Reports

Gulf Stream: Velocity Fluctuations During the Late Cenozoic

Abstract. *Biostratigraphic analysis of seven piston cores from the southeastern Blake Plateau suggests that the upper Miocene to Recent sedimentary section at this location represents a history of deposition of calcareous ooze alternating with current-induced nondeposition or erosion. This record is primarily a result of long-term fluctuations in the velocity of the western boundary current or Gulf Stream, which sweeps the plateau. High-velocity phases of this current system, as signaled by hiatuses in the section, lie within the time limits 4.8 to 6.1, 3.9 to 4.4, 2.3 to 2.9, and 0 to 1.5 million years before present (B.P.). These time intervals are coeval with dated episodes of climatic decline and glaciation. The most intense acceleration of the Gulf Stream, as indicated by deep erosion of the Blake Plateau, occurred in the latest Miocene to earliest Pliocene (4.8 to 6.1 million years B.P.) in conjunction with a major expansion of the Antarctic ice cap. Subsequent accelerations of the Gulf Stream coincide with early Pliocene cooling in the Southern Hemisphere, worldwide expansion of high-altitude–high-latitude glaciers in the late Pliocene, and the classical glaciations of the Pleistocene. An additional, protracted increase in the average velocity of the Gulf Stream, which began in the late Miocene and culminated in the mid-Pliocene (about 3.8 million years B.P.), can be attributed to the gradual emergence of the Central American isthmus.*

The Gulf Stream dominates the circulation of the North Atlantic by the sheer magnitude of its velocity and volume transport. Instead of a warm, surface extension of the equatorial current system, as it is often represented, the Gulf Stream is now considered to be a truly deep, geostrophic flow that includes most or all of the water column along its path (*1*). In view of the significant role that this current system has probably played in the evolution of North Atlantic circulation and climate (*2*), it is important to determine whether the Gulf Stream has been a stable component of the North Atlantic circulation or whether its past behavior has differed markedly from that of today. I present here a record of long-term, apparently climatically and geographically linked fluctuations in the velocity of the Gulf Stream from the late Miocene to Recent as seen in the stratigraphic record of the southeastern Blake Plateau.

As the Gulf Stream enters the North Atlantic, it is forced to flow over the shallow (800 to 1200 m), confining surface of the Blake Plateau. The plateau is therefore a site of active sediment transport and erosion (*3*). The western margin of the plateau, which lies beneath the narrow, intense flow of the Florida Current branch of the Gulf Stream, is stripped bare of loose sediment and eroded into a series of linear channels (*4*) in which sediments as old as the Paleocene are exposed (*5*). The broader and more diffuse flow of the Antilles Current sweeps the rest of the plateau, whose surface is characterized by a patchy accumulation of current-washed, rippled foraminifer-pteropod sand (*6–8*). This layer is locally superimposed on older Tertiary and Cretaceous sediments (*6*), whereas elsewhere it grades downward within a few meters and with apparent stratigraphic continuity to Pliocene and Miocene calcareous ("*Globigerina*") ooze of normal composition and texture (*6, 7, 9*). This graded sequence has been interpreted as an accumulation of calcareous pelagic ooze deposited continuously in a strengthening current field (*6, 9*). I present evidence here to show that the sequence is stratigraphically highly discontinuous; it contains identifiable and datable stratigraphic gaps in which considerable portions of the section from the late Miocene to Recent are missing.

This report is based on a biostratigraphic analysis of seven piston cores from the southeastern Blake Plateau (Fig. 1; Table 1). All but one of the cores, which range in length from 5.4 to 17.8 m, penetrate to levels in the upper Miocene, indicating a variable but extreme degree of stratigraphic condensation. The cored sediments are tan to pale brown calcareous ooze, similar in appearance and composition to sediments accumulating at moderate depths elsewhere in the Atlantic-Caribbean area. They are distinguished only by the pronounced upward loss of finer components.

