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Foraminiferal Ecology, Ala Wai Canal, Hawai'i[1]

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ABSTRACT: The foraminiferal fauna of the Ala Wai Canal, described for the first time here, is controlled principally by the canal's shallow coastal location, normal marine salinity range, sedimentation from a major point source, and phytoplankton productivity. Various pollutants may have produced up to 7% abnormalities in test growth, but low oxygen conditions in the back basin are counterbalanced by food availability there to produce the largest surface foraminiferal abundance of 140 tests per gram of sediment. For at least the past 50 yr, the Ala Wai Canal has harbored a foraminiferal assemblage dominated by five species that compose from 53 to 92% of the foraminifera. These dominant species, *Ammonia beccarii* (Linné) vars., *Bolivinellina striatula* (Cushman), *Cribroelphidium vadescens* Cushman & Brönnimann, *Quinqueloculina poeyana* d'Orbigny, and *Quinqueloculina seminula* (Linné), are widespread geographically, but are generally found together in lagoons or embayments where salinities are normal marine to hypersaline rather than in estuaries. The maximum number of species per sample (31) was found near the entrance and the diversity decreased into the canal.

FORAMINIFERA ARE shelled protists whose species are sensitive indicators of various marine and marginal marine environments, including those that have been modified by human activity (Boltovskoy and Wright 1976:48–50). A study of the foraminifera of the Ala Wai Canal, located between Waikīkī Beach and the Honolulu plain, was conducted in July and August 1991, in conjunction with a research program involving various aspects of the water properties, microbiology, and geology of the canal. The foraminifera of the Ala Wai had not been documented previously; therefore this study sought to (1) determine which species currently live on the floor of the canal, their distribution and abundance, (2) compare the canal's assemblages to those of estuarine settings elsewhere, (3) detect temporal environmental change through downcore assessment of species composition, and (4) determine whether environmental pollution has affected the foraminiferal populations of the canal.

An excellent review of the history of the canal and the changes it produced in the drainage pattern and topography of the Waikīkī area is given by Acson (1983). The Ala Wai Canal was constructed in 1927 by the Army Corps of Engineers for the purpose of draining the swampy plain. The dredged material was piled seaward to elevate a few feet above sea level the strip of land that is now the tourist center of O'ahu. Gonzalez (1971) and Laws et al. (1993) mapped the bathymetry of the canal. From the entrance at the Ala Wai Yacht Harbor for about one-third of its 3-km length, the canal trends toward the northeast and is ca. 50 m wide and 2–4 m deep; then it turns 45° toward the southeast, widens to ca. 76 m and dead-ends. This longer leg of the canal is divided about midway by a sill formed where the stream from the narrower Mānoa-Pālolo Stream drainage

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canal deposits its load of suspended sediment. Toward the closed end of the canal, a basin 3.5–4 m deep has restricted water circulation below sill depth.

Characteristics of the water column were monitored by Miller (1975) over the period of a year. A brackish water lens (mean annual salinity [S] 16.8–32.8‰) 1 m thick at the surface overlies seawater (mean annual salinity 25.28–34.87‰) in a density stratification. Mean annual bottom temperature is 25.71–27.74°C. Oxygen content at the bottom of the deep back basin is less than 1 ml/liter, at least part of the year (Gonzalez 1971).

High levels of nutrients are introduced into the canal through runoff, resulting in a high level of primary production estimated at 5.26 g C m^{-2} d^{-1} (Harris 1975). In July 1991, when the samples for the foraminiferal study were taken, Laws et al. (1993) reported production values of 2.7 ± 0.8 to 7.9 ± 1.2 g C m^{-2} d^{-1} from the entrance to near the closed end of the canal and ranked the Ala Wai among the most heavily fertilized estuaries in the world. Nitrates, contributed from periodic fertilization of the Ala Wai Golf Course, probably enhanced primary production in the closed end of the canal (Gonzalez 1971), where the phytoplankton constituents at the time of our study were primarily dinoflagellates; the diatom *Skeletonema costatum* (Greville) Cleve dominated the plankton forward of the sill (Beach et al. 1995).

Sedimentation is estimated to remove ca. 18% of the carbon produced in the overlying water (Laws et al. 1993). The organic carbon content of the bottom mud ranges from ca. 4.5–6% near the sediment-water interface to 1–3% below ca. 70 cm (Glenn et al. 1995). These sediments generally have a $CaCO_3$ content of less than 10% except for a few high-carbonate layers (Glenn et al. 1995). Sediments cored for our study near the mouth of the Ala Wai Canal have accumulated since about 1960 (McMurtry et al. 1995). Between the McCully Street bridge and the Mānoa-Pālolo Stream drainage canal, the cored sediments have accumulated since 1978–1979, when the area most strongly affected by sediment deposition was dredged to a depth of 3 m. This area had been previously dredged in 1966. Sediments cored in the deep basin nearest the closed end of the canal have accumulated since about 1935, based on radio cesium dating by McMurtry et al. (1995) and extrapolated sedimentation rates (Glenn et al. 1995).

Crustaceans, including four crab and one shrimp species, are among the most abundant benthic invertebrates found in the canal. These invertebrates are less abundant or absent under low oxygen conditions at the closed end of the canal (Miller 1975).

MATERIALS AND METHODS

Five sediment cores were taken in the canal by pushing a plastic core-liner tube through the bottom mud from a boat. The sampling stations were distributed along the canal from the yacht harbor to the closed end (Figure 1). The core designations correspond with stations formerly used by Miller (M), Harris (H), and Gonzalez (G).

Samples were taken at the surface of the cores and generally at 20-cm intervals throughout their length. The sediment was dried, weighed, wet seived through a mesh with a screen opening of 0.063 mm, dried again, and the sand fraction was weighed. Organic detritus, although light, makes up part of the weight of the sand fraction. Foraminifera were identified and counted from the entire sand fraction or an aliquot portioned with a microsplitter to contain generally between 200 and 400 specimens. The species census given in the tables is reported in percentage representation (relative frequency) and number of specimens per gram of dry sediment (abundance). In contrast to the numerous benthic specimens, planktonic foraminifera were represented by scattered rare juvenile specimens and were not included in the report.

Assemblages were evaluated for abnormality according to the modes of test (shell) deformation reported by Alve (1991) in an industrially polluted Norwegian fjord. The incidence of pyrite-infilled tests as an indica-

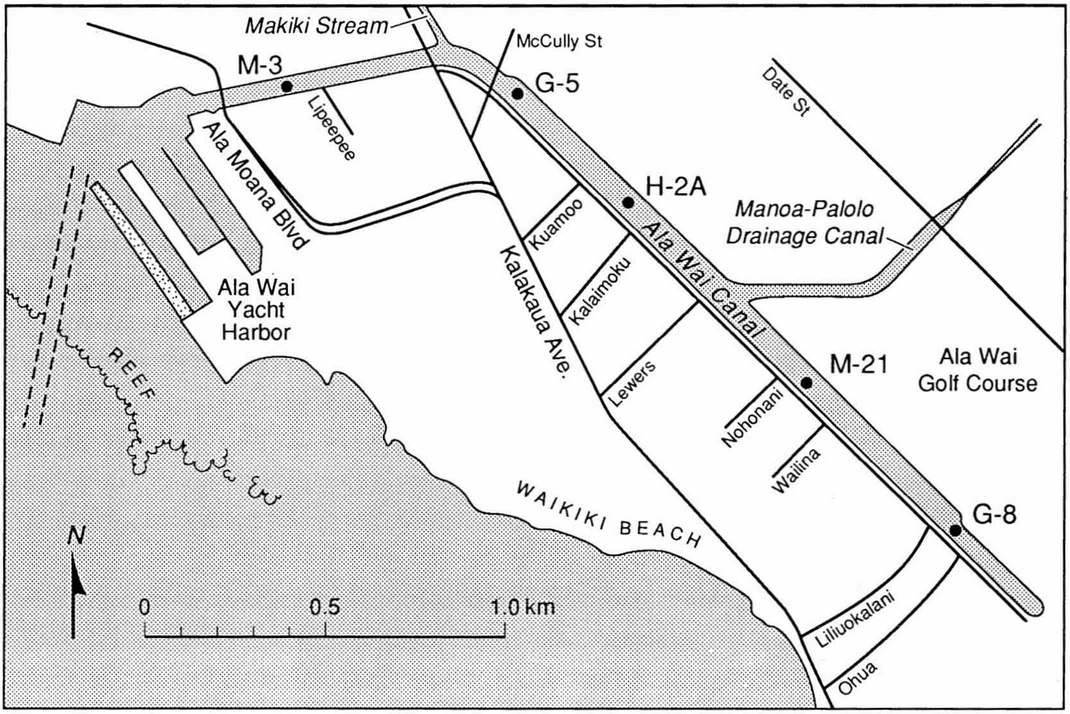


FIGURE 1. The Ala Wai Canal and location of cores used in this study.

tion of sulfate reduction under sediment or microenvironmental anoxia was also recorded.

RESULTS

Taxonomic Remarks

An abbreviated faunal reference list is provided in Appendix 1 to accommodate the many changes in generic designation that have taken place among the Foraminiferida. Descriptive data for the type species are reproduced under the original species name in the *Catalogue of Foraminifera* (Ellis and Messina 1940 and supplements).

The nomenclature of two species identified in this study is controversial. *Ammonia beccarii* (Linné) variants were reviewed by Walton and Sloan (1990), who regard forma *tepida* (Cushman) (simple ventral sutures, no umbilical plug) and forma *parkinsoniana* (d'Orbigny) (simple ventral sutures, one or more umbilical plugs) as ecophenotypes. These two morphologies were not separated in the census counts for the Ala Wai Canal and are here assigned to *Ammonia beccarii* vars.

