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Foraminiferal trends in the Quaternary of Tanner Basin, California

ABSTRACT

Microfaunas in three piston cores from Tanner Basin, an outer basin in the continental borderland of southern California, were investigated to define climatic and oceanographic variations that occurred during late Pleistocene to Recent times. Two distinct planktonic foraminiferal faunas alternate throughout the cores, a cold-water or subarctic fauna dominated by left-coiling *G. pachyderma* and a warmer-water or transitional fauna characterized by dominantly right-coiling *G. pachyderma* associated with additional planktonic species. During the deposition of the sediments in the cores, subarctic water masses expanded into southern California at least twice, alternating with two periods of warmer water, including the present.

Variations in absolute numbers of planktonic foraminifera and radiolarians in the sediments reflect changes in rates of sedimentation. Benthonic foraminifera occur in greater abundance in association with the cooler-water planktonic foraminiferal faunas probably due to the lowering of sea level.

INTRODUCTION

Various studies of the catches of living planktonic foraminifera in plankton tows and of their empty tests in bottom sediments have been carried out by different investigators since the pioneering work of Murray (1897). These studies revealed that most planktonic foraminiferal species are restricted to certain characteristic temperature ranges and that their relative and absolute abundances change with water mass characteristics (Boltovskoy, 1959; Bradshaw, 1959; Bé, 1959, and MS. in press; Kustanowich, 1963; Bé and Hamlin, 1967; Kennett, MS. in press). Because of these relationships, planktonic foraminifera have been used extensively in the interpretation of paleoclimatology and paleo-oceanography, especially with respect to the Pleistocene (Schott, 1935; Ericson and Wollin, 1956; Emiliani, 1957; Bandy, 1959, 1960, and 1968; Emiliani, Mayeda and Selli, 1961; Ingle, 1967).

The purpose of this study is to describe the quantitative trends in the stratigraphic distribution of planktonic foraminifera in three piston cores from Tanner Basin, an outer basin in the continental borderland of southern California (text-figure 1). These trends should in turn be informative of past climatic variations and of changes in the distribution of water masses for the time interval represented in the three cores. The same three piston cores (132 samples) were used in an investigation of Holocene sedimentation in the same basin by Gorsline, Drake and Barnes (1968).

Bandy (1959, 1960) and Ericson (1959) have shown that the planktonic foraminifer, *Globigerina pachyderma* (Ehrenberg), changes its coiling direction with changes in surface-water temperature. Left-coiling (sinistral) populations of this species are at present restricted to polar and subpolar seas, whereas right-coiling (dextral) populations occur in warmer waters. This discovery is of importance in determining past climatic and oceanographic variations within the stratigraphic range of the species. Radiometric dating of basin cores off southern California has shown that the last shift in the coiling direction of *G. pachyderma*, from sinistral to dextral, occurred 11,000 to 12,000 years B.P. and marks the Pleistocene-Recent boundary (Bandy, 1960, 1967).

PREVIOUS WORK

The general characteristics of the continental borderland basins were summarized by Emery (1960) and Moore (1966). Several papers have been published concerning the distribution of benthonic and/or planktonic foraminifera in surface sediments off the coast of California (Bandy, 1953; Resig, 1958; Zalesny, 1959; Uchio, 1960; Ingle, 1967).

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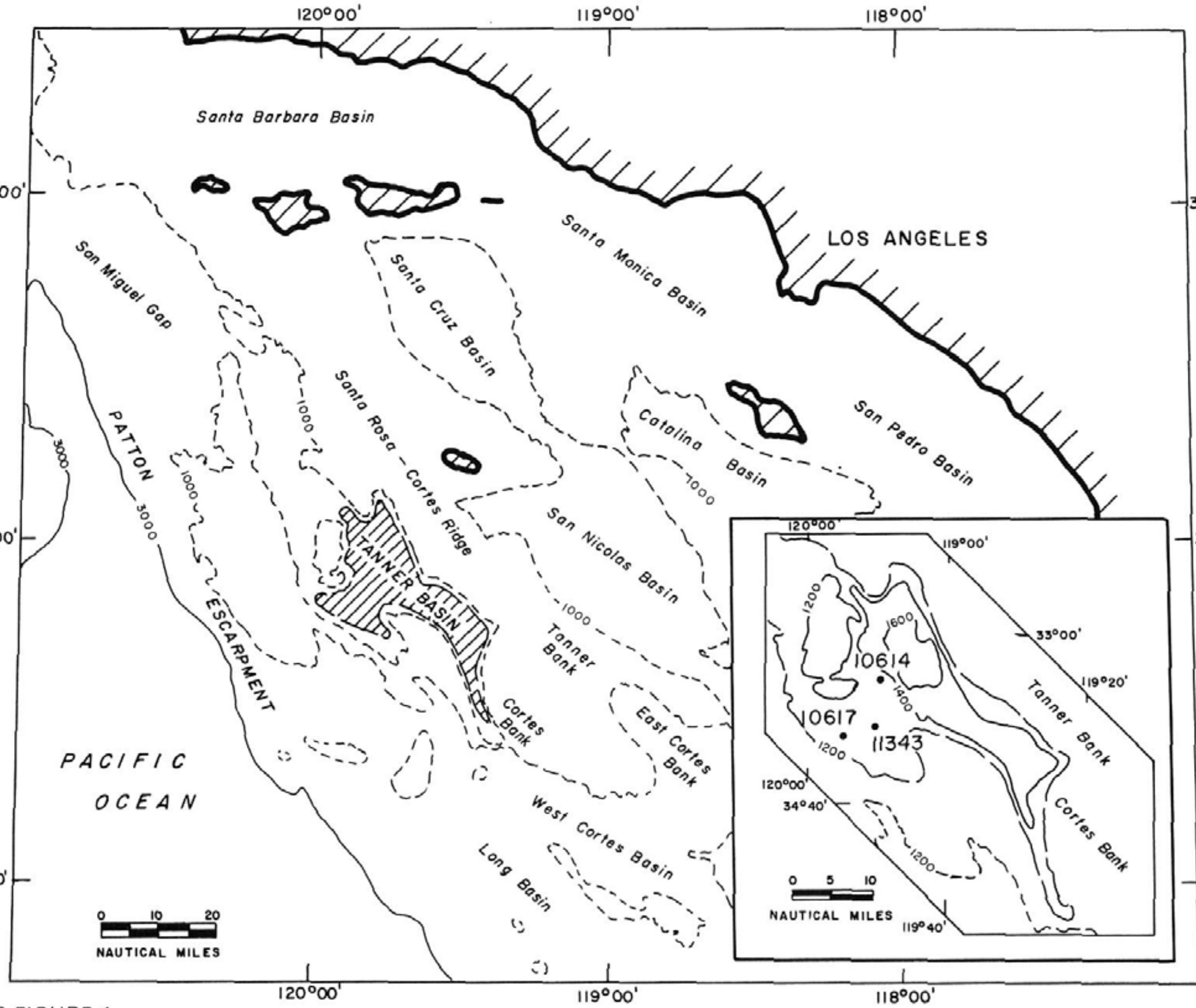


TEXT-FIGURE 1

Location of Tanner Basin in the continental borderland of southern California. The inset shows the positions where the cores from the basin were taken. All depth contours in meters.

Neogene planktonic foraminiferal zonation for southern California has been proposed by Bandy (1960, 1967) on the basis of the preferential coiling direction of *Globigerina pachyderma*. It was shown that dextral populations of this species have existed off the coast of California for the last 11,000 to 12,000 years and were preceded by sinistral populations during the Pleistocene except for a short dextral occurrence within the sinistral sequence. Dextral forms occurred in the Upper Pliocene, sinistral populations in the Middle Pliocene, and dextral populations in the Lower Pliocene. Later, Ingle (1963) and Parker (1964) noted that the sinistral form of this species also occurs within the Upper Miocene.

Gorsline, Drake and Barnes (1968) completed a detailed study of the Holocene sedimentation in Tanner Basin. They observed that carbonate sedimentation rates (mean of 7 mg./cm.^{2}/year) were constant for the last 17,000 years but that detrital (terrigenous) sedimentation rates underwent significant changes. As determined by radiocarbon dating, higher rates of terrigenous sedimentation (mean of 17 mg./cm.^{2}/year) were characteristic of the period before 7,500 B.P., and lower rates (mean of 10 mg./cm.^{2}/year) were characteristic of the last 7,500 years. This change in the detrital sedimentation rate was explained as the result of a period of lower sea level prior to 12,000 years B.P., during which a greater exposure of land area, including the Santa Rosa–Cortes–Tanner Bank system on the eastern margin of the basin, provided sources for the sediment. As sea level rose, the detrital contribution decreased during the period 12,000 to 7,500 years B.P. In the last 7,500 years, the major contribution of terrigenous material has been in the form of fine suspended sediment.

