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Calcium Carbonate, Opal, and Quartz in Holocene Pelagic Sediments and the Calcite Compensation Level in the South Atlantic Ocean[1]

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ABSTRACT

Calcium carbonate is the dominant component in the pelagic sediments of the South Atlantic; its distribution pattern can be explained by use of bottom-water circulation. Biogenous opal concentrations occur in two bands, near the Equator and around 50°S; these concentrations are associated with zones of high biological productivity in surface waters. Quartz occurs mainly near the continental margins but its area also includes a significant ice-rafted component. Clay minerals in large concentration occur in the Brazil Basin and in a tongue extending southward into the Angola Basin from the Congo River mouth.

The calcite compensation level in the South Atlantic varies from basin to basin. In the Brazil and northern Argentine basins it lies at 4800 m, in the Cape Basin at 5100 m, and in the Angola Basin at or below 5400 m. Physico-chemical factors are more important in the control of the calcite compensation level than are biological ones.

Introduction. The South Atlantic Ocean has been studied from many points of view and its sediments have been extensively sampled. It thus offers an ideal subject for quantitative studies of sedimentation because of the availability of much background information. After early studies, beginning with the CHALLENGER Expedition (Murray and Renard 1891), Pratje (1939) provided the first comprehensive discussion of sedimentation in this region by utilizing the data in physical oceanography compiled by Wüst (1936); he postulated that the Antarctic Bottom Water (AABW) is the single most important factor in controlling sedimentation patterns. The AABW flows northward through

the Argentine Basin, passing through breaches in the Rio Grande Rise into the Brazil Basin. East of the Mid-Atlantic Ridge it flows into the Agulhas and Cape basins but is barred from the Angola Basin by the Walvis Ridge.

Since the cold AABW is rich in dissolved carbon dioxide and enhances solution of calcium carbonate, this flow pattern accounts for the presence of calcareous oozes in the deep Angola Basin and for their absence in the deepest parts of other basins. Part of the western branch of bottom flow extends into the northern Angola Basin through the Romanche Fracture Zone; however, water below 3000 m in this area contains only 15%–20% AABW (Edmond 1970).

Since Pratje's major paper, relatively little quantitative information has been added. Turekian (1964) has presented a map of the $CaCO_3$ distribution to 40°S, Goldberg and Griffin (1964) and Biscaye (1965) have discussed the clay mineral patterns, and Lisitzin (1971) has presented the opal distribution. All of these studies, however, are couched in broad terms.

Bramlette (1961) has shown that, in the Equatorial Pacific, a large change in the calcium carbonate content from very high to very low values occurs near 4700 m. He termed this the calcite compensation level, the depth at which the supply of calcium carbonate is in equilibrium with dissolution. The calcite compensation level has recently been studied by many authors and it has been found that appreciable solution of calcium carbonate begins well above the calcite compensation level at a depth called by Berger (1968) the lysocline—the depth at which the maximum change in dissolution of the foraminiferal assemblage occurs. Berger determined the lysocline in the South Atlantic and found that it could be mapped because of its close association with the 2° isotherm. Heath and Culberson (1970) have shown that the calcite compensation level may well result from a linear increase in the carbonate dissolution rate with depth below the lysocline.

In this paper, the distributions of calcium carbonate, biogenous opal, and quartz in the surface sediments of the South Atlantic are discussed, and the depth of the calcite compensation level is inferred. By restricting the study to the uppermost portion of the sedimentary cover, complications caused by uplift and subsidence of the ocean floor and by glacial periods are avoided. The masking influence of sediment input from the continent has been largely avoided by selecting samples well beyond the continental margins and by excluding the southern portion of the Argentine Basin, where the deposits are mainly terrigenous. All readily available cores in the collections of the various oceanographic institutions have been used (Fig. 1[3]). They represent a depth range of 733 m–6020 m, with a concentration of samples in the 3000 m–5000 m range.

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3. Sample and method details and analytical data have been fully reported by Ellis (1972).
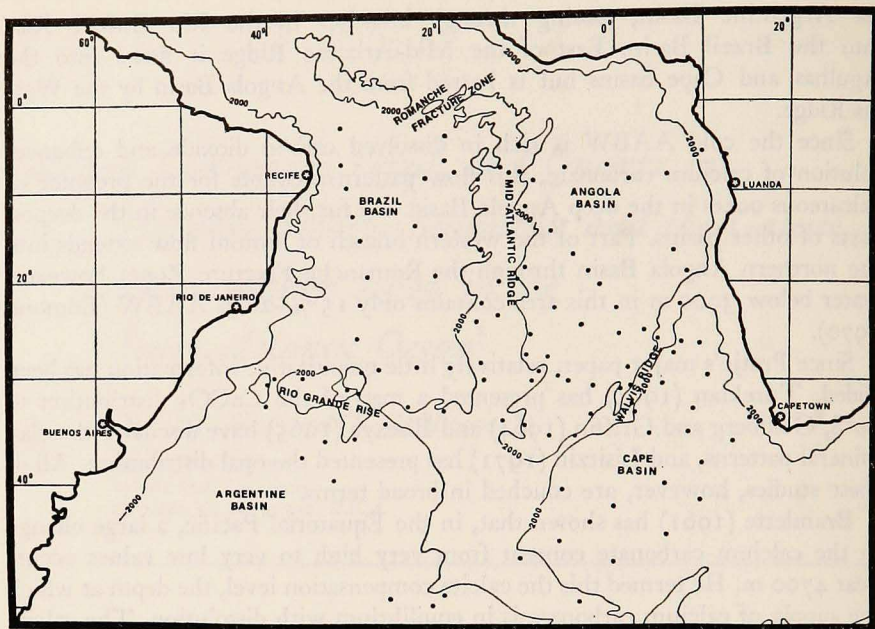
Figure 1. Location of samples and place names in the South Atlantic. Sites of samples used shown with black dots. Depth contours in fathoms.

