Pacific Science (1989), vol. 43, no. 1

Calcareous Organisms and Sediment Mineralogy on a Mid-Depth Bank in the Hawaiian Archipelago[1]

CATHERINE R. AGEGIAN[2] AND FRED T. MACKENZIE[3]

ABSTRACT: The dominant calcareous organisms on Penguin Bank, a mid-depth bank (40–100 m) off the southwestern tip of the island of Molokai, Hawaii, are red and green algae, benthic foraminifera, and bryozoans. The sediments on Penguin Bank are a mixed mineralogic assemblage of benthically derived magnesian calcite and aragonite. A low pelagic input of foraminifera and coccolithophorids to the sediments was indicated by the small percentage of low magnesian calcite found only in the smallest size fractions and the lack of recognizable particles of these organisms in these size fractions. The benthic community on Penguin Bank, composed of coralline algae, benthic foraminifera, and bryozoans, produces magnesian calcite with a range in magnesium content of about 6–16 mole % $MgCO_3$. Calcareous green algae (predominantly *Halimeda*) are the dominant producers of aragonite. Sediments on Penguin Bank are dominated by magnesian calcite particles in all size fractions (<45–3962 μm). The ratio of the percentage of high magnesian calcite (>5 mole %) to aragonite increases in the smaller size fractions and with increasing water depth from 40 to 93 m. The magnesium content of the sediments decreases within the same depth range. Mid-depth banks may be potential sources of highly chemically reactive carbonate particles to the open ocean. The magnitude of this input has not been quantitatively assessed but may be important in global biogeochemical cycles of calcium and carbon in the ocean reservoir.

SKELETAL DEBRIS FOUND in shallow marine calcareous sediments usually is produced in the upper part of the euphotic zone (<30 m) in tropical and subtropical environments. The physicochemical properties of the upper layer of the euphotic zone favor photosynthetically mediated precipitation of the highly reactive carbonate minerals aragonite and magnesian calcite in skeletons.

Recently, descriptions of tropical, deep-water calcareous marine communities have shown that significant production of calcium carbonate by benthic organisms may be possible at depths greater than 50 m (Littler et al. 1985). A rich assemblage of carbonate organisms consisting of red and green calcareous algae, bryozoans, pen shells, and corals was observed at 40–90 m on Penguin Bank (Figures 1 and 2), Hawaii, from the submersible *Makali'i* (Agegian and Abbott 1985). A similar community composition was described at comparable depths from Kure Atoll (Dana 1970), from collections made by the submersible in the Northwestern Hawaiian Islands at French Frigate Shoals and Gardner Pinnacle [Hawaii Undersea Research Laboratory (HURL) data archives], and from dredge hauls throughout the Northwestern Hawaiian Islands (Adey et al. 1982). Coralline algal communities have been described from the Caribbean to a depth of 267 m (Littler et al. 1985). Thickets of the calcareous green alga *Halimeda* have been observed on the deep

[1] This work was supported in part by the Petroleum Research Fund (American Chemical Society), ACS-PRF grant 17371-AC2, and in part by the Hawaii Undersea Research Laboratory (HURL) through NOAA funding. Hawaii Institute of Geophysics Contribution 2053. Manuscript accepted 1 May 1988.

[2] University of Hawaii, Hawaii Institute of Geophysics, Honolulu, Hawaii 96822.

[3] University of Hawaii, Hawaii Institute of Geophysics and Department of Oceanography, Honolulu, Hawaii 96822.

