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Distribution of foraminifera in the Russian River estuary, northern California

ABSTRACT

Benthonic foraminifera were obtained from samples representing the upper few centimeters of the substratum throughout the estuarine and offshore regions of the Russian River, Sonoma County, northern California. Cluster analysis in the Q-mode separated the samples into three large, areally recognizable groups: an offshore group containing species typically marine; a group from the main channel of the estuary containing marine species carried into the estuary; a group from a minor, shallow channel that is dominated by a few species. In the upper reaches of the estuary, only thecamoebians were present. No indigenous or characteristically estuarine foraminiferal fauna has developed within the Russian River estuary. Estuarine samples taken during the winter did not contain foraminifera, due to high river discharge. The salt-water wedge is attenuated, producing a fresh-water environment throughout the estuary. The higher rates of discharge move the river bed seaward as tractive and suspended sediments, which prevents a resident fauna from becoming established.

INTRODUCTION

There are a variety of estuary types, resulting chiefly from the relationship of duration of runoff and degree of circulation with the ocean. Typically, estuaries have a persistent zone of mixing sea and fresh water. However, some have low runoff with intrusion of sea water upstream where evaporation increases salinity, while others have persistent high runoff which prevents much mixing; still others have an alternation of high and low runoff. These different conditions result in differing distributional patterns of foraminifera in the various estuaries (Lipps and Erskian, 1969a). The purpose of this study is to describe the foraminiferal faunas found in a seasonally high-discharge estuary, namely, the Russian River in northern California, and to compare them with those found in other estuaries.

The Russian River

The Russian River rises in northern California north of Ukiah, Mendocino County, flows south into Sonoma County, and turns west to the Pacific about 60 miles north of San Francisco. It drains an area of 1486 square miles in the California Coast Range, and enters the Pacific Ocean at Jenner (text-figures 1, 2).

The lower course of the Russian River is a drowned river valley, eroded during an early Pleistocene stand of sea level and now filled with alluvium (Higgins, 1952). Modern sediments of the Russian River include alluvium in the form of flood plain, alluvial fan, and colluvial deposits in valley areas from the mouth of the river upstream into the middle course. Stream channel deposits occur along the active channels of the river and consist of unconsolidated, poorly sorted clay, silt, sand, and gravel (California State Department of Water Resources, 1964).

The river bed throughout the lower course is below mean sea level (text-figure 3). The river bed near Bridgehaven, $2\frac{1}{4}$ miles upstream, is approximately 9 feet below mean sea level, increasing in depth near Duncan Mills, 5 miles upstream from the mouth of the river. There is a steep rise in the bed near Duncan Mills from 14 feet below mean sea level to 2 feet above mean sea level (text-figure 3). Channel gradient and water depth are influenced by tides as far as $8\frac{1}{2}$ miles upstream near the town of Monte Rio, and changes in the level of the river produced by ocean tides occur as far upstream as Duncan Mills (text-figure 2). The diurnal tidal range in this section of the northern California outer coast is approximately 6 feet (U. S. Coast and Geodetic Survey, 1969). The charac-

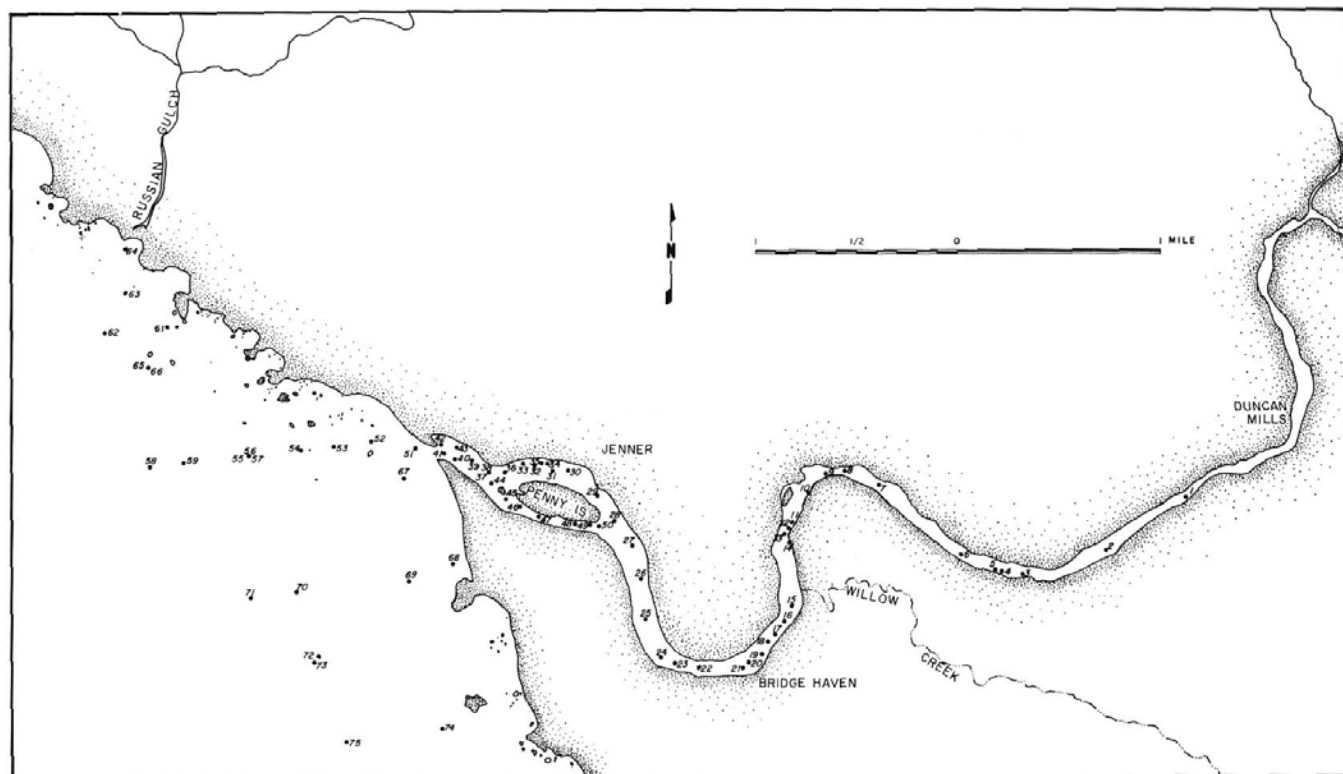


TEXT-FIGURE 1

Map of central and northern California showing location of Russian River and principal cities nearby.

teristics of the Russian River are those of the normal or positive-type estuary (Emery and Stevenson, 1957) in which salinities are reduced upstream (at least in summer) as a result of river discharge and mixing.

