PALEOSALINITY, PALEOTEMPERATURE, AND ISOTOPIC FRACTIONATION RECORDS OF NEogene FORAMINIFERA FROM DSDP SITE 173 AND THE CENTERVILLE BEACH SECTION, CALIFORNIA

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Abstract


The oxygen isotope record of the planktonic foraminifera Globigerina bulloides and Neogloboquadrina pachyderma from Pliocene and early Pleistocene sediments at both DSDP site 173 and the Centerville Beach section in California suggests a large influx of isotopically light water in this area during late Pliocene and early Pleistocene time. Salinity may have been reduced by as much as 2 to 4‰. Surface sea water paleotemperatures for the lower Pliocene range from 9.5°C to 15.5°C. The oxygen isotope record of the benthonic genus Uvigerina shows little variation indicating environmental stability at depth. At DSDP site 173 the small variation in Uvigerina is due to variation in the oxygen isotopic composition of the oceans as glaciers waxed and waned. At the Centerville Beach section the oxygen isotopic composition of Uvigerina reflects the gradual shoaling of the Humboldt Basin. Carbon and oxygen isotope ratios in G. bulloides and N. pachyderma are inversely correlated at the 95% confidence level. This may indicate that the oxygen and carbon isotopic composition of foraminifera are influenced by the same factors. On the other hand, the inverse correlation may be due to metabolic fractionation. No correlation was found between oxygen and carbon isotopic composition in Uvigerina.

Introduction

The purpose of this study of the oxygen and carbon isotopic composition of foraminiferal tests from Deep Sea Drilling (DSDP) site 173 and the Centerville Beach section, California is threefold: first, to determine the climatic history during the Pliocene and early Pleistocene of this region; second, to determine the oxygen isotopic variation in seawater due to glacial melting and freshwater run-off; and third, to establish better correlation between the deep-sea record and the marine record exposed on land.

This study is the first of its kind in the northeast Pacific Ocean. The two sites were chosen for study because of their close proximity to one another (Fig. 1) and because of previous biostratigraphic (Ingle, 1973b, 1976) and paleomagnetic (Heinrichs, 1973; Dodd et al., 1977) studies of these sites. The geological significance of stable isotopes was first realized by Urey (1947). The thermodynamic properties of oxygen isotopes are such that the oxygen isotopic composition of calcium carbonate is directly related to the temperature during precipitation and the isotopic composition of the available ions. A few years later this relationship was used to determine the thermal history of Cre-
Taceous belemnites (Urey et al., 1951). Many early studies of oxygen isotopic variations in fossils inadequately evaluated the contribution of changes in the $^{18}$O content of sea water (Emiliani, 1955; Shackleton, 1967), thus causing an inaccurate estimate of paleotemperatures. Dansgaard and Tauber (1969) have suggested that as much as 70% of the variation in the $^{18}$O content of foraminifera may reflect changes in glacial ice volumes on the continents. Emiliani and Shackleton (1974), however, propose that the variation due to glacial effect is only approximately 25%. $^{16}$O, the lighter isotope, is concentrated in rain and snow because of fractionation during evaporation. In the interpretation of oxygen isotope values the effects of both temperature and the $^{18}$O content of the original sea water must be considered, especially when there are major isotopic fluctuations resulting from the growth or melting of ice caps.

The oxygen isotopic composition of foraminifera from deep-sea cores have been extensively used for studying the earth’s climatic record (Emiliani, 1954, 1955; Douglas and Savin, 1972, 1973, 1975; Saito and Van Donk, 1974; Savin et al., 1975; Savin, 1977; Shackleton and Kennett, 1975a, b; and many others). For the most part, investigators have tended either to make a detailed study of the Quaternary record (e.g. Emiliani, 1955; Broecker and Van Donk, 1970; Shackleton and Opdyke, 1973), or they have studied the record of the entire Cenozoic (Savin et al., 1975; Savin, 1977; Shackleton and Kennett, 1975a, b). The records for the individual Cenozoic epochs, other than the Pleistocene, have been studied only briefly. With the exception of Devereux and others study (1970) most oxygen isotopic studies have only considered a few points in the Pliocene.

