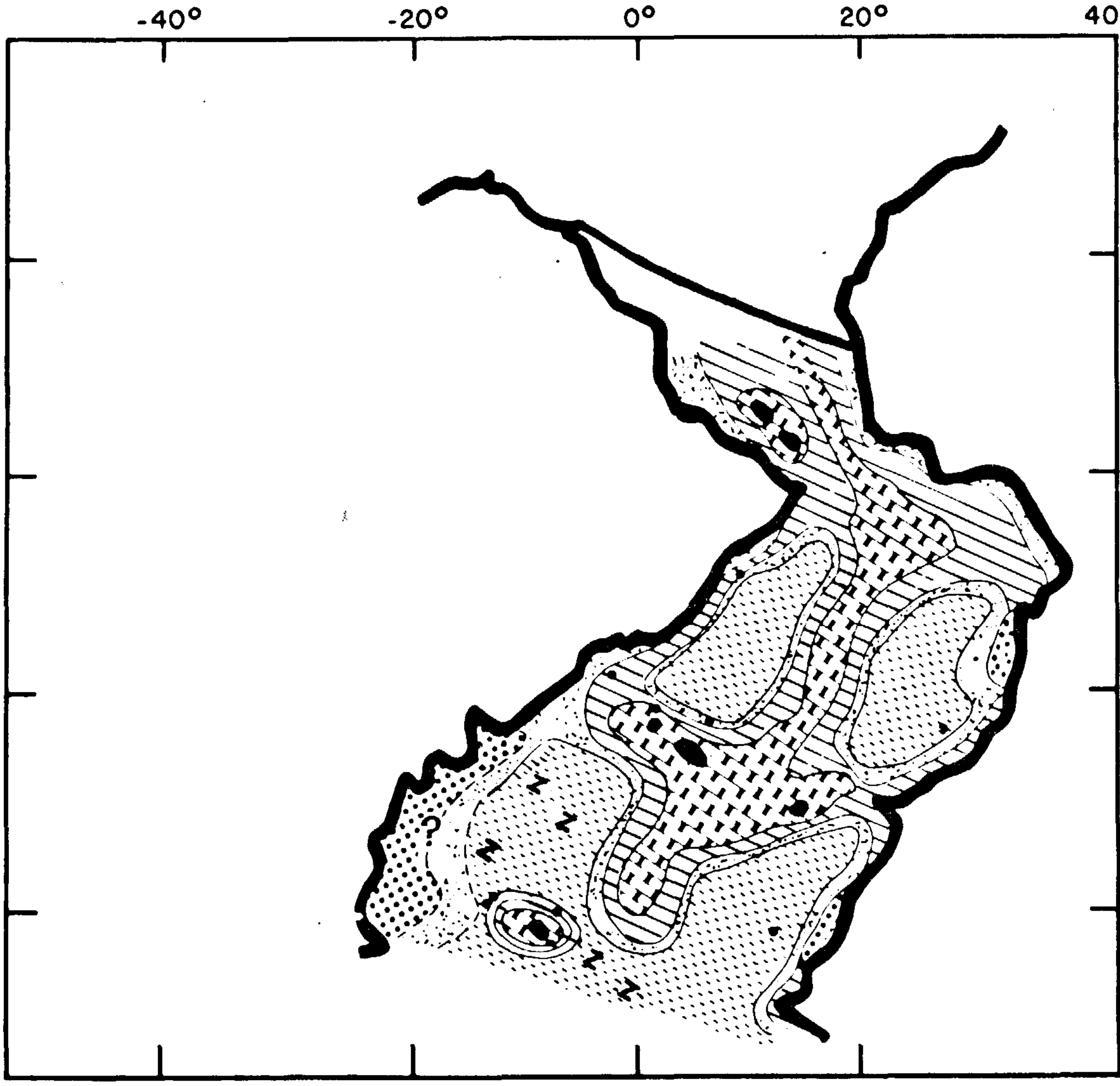

Figure 20. Maastrichtian-Paleocene (anomaly 29 : 64 m.y.) sedimentary facies distribution based on DSDP legs 36, 39, 40 data (BARKER, DALZIEL et al., 1974; PERCH-NIELSEN, SUPKO et al., in press; BOLLI, RYAN et al., in press). We have used the same reconstruction as in figure 19. CCD level around 3 000 m in the Cape-Argentine basins, and 3 500 m in the Angola and Brazil basins. For symbols see figure 5.

Present-day pattern: Upper Oligocene-Present (30-0 M.y.) Fig. 21, 22.

The modern deep-sea circulation was firmly established in Oligocene. This is the time at which the narrow passages, such as the Falkland and Vema channels, reached a depth greater than 4 000 m. It is also the time at which the new current-related sediment deposition pattern gets established in the Argentine basin (reflector A of EWING et al., 1973). Hiatuses are fairly widespread all over the western side of the South Atlantic ocean. The deep AABW circulation might have been the cause of the shallow CCD (3 000 m in the Cape and Argentine basins). In any case, the pelagic clay facies covers a large surface.