A study of the calcareous nannoplankton in seven cores from Tanner Basin was carried out by Wilcoxon (MS., in press). From his study, it is evident that a significant increase in reworked Eocene nannoplankton occurred below the 12,000 B.P. horizon in each core. This increase was also related to a change in sea level.

Distribution of living planktonic foraminifera in the North and equatorial Pacific was outlined by Bradshaw (1959). This will be discussed in more detail later.

METHODS OF STUDY

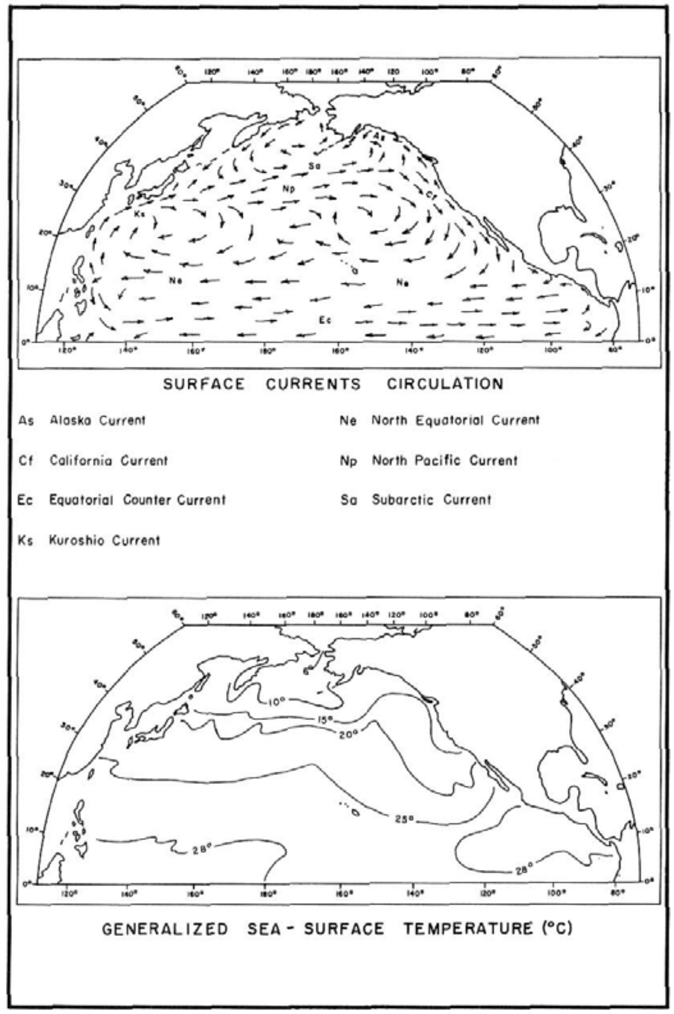
Samples 2 to 3 cm. long were taken at 10-cm. intervals in the cores for foraminiferal analysis. Since the top few centimeters of piston cores are usually missing, the tops of trigger cores were used for details of surface sediments. All samples were dried, weighed and then washed on a 250-mesh Tyler screen with 61-micron openings. Prior to counting, the samples were screened on an 88-micron screen in order to eliminate very small juvenile specimens, the positive identification of which is often difficult. A modified Otto microsplitter was used to obtain a representative split of the sample. Counts were made of an average of 750 specimens per sample in order to determine the following: 1) percentages of sinistral and dextral forms of *Globigerina pachyderma*, 2) relative and absolute abundance of planktonic foraminiferal species, 3) planktonic and benthonic foraminiferal numbers and radiolarian numbers per gram of dry sediment, and 4) absolute abundance of selected benthonic species.

After counting each sample fraction, the entire sample was studied for minor species not present in the counted fraction, since their presence or absence may be significant. A few reworked foraminifera were occasionally encountered in the samples. Reworked planktonic forms were easily identified by their abraded surface and yellowish color, and were not included in the counts.

GEOLOGY

Tanner Basin is one of the outer seaward basins of the southern California continental borderland. Structurally it is a fault-controlled feature initiated in Middle or Late Miocene time as a result of deformation of the continental margin (Emery, 1960). This basin is situated between latitudes 32°20′ and 33°10′ North and longitudes 119°20′ and 120°00′ West, and has a maximum depth of 4180 m. along the steeper eastern margin of the basin and of 1100 m. in the shallower western portion. The long axis of the basin is oriented northwest to southeast and extends for 90 km. The short axis is 40 km. across.

The Tanner and Cortes Banks form the eastern and southeastern walls of the basin. Dredge samples

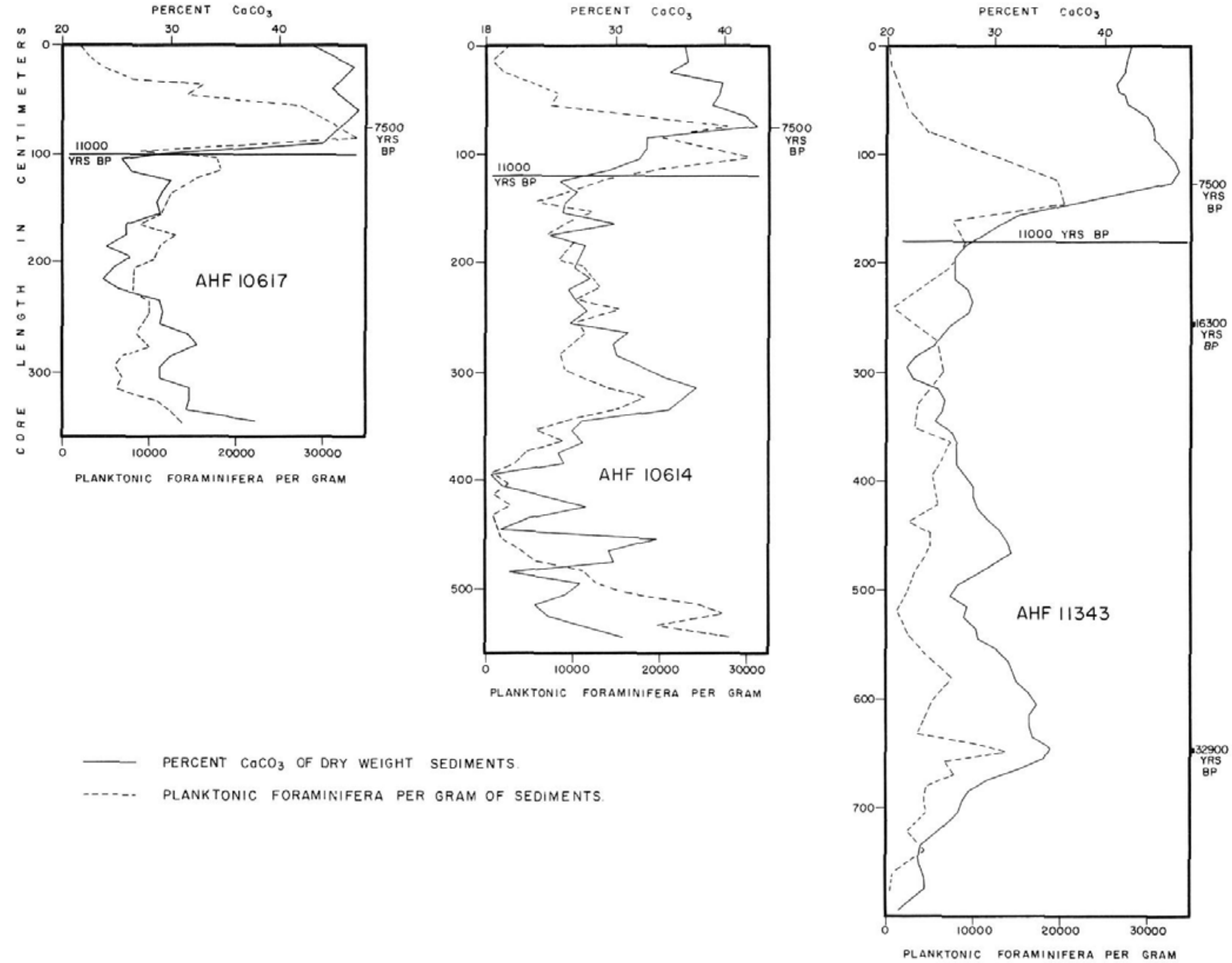


TEXT-FIGURE 2
Generalized surface current circulation and summer surface temperature (°C) in the North Pacific. Adapted from Sverdrup, Johnson and Fleming (1942) and Bradshaw (1959).

collected from these banks contained boulders of siliceous shales, metamorphic rocks and a sandy siltstone containing radiolarians of Middle Miocene and possibly Late Miocene time (Gorsline, Drake and Barnes, 1968). Basaltic rocks of the upper part of the Patton Escarpment to the west, along with northern and southern sills at depths of 1100 and 1000 m. respectively, form the other boundaries of the basin.