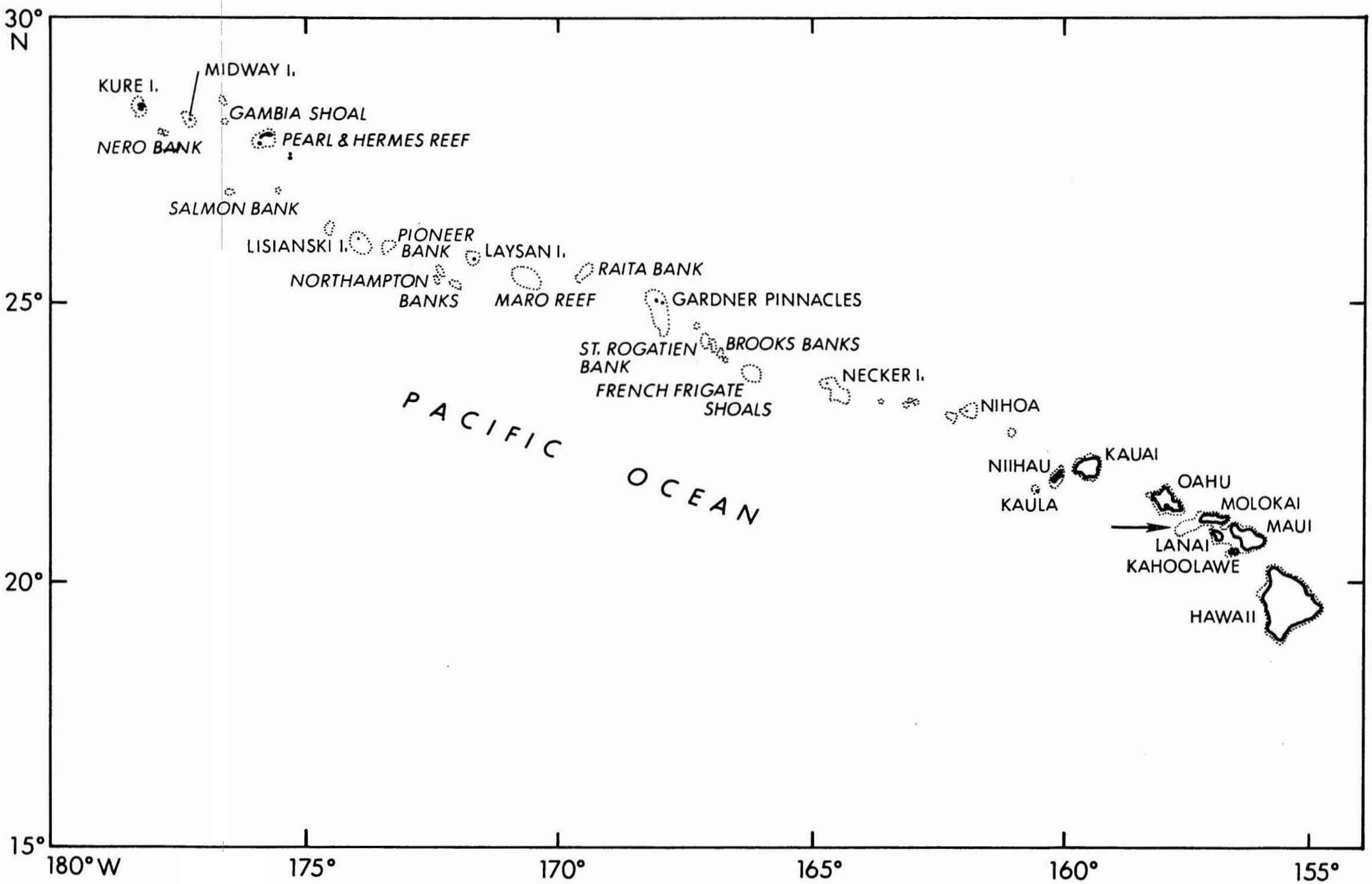

FIGURE 1. Map showing location of Penguin Bank (black arrow) and other mid-depth banks throughout the Hawaiian archipelago. Dotted lines mark position of 100-m depth contour.

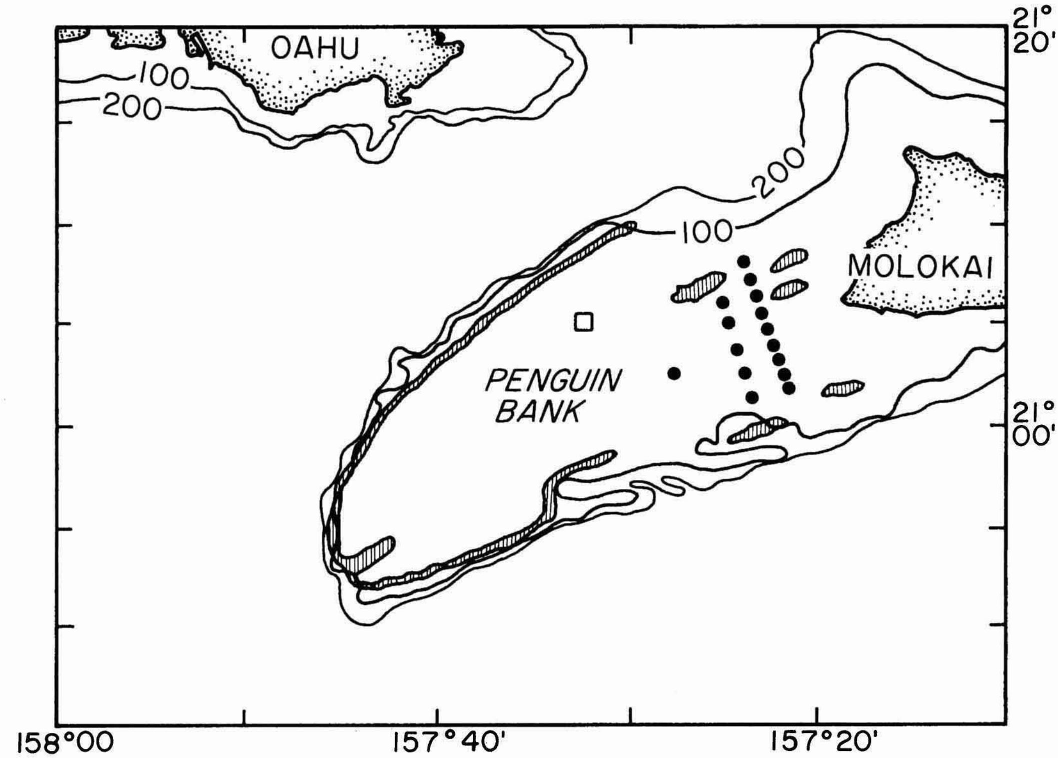

FIGURE 2. Map of Penguin Bank showing sites where sediments were collected with a bottom grab (black dots) and the area where observations were made with the submersible *Makali'i* (small square). Crosshatched areas show the locations of some of the thicker (> 9 m) sand deposits around the rim of the bank (Moberly et al. 1975). Depth contours are in fathoms.