The cores were sampled at an average interval of 20 cm for biostratigraphic study. I prepared foraminifer residues by using standard micropaleontological techniques. The downcore presence or absence of species was charted, and the ranges of biostratigraphically significant species so determined are the basis of a local scheme of 15 zones (Table 2) that was used to correlate the cores. The percent (by weight) of coarse (> 62.5 μm) residue was also determined, and a representative plot of these data is given in Fig. 2. A reconnaissance effort at determining the paleomagnetic stratigraphy of the section proved unfruitful (*10*); as a result, the determination of absolute ages in the section relies on paleontological correlation with earlier cores from the Atlantic (*11, 12*) and Indo-Pacific (*13, 14*) in which the paleomagnetic and biostratigraphic sequences have been intercalibrated.

Correlation of the cores by means of the local zonation (the Miocene-Pliocene contact was used as the horizontal datum) is shown in Fig. 1. Biostratigraphically and on the evidence of certain horizons against which some zones consistently thin and pinch out, the section can be divided into five hiatus-bounded depositional units as follows.

Unit I (zone 15) represents the Recent (< 11,000 years). The nearly pure (> 80 percent coarse) foraminifer-pteropod sand that characterizes this interval contains a typical postglacial fauna of zone *Z* of the Ericson zonation (*6*), including the indicator species *Globorotalia menardii* (Parker, Jones, and Brady) and *G. tumida* (Brady). Also present is *G. fimbriata* (Brady), a variant of *G. menardii* that is restricted to Recent sediments of the Caribbean area (*15*).

Unit II (zones 13 and 14) contains a series of assemblages that typify the faunal succession from just below to just above the Pliocene-Pleistocene boundary in the Atlantic-Caribbean area. This succession was originally described by Ericson *et al.* (*16*) in, among others, two of the cores used in the present study (V3-152 and V3-153) and has more recently been substantiated in other, paleomagnetically dated cores from the Atlantic (*11, 12*). In terms of paleomagnetic stratigraphy, unit II correlates with the lower Matuyama series, from somewhat below to somewhat above the Olduvai event. The top of unit II is not appreciably younger than the lower Matuyama, as indicated by the presence to its top of *G. triangula* Theyer, a form in the past referred to as "*Globorotalia* sp. 1 of Phleger, Parker, and Peirson, 1953" (*11*). This species disappears in the Atlantic

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Table 1. Core locations and water depths.

Core	Latitude	Longitude	Water depth (m)	Core length (cm)
V3-152	28°10′N	77°37′W	1033	562
V3-153	28°24′N	77°56.5′W	994	545
RC11-249	28°15′N	77°29′W	1073	1131
RC11-250	28°08.8′N	77°43.2′W	1027	908
RC11-251	28°13.5′N	77°34.8′W	1051	1125
RC11-252	28°20′N	77°28′W	1069	1109
V26-145	28°08.8′N	77°58.4′W	1024	1778

just above the Olduvai event, at an absolute age horizon of 1.5 Ma (million years before present) (*11*). Since the sediments overlying unit II are Recent, the contact between units I and II is equivalent to a stratigraphic gap in which most of the Pleistocene is missing.

Unit III (zones 8 through 12) represents the mid-Pliocene. It contains several well-established foraminiferal data that indicate deposition from approximately 4.0 to 2.9 Ma. The extinction of *Sphaeroidinellopsis* spp., the first occurrence of *G. tosaensis* Takayanagi and Saito, and the extinction of *Globoquadrina altispira* (Cushman and Jarvis), occur in rapid succession near the top of the unit. These closely associated events have been recognized to occur in the middle Gauss paleomagnetic series, within the age range of about 2.9 to 3.0 Ma (*13*). Since overlying sediments of unit II are lower Matuyama, the contact between units II and III is a hiatus in which the equivalents of the upper Gauss and lower Matuyama are missing.