OCEANOGRAPHY

Along the coast of California, the southward moving waters are known as the California Current, which is a part of the great clockwise circulation of the North Pacific Ocean. Influenced by prevailing westerlies, the Subarctic Current (Aleutian Current) at high latitudes flows eastward and divides into two branches before reaching the American coast (Sverdrup, Johnson and



TEXT-FIGURE 3
Percentage of calcium carbonate (after Gorsline, Drake and Barnes, 1968) and planktonic foraminiferal numbers in cores AHF–10617, AHF–10614, and AHF–11343. The change in coiling direction of *Globigerina pachyderma* (Ehrenberg) from sinistral (Pleistocene) to dextral (Recent) is the basis for designation of the 11,000 years B.P. datum. Numbers to the right of the cores are corrected radiocarbon dates.

Fleming, 1942). The smaller branch turns northward into the Gulf of Alaska, while the larger branch turns southeastward to become the California Current, which is characterized by low temperature, low salinity, high oxygen and high phosphate. These characteristics are typical of subarctic water masses. The current becomes warmer southwards until it reaches 25°N., where it becomes part of the west-flowing North Equatorial Current (text-figure 2).

The detailed oceanography of the area off southern California has been described by Sverdrup and Fleming (1941). They reported a deep countercurrent below 200 m. along the coast, carrying large quantities of warmer and more saline Equatorial Water northward. During the fall and early winter, when the north winds are weak or absent, this current rises to the surface as the Davidson Current, flowing on the coastal side of the California Current as far north as latitude 48°.

The predominance of northwesterly winds in the spring and summer causes an offshore transport of surface water and is an important factor in the development of coastal upwelling (Reid, Roden and Wyllie, 1958), which produces complex oceanographic conditions in certain areas. Upwelling returns nutrients to the euphotic zone and thus increases surface plankton productivity.

SEDIMENTOLOGY

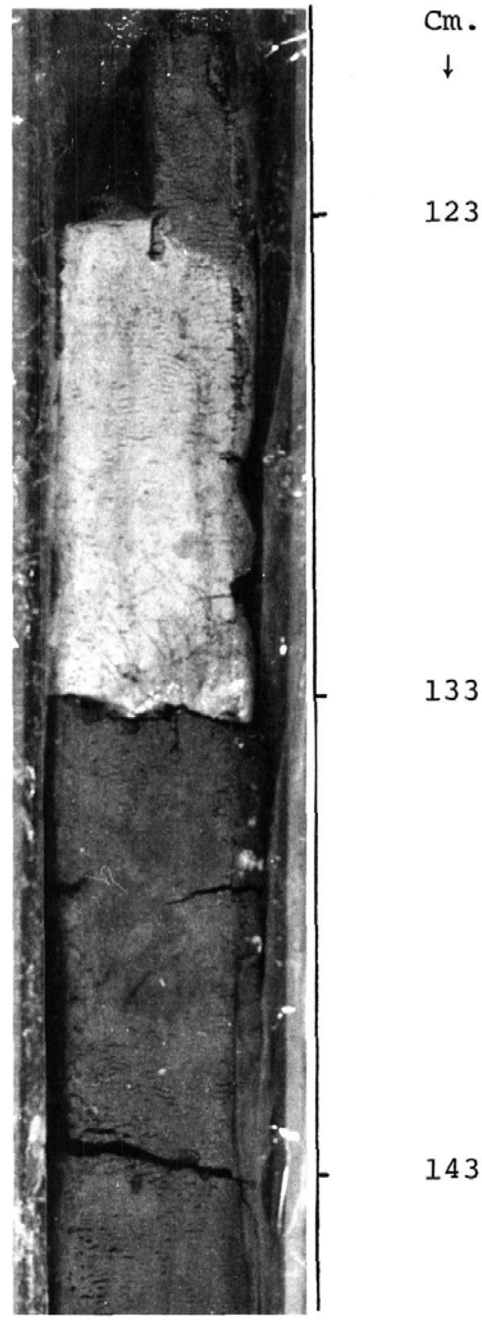
The most complete sedimentological data on the Tanner Basin have been presented by Gorsline, Drake and Barnes (1968), and most of the data provided below are from their work. Inasmuch as the present study is concerned primarily with the stratigraphic distribution of planktonic foraminifera in the cores, a detailed discussion of sedimentation is not presented here.

Surface sediments throughout most of the area consist of light olive-gray clayey silt with a uniform mean grain size of about 8 microns in the central part of the basin and coarser sediments with mean grain diameters of 16 to 32 microns on the surrounding slopes. Mean diameters throughout the cores, exclusive of the turbidites, are a relatively constant 6–10 microns and show no significant pattern. The coarse fraction, consisting of particles >61 microns, is composed mainly of foraminiferal tests (90–95%), Radiolaria, sponge spicules and a small amount of terrestrially derived sand. Turbidites, though present elsewhere in the area, were absent in all three of the cores which were studied. However, the 380–430 cm. section of Core AHF–10614 may be the result of a turbidity current, inasmuch as most of the foraminifera were crushed and discolored.

The carbonate content of surface sediment is high, but values vary downward in each core. As shown in text-figure 3, carbonate content is relatively high in the upper part of each core, diminishing to a minimum at about 11,000–12,000 years B.P., when the last shift in coiling direction of *G. pachyderma* occurred. At the base of the layer of uniformly high carbonate content in cores from different parts of the basin, radiocarbon dates give an age of about 7,500 years B.P. Below the Pleistocene-Recent boundary, values are low and almost constant, except for a restricted peak which in core AHF–11343 coincides with a carbon-14 date of 32,900 years B.P.

Superimposed on the carbonate curves are the curves of total planktonic foraminiferal numbers. A general correlation exists between these two parameters, except for the uppermost parts of the cores, indicating that tests of planktonic foraminifera are the main factor controlling the carbonate content of the sediment. The differences between carbonate content and foraminiferal numbers at the tops of the three cores are due to reworked foraminifera, which are not included in the counts, and to the increase in abundance of indigenous calcareous nannoplankton in the tops of the cores (Wilcoxon, personal communication).

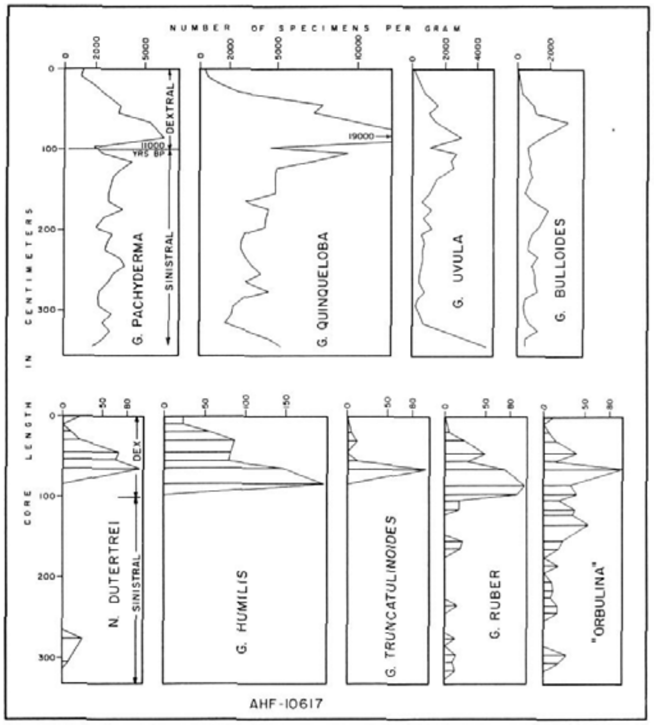
The segments of the cores with high carbonate content are generally far removed from sources of terrigenous sediments and are almost completely composed of tests of planktonic foraminifera. This is reflected in the light color of the sediments as shown in the upper part of core AHF–11343 (text-figure 4). The boundary between the light and dark colors in this core segment coincides with the drop in the carbonate curve.