slopes of Enewetak Atoll (Hillis-Colinvaux 1985), in the Caribbean (Littler et al. 1985), and on the Great Barrier Reef (Drew and Abel 1985).

Smith (1978) estimated that reefs precipitate approximately 50% of the annual input of calcium delivered to the oceans by rivers. Because of the morphology of Pacific islands and atolls, much of this material may be retained within the reef structure (Smith et al. 1971) and deposited in calm, lagoonal environments. Deep-water calcareous communities may represent an additional significant sink of calcium. These deep-water communities are found on banks located at mid-depth (50–100 m) in the Pacific. Because of the lack of sediment barriers (such as atoll reefs surrounding lagoons), skeletal particles, primarily of aragonite and magnesian calcite, derived from these communities may be transported directly into the deep sea and be sedimented or dissolved en route or after deposition at depths shallower than those of calcite dissolution.

Carbonate skeletal sediments deposited on tropical and subtropical mid-depth (50–100 m) banks associated with islands in the Pacific can have several sources. One source is the benthic communities living on the bank. Mechanical and biological erosion of the skeletons of organisms in these communities can lead to in situ production of carbonate particles of a myriad of grain sizes. Two other sources, in these cases of allochthonous particles, are benthic and pelagic skeletal organisms living in the upper layer of the euphotic zone at 0–50 m. Inputs of skeletal debris from these latter two sources to mid-depth banks require, respectively, suspended or traction transport of shoal-water calcareous particles, or gravity settling of pelagic calcareous debris. In the present study, we document the sites of production of mid-depth bank skeletal sediments, emphasizing the nature of the benthic communities found in this environment and their contribution to production of highly chemically reactive aragonite and magnesian calcite skeletal particles. Furthermore, this paper represents the first description of benthic communities and calcareous sediments found on Pacific mid-depth banks.

MATERIALS AND METHODS

Collection of calcareous benthic organisms were obtained using the submersible *Makali'i* during a series of dives conducted along the northern edge of Penguin Bank (Figure 2) between 1985 and 1986.

Fifteen Shipeck bottom grabs were obtained from the research vessel *Townsend Cromwell* during the National Marine Fisheries cruise TC 85-02. Samples were taken on 22 April 1986 at sites shown in Figure 2. In general, the sampling depth increases near the edges of the bank.

Organic matter was removed from all samples with hydrogen peroxide buffered to a pH of about 7. The sediment–hydrogen peroxide mixture was centrifuged, and the supernatant removed and retained. Distilled water was then added to the sediment, the slurry was stirred, and the supernatant was collected by ultracentrifugation. This rinsing process was repeated twice. All the supernatants of an individual sample were filtered through a 0.45-μm millipore filter, which was rinsed with distilled water. The filtered sediment residues were added to the bulk sample, and the total weight of the cleaned sample was obtained after oven drying at 60°C overnight.

Each dried sediment sample was size fractionated using the wet-sieving procedure described by Neumann (1965). Representative portions of each size fraction less than 4 mm were ground using a mortar and pestle, sieved, and the <62-μm fraction used for X-ray diffraction analysis. Individual calcareous organisms were treated similarly. The mineralogy and mole % $MgCO_3$ of the organisms and sediments were determined using the methods of Neumann (1965), with the exception that the weight percentages of low magnesian calcite (<5 mole % $MgCO_3$) and aragonite were determined using the triangle method of Mann and Fischer (1982) modified for carbonates. A qualitative visual and binocular microscopic investigation of the skeletal composition of the grains was performed.

RESULTS

The benthic calcareous community on Penguin Bank is composed primarily of unattached, calcareous red and green algae, benthic foraminifera, and bryozoans overlying a sediment-covered carbonate platform. The community has a patchy distribution throughout the area of observation and covers, on the average, 10–40% of the sediment-covered substratum.