At the middle of unit III (top of zone 9) occurs the extinction horizon of *Globorotalia margaritae* Bolli and Bermúdez, which is correlated with the base of the Gauss series and an age of 3.3 Ma (*13*). Somewhat below is the extinction horizon of *Globigerina nepenthes* Todd and a nearly simultaneous shift from left- to right-coiling *Pulleniatina primalis* Banner and Blow, a combination of events associated with the top of the Cochiti event of the Gilbert paleomagnetic series and an age of 3.7 Ma (*13*). The base of unit III is marked by the first

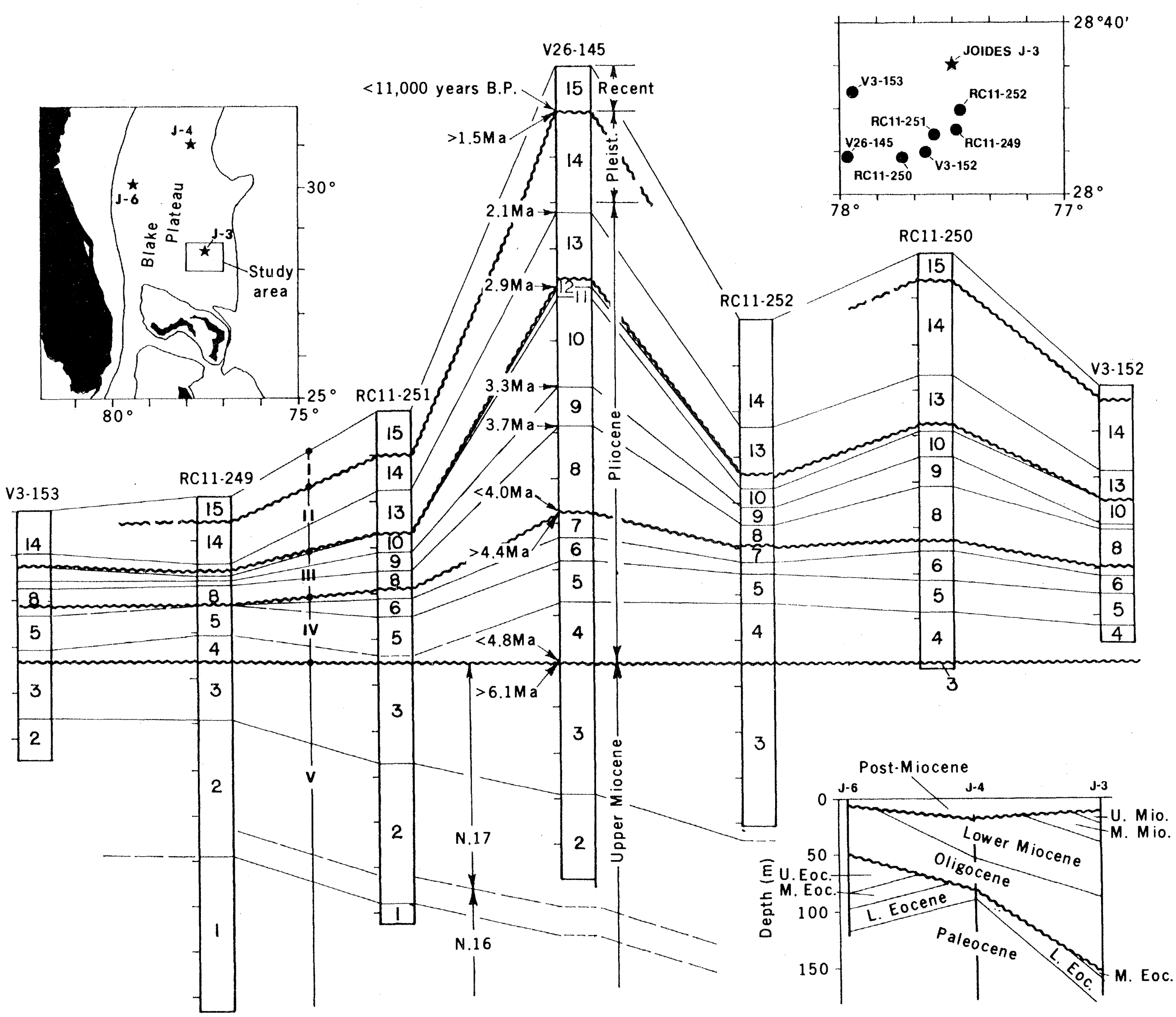

Fig. 1. Location and correlation of piston cores from the Blake Plateau. Lines of correlation are zonal boundaries as given in Table 2. Heavy wavy lines indicate levels of stratigraphic hiatus. Absolute ages are given to the left of core column V26-145. Tick marks indicate the depth in meters from the top of the core. Inset (lower right) shows the deeper stratigraphy of the plateau on the basis of JOIDES (*5*) drilling results.

occurrence of *Globorotalia crassaformis* (Galloway and Wissler), a species that first appears near the Nunivak event of the Gilbert series (*17*), indicating a maximum age of 4.0 Ma for the base of the unit.

Unit IV (zones 4 through 7) represents the lower Pliocene. This correlation is based on the joint first occurrence at the base of the unit of *Globorotalia tumida* and *Sphaeroidinella dehiscens* (Parker and Jones) and the absence of the coccolith species *Ceratolithus rugosus* Bukry and Bramlette, a key species that in the present section first appears at the base of unit III (*18*). Since *G. tumida* and *S. dehiscens* first appear within the lowermost reversed interval of the Gilbert series, at age horizons of 4.9 and 4.8 Ma, respectively (*14*), and *C. rugosus* does not appear until the "c" event of this series (*19*), at an age horizon of 4.4 Ma, the interval of unit IV must lie within the age span of 4.4 to 4.8 Ma, although more precise limits cannot be assigned. Nevertheless, it appears that the contact between units III and IV is a stratigraphic gap with a minimum duration of 0.5 million years (3.9 to 4.4 Ma).