The mean annual precipitation in the Russian River watershed is about 44 inches, occurring principally as rainfall. The rainy season extends from October through May; rainfall is light in June (< 1 inch), and July, August, and September are virtually dry. The pattern of runoff and stream flow closely follow the seasonal distribution of precipitation as a result of high topographic relief in the area and shallow soils underlain by rather impervious bedrock within the watershed, which lead to low infiltration rates and periodic damaging floods. Ninety percent of the total annual runoff occurs between December and March when it exceeds 200,000 acre feet of water (text-figure 4). Mean annual natural runoff from the river is about 1,510,100 acre feet, as recorded at Guerneville, 11 miles upstream. Maximum instantaneous flow during a 50-year period from 1910 to 1960 was 90,000 cubic feet per second (cfs), recorded in December, 1955. Minimum flow during these same years was 57 cfs, recorded in July, 1950 (California State Department of Water Resources, 1964). Mean discharge during July, 1968 was 151 cfs (U.S. Geological Survey, 1968a). During January, 1969 mean discharge increased to 18,270 cfs (U.S. Geological Survey, 1969), over two orders of magnitude greater than summer discharge. Water depth during winter flood stages at Bridgehaven



TEXT-FIGURE 2

Map showing collecting stations in the Russian River and offshore, Sonoma County, California.

commonly has exceeded depths of 20 to 30 feet (text-figure 3).

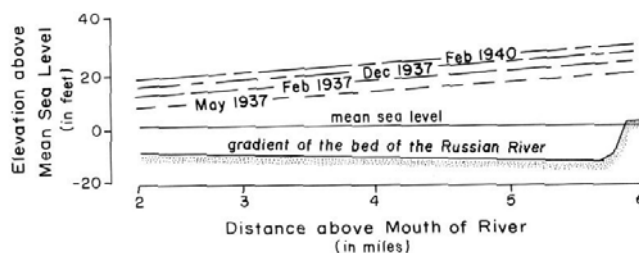
Estuarine sediments alternate between fluvial, coarse-grained types during winter floods and an increase in marine sands transported in by tidal action during the summer. Discharge of suspended sediments from October, 1967 to September, 1968 totaled 1,147,000 tons (U.S. Geological Survey, 1968b). During the winter months of January and February, over 1,001,000 tons (87% of the yearly total) of suspended sediment was discharged (text-figure 5). The summer period from July to September accounted for less than 0.05% of the annual suspended sediment discharge. The pattern of annual discharge results in extensive scouring, reworking, and redepositing of fluvial material during the winter periods of high discharge. Wastewater discharge, either with or without primary treatment, occurs from towns, cities, and numerous apple processing plants situated within the drainage basin.

METHODS AND MATERIALS

Samples of foraminifera were collected on four field trips during the summer of 1968 and the winter of 1969. Seventy-five stations, 50 estuarine and 25 offshore (text-figure 2), were established during the summer. Sampling began June 21, downstream from Duncan Mills, Station 1, and continued to Jenner, Station 33, following the main river channel. Stations 34 to 50 were collected two days later in the shallow southern part of the estuary. Offshore samples were collected in August along a series of transects out from the shoreline near the river. Winter samples were collected in January, 1969 at Stations 29, 39, 40, and 47 only. Dangerous currents and flooding of the river during the winter prevented collecting at many stations.

Sediment and water samples were collected with the use of an underway bottom sampler called "Scoopfish" (G. M. Manufacturing and Instrument Corporation). Selection was random but biased toward deeper water and areas of finer sediments.

Samples averaged 45 cubic cm. of sediment and represented approximately the top few centimeters of the substratum. Sediment and interstitial fauna were preserved in a 10% buffered formalin solution and stained with rose bengal, as suggested by Walton (1952) for the determination of living foraminifera. Since we found this method to be unreliable and misleading, as have others (Martin and Steinker, 1973), we were compelled to consider the entire assemblage in our analyses. Samples were wet-screened through a



TEXT-FIGURE 3

Longitudinal section of a portion of Russian River estuary showing gradient of river bed and level of four flood stages (from unpublished data, U.S. Army Corps of Engineers, 1945).

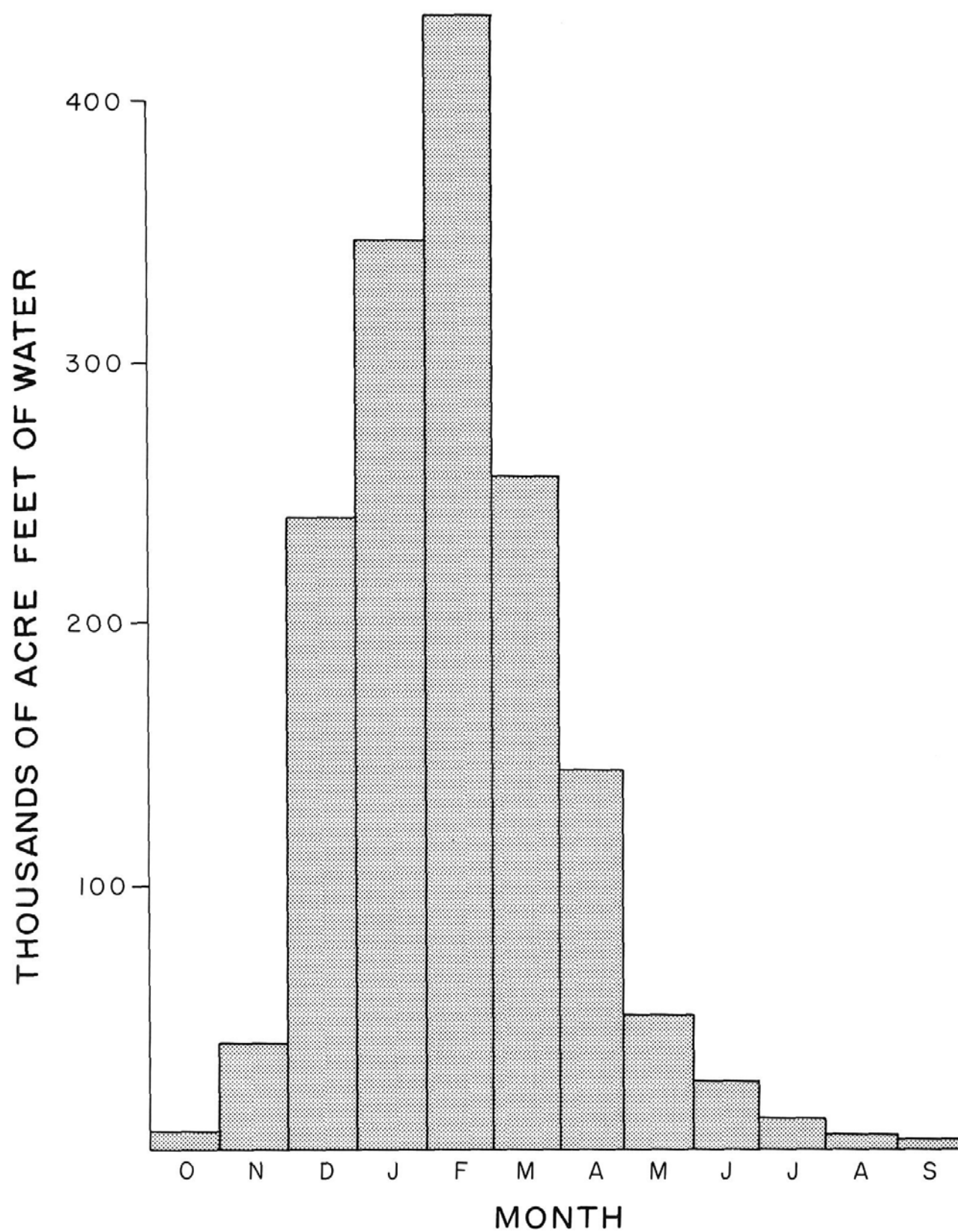
200- μ mesh sieve to remove very fine sand and clays. Larger sediments and foraminifera retained in the sieve were then dried. Foraminifera were separated from the sediments by flotation and differential settling in a solution of carbon tetrachloride. Foraminifera and thecamoebians in the supernate were decanted, dried, and mounted on slides for counting and identification. Residues were also searched for foraminifera to ensure that all species had been counted.