The mineralogical composition of the benthic organisms is magnesian calcite, aragonite, or a mixture of the two phases. The presence of aragonite in coralline algae and magnesian calcite in *Peysonellia* reflects either detrital contamination or secondary precipitation of cements. Alexandersson (1974) documented the occurrence of aragonite and magnesian calcite cements in cellular spaces of coralline algal thalli. Brissid urchins and one species of bryozoan contain a mixture of magnesian calcite and aragonite. The magnesian calcite component of these organisms has a compositional range of about 6–16 mole % $MgCO_3$ (Table 1). The average magnesium content of the magnesian calcite component of all organisms analyzed was 12.1 mole % $MgCO_3$. The dominant aragonitic organisms are the green algae *Halimeda* spp. and *Neomeris*, the leafy red alga *Peysonellia*, and the hermatypic corals *Leptoseris* and *Montipora*. In contrast to the other organisms described above, hermatypic corals are not abundant and have a more restricted distribution, growing attached to the substratum along the edges of the bank at a depth of approximately 100 m.

The magnesium content of the magnesian

TABLE 1

MINERALOGY OF DOMINANT ORGANISMS AND MAGNESIUM CONTENT OF MAGNESIAN CALCITE COMPONENT ON PENGUIN BANK DETERMINED BY X-RAY DIFFRACTION

ORGANISM	HIGH MAGNESIAN CALCITE	ARAGONITE	MAGNESIUM CONTENT (mole % $MgCO_3$)
Coralline algae			
Lithothamnium	95.5	4.5	16.3
Mesophyllum	67.7	32.3	14.7
Foraminifera	100.0	—	14.3
Brissid urchins	88.2	11.8	12.3
Bryozoan #1	83.2	16.8	6.9
Bryozoan #2	100.0	—	9.9
Bryozoan #3	100.0	—	10.3
Mean (SD, *n*)			12.1 (3, 7)
Halimeda	—	100.0	—
Peysonellia	3.5	96.5	—

NOTE: The presence of aragonite in coralline algae and magnesian calcite in *Peysonellia* is the result of either sample contamination or secondary (inorganic) precipitation of these minerals as cements, i.e., pores and spaces of the algal thalli.

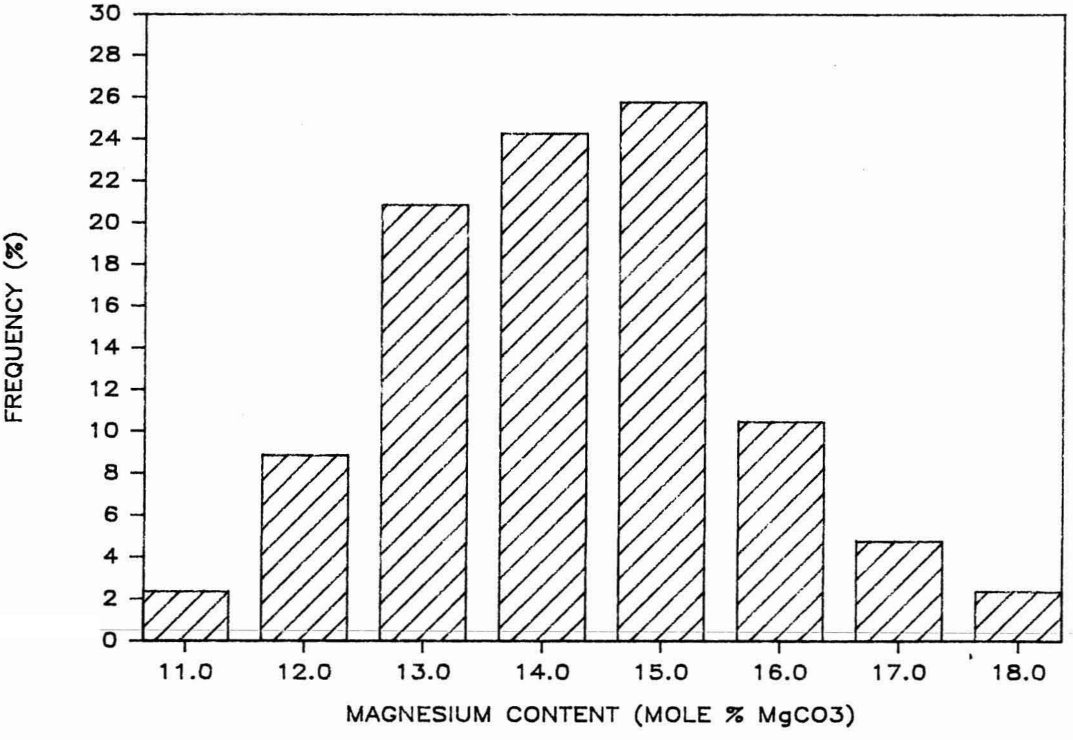

FIGURE 3. Histogram showing the frequency of sediment samples as a function of the magnesium content of the calcite component of sediments on Penguin Bank, Hawaii.