The upper Miocene interval of unit V (zones 1 through 3) completes the section to the depth of maximum core penetration. The interval straddles the boundary between zones N.16 and N.17 of the standard Neogene foraminiferal zonation of Blow (*20*). This boundary occurs in the lower part of zone 2 of the present study (Fig. 1). *Pulleniatina primalis*, whose first appearance is a good index for the midpoint of zone N.17 (*21*), is not present in unit V; its absence suggests that at least the upper part of zone N.17 is missing in a hiatus at the Miocene-Pliocene contact. The age of the initial appearance of *P. primalis* has been determined to be about 6.1 Ma (*22*); since the basal Pliocene in the section is younger than 4.8 Ma, there is a time gap of at least 1.3 million years at the Miocene-Pliocene contact.

Thus the section is highly incomplete, with over half (core V26-145) to nearly all (core V3-153) of the post-Miocene as well as a portion of the upper Miocene sedimentary record missing (Fig. 3). The sediments have been removed en masse and during discrete intervals rather than by a process of quasi-continuous attrition due to winnowing, as has been previously proposed (*6, 9*). This undoubtedly accounts for most of the stratigraphic condensation observed although winnowing is certainly a factor, especially in the upper part of the section (Fig. 2).

Inasmuch as slope-sensitive mechanisms for producing hiatuses (slumping or erosion by turbidity currents) can be excluded for the Blake Plateau, it is clear that the record of alternating deposition and nondeposition or erosion in the study area is primarily a response to fluctuations in the competence of currents associated with the Gulf Stream to transport sediments. This implies that the Gulf Stream has fluctuated considerably in velocity and thus volume transport since the late Miocene. The history that can be deduced from the sedimentary section includes the following major features:

Table 2. Definition of zones.