The elphidiids also exhibit large phenotypic variation. The specimens here referred to *Cribroelphidium vadescens* Cushman & Brönnimann differ from the holotype and paratypes of that species in their more depressed sutures, more lobate periphery, and more prominent umbilical bosses; but they resemble the primary types in size, number of chambers, roundness of periphery, and apertural characteristics (fide B. Huber). It is presumed here that the Ala Wai specimens lie within the range of variation of the species because the same differences are shown by hypotypes of *C. vadescens* from the Gulf of Paria, Trinidad, illustrated by H. J. Hansen

TABLE 1

FORAMINIFERAL DISTRIBUTION,[a] CORE M-3

	DEPTH IN CORE (cm)											
	0–2	0–2	20–22	20–22	30–32	30–32	40–42	40–42	60–62	60–62	80–82	80–82
SPECIES	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g
Ammonia beccarii vars.	27	12.5	16	16.4	26	3.2	12	19.5	10	10.7	7	2.1
Bolivina glutinata	1	0.5	×	0.4	3	0.4	2	3.2			1	0.2
Bolivinellina limbata	×	0.2		0.4								
Bolivinellina striatula	11	5.0	9	9.3	7	0.9	9	14.9	3	3.4	14	3.7
Buccella cf. *inusitata*	2	0.9										
Bulimina marginata	×	0.4	×	0.4	1	0.1	2	2.8	1	1.5	2	0.5
Buliminella elegantissima	×	0.2	×	0.4			2	3.7	1	0.5		
Cibicides lobatulus	2	0.9					×	0.5	1	1.5		
Cornuspira planorbis	×	0.2	1	0.7			2	3.7			3	0.7
Cribroelphidium mexicanum	4	1.8	1	1.1	2	0.3	×	0.5	1	1.0	3	0.7
Cribroelphidium simplex	1	0.5										
Cribroelphidium vadescens	8	3.6	5	5.4	30	3.7	5	8.8	1	0.5	3	0.7
Cymbaloporetta squammosa	1	0.5	1	1.1	3	0.4	1	0.9	1	1.0		
Elphidium advenum	3	1.4										
Fissurina cucurbitasema basispinata	×	0.4	1	1.1	2	0.2	5	7.9	2	2.4	2	0.5
Fursenkoina punctata	4	1.8	2	2.5	2	0.3	2	3.2	5	5.3	1	0.2
Glabratella sp.	1	0.5					1	0.9	×	0.5	2	0.5
Helenina anderseni	1	0.5			1	0.1	×	0.5			1	0.2
Hopkinsina pacifica	1	0.5	2	1.8	2	0.2	2	2.8	2	1.9	3	0.9
Miliolinella subrotunda	×	0.4	3	2.9			1	1.4	1	1.5		
Nonionoides limbatostriata	6	2.5	4	3.9	1	0.1	7	11.6	6	6.3	4	1.2
Peneroplis pertusus	×	0.2	×	0.4			5	8.8				
Protelphidium sp.	2	0.9	5	4.6	4	0.5			8	8.2	4	1.2
Quinqueloculina bosciana	7	3.2	9	8.9			6	9.3	8	8.7	1	0.2
Quinqueloculina lamarckiana	×	0.2										
Quinqueloculina poeyana	5	2.3	7	7.1	2	0.2	9	14.4	9	9.2	9	2.6
Quinqueloculina seminula	5	2.3	21	21.4	13	1.6	22	37.2	30	31.0	36	9.8
Quinqueloculina spp.	×	0.4										
Rosalina floridana	×	0.4										
Spirillina vivipara	×	0.2	×	0.4	1	0.1	1	1.4	1	1.0	1	0.2
Trochammina inflata	×	0.2										
Buliminoides parallela			×	0.4							×	0.2
Cassidulina minuta			1	0.7			×	0.5			×	0.2
Hauerina pacifica			1	1.4							×	0.2

Miliammina fusca			2	1.8			1	1.4	1	0.5	1	0.2
Pseudoparrella sp.			×	0.4								
Siphogenerina costata			×	0.4								
Spiroloculina communis			1	0.7			×	0.5	×	0.5		
Spiroloculina corrugata			1	0.4								
Triloculina linneiana			×	0.4								
Triloculina oblonga			×	0.4			1	1.4	1	0.5	1	0.2
Triloculina trigonula			1	1.4					1	1.0		
Triloculina sp.			1	0.7								
Hauerina bradyi							×	0.5				
Lamellodiscorbis aguayoi							×	0.5				
Quinqueloculina distorqueata							×	0.5	1	1.5		
Quinqueloculina polygona							×	0.5	1	1.5		
Fischerinella helix									1	0.5		
Triloculina striatotrigonula									1	0.5		
Patellina corrugata											×	0.2
Detrital foraminifera			3	3.3			1	2.4	×	1.0		
Count	255		286		123		357		213		118	
No. per gram		45.5		102.6		12.3		166.1		103.6		27.3

[a] × = <1%.

and A. L. Lykke-Andersen in 1976 and reproduced by Loeblich and Tappan (1987: pl. 784, figs. 1–4). The genus *Cribroelphidium* is retained here following Loeblich and Tappan (1987), who regard the perforate, rounded periphery and lack of a keel as distinctive from the genus *Elphidium*. Other foraminiferal specialists might refer these specimens to *Elphidium excavatum* (Terquem), a species characteristic of temperate seas (Buzas et al. 1985), or to one of its morphotypes (Miller et al. 1982).

Surface Species Distribution

Tables 1–5 show the foraminiferal census data in which species abundances are based on the sample weights presented in Appendix 2. Five foraminiferal species, *Quinqueloculina poeyana* d'Orbigny (Figures 2, 3), *Quinqueloculina seminula* (Linné) (Figure 4), *Bolivinellina striatula* (Cushman) (Figures 5, 6), *Cribroelphidium vadescens* (Figures 7, 10), and *Ammonia beccarii* vars. (Figures 8, 9), dominated the surface samples at all sampling stations. The distribution of these species at the surface and downcore is shown in Figure 11. Minor species, some of which are illustrated in Figures 12–22, are most numerous toward the open end of the canal, nearest the marine connection, where 26 minor species, composing about 44% of the surface assemblage, were recorded. In contrast, only 5–12 minor species occurred in the surface sediments throughout the remainder of the canal. Almost all of these minor species and all of the major species have calcareous perforate or imperforate tests. Agglutinated tests are represented by single specimens of *Trochammina inflata* (Montagu) and *Siphotextularia* sp.

In the surface sediments, foraminifera are more abundant in the deep back basin (100–140 per gram) than on and forward of the sill (29–57 per gram). High sedimentation rates seaward from the Mānoa-Pālolo Stream drainage canal may dilute the concentration of tests. Therefore, the relative frequencies of species do not portray population densities in the canal. For example, in core H-2A *C. vadescens* composes 28% of the surface as-

TABLE 2

FORAMINIFERAL DISTRIBUTION,[a] CORE G-5

SPECIES	DEPTH IN CORE (cm) 0–2 %	0–2 No./g	20–22 %	20–22 No./g	40–42 %	40–42 No./g	60–62 %	60–62 No./g	80–82 %	80–82 No./g
Ammonia beccarii vars.	18	10.5	17	14.4	17	1.6	13	40.9	19	28.9
Bolivinellina striatula	8	4.5	12	9.6	9	0.9	7	22.7	2	2.3
Buliminella elegantissima	×	0.5	2	1.7			2	5.5	1	1.1
Cribroelphidium vadescens	25	14.5	8	6.3	3	0.2	8	26.4	16	23.7
Hopkinsina pacifica	5	3.0	3	2.5	4	0.4	2	7.3	1	0.8
Nonionoides limbatostriata	4	2.5	3	2.3			4	12.7	1	1.9
Quinqueloculina bosciana	7	4.0	5	3.8	6	0.6	7	23.6	4	5.6
Quinqueloculina poeyana	19	11.0	14	11.9	31	3.0	19	61.8	19	28.9
Quinqueloculina seminula	11	6.3	27	22.1	17	1.6	19	60.0	29	43.9
Spirillina vivipara	×	0.5					×	0.9		
Bulimina marginata			2	1.5	1	0.1	1	1.8	1	1.1
Cornuspira planorbis			×	0.4			2	5.5	×	0.4
Cribroelphidium mexicanum			1	1.0	1	0.1	2	6.4	1	1.1
Fissurina cucurbitasema basispinata			1	1.0	3	0.2	3	9.1	1	1.9
Fursenkoina punctata			3	2.3			4	11.8	1	1.1
Glabratella sp.			×	0.4			×	0.9		
Lamellodiscorbis aguayoi			×	0.2			×	0.9		
Miliolinella spp.			×	0.4						
Protelphidium sp.			1	1.0	6	0.6	5	15.5	3	3.8
Pseudoparrella sp.			×	0.2						
Quinqueloculina polygona			×	0.2						
Textularia sp.			×	0.2						
Cymbaloporetta squammosa					1	0.1				
Helenina anderseni					1	0.1	×	0.9		
Hauerina pacifica							×	0.9	×	0.4
Miliammina fusca							1	2.7	1	1.5
Miliolinella subrotunda							×	0.9		
Spiroloculina communis							×	0.9		
Triloculina trigonula							1	2.7	×	0.4
Spiroloculina corrugata									×	0.4
Triloculina sp.									×	0.4
Count	229		400		78		355		398	
No. per gram		57.2		83.4		9.5		322.7		149.6

[a] × = <1%.

