Relationship of Potential Temperature and Silicate in the Deep Waters Between Cape Lookout, North Carolina, and Bermuda[1]

Unnsteinn Stefánsson[2] and Larry P. Atkinson[3]

Marine Laboratory
Duke University
Beaufort, North Carolina 28516

ABSTRACT

The relationship between potential temperature (Θ) and silicate for potential temperatures below 15°C is more descriptive than the conventional temperature-salinity relationship. The scatter diagram of Θ and silicate consists of four linear segments. This pattern suggests four major water masses: (i) North Atlantic Central Water, with silicate concentrations increasing as potential temperatures decrease from 15° to 8.2°C, where an intermediate silicate maximum occurs; (ii) Subarctic Water, with a silicate minimum around 4°C; (iii) North Atlantic Deep Water, with silicate concentrations increasing as potential temperatures decrease from 4° to 2°C; and (iv) Bottom Water ($\Theta < 2°$ C), where silicate concentrations increase rapidly as potential temperatures decrease. The increase in silicate concentrations with decreasing temperatures within the North Atlantic Deep Water is believed to arise mainly from the re-solution of silica from particulate matter. Three mechanisms that contribute to the rapidly increasing silicate concentrations with decreasing potential temperature of the Bottom Water are discussed: (i) re-solution of silica from bottom sediments, with subsequent upward diffusion; (ii) solution of silica in suspension; and (iii) silicate enrichment that results from mixing with Antarctic Bottom Water. It is concluded that Antarctic Bottom Water represents the main source of silicate enrichment in the Bottom Water. It is suggested that silicate observations may provide the best available means for tracing the penetration of Antarctic Bottom Water into the North Atlantic.

Introduction. Although silicon is one of the minor constituents of seawater, it has aroused considerable interest among oceanographers in the past 30 to 40 years. This interest has been generated mainly by the biochemical and geochemical importance of this element. However, the available data on deep-

water silicon are not voluminous, and such data have been used in only limited studies and analyses of water masses.

Cooper (1952) was probably the first to suggest the use of dissolved silicate in identifying certain deep-water masses, which are difficult to distinguish by means of their temperature and salinity characteristics. Richards (1958) showed that, in the Antilles Arc region, the temperature-silicate relationship could be used to identify Caribbean and Atlantic water in the temperature range 4–5°C; the temperature-salinity correlation indicates that these two water masses are almost identical. In studying the silicate distribution in the deep North Atlantic, Metcalf (1969) has shown that, at a potential temperature of 2°C, silicon concentrations range between about 5 μg-at/l in the North (Irminger Sea) and about 50 μg-at/l in the south (tropical Atlantic) while geographical variations in salinity at 2°C seldom exceed 0.04°/oo. He also demonstrated the usefulness of a temperature-silicate correlation in identifying water masses in the western equatorial Atlantic.

The present communication describes the relationship between potential temperature and silicate in the deep water between Cape Lookout, North Carolina, and Bermuda, and an attempt has been made to use this relationship to identify the major water masses.

Data and Methods. A section extending from near Cape Lookout across the Gulf Stream to 69°50'W was completed during two R/V EASTWARD cruises: August 1–3, 1967 and August 6–8, 1968. The observations at various levels, down to 4900 m, included temperature, salinity, dissolved oxygen, and reactive silicate. Additional data utilized in this paper were obtained in 1966, 1967, and 1968 during various R/V EASTWARD cruises in the North Carolina slope region (Fig. 1).

In situ temperature and observational depths were determined by means of precision deep-sea reversing thermometers, protected and unprotected. Salinity was measured with an inductive salinometer; oxygen was determined by Winkler titration, reactive silicate by the method of Mullin and Riley (1955). The silicate samples were drawn into polyethylene bottles, quick-frozen, and stored in a freezer until they were thawed and analyzed ashore. The apparent oxygen utilization (AOU)[4] was computed by using the solubility data of Carpenter (1966).

The station data for February 1966 to April 1967 are available in Stefánsson and Atkinson (1967); the remaining data are on file at the Marine Laboratory of Duke University.