Salinity, depth, pH, and temperature were measured at as many stations as possible. Salinity was based on refractive index using an American Optics Refractometer, calibrated with a known NaCl solution. In the estuary, depth was measured directly from soundings with a weighted line; offshore, depth was measured with a Bendix Depth Finder. A portable Beckman model N pH meter was used for the measurement of pH. Bottom and surface temperature measurements were made using a Tri-R telethermometer with a thermistor mounted on a 200-foot cable.

Particle size of sediments from 22 stations were analyzed. These stations were chosen along the major and minor channels at intervals of 0.1 mile from Station 23 and from the stations in the transects offshore of the mouth of the river. The mechanical sedimentary analysis of Krumbein and Pettijohn (1938) were followed. Screens used ranged from -3.0 to 4.0 phi units. The sieve series consisted of a set of whole phi intervals to 0.0 phi, then half phi intervals beginning 0.25 phi. Each sediment sample was placed in the upper sieve, and the series was vibrated for 10 minutes on a mechanical sieve shaker. Contents of each sieve fraction were weighed.

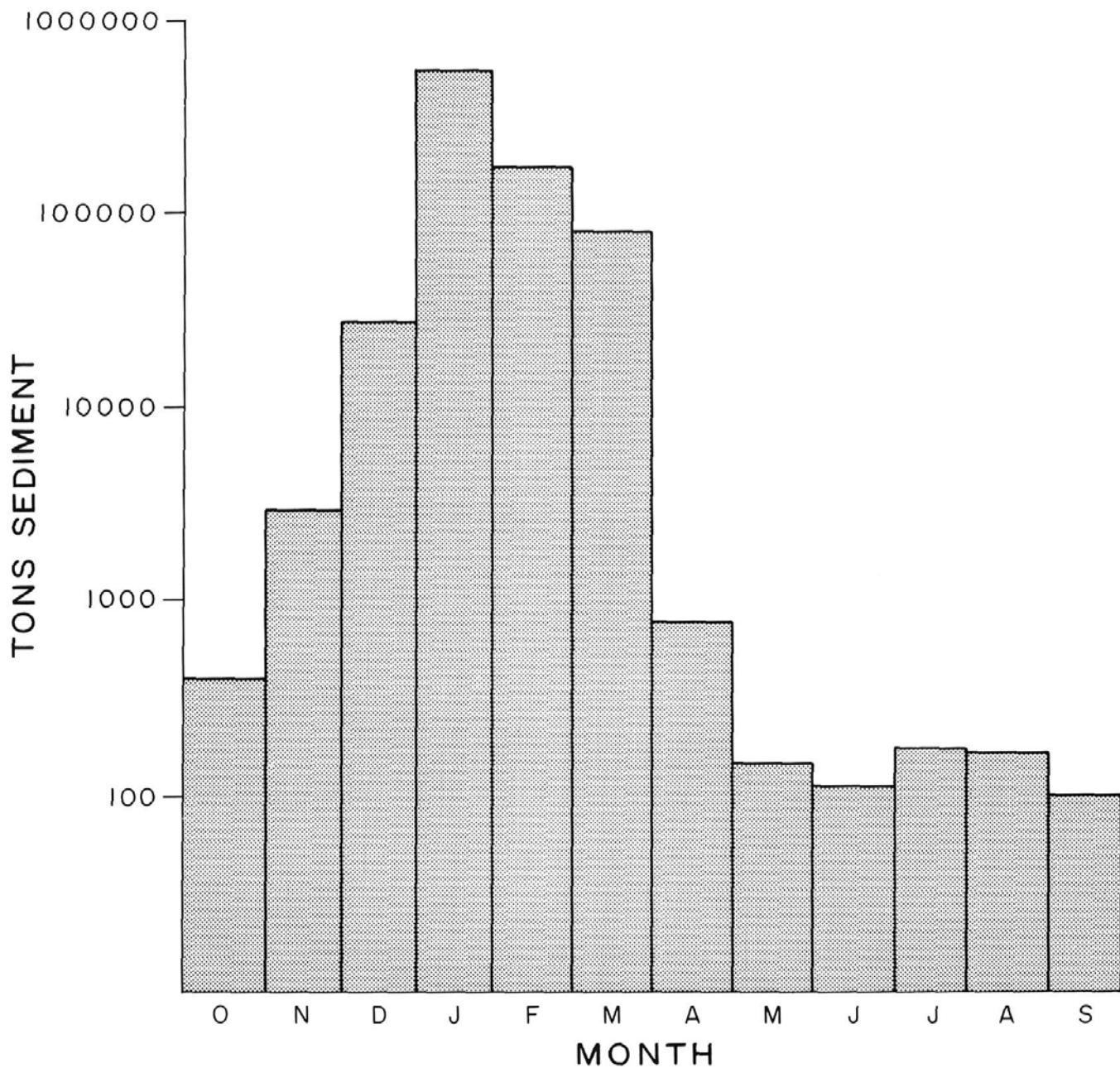
RESULTS

During the summer, the physical characters of the Russian River grade downstream with the mixing of fresh and marine water masses. Although the warmer fresh water of the river gradually mixes with the incur-



TEXT-FIGURE 4

Average monthly discharge of water in Russian River for years 1910–1960, as measured at Guerneville, 11 miles upstream of river mouth (after California State Department of Water Resources, 1964).



TEXT-FIGURE 5

Monthly discharge of suspended sediment from Russian River, from October, 1967 to September, 1968 (after U.S. Geological Survey, 1968b).

sion of cooler sea water, both water masses are distinct in the estuary. Surface and bottom water layers remain thermally distinct throughout the entire study area, except in shallow areas where the water temperature is constant from top to bottom. In headward estuarine stations the bottom water temperature varies with water depth, ranging from 13 to 22°C.

(table 1). Estuarine stations near the river mouth are cooler, ranging in temperature from 11 to 14°C. Stations in the minor channel have an anomalously high mean temperature of 15.8°C. because of their shallow depth. Offshore of the river mouth, stations showed little variation in temperature during the study, ranging from 10 to 13°C.

TABLE 1

Summary of environmental parameters measured in summer, 1968 for the chief foraminiferal biofacies as determined by cluster analysis in the Russian River and the offshore area. The values change radically from season to season depending on runoff and flood conditions.