TABLE 3

FORAMINIFERAL DISTRIBUTION,[a] CORE H-2A

	DEPTH IN CORE (cm)									
	0–2	0–2	20–22	20–22	40–42	40–42	60–62	60–62	80–82	80–82
SPECIES	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g
Ammonia beccarii vars.	10	2.9	11	3.7	18	1.3	13	3.9	15	7.0
Bolivinellina striatula	2	0.5	7	2.3	13	1.0	4	1.1	3	1.5
Buliminella elegantissima	×	0.2	1	0.5	2	0.2	2	0.5	1	0.5
Cornuspira planorbis	2	0.5	×	0.2			1	0.2	1	0.3
Cribroelphidium vadescens	28	8.3	2	0.8	4	0.3	9	2.8	17	8.2
Elphidium advenum	2	0.5								
Fissurina cucurbitasema basispinata	×	0.2			2	0.2	2	0.5	1	0.3
Hauerina pacifica	×	0.2	2	0.8					1	0.5
Hopkinsina pacifica	×	0.2					2	0.5	1	0.6
Quinqueloculina lamarckiana	1	0.3								
Quinqueloculina neostriatula	×	0.2								
Quinqueloculina poeyana	30	8.6	41	13.5	20	1.5	21	6.2	17	8.4
Quinqueloculina seminula	19	5.6	25	8.3	25	1.8	31	9.0	30	14.6
Quinqueloculina spp.	2	0.5								
Siphotextularia sp.	×	0.2								
Spirillina vivipara	×	0.2								
Triloculina sp.	×	0.2								
Buliminoides parallela			×	0.2	2	0.2				
Cribroelphidium mexicanum			4	1.2			1	0.2	×	0.2
Fursenkoina punctata			2	0.6			5	1.5	×	0.1
Helenina anderseni			×	0.2					1	0.2
Lamellodiscorbis aguayoi			×	0.2					×	0.1
Monalysidium politum			×	0.2						
Nonionoides limbatostriata			1	0.3			2	0.7	1	0.2
Protelphidium sp.			×	0.2			2	0.5	3	1.3
Quinqueloculina bosciana			×	0.2	4	0.3	3	0.8	4	2.0
Triloculina oblonga			1	0.3			1	0.3	×	0.1
Bolivina glutinata					2	0.2				
Glabratella sp.					2	0.2	×	0.2	×	0.1
Miliammina fusca					4	0.3				
Siphogenerina costata					2	0.2				
Bulimina marginata							1	0.2	1	0.4

TABLE 3 (continued)

SPECIES	DEPTH IN CORE (cm) 0–2 %	0–2 No./g	20–22 %	20–22 No./g	40–42 %	40–42 No./g	60–62 %	60–62 No./g	80–82 %	80–82 No./g
Cibicides lobatulus							×	0.2	×	0.1
Heterostegina depressa juv.							×	0.2		
Bolivinellina limbata									×	0.1
Cymbaloporetta squammosa									×	0.1
Nonion cf. *boueanum*									1	0.6
Peneroplis pertusus									×	0.2
Quinqueloculina polygona									×	0.1
Triloculina striatotrigonula									×	0.1
Count	185		217		46		179		707	
No. per gram		29.3		33.7		7.7		29.5		47.9

[a] × < 1%.

semblage in an abundance of eight specimens per gram of sediment, whereas in core G-8 it composes only 12% of the surface assemblage but has an abundance of 16 specimens per gram of sediment. Nevertheless, the percentage frequencies reveal relative affinities of the various species with the local environments or with sedimentary processes, such as sorting by currents, operating in those environments.

The dominant species are fairly consistent in their occurrences in the surface sediments of the canal. Of the five cores, M-3, from the short leg of the canal nearest the entrance, departs most from the pattern of species occurrences in that the miliolids, *Quinqueloculina* spp., are of relatively low frequency in the surface sediments. Among the minor species, *Nonionoides limbatostriata* (Cushman) attains frequencies of 6 and 4%, respectively, in cores M-3 and G-5 forward of the sill, but only occurs as traces in the back basin. This suggests that although the dominant species are tolerant of the range exhibited by environmental parameters in the canal, the marine connection exerts an influence over populations nearest the entrance. In fact, at stations M-3 and G-5, the bottom salinity is somewhat higher and the bottom temperature somewhat lower than they are in the remainder of the canal (Figure 11).

Subsurface Species Distribution

Except for some modifications in assemblage composition in core G-8 from the deep basin, the dominant species of the surface sediment continue downward in the cores, but show changes in frequency and abundance (Figure 11). The lowermost section of core G-8 has the lowest abundance of foraminiferal tests as well as a low frequency of *Ammonia* and a high frequency of *Cornuspira planorbis* Schultze and *Spirillina vivipara* Ehrenberg, which together compose up to 31% of the assemblage. Chave (1987) found planispirally coiled forms such as these attached to algae or firm reefal substrate. High rates of accumulation of finely particulate $CaCO_3$ occur in this interval (Glenn et al. 1995) and may be responsible for both the

TABLE 4

Foraminiferal Distribution,[a] Core M-21

	Depth in core (cm)																	
	0–2	0–2	20–22	20–22	40–42	40–42	60–62	60–62	80–82	80–82	100–102	100–102	120–122	120–122	140–142	140–142	160–162	160–162
Species	%	No/g	%	No/g	%	No/g	%	No/g	%	No/g	%	No/g	%	No/g	%	No/g	%	No/g
Ammonia beccarii vars.	18	17.8	16	13.3	19	35.3	16	49.5	5	2.2	24	11.6	34	11.9	32	12.5	61	8.7
Bolivinellina striatula	5	5.4	13	11.4	7	12.7	4	13.7	3	1.5	3	1.4	3	1.1	3	1.1	12	1.6
Buliminella elegantissima	2	1.9	2	2.0	×	0.7	2	7.4	1	0.9	×	0.2	1	0.5	1	0.3	×	0.1
Buliminoides parallela	×	0.3									×	0.1			1	0.6		
Cornuspira planorbis	×	0.3	×	0.4	×	0.7	×	1.1	2	0.8			×	0.2	1	0.5		
Cribroelphidium mexicanum	×	0.3	1	1.2	×	0.7	×	1.1			×	0.1	1	0.5	1	0.5		
Cribroelphidium vadescens	4	4.4	11	9.4	29	55.3	36	113.7	2	0.8	12	5.6	10	3.4	5	1.9	2	0.2
Fissurina cucurbitasema basispinata	×	0.3	1	1.2							2	0.7	×	0.2	1	0.3	×	0.1
Glabratella sp.	1	1.3	1	0.8	1	2	×	1.1	×	0.1	×	0.2			1	0.3		
Hopkinsina pacifica	7	6.7	6	5.1	3	5.3	2	7.4	2	0.8	3	1.3			4	1.6	2	0.2
Nonionoides limbatostriata	×	0.6	1	0.8	1	1.3	×	1.1	1	0.4					×	0.2	×	0.1
Protelphidium sp.	2	1.9	4	3.1	2	3.3	1	2.1	3	1.4	5	2.2	4	1.5	1	0.6		
Quinqueloculina poeyana	41	40.6	10	8.2	8	15.3	13	42.1	5	2.2	9	4.5	7	2.6	1	0.4	2	0.2
Quinqueloculina seminula	18	18.1	26	22.0	26	49.3	16	50.5	65	29.5	36	16.9	23	8.1	27	10.7	15	2.1
Quinqueloculina spp.	×	0.3																
Bolivina glutinata			1	0.8			1	3.2			×	0.2			1	0.4		
Bulimina marginata			1	0.8	1	1.3	1	3.2	×	0.1			×	0.2	1	0.4	4	0.5
Cymbaloporetta squammosa			1	1.2	1	2.0	1	2.1	×	0.4	1	0.3	2	0.6	1	0.4		
Fursenkoina punctata			3	2.7			1	2.1	1	0.4					2	1.0	×	0.1
Lamellodiscorbis aguayoi			×	0.4	×	0.7									×	0.1		
Quinqueloculina bosciana			×	0.4	×	0.7	4	12.6	7	3.0	4	1.7						
Triloculina striatotrigonula			×	0.4							×	0.1					1	0.2
Helenina anderseni					×	0.7			×	0.1			1	0.3				
Spirillina vivipara					1	2.0			3	0.4			×	0.2	1	0.6		
Miliammina fusca									1	0.3								
Neoconorbina frustata									×	0.1								
Triloculina trigonula									1	0.3					×	0.1		
Pseudoparrella sp.											×	0.1						
Spiroloculina sp.											×	0.1						
Cibicides lobatulus													1	0.3	1	0.3	×	0.1
Hauerina pacifica													2	0.6	1	0.3	×	0.1
Rosalina sp.													×	0.2				
Spiroloculina cf. *elegantissima*													×	0.2	×	0.1		
Triloculina oblonga													6	1.9	8	3.0		
Triloculina sp.													2	0.6	×	0.1		
Tubinella funalis													×	0.2				
Bolivinellina limbata															×	0.1		
Cassidulina minuta															×	0.1		
Lagena laevis															×	0.1		
Miliolinella subrotunda															2	0.7		
Quinqueloculina distorqueata															×	0.2		
Quinqueloculina sp.															×	0.2		
Count	316		217		284		298		353		466		220		406		191	
No. per gram		100.2		85.6		189.3		314.0		45.7		47.3		35.3		39.7		14.3

[a] × = <1%.