TABLE 2

MINERALOGY OF SEDIMENTS FROM PENGUIN BANK AND MAGNESIUM CONTENT OF MAGNESIAN CALCITE COMPONENT BY SIZE FRACTION

SIZE FRACTION (μm)	% HMC ($\bar{x}$, SD)	% LMC ($\bar{x}$, SD)	% ARG ($\bar{x}$, SD)	% HMC/% ARG	mole % $MgCO_3$ ($\bar{x}$, SD)	n
3962	57 (34)	0	39 (31)	1.5	15.9 (0.9)	6
1981	66 (21)	1 (5)	28 (11)	2.4	14.9 (3.6)	15
495	81 (8)	2 (7)	17 (6)	4.8	15.1 (1.2)	16
246	77 (11)	8 (11)	15 (4)	5.1	14.8 (0.8)	16
124	71 (12)	7 (12)	19 (7)	3.7	14.6 (0.8)	16
61	55 (14)	30 (20)	15 (8)	3.7	13.7 (1.2)	16
45	56 (11)	31 (17)	13 (11)	4.3	13.9 (1.6)	15
<45	69 (16)	18 (18)	13 (9)	5.3	14.3 (0.9)	14

NOTE: HMC = high magnesian calcite, LMC = low magnesian calcite, ARG = aragonite, $\bar{x}$ = mean, SD = standard deviation, n = number of samples.

calcite component of the sediments on Penguin Bank is similar to that of the deep-water benthic community. The bulk magnesium content of the sediments ranged between 11 and 18 mole % $MgCO_3$ (Figure 3). The mean composition is 14.7 mole % $MgCO_3$. In 93% of the samples analyzed, the magnesian calcite component contained magnesium contents within the compositional range of the deep-water benthic organisms.

The average magnesium content of the magnesian calcite component of the sediments decreased (Table 2) with decreasing size fraction. Coarse-grained sediments (size fractions between 124 μm and 3962 μm) had slightly higher magnesium contents than size fractions less than 124 μm. The ratio of the percentage of high magnesian calcite to aragonite in each size fraction was variable (Table 2) but generally was low in the large size fractions.

High magnesian calcite (magnesian content > 5 mole % $MgCO_3$) particles were the dominant mineral component of all samples (Figure 4), comprising 50–80% of each size fraction, on the average. The average normalized percentage of aragonite was low and constant over most of the size fractions and only increased in the two largest fractions. The composition of the sediments was dominated by magnesian calcite and aragonite in size fractions greater than 124 μm and by magnesian calcite and calcite with a low magnesium content (<5 mole % $MgCO_3$) in the remaining, smaller size fractions.

The mineralogic composition of the sediments on Penguin Bank varies spatially. Overall, the average ratio of magnesian calcite to aragonite in the sediments increases between the depths of 40 and 93 m (Table 3). The average mole % $MgCO_3$ decreases slightly over the same depth range (Table 3).

DISCUSSION

Penguin Bank and possibly other mid-depth banks in the Pacific are herein identified as carbonate-producing environments that are biologically and mineralogically different

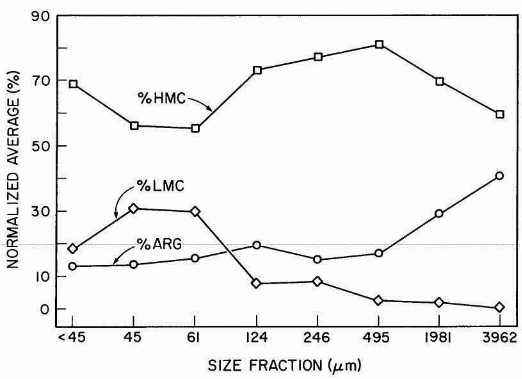

FIGURE 4. Average normalized percentage of high magnesian calcite (% HMC > 5 mole % $MgCO_3$), low magnesian calcite (% LMC < 5 mole % $MgCO_3$), and aragonite (% ARG) of sediments on Penguin Bank by size fraction.

TABLE 3

MINERALOGY OF SEDIMENTS AND MAGNESIUM CONTENT OF MAGNESIAN CALCITE COMPONENT BY DEPTH

DEPTH (m)	% HMC ($\bar{x}$, SD)	% ARG ($\bar{x}$, SD)	% HMC/% ARG	MAGNESIUM CONTENT $\bar{x}$ mole % $MgCO_3$	SD	n	% HMC/% ARG ($\bar{x}$, SD)	mole % $MgCO_3$ ($\bar{x}$, SD)	n
40	64.8 (12.8)	22.1 (8.4)	2.9	15.2	0.7	6			
45	58.1 (20.3)	30.7 (23.6)	1.9	14.8	2.3	7	2.4 (0.7)	15.0 (0.3)	2
55	62.5 (9.4)	22.4 (9.2)	2.8	14.6	1.4	8			
55	58.1 (28.8)	32.1 (33.4)	1.8	15.7	0.9	7			
55	60.4 (12.8)	17.6 (9.8)	3.4	15.2	1.5	8			
56	76.5 (17.9)	12.5 (8.7)	6.1	15.2	1.3	8			
58	68.4 (10.6)	29.7 (11.6)	2.3	14.9	1.0	8	3.3 (1.7)	15.1 (0.4)	5
60	78.9 (13.3)	12.3 (10.1)	6.4	14.5	1.0	8			
60	68.4 (19.8)	13.5 (7.4)	5.1	14.7	1.3	8			
62	54.1 (31.8)	12.9 (3.6)	4.2	15.3	1.3	7			
64	61.9 (19.6)	30.2 (21.5)	2.0	14.5	1.2	8			
67	68.2 (24.1)	22.6 (20.3)	3.0	14.9	1.5	6	4.1 (1.7)	14.8 (0.3)	5
78	70.3 (12.3)	14.4 (6.9)	4.9	13.4	1.0	8			
91	78.8 (14.4)	10.5 (2.8)	7.5	14.3	0.9	8			
91	67.3 (25.4)	21.6 (23.6)	3.1	14.9	1.0	8			
93	76.6 (9.9)	17.4 (8.1)	4.4	14.6	1.3	8	4.9 (1.8)	14.3 (0.6)	4