Methodology. Calcium carbonate determinations were made on approximately two grams of sample with a WR-12 furnace and a LECO Carbon Determinator (Laboratory Equipment Corporation) in a conventional manner (Boyce and Bode 1972) with a ± 1% coefficient of variation.

Biogenous opal was determined with a modified form of the method first introduced by Goldberg (1958) and Calvert (1966). The method is based upon the fact that amorphous opal, upon heating, converts to cristobalite, which can be quantitatively determined by *X*-ray diffraction. The conversion temperature lies near 1000°C, and the effectiveness of the conversion is a function of temperature and of the duration of the heating process. The samples were treated with buffered acetic acid to remove calcium carbonate, washed with distilled water, and then ground in a mechanical grinder. Following homogenization, the samples were heated for 24 hours at 1000°C, reground, and the cristobalite content was determined by *X*-ray diffraction with an internal standard and comparison using an opal standard curve prepared from pure opal. The results are estimated to be reliable to ± 5%.

The quartz content was determined during the same *X*-ray diffraction run because the heating process reduces interference from clay peaks and enhances the quartz peaks. The quartz content was determined by comparison with a standard curve of ground optical quartz.
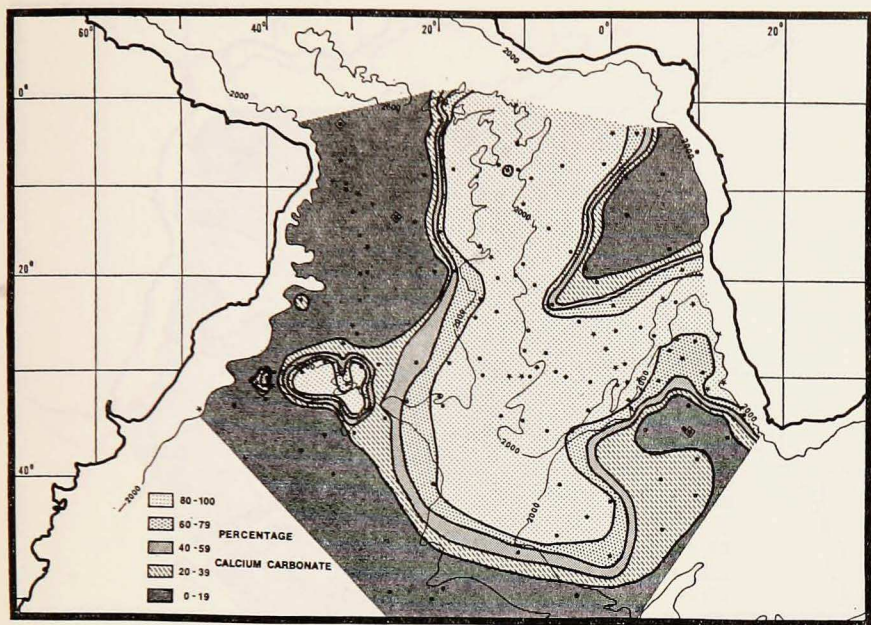
Figure 2. Concentrations of CaCO₃ expressed in percent of the total sample. Starred data courtesy of K. K. Turekian.

Distribution of Sediment Components. CALCIUM CARBONATE. The distribution of calcium carbonate in the South Atlantic (Fig. 2) illustrates the influence of the bottom-water circulation postulated by Pratje (1939). The shallow portions of the Mid-Atlantic Ridge, the Walvis Ridge, and the Rio Grande Rise are very high in carbonate while the deep basins are generally low. South of the 40th parallel, a strong carbonate gradient crosses the Mid-Atlantic Ridge and indicates a northward-dipping calcite compensation level intersecting the Ridge. This is in agreement with Berger's conclusion that the lysocline in this region dips northward (1968) and fits Kennett's (1966) observation of a very shallow (500-m) compensation level in the Ross Sea. The alternate hypothesis, that Foraminifera are scarce in this region, is not supported by the observation that the abundance of these organisms increases in the surface waters to the south (Be and Tolderlund 1971).