TABLE 5

FORAMINIFERAL DISTRIBUTION,[a] CORE G-8

	DEPTH IN CORE (cm)											
	0–2	0–2	20–22	20–22	38–40	38–40	60–62	60–62	80–82	80–82	100–102	100–102
SPECIES	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g
Ammonia beccarii vars.	27	38.3	36	64.7	13	6.1	27	48.0	29	34.6	39	42.7
Bolivinellina striatula	10	14.3	6	11.7	3	1.5	3	5.9	3	3.1	8	8.4
Buliminella elegantissima	×	0.6	1	2.0			1	1.1	×	0.4	×	0.4
Cibicides lobatulus	×	0.6							×	0.4		
Cribroelphidium vadescens	12	16.0	10	18.5	4	1.8	11	18.7	2	2.3	×	0.4
Fissurina cucurbitasema basispinata	×	0.6			1	0.3						
Glabratella sp.	3	4.6			1	0.3	×	0.5	×	0.4		
Hauerina pacifica	×	0.6	×	0.5	2	0.9					×	0.4
Hopkinsina pacifica	×	1.1	×	1.1			1	2.1	2	1.8	2	1.8
Lamellodiscorbis aguayoi	×	0.6										
Nonionoides limbatostriata	×	0.6	×	0.9					2	2.3	2	1.8
Peneroplis pertusus juv.	×	0.6			1	0.3						
Protelphidium sp.	4	5.7			1	0.3			1	1.2	2	2.2
Quinqueloculina bosciana	2	2.3	1	2.0	6	2.7	1	2.1	×	0.4	1	0.9
Quinqueloculina poeyana	18	24.6	30	52.9	11	5.2	4	6.4	1	0.8	7	7.6
Quinqueloculina seminula	20	28.0	10	17.1	46	21.8	39	68.8	41	48.9	34	37.3
Quinqueloculina spp.	×	0.6	×	0.5								
Bolivina glutinata			×	0.3	3	1.5	1	1.1				
Buliminoides parallela			×	0.5								
Cribroelphidium sp.			1	2.1								
Elphidium advenum			1	2.1	1	0.6	1	1.6	1	0.8		
Helenina anderseni			1	2.1	1	0.6	×	0.5	1	0.8		
Cornuspira planorbis					1	0.6						
Cymbaloporetta squammosa					1	0.6			×	0.4	1	1.3
Fursenkoina punctata					2	0.9						
Nonion cf. *boueanum*					1	0.6	1	1.6				
Quinqueloculina distorqueata					1	0.3						

TABLE 5 (continued)

	DEPTH IN CORE (cm)											
	0–2	0–2	20–22	20–22	38–40	38–40	60–62	60–62	80–82	80–82	100–102	100–102
SPECIES	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g
Rotorboides granulosus							×	0.5				
Triloculina striatotrigonula							10	17.6	16	19.4		
Triloculina trigonula							×	0.5				
Miliolinella subrotunda									1	0.8		
Quinqueloculina neostriatula									×	0.4		
Buliminella sp.											1	0.9
Cribroelphidium mexicanum											2	2.7
Sigmavirgulina tortuosa											×	0.4
Fijiella simplex												
Quinqueloculina polygona												
Triloculina subgranulata												
Dentalina sp.												
Lingulina sp.												
Murrayinella murrayi												
Rosalina sp.												
Siphogenerina costata												
Spiroloculina spp.												
Triloculina oblonga												
Spirillina vivipara												
Bolivina sp.												
Epistominella pulchra												
Patellina corrugata												
Pseudoparrella sp.												
Quinqueloculina kerimbatica												
Tubinella funalis												
Bolivinellina sp.												
Patellinoides sp.												
Detrital foraminifera												
Count	244		592		155		332		307		246	
No. per gram		139.7		179.0		46.9		177.0		119.3		109.2

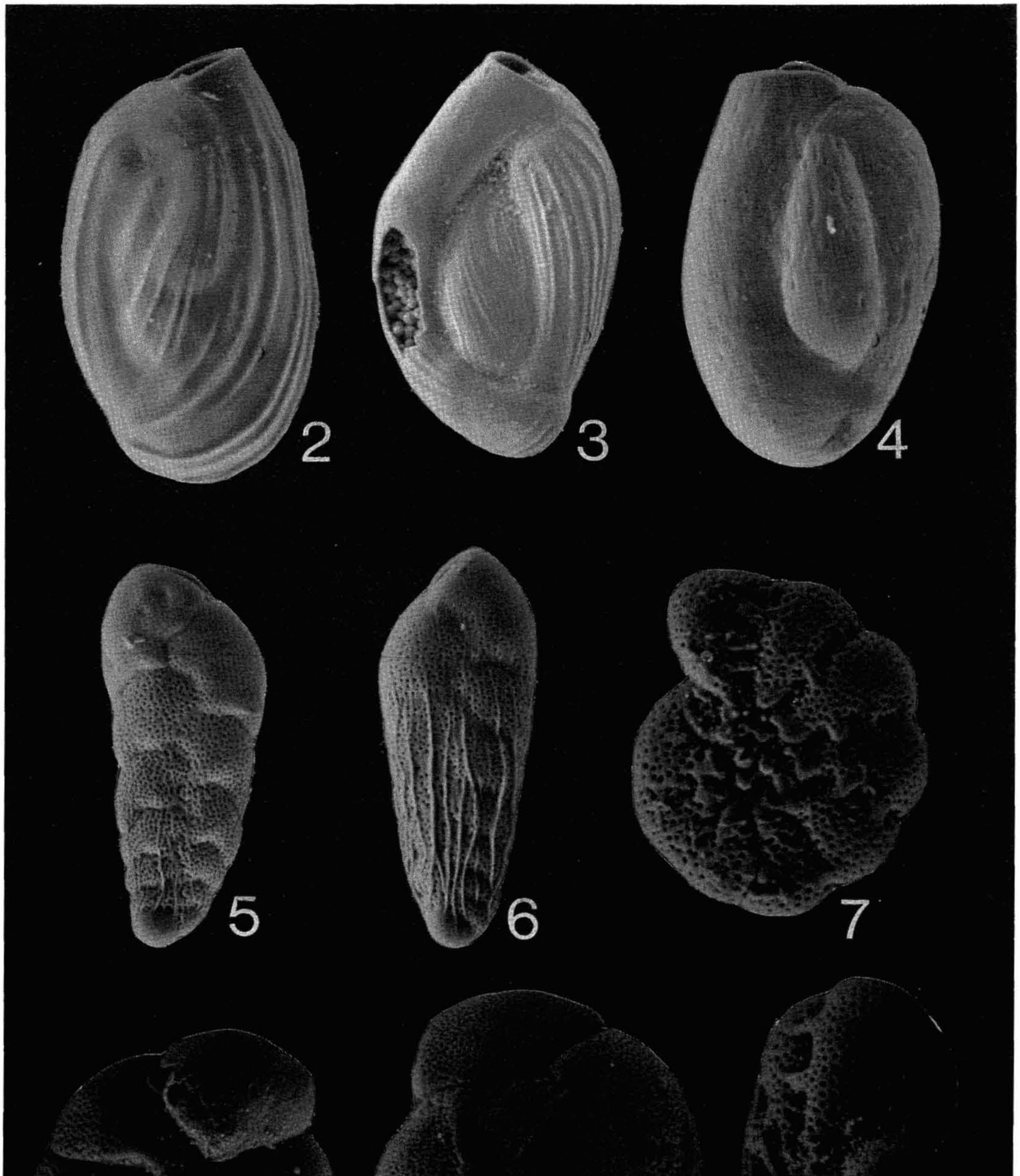
TABLE 5 (continued)

	DEPTH IN CORE (cm)									
	120–122	120–122	140–142	140–142	158–160	158–160	170–172	170–172	190–192	190–192
SPECIES	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g
Ammonia beccarii vars.	32	20.9	30	5.2	16	15.9	1	0.1		
Bolivinellina striatula	4	2.4	7	1.3	2	1.7	1	0.2	1	0.1
Buliminella elegantissima	1	0.6	2	0.3						
Cibicides lobatulus										
Cribroelphidium vadescens	2	1.1					×	0.1		
Fissurina cucurbitasema basispinata			1	0.1			1	0.1	2	0.1
Glabratella sp.	×	0.2	1	0.1			2	0.3	3	0.2
Hauerina pacifica			5	0.9	3	3.5	3	0.4		
Hopkinsina pacifica			2	0.3						
Lamellodiscorbis aguayoi			2	0.4						
Nonionoides limbatostriata	1	0.7								
Peneroplis pertusus juv.	×	0.2	1	0.1	1	1.4				
Protelphidium sp.	3	1.9	3	0.5	5	5.2	1	0.2		
Quinqueloculina bosciana	5	3.4			×	0.3			4	0.3
Quinqueloculina poeyana	3	1.9	1	0.1	3	2.6	1	0.1	4	0.3
Quinqueloculina seminula	43	27.9	21	3.6	57	58.0	28	4.1	31	2.4
Quinqueloculina spp.			×	0.1			3	0.4	×	0.1
Bolivina glutinata					2	2.3	6	0.9		
Buliminoides parallela										
Cribroelphidium sp.										
Elphidium advenum	1	0.4			3	2.6	×	0.1	2	0.1
Helenina anderseni	1	0.6	2	0.3						
Cornuspira planorbis	1	0.6					16	2.3	12	0.9
Cymbaloporetta squammosa	1	0.6	1	0.1			1	0.1	7	0.6
Fursenkoina punctata										
Nonion cf. *boueanum*			2	0.4	×	0.3	1	0.1		
Quinqueloculina distorqueata	×	0.2			×	0.3	1	0.1		

TABLE 5 (continued)

	DEPTH IN CORE (cm)									
	120–122	120–122	140–142	140–142	158–160	158–160	170–172	170–172	190–192	190–192
SPECIES	%	No./g	%	No./g	%	No./g	%	No./g	%	No./g
Rotorboides granulosus										
Triloculina striatotrigonula	1	0.4			×	0.3				
Triloculina trigonula										
Miliolinella subrotunda							2	0.3	1	0.1
Quinqueloculina neostriatula	×	0.2			×	0.3				
Buliminella sp.			1	0.1	1	0.6			3	0.2
Cribroelphidium mexicanum			8	1.5						
Sigmavirgulina tortuosa							×	0.1		
Fijiella simplex	×	0.2								
Quinqueloculina polygona	×	0.2								
Triloculina subgranulata	×	0.2								
Dentalina sp.			×	0.1						
Lingulina sp.			×	0.1						
Murrayinella murrayi			×	0.1						
Rosalina sp.			5	0.9	×	0.6			2	0.1
Siphogenerina costata			×	0.1	×	0.6				
Spiroloculina spp.			×	0.1	×	0.3				
Triloculina oblonga			3	0.5	5	4.6	8	1.2	3	0.2
Spirillina vivipara					1	0.9	15	2.1	8	0.6
Bolivina sp.							×	0.1		
Epistominella pulchra							2	0.3		
Patellina corrugata							1	0.2		
Pseudoparrella sp.							2	0.3		
Quinqueloculina kerimbatica							×	0.1		
Tubinella funalis							2	0.3	3	0.2
Bolivinellina sp.									10	0.8
Patellinoides sp.									4	0.3
Detrital foraminifera			2	0.2						
Count	345		189		353		216		106	
No. per gram		64.8		17.5		102.3		14.6		7.6

[a] × = <1%.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dilution or reduced production of foraminiferal tests and the unusual assemblage, which may show substrate preference. An interval higher in core G-8, from 60 to 80 cm, contains numbers of *Triloculina striatotrigonula* Parker & Jones (= *Triloculina trigonula* [Lamarck], costate variety Todd), a species Chave (1987) found attached to algal mats and filamentous algae in shallow waters of Māmala Bay, outside of the Ala Wai Yacht Harbor. Unusual algal growth in or around the deep basin may have characterized this interval. According to the dating of McMurtry et al. (1995), the top of this interval approximates the 1966 dredging of the sill. This may have altered circulation in the back basin and shifted the assemblage toward a more modern aspect, with increased frequency of *Q. poeyana* and *C. vadescens*. Likewise, peak percentages of *Q. seminula* at 40 cm in core G-8 and 80 cm in core M-21 approximate the 1978 dredging of the sill.