The significance and causal mechanism of changes in stable carbon isotopes in organically precipitated calcium carbonate is not well understood. The bicarbonate ion in sea water serves as the source for carbon isotopes in calcium carbonate (Deuser and Degens, 1967; Degens, 1969; and Emrich et al., 1970). The bicarbonate ion is in equilibrium with aqueous carbon dioxide, which in turn is in equilibrium with atmospheric carbon dioxide. Thus, the isotopic composition of the bicarbonate ion can be ultimately influenced by the isotopic composition of the atmospheric carbon dioxide. Whether or not the carbon isotopic variation of calcium carbonate actually reflects changes in atmospheric carbon dioxide is unknown. The fractionation of carbon isotopes during the secretion of calcium carbonate is poorly understood. There is some evidence that the origin of the carbon in the test is a mixture of metabolic and inorganic carbon dioxide (H. Craig, in Revelle and Fairbridge, 1957, p. 275; Vinot-Bertouille and Duplessy, 1973). Carbon isotope ratios have been found to reflect depth in the water column at the time of secretion of calcite by foraminifera (Deuser and Hunt, 1969; Saito and Van Donk,
1974; Weiner, 1975). Primary production by phytoplankton causes a depletion of $^{12}$C in the bicarbonate ion in surface waters. Hence, planktonic foraminifera have a higher $^{13}$C content than benthonic foraminifera.

**Geographic and stratigraphic setting**

**DSDP site 173**

Site 173 (Fig. 1) is located at the base of the continental slope 100 km southwest of Cape Mendocino. The site was drilled on June 10–12, 1971 at a depth of 2927 m (Kulm et al., 1973). The upper 138 m of section consists of Pliocene and Pleistocene terrigenous muds and some fine sands. The fauna contains abundant foraminifera, diatoms, and silicoflagellates. The planktonic foraminifera are especially well preserved. Ingle (1973a, b) as a member of the shipboard scientific party, extensively studied the planktonic foraminifera and subdivided the section into the planktonic zones of Blow (1969). Other organisms used for biostratigraphic zonation of site 173 include diatoms, coccoliths, and radiolarians (Kulm et al., 1973). Because of its rich fauna, site 173 has been proposed as a standard section for the Neogene in the northeast Pacific region (Ingles, 1973b). Because the biostratigraphic zonation of site 173 is well understood it was chosen for comparison with the on-land section at Centerville Beach.

**Centerville Beach section**

The Centerville Beach section is exposed in sea cliffs south of Centerville Beach and along the southern margin of the northwest trending Humboldt or Eel River Basin surrounding Eureka, California (Fig. 1). Seismic studies by Silver (1969) and Hoskins and Griffiths (1971) indicate that the major part of the basin lies on the submerged continental margin off the coast of California and Oregon. At Centerville Beach 1900 m of late Neogene marine terrigenous sediments are in fault contact with the metasediments of the Upper Jurassic—Lower Cretaceous Yager Formation (Ogle, 1953). These Neogene sediments make up the Pullen, Eel River, and Rio Dell Formations of Ogle (1953) and are part of the larger Wildcat Group, which also includes the overlying marine and nonmarine Scotia Bluffs Sandstone, and Carlotta Formation. Mudstones, siltstones, and fine to coarse sandstones make up the basinal turbidites, slope deposits, and continental shelf deposits of these marine units (Piper et al., 1976). The sequence of sediments records a gradual shoaling of the area through geologic time.

The Centerville Beach section has been assigned various ages. Gabb (1866) was the first to assign an age to the rocks of Humboldt County when he described six molluscan species of Pliocene age. Lawson (1894) assigned the name Wildcat “series” (more properly called the Wildcat Group) to the rocks of the Humboldt Basin and assigned them a Pliocene age on the basis of molluscs and echinoids. Subsequent workers (Martin, 1916; Smith, 1919; Grant and Gale, 1931; and Faustman, 1964) have also assigned a Pliocene age to these sediments based on molluscan assemblages.

Age assignments based on foraminifera have not always agreed with those based on molluscs. Although Cushman et al. (1930) placed the Wildcat Group in the Pliocene, Stewart and Stewart (1949) later recognized the possibility of the younger beds (e.g. Carlotta Formation) being Pleistocene in age. On the basis of benthonic foraminiferal assemblages Ogle (1953) placed the Miocene—Pliocene boundary in the basal Pullen and the Pliocene—Pleistocene boundary in the Carlotta Formation. Haller (1967) in a more complete study of the foraminifera of the Humboldt Basin placed the Pliocene—Pleistocene boundary in the upper Rio Dell Formation.