---

4. The AOU is defined as the difference between the oxygen concentration of water in equilibrium with a normal atmosphere at the temperature and salinity *in situ* and the oxygen concentration as measured (Redfield 1942). The AOU is used here in preference to dissolved oxygen, since the former quantity is assumed to be more directly related to changes in nutrients due to oxidation of organic matter.
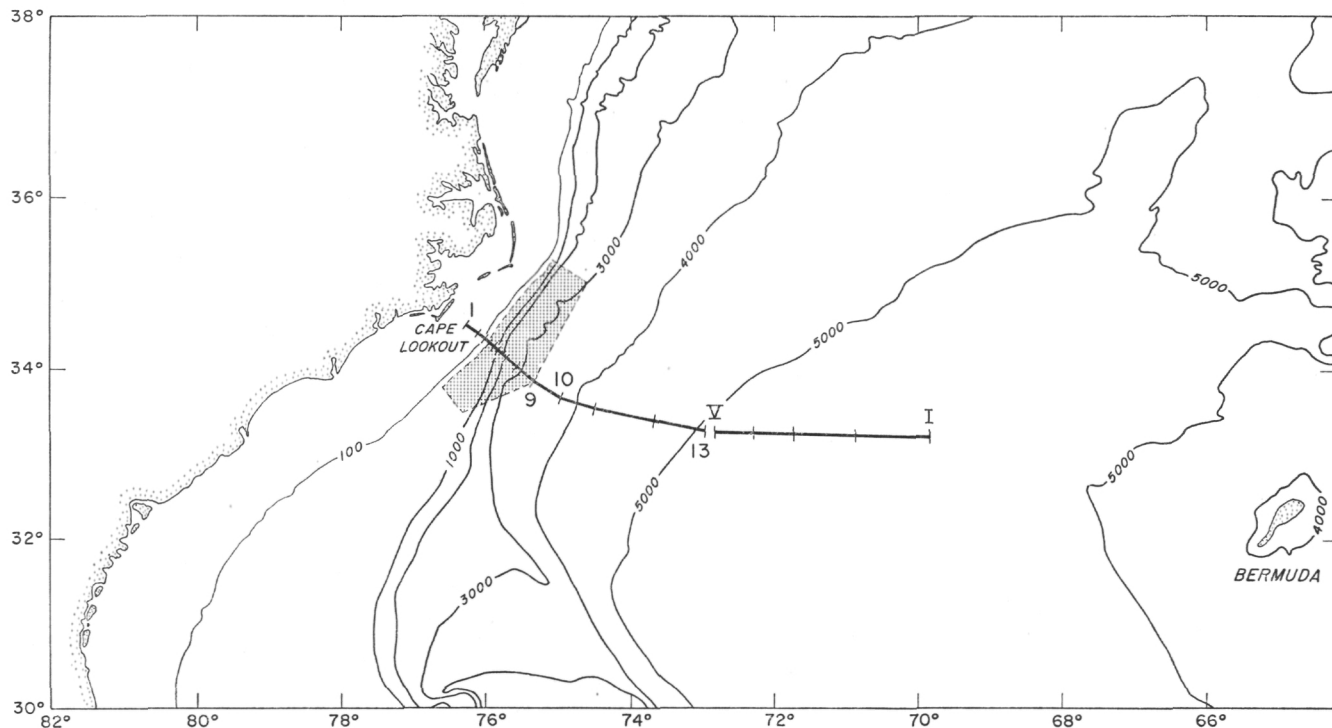
Figure 1. Location of stations occupied on a section extending from Cape Lookout, North Carolina, toward Bermuda. Sts. 1–13 were occupied August 1–3, 1967, Sts. I–VI, August 6–8, 1968. Additional data were obtained within the shaded area during ten R/V Eastward cruises in 1966, 1967, and 1968. The station data for February 1966 to April 1967 were compiled in a technical report (Stefánsson and Atkinson 1967); the remaining data are kept on file at the Duke University Marine Laboratory. Depth contours (in meters) were reproduced from Pratt (1968).
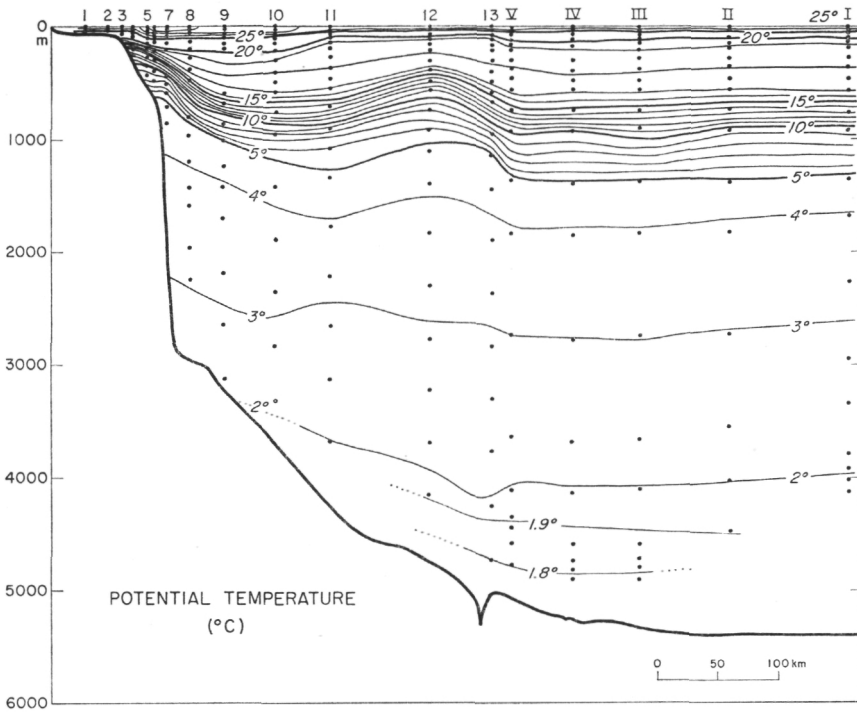
Figure 2. Vertical section showing potential temperature (°C) in the Cape Lookout Section (see Fig. 1). Numbers on horizontal scale at top refer to station numbers. Depth in meters.