Just as in the surface samples, *N. limbatostriata* is most frequent and abundant forward of the sill in the downcore samples (compare Tables 1–5) and agglutinated species rarely occur. A maximum of 1% *Miliammina fusca* (Brady) was recorded at 80 cm in core M-21.

The greatest changes in percentage representation of species downcore tend to occur in samples in which foraminiferal abundance is low, but the species response in these low abundance samples is not always the same. For example, *C. vadescens* gains in percentage representation in the low abundance sample at 30 cm in core M-3, but is represented less at 40 cm in core G-5, whereas *Q. poeyana* gains in percentage at that level. The genera *Cribroelphidium* and *Quinqueloculina* are different in shape and wall structure, which suggests that environmental effects such as sorting by local currents or preservational bias, as well as spotty distribution and degree of environmental tolerance of the species, may influence their occurrence in these deposits with low foraminiferal abundance. The specimens of both of these genera are small, and breakage, at least partially attributable to sample processing, is common, particularly in *Q. seminula*. Thinly calcified tests showing the brownish tinge of their organic linings were noted in the *Q. poeyana* of some samples. However, dissolution of tests, which tends to obscure or modify lamination, surface detail, and porosity, as well as to affect the distribution of specimens, was not observed in any of the canal specimens.

Regardless of whether the low foraminiferal abundance has pre- or postmortem causes, these low abundance samples signify conditions unfavorable for the development of large death assemblages. Core M-3, nearest the entrance, shows relatively low abundance of tests at the surface, but high and low abundances fluctuate downcore. Radio cesium dating indicates an age of ca. 35 yr for the base of this 90-cm-long core (McMurtry et al. 1995), which suggests current winnowing at the mouth of the canal as a plausible agent active in sediment and test removal. Core G-5 has highest test abundance toward its base at 60 and 80 cm. Core H-2A on the sill has low foraminiferal abundance throughout. Cores M-21 and G-8 in the back basin show highest test abundance in the upper parts of the cores and low abundance below 60 cm in core M-21 and below 100 cm in core G-8 (except for the assemblage at 160 cm). The 100-cm level in core G-8 (late 1950s) corresponds with a negative shift in $\delta^{13}C$, with light values extending to the top of the core (Glenn et al. 1995). This implies a direct relationship

FIGURES 2–10. Dominant species of benthic foraminifera, Ala Wai Canal. 2, *Quinqueloculina poeyana* × 150; G-8, 0–2 cm. 3, *Quinqueloculina poeyana* × 131; G-8, 0–2 cm. Note botryoidal pyrite infilling test. 4, *Quinqueloculina seminula* × 150; G-8, 0–2 cm. 5, *Bolivinellina striatula* × 150; G-8, 0–2 cm. Specimen with few costae. 6, *Bolivinellina striatula* × 200; G-8, 0–2 cm. Highly costate specimen. 7, *Cribroelphidium vadescens* × 200; G-5, 0–2 cm. Side view. 8, *Ammonia beccarii* var. × 200; G-8, 0–2 cm. Umbilical side showing small umbilical plug, not present in all specimens. 9, *Ammonia beccarii* var. × 200; G-8, 0–2 cm. Spiral side showing limbate, raised sutures. 10, *Cribroelphidium vadescens* × 250; G-5, 0–2 cm. Edge view. Note apertural pore on face of ultimate chamber.

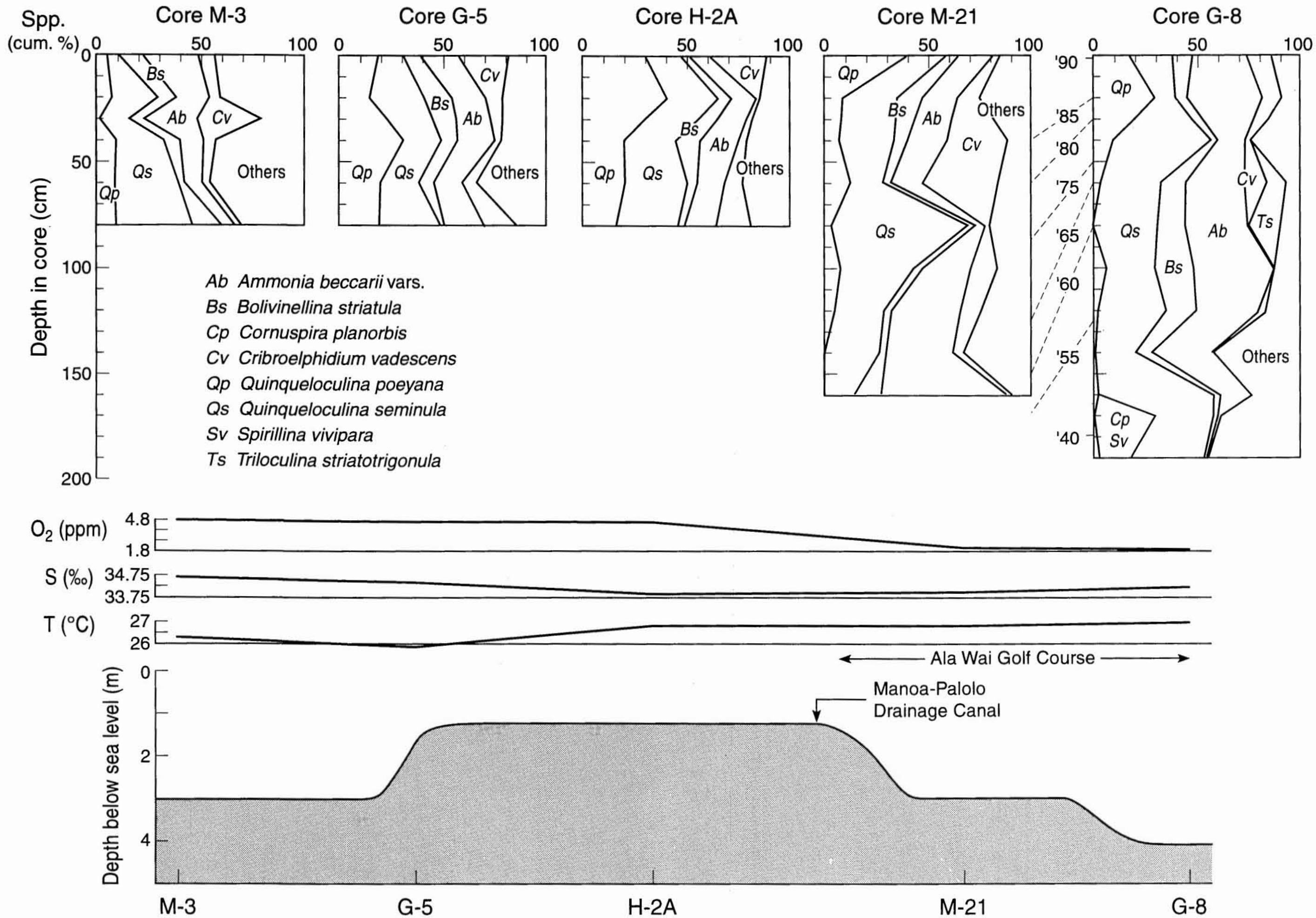


FIGURE 11. Foraminiferal distribution in Ala Wai cores relative to bottom topography, temperature (T), salinity (S), and O_2 of the bottom water. Bathymetry and water properties from Miller (1975); correlation in years based on cesium dating of McMurtry et al. (1995).

between population density of benthic foraminifera in the back basin and organic productivity.

Abnormal Tests and Pyrite

Alve (1991) reported seven test abnormalities in foraminifera from Sørfjord, Norway, five of which were recognized in the Ala Wai Canal (Appendix 3). These modes of test deformation and the species exhibiting them are as follows:

1. Reduced chamber size: *Ammonia beccarii* vars., *Bolivinellina striatula*, *Bulimina marginata*, *Cibicides lobatulus*, *Cribroelphidium vadescens*, *Elphidium articulatum*, *Protelphidium* sp., *Quinqueloculina poeyana*, *Quinqueloculina seminula*.
2. Protuberances: *Ammonia beccarii* vars., *Bolivinellina striatula*, *Cribroelphidium vadescens*, *Hopkinsina pacifica*, *Nonionoides limbatostriata*, *Quinqueloculina poeyana*, *Triloculina* sp.
3. Twisting or distortion: *Ammonia beccarii* vars., *Bolivinellina striatula*, *Cribroelphidium vadescens*, *Nonion* cf. *boueanum*, *Protelphidium* sp., *Quinqueloculina poeyana*, *Quinqueloculina seminula*.
4. Aberrant or bizarre chamber shape: *Ammonia beccarii* vars., *Cibicides lobatulus*, *Cribroelphidium vadescens*.
5. Twinned specimens: *Ammonia beccarii* var.