	River	Estuary Channels Major	Minor	Offshore Marine
Temperature (°C.)				
range	13–22	11–14	12–22	10–13
mean	16.18	11.41	15.83	11.1
st dv	2.32	3.29	4.26	0.59
pH				
range	6.2–8.7	6.6–8.2	6.8–7.2	6.7–8.0
mean	7.56	7.21	7.03	7.5
st dv	0.69	0.58	0.15	0.50
Salinity (‰)				
range	FW-31	23–29	16–27	25–34
mean	20.8	26.0	22.33	32.17
st dv	12.45	2.45	5.68	3.38
Depth (meters)				
range	0.3–7.0	2.0–3.5	0.2–1.5	1.0–34.0
mean	2.05	2.40	0.80	13.4
st dv	1.83	1.13	0.57	9.11

Salinity increases downstream for both surface and bottom water masses. At Stations 1 through 7, the surface water was entirely fresh. Salinity of the surface water in the estuary increased to 15‰ near the river mouth. Bottom water salinity approaching concentrations of sea water occurred at many places along the course because of the incursion and entrapment of denser saline water in deep holes. Toward the mouth of the river, bottom salinity in the estuary approached that of sea water. With few local exceptions, bottom salinities downstream of Station 20 are greater than 23‰. This sort of dilution is characteristic of a positive-type estuary. Salinity of water offshore was near constant, at 34‰, with only slight variation of surface and bottom water. Bottom water was of a higher salinity, whereas the surface was diluted slightly due to river discharge. The lower mean salinity (table 1) is due to the lower salinity water of the estuarine stations included with the offshore stations and used in the calculation of the mean.

Water at the bottom of the estuary had nearly neutral pH values. Variation in pH was considerable throughout the estuary, ranging from 6.2 to 8.7 (table 1). Water samples taken offshore are slightly more alkaline than in the estuary, with pH values ranging from 7.6 to 8.0. Stations north of the river mouth have a lower pH, whereas those south have a high pH; this is perhaps a result of currents carrying river discharge along the shore.

The characteristics of the water are radically different during the high-discharge winter months and the low-discharge summer months. Average monthly water temperature at Guerneville (U.S. Dept. of Interior,

1968a) ranged from 7 to 8°C. Surface sea water temperature during the same period recorded at Bodega Bay, about 10 miles south of the Russian River, ranged from 10 to 11°C. As high discharge of fresh water prevents the salt water incursion from penetrating into the estuary, salinities along the entire course are of normal fresh water. Offshore, the lighter density, sediment laden discharge moves for miles south of the river mouth, diluting the surface salinities.

Sediment samples [of approximately 45 cubic cm. each], from 22 stations, estuarine and offshore, were analyzed. From each weight fraction, phi median, phi deviation, and phi skewness were calculated. Results of the sediment analysis are summarized (table 2).

Sediments along the Russian River and offshore are variable due to local topography and dynamics of flow. In river stations headward of Station 26, phi median diameter, Md_ϕ , is in the pebble (-3.0ϕ) to coarse sand (0.95ϕ) range. These stations are poorly sorted (phi deviation > 1) and tend to be skewed toward smaller diameter sediments. At stations in the major channel of the estuary, phi median diameter ranges from granular (0.2ϕ) to very fine sand (3.15ϕ). Most of the stations are poorly sorted with phi deviations greater than 1. Station 26 is well sorted with O_ϕ below 0.5ϕ . Distribution of sediment size is approximately symmetrical with phi skewness approaching zero. In the minor channels of the estuary, Md_ϕ ranges from fine sand (2.77ϕ) to very fine, but poorly sorted

TABLE 2
Sediment size distributions.

Biofacies	Station	Md_ϕ	M_ϕ	O_ϕ	α_ϕ	β_ϕ
River	23	0.00	0.21	1.31	0.16	0.41
	24	0.95	-0.45	2.15	0.23	-0.02
	25	-3.00	-1.67	1.32	1.00	0.79
Estuary Major channel	26	1.21	1.33	0.43	0.27	3.04
	27	0.92	0.45	1.20	-0.39	0.50
	28	0.85	0.77	1.02	-0.07	0.67
	29	1.00	0.97	0.65	-0.04	0.86
	32	1.10	1.25	0.80	0.18	0.87
	37	3.15	3.11	0.71	-0.05	1.09
	39	1.95	1.39	1.29	0.43	0.98
	41	-0.20	-0.45	1.06	0.61	0.50
Minor channel	45	3.20	2.41	1.49	0.53	0.44
	47	3.30	3.28	0.61	-0.03	0.96
	49	2.77	-2.20	0.80	-6.21	0.56
Offshore	30	1.35	1.05	1.05	-0.28	0.82
	51	1.84	1.71	0.71	-0.18	0.73
	52	1.47	1.43	0.51	-0.07	0.70
	53	1.75	0.90	1.45	-0.58	0.65
	55	0.07	-0.14	0.76	-0.27	0.34
	58	1.48	1.53	0.56	0.08	1.17
	59	1.27	1.18	0.67	-0.13	0.76
	60	3.20	3.31	0.49	0.22	0.57

Phi median diameter, Md_ϕ ; phi mean diameter, M_ϕ ; phi deviation, O_ϕ ; phi skewness, α_ϕ , and phi kurtosis, β_ϕ ; calculated from mechanical sieve analysis. Biofacies determined by cluster analysis.

sand (3.3 ϕ). Sediments in the offshore stations range from coarse sand (0.07 ϕ) to very fine sand (3.2 ϕ); though poorly sorted, they tend to be skewed toward larger sediment diameter. Station 60, furthest offshore, consists of very fine sand, well sorted and slightly skewed toward smaller sediments.

DISTRIBUTION OF FORAMINIFERA AND THECAMOEBIANS

A total of 29 species (table 3) represented by 12,040 individual foraminifera and thecamoebians were collected along the course of the Russian River and offshore. Of this total, 4325 individuals were collected in the estuary (Stations 26 to 50) and 7715 offshore (Stations 51 to 75). Upstream of Station 26, no foraminifera were found, but 36 specimens of thecamoebians of the genera *Centropyxis* and *Diffugia* were present. In the estuary, foraminifera were common in the summer collections but absent in the winter ones.

Eleven species of foraminifera were on inspection found to be restricted to the offshore habitat. Their occurrence was rare, often contributing less than 1% of the total number of individuals in each sample. Species restricted to the offshore areas include:

Bolivina compacta Sidebottom
Cassidulina limbata Cushman and Hughes
Elphidium crispum (Linné)
Entosolenia costata Williamson
Fissurina lucida (Williamson)
Glabratella ornatissima (Cushman)
Lagena striata (d'Orbigny)
Nonionella basispinata (Cushman and Meyer)
N. stella Cushman and Meyer
Quinqueloculina akneriana d'Orbigny
Spirillina vivipara Ehrenberg

One species of foraminifera, *Textularia schencki* Cushman and Valentine, and two genera of thecamoebians, *Centropyxis* and *Diffugia*, were the only ones that were restricted to the estuary. *Textularia schencki* is a rare species, occurring only twice throughout the study area. *Centropyxis* and *Diffugia* were found throughout the estuary and in many upstream samples as well. *Centropyxis* is more abundant in upstream stations, whereas *Diffugia* becomes more common in the stations near the mouth of the river.