NOTE: HMC = high magnesian calcite, ARG = aragonite, $\bar{x}$ = mean, SD = standard deviation, n = number of samples.

from adjacent shoal-water reefs and lagoons. The top of Penguin Bank and other banks and shelves throughout the Pacific basin are found at similar depths, because these banks were formed by an interplay between reef growth and past low stands of global sea level (Gregory and Kroenke 1982, Grigg 1982, Stearns 1974).

Mid-depth bank communities have a biological species composition and community structure different from that generally found in shoal-water reef areas (Agegian and Abbott 1985). Of the dominant magnesian calcite organisms on Penguin Bank (coralline algae, benthic foraminifera, and bryozoans), bryozoans are rare in shoal-water environments. In the Hawaiian archipelago, however, they and calcareous algae increase northwestward relative to corals, probably because of decreasing mean temperature of the marine environment southeast to northwest along the trend of the archipelago (Schlanger and Konishi 1975). Hermatypic corals, the dominant aragonitic organisms in shoal-water environments, are replaced by calcareous green algae and the leafy red alga *Peysonellia* on Penguin Bank. This assemblage of organisms resembles a mixture of the "foramol" and "chlorozoan" associations described by Lees and Buller (1972), because bryozoans, typically rare in tropical and subtropical assemblages, are a dominant constituent of the community. The skeletal grain association found on Penguin Bank may be viewed in terms of a temperature–salinity relationship (Figure 5). This association is like that of shoal-water environments of the Northwestern Hawaiian Islands (Gross et al. 1969), where average annual temperatures are lower compared to shoal-water environments in the main Hawaiian Islands.

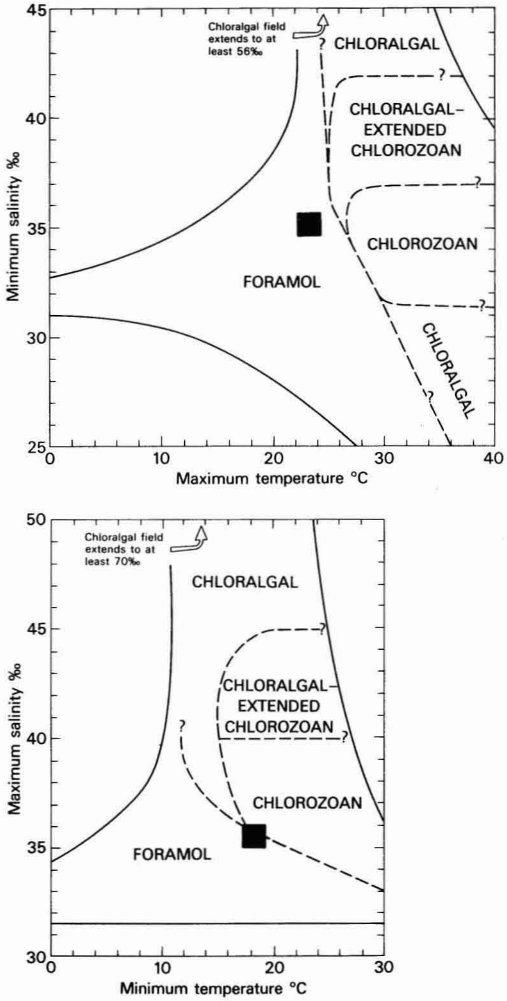

FIGURE 5. Skeletal grain associations and their relationships to salinity–temperature ranges for modern shelf carbonate sediments (after Lees 1975). The solid squares represent data from Penguin Bank, Hawaii.

Pacific mid-depth banks, in general, lie within the deep euphotic zone at the top of the nutricline; hence, deep-water, benthic, calcareous organisms are influenced by physicochemical properties of seawater that are distinctly different from those of shoal-water reefs and lagoons. Mean annual temperature and carbonate saturation state are lower than in immediate shoal-water areas. Consequently, the magnesium content of calcitic benthic organisms, which is influenced largely by temperature, the calcite saturation state of seawater, and skeletal growth rate (Agegian 1985), is, in general, lower in the skeletons of deep-water organisms than in their shoal-water counterparts. Shoal-water species of coralline algae in the Hawaiian Islands have magnesium contents ranging between 18 and 30 mole % $MgCO_3$ (Agegian 1985), whereas the magnesium contents of two similar deep-water species on Penguin Bank were 14.0 and 16.5 mole % $MgCO_3$.