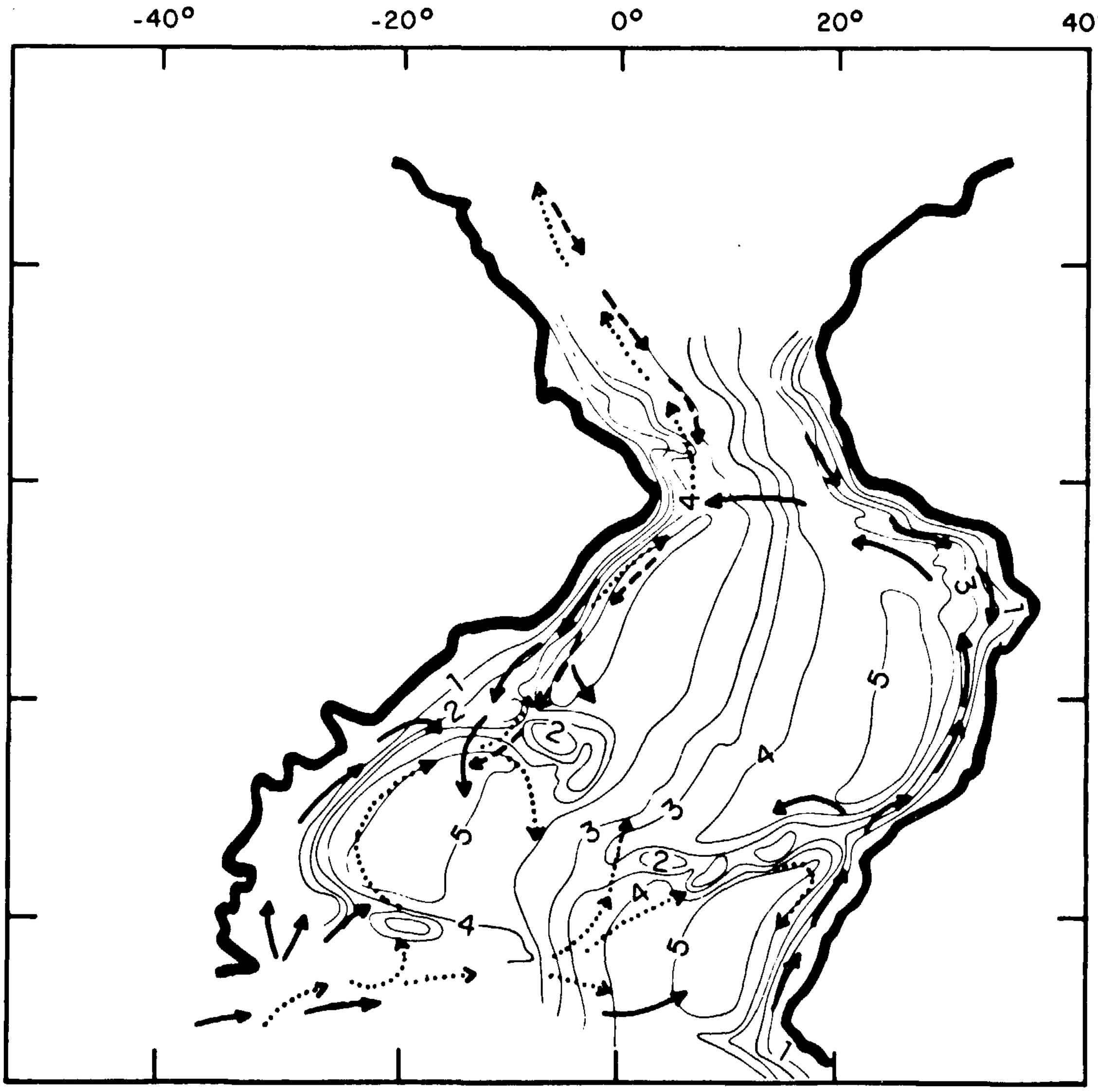

Figure 21. Paleobathymetry and paleocirculation of the South Atlantic Ocean during lower Oligocene time (anomaly 13 : 34 m.y.). Heavy arrows : intermediate/surface currents; dashed arrows : NADC; dotted arrows : AABW. Water depths in km.

It is clear that, by lower Oligocene, the ocean basins have reached a size, which is comparable to their present size; their depths exceed 5 000 m and the deep water circulation is well established. Thus, from then on, the facies distribution can be considered as representative of the present oceanic environment. Its evolution is going to reflect, primarily, the progressive deterioration of the climate which leads to progressively colder surface temperatures, variations in the intensity of the AABW circulation and in the continent erosion pattern.