By far, the most common abnormalities were twisted or distorted tests, followed by the reduction in size of one or more chambers. One aberrant specimen of *Ammonia* had a fistulose apertural growth. The only two pairs of twins found were *Ammonia* from 120 and 140 cm in core M-21.

Abnormal tests composed 0–6.9% of the assemblages analyzed: <1–3.5% of the surface assemblages. Surface assemblages in the silled basin near the closed end of the canal exhibited the least frequent abnormality; the most frequent occurred at the sill (Appendix 3). The frequency of abnormal tests fluctuated downcore in no apparent pattern relative to the other parameters measured, but the lowermost samples of the two long cores from the back basin, which had low foraminiferal abundance, also lacked abnormal specimens.

Pyrite is present as botryoidal infilling (Figure 3) in <1–33% of the foraminiferal tests (Appendix 3). This percentage varies downcore, apparently independent of the other parameters measured.

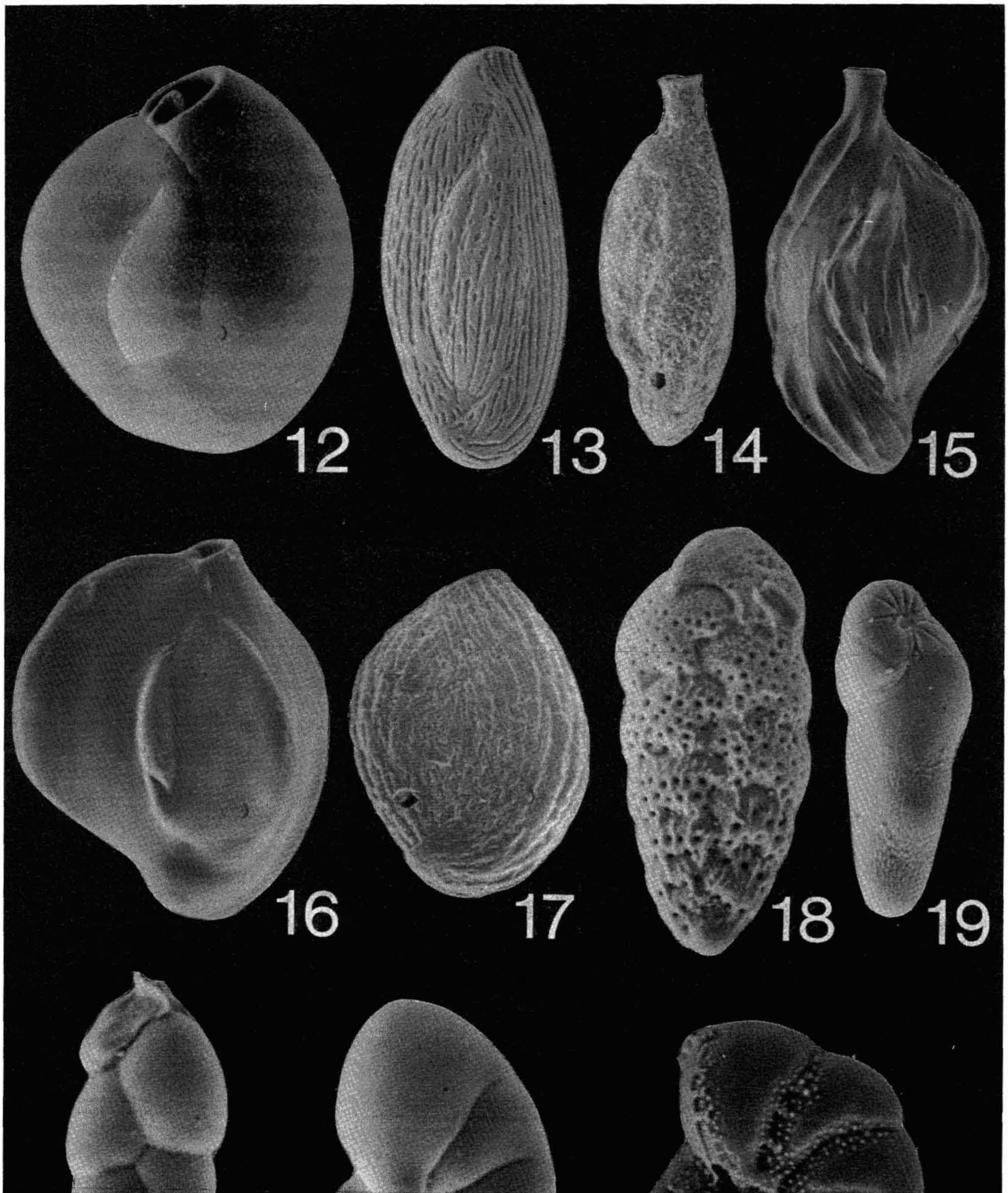
Foraminifera and Sediment Texture

The sand fraction composes 46–<1% of the sediment sampled, in an overall pattern of decreasing sand fraction from the entrance of the canal to the back basin (Appendix 2). In addition to the foraminifera, the sand fraction consists mainly of plant debris and detrital volcanic rock and mineral grains, but diatoms, ostracodes, fecal pellets, molluscan shells, coral and shell fragments, and fish teeth and scales occur in some samples. Shell fragments occur throughout core M-3, nearest the entrance, and are abundant in some horizons, whereas they are few in samples from cores M-21 and G-8 in the back basin where the detrital sediment is relatively fine grained.

Increases in foraminiferal abundance accompany increases in sand fraction in cores M-3 and G-5, but not in most samples from core H-2A at the sill or from M-21 and G-8 in the back basin. This indicates that the small foraminiferal tests are not the prime determinants of sediment texture throughout the canal. Their distribution better relates to substrate parameters such as a combination of calcium carbonate content (to facilitate test secretion) and organic carbon content (a measure of nutrients and food supply), as well as sedimentation rate (Glenn et al. 1995).

DISCUSSION

Laws et al. (1993) classified the Ala Wai Canal as a type B estuary of Briggs and Cronin (1981) in which the volume of the tidal prism is 10–20 times that of the freshwater discharge during half a tidal period, the amount of sediment lost through discharge to the sea is low, and the level of biological productivity is high. As a consequence of this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condition, foraminiferal assemblages of the canal differ from those reported in most estuaries (Murray 1973). They lack the large component of agglutinated tests found in the low-salinity upper reaches of estuaries and have instead a large component of miliolids, characteristic of only the lower parts of estuaries most subject to marine influx. The foraminiferal assemblages, in which *Quinqueloculina* spp., *Ammonia*, *Cribroelphidium* (or *Elphidium*), and *Bolivinellina striatula* are principal components, are more typical of normal marine (S = 30–40‰) to hypersaline (S = >40‰ lagoons (cf. Murray 1968, 1973, Boltovskoy and Wright 1976) than they are of most estuaries. The assemblages of species present in the canal are widespread in clastic littoral environments, in spite of the geographic isolation of the Hawaiian Islands.

For an estuarine setting, foraminiferal species densities have been linked to the amount and kind of food (Buzas 1969). Published measurements for chlorophyll *a* from water samples at 1-m depth, taken concurrently with the Ala Wai cores (Laws et al. 1993) show the highest values of ca. 35–45 mg/m^3 in the back basin and values of ca. 15–25 mg/m^3 in the remainder of the canal. Particulate nitrogen and carbon show a similar trend. This suggests that the large supply of organic nutrients contributes to high production of benthic foraminifera in the surface sediments of the back basin and substantiates the conclusion drawn from the $\delta^{13}C$ analysis of downcore carbonate (Glenn et al. 1995). Furthermore, the tests of dead individuals would tend to concentrate under the relatively slow rate of sediment accumulation behind the Mānoa-Pālolo Stream drainage canal, as evidenced by the small fraction of sand particles there and the reduced need for dredging. Finally, the relatively few benthic macroinvertebrates in the back basin (Miller 1975) would limit the loss of foraminifera through predation.

These large populations of benthic foraminifera inhabit the back basin under almost anoxic conditions for at least part of the year, particularly in the spring and summer (Gonzalez 1971). Clearly, the five dominant species adapt well to these low oxygen conditions. *A. beccarii* was found to survive extremely low oxygen levels of 0.1–0.8 mg/liter in waste ponds (LeFurgey and St. Jean 1976) and lived infaunally under reduced oxygen levels in eastern U.S. salt marshes (Steineck and Bergstein 1979, Goldstein and Harben 1993). Moodley and Hess (1992) reported *A. beccarii*, *Q. seminula*, and a species of *Elphidium* to have survived anoxia in a 24-hr laboratory experiment. These species can be considered facultative anaerobes: those surviving as well in low- and high-oxygen environments (Sen Gupta and Machain-Castillo 1993).

One strategy of accommodation for those species requiring higher levels of oxygen for their metabolism involves the utilization of oxygen produced by symbionts, which various elphidiids, nonionids, buliminids, and buliminellids are reported to have (Boltovskoy and Wright 1976: 263). A greenish brown color was seen in the tests of some specimens of *C. vadescens* from the Ala Wai. Chave (1987) noted brownish-colored protoplasm in *Q. bosciana* but only gray color in *Q. poeyana* and pink protoplasm in several other small miliolids, suggesting that at least some small miliolids may have symbionts. Shallow-water Hawaiian bolivinid species were all brownish in color (Chave 1987). The brownish or greenish coloration often signals the presence of symbionts, although a food source for the color cannot be ruled out at this time. As a group, the bolivinids are aften associated with oxygen-minimum zones on the outer

FIGURES 12–22. Minor species of benthic foraminifera, Ala Wai Canal. 12, *Triloculina* sp. × 180; H-2A, 0–2 cm. 13, *Quinqueloculina* sp. × 150; M-3, 0–2 cm. 14, *Quinqueloculina* sp. × 100; H-2A, 0–2 cm. 15, *Quinqueloculina* sp. × 175; M-21, 0–2 cm. 16, *Quinqueloculina lamarckiana* × 225; M-3, 0–2 cm. 17, *Quinqueloculina neostriatula* × 124; H-2A, 0-2 cm. 18, *Bolivina glutinata* × 250; M-3, 0–2 cm. 19, *Buliminoides parallela* × 175; M-3, 20–22 cm. 20, *Hopkinsina pacifica* × 250; M-21, 0–2 cm. 21, *Nonionoides limbatostriata* × 300; G-5, 0–2 cm. 22, *Protelphidium* sp. × 250; M-21, 0–2 cm.

continental shelf and upper slope (e.g., Harman 1964, Phleger and Soutar 1973, Resig 1981) where symbiosis is not a factor. The metabolic activity of these bolivinids has adapted to very low oxygen levels, and similar adaptation is suggested for the asymbiotic Ala Wai species.