Fifteen of the 29 species collected occurred in both the estuarine and offshore areas and comprised the majority of the individuals found at each station. They include:

Buccella tenerrima (Bandy)
Buliminella elegantissima (d'Orbigny)
Cibicides fletcheri Galloway and Wissler

C. lobatulus (Walker and Jacob)
Criboelphidium translucens (Natland)
C. tumidum Natland
Cribrononion frigidus (Cushman)
Elphidiella hannai (Cushman and Grant)
Glabratella ornatissima (Cushman)
Haplophragmoides columbiense Cushman
Miliammina fusca (Brady)
Quinqueloculina vulgaris d'Orbigny
Rosalina globularis d'Orbigny
Rotorbinella campanulata (Galloway and Wissler)
Trochammina pacifica Cushman

Species occurring in both the offshore and estuarine stations are found in three major groupings in the estuary. The first group or assemblage of species occurs in Stations 36 to 45, near the mouth of the estuary. This group includes:

Buccella tenerrima
Cibicides lobatulus
Criboelphidium translucens
Glabratella ornatissima
Rotorbinella campanulata

These species have a greater percentage of occurrence in the offshore than in the estuarine stations. Of this group only *Glabratella ornatissima* occurs in a greater percentage in the estuary than in the offshore stations.

The second group occurs in the major channel of the estuary up to Station 30. Species of this group do not occur along the minor channel. This group includes:

Cibicides fletcheri
Criboelphidium tumidum
Haplophragmoides columbiense
Rosalina globularis
Trochammina pacifica

Percentage of occurrence of *Cibicides fletcheri* is greatest within the estuary. The other four species of this group have a higher percentage of occurrence in the offshore stations. Most of the species in this group occur more abundantly from Stations 36 to 45, while only single individuals were found in Stations 30 to 36.

A third species complex more characteristic of the estuary includes:

Cribrononion frigidus
Elphidiella hannai
Miliammina fusca
Quinqueloculina vulgaris

These species were found throughout the estuary and offshore. *Elphidiella hannai* and *Quinqueloculina vulgaris* occur in larger percentages in samples taken

TABLE 3

Numerical occurrences of benthic foraminifera.
Stations in which samples were not obtained are omitted.

Species	Station																			
	1	2	3	19	24	26	27	29	30	31	32	33	34	35	36	37	38	39	40	42
<i>Centropyxis</i> sp.	20	5	8	1				2	1			2					9			
<i>Diffugia</i> sp.										1		1		1			1			
<i>Angulodiscorbis charlottensis</i>																				
<i>Bolivina compacta</i>																				
<i>Buccella tenerrima</i>																	1		36	7
<i>Buliminella elegantissima</i>													2							8
<i>Cassidulina limbata</i>																				
<i>Cibicides fletcheri</i>									1						5	4	2	3	12	4
<i>C. lobatulus</i>																	1		24	1
<i>Cribrorhaphidium translucens</i>										1					1	1		3	1	4
<i>C. tumidum</i>										1					1	2		1	38	2
<i>Cribronion frigidus</i>						113	252	45	42	820	24	129	363	137	71	241	97	28	43	34
<i>Elphidiella hanna</i>							1		1	6	4	1	2	5	1	3	2	4	48	5
<i>Elphidium crispum</i>																				24
<i>Entosolenia costata</i>																				8
<i>Fissurina lucida</i>																				
<i>Glauertella ornatisima</i>																3	3	5	36	6
<i>Haplophragmoides columbiense</i>										1		1					2		1	29
<i>Lagena striata</i>																				1
<i>Miliammina fusca</i>						1			1				1				1			3
<i>Nonionella basispinata</i>																				
<i>N. stella</i>																				
<i>Quinqueloculina akneriana</i>																				
<i>Q. vulgaris</i>						1	1								1			9		4
<i>Rosalina globularis</i>										3					2	6	2	2	9	2
<i>Rotorbinaella campanulata</i>																	1		9	1
<i>Spirillina vivipara</i>																				3
<i>Textularia schencki</i>											1						1			
<i>Trochammina pacifica</i>									1	2							1			6

near the mouth of the river. The most characteristic species of the estuary, *Cribronion frigidus* and *Miliammina fusca*, occur in a high percentage at all the estuarine stations. *Miliammina fusca* is the dominant species, making up 96% of the sample in the shallow muds at Station 50. *Cribronion frigidus* was present in all stations where foraminifera were found. This species occurred abundantly from Stations 26 to 75. Its contribution to the estuarine stations accounts for nearly 82% of the individuals. Specimens from Stations 26 to 31 are greater than 90% *C. frigidus*.

These biofacies were confirmed using statistical techniques. For our test, we chose a cluster analysis technique (recurrent group analysis), developed by Fager (1957; see also Fager and McGowan, 1963). Each sample is compared with every other sample on the basis of presence or absence of species. The similarity of stations is expressed by an unweighted coefficient (Fager, 1957) calculated by the formula:

$$FC \text{ (Fager's Coefficient)} = \frac{C}{\sqrt{ab}} - \frac{1}{2\sqrt{\max(a, b)}}$$

where C is the number of species in common with sample A and sample B, a and b are the number of species in sample A and B respectively, and max (a, b) is the larger number of a or b. The samples are then grouped into clusters (Valentine and Peddichord, 1967;

Mello and Buzas, 1968; Buzas, 1969b). The similarity between groups of samples can be plotted in a dendrogram (Valentine and Peddichord, 1967; Mello and Buzas, 1968), from which the relatedness of groups can be distinguished.

Results of cluster analysis in the Q-mode (sample by sample comparison of species) are shown in the dendrogram (text-figure 6). Clustering at the 0.4 level shows three major groups. Two small clusters (A and B) occur in the estuary and a large one occurs offshore (C). Cluster A is a grouping of five stations in the minor channel of the estuary. Stations in this cluster are characterized by low species diversity. *Cribronion frigidus* is the main constituent, accounting for over 95% of the species at all five stations except station 50, where *Miliammina fusca* dominates. Stations in the major channel are included in cluster B. These stations are similar in diversity with 2 to 8 species of foraminifera. Cluster C includes all the offshore stations and a few of the estuarine stations. This cluster is characterized by relatively higher diversity, with five to 22 species. Five stations in the major channel of the estuary are included in the offshore cluster C. These stations occur near the mouth of the estuary. Station 45 does not cluster into any of the three main groups at the 0.4 level. Although it must be considered independent by the assumptions of the clustering technique,

Station																											
45	46	47	48	49	50	51	52	53	55	56	57	58	59	60	62	63	64	65	66	67	69	71	72	73	74	75	
4	2	1																									
	1																										

Station 45 may be included in cluster A. At a lower probability level, Station 45 clusters with the stations in the minor channel. Because of a lack of foraminifera upstream of Station 26, headward stations were not included in the analysis. These stations are included in a separate group of wholly fresh-water stations.