TEXT-FIGURE 4
Part of the upper portion of core AHF–11343. The light color in the upper segment of the core is caused by very high numbers of planktonic foraminifera.

PLANKTONIC FORAMINIFERA

Two assemblages of planktonic foraminifera were recognized in the cores of Tanner Basin, one a cold-



TEXT-FIGURE 5
Absolute abundances of the most important planktonic foraminiferal species in core AHF–10617. The zones of dextral and sinistral *Globigerina pachyderma* (Ehrenberg) are shown alongside the frequency curves of *G. pachyderma* and *Neogloboquadrina dutertrei* (d'Orbigny).

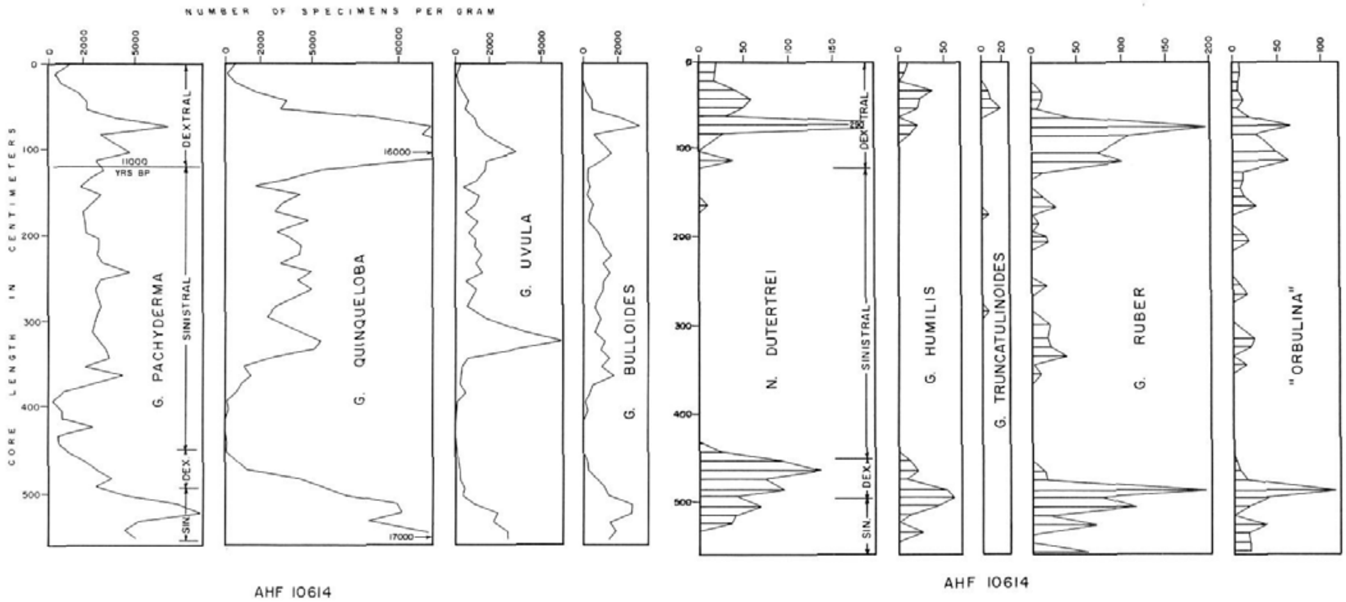
water or subarctic fauna characterized by dominantly left-coiling *Globigerina pachyderma*, the other a warmer-water or transitional (temperate) fauna characterized by dominantly right-coiling *G. pachyderma* and by *Neogloboquadrina dutertrei, Globigerinoides ruber, Globorotalia truncatulinoides, Globorotalia inflata, Globigerinita humilis* and *Globigerinella siphonifera*. Associated with both groups are *Globigerina quinqueloba, Globigerina bulloides, Globigerinita uvula, Globigerinita glutinata, Globigerinita iota, Globorotalia scitula, Globoquadrina hexagona,* and "*Orbulina*" chambers. Figures of all these species have been presented and their taxonomies discussed by Parker (1962) and Bradshaw (1959).

Text-figures 5–7 show the absolute abundance of the most important planktonic foraminiferal species in cores AHF–10617, AHF–10614 and AHF–11343 respectively. Zones of dextral and sinistral *G. pachyderma* are superimposed on the frequency curves of *G. pachyderma* and *N. dutertrei*. The change from sinistral to dextral in the upper portion of the cores occurred at 11,000 B.P., the Pleistocene-Recent boundary. A second zone of dextral *G. pachyderma* appears in the lower portion of two cores. This zone is absent in core AHF–10617 because it lies below the depth of penetration of this core. Between these two zones of dextral *G. pachyderma*, sinistral forms of *G. pachyderma* are dominant. However, a minor decrease in the percentage of sinistral forms occurs within the sequence as shown in the coiling ratio curves of *G. pachyderma* (text-figure 8). This decrease occurs in most cores within the California borderland basins (Bandy, 1960) at a level dated by the radiocarbon method at about 17,000 B.P. Similar alternating dextral and sinistral coiling changes in *G. pachyderma* were reported by Jenkins (1967) to occur also in the Pleistocene of New Zealand.

Globigerina pachyderma (Ehrenberg) is one of the most abundant species, and throughout most of the length of each core it constitutes 30 to 40% of the total planktonic foraminiferal assemblage. However, a significant increase in frequency to about 70% occurs at a horizon in the cores immediately above the second zone of *G. pachyderma* with dextral coiling (text-figure 8).

The number of specimens of *G. pachyderma* per gram of dry sediment (absolute abundance) also shows significant trends. The absolute abundance of this species in the segments above the Pleistocene-Recent boundary is much higher (average 5,000 specimens) than in those below this boundary (average 2,500) except in core AHF–10614. In this core, a horizon of high absolute abundance (8,000 specimens) occurs at the base of the core. This horizon is absent from core AHF–11343, and core AHF–10617 did not penetrate to this depth.

Globigerina quinqueloba Natland is another common species, constituting 30 to 40% of the total planktonic foraminiferal assemblage throughout most of the length of the cores. Although its relative abundance varies, its frequency is higher in the zones of right-coiling *G. pachyderma*. Trends in absolute abundance of *G. quinqueloba* show a well-developed pattern. High numbers of specimens (13,000–19,000 per gram) occur in the Recent core segments, while numbers are greatly reduced (2,000–3,000 per gram) below the Pleistocene-Recent boundary. In core AHF–10614, there is a large increase in the numbers of *G. quinqueloba* occurring in the lowest segments of the core, immediately below the second zone of dextral *G. pachyderma*. A similar but much smaller increase occurs in core AHF–11343, but in this core the increase coincides with the coiling shift. The difference in magnitude between the two increases may be caused by higher sedimentation rates in the vicinity of core AHF–11343, while the difference in the stratigraphic horizon of occurrence may be due to reworking by organisms. It should be noticed that this latter difference represents less than 15–20 cm. of core length.



TEXT-FIGURE 6
Absolute abundances of the most important planktonic foraminiferal species in core AHF–10614. The zones of dextral and sinistral *Globigerina pachyderma* (Ehrenberg) are shown alongside the frequency curves of *G. pachyderma* and *Neogloboquadrina dutertrei* (d'Orbigny).

Coiling ratios of *G. quinqueloba* are variable, and dextral and sinistral varieties occur in approximately equal proportions throughout the cores.

Distribution of *Globigerinita uvula* (Ehrenberg) throughout the cores varies, but on the average this species constitutes about 10% of the total population. Its greatest abundance (40%) was recorded in core AHF–11343 within the lower zone of dextral *G. pachyderma*.

Globigerina bulloides d'Orbigny usually comprises less than 10% of the fauna throughout the cores. Forms similar to *Globigerina falconensis* Blow were encountered randomly in the samples. However, due to morphological intergrading between the two species, *G. falconensis* was included in counts of *G. bulloides*.