A comparison of the mineralogy of the organisms to the carbonate sediments found on Penguin Bank suggests that the sediments are formed in situ rather than sedimented as the skeletons of benthic or planktonic organisms living in the shallow euphotic zone. Magnesian calcite was the dominant mineralogic component (55–80%) of the bank sediments in all size fractions, whereas the composition of shoal-water debris is typically dominated by aragonite (Chave 1962, Gross et al. 1969). The range in magnesium contents of benthic organisms and the underlying sediments was similar. The predominance of specific magnesium contents in some size fractions appears to correspond to the composition of specific source organisms, e.g., benthic foraminifera of 14.3 mole % in the <45 μm size fraction. The contribution of pelagically derived carbonates to the top of the bank from the shallow euphotic zone waters of 0–50 m is small, as shown by the low percentage of calcite low in magnesium content over a range in size fractions and lack of these skeletons in the size fractions observed visually. A small percentage of calcite with a low magnesium content, however, was observed only in size fractions less than 124 μm, a size range comparable to that of pelagic skeletal debris composed of coccoliths and forams.

Repeated visual observations on Penguin Bank from the submersible have indicated several possible mechanisms by which calcareous organisms are transformed by biological, physical, and chemical degradative processes into sediments. Variability in mineralogy and magnesium content of the sediment on Penguin Bank with either depth or size fraction may reflect, in part, differential abrasion rates of benthic organisms (Moberly 1968); preferential dissolution of highly reactive, fine-grained magnesian calcite particles (Mackenzie et al. 1983); preferential lateral transport of carbonate particles off the bank; or all these mechanisms.

Significant lateral transport of the sediments produced on Penguin Bank is suggested by the increase with depth in sediment thickness from a thin layer of sediments on top of the bank (Figure 2) to thick deposits on the deeper slopes of the bank (Moberly et al. 1975). Sediment accumulation on top of the bank is probably minimal because of the open morphology of the bank, in contrast to shoal-water environments of the Pacific, where much of the carbonate material produced is retained within the reef structure (Smith et al. 1971).

CONCLUSIONS AND SPECULATION

Penguin Bank has been identified as an important type of carbonate depositional environment with a distinct biological community contributing to sediments with a composition dominated by a high ratio of magnesian calcite to aragonite. Deep-water calcareous communities have been reported from other areas of the Pacific (Drew and Abel 1985, Hillis-Colinvaux 1985), suggesting that this type of depositional environment might be found throughout the Pacific. Sediments from mid-depth banks are transported laterally off the bank into the base of the mixed layer. These features distinguish Penguin Bank and other Pacific mid-depth banks from shoal-water environments in the Pacific, from the classical, better-known bank environments of the Bahamas in the Atlantic, and from shelf environments (20–150 m) in the Gulf of Mexico (Chave 1962).

Furthermore, these biogenically produced bank sediments are composed of highly reactive skeletal particles with mineralogies dominated by high magnesium calcite and aragonite. These skeletal particles are structurally disordered and chemically heterogeneous, and have complex microarchitectures (Mackenzie et al. 1983, Urmos et al. 1986, Walter 1983). These factors enhance the solubilities and dissolution reaction rates of the biogenic particles. After being swept off banks, such particles may dissolve at shallower oceanic depths than pelagic calcite skeletons settling through the water column. Thus, it has been suggested (Agegian et al. 1988) that the process of dissolution of these particles and release of carbon to the oceanic water column may be a contributing factor to the alkalinity maximum observed at intermediate water depths (2000 m; Fiadiero 1980) in the Pacific Ocean.

ACKNOWLEDGMENTS

We greatly appreciate the help of Steve Ralston, who collected many of the sediment samples analyzed in this study during a National Marine Fisheries Cruise aboard the R/V *Townsend Cromwell*. We also wish to thank Nolli Silva, for sample preparation and analysis, and Jane Schoonmaker and Ralph Moberly, who provided critical reviews of the manuscript.

LITERATURE CITED

ADEY, W. H., R. A. TOWNSEND, and W. T. BOYKINS. 1982. The crustose coralline algae (Rhodophyta: Corallinaceae) of the Hawaiian Islands. Smithsonian Contr. Mar. Sci. No. 15.

AGEGIAN, C. R. 1985. The biogeochemical ecology of *Porolithon gardineri* (Foslie). Ph.D. Thesis. University of Hawaii, Honolulu.

AGEGIAN, C. R., and I. A. ABBOTT. 1985. Deep-water macroalgal communities: A comparison between Penguin Bank, Hawaii and Johnston Atoll. Proc. 5th Internat. Coral Reef Congr., Tahiti 5:47–51.