Recent advances in planktonic foraminiferal biostratigraphy and paleomagnetic and radiometric time scales (Berggren, 1969; Blow, 1969; Cox, 1969; Opdyke, 1972; Berggren and Van Couvering, 1974) allow a
more precise subdivision of Neogene rocks. Analysis of planktonic foraminifera from Centerville Beach (Ingle and Takayanagi, 1968; Ingle, 1969; Orr and Zaitzeff, 1971) indicates that the Wildcat Group was deposited between early Pliocene and early Pleistocene time. Biostratigraphic comparison of the Centerville Beach section and DSDP site 173 by Ingle (1973a, b, 1976) suggests that the Pliocene–Pleistocene boundary is in the middle Rio Dell Formation. Dodd et al. (1977) in a paleomagnetic study of the Centerville Beach section placed the beginning of the Olduvai event, which is also defined as the beginning of the Pleistocene (Berggren and Van Couvering, 1974), in the middle Rio Dell Formation.

Samples

**DSDP site 173**

Twenty-three core samples, regularly spaced approximately every 3.5 m, from cores 6-14 of site 173 were obtained from the DSDP curator at Scripps Institution of Oceanography. Cores 6 through 14 were chosen for study because they are approximately stratigraphically equivalent to the section at Centerville Beach (Fig. 2). Samples were chosen on the basis of preservation and abundance data presented by Ingle (1973a) for site 173. The average sediment sample size was 10 cm³. The rate of sedimentation at site 173 was approximately 3 cm per 1000 years (Heinrichs, 1973), indicating that samples were spaced at approximately 130,000-year intervals. All samples from site 173 are fossiliferous and most of the foraminifera appear to be better preserved than those from the Centerville Beach section.

**Centerville Beach section**

Thirty-four 750 g sediment samples were collected, approximately every 60 m stratigraphically, from the Pullen, Eel River, and Rio Dell Formations in June 1976 (Fig. 3). On the basis of the paleomagnetic work of Dodd et al. (1977) the rate of sedimentation during Rio Dell time was found to be approximately 70 cm per 1000 years. Thus, the spacing between samples from the Rio Dell Formation represents approximately 85,000 years. Sedimentation rates for the Eel River and Pullen were probably significantly less (Piper et al., 1976). The samples collected from the upper Rio Dell were more widely spaced to compensate for increased rates of sedimentation (Ingle, 1976; Piper et al., 1976). Some samples were more widely spaced than desired due to lack of outcrop.

Not all the samples contained specimens which could be used for isotope analysis. Those samples collected from the Pullen Formation (CB-1 through CB-5) were either barren or yielded too few foraminifers for analysis. A few samples had undergone extensive diagenetic alteration (heavy iron staining is visible on the foraminifers) and were omitted from the study.
Experimental methods

Sample preparation

The sediment samples from DSDP site 173 were boiled in water with Calgon to aid in deflocculation of the clay particles. The Centerville Beach samples were first crushed and then boiled in water. All samples were washed and sieved through a 100-mesh screen. The washed residue was picked under a microscope with a fine-haired brush. For each sample, specimens of *Globigerina bulloides*, *Neogloboquadrina pachyderma*, and *Uvigerina* were separated onto cardboard slides. Specimens which displayed heavy secondary calcitic crusts and/or chamber infilling were avoided.

The experimental procedure for preparation of CO$_2$ from the carbonate samples was modified from Shackleton (1965) and Shackleton and Opdyke (1973). The forams were placed in quartz thimbles and roasted in a vacuum at 425°C for 15 min, the temperature and roasting time suggested by N.J. Shackleton (pers. comm.). During roasting, the foraminifers darkened due to charring of the organics.

CO$_2$ samples were prepared, purified, and collected in a standard vacuum line. The vacuum was maintained by a mechanical pump backing an all-glass mercury diffusion pump. The apparatus was evacuated to better than 0.01 Torr for an hour or more to remove any trapped gas molecules from the phosphoric acid. The sample, in its quartz thimble, was dropped from the bucket of the side arm of the reaction vessel into 3 ml of 95% phosphoric acid where the reaction took place at 50°C. At this temperature the reaction is rapid and is completed within 5 min. The reaction products were instantaneously pumped off cryogenically to prevent any exchange of oxygen isotopes between CO$_2$ and H$_2$O. The sample CO$_2$ was passed through a pentane slush trap at -130°C to remove water and other impurities before being frozen in a liquid nitrogen trap at
-196°C. The volume and pressure of the CO₂ was measured in order to calculate the moles of carbon dioxide for use by the mass spectrometer operator. The sample CO₂ was packaged finally in a glass tube and sealed with a torch (Des Marais and Hayes, 1976).