Boundary between zones	Defining datum
1 and 2	†*Globorotalia miozea conoidea*
2 and 3	Right- to left-coiling shift of *Globorotalia cibaonesis*
3 and 4	**Globorotalia tumida, Sphaeroidinella dehiscens*
4 and 5	*(Nonevoluntary) of *Pulleniatina primalis*
5 and 6	†(Local) *Pulleniatina primalis*
6 and 7	†(Local) *Globorotalia tumida*
7 and 8	**Globorotalia crassaformis*
8 and 9	†*Globigerina nepenthes*
9 and 10	†*Globorotalia margaritae*
10 and 11	†*Sphaeroidinellopsis* spp.
11 and 12	†*Globoquadrina altispira*, **Globorotalia tosaensis*
12 and 13	**Globorotalia miocenica* and *Globorotalia exilis*
13 and 14	†*Globorotalia miocenica*
14 and 15	†*Globorotalia triangula*

*First occurrence. †Last occurrence.

1) In comparison with the present, circulation over the plateau was relatively sluggish in the late Miocene. This is suggested by the low coarse-fraction values (Fig. 2), which are typical for calcareous ooze deposited under quiescent conditions. (The values approaching 40 percent, however, may indicate that slight winnowing was intermittently occurring.)

2) The hiatus at the Miocene-Pliocene contact indicates an intensified Gulf Stream in the latest Miocene to earliest Pliocene. Moreover, the stratigraphic evidence suggests that this is the most dramatic excursion in the velocity of the Gulf Stream recorded by the section. Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) drilling results on the plateau (*5*), summarized in Fig. 1, show a regional sub-Pliocene erosional surface that truncates sediments as old as the lower Miocene (hole J-4) and Oligocene (hole J-6). The same erosional surface can be seen on a smaller scale in the present study area, where the Miocene-Pliocene contact is visibly discordant with underlying zonal boundaries (Fig. 1). Judging from the uneroded thicknesses of Oligocene and younger strata, up to 100 m of sediment were stripped from the plateau at this time, with erosion concentrated toward the landward edge of the plateau. This trend in the depth of erosion is a reflection of the westward increase in velocity of the Gulf Stream and suggests that in the late Miocene to early Pliocene the Gulf Stream, although considerably intensified, was in more or less its present configuration.

A possible indication of the strength of the Gulf Stream at this time is provided by some anomalous current-shaped features that occur downstream of the

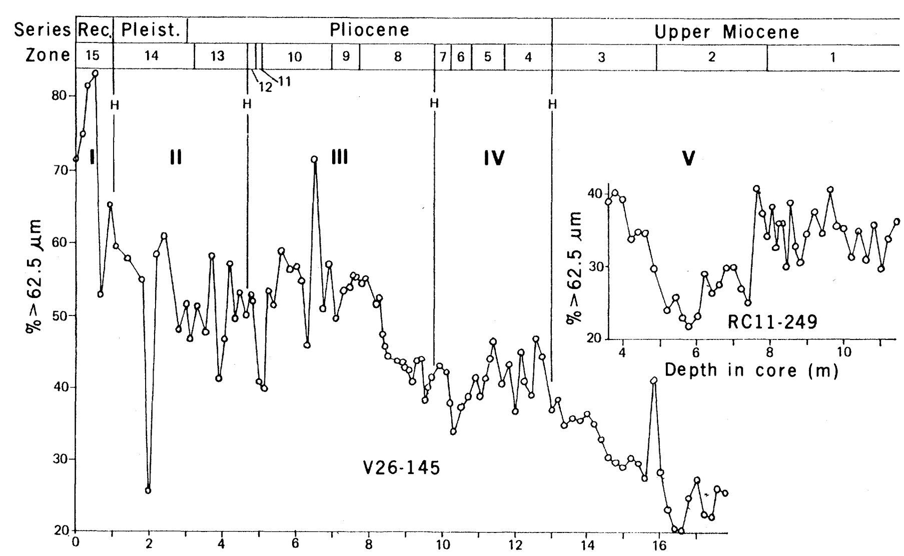

Fig. 2. Plot of coarse (> 62.5 µm) material (essentially foraminifer tests) as the percentage (by weight) of dry sediment for core V26-145 and the Miocene portion of core RC11-249. Local zones as they occur in these cores are indicated in the second row from the top; *H*, hiatus.