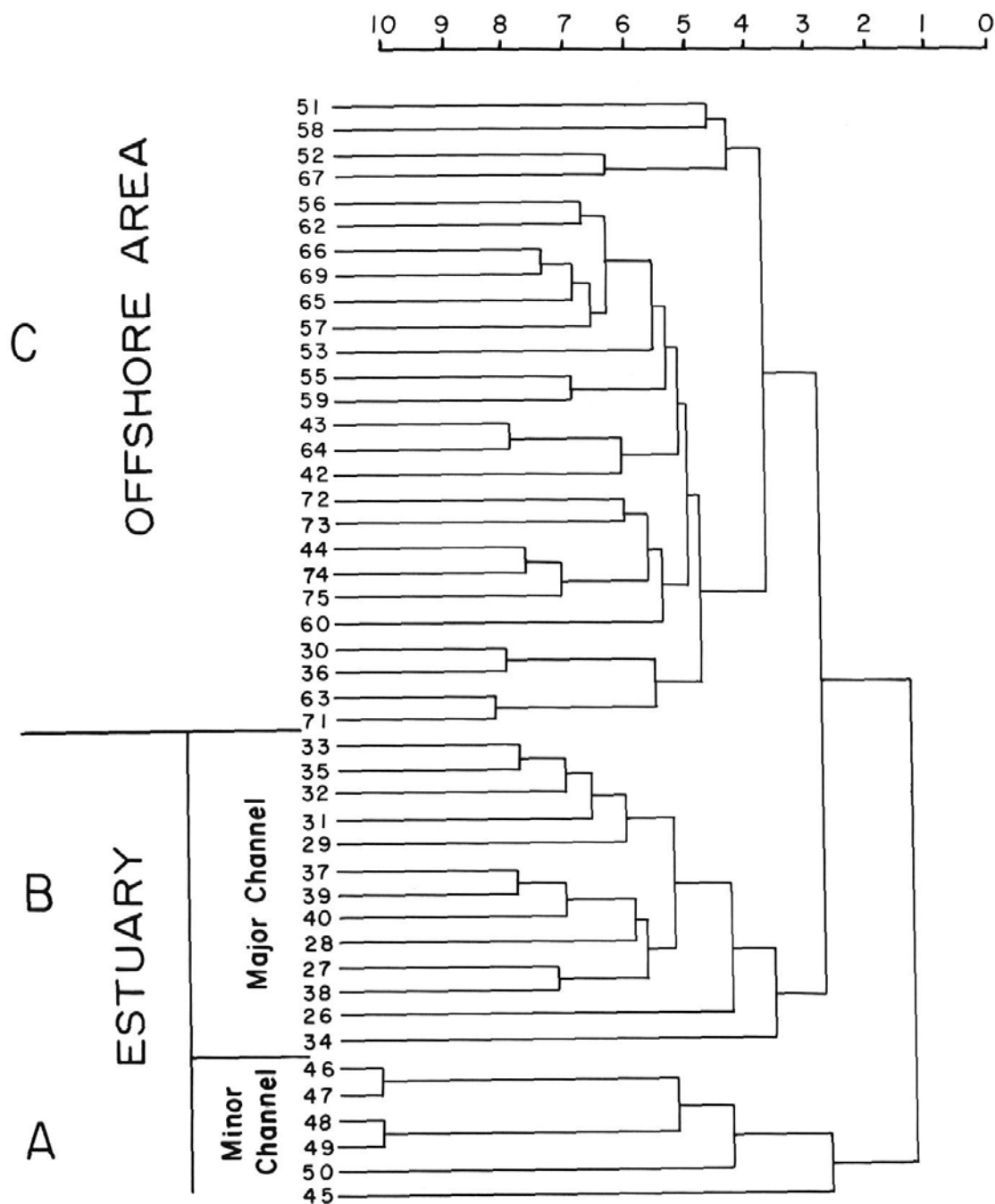
The correlation coefficient (r) between numbers of species and the measured depth, pH, temperature, and salinity was calculated (see Watt, 1968) to clarify the relationship of environmental factors to the distribution of foraminifera. A positive correlation ($r = 0.63$) exists between numbers of species and depth, significant by a t -test at the 5% level. The stations with the higher numbers of species occur in the deeper sections of the estuary and offshore. The shallowest areas in the study occur in the minor channel where the numbers of species are lowest. A decrease in sediment size or increase in the mean phi diameter is positively correlated ($r = 0.79$) with the number of species, significant at the 5% level. Correlation of number of species with salinity indicates a positive relationship ($r = 0.70$), significant at the 5% level. The highest salinity and numbers of species occur in the offshore stations, whereas the lowest salinity and number of species occur in the minor channel. Temperature and number of species correlate negatively ($r = -0.52$), significant at the 5% level. The warmest stations with the lowest

diversity occur in the upstream stations and the minor channel, whereas the coolest and more diverse stations occur offshore. Variability of pH throughout the study area is evident in the lack of correlation ($r = 0.0054$) of pH with number of species.

DISCUSSION

In general, the distribution of benthic foraminifera in an estuary can be divided into three regions. Typical estuaries are two-layered systems, stratified by differences in salinity and temperature. In the lower part of the estuary, under normal conditions of inflow, a vertical salinity gradient separates an upper layer of fresh water from a lower layer of more saline water. The lower water mass has characteristically greater salinity, reduced turbulence, and a net flow upstream, usually called the salt-water wedge (Phleger, 1960; Nichols and Ellison, 1967). Salinity of the upper layers decreases rapidly with distance upstream in a section of the estuary known as the gradient zone where the water is relatively well mixed as a result of tidal action. Headward of the gradient zone the water is fresh.

Each of these sections of the estuary has a characteristic microfauna. The fresh-water sections of the upper estuary do not support populations of foraminifera. Thecamoebina of two genera, *Diffugia* and *Centropyxis*, were found in many upstream stations of the Russian



TEXT-FIGURE 6
Dendrogram showing clustering of stations in the Q-mode, delineating foraminiferal biofacies.

River. Salinity tolerances of thecamoebina extend from fresh water to more or less undiluted sea water with their optimum in fresh water (chlorinity $< 1\%$; Murray, 1968b). Occurrence of thecamoebina in the headward sections is common in many temperate estuaries (Nichols and Ellison, 1967; Murray, 1968b; Tapley, 1969).

In the Russian River, foraminifera first appear in the gradient zone in summer. This section of the estuary is characterized by a salinity which is that of diluted sea water, shallow depths, moderate temperatures, and sediments of both mud and sand. The numbers of species and individuals of foraminifera in this area are low. The absence of an extensive salt marsh and tidal

flat precludes the development of an agglutinated foraminiferal fauna as commonly found in many other temperate estuaries. Although agglutinated foraminifera are found throughout the area, their occurrence does not represent a biological unit such as the shoal facies of Nichols and Ellison (1967). The paucity of foraminifera at Stations 48, 49, and 50 is probably due to the shallow water depth measuring only 0.25 meters. Thus, only surface water with low salinity and high temperature was available at higher tidal levels, while at low tidal levels these stations were exposed.

The third region of the estuary is the basin subfacies of Nichols and Ellison (1967). Occurring near the mouth of the estuary, this portion of the estuary contains a marginal marine fauna. Cluster analysis includes five estuarine stations in the offshore cluster. Species diversity in these stations is similar to the offshore stations. Foraminifera, many while still living, are probably carried into the estuary in suspension. Loose (1970) found numerous normally benthic species in plankton tows made next to the shoreline a few miles south of the Russian River.

Certain foraminifera are recognized as typically estuarine (Phleger, 1960; Murray, 1973). Among those species so considered, Phleger (1960) included *Ammonia beccarii* (Linne) and *Ammobaculites* sp. These species were present neither in the Russian River nor offshore. Other estuaries in the vicinity of the Russian River, however, support abundant populations of these species. The foraminiferal fauna of the Russian River is similar in composition to the generalized open-ocean near-shore fauna of Lankford and Phleger (1973). Of the genera considered characteristic of the near-shore fauna, 10 are common to the estuary and offshore areas.