Measurement of stable isotope ratios

Measurements of $^{18}$O/$^{16}$O and $^{13}$C/$^{12}$C ratios were made on a Varian GD150 mass spectrometer equipped with a Nuclide dual electrometer and radiometer. The isotope ratios from a known carbonate standard (Harding Iceland Spar, $\delta^{18}$O_PDB = -18.16°/00, $\delta^{13}$C_PDB = -4.91°/00) were compared with those from the sample CO₂. Corrections were made for the peak overlap for masses 45 and 46, for background ion currents, for $^{17}$O contributions to the ion current at mass 45, and for cross contamination due to valve leakage at the dual inlet (Craig, 1957). The difference between sample and standard is expressed by the following equation:

$$\delta = \left[ \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 1000$$

where $R$ is the $^{18}$O/$^{16}$O or $^{13}$C/$^{12}$C ratio; and $\delta$ is expressed in parts per thousand (°/00). The standard deviation of the mean for oxygen and carbon isotope measurements of standards was 0.4°/00 and 0.1°/00, respectively. Such a large variance in the oxygen isotopic composition of standards would be unacceptable if the isotopic variation of the experimental samples was small. The standard deviation of the mean for planktonic oxygen values from the Centerville Beach section and DSDP site 173 was 1.9°/00 and 1.1°/00, respectively. These large standard deviations help to reduce the significance of the large variance of the oxygen isotope measurements.

In order to compare the oxygen isotope values of different labs, isotope workers reference their results to a standard (Craig, 1957). All oxygen and carbon isotope values from this study are referenced to the PDB standard. The preparation of carbonate standards requires that the calcium carbonate be dissolved in 100% phosphoric acid and the products allowed to equilibrate for 12 to 24 h. If samples are prepared differently from the above method they can not be directly compared with the PDB standard. To correct for the lack of oxygen isotopic exchange between CO₂ and H₂O in the Shackleton method an in-house standard was prepared by both the McCrea method (1950) and the Shackleton method. Oxygen isotopic values were found to be 1.22°/00 lighter when prepared by the Shackleton method. A correction constant of 1.22°/00 was added to the oxygen data from all the samples. No such correction was required for the carbon data because no exchange of carbon isotopes can take place during the preparation of CO₂.

Choice of taxa for analysis

Planktonic foraminifera

Previous studies of the Centerville Beach section (Haller, 1967) and cores from DSDP site 173 (Ingle, 1973a) indicate that the genera Globigerina and Neogloboquadrina are the most common planktonic foraminiferal genera. Haller reported (1967, fig. 7) N. pachyderma and G. bulloides as the most common planktonic foraminifera from the Centerville Beach section. On the average, planktonic foraminifera are not abundant in the Centerville Beach section (Haller, 1967, fig. 9). Ingle’s work (1973a) on the foraminifera from DSDP site 173 indicates a high diversity and abundance of planktonic foraminifera. Species equitability is low, however, for in most samples G. bulloides and N. pachyderma comprise 80% or more of the planktonic foraminifera.

To minimize differences in isotopic fractionation resulting from analysis of different species, only one species was analyzed where possible. Because planktonic species are used
to determine surface, or near-surface, water
temperatures, a species should be used which
lives high in the water column. Studies on
living foraminifera indicate that *G. bulloides*
inhabits shallower depths than does *N. pachyderma* (Bradshaw, 1959; Casey, 1963; Bé and Hamlin, 1967; and Berger, 1969). Bradshaw (1959) found *G. bulloides* concentrated in the upper 100 m of the water column, whereas *N. pachyderma* was mostly restricted to depths greater than 100 m. Van Donk and Mathieu (1969) found that *N. pacyderma* secreted half of its calcite below 300 m. Oxygen isotopic studies by Kennett et al. (1977) indicate the reverse situation; oxygen isotopic values for *N. pachyderma* and *G. bulloides* indicated that *N. pachyderma* secreted calcite in shallower water.

Based on the conflicting literature it is
hard to make a choice as to which taxon is
best for isotope analysis. It was decided that
*G. bulloides* was preferred to *N. pachyderma* for this study. Nearly all the samples from DSDP site 173 yielded sufficient quantities of *G. bulloides* for isotopic analysis; however, a few required the combined analysis of *G. bulloides* and *N. pachyderma* so that enough calcite was available for analysis (see Fig. 4). In most instances the Centerville Beach samples did not yield enough specimens of either species for a single species analysis. Because of this a mixed assemblage of *G. bulloides* and *N. pachyderma* was analyzed from the Centerville Beach section.