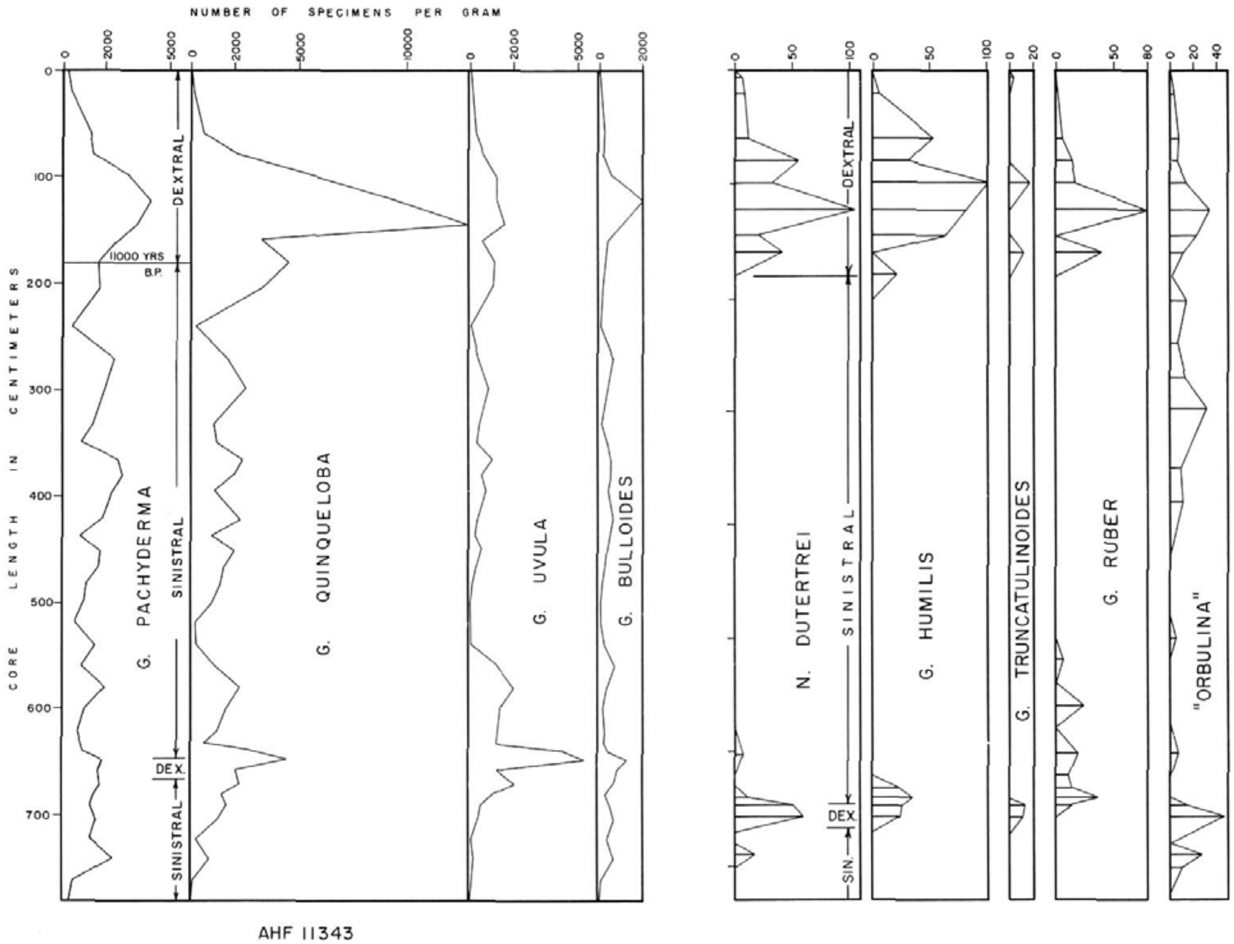
No apparent trends were found in the coiling direction of *G. bulloides*. Throughout the cores, populations have coiling ratios ranging between 60% and 80% sinistral. The same trends in the number of specimens per gram which were noted above for *G. pachyderma* and *G. quinqueloba* also apply to *G. bulloides*.

Neogloboquadrina dutertrei (d'Orbigny) is an uncommon species, never constituting more than 6% of the population. Although it does usually occur within the zones of right-coiling *G. pachyderma* (text-figures 5–7), this form also is occasionally present within the left-coiling *G. pachyderma* sequence, where the left-coiling ratio is 60–70%. It is of interest to note that this species is usually restricted to the zones of right-coiling *G. pachyderma* and that its greatest abundance (100–270 specimens per gram) occurs above the Pleistocene-Recent boundary. Coiling direction is 99–100% dextral, and none of the specimens has umbilical teeth.

The name *Neogloboquadrina dutertrei* has been tentatively considered to be synonymous with *Globigerina eggeri* Rhumbler, *Globigerina subcretacea* Lomnicki and *Globoquadrina dutertrei* (d'Orbigny) of authors. There appear to be morphological similarities between this species and right-coiling *G. pachyderma*, and, as Bé (MS. in press) noted, it is possible that a continuous gradient may exist from sinistrally coiling to dextrally coiling populations of *G. pachyderma* and that the latter may grade into *Neogloboquadrina dutertrei*. However, more evidence is needed before conclusions can be drawn. The generic assignment follows the usage of Bandy, Frerichs and Vincent (1967).

Globigerinita humilis (Brady) and *Globorotalia truncatulinoides* (d'Orbigny) are rare (< 1%) and show the same trends as *N. dutertrei*. Both species occur within the zones of right-coiling *G. pachyderma* and usually have their maximum abundance above the Pleistocene-Recent boundary. There are too few specimens of *G. truncatulinoides* to give significant coiling direction ratios.

Globigerinoides ruber (d'Orbigny) and *"Orbulina"* chambers are rare (< 1%) but persistent throughout the length of the cores. Their highest frequencies (100–



TEXT-FIGURE 7
Absolute abundances of the most important planktonic foraminiferal species in core AHF–11343. The zones of dextral and sinistral *Globigerina pachyderma* (Ehrenberg) are shown alongside the frequency curves of *G. pachyderma* and *Neogloboquadrina dutertrei* (d'Orbigny).

200 specimens per gram) occur within the zones of right-coiling *G. pachyderma* (text-figures 5–7).

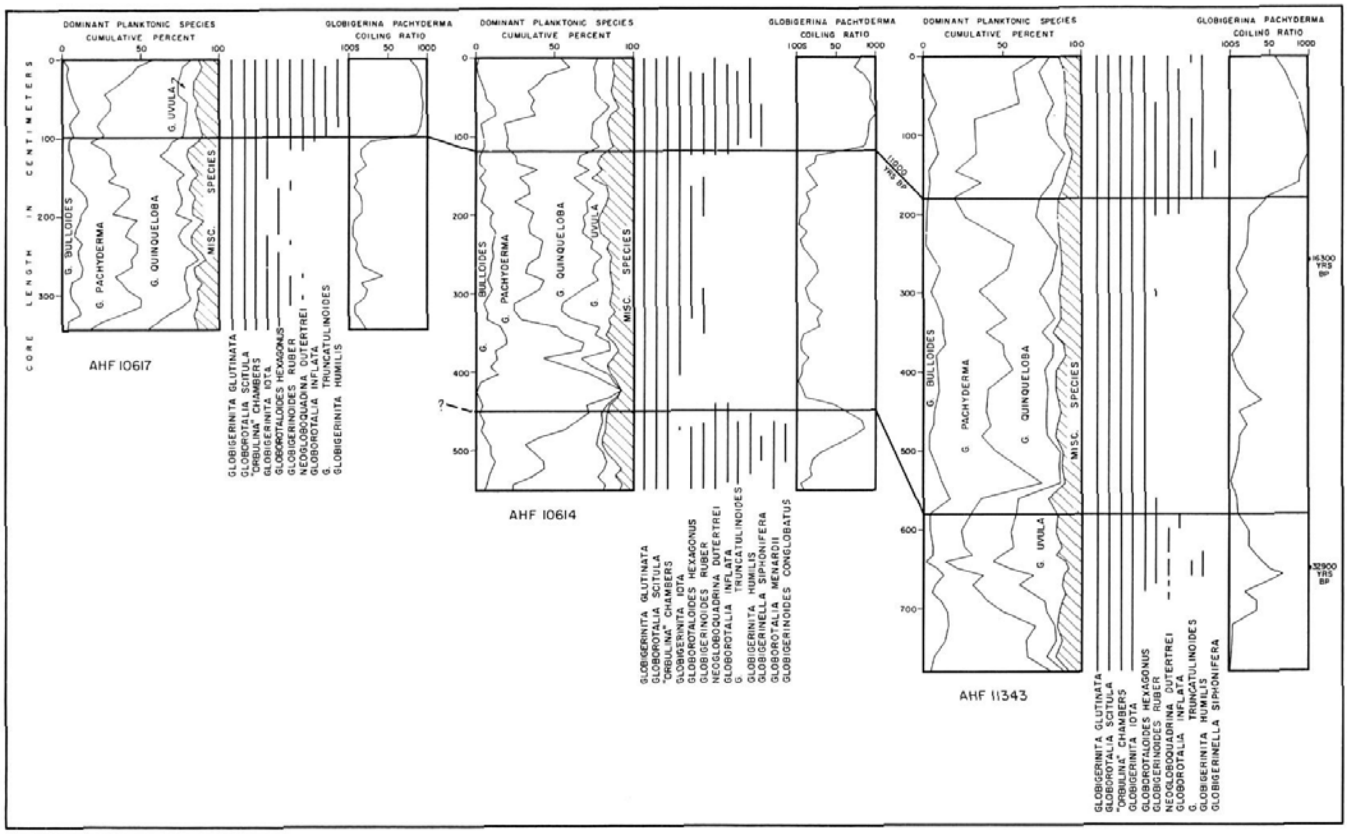
Globorotalia inflata (d'Orbigny) is either rare (<1%) or absent in most parts of the cores. As shown in text-figure 8, this species occurs within the zones of right-coiling *G. pachyderma* and is usually absent within the zones of the left-coiling form. Although there were too few specimens to give significant coiling ratios, all of the specimens observed were coiled sinistrally.