Depth Distribution of Properties. The distributions of potential temperature, salinity, AOU, and reactive silicate in the section extending from Cape Lookout across the Gulf Stream are presented in Figs. 2–5. These distributions illustrate the characteristic features of the deep-water structure of both conservative and nonconservative properties. The following main features are revealed.

(i) Within the Gulf Stream, all properties tend to slope upward from east to west; in the Sargasso Sea, however, horizontal gradients are small.

(ii) In the Sargasso Sea, below the permanent thermocline, the potential temperature decreases gradually to 4°C at 1600–1800 m, to 3°C at 2600–2800 m, and to 2°C at about 4000 m. Between 4000 m and 4900 m, the potential temperature lies in the range 1.78°–2.00°C. In the western part of the section, over the continental rise, the deep-water isotherms slope slightly upward from east to west.

(iii) Below the marked halocline, which coincides with the permanent thermocline, salinity decreases slowly with depth. In the western part of the section, the 35 °/₀₀ isohaline is at a depth near 1000 m, the 34.95 °/₀₀ isohaline near
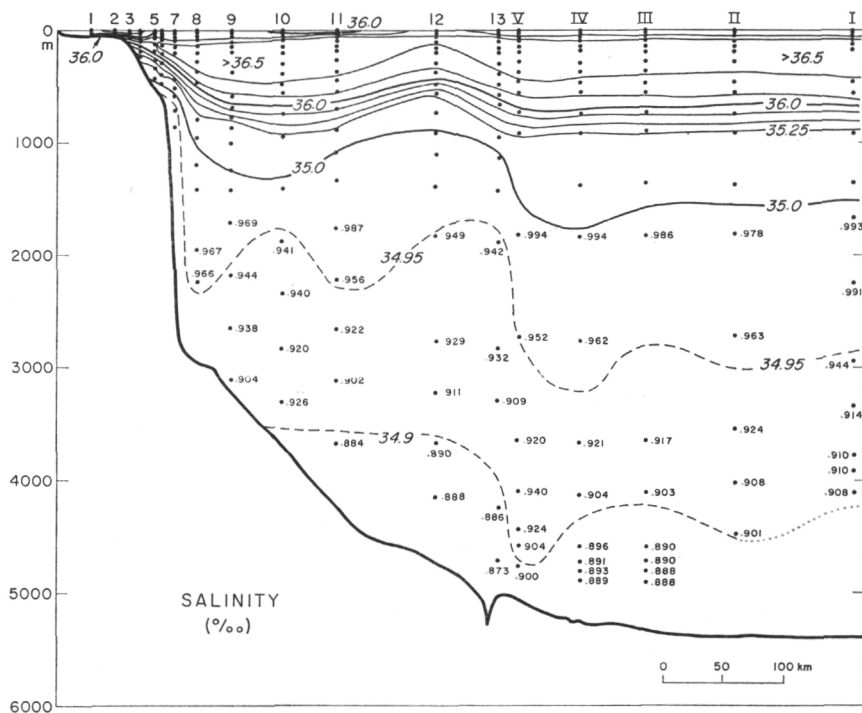
Figure 3. Vertical section showing salinity (°/₀₀) in the Cape Lookout Section (see Fig. 1). Numbers on horizontal scale at top refer to station numbers. Depth in meters.

2000 m. In the eastern part of the section these isohalines are at about 1700 m and 3000 m, respectively. Between 4000 and 4900 m the salinity values range from 34.87 °/₀₀ to 34.94 °/₀₀.

(iv) In general, the main features of the distribution of the AOU closely resemble those of the primary nutrients, phosphates and nitrates. The AOU reaches a maximum (> 3.0 ml/l) at 800–1000 m in the Sargasso Sea but at shallower depths (300–500 m) over the continental slope. In this layer (almost coinciding with the layer of oxygen minimum), nutrients of oxidative origin reach a maximum. A minimum oxygen consumption (1.1–1.2 ml/l) occurs at about 2000 m, with even lower values (1.0 ml/l) near the continental slope. Below 2000 m the AOU increases slightly with depth, reaching a value of 1.6 ml/l in the bottom layers in the easternmost part of the section.

