Micronesica 24(2): 231–248, 1991

Shallow Reef-front Detrital Sediments from the Northern Mariana Islands

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Abstract—Sediments collected from reef fronts off six islands in the Mariana Islands were analyzed for composition and texture. These deposits are highly varied binary mixtures: coarser, poorly-sorted reef-derived bioclastics, and finer, better-sorted terrigenous materials.

Compositional variation is statistically related to extrabasinal parameters including: island area, erodable volcanic terrain, coastal-exposure direction, and perhaps volcanic activity and/or latitude. Bioeroder population differences among the islands may be a contributing factor to compositional variability.

Texture (size/sorting) of the terrigenous silicate fraction is strongly influenced by coastal exposure direction as well as erodable island terrain; texture in biogenic fractions is controlled by skeletal geometry and reef productivity (availability).

Bioclastic sediment diversity and taxon variability are greatest within finer-size fractions and especially in samples collected around southern limestone islands of the older arc. Factor analysis indicates that sediment variability can be simplified into carbonate framework clasts in coarser sediments, and non-framework particles in