Globigerinita glutinata (Egger) has a relatively uniform and continuous distribution throughout the length of the cores, with frequencies ranging from 2 to 5% of the total planktonic foraminifera. Although no measurements were taken, specimens of this species associated with the left-coiling form of *G. pachyderma* appear to be larger than those associated with dextral *G. pachyderma*.

Globorotalia scitula (Brady) and *Globigerinita iota* Parker are found throughout the cores, but their individual frequencies are seldom more than 1% of the total populations. A few specimens resembling *Globorotalia hirsuta* (d'Orbigny) were also noticed, but, due to uncertainty of identification, they were included in counts of *G. scitula*.

Globorotaloides hexagonus (Natland) is a very rare species, and its frequency never exceeds more than 1% of the total population. It occurs in most parts of the cores, but it is more abundant within the zones of right-coiling *G. pachyderma*.

Globigerinella siphonifera (d'Orbigny), *Globigerinoides conglobatus* (Brady) and *Globorotalia menardii* (d'Orbigny) are extremely rare. Only a few specimens of these species were observed, all within the zones of right-coiling *G. pachyderma*.



TEXT-FIGURE 8
Cumulative frequencies of dominant planktonic foraminiferal species, coiling ratio changes of *Globigerina pachyderma* (Ehrenberg) and stratigraphic ranges of the less dominant planktonic foraminiferal species within cores AHF–10617, AHF–10614, and AHF–11343. The upper solid line represents the Pleistocene-Recent boundary. The lower solid line marks the correlation of the Pleistocene segments in cores AHF–10614 and AHF–11343.

PALEO-OCEANOGRAPHIC VARIATIONS

Any attempt to explain changes in past climatic and oceanographic conditions by the evidence obtained from planktonic foraminifera requires a preliminary examination of distribution trends in modern assemblages and relationships between such assemblages and present oceanographic conditions.

The distribution of living planktonic foraminifera in the North and equatorial Pacific was described by Bradshaw (1959), who divided the species present into three general groups: a northern cold-water or subarctic fauna, a transitional fauna, and a southern or warm-water fauna.

The cold-water or subarctic fauna is characterized by *Globigerina pachyderma, G. quinqueloba, G. bulloides, Globigerinita uvula,* (*Globigerinoides* cf. *G. minuta* of Bradshaw) and *G. glutinata,* species which are generally found north of the Subarctic Convergence at 40°–45°N. latitude. When the convergence is not distinct, the 15° surface summer isotherm (text-figure 2) marks the southern boundary of this fauna.

The transitional fauna consists of a mixture of the subarctic fauna and the southern warm-water fauna. The most common species are *Globigerina quinqueloba, G. bulloides,* large specimens of *G. eggeri* (*Neogloboquadrina dutertrei* of this paper), *Globigerinoides ruber* and "*Orbulina universa*". Northern and southern limits of this fauna are marked by the 15° and 20°C summer isotherms respectively.

The warm-water fauna is divided into two subassemblages. The first or Central Water subassemblage is characterized by *Globorotalia inflata* and *G. truncatulinoides,* which occur in the Central Water masses (as defined by Bradshaw, 1959) of the North Pacific. These species are not present in the surface water of the equatorial region. The second or Equatorial Water subassemblage is characterized by species which are confined to water of the most tropical character, and which include *Globigerina conglomerata, Globorotalia tumida, Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens.*

Associated with both subassemblages are *Globorotalia hirsuta, G. scitula, G. menardii, Globigerinoides conglobatus, G. ruber, G. sacculifera, Globorotaloides hexagonus, Globigerinita glutinata, Globigerinella siphonifera* (*G. aequilateralis* of Bradshaw), *Candeina nitida, Hastigerina pelagica* and *Hastigerinella rhumbleri*. The 20 °C summer isotherm marks the northern and also presumably the southern extent of the warm-water fauna in the Pacific. According to Bradshaw (1959), the distribution of most species shows a general agreement with latitude, but an even better correlation exists with sea-surface temperatures.

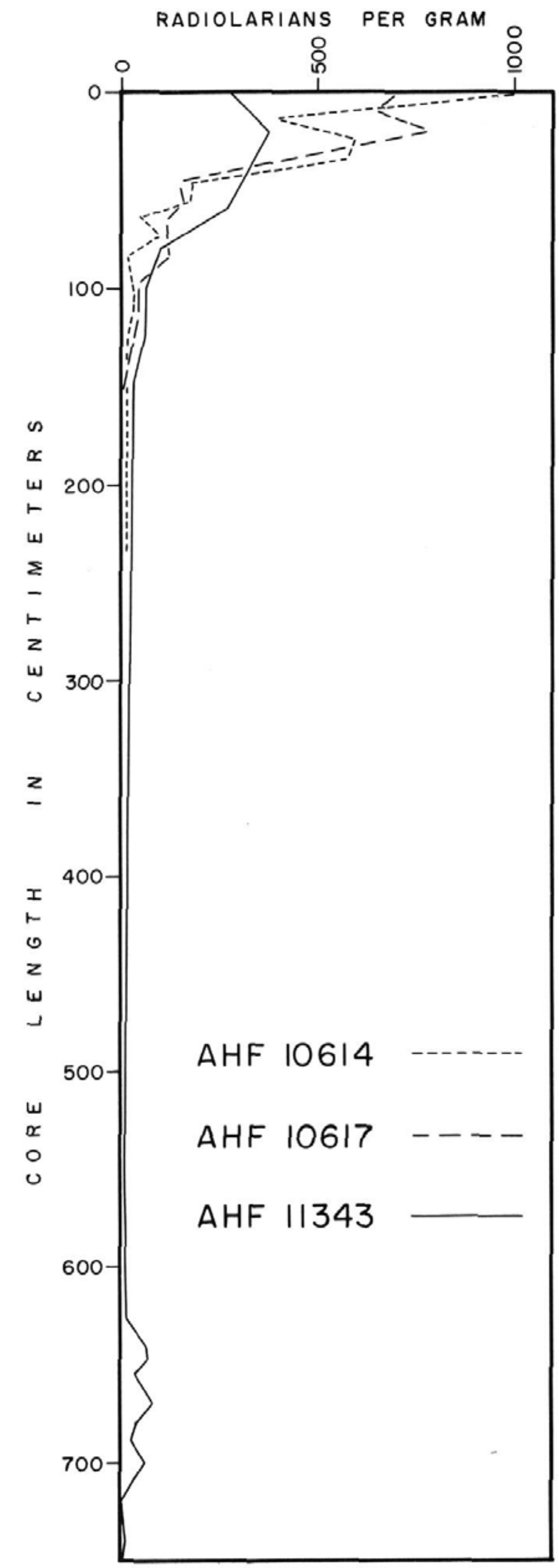
The change in the coiling direction of *G. pachyderma* from dominantly sinistral to dominantly dextral populations today occurs at about 45 °N. latitude for the eastern North Pacific (Ingle, 1967), so that right-coiling *G. pachyderma* is largely confined to the transitional zone. Furthermore, this change in coiling direction coincides with the 15 °C. summer isotherm (Enbysk, personal communication). It should be remembered that the boundary between these sinistral and dextral populations is gradational and that currents, divergences and convergences play an important role in shaping the species distribution. For example, the California Current carries the dextrally coiled specimens of the transitional fauna southward to about 20°–25 °N. latitude.