Oxygen levels in the Ala Wai Canal do not appear to be critical for the dominant species. They reproduce within the range of temperature and salinity prevalent there and are most abundant where food supply and sedimentary regime dictates. Among the minor species, however, the greater diversity of surface assemblages nearest the canal entrance and the greater concentration of species such as *N. limbatostriata* forward of the sill are likely caused by gradients in environmental parameters and an inhibitive effect for these species of low-oxygen conditions in the back basin.

The Ala Wai Canal, although free of industrial waste, receives various pollutants commensurate with its location in an urban-recreational setting. These pollutants, summarized by Laws et al. (1993), include trash, heavy metals, pesticides, and pathogens. The high nutrient input and restricted circulation also result in pollution through eutrification. Comparison of some pollution-significant parameters between Sørfjord, Norway (Alve 1991), and the Ala Wai Canal (Table 6) reveals values for test abnormality in the canal's sediments comparable with those of moderately and severely polluted fjord strata. Alve attributed the highest percentage of abnormal tests (7%) to conditions of severe oxygen depletion. Reinforcement of a possible link between abnormality and pollution was provided by Lidz (1965), who estimated up to 30% abnormal tests on highly organic substrate nearest the town site on the shores of Nantucket Bay, Massachusetts. However, Lidz also cited extreme seasonal variation in temperature and salinity as a factor that could contribute to variable chamber formation. Wang et al. (1985) noted that abnormal tests are frequent in waters that deviate from normal marine salinity along the coast of China. Caralp (1989) linked high proportions of abnormality and highly organic substrate. Almogi-Labin et al. (1992) reported up to 17% abnormal *A. beccarii* in a hypersaline inland pool that was subject to large temperature fluctuations. In their summation of conditions contributing to test abnormality, Boltovskoy et al. (1991) cited salinity variation, too little or too much food, low oxygen, and pollution.

The Ala Wai Canal has several of these conditions that have been suggested to produce test abnormality: highly organic substrate, the possibility of rainfall-related salinity excursions below normal marine, low oxygen, and pollution. The greatest frequency of abnormality in the canal is in the sill area, near the juncture of the Mānoa-Pālolo Stream, not in the oxygen-depleted back basin. This suggests that at least some of the abnormal test growth results from the variable stream discharge. In fact, without further consideration of the incidence, type, and cause of abnormal test growth in unspoiled

TABLE 6

COMPARISON OF NORWEGIAN FJORD AND ALA WAI DATA

POLLUTION-RELATED PARAMETERS	SØRFJORD, NORWAY (ALVE 1991)		ALA WAI CANAL, HAWAI'I (THIS STUDY)	
	MODERATE POLLUTION	SEVERE POLLUTION	SURFACE	DOWNCORE
Abnormality (%)	2–3	1–7	0.9–3.8	0–6.9
Pyrite infilling (%)	2–6	5–11	0–3.2	0–32.9
Foraminifera per gram of sediment	50–60	0–30	29–140	8–323
No. of species	30	0–25	10–31	10–32
Organic carbon (%)	2	0.5–4	4.5–6.2	0.6–7.8

coastal environments, the importance of abnormality in polluted environments cannot be evaluated fairly.

Pyrite precipitation in botryoidal form occurs under microenvironmental anoxia in foraminiferal tests. In Sørfjord, the incidence of pyrite-infilled tests was related directly to the degree of pollution (Alve 1991). The range of frequency of infilling in the Ala Wai Canal is greater than in the fjord and the values reached are up to three times those in the fjord (Table 6). This is probably related to higher amounts of organic matter present in the canal along with the larger foraminiferal populations found there.

In Sørfjord, a reduction in both the number of species and the abundance of tests was related directly to pollution (Alve 1991). In contrast, half of the test abundance figures for the Ala Wai were far above those for polluted strata of the fjord. In summation, urban pollution may have affected the Ala Wai foraminiferal populations somewhat in test growth, but not to the extent of inhibiting productivity in the canal.

CONCLUSIONS

The foraminiferal assemblages throughout the Ala Wai Canal are dominated by five species: *Ammonia beccarii* vars., *Bolivinellina striatula*, *Cribroelphidium vadescens*, *Quinqueloculina poeyana*, and *Quinqueloculina seminula*. This association of species is indicative of marine salinities that are prevalent at the sediment-water interface. Subsurface deposits contain essentially the same assemblages, except for the base of the longest stratigraphic section, cored in the back basin, where distinctive species are associated with a substrate high in calcium carbonate. Dredging events that affect water circulation in the canal may be reflected by changes in species frequencies in the back basin. Assemblages high in agglutinated taxa indicative of persistent hyposaline conditions were not found.

The five dominant species are facultative anaerobes, tolerant of the nearly anoxic conditions in the back basin. Because of nutrient enrichment and high phytoplankton productivity, the abundance of foraminiferal tests at the sediment surface was highest in the back basin, reaching 140 specimens per gram of sediment. A link is suggested between the higher foraminiferal abundance generally present in the back basin since the late 1950s and organic productivity. Species diversity was highest nearest the canal entrance.

Subsurface fluctuations in foraminiferal abundance are attributed mainly to variation in sedimentation rate, because the midsill site (H-2A) bears the overall lowest abundance of tests. However, sorting by tidal currents or environmental controls on foraminiferal productivity probably play a role.

Test abnormality, which ranges up to 4% at the surface and 7% subsurface is suggestive of the pollution inherent to the canal. The severity of the pollution has not been great enough to date to alter the species composition or to inhibit productivity of these highly adaptive protists.

ACKNOWLEDGMENTS

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APPENDIX 1

FAUNAL REFERENCE LIST

Listed below are the species names used in this work followed by the original name designated by the author. Complete references and descriptions for the type species are reproduced under the original name in the *Catalogue of Foraminifera* (Ellis and Messina [1940 and supplements]).

Ammonia beccarii (Linné) vars. = *Nautilus beccarii* Linné, 1758, Syst. Nat. ed. 10, 1: 710.

Bolivina glutinata Egger, 1893, Abh. Kön. Bay. Akad. Wiss. München 18: 297.

Bolivina sp.

Bolivinellina limbata (Brady) = *Bolivina limbata* Brady, 1881, Q. J. Microsc. Soc., n.s. 21: 57.

Bolivinellina striatula (Cushman) = *Bolivina striatula* Cushman, 1922, Carnegie Inst. Washington Publ. 311: 27.

Bolivinellina sp.

Buccella cf. *inusitata* Andersen, 1952, J. Wash. Acad. Sci. 42: 148.

Bulimina marginata d'Orbigny, 1826, Ann. Sci. Nat. 7: 269.

Buliminella elegantissima (d'Orbigny) = *Bulimina elegantissima* d'Orbigny, 1839, Voy. dans l'Amerique Méridionale 5: 51.

Buliminella sp.

Buliminoides parallela (Cushman & Parker) = *Buliminella parallela* Cushman & Parker, 1931, Proc. U.S. Natl. Mus. 80(3): 13.

Cassidulina minuta Cushman, 1933, Contrib. Cushman Lab. Foraminiferal Res. 9: 92.

Cibicides lobatulus (Walker & Jacob) = *Nautilus lobatulus* Walker & Jacob, 1798, *in* F. Kanmaker, Adams' Essays Micr. 2nd ed., p. 642.

Cornuspira planorbis Schultze, 1854, Organismus Polythal., p. 40.

Cribroelphidium mexicanum (Kornfeld) = *Elphidium incertum* (Williamson) var. *mexicanum* Kornfeld, 1931, Contrib. Stanford Univ. Dep. Geol. 1: 89.

Cribroelphidium simplex (Cushman) = *Elphidium simplex* Cushman, 1933, U.S. Natl. Mus. Bull. 161: 52.

Cribroelphidium vadescens Cushman & Brönnimann, 1948, Contrib. Cushman Lab. Foraminiferal Res. 24: 18.

Cribroelphidium sp.

Cymbaloporetta squammosa (d'Orbigny) = *Rosalina squammosa* d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba, p. 91.

Dentalina sp.

Elphidium advenum (Cushman) = *Polystomella advena* Cushman, 1922, Carnegie Inst. Washington Publ. 311: 56.

Epistominella pulchra (Cushman) = *Pulvinulinella pulchra* Cushman, 1933, Contrib. Cushman Lab. Foraminiferal Res. 9: 92.

Fijiella simplex (Cushman) = *Trimosina simplex* Cushman, 1929, J. Wash. Acad. Sci. 19: 158.

Fischerinella helix (Heron-Allen & Earland) = *Fischerina helix* Heron-Allen & Earland, 1915, Trans. Zool. Soc. Lond. 20: 591.