**Benthonic foraminifera**

A benthonic genus was also analyzed in
order to monitor changes in the isotopic
composition of the ocean. Shackleton (1974)
found that *Uvigerina* deposits its test at or
near isotopic equilibrium in the temperature
range from 0.8°C to 7°C. Thus, values for the
isotopic composition of tests can be explained
in terms of changes in the mean oxygen
isotopic composition of the ocean if abyssal
temperatures are assumed to remain constant. Oceanographic studies of modern water mass-
es have shown that deep water greater than
1000 m is constant in temperature and free
from thermal fluctuations (Barbee, 1965). Study of late Pleistocene benthonic foraminiferal assemblages from the North Atlantic (Streeter, 1973) suggests that bottom waters may have varied by as much as 2°C in the last 150,000 years. Studies of this nature are lacking for the Pacific Ocean, but it is probably safe to assume no large variation in abyssal temperatures during the late Neogene.

The genus *Uvigerina* is common at Center-
ville Beach and DSDP site 173. Haller (1967, fig. 7) lists *U. peregrina* as the dominant species of *Uvigerina* at Centerville Beach. Ingle (1973a, table 8, p. 536) lists seven species of *Uvigerina* from site 173. Due to the complex taxonomy no attempt was made to identify specimens of *Uvigerina* from site 173 to the specific level. The first 15 to 20 specimens encountered were used for iso-
topic analysis.

**Adequacy of the data**

Whenever a study of oxygen isotopes is
attempted, certain *a priori* assumptions must
be justified. First, did the organism deposit
its calcite in isotopic equilibrium with sea
water? Second, has there been any diagenetic
alteration of the calcite (or aragonite)? Sever-
al studies of oceanic foraminifera have indi-
cated that foraminiferal tests are deposited at
or near isotopic equilibrium (Shackleton,
1974; Savin et al., 1975). However, Shackle-
ton et al. (1973) found some planktonic spe-
cies deviated from isotopic equilibrium by
as much as -0.50‰. Providing that the
foraminifera were deposited on the sea floor
above the carbonate compensation depth,
foraminifera in deep-sea clays should have
experienced a minimum of diagenesis. Dia-
genetic alteration could be more of a prob-
lem with the Centerville Beach samples, but
for the most part the mudstones should have
low permeability to groundwater flow.

The standard deviation of the mean for the
oxygen isotopic analysis was found to be
$0.4^\circ/_{oo}$ (see above section of Measurement of Stable Isotope Ratios). Due to the large isotopic variation found in this study, such a large standard error does not greatly limit the interpretation of the data.

Measurement of carbon isotope ratios is easier because the natural abundance of $^{13}C$ is one part in 90 as compared with $^{18}O$ which is one part in 500. The standard deviation of the mean for carbon isotope measurements was $0.1^\circ/_{oo}$. 

**Interpretation of paleotemperatures and paleosalinities**

If the isotopic composition of sea water is known, oxygen isotope values can be used for paleotemperature determinations (Savin et al., 1975; Shackleton and Kennett, 1975a). However, in working with fossils of post-Miocene age, particularly Quaternary fossils, there is the strong possibility that the oxygen isotope record of these fossils reflects glacial events rather than actual changes in ocean surface temperatures. Early studies (Emiliani, 1955) of Pleistocene paleotemperatures did not believe that the changes in the oxygen isotopic composition of the sea water due to waxing and waning of glaciers was a significant factor in determining paleotemperature (Shackleton, 1967). Later workers have made estimates of 70% (Dansgaard and Tauber, 1969) and 25% (Emiliani and Shackleton, 1974) for the amount of variation in isotopic

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Fig. 4. DSDP site 173: sample numbers indicate core number, section number, and the number of centimeters below top of section. A, coiling ratios of *N. pachyderma* (Ingle, 1973a); B, oxygen isotopic composition of *G. bulloides*; C, oxygen isotopic composition of *Uvigerina*; D, carbon isotopic composition of *G. bulloides*; E, carbon isotopic composition of *Uvigerina*. (* indicates mixed assemblage of *G. bulloides* and *N. pachyderma*.)
values due to changing ice volumes on the earth's surface.