Channels in the Rio Grande Rise, forming the passage for the northward movement of the Antarctic Bottom Water, are well delineated by the carbonate distribution. Very low values are found in the primary passage (Vema Channel, 39°W), and somewhat higher ones in the secondary one (Hunter Channel, 26°W). From there, the bottom water flows northward along the western side of the Brazil Basin while warmer North Atlantic Deep Water is deflected to the east (Olsen 1968). This produces, in combination with a westward slope
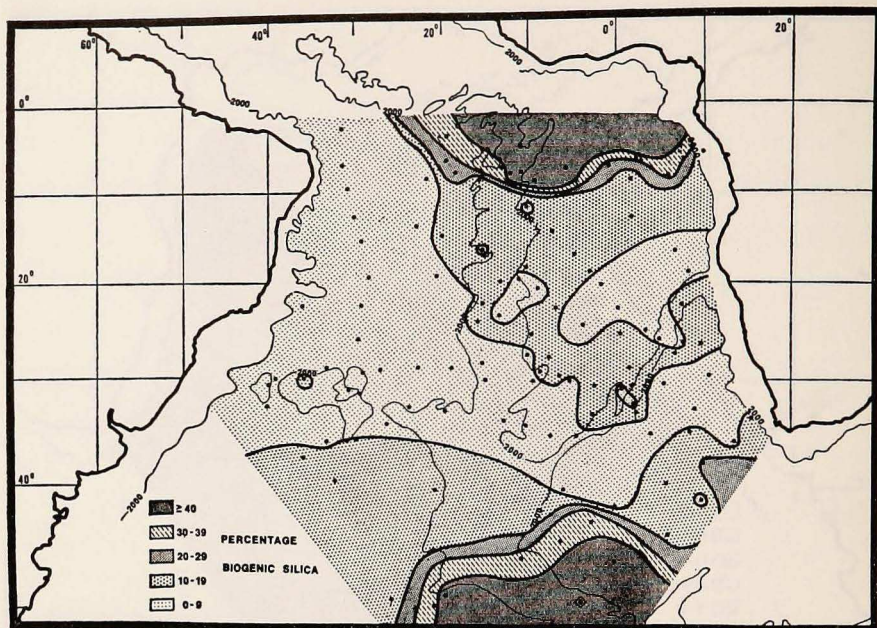
Figure 3. Concentrations of biogenous silica (opal) expressed in percent of carbonate-free sample.

of the seafloor, the east-west $CaCO_3$ gradient. From the Brazil Basin, the water passes through the Mid-Atlantic Ridge to the east by way of the Romanche Deep, causing a deflection of the $CaCO_3$ contours to the east. A sill in the Romanche Deep at 4300 m prevents the deepest and coldest water from passing through, and the bottom water entering the Angola Basin is 0.5°C (potential temperature) warmer than that of the Brazil Basin.

The lowest $CaCO_3$ values in the Angola Basin are not found near the point of entrance of the bottom water, but rather in the deepest and coldest northeastern part of the Basin. The low values may be the result of dissolution by the bottom water, but the region also receives an input of terrigenous material from the Congo River. Although some corrosion of planktonic Foraminifera in the sediments has been observed microscopically, the absence of a low carbonate zone between this region and the point of entrance of the Antarctic Bottom Water indicates that dilution rather than dissolution is responsible for the low carbonate content.

BIOGENIC SILICA (OPAL). The opal distribution (Fig. 3) shows maxima that are significant in terms of the precision of the data in the northeastern and central-southeastern parts of the South Atlantic. Although the values in the Angola Basin are generally higher than those to the west, the contours within this region are close to the uncertainty of the data and may or may not be real. The maxima are in the same areas as the regions of high-standing crops
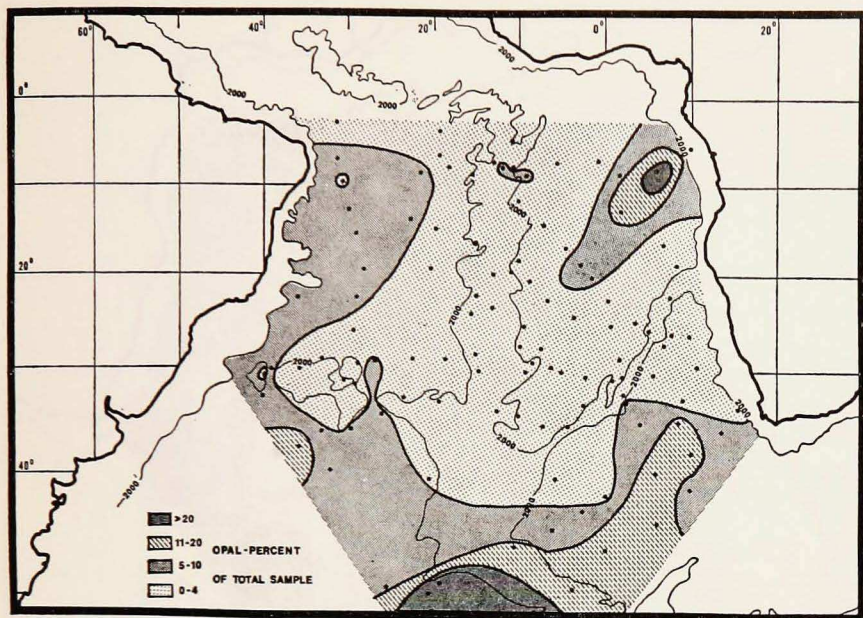
Figure 4. Concentrations of biogenous silica (opal) expressed in percent of total sample.

of plankton (Hentschel 1933) and, in particular, they coincide with the high-standing crops of diatoms. Its marked asymmetry resembles that of various maps of biological productivity. The absence of high opal values off the African Coast is noteworthy since this is a region of strong coastal upwelling, but Smith (1968) has shown that the upwelling takes place mainly within 60 km of the shoreline. The cores used in this study are located much farther offshore. Lisitzin (1971) has found that high opal values are common close to the coast.

In order to minimize the influence of dilution by the major component, calcium carbonate, Fig. 3 shows the opal distribution in percent of the carbonate-free fraction of the sediment. The magnitude of this effect can be visualized in Fig. 4, where only one significant zone of opal concentration, the south-eastern one, is still clearly in evidence. In this zone, high opal productivity and a high level of carbonate dissolution coincide.