Text-figure 8 shows the cumulative frequencies of common planktonic foraminiferal species, the coiling ratio changes of *G. pachyderma*, and the stratigraphic ranges of the less common planktonic foraminiferal species within cores AHF–10617, AHF–10614 and AHF–11343. *Globigerina pachyderma, G. quinqueloba, G. bulloides* and *Globigerinita uvula* are the dominant species throughout the cores. However, the upper zone of each of the three cores is characterized by a transitional fauna, which includes dominantly dextral *Globigerina pachyderma* and small amounts of *Neogloboquadrina dutertrei, Globigerinita humilis, Globigerinoides ruber, Globorotalia truncatulinoides* and *G. inflata*. There is a change from this fauna to the subarctic fauna of Bradshaw, characterized by colder-water forms such as left-coiling *G. pachyderma*, below the Pleistocene-Recent boundary. This change is best illustrated by the coiling direction of *G. pachyderma*, which down each core abruptly switches from dextral to sinistral with the disappearance of the temperate fauna.

Below the Pleistocene–Recent boundary, left-coiling *Globigerina pachyderma* with its associated fauna remains dominant until it reaches its maximum frequency, averaging 65% of the total population, and then changes its coiling direction again at the top of the second zone of dextral *G pachyderma* in cores AHF–10614 and AHF–11343. Temperate species, including *Neogloboquadrina dutertrei, Globorotalia truncatulinoides, Globigerinita humilis, Globigerinoides ruber* and *Globorotalia inflata*, reappear in small numbers after their absence during the predominance of the subarctic fauna. Furthermore, some warm-water species, such as *Globorotalia menardii, Globigerinoides conglobatus* and *Globigerinella siphonifera*, were observed occasionally associated with the temperate fauna. However, these species are rare, and their presence may not be significant. Below this temperature zone *G. pachyderma* again changes coiling direction from dextral to sinistral. Simultaneously, the temperate fauna disappears and *G. pachyderma* increases in abundance.

According to Bradshaw (1959), the region off the shore of southern California is occupied today by a transitional planktonic foraminiferal assemblage, separating a dominantly subarctic fauna to the north from a warm-temperate fauna to the south. The observed alternations of transitional and subarctic planktonic foraminiferal faunas within the Tanner Basin cores are attributed to the result of northward and southward migration of subarctic and transitional water masses and their respective planktonic faunas. The invasion of the southern California region by the subarctic fauna in response to significant cooling during the Pleistocene has been previously shown by Bandy (1967). During glacial periods, the subarctic fauna, characterized by a sinistrally coiling population of *G. pachyderma*, extended farther south to the waters off the southern California region. Conversely, during periods of glacial retreat, the transitional fauna occurred off southern California as it does today. Fowler and Duncan (1967) examined long deep-sea sediment cores taken off Oregon and found that *G. pachyderma* is dominantly sinistral throughout the entire length of the cores, representing the last 50,000–70,000 years. At no horizon in the cores did they find a transitional fauna, and thus transitional water masses with their characteristic fauna never extended as far north as the coast of Oregon during the time of deposition of the sediment of the cores.

The cores from Tanner Basin show that there were at least two periods of subarctic surface-water temperatures during Late Pleistocene time. The absence in the Tanner Basin cores of the warm-water fauna of Bradshaw (1959), which is characteristic of temperatures above 20 °C., shows that surface-water temperatures were at no time during deposition of the cores warmer than those of the present day. Furthermore, the absence of an arctic planktonic fauna, composed entirely of sinistral *G. pachyderma*, implies that the surface water temperature was not at any time less than 6 °C. Mean surface-water temperatures have thus ranged between



TEXT-FIGURE 9
Abundance of radiolarians in specimens per gram of sediment.

6° and 20°C. during the glacial advances and retreats which are represented in the Tanner Basin cores. These values agree reasonably well with the paleotemperature curve obtained from oxygen isotope ratios in planktonic foraminiferal tests from other cores of the same basin (Gorsline and Drake, in preparation).

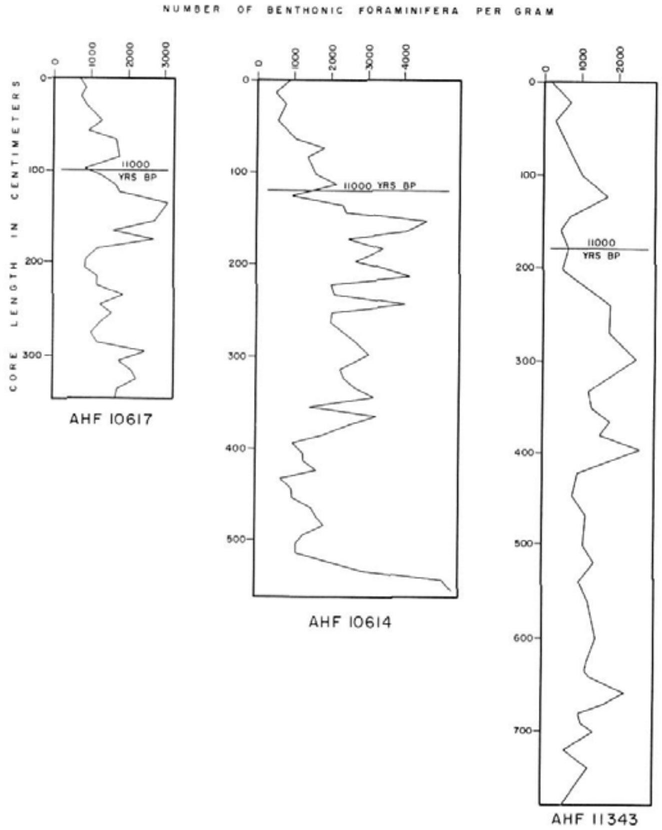
DISCUSSION

Comparisons of rates of sedimentation and trends in absolute abundance of planktonic foraminiferal species in the cores of Tanner Basin reveal that certain general relationships exist between these two parameters. As noted earlier, for most species high numbers of specimens per gram of sediment occur within the Recent portions of the cores, with lower numbers occurring below the Pleistocene-Recent boundary. These low numbers remain fairly constant except in the second zone of dextral *G. pachyderma*, where the number of specimens per gram increases, although usually not to the high figures of the Recent parts of the cores.

Radiolarians showed the same trends as the planktonic foraminifera, occurring at the high rate of 300–1,000 specimens per gram in the tops of the cores and diminishing to 10–20 specimens per gram below the Pleistocene-Recent boundary (text-figure 9). This trend has been previously reported for the major offshore basins by Bandy (1967). A minor increase in the number of radiolarians per gram was also noticed in core AHF–11343 within the second zone of dextral *G. pachyderma*.

A considerable change in the number of specimens of planktonic faunas in an undisturbed stratigraphic sequence is a result either of change in the rate of sedimentation or of change in the rate of plankton productivity. From studies of sedimentation in Tanner Basin, Gorsline (1967) concluded that the carbonate sedimentation rate was nearly constant during the time represented by deposition of the cores, but that the terrigenous sedimentation rate has varied significantly. Gorsline also reported a converse relationship between the detrital sedimentation rate and the carbonate content of the sediments. The rate of detrital contribution was low during the high peak in the carbonate curve at 32,900 B.P., then increased until it reached a maximum at about 12,000 years ago, decreasing again to a minimum at 7,500 years B.P. and remaining low to the present. Furthermore, Uchupi and Emery (1963), in a study of deep-sea cores from the continental slope and rise off southern California, stated that sedimentation rates were eight times higher during the Late Pleistocene than in the Recent.

Thus, it seems reasonable to assume that the absolute abundance of planktonic foraminifera and radiolarians in the sediments is controlled to a large extent by sedimentation rate. The high number of specimens per gram in the upper portion of each core and within the second zone of dextral *G. pachyderma* is due to the lower sedimentation rate, whereas the low number of specimens in those Pleistocene segments associated with sinistral *G. pachyderma* is caused by a considerably higher rate of sedimentation. However, it should be remembered that the only occurrences of certain rare temperate species, such as *Neogloboquadrina dutertrei, Globorotalia truncatulinoides, Globigerinita humilis, Globorotalia inflata* and *Globigerinella siphonifera*, are within the zones of dextral *G. pachyderma*, whereas these species are absent from the zones of sinistral *G. pachyderma*. This can not be due to dilution by the sediments, but is the result of changes in water mass boundaries. Similar changes in planktonic foraminifera during the Late Pleistocene and Recent have been reported by Caralp (1967) in a core from the Bay of Biscay. The core was taken in 1800 m. of water near the base of the continental slope at 45°09′N. latitude and 3°23′W. longitude. The same temperate fauna which occurs in the Tanner Basin cores was found in this core, where, as in Tanner Basin, it is restricted to the zones of right-coiling *G. pachyderma* and is absent within the zones of left-coiling *G. pachyderma*.