Salinity changes, reflecting mixing of fresh and marine waters, can greatly influence the oxygen isotope record. Brackish and freshwater environments are characterized by lighter oxygen isotope values (Epstein and Mayeda, 1953). Dodd and Stanton (1975) successfully used oxygen isotope analysis to differentiate open marine environments from brackish and freshwater environments in the Pliocene of California. Study of the oxygen isotopic composition of foraminifera and water samples from the Arctic Ocean by Van Donk and Mathieu (1969) indicated a depletion in $\delta^{18}O$ of about 4°/oo, corresponding to a salinity of approximately 30°/oo, due to melting of glacial ice. The estimated isotopic composition of freshwater runoff was $-22°/oo$. The $\delta^{18}O$ profile was found to closely follow the salinity profile with $\delta^{18}O$ changing by about 0.8°/oo per 1°/oo salinity change. At

Fig. 5. Centerville Beach section: A, oxygen isotopic composition of *N. pachyderma*—*G. bulloides* mixed assemblages; B, oxygen isotopic composition of *Uvigerina*; C, carbon isotopic composition of *N. pachyderma*—*G. bulloides* mixed assemblages; D, carbon isotopic composition of *Uvigerina*.
depths greater than 350 m, normal marine salinity was reached. In a study of three Gulf of Mexico deep-sea cores, Kennett and Shackleton (1975) found an oxygen isotopic anomaly as large as -1.5‰ hundreds of miles from the mouth of the Mississippi River. This anomaly is representative of a reduction in salinity of approximately 3‰ and was interpreted by Kennett and Shackleton as representing the rapid melting of the Laurentide ice sheet during late Quaternary time. The estimated isotopic composition of the glacial meltwater was -30‰.

The present study also documents the occurrence of isotopically light water and reduced salinity conditions offshore (Figs. 4 and 5). At both of the study sites the oxygen isotopic record for the late Pliocene and early Pleistocene shows large negative anomalies that are interpreted as low salinity conditions. Such anomalies could represent changes of as much as 10–15°C in surface water temperatures, if interpreted in light of the paleotemperature equation; however, such large changes over so short a time period does not seem geologically feasible. Instead the anomalies more likely represent an influx of isotopically light water from the ancestral Eel and Columbia Rivers brought south along the coast by the southward flowing California Current. At DSDP site 173, anomalies as large as 2–3‰ are recorded (8-6, 50-52; 10-4, 49-51) and may represent reduced salinity conditions of approximately 2‰. At Centerville Beach, anomalies as large as 3–4.5‰ are recorded (CB-19 through CB-26) and may correspond to reduced salinities of as much as 3–4‰. The greater reduction in salinity at Centerville Beach is to be expected because of its proximity to the shoreline. Absolute changes in salinity can only be estimated because there is no accurate way to estimate the isotopic composition, or the volume, of the freshwater influx.

The Centerville Beach section was deposited a few tens of kilometers from the mouth of the Eel River and DSDP site 173 was approximately 120 km from the Eel River. The benthonic record at DSDP site 173 shows fluctuations in the δ¹⁸O values but no major anomalies like those at the surface. The bottom waters at DSDP site 173 have a subarctic source (Sverdrup et al., 1942) and are thus not influenced by local effects. The benthonic record for the Centerville Beach section shows no major anomalies either, but it does show a gradual decrease in δ¹⁸O content probably due to warmer bottom water temperatures as the section gradually shoaled (Ingle, 1976; Piper et al., 1976). Major anomalies in the planktonic but not the benthonic record probably indicate that isotopically light fresh water, which is less dense than sea water, may have moved across the ocean surface for a long distance before being thoroughly mixed with seawater. The surface record at DSDP site 173 shows strong fluctuations between isotopically light conditions and normal marine conditions, but at Centerville Beach there was a long period of isotopically light conditions unpunctuated by normal marine conditions (CB-19 through CB-26). This should be the expected pattern because the Centerville Beach section is much closer to the source of isotopically light water than is DSDP site 173.

Both sites show stability of the record for the lower Pliocene. Based on an assigned temperature of 3°C [the temperature at 1500 m depth (Barbee, 1965)] for *Uvigerina*, the isotopic composition of the sea water can be calculated by the following equation which approximates conditions in the 0–10°C range (Shackleton, 1974):

\[
T°C = 3°C - 16.9 - 4.0(δc - δw)
\]

where δc = the isotopic composition of *Uvigerina*; and δw = the isotopic composition of the sea water. Knowing the value of δw, the surface water temperature can be calculated by either the above equation or by the following equation, both of which approximate conditions in the 10–25°C range (Shackleton, 1974):

\[
T = 16.9 - 4.38(δc - δw) + 0.10(δc - δw)^2
\]
TABLE I
Calculated surface water paleotemperatures for the lower Pliocene at DSDP site 173 and the Centerville Beach section