QUARTZ. Quartz is generally considered to be an indicator of terrigenous sediment supply. Fig. 5 shows that this is true to some extent for the South Atlantic. Low quartz concentrations occur in areas remote from land, on and near ridges, while high values are common close to the continental margins. Less easily explained are two major quartz areas that lie off southwestern Africa and just south of the Rio Grande Rise. The area off southwestern Africa can be attributed to a combination of terrigenous input by turbidity currents from Africa (Ewing et al. 1966) and ice-rafted detritus from Antarctica. The
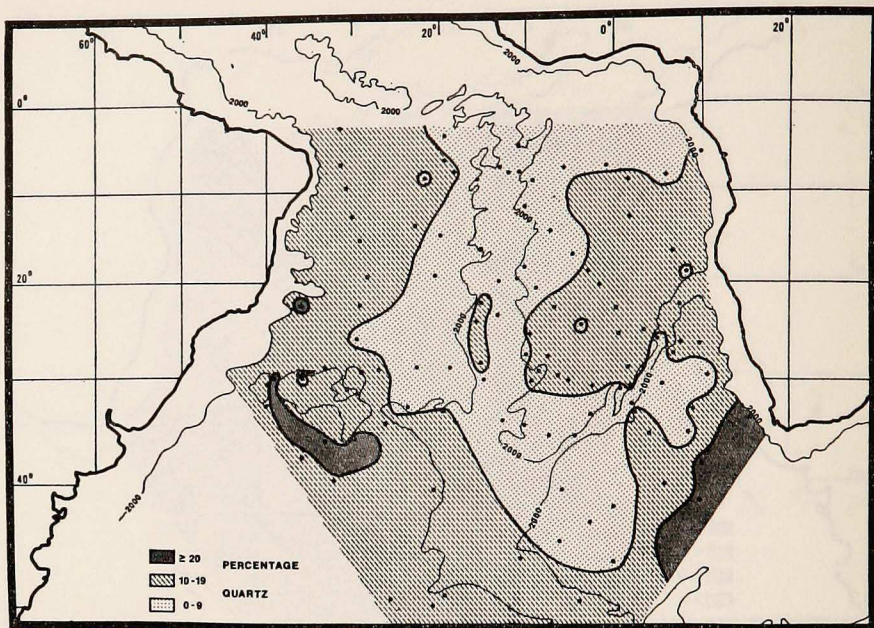
Figure 5. Concentrations of quartz expressed in percent of carbonate-free sample.

northern limit of sea ice lies at about 35°S off the tip of Africa (U.S. Navy Hydrographic Office, 1961: chart 15254). An eolian component may also be present (Arrhenius 1963), but its importance is probably minor.

The northern limit of sea ice crosses the Mid-Atlantic Ridge near 40°S and extends northward along the southern edge of the Rio Grande Rise. Two high quartz samples in the Argentine Basin lie south of this limit. However, most of the sediment of the Argentine Basin is derived from the south through bottom currents (Jones et al. 1970) rather than from pelagic material or from South American rivers (Biscaye 1965, Biscaye and Dasch 1968). As a result of this bottom-water transport, a tongue of quartz-rich mud extends northward into the Basin from the Weddell Sea (Hollister and Elder 1969). The very high quartz values in some of the sediments may reflect a combination of bottom supply and ice-rafted detritus. It may be noted here that quartz is a quantitatively minor component of the South Atlantic sediments.

CLAY. The "clay" content of the samples was not measured directly; it was obtained as the difference between the total and the sum of the calcium carbonate, opal, and quartz contents. The label "clay" for the residue is an operational one. The location of the two areas of high-clay content (Fig. 6) suggests a continental origin for this component, which is in agreement with Biscaye's data (1965); these data show that kaolinite and illite in the South Atlantic have a continental origin. The Angola Basin tongue, which consists of ap-
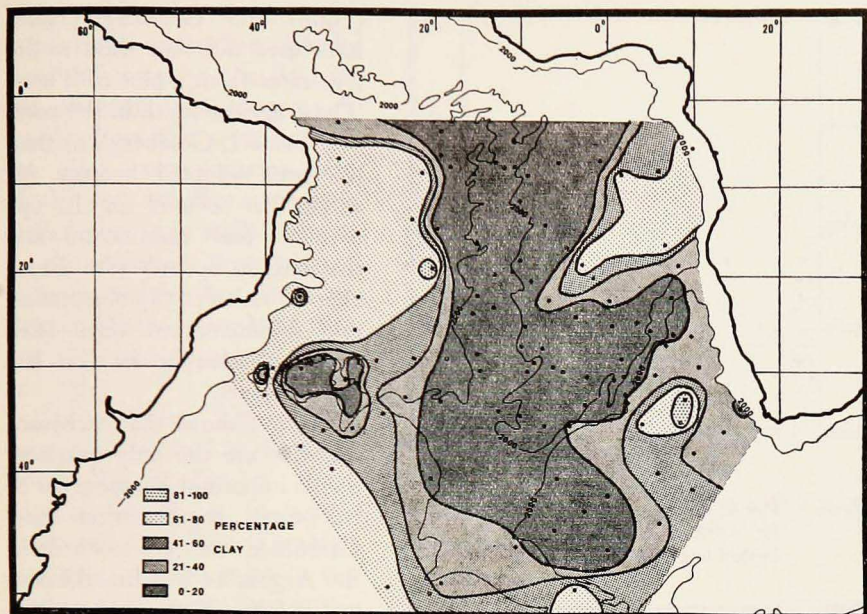
Figure 6. Concentrations of clay; the values are the difference between *100* percent and the sum of carbonate, opal, and quartz.

proximately equal parts of illite and kaolinite, represents the output of the Congo River, which has no delta because the Congo Submarine Canyon directly enters the river mouth (Heezen et al. 1964). The clay in the Brazil Basin is dominantly kaolinite (Biscaye 1965).