(v) The silicate distribution is characterized by an intermediate maximum that practically coincides with the layer of oxygen minimum. These maximum values are somewhat higher in the Gulf Stream (18–20 μg-at/l) than in the Sargasso Sea (14–16 μg-at/l). A silicate minimum (< 12 μg-at/l) occurs at a depth of about 1500 m, with somewhat lower values near the continental
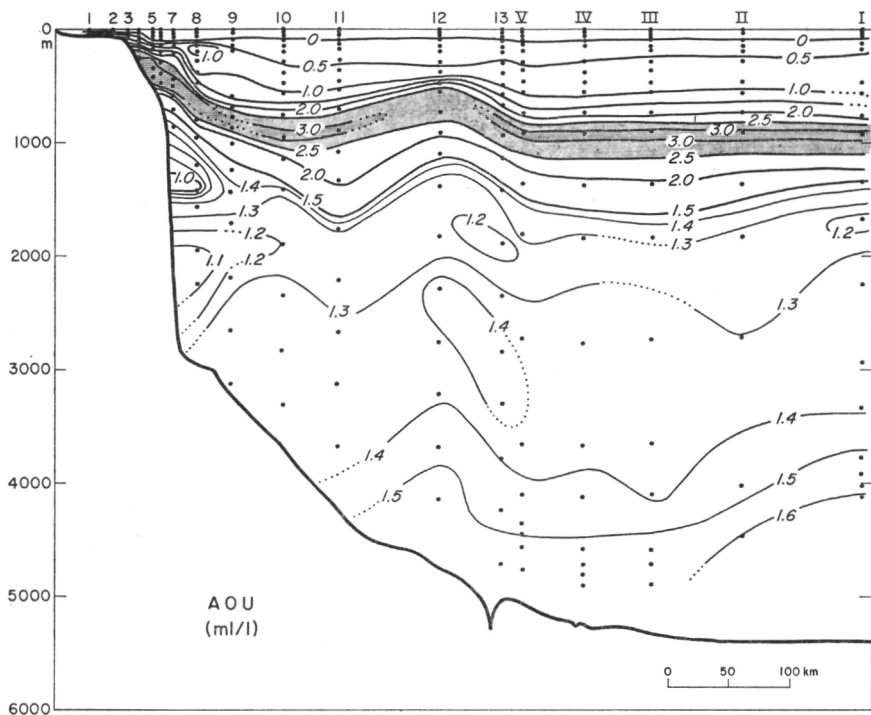
Figure 4. Vertical section of apparent oxygen utilization (AOU, ml/l) in the Cape Lookout Section (see Fig. 1). Numbers on horizontal scale at top refer to station numbers. Depth in meters.

slope (on the west side) than in the Sargasso Sea. Below this minimum layer, the silicate concentration increases gradually to about 25 μg-at/l at 3400–4000 m. At greater depths, the concentration increases more rapidly, to more than 40 μg-at/l in the bottom waters. Thus the maximum vertical-concentration gradients of silicate occur where the temperature and salinity are uniform; they change by less than about 0.1°C and 0.02°/oo, respectively, with a depth increase of 500 m.

Relationship between Potential Temperature and Silicate. In the temperature range 15°–28°C, the silicate concentration increases more or less exponentially with decreasing temperature, from 0.5–3.0 μg-at/l in the near-surface water, where the temperature is 20–28°C, to about 6 μg-at/l at 15°C. However, within this warm water there is a relatively wide scatter in the correlation of Θ and silicate.