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>°C</th>
<th>Sample No.</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-5, 53-55</td>
<td>9.6</td>
<td>CB-16</td>
<td>10.8</td>
</tr>
<tr>
<td>13-1, 47-49</td>
<td>12.4</td>
<td>CB-13</td>
<td>10.8</td>
</tr>
<tr>
<td>13-3, 50-52</td>
<td>15.4</td>
<td>CB-10</td>
<td>13.9</td>
</tr>
<tr>
<td>13-5, 48-50</td>
<td>10.5</td>
<td>CB-9</td>
<td>15.6</td>
</tr>
<tr>
<td>14-1, 49-51</td>
<td>12.7</td>
<td>CB-8</td>
<td>15.0</td>
</tr>
<tr>
<td>14-2, 100-102</td>
<td>13.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where $\delta c$ = the isotopic composition of *Globigerina* or *Neogloboquadrina*. Calculated paleotemperatures for the lower part of the record for each section show the expected temperatures for the temperate North Pacific (Table I).

The upper parts of both sections show a large influx of light water which masks the temperature effect. This influx of light water in the late Pliocene and early Pleistocene might represent a period of heavier precipitation in the continental Pacific northwest than today, or a change in drainage pattern for this region. According to Faustman (1964), molluscan faunas record cool temperatures for this period.

Studies of coiling ratios in *Neogloboquadrina pachyderma* (Erickson, 1959; Bandy, 1960) have shown this foraminiferal species to be sensitive to changes in sea water surface temperatures. Predominantly left-hand coiled (sinistral) assemblages of *N. pachyderma* are indicative of cold water conditions; right-hand coiled (dextral) assemblages indicate warm conditions. Coiling ratios of *N. pachyderma* from DSDP site 173 reveals no positive correlation with the planktonic oxygen isotope record (Fig. 4). If there was no influence from isotopically light water, then light oxygen values would be associated with dextral coiling populations and vice versa. In fact, two apparent intervals of obvious negative correlations occur at the level of 10-1 and 7-2. This indicates that great caution must be used in the interpretation of paleotemperatures that are based on the $\delta^{18}O$ record at DSDP site 173. The negative anomaly at level 8-6, 50-52 does correspond well with the warm period indicated by foraminiferal coiling ratios.

Another indicator of a strong influence of fresh water is the mean value for the carbon data (Figs. 4 and 5). Typical values for the carbon isotope ratios in *Uvigerina* for open ocean conditions are about $0^\circ/_{oo}$ to $4^\circ/_{oo}$ during the Pliocene (Shackleton and Kennett, 1975b). The mean carbon isotope ratio for *Uvigerina* from DSDP site 173 is $-2.85^\circ/_{oo}$ and that from the Centerville Beach section in $-2.36^\circ/_{oo}$. This is significantly lighter than the carbon isotope ratio for any open ocean benthonic foraminifera (Savin et al., 1975) and thus indicates a strong terrestrial component in the carbon isotope values or possibly diageneric alteration. The oxygen isotope data, however, does not support the latter possibility.

**Relationship of carbon and oxygen isotopes in foraminifera**

When the oxygen and carbon isotopic records for the planktonic foraminifera were compared, an inverse trend was observed between carbon and oxygen (Figs. 4 and 5). As the isotopic values for oxygen became lighter, carbon isotopic values became heavier, and vice versa. To test for the significance of this trend, the number of times that carbon and oxygen values varied together was calculated and compared to the expected value (50%) by use of the $\chi^2$ test (Table II). The null hypothesis would be a situation where oxygen and carbon isotope values would vary randomly so that only 50% of the time there would be an inverse correlation. It was found that at the 95% confidence level the null hypothesis can be rejected. Thus it can be reasonably assumed that in *G. bulloides* and *N. pachy-
TABLE II

$x^2$ values and confidence levels for the inverse association between oxygen and carbon isotope values in foraminifera from the two study sites