An indirect confirmation that the "clay" of this study is the equivalent of mineralogical clay can be obtained as follows. Turekian and Stuiver (1964) have given sedimentation rates for mineralogically determined clay in two cores. These rates are very close to rates obtained when the "clay" values obtained in this study on the same cores are substituted in the calculation.

	V 12–66	V 16–36
Turekian and Stuiver (1964)	0.13 g/cm²/1000yrs	0.05 g/cm²/1000yrs
This study	0.12 g/cm²/1000yrs	0.06 g/cm²/1000yrs

In principle, the clay content is a better indicator of continent-derived detritus in the South Atlantic than is the quartz content, since the latter is strongly influenced by ice-rafted material.

ACCUMULATION RATES. Various investigators have determined the accumulation rates on 11 South Atlantic cores; the results are presented in Table I in terms of accumulation rates for the four principal components. Ku et al.
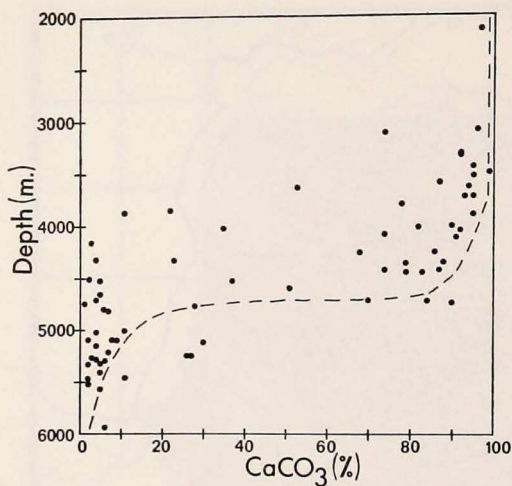
Figure 7. Plot of CaCO$_3$ content versus depth of sample for northern Argentine and Brazil basins. Dashed line is calcite compensation level.
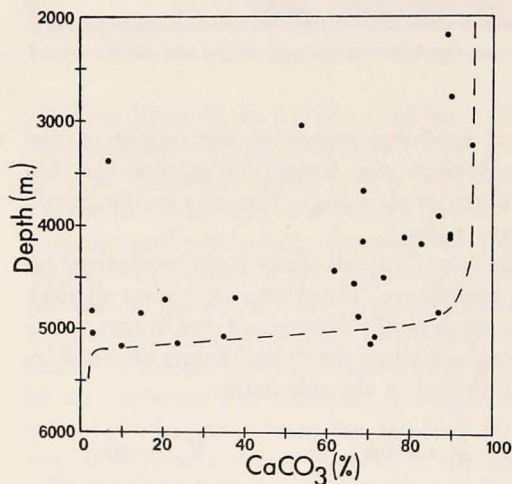

Figure 8. Plot of CaCO$_3$ content versus depth of sample for the Cape Basin. Dashed line is calcite compensation level.

(1968) and Goldberg (1968) have used different ways to derive rates from a plot of Th^{230}/Th^{232} against depth in the core. For Table I, Goldberg's method has been adopted because his values can be used for the uppermost few centimeters and they are in accord with Broecker et al.'s (1958) observation that sedimentation rates have decreased sharply in the last 11,000 years.

Table I shows that carbonate and clay are the only quantitatively important components of the total accumulation rate. Carbonate rates are low only in the Argentine and Brazil basins and otherwise are 5–10 times larger than those of clay. Opal rates are 5–10 times smaller than clay rates and are similar to those of quartz.

Calcite Compensation Level. BRAZIL AND ARGENTINE BASINS. In Fig. 7, all carbonate numbers for the region west of the Mid-Atlantic Ridge have been plotted against water depth, yielding a calcite compensation level of about 4800 m. Berger (1968) has estimated that the lysocline should lie at about 4400 m, because total dissolution of Foraminifera occurred at 4900 m, a point that is commonly about 500 m below the lysocline. Fig. 7 shows considerable scatter of carbonate values above the line that indicates zero carbonate, illustrating the diversity of the diluents and of the bottom-water conditions in the western South Atlantic. The influence of Antarctic Bottom Water is shown by low CaCO$_3$ values at a relatively shallow depth on the southern Mid-Atlantic

Ridge while the Ridge sediments north of the Rio Grande Rise and those on the Rise itself are high in carbonate. A sample from the west end of this Rise even contains tests of the very soluble aragonite-shelled pteropods while samples in the adjacent deep passage through which the Antarctic Bottom Water flows have very low carbonate contents (1, 5, and 7%).