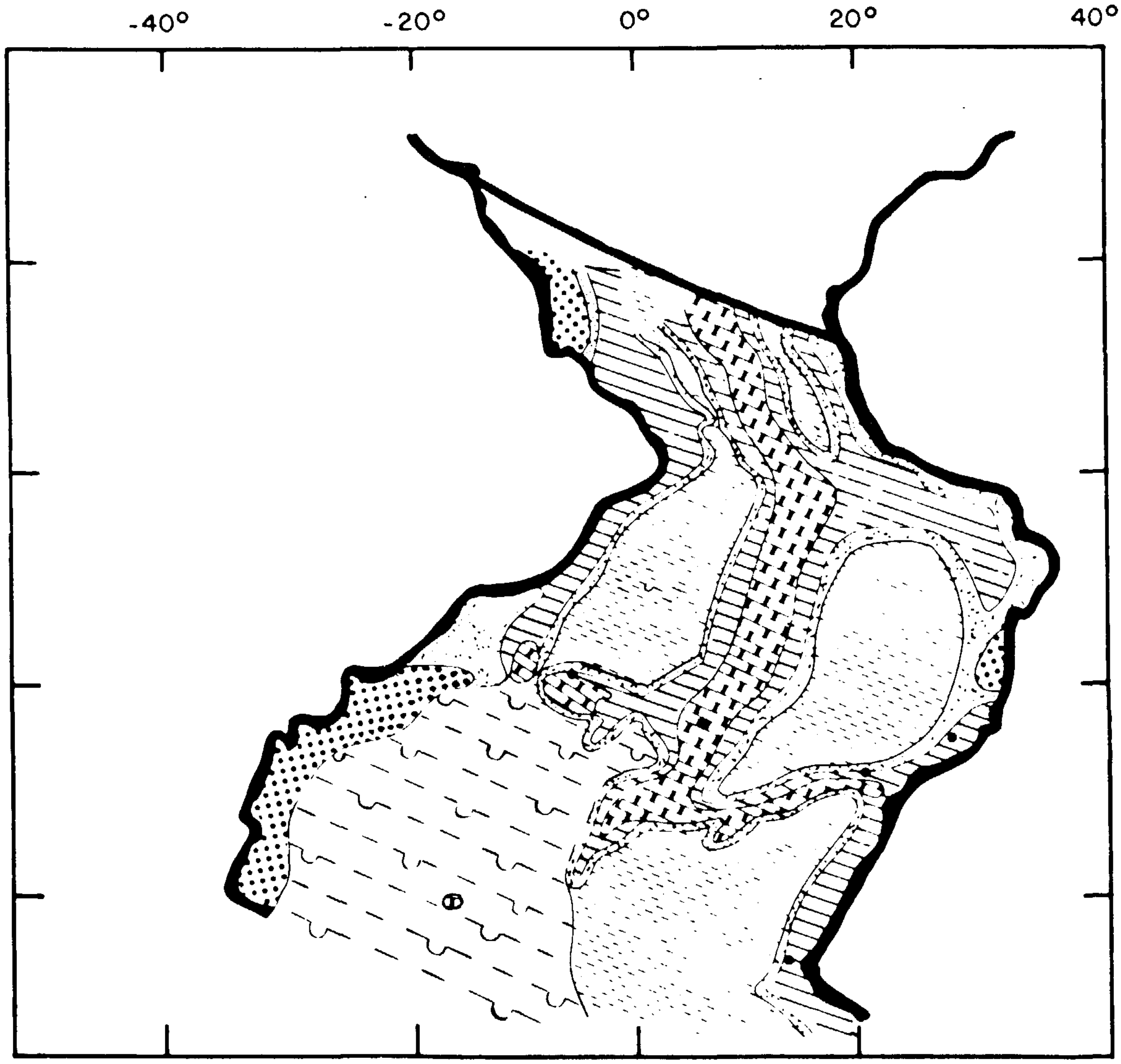

Figure 22. Lower Oligocene (anomaly 13 : 34 m.y.) sedimentary facies distribution based on DSDP leg 3, 36, 39, 40 data (MAXWELL et al., 1970; BARKER et al., 1974; PERCH-NIELSEN et al., in press; BOLLI et al., in press). CCD level around 3 000 m in the Cape and Argentine basins, 3 500 m in the Brazil basin, 4 000 m in the Angola basin. The CCD differentiation from basin to basin is due to the establishment of the AABW circulation. For facies symbols see figure 5.

TABLE 1: Parameters of reconstruction of positions of South America with respect to Africa

EPOCH	MAGNETIC ANOMALIES	Age in M.Y.	LATITUDE	LONGTITUDE	ANGLE OF ROTATION
Albian[1]	MO	100	46.64 N	31.09 W	52.39
Conacian-Santonian[2]	34	86	63. N	36. W	33.8
Maastrichtian[2]	31	68	63. N	36. W	25.8
Lower Oligocene[2]	13	34	58. N	35. W	13.5

1. after SIBUET and MASCLE (in preparation)
2. after LADD (in press)

CONCLUSION

As mentioned in the introduction, paleoenvironmental oceanography is a new science which is progressing very rapidly. This study is not a synthesis but tries to offer a working model of the evolution of the sea-floor of the South Atlantic ocean, based on plate tectonics considerations and integrating recent deep sea drilling results. The emphasis is put on the methodology now available to reconstruct the ocean crust morphology and its sedimentary cover. Three main stages are recognized in the opening of the South Atlantic, a confined basin stage, from 130 to 80 M.y., an embryonic deep circulation stage from 80 to 35 M.y. and a modern stage from 35 m.y. to present. Paleobathymetric, deep paleo-water circulation and paleo-sedimentary facies maps at five different ages illustrate this schematic reconstruction.

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