The distribution of foraminifera in the Russian River during the summer suggests a sorting of species headward through the estuary. Correlation of numbers of species with physical parameters measured in the present study indicates that the distribution of foraminifera results from the incursion of sea water up the estuary. Higher diversity is correlated with greater depth, small sediment size, greater salinity, and lower temperature, conditions characteristic of the offshore marginal marine environment where foraminifera assemblages are more diverse. The rigors of the estuarine environment reduce the number of species only to those that are tolerant of a wide range of environmental variation.

Most distributional studies of foraminifera have been done during only one season of the year, chiefly

summer (Cooper, 1961; Nichols and Ellison, 1967; Tapley, 1969). Seasonal studies (Boltovskoy, 1956, 1964; Murray, 1968a; Buzas, 1969a) have shown a periodicity in environmental parameters with a concomitant variation in species density and composition. Murray (1968a, 1968b) found that foraminifera, much more abundant during summer and autumn than winter, responded to higher winter discharge. The Russian River probably represents an extreme in seasonal variation, having an abundant foraminiferal population in the summer and none in the winter.

Seasonality of the foraminiferal fauna in the Russian River results from high discharge during the winter. River discharge, if tidal and basin characteristics are constant, is the principal factor controlling the type of hydrographic system present during the year (Kulm and Byrne, 1967). Discharge during the winter months from December through March represents 90% of the total annual runoff from the Russian River watershed. This large volume of fresh water prevents the incursion of salt water and physically scours the river bed. These conditions within the estuary prevent foraminifera from living there in the winter. Recruitment into the estuary from the sea is also precluded by the high discharge.

Colby (1961) related increase in river velocity and flow to increase in material transported as tractive or suspended sediments. A net movement of the river bed seaward may be inferred by the high winter discharge. Concomitant with this movement is the removal of the foraminiferal fauna from the estuary. Within this model of flow it is unlikely that a foraminiferal fauna exists during periods of high discharge. Winter samples contain no foraminifera in the Russian River.

CONCLUSIONS

Distribution of estuarine foraminifera in previous studies has been related chiefly to the distribution of environmental factors such as temperature and salinity. Their distribution in the Russian River, however, differs from those described previously (Phleger, 1960; Buzas, 1965; Nichols and Ellison, 1967; Murray, 1968a, 1973). Due to the lack of extensive salt marshes, tidal flats, and permanent estuarine conditions, no characteristic estuarine fauna has been able to develop. The summer fauna present in the estuary is an incursive marginal marine fauna. During the summer months of low discharge, this fauna is carried into the estuary and the species then sorted according to their physiological tolerance. High river discharge during the winter prevents the incursion of the offshore fauna and carries resident foraminifera out of the estuary. The salt-water wedge is either attenuated or eliminated during winter months, and the river bed is physically scoured. Thus,

foraminifera are eliminated from the estuary of the Russian River during periods of high discharge. Foraminiferal faunas typical of normal estuaries cannot become permanently established in the Russian River with its present hydrology.

The foraminifera and sediments removed from the river are carried to sea and southward along the coast where they are reworked by turbulent nearshore wave and current action. Most species of foraminifera and thecamoebians are destroyed in this environment. It seems unlikely that foraminiferal or thecamoebian evidence of a river system such as the Russian River would ever be found in the geologic record.

FAUNAL REFERENCE LIST

(Systematic arrangement after Loeblich and Tappan, 1964)

Order ARCELLINIDA Kent, 1880

Family CENTROPYXIDAE Jung, 1942

Centropyxis sp.

A species of this genus, occurring throughout the estuary, was found in greater abundance upstream of Station 26.

Family DIFFLUGIIDAE Wallich, 1864

Diffugia sp.

Diffugia sp. was less commonly found than *Centropyxis*. It was more abundant in the middle part of the estuary.

Order FORAMINIFERIDA Eichwald, 1830

Family RZEHAENIDAE Cushman, 1933

Miliammina fusca (Brady)

Quinqueloculina fusca BRADY, 1870, p. 286, pl. 11, figs. 2a-c, 3.

This arenaceous species was commonly found in the estuary and offshore. Offshore specimens were found in stations south of the river mouth. Estuarine populations extend far into the estuary in both the minor and major channels. Average occurrence (percentage of abundance) in the estuary is 14.4%. Station 50 was composed of 96% *M. fusca*.

Family LITUOLIDAE de Blainville, 1825

Haplophragmoides columbiense Cushman

Haplophragmoides columbiensis CUSHMAN, 1925, p. 39, pl. 6, fig. 2.

This species was commonly found in both the estuary and offshore. Deeper offshore, abundances increased to 25% at some stations. The average occurrence offshore was 9.4%, whereas estuarine occurrences were only 1%.

Family TEXTULARIIDAE Ehrenberg, 1838

Textularia schencki Cushman and Valentine

Textularia schencki CUSHMAN and VALENTINE, 1930, p. 8, pl. 1, fig. 3.

This is the only species of foraminifera found exclusively in the estuary. Only two individuals were found.

Trochammina pacifica Cushman

Trochammina pacifica CUSHMAN, 1925, p. 39, pl. 6, fig. 3.

Distribution of this species includes both estuarine and offshore stations. This species, moderately common in mid-estuary, is more common in the offshore stations.

Family MILIOLIDAE Ehrenberg, 1839

Quinqueloculina akneriana d'Orbigny 1826, p. 302, no. 33.

Quinqueloculina akneriana D'ORBIGNY, 1846, p. 290, pl. 18, figs. 16-21.

This moderately rare species was found only offshore. Cooper (1961) reported this species north of the Russian River and near San Francisco.

Quinqueloculina vulgaris d'Orbigny

Quinqueloculina vulgaris d'Orbigny 1826, p. 302, no. 33.

This species was commonly found in both the estuary and offshore. Occurrence in the offshore station averaged 3%. Estuarine populations were distributed throughout the estuary to Station 26.

Family NODOSARIIDAE Ehrenberg, 1838

Lagena striata (d'Orbigny)

Oolina striata D'ORBIGNY, 1839, p. 21, pl. 5, fig. 12.

Only one individual of this species was found.

Family GLANDULINIDAE Reuss, 1860

Fissurina lucida (Williamson)

Entosolenia marginata (Montagu) var. *lucida* WILLIAMSON, 1848, p. 17, pl. 2, fig. 17.

Only five individuals of this species were found in two offshore stations.

Entosolenia costata Williamson

Entosolenia costata WILLIAMSON, 1858, p. 9, pl. 1, fig. 18.

This rare species was found in only a few offshore stations.

Family TURRILINIDAE Cushman, 1929

Buliminella elegantissima (d'Orbigny)

Bulimina elegantissima D'ORBIGNY, 1839, p. 51, pl. 7, figs. 13, 14.

This species is a major constituent in many offshore stations and accounts for about 11% of the individuals in stations where found. Only two individuals were found in the estuary.

Family BOLIVINITIDAE Cushman, 1927

Bolivina compacta Sidebottom

Bolivina robusta Brady var. *compacta* SIDEBOTTOM, 1905, p. 15, pl. 3, fig. 7.