CAPE BASIN. The calcite compensation level in the Cape Basin (Fig. 8) lies at about 5100 m, which is in agreement with data from Turekian (1964). Only one point in the plot contains more than 90% calcium carbonate, because the shallow portion of this Basin near the Walvis Ridge has been relatively poorly sampled and because the shallow part of the Mid-Atlantic Ridge adjacent to the Basin is strongly influenced by Antarctic Bottom Water.

ANGOLA BASIN. Fig. 9 suggests that no true calcite compensation level can be determined for the Angola Basin since only one sample contains less than 18% CaCO3. Berger (1968) found that the lysocline lies at, or possibly below, 5200 m, and the dashed boundary in Fig. 9 lies at an average depth of 5400 m. Usually, the calcite compensation level is at
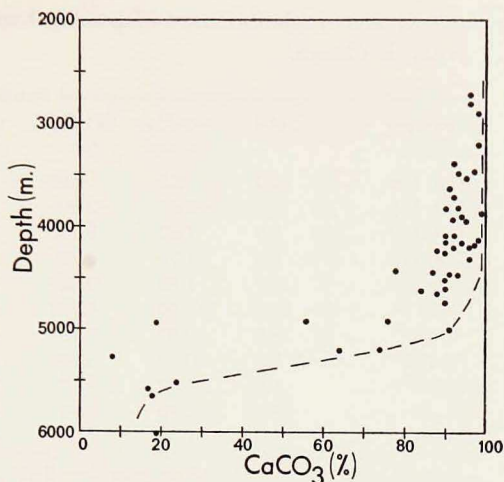

Figure 9. Plot of CaCO3 content versus depth of sample for the Angola Basin. Dashed line is calcite compensation level.

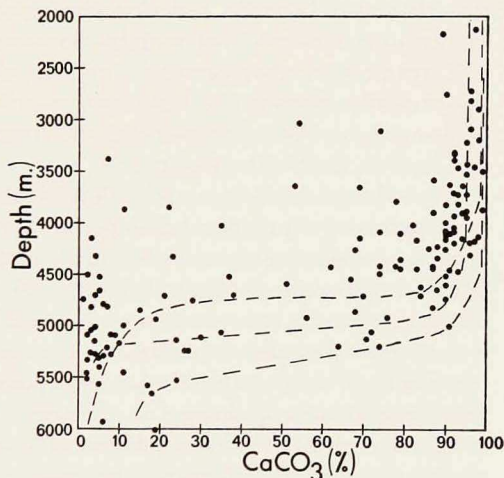Figure 10. Plot of CaCO3 content versus depth of sample for the entire South Atlantic. Dashed lines represent calcite compensation levels for the Brazil (top), Cape (center), and Angola (bottom) basins.

least 500 m below the lysocline, and the 5400-m depth must be considered as no more than a minimum value for this level. More than half of the samples contain 90% or more CaCO3, demonstrating the uniformity of the

Table I. Accumulation rates of principal sediment components in the South Atlantic Ocean.

Sample	Total	CaCO₃	CaCO₃-free	Opal	Quartz	"Clay"	Source and method
			Rate*				
LSDA 159....	13.0	8.9	4.0	0.44	1.36	2.21	+
LSDA 163....	2.2	2.11	0.09	0.02	0.01	0.07	+
LSDA 168....	1.6	1.47	0.13	0.02	0.02	0.10	+
LSDA 178....	1.9	1.75	0.15	0.02	0.02	0.11	+
LSDA 183....	2.0	1.98	0.02	0.00	0.00	0.02	+
V 9–11**....	15.0	10.50	4.50	0.23	0.45	3.75	⧺
V 9–16**....	0.8	0.05	0.75	0.06	0.06	0.62	⧺
V 12–16**....	4.0	0.20	3.80	0.30	0.27	3.20	⧺
V 12–52**....	1.8	0.07	1.70	0.17	0.32	1.22	⧺
V 12–66......	23.0	20.70	2.30	0.37	0.28	1.61	Δ
V 16–36......	13.0	11.96	1.00	0.05	0.08	0.91	Δ

* In cm/1000 yrs. ** Brazil and Argentine Basin.
\+ Goldberg and Griffin (1964), Io-Th; ⧺ Goldberg and Koide (1962), Io-Th;
Δ Ku et al. (1968), C-14 (from Turekian and Stuiver 1964).

conditions that prevail through most of the Angola Basin. However, the fact that there is a lysocline and that Foraminifera in the sediments show signs of corrosion indicates that some carbonate dissolution occurs.

TOTAL SOUTH ATLANTIC. In Fig. 10, all data have been combined. This figure clearly shows that a single compensation level for the entire ocean cannot be determined. Points representing the Angola Basin control the definition of this level in the South Atlantic.

Since the calcite compensation level is the result of progressive dissolution with increasing depth, dissolution percentages can be estimated from the pooled data. Basin-wide averages can be calculated for 500-m depth increments below 2000 m. Using the method of Heath and Culberson (1970), percentages of dissolution can be estimated for each depth interval (Table II). This calculation assumes that the carbonate and the diluent are supplied at constant rates over the basin and that the solution takes place only on the ocean floor. Allowing these simplifications, changes in carbonate concentrations with depth should reflect changes in the rate of solution. The amount of diluent assumed is based on the upper limit of the carbonate concentration for each basin: 6% for the Angola, Brazil, and Argentine basins, 10% for the Cape Basin.