Blake Plateau on the North American continental rise. At the base of the rise off Cape Hatteras, partly buried by turbidites of the Hatteras Abyssal Plain, is a series of low, east-west elongate hills, 60 to 100 m high and 4 to 6 km long (the Lower Continental Rise Hills). One of these hills was drilled during Deep Sea Drilling Project leg 44; the drilling showed it to be a constructional feature postdating the middle Miocene (*23*). This result supports the inference of Fox *et al.* (*24*), based on internal layering seen in seismic reflection profiles, that the hills are large abyssal mud dunes. Nevertheless, their internal structure is peculiar in that it indicates migration of the dune field in a northeasterly direction, in a sense opposite to the regional flow of the Western Boundary Undercurrent, which at present sweeps the area. Fox *et al.* therefore termed the hills "antidunes" and tentatively suggested that, like dunes formed under high flow velocities, they may have migrated upstream with respect to the Western Boundary Undercurrent. But, since they are now known to be younger than the middle Miocene and are partly buried by Pleistocene turbidites, these antidunes may be normal abyssal mud dunes formed under the northeastwardly directed flow of an intensified late Miocene Gulf Stream. Similar reasoning may explain the "Krause foredrift" (*25*), a sediment drift that extends to the northeast of a knoll (Knauss Knoll) on the continental rise southeast of New York. Instead of a foredrift, as proposed by Lowrie and Heezen (*25*), this may be a normal lee drift of sediment deposited beneath an intensified, northeast-flowing Gulf Stream.

3) Currents slackened and sediment accumulation resumed in the early Pliocene. Pliocene and Pleistocene time has been characterized by, on average, higher current velocity than during the late Miocene depositional phase, as indicated by the intermittent accumulation of increasingly winnowed ooze (Fig. 2). Superimposed on this protracted trend of intensifying flow are further velocity excursions that prevented the accumulation of sediment. These are bracketed by ages of 3.9 to 4.4, 2.3 to 2.9, and 0 to 1.5 Ma.

Such shifts in the velocity of the Gulf Stream as it crosses the Blake Plateau may have several causes. (i) They may represent adjustments of Gulf Stream velocity to tectonic or other modifications to its path or boundaries. I think this is unlikely, however, since such changes would tend to be irreversible whereas the Gulf Stream velocity excursions are a repeating phenomenon. (ii) They may reflect shifts in the position of the Gulf Stream axis on the plateau and thus may not necessarily be associated with any real change in velocity or volume transport. This explanation also seems unlikely, because the Gulf Stream is hydrodynamically required to lose angular momentum by flowing tightly pressed to the Florida-Hatteras continental slope. It does so at present, and evidence presented above suggests that it was in approximately the same position in the late Miocene. (iii) Since the Gulf Stream is an inseparable part of the North Atlantic circulation, the origin of the perturbations in its flow may reflect events in the ocean-atmosphere system and thus in global climate.