TEXT-FIGURE 10
Abundance of benthonic foraminifera in specimens per gram.

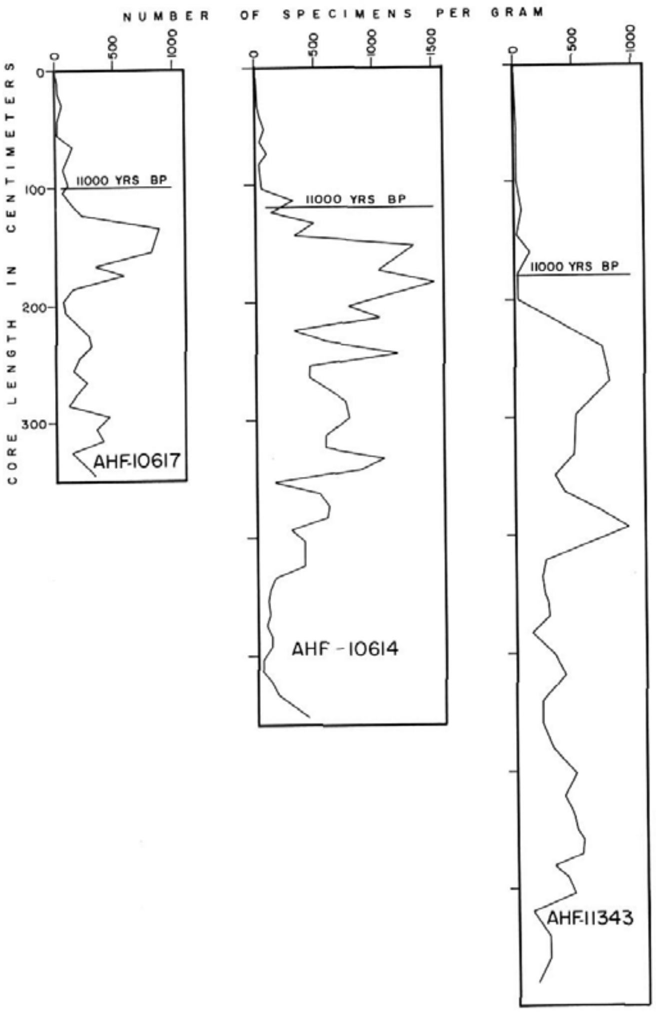
Although it seems likely that the rate of sedimentation is the main factor controlling species abundances, there are a number of exceptions. The top 20 cm. in all three cores are characterized by very low numbers of planktonic foraminifera, indicating the effects of factors other than sedimentation rates. Trends in the number of total benthonic foraminifera unexpectedly show a parallel relationship with the sedimentation rate instead of the normal converse relationship, as will be discussed later.

Changes in the terrigenous sedimentation rate for the last 12,000 years in Tanner Basin have been correlated by Gorsline, Drake and Barnes (1968) with the curves of sea-level variation summarized by Curray (1961), and by Shepard and Curray (1967). These two authors have shown that prior to 30,000 B.P. the sea level began to rise from a low level, reaching —20±4 m. from the present level at about 30,000 B.P. Sea level then dropped to —125 m. in approximately 18,000 to 20,000 B.P. in response to major ice advances, then rose to —15 m. at 7,000 B.P. and reached present levels about 3,000 years ago. It appears that the second zone of dextral *G. pachyderma*, which is characterized by a relatively low detrital sedimentation rate, high carbonate content and a temperate fauna, can also be correlated with the high stand of sea level at the 30,000 B.P. interstadial. Support for this concept comes from the carbon-14 date of 32,900 years at the 640–650 cm. interval in core AHF–11343. Thus, in the Tanner Basin cores, the two periods characterized by a subarctic foraminiferal fauna are synchronous with two periods of glacial advance, high detrital sedimentation, and low stands of sea level, whereas the two warm phases, characterized by a temperate foraminiferal fauna, are synchronous with waning glaciation, lower detrital sedimentation, and high stands of sea level.

BENTHONIC FORAMINIFERA

Although the major investigation was concerned with planktonic species, some observations were made on the benthonic foraminifera. Benthonic populations are present throughout the cores, usually comprising less than 20% of the total foraminiferal population. Among the most significant species are:

Uvigerina peregrina Cushman
Uvigerina hispida Schwager
Bulimina striata mexicana Cushman
Bulimina subacuminata Cushman and R. E. Stewart
Cassidulina delicata Cushman
Cassidulina californica Cushman and Hughes
Cassidulina limbata Cushman and Hughes
Epistominella pacifica smithi (R. E. and K. C. Stewart)
Valvulineria araucana (d'Orbigny)



TEXT-FIGURE 11
Abundance of *Uvigerina peregrina* Cushman in specimens per gram.

Gyroidina altiformis R. E. and K. C. Stewart
Hoeglundina elegans (d'Orbigny)
Bolivina sp.

Trends in the total number of benthonic foraminifera per gram (text-figure 10) showed parallel relationships with the sedimentation rate and converse relationships with the total number of planktonic foraminifera per gram. High numbers of specimens per gram occur below the Pleistocene-Recent boundary, whereas low numbers occur in the Recent parts of the cores. This is best reflected in the number of specimens per gram of *Uvigerina peregrina* Cushman (text-figure 11), which comprises 30 to 40% of the total benthonic foraminifera below the Pleistocene-Recent boundary.

Uvigerina peregrina has an upper limit of occurrence of 100±50 m. in most oceanic areas (Bandy and Chierici, 1966), and its lower depth boundary varies from place to place. Off southern California, this species ranges down through the upper and middle bathyal zones, but its highest frequencies usually occur above 1,000 m.

The three cores which were studied in this investigation were taken at about 1,200 m. in depth of water. A possible explanation for the low number of specimens of *U. peregrina* per gram in the Recent part of the cores might be the high stand of sea level which eliminated the depths of greatest abundance of this species in the local area during this time. However, this is speculation, and other factors may have been involved.

Random occurrences of species which have been displaced from shallow depths were noticed throughout the cores. These displaced specimens are much more abundant in the Pleistocene segment of each core than in the Recent segment. Other displaced specimens occur and are often difficult to identify as having been displaced. This difficulty sometimes results in higher figures for populations than the true figures. Finally, changes in environmental factors, such as available nutrients, may also account for the high totals of benthonic foraminifera within the Pleistocene segments of the cores.

CONCLUSIONS

1) Two distinct assemblages of planktonic foraminifera are recognized in piston cores from Tanner Basin, a cold-water or subarctic fauna characterized by dominantly left-coiling *Globigerina pachyderma* and a warmer water or transitional fauna characterized by dominantly right-coiling *G. pachyderma* associated with *Neogloboquadrina dutertrei, Globigerinoides ruber, Globorotalia inflata, G. truncatulinoides, Globigerinita humilis* and *Globigerinella siphonifera*.

2) Alternations of these subarctic and transitional foraminiferal assemblages within the length of the cores reflect a series of oscillations of subarctic and transitional water masses in response to worldwide climatic changes. During glacial periods the subarctic fauna occurred off southern California, whereas the transitional fauna prevailed during periods of glacial retreat. During Late Pleistocene to Recent time there were at least two periods characterized by subarctic water temperatures, and two periods of temperate surface-water temperatures off southern California.

3) The planktonic foraminiferal faunas throughout the cores indicate that surface-water temperatures were never warmer than those of the present, during the periods of time represented by the cores. Mean surface-water temperatures ranged between 6°C. and 20°C. during this period.

4) Absolute abundances of planktonic foraminifera and radiolarians in the sediments are controlled mainly by the sedimentation rate. However, other factors, such as productivity variation, are known to be important in some cases.

5) Planktonic foraminiferal faunal variations throughout the cores correlate with eustatic changes of sea level summarized by Curray (1961), and Shepard and Curray (1967). The two periods characterized by subarctic faunas are synchronous with low stands of sea level. The two warm periods, characterized by temperate faunas, are synchronous with high stands of sea level.

6) Benthonic foraminiferal numbers are generally much higher within the section of cores characterized by cooler-water planktonic assemblages. High benthonic numbers are probably the result of the shallowing of facies due to eustatic lowering of sea level, increasing the standing crops of benthonic forms.

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