Table II shows a large increase in dissolution at a relatively shallow depth. Even in the Angola Basin, where the level of the greatest increase (4500 m) is 1500 m deeper than in the other basins, it lies 1000 m above the compensation level and 700 m above Berger's (1968) level of the lysocline. In the other basins, the depth of greatest increase is 1400 m above the lysocline and 2000 m above the compensation depth. The increase at 3000 m is consistent with Berger's (1968) increase in the rate of dissolution of Foraminifera at this level.

Table II. Averages of calcite content and percentage of dissolution with depth in the South Atlantic Ocean.

Depth (m)	Angola Basin		Brazil & Argentine basins		Cape Basin	
	% CaCO₃	% disso-lution	% CaCO₃	% disso-lution	% CaCO₃	% disso-lution
2250.....	—	—	97	0	89	0
2750.....	97	0	—	0 (assumed)	90	0
3250.....	94	0	87	54	52*	79
3750.....	94	0	75	76	78	55
4250.....	91	33	67	82	78	55
4750.....	74	77	30	91	43	82
5250.....	59	85	9	93	36	84
5750.....	20	93	4	94	—	—

* Poor areal coverage.

However, the large discrepancy between the depth of greatest increase in solution (lysocline according to Heath and Culberson 1970) and Berger's values for the lysocline in the South Atlantic indicates a weakness in the original definition of the lysocline.

In practice, the lysocline as defined by Berger (1968) does not coincide with the lysocline as used by Heath and Culberson (1970). The level at which the rate of carbonate dissolution appears to be highest lies above the level of increase in the rate of destruction of the foraminiferal assemblage. Perhaps a systematic weight decrease of the foraminiferal fraction without complete destruction of the more soluble species could produce this 700-to-1400-m disparity. As noted by Berger (1971), even the best preserved foraminiferal assemblages may be considerably dissolved. Based on rather imprecise data, Berger has postulated that the sedimentary lysocline marks the level at which 80% of the carbonate has been dissolved. A comparison of the lysocline depth (Berger 1968) given for the Brazil Basin (4400 m) and for the Angola Basin (5200 m) with the percent dissolution of the total carbonate given in Table II shows that this estimate is approximately correct for these two basins.

BIOLOGICAL FACTORS. The assumption that surface productivity is directly related to CaCO₃ concentrations in sediments is implicit in several discussions, such as that by Bramlette (1961). The assumption can be evaluated by a comparison of Hentschel's (1933) chart of the total number of planktonic organisms in the upper 50 m of the water column with the data from this study. Steeman Nielsen and Jensen (1957) have established a correlation between the plankton crop and the biological productivity off the coast of southwestern Africa.

In Figs. 11 and 12, the percentages of CaCO₃ and opal are plotted against the standing-crop numbers derived from the Hentschel map. Since the opal and CaCO₃ values are not normally distributed, the medians have been used as a measure of central tendency. It is obvious that there is no correlation or any
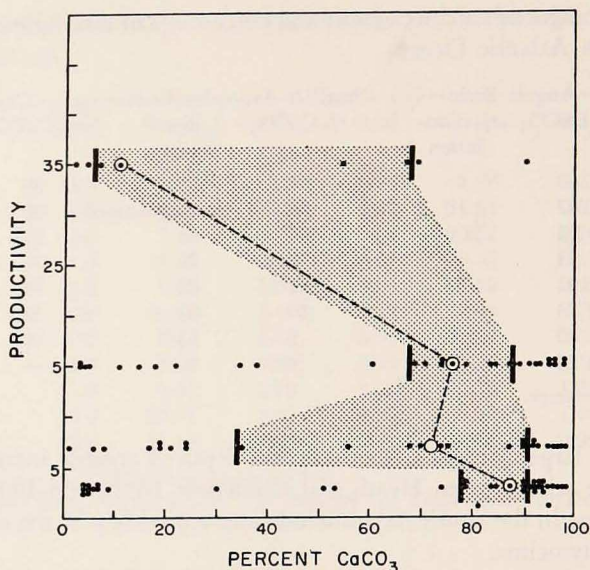
Figure 11. Plot of CaCO₃ content of samples versus standing crop of planktonic organisms (in thousands) in upper 50 m of water column (data from Hentschel 1933). Medians are circled and connected with dashed lines. Area between 80% confidence limits shaded.

meaningful relationship between the average CaCO₃ content and the productivity.

The correlation between the opal content and the productivity is somewhat better than that between the CaCO₃ content and the productivity. Fig. 12 shows that there is a general increase in opal with increasing productivity levels, but the significance of this is small. Certainly the areas of highest biological productivity give rise to sediments that are rich in opal. The absence of a more precise correlation of productivity with opal may result from the effect of variation in the dilution by terrigenous debris and by the lack of good long-term average measurements of biologic productivity in the surface waters.