For potential temperatures below 15°C, the diagram reveals a distinctive pattern of points that fall within a relatively narrow envelope (Fig. 6). This
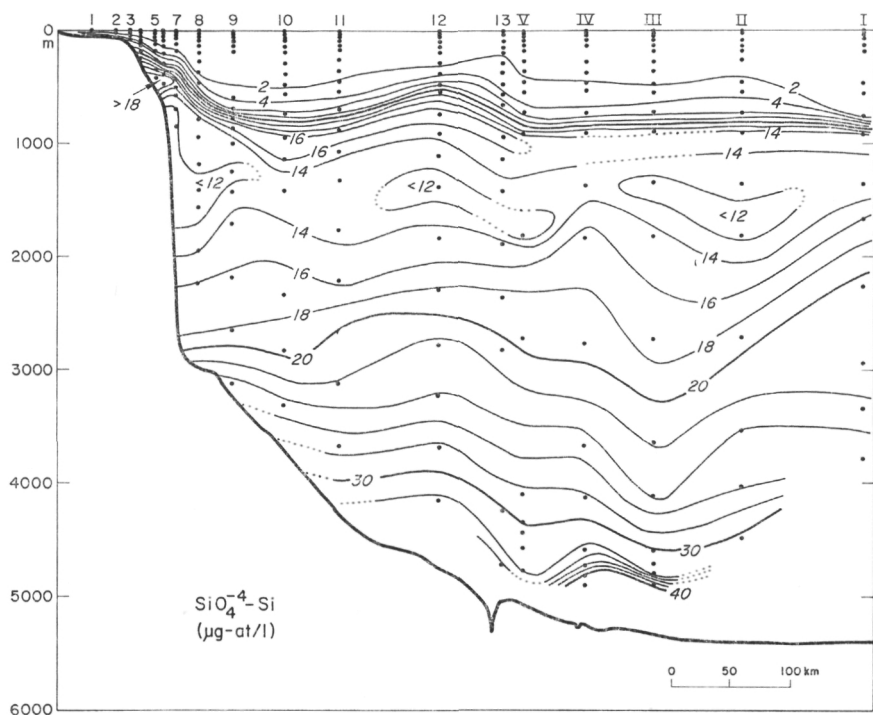
Figure 5. Vertical section showing reactive silicate (μg-at/l) in the Cape Lookout Section (see Fig. 1). Numbers on horizontal scale at top refer to station numbers. Depth in meters.

envelope consists of four linear segments that can be described by means of the simple equation

$$Si = a_i + b_i \Theta, \tag{1}$$

where a_i and b_i denote the intercept and the slope of the central line of segment i. The pertinent statistical data (Table I) indicate that the change in slope for $\Theta < 2°$ is significant.

Discussion. The envelope of Θ and silicate (Fig. 6) suggests several distinct water masses:

(i) The uppermost segment (I) represents North Atlantic Central water (Sverdrup et al. 1946: 668).

(ii) In the layer of maximum AOU, a silicate maximum occurs at a temperature of about 8.2°C. This is indicated by the intersection of segments I and II.

(iii) The intersection of segments II and III represents another core layer that is characterized by a silicate minimum. We refer to this water type as Subarctic Water. Its values—temperature (4°C), salinity ($\approx 34.95°/oo$), AOU

Table I. Regression analysis. Silicon (Si) is a function of potential tempera-
ture (Θ).

Poten. temp. range (°C)	N° of observ.	Intercept a_i (μg-at/l)	Slope b_i (μg-at/l x°C^{-1})	Stand. error of slope (μg-at/l x°C^{-1})	95% confid. limits (μg-at/l)	Correl. Coef.
8.26–15.00	219	31.72	− 1.75	0.037	± 2.12	− 0.96
4.00–8.25	92	6.54	+ 1.32	0.08	± 2.08	+ 0.87
2.00–3.99	62	38.80	− 6.72	0.46	± 4.76	− 0.87
< 2.00	20	118.0	−46.00	11.2	± 6.48	− 0.70
Total	393					

(≈ 1.3 ml/l), dissolved inorganic phosphate (≈ 1.1 μg-at/l), nitrate (≈ 15 μg-at/l), and reactive silicate (≈ 12 μg-at/l)—resemble closely those in the water found in summer at intermediate depths (1000–1500 m) in the Irminger Sea, between western Iceland and Greenland (Stefánsson 1968). These values suggest a common origin, viz., the area east and southeast of Greenland, where winter convection leads to the formation of water having temperatures of 3.5–4.0°C and salinities of 34.92–34.97 °/oo (Dietrich 1957, Stefánsson 1968).

(iv) Segment III represents North Atlantic Deep Water (Sverdrup 1946: 668).

(v) Finally, the change in slope of the envelope of Θ and silicate that occurs at 2°C indicates the influence of still another new water mass that mixes with North Atlantic Deep Water. This lowest portion of the envelope, segment IV, is referred to here as Bottom Water.

A similar plot, using salinity instead of silicate (Fig. 7), shows a relationship that is much less distinctive than the relationship of Θ and silicate and fails to define the three deep-water masses: Subarctic Water, North Atlantic Deep Water, and Bottom Water.

In the relationship of Θ and silicate described by Metcalf (1969) for the equatorial Atlantic, the intermediate silicate maximum does not appear, probably because it is masked by the underlying silicate-rich Antarctic Intermediate Water that is absent in the Hatteras Basin. The lowest portion of the envelope, however, is similar for the two areas, and in both cases a change in slope is indicated at a potential temperature of about 2°C. Metcalf (1969) has suggested that the increasing silicate concentrations for $\Theta < 4$°C indicate mixing with Antarctic Bottom Water.