Fissurina cucurbitasema basispinata Ujiie,

1963, Tokyo Kyoiku Daigaku Sci. Rep., C 8:232.
Fursenkoina punctata (d'Orbigny) = *Virgulina punctata* d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba, p. 139.
Glabratella sp.
Hauerina bradyi Cushman, 1917, U.S. Natl. Mus. Bull. 71(6): 62.
Hauerina pacifica Cushman, 1917, U.S. Natl. Mus. Bull. 71(6): 64.
Helenina anderseni (Warren) = *Pseudoeponides anderseni* Warren, 1957, Contrib. Cushman Found. Foraminiferal Res. 8: 39.
Heterostegina depressa d'Orbigny, 1826, Ann. Sci. Nat. 7:304, 305.
Hopkinsina pacifica Cushman, 1933, Contrib. Cushman Lab. Foraminiferal Res. 9:86.
Lagena laevis (Montagu) = *Vermiculum laeve* Montagu, 1803, Test. Britannica, p. 524.
Lamellodiscorbis aguayoi (Bermúdez) = *Discorbis aguayoi* Bermúdez, 1935, Mem. Soc. Cubana Hist. Nat. 9:204.
Lingulina sp.
Miliammina fusca (Brady) = *Quinqueloculina fusca* Brady, 1870, Ann. Mag. Nat. Hist., ser. 4 6:47.
Miliolinella subrotunda (Montagu) = *Vermiculum subrotundum* Montagu, 1803, Test. Britannica, p. 521.
Miliolinella spp.
Monalysidium politum Chapman, 1900, Linn. Soc. Lond., J. Zool. 28(179): 4.
Murrayinella murrayi (Heron-Allen & Earland) = *Rotalia murrayi* Heron-Allen & Earland, 1915, Trans. Zool. Soc. Lond. 20:720.
Neoconorbina frustata (Cushman) = *Discorbis frustata* Cushman, 1933, Contrib. Cushman Lab. Foraminiferal Res. 9:88.
Nonion cf. *boueanum* (d'Orbigny) = *Nonionina boueana* d'Orbigny, 1846, Foram. Foss. Bassin Tertiaire Vienne, p. 108.
Nonionoides limbatostriata (Cushman) = *Nonionella limbato-striata* Cushman, 1931, Contrib. Cushman Lab. Foraminiferal Res. 7:30.
Patellina corrugata Williamson, 1858, Recent Foraminifera Great Britain, p. 46.
Patellinoides sp.
Peneroplis pertusus (Forskål) = *Nautilus pertusus* Forskål, 1775, Descr. Anim., p. 125.
Protelphidium sp.
Pseudoparrella sp.
Quinqueloculina bosciana d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba 8:191.
Quinqueloculina distorqueata Cushman, 1954, U.S. Geol. Surv. Prof. Pap. 260-H, p. 333.
Quinqueloculina kerimbatica (Heron-Allen & Earland) = *Miliolina kerimbatica* Heron-Allen & Earland, 1915, Trans. Zool. Soc. Lond. 20:574.
Quinqueloculina lamarckiana d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba 8:189.
Quinqueloculina neostriatula Thalmann, 1950, Contrib. Cushman Found. Foraminiferal Res. 1:45.
Quinqueloculina poeyana d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba 8: 191.
Quinqueloculina polygona d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba 8: 198.
Quinqueloculina seminula (Linné) = *Serpula seminulum* Linné, 1758, Syst. Nat. ed. 10, 1:786.
Quinqueloculina spp.
Rosalina floridana (Cushman) = *Discorbis floridana* Cushman, 1922, Carnegie Inst. Washington Publ. 311:39.
Rosalina sp.
Rotorboides granulosus (Heron-Allen & Earland) = *Discorbina valvulata* (d'Orbigny) var. *granulosa* Heron-Allen & Earland, 1915, Trans. Zool. Soc. Lond. 20:695.
Sigmavirgulina tortuosa (Brady) = *Bolivina tortuosa* Brady, 1881, Q. J. Microsc. Soc., n.s. 21:57.
Siphogenerina costata Schlumberger, 1883, Feuille Jeunes Naturalistes 13:26.
Siphotextularia sp.
Spirillina vivipara Ehrenberg, 1841, Abh. Akad. Wiss. Berl., 1841, p. 442.
Spiroloculina communis Cushman & Todd, 1944, Cushman Lab. Foraminiferal Res. Spec. Publ. 11:63.
Spiroloculina corrugata Cushman & Todd, 1944, Cushman Lab. Foraminiferal Res. Spec. Publ. 11:61.
Spiroloculina cf. *elegantissima* Said, 1949,

Cushman Lab. Foraminiferal Res. Spec. Publ. 26:15.

Spiroloculina spp.

Textularia sp.

Triloculina linneiana d'Orbigny, 1839, *in* de la Sagra, Hist. Physiq. Nat. Cuba 8:172.

Triloculina oblonga (Montagu) = *Vermiculum oblongum* Montagu, 1803, Test. Britannica, p. 522.

Triloculina striatotrigonula Parker & Jones, 1941, *in* W. J. Parr, Mining and Geol. J. 2:305.

Triloculina subgranulata Cushman, 1918, Carnegie Inst. Washington Publ. 213:290.

Triloculina trigonula (Lamarck) = *Miliolites trigonula* Lamarck, 1804, Ann. Paris Mus. Natl. Hist. Nat. 5:351.

Triloculina sp.

Trochammina inflata (Montagu) = *Nautilus inflatus* Montagu, 1808, Test. Britannica, p. 81.

Tubinella funalis (Brady) = *Articulina funalis* Brady, 1884, Rep. Voy. Challenger, Zool. 9:185.

APPENDIX 2

ALA WAI SAMPLE DATA

CORE, INTERVAL (cm)	DRY WT. (g)	SAND FRACTION (g)	% SAND	NO. FORAM./g
M-3, 0–2	5.6	1.2	21.4	45.5
M-3, 20–22	11.2	5.1	45.5	102.6
M-3, 30–32	10	0.8	8.0	12.3
M-3, 40–42	17.2	5.6	32.5	166.1
M-3, 60–62	16.5	3.5	21.2	103.6
M-3, 80–82	17.2	2.0	11.6	27.3
G-5, 0–2	4.0	0.3	7.5	57.2
G-5, 20–22	9.6	1.2	12.5	83.4
G-5, 40–42	8.1	0.2	2.4	9.5
G-5, 60–62	17.6	2.8	15.9	322.7
G-5, 80–82	21.3	3.3	15.4	149.6
H-2A, 0–2	6.3	1.2	19.0	29.3
H-2A, 20–22	6.5	0.3	4.6	33.7
H-2A, 40–42	6.1	0.6	9.8	7.7
H-2A, 60–62	6.1	0.2	3.2	29.5
H-2A, 80–82	14.7	1.2	8.1	47.9
M-21, 0–2	6.3	0.1	1.5	100.2
M-21, 20–22	5.1	0.05	0.01	85.6
M-21, 40–42	6.0	0.2	3.3	189.3
M-21, 60–62	7.6	0.2	2.6	314.0
M-21, 80–82	7.8	0.7	8.9	45.7
M-21, 100–102	9.8	0.06	0.01	47.3
M-21, 120–122	12.4	1.0	8.0	35.3
M-21, 140–142	10.3	0.1	0.9	39.7
M-21, 160–162	13.5	0.03	0.002	14.3
G-8, 0–2	3.5	0.2	5.7	139.7
G-8, 20–22	6.6	0.2	3.0	179.0
G-8, 38–40	3.3	0.05	0.01	46.9
G-8, 60–62	7.5	0.1	1.3	177.0
G-8, 80–82	10.3	0.1	0.9	119.3
G-8, 100–102	9.0	0.1	1.1	109.2
G-8, 120–122	10.7	0.2	1.8	64.8
G-8, 140–142	11.0	0.2	1.8	17.5
G-8, 158–160	6.9	0.2	2.8	102.3
G-8, 170–172	15.0	0.1	0.6	14.6
G-8, 190–192	13.9	0.1	0.7	7.6

APPENDIX 3

PYRITE INFILLING AND TEST ABNORMALITY

CORE, INTERVAL (cm)	COUNT	PYRITE %	REDUCED CHAMBER NO.	PROTUBERANCE NO.	DISTORTED NO.	ABERRANT NO.	TWINNED NO.	TOTAL ABNORMAL %
M-3, 0–2	255	2.0			5			2.0
M-3, 20–22	286	17.1	1		5	1		2.4
M-3, 30–32	123	5.7	1		1			1.6
M-3, 40–42	357	10.4				1		0.3
M-3, 60–62	213	15.0			1	1		0.9
M-3, 80–82	118	16.1	1		1			1.7
G-5, 0–2	229	0.0	1	2	5			3.5
G-5, 20–22	400	2.3			3			0.8
G-5, 40–42	78	5.1	2		1	1		5.1
G-5, 60–62	355	19.2	6	1	11			5.1
G-5, 80–82	398	16.6	2	1	8	1		3.0
H-2A, 0–2	185	0.5	2	2	3			3.8
H-2A, 20–22	217	0.9	1	1	13			6.9
H-2A, 40–42	46	6.5	1					2.2
H-2A, 60–62	179	1.7			1			0.6
H-2A, 80–82	707	9.1	2		20			3.1
M-21, 0–2	316	0.9	1		4			1.6
M-21, 20–22	217	2.8	2		12			6.5
M-21, 40–42	284	8.8	1	1	8			3.5
M-21, 60–62	298	4.4	1		17	1		6.4
M-21, 80–82	353	8.5			7	1		2.3
M-21, 100–102	466	2.6	4		8	1		2.8
M-21, 120–122	220	4.5	2	2	6		1	5.0
M-21, 140–142	406	3.9	1	1	5		1	2.0
M-21, 160–162	191	2.6						0.0
G-8, 0–2	244	3.2		1	1			0.9
G-8, 20–22	592							
G-8, 38–40	155	0.6			3			1.9
G-8, 60–62	332	1.8	3	2	5			3.0
G-8, 80–82	307	32.9	2	1	3			2.0
G-8, 100–102	246	23.2	2	1	7			4.1
G-8, 120–122	345	4.3	2		2			1.2
G-8, 140–142	189	5.3	3		1			2.1
G-8, 158–160	353	0.6			4			1.1
G-8, 170–172	216	4.6						0.0
G-8, 190–192	106	0.9						0.0