THE CALCITE COMPENSATION LEVEL AND TEMPERATURE. In order to evaluate the relationship of calcite dissolution to bottom-water masses, the water temperatures (quasiconservative properties of the water masses in the region) can be compared with the calcite contents of the sediments at a number of stations. Determinations of bottom-water temperatures can be obtained from the METEOR Expedition Atlas (Wüst and Defant 1936) and from the Atlantic Ocean Oceanographic Atlas (Fuglister 1960) by cross-indexing depth and longitude to locate cores lying within one degree of published physical-oceanographic traverses. This permits identification of bottom-water temperatures in situ to approximately 0.1°C.
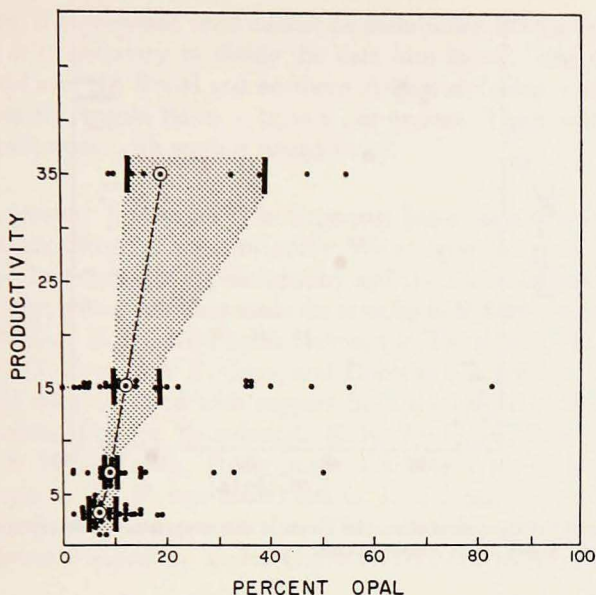
Figure 12. Plot of opal content of samples versus standing crop of organisms (in thousands) for upper 50 m of water column (data from Hentschel 1933). Medians circled and connected with dashed line. Area between 80% confidence limits shaded.

A plot of bottom-water temperatures versus the $CaCO_3$ content (Fig. 13) shows a close resemblance to a Bramlette-type (1961) calcite compensation depth curve, the 1.1-to-1.0° isotherm being analogous to the calcite compensation level. This is not the result of sampling bias. No well-defined compensation level is shown by a plot of depth versus carbonate content for the same samples (Fig. 10), because it reflects the difference between various basins in the South Atlantic. The isotherm-$CaCO_3$ plot clearly resolves these differences. Only the deepest and easternmost of the Angola Basin points, with high temperatures and low carbonate values, stand apart on the plot. This may imply that dilution with Congo River clay is a major factor in the low carbonate of this region.

A geographical comparison can be made between the 1° isotherm and the regions of steep $CaCO_3$ values along the west side of the Mid-Atlantic Ridge. Wüst has not shown isotherms in regions that are shallower than 4000 m; interpolation for the region between the Rio Grande Rise and the Cape Basin-Mid-Atlantic Ridge boundary suggests that the 1° isotherm crosses the Mid-Atlantic Ridge at approximately 42°S. Its shape follows that of the carbonate contours but it is located slightly north of the 80% contour. In the Cape Basin, where the correspondence is not so good, the main feature, a tongue of cold water extending north to the edge of the Walvis Ridge, is reflected by lower
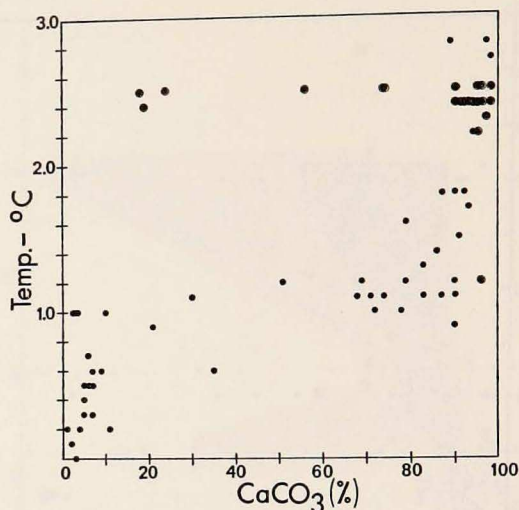
Figure 13. Plot of CaCO₃ content of samples versus in situ temperature of bottom water (after Wüst 1936). Angola Basin samples circled.

carbonate values in this area. For the rest of the Cape Basin, the 1.2° isotherm correlates most closely with areas of intermediate carbonate content.

It should be emphasized that the temperature values are important as tracers for the Antarctic Bottom Water, not as physico-chemical parameters of any great significance in the solution chemistry of calcite. There is no evidence that a temperature change from 0.9° to 1.2°C changes the rate of calcite solution any more than a comparable change in slightly warmer or colder water (MacIntyre 1965), but since there is much evidence that the Antarctic Bottom Water possesses corrosive properties that strongly enhance calcite dissolution, its conservative temperature characteristics can be used as an indicator of its presence, absence, or relative importance.

Summary. The South Atlantic is a carbonate ocean; calcite concentrations overshadow those of opal and quartz. Bottom-water circulation and relationship to depth are the most important factors that determine the distribution of calcite. Clay is next to calcite in importance in setting sedimentary patterns, and in the northeastern Angola Basin it is probably more important. The clay consists of terrigenously derived kaolinite and illite. It is likely a better indicator of continental input than is quartz, which contains a significant ice-rafted component south of 35°S. Opal, which occurs in somewhat greater concentrations than quartz, is found in two bands across the north and south of the study area. This areal distribution resembles productivity patterns, particularly that of diatoms. Opal concentrations are positively correlated with surface-productivity values.

The calcite compensation level cannot be determined for the South Atlantic as a whole; it is necessary to divide the data into basins. The compensation levels obtained are: the Brazil and northern Argentine basins – 4800 m; Cape Basin – 5100 m; Angola Basin – 5400 m, or greater. There is no correlation of calcium carbonate with surface productivity.

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