The available evidence favors the last explanation. The depositional record in the study area is apparently related to what is presently known of the climatic development of the late Cenozoic, as shown in Fig. 3. It is evident that hiatuses in the section occur at levels where the climatic record indicates glacial climate or glacially related phenomena. Thus, the most recent phase of intensified circulation (0 to 1.5 Ma) includes the classical glaciations of the Pleistocene. Similarly, the late Pliocene phase (2.3 to 2.9 Ma) is coeval with glacial conditons in Iceland (*26*), the Sierra Nevada (*27*), and New Zealand (*28*) and with the initiation of widespread continental glaciation in the Northern Hemisphere (*29*). Although the chronology and extent of earlier Pliocene climatic events is not yet precisely known, there is evidence of Southern Hemisphere cooling centered on the "c" event of the Gilbert paleomagnetic series (*17*), at 4.4 Ma, which may correspond with the hiatus at 4.0 to 4.4 Ma. Finally, the major erosional episode signified by the hiatus at the Miocene-Pliocene contact probably represents the peak of Antarctic glaciation, as signaled by a major increase in the extent of the Antarctic ice cap that is now known to have occurred in the late Miocene and to have been dissipated by the early Pliocene (*30*).

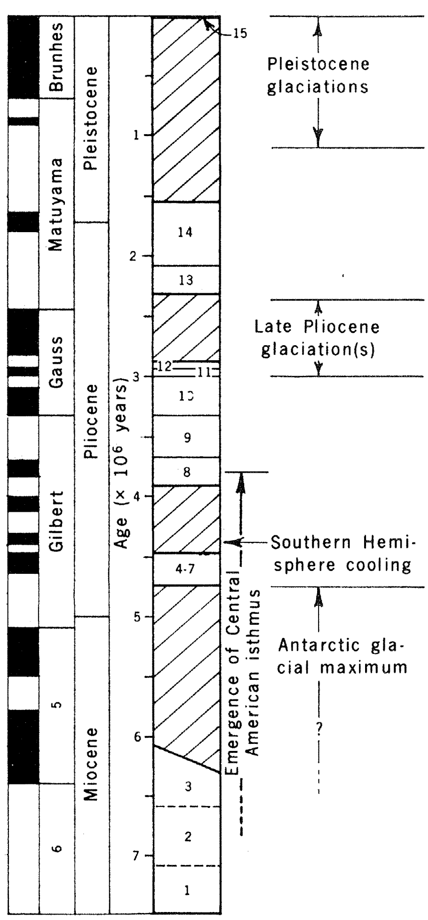

Fig. 3. Time-stratigraphic summary of the Blake Plateau section, showing the extent of depositional units and hiatuses. The inferred correlation to the paleomagnetic reversal sequence and the absolute time scale (in millions of years) are shown on the left side; climatic and tectonic events are shown on the right.

Along with these apparently climatically linked velocity excursions there is, however, a long-term velocity trend that may be amenable to explanation on the basis of tectonic modifications. Figure 2 shows that, on the evidence of current winnowing, the Gulf Stream has increased in average velocity since the late Miocene. This has been interpreted as indicative of either overall intensification of the oceanic circulation (*6*) or strengthening of the Gulf Stream by the emergence of the Central American isthmus (*9*). As noted by Emiliani *et al.* (*9*), this event would have added to the Gulf Stream a component of the North Atlantic circulation that formerly flowed into the Pacific. Although the results of the study presented here suggest a date for this event considerably younger than that proposed by Emiliani *et al.* (owing to differences in biostratigraphic interpretation), their hypothesis provides a likely explanation for the long-term increase in the velocity of the Gulf Stream.

According to Fig. 2, the velocity increase begins in the late Miocene and peaks in the mid-Pliocene (mid-zone 8), above which values fluctuate widely but show no further protracted increase. Since the emergence of the Central American isthmus was probably not a sudden event (*31*), it is likely that the velocity trend indicates a gradual choking off of the seaways across the isthmus that began in the late Miocene and reached completion in the mid-Pliocene. The level at which this process is complete is, in particular, close to one considered on zoogeographic grounds to mark the separation of the Atlantic-Caribbean and Indo-Pacific faunal provinces (*32*). On the basis of the chronology of the section, this level has an age of about 3.8 Ma, in good agreement with the previously estimated minimum age of 3.6 Ma (*32*).