This species was found rarely in the offshore stations.

Family DISCORBIDAE Ehrenberg, 1838

Buccella tenerrima (Bandy)

Rotalia tenerrima BANDY, 1950, p. 278, pl. 42, fig. 3.

This species is a common representative in both offshore and estuarine stations. Average occurrence is 9% in the offshore stations and 6% in the estuary.

Rosalina globularis d'Orbigny

Rosalina globularis D'ORBIGNY, 1826, p. 271, pl. 13, figs. 1-4.

Distribution of this species includes both estuarine and offshore stations. It is commonly found in all offshore stations with an occurrence of 7%. Estuarine populations are restricted to the deeper major channel near the mouth of the river. *Rosalina globularis* attaches to various firm substrates and shows some variation in morphology (DeLaca and Lipps, 1972). Lankford and Phleger (1973) recorded this species as *R. columbiensis* (Cushman), but Douglas and Sliter (1965) considered *R. columbiensis* identical with *R. globularis*.

Rotorbinella campanulata (Galloway and Wissler)

Globorotalia campanulata GALLOWAY and WISSLER, 1927, p. 58, pl. 9, fig. 4.

This species was found both in the estuary and offshore. Its occurrence was common to rare in the offshore stations and restricted to a few stations in the estuary near the river mouth.

Family GLABRATELLIDAE Loeblich and Tappan, 1964

Angulodiscorbis charlottensis (Cushman)

Discorbis charlottensis CUSHMAN, 1925, p. 42, pl. 7, fig. 2.

This species was rare, occurring in only a few offshore stations. The individuals found were collected along the transect off the mouth of the river.

Glabratella ornatissima (Cushman)

Discorbis ornatissima CUSHMAN, 1925, p. 42, pl. 6, figs. 11, 12.

In both estuarine and offshore stations this species was abundant. Nearly all offshore stations contained *G. ornatissima*, averaging 9% occurrence. Within the

estuary this species was restricted to those stations near the river mouth, with an occurrence of 9%. In this study we include *Discorbis ornatissima* Cushman and *Eponides columbiensis* (Cushman) in *Glabratella ornatissima* because the species is bimorphic (Lipps and Erskian, 1969b; Lankford and Phleger, 1973). Different names have been used for the schizont and gamont; these are discussed by Lipps and Erskian (1969b) and Lankford and Phleger (1973). Lankford and Phleger (1973) assigned the species to *Trichohyalus*, but we assign it to *Glabratella* (Lipps and Erskian, 1969b).

Family SPIRILLINIDAE Reuss, 1862

Spirillina vivipara Ehrenberg

Spirillina vivipara EHRENBURG, 1843, pp. 223, 422, pl. 3, VII, fig. 41.

This species was found at a single offshore station only.

Family ELPHIDIIDAE Galloway, 1933

The taxonomy of species in this family has been a problem for many years. Cushman (1944) perhaps best described it: "There are either many species or else a great amount of variation." In discriminating morphological groups of *Elphidium*, using a multivariate statistic based on morphologic characters, Buzas (1966, 1967) recognized only a few species with a great deal of variation. However, Loeblich and Tappan (1964) distinguished several genera in the family, and their arrangement is followed here.

Criboelphidium translucens (Natland)

Elphidium translucens NATLAND, 1938, p. 144, pl. 5, figs. 3, 4.

This species was found both in the estuary and offshore. In many offshore stations its occurrence was common, with the largest populations found at Station 60. Within the estuary this species seemed restricted to only a few stations near the mouth of the river.

Criboelphidium tumidum (Natland)

Elphidium tumidum NATLAND, 1938, p. 144, pl. 5, figs. 5, 6.

This species was common both in the estuary and offshore. It was found at stations near the river mouth and along the major channel to mid-estuary. Percentage of occurrence is higher within the estuary (9%) than offshore (2%).

Cribrononion frigidus (Cushman)

Elphidium frigidum CUSHMAN, 1933, p. 5, pl. 1, fig. 8.

Stations 26 through 75, which include all stations both in the estuary and offshore, contained this species.

Average occurrence within the estuary was 82%. Headward along both the major and minor channel, percentage of occurrence increased to 99% in the major channel and 100% in the minor channel; stations near the river mouth were less dominated by this species. Station 50 was the only headward station with a low occurrence of *C. frigidus*. In offshore stations the average occurrence was lower (42%). The occurrence at each station decreased seaward; stations nearshore and in the vicinity of the river mouth were composed of a higher percentage of this species.

In samples collected in the Russian River, individuals of each variant morph can be recognized; however, on a population level the morphologies grade into one another. Included in our working concept of the species *C. frigidus* (Cushman) are forms which would fit within *C. lenis* (Cushman and Murdock), *C. incertus* (Williamson), and *C. clavatus* (Cushman). Possibly a species with a great deal of genetic and morphological plasticity is better adapted for invasion of the estuarine environment.

Elphidiella hannai (Cushman and Grant)

Elphidium hannai CUSHMAN and GRANT, 1927, p. 78, pl. 8, fig. 1.

This species is abundant in both the estuary and offshore. Highest concentrations were found in the deeper offshore stations, with an average occurrence of 9%. Occurrence in the estuary averaged 5%. Cooper (1961) reported only 2% occurrence in beach samples.

Elphidium crispum (Linné)

Nautilus crispus LINNÉ, 1758, p. 709.

Three individuals were found in two offshore stations.

Family CIBICIDIDAE Cushman, 1927

Cibicides fletcheri Galloway and Wissler

Cibicides fletcheri GALLOWAY and WISSLER, 1927, p. 64, pl. 10, figs. 8, 9.

Found in nearly all offshore stations, this species has an average occurrence of 3%. In the estuary it is limited to areas near the mouth of the river. Average occurrence in the estuary is 3%. Cooper (1961) found this species averaging 8% in his intertidal samples.

Cibicides lobatulus (Walker and Jacob)

Nautilus lobatulus WALKER and JACOB, 1798, p. 642, pl. 14, fig. 36.

This species is more restricted to the offshore stations and stations near the river mouth. Although found in fewer stations than is *C. fletcheri*, it occurs in a higher

percentage in offshore stations (3.8%) and in estuarine stations (3.7%). Cooper (1961) reported a 2% occurrence of this species in beach sands.

Family CASSIDULINIDAE d'Orbigny, 1839

Cassidulina limbata Cushman and Hughes

Cassidulina limbata CUSHMAN and HUGHES, 1925, p. 12, pl. 2, fig. 2.

This species was found only rarely in the offshore stations, with an average occurrence of 1 to 2%. Cooper (1961) reported *C. limbata* at a 7% occurrence in beach samples near the Russian River.

Family NONIONIDAE Schultze, 1854

Nonionella basispinata (Cushman and Moyer)

Nonion pizarrense var. *basispinata* CUSHMAN and MOYER 1930, p. 54, pl. 7, fig. 18.

This rare species was found in only a few offshore stations.

Nonionella stella Cushman and Moyer

Nonionella stella CUSHMAN and MOYER, 1930, p. 56, pl. 7, fig. 17.

This rare species was found in a few offshore stations only. *Nonionella stella* and *N. basispinata* co-occur in 60% of the stations in which they are found.

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