Several hypotheses that explain the marked increase in silicate concentration with depth in the eastern North Atlantic have been discussed by Cooper (1952). Some of these hypotheses may apply to our study area also. In the western boundary undercurrent below the Gulf Stream, silicate concentrations increase with decreasing temperatures in the range of 2°–4°C in much the same way as elsewhere in our section (Fig. 5). It is thought that this southward-moving
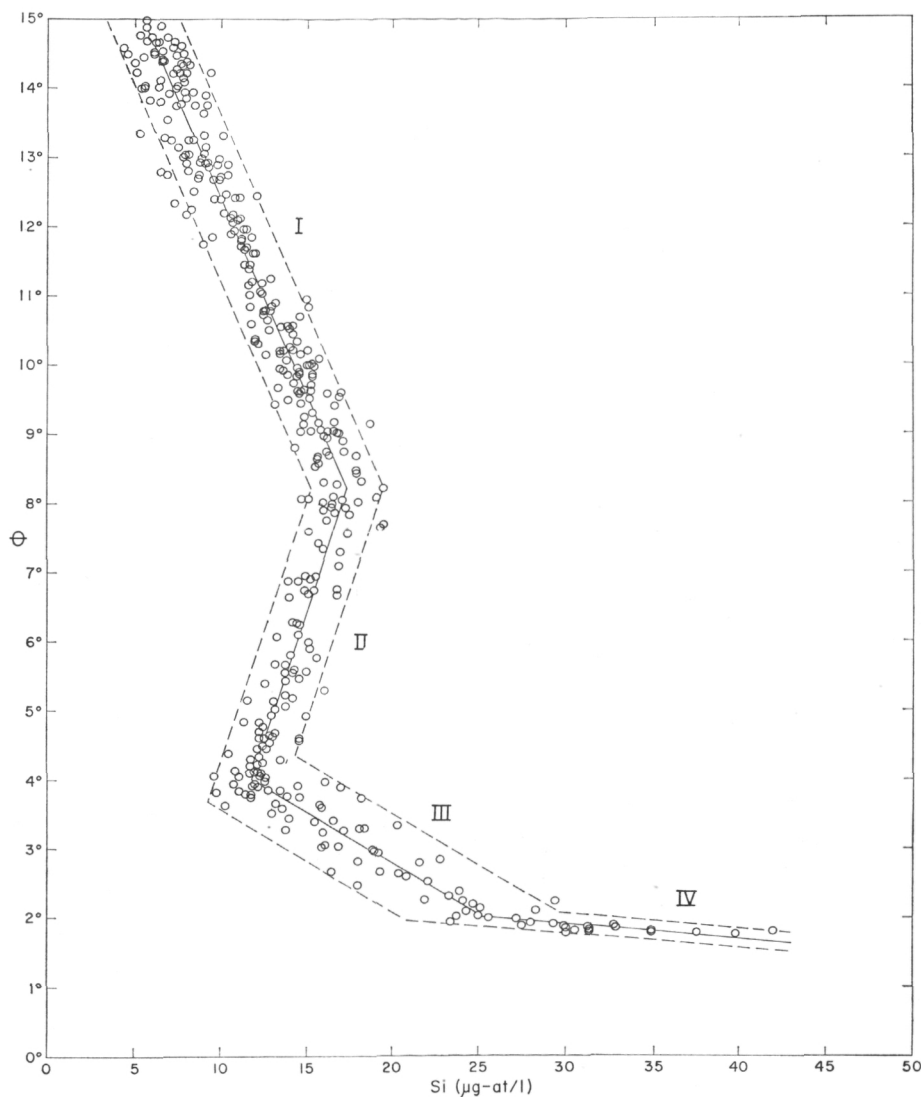
Figure 6. Relationship between potential temperature and silicate in the study area for potential temperatures of less than 15°C based on data referred to in the legend for Fig. 1. Broken lines indicate the 95-% confidence limits. Segments labeled I–IV explained in text.