<table>
<thead>
<tr>
<th>δ¹⁸O—δ¹³C</th>
<th>Observed inverse correlation</th>
<th>Expected inverse correlation</th>
<th>d.f.</th>
<th>$x^2$</th>
<th>Confidence level of rejecting null hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>G. bulloides</em> DSDP 173</td>
<td>14</td>
<td>9.5</td>
<td>1</td>
<td>4.26</td>
<td>&gt;95%</td>
</tr>
<tr>
<td><em>N. pachyderma</em>—<em>G. bulloides</em> Centerville Beach</td>
<td>8</td>
<td>5</td>
<td>1</td>
<td>3.60</td>
<td>&gt;90%</td>
</tr>
<tr>
<td><em>N. pachyderma</em>—<em>G. bulloides</em> total</td>
<td>22</td>
<td>14.5</td>
<td>1</td>
<td>3.88</td>
<td>&gt;95%</td>
</tr>
<tr>
<td><em>Uvigerina</em> DSDP 173</td>
<td>7</td>
<td>9.5</td>
<td>1</td>
<td>1.32</td>
<td>&gt;70%</td>
</tr>
<tr>
<td><em>Uvigerina</em> Centerville Beach</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>0.29</td>
<td>&gt;30%</td>
</tr>
<tr>
<td><em>Uvigerina</em> total</td>
<td>13</td>
<td>16.5</td>
<td>1</td>
<td>0.74</td>
<td>&gt;50%</td>
</tr>
</tbody>
</table>

derma carbon and oxygen isotope values are inversely correlated. This was not the case for *Uvigerina* (Table II). The binomial test was also applied to the data and an inverse correlation was also indicated for the planktonic foraminifera at the 95% confidence level.

Previous workers have also noted an inverse correlation between oxygen and carbon isotope ratios in foraminifera. In a detailed study of DSDP site 284, west of New Zealand, Shackleton and Kennett (1975b) found a good inverse correlation in *Uvigerina* for parts of the Miocene and Pleistocene but not the Pliocene. Because the two isotope patterns were found to be related, and oxygen isotopes are in part temperature controlled, they proposed that carbon isotope values are also temperature controlled. This inverse relationship is the reverse of what would be predicted on the basis of thermodynamics (Urey, 1947). Savin et al. (1975) have also noted the same relationship in both planktonics and benthonics. They merely point out the relationship and offer no explanation.

The oxygen isotope data from this study is best explained by large changes in the δ¹⁸O content of the sea water and not necessarily by temperature changes. Hence, if carbon isotope values are temperature controlled, as proposed by Shackleton and Kennett (1975b), then the inverse relationship between δ¹⁸O and δ¹³C noted in this study would not be present. Because this relationship is found, the hypothesis of temperature control seems dubious. It is possible that the environmental conditions of the study area are unique and different from open ocean conditions and thus are responsible for this unique correlation. Perhaps the correlation is the result of fractionation during metabolism and the secretion of calcite by the foraminifera. As Savin et al. (1975, p. 1509) have stated, too little is presently known about these processes to speculate further.

Carbon isotope variation

Traditionally the results of carbon isotope analysis in foraminifera have been largely ignored because the factors controlling their distribution are poorly understood. Based on the measurements of inorganic carbon isotope ratios in ocean water, Deuser and...
Hunt (1969) found that surface waters are characterized by heavier carbon isotope values because of the selective removal of $^{12}\text{C}$ by phytoplankton during photosynthesis. Saito and Van Donk (1974) and Weiner (1975) have used this relationship to study depth stratification in foraminifera. In this study planktonic carbon isotope values were found to be heavier than benthonic values (Figs. 4 and 5). This is in agreement with the work of Deuser and Hunt (1969).

The pattern of change in carbon isotope ratios is independent of depth in the water column (Figs. 4 and 5). Though the patterns appear to be cyclic there is no known mechanism to explain the changes. The carbon isotope composition of dissolved bicarbonate in sea water is controlled by factors near the surface such as primary production rates and the equilibrium exchange between atmospheric carbon dioxide, aqueous carbon dioxide, and the bicarbonate ion (Deuser and Degens, 1967; Emrich et al., 1970). It has already been shown that carbon isotope variation is related to oxygen isotope variation thus adding to the complexity of the controlling factors. Too little is presently known to explain the controlling mechanism behind carbon isotope variation.

Summary and conclusions

(1) During the late Pliocene and early Pleistocene there was a large influx of isotopically light water at DSDP site 173 and the Centerville Beach section. Salinity may have been reduced by as much as $2-4^{\%}/\text{o}$.

(2) During the early Pliocene surface sea water temperatures ranged from 9.5 to 15.5°C.

(3) Benthonic oxygen isotope data from the Centerville Beach section records the gradual shoaling of the Humboldt Basin.

(4) Oxygen and carbon isotope variations are inversely correlated at the 95% confidence level in *Globigerina bulloides* and *Neogloboquadrina pachyderma*. This inverse correlation is probably not related to temperature changes. Presently, there is no known mechanism to explain this correlation.

(5) Planktonic carbon isotope values are heavier than benthonic values; this is in agreement with the work of Deuser and Hunt (1969).

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