AGEGIAN, C. R., F. T. MACKENZIE, J. S. TRIBBLE, and C. SABINE. 1988. Carbonate production and flux from a mid-depth bank ecosystem, Penguin Bank, Hawaii. Symposia Series for Undersea Research NOAA Undersea Research Program. U.S. Dept. Commerce, Washington, D.C.

ALEXANDERSSON, T. 1974. Carbonate cementation in coralline algal nodules in the Skagerrak, North Sea: Biochemical precipitation in undersaturated waters. J. Sed. Petrol. 44:7–26.

CHAVE, K. E. 1962. Factors influencing the mineralogy of carbonate sediments. Limnol. Oceanogr. 7:218–223.

DANA, T. F. 1970. On the reef corals of the world's most northern atoll (Kure: Hawaiian archipelago). Pac. Sci. 25:80–87.

DREW, E. A., and K. M. ABEL. 1985. Biology, sedimentology and geography of the vast inter-reefal Halimeda meadows within the Great Barrier Reef province. Proc. 5th Internat. Coral Reef Congr., Tahiti 5:15–20.

FIADIERO, M. 1980. The alkalinity of the deep Pacific. Earth and Planet. Sci. Lett. 49: 499–505.

GREGORY, A. E., III, and L. W. KROENKE. 1982. Reef development on a mid-oceanic island: Reflection profiling studies of the 500-meter shelf south of Oahu. Amer. Assoc. Petrol. Geol. Bull. 66:843–859.

GRIGG, R. W. 1982. Darwin Point: A threshold for atoll formation. Coral Reefs 1: 29–34.

GROSS, M. G., J. D. MILLIMAN, J. I. TRACEY, JR., and H. S. LADD. 1969. Marine geology of Kure and Midway Atolls, Hawaii: A preliminary report. Pac. Sci. 23:17–25.

HILLIS-COLINVAUX, L. 1985. Halimeda and other deep fore-reef algae at Enewetak Atoll. Proc. 5th Internat. Coral Reef Congr., Tahiti 5:9–14.

LEES, A. 1975. Possible influences of salinity and temperature on modern shelf carbonate sedimentation. Mar. Geol. 19:159–198.

LEES, A., and A. T. BULLER. 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Mar. Geol. 13:67–73.

LITTLER, M. M., D. LITTLER, S. BLAIR, and J. N. NORRIS. 1985. Deepest known plant life discovered on an uncharted seamount. Science 227:57–59.

MACKENZIE, F. T., W. T. BISCHOFF, F. C. BISHOP, M. LOIJENS, J. SCHOONMAKER, and R. WOLLAST. 1983. Magnesian calcites: Low-temperature occurrence, solubility, and solid solution behavior. Pages 97–144 *in* R. J. Reeder, ed., and P. H. Ribbe, series ed. Carbonates: Mineralogy and chemistry. Reviews in Mineralogy vol. 11. Mineralogical Society of America, Washington, D.C.

MANN, U., and K. FISCHER. 1982. The triangle method—semiquantitative determination of clay minerals. J. Sediment. Petrol. 52:654–657.

MOBERLY, R. 1968. Loss of Hawaiian littoral sand. J. Sed. Petrol. 38:17–34.

MOBERLY, R., J. F. CAMPBELL, and W. T. COULBOURN. 1975. Offshore and other sand resources for Oahu, Hawaii. Sea Grant Techn. Rep. UNIHI-SEAGRANT-TR-75-03.

NEUMANN, A. C. 1965. Processes of recent carbonate sedimentation in Harrington Sound, Bermuda. Bull. Mar. Sci. 15:987–1035.

SCHLANGER, S., and K. KONISHI. 1975. The geographic boundary between the coral–algal and the bryozoan–algal limestone facies: A plaeolatitude indicator. Paper, IX Internat. Conf. Sed., Nice.

SMITH, S. V. 1978. Coral reef area and contributions of reefs to processes and resources of the world's oceans. Nature 273:225–120.

SMITH, S. V., K. J. ROY, H. G. SCHIESSER, G. L. SHEPHERD, and K. E. CHAVE. 1971. Flux of suspended calcium carbonate ($CaCO_3$), Fanning Island Lagoon. Pac. Sci. 25:145–160.

STEARNS, H. T. 1974. Submerged shorelines and shelves in the Hawaiian Islands and a revision of some of the eustatic emerged shorelines. Geol. Soc. Amer. Bull. 85:795–804.

URMOS, J., S. K. SHARMA, and F. T. MACKENZIE. 1986. Characterization of biominerals with raman spectroscopy. Poster paper, American Geophysical Union Fall Meeting, Dec. 8–12, San Francisco, Ca.

WALTER, L. M. 1983. The dissolution kinetics of shallow-water grain types. Effects of mineralogy, microstructure, and solution chemistry. Ph.D. Thesis. University of Miami, Fla.