undercurrent is created from surface waters that sink in the arctic regions. Therefore, we propose that, in our section, the silicate increase with decreasing temperatures between 2° and 4°C is not due to the admixture of Antarctic Water. It appears more likely that the observed distribution for this potential
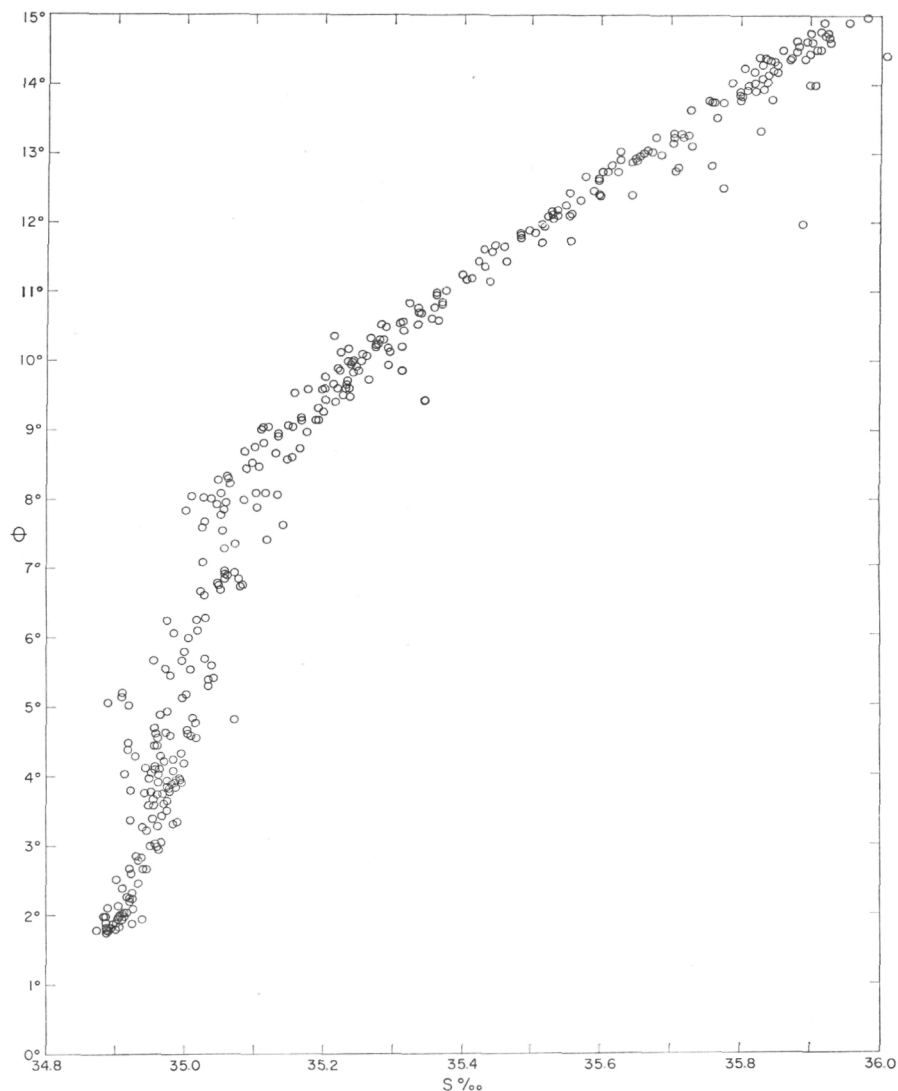
Figure 7. Relationship between potential temperature and salinity in the study area for potential temperatures of less than 15°C based on data referred to in the legend for Fig. 1.

temperature range results mainly from the re-solution of silica from particulate matter that may remain in the deeper water following the complete regeneration of phosphate and nitrates in shallower strata (Richards 1958). As described below, dissolution from suspended sediment matter may also be a contributing factor.

For an explanation of the rapidly increasing silicate concentrations with decreasing temperature in the Bottom Water ($\Theta < 2°C$) in the study area, three mechanisms are considered: (i) re-solution of silica from bottom sediments, with subsequent upward diffusion, (ii) solution of silica in suspension, and (iii) silicate enrichment resulting from mixing with Antarctic Bottom Water.

It is not clear to what extent silica dissolution from the sea floor may affect the concentration of the overlying water. Silica concentrations within sediment cores may either decrease or increase with depth (Siever et al. 1965). In the latter case, silica must move upward through the sediment. Yet, sediment pore material does not seem to exchange freely with the overlying water (Siever et al. 1965, Harriss 1966), but Calvert (1968) has pointed out that, in those sediments where silica concentrations are close to saturation, dissolved silica and other nutrients must be released during compaction into the overlying waters. Koczy (1950) observed that, with depth, there is a sharp increase in silica, phosphate, and turbidity 20–50 m above the bottom and then a sharp decrease in these properties between these maxima and the sea floor. On the other hand, we observed sharp vertical silicate gradients as far as 500–1000 m above the sea floor (Fig. 5), and Richards (1958) obtained similar results for the Puerto Rico Trench, where the strongest gradients occurred between 4400 and 5400 m, followed by a slight decrease down to 5900 m. These data suggest that the high silicate content of the Bottom Water does not result from silica dissolution from the underlying sediment.

Recent measurements (Eittreim et al. 1969) have revealed that there is, in association with the southerly moving bottom waters of the continental margin of the North American Basin below 3000 m, a layer in which strong light scattering occurs due to suspended sediment matter. Scattering intensities were the greatest above the lower continental rise and above the Abyssal Plain north of Cape Hatteras. It is conceivable that silica dissolution from this turbulent suspended layer contributes significantly to the observed silicate increase in the deep and bottom waters over the Hatteras Plain. Examination of simultaneous light scattering and silicate measurements and of the particulate matter might lead to clarification of the role of this source in the dissolved silicon budget.