The Blake Plateau section, then, is a record of both tectonic and climatic events as they have affected the North Atlantic circulation. The results in general support the generally although not universally held view that the planetary circulation should be invigorated during times of glacial climate (*33*). But instead of short-term (10^3 to 10^4 years) glacial-interglacial fluctuations, such as those of the late Pleistocene on which this concept is based, the Blake Plateau section seems to be a response to climatic trends extending over a period of 10^5 to 10^6 years that can perhaps be characterized as fluctuations between long-term relatively glacial and relatively nonglacial modes of circulation.

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Dynamic Chemical Equilibrium in a Polar Desert Pond: A Sensitive Index of Meteorological Cycles

Abstract. *The dramatic variation in the composition of a brine pond in Antarctica is a seasonal phenomenon. The phase relations of salts in solution are such that hydrologic conditions and temperature determine composition during the austral summer. Temperature is the primary determinant of composition during the winter.*

Don Juan Pond is situated in a closed basin in the ice-free region (*1*) of southern Victoria Land, between the East Antarctic Ice Cap and the Ross Sea. The pond, discovered in 1961 (*2*), has attracted considerable attention because of its extraordinary, highly variable chemistry and because it remains unfrozen for most of the year in a region where the mean annual air temperature is approximately −18°C. Salinities ranging from 200,000 to almost 400,000 parts per million (ppm) have been reported, and 90 percent of the salt is calcium chloride (*3, 4*). The mineral antarcticite ($CaCl_2 \cdot 6H_2O$), discovered in 1965 (*5*), is peculiar to the Don Juan basin. Geophysical studies (*6*) preliminary to the Dry Valley Drilling Project (DVDP) (*7*) indicated that rock units underlying the basin are highly saline and perennially unfrozen, suggesting the presence of a reservoir of liquid groundwater. Drilling revealed that unfrozen water with a salinity of almost 200,000 ppm and a temperature of about −16°C is present to a depth of at least 75 m; the basin is, in fact, the site of the only known Antarctic occurrence of groundwater discharge from a confined aquifer (*8*).

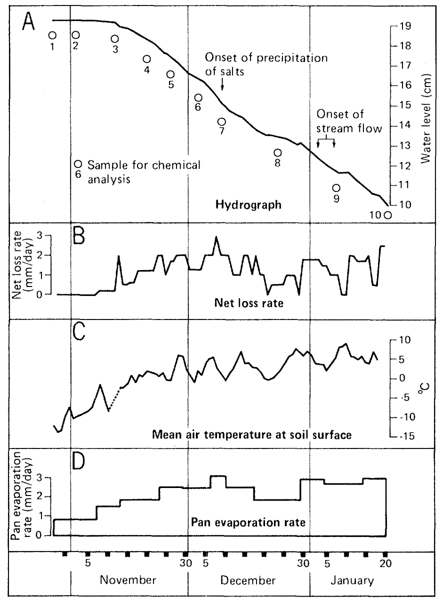

Fig. 1. (A) Hydrograph of Don Juan Pond, 27 October 1975 to 20 January 1976. (O) Date of sample for chemical analysis; samples are numbered sequentially. Precipitation of salts was first observed on 9 December; streamflow began between 3 and 6 January. (B) Net loss rate. (C) Mean air temperature at the soil surface 100 m southwest of the pond. (D) Average of evaporation rates in two pans containing pond water, one at the southwest and the other at the northeast edge of the pond.

During the austral summer of 1975 to 1976, two of us studied the mass balance of the pond as part of a research program begun in 1973 (*9*). The study included (i) bathymetric mapping, (ii) continuous measurement of fluid levels in the pond and DVDP borehole number 13, (iii) continuous measurement of air temperature, (iv) pan measurement of pond water evaporation rates, and (v) sampling of waters for chemical analysis. We can now demonstrate that the peculiar chemical behavior of Don Juan Pond is controlled by both hydrologic factors and temperature.

The flux of pond water occurs by four distinct mechanisms, of which at least three are highly sensitive to meteoro-