According to Wüst (1936), Antarctic Bottom Water extends to 40°N in the Western Atlantic Basin. Evidence of the Antarctic Bottom Current above the Bermuda Rise and above the Hatteras Abyssal Plain has been demonstrated in bottom photographs (Heezen et al. 1966). The occurrence of this water on the Hatteras Plain is also suggested in the distribution of bottom potential temperature. A chart that shows the depth of the surface where the potential temperature is 1.8°C in the North Atlantic (Worthington 1969) indicates two sources of deep cold water: the Arctic overflow and the South Atlantic source. These two sources appear to be geographically separated, with the bottom waters of the Hatteras Plain belonging to the southern source. Finally, the

decrease in salinity to less than 34.90°/oo at depths that exceed 4000 m in our section (Fig. 3) strongly suggests the influence of Antarctic Bottom Water.

Thus, the available data leave little doubt that Antarctic Bottom Water mixes with North Atlantic Deep Water in the deepest strata of the study area. We believe that this is the most important source of silicate enrichment in the Bottom Water. If this postulate holds true, then silicate determinations should provide the best available means of tracing the penetration of Antarctic Bottom Water in the North Atlantic.

REFERENCES

Calvert, S. E.
  1968. Silica balance in the ocean and diagenesis. Nature, London, *219*: 919–920.

Carpenter, J. H.
  1966. New measurements of oxygen solubility in pure and natural water. Limnol. Oceanogr., *11*: 264–277.

Cooper, L. H. N.
  1952. Factors affecting the distribution of silicate in the North Atlantic Ocean and the formation of North Atlantic deep water. J. mar. biol. Ass. U.K., *30*: 511–526.

Dietrich, Günter
  1957. Schichtung und Zirkulation der Irminger See in Juni 1955. Ber. dtsch. Komm. Meeresforsch., *14*: 255–312.

Eittreim, Stephen, Maurice Ewing, and E. M. Thorndike
  1969. Suspended matter along the continental margin of the North American Basin. Deep-sea Res., *16*: 613–624.

Harriss, R. C.
  1966. Biological buffering of oceanic silica. Nature, London, *212*: 275–276.

Heezen, B. C., E. D. Schneider, and D. H. Pilkey
  1966. Sediment transport by the Antarctic Bottom Current on the Bermuda Rise. Nature, London, *211*: 611–612.

Koczy, F. F.
  1950. Die bodennahe Wasserschichten der Tiefsee. Naturwissenschaften, *37*(15): 360.

Metcalf, W. G.
  1969. Dissolved silicate in the deep North Atlantic. Suppl., Deep-sea Res., *16*: 139–145.

Mullin, J. B., and J. P. Riley
  1955. The colorimetric determination of silicate with special reference to sea and natural waters. Anal. Chim. Acta, *12*: 162–176.

PRATT, R. M.
  1968. Atlantic Continental Shelf and Slope of the United States. Plate 1. Physiography and sediments of the Deep-sea basin. Prof. Pap. U.S. geol. Surv., 529-B.

REDFIELD, A. C.
  1942. The processes determining the concentration of oxygen, phosphate and other organic derivatives within the depths of the Atlantic Ocean. Pap. phys. Oceanogr. Meteorol., 9(2): 1–22.

RICHARDS, F.A.
  1958. Dissolved silicate and related properties of some western North Atlantic and Caribbean waters. J. mar. Res., 17: 449–465.

SIEVER, RAYMOND, K. C. BECK, and R. A. BERNER
  1965. Composition of interstitial waters of modern sediments. J. Geol., 73: 39–73.

STEFÁNSSON, UNNSTEINN
  1968. Dissolved nutrients, oxygen and water masses in the northern Irminger Sea. Deep-sea Res., 15: 541–575.

STEFÁNSSON, UNNSTEINN, and J. P. ATKINSON
  1967. Physical and chemical properties of the shelf and slope waters of North Carolina. Tech. Rep. Duke Univ. Mar. Lab., 230 pp. Unpublished ms.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING
  1946. The Oceans, their physics, chemistry and general biology. Prentice-Hall, Inc., Englewood Cliffs, N.J. x + 1087 pp.

WORTHINGTON, L. V.
  1969. An attempt to measure the volume transport of Norwegian Sea overflow water through Denmark Strait. Suppl., Deep-sea Res., 16: 421–432.

WÜST, GEORG
  1936. Schichtung und Zirkulation des atlantischen Ozeans, das Bodenwasser und die Stratosphäre. Wiss. Ergebn. dtsch. atlant. Exped. "Meteor" 1925–1927, 6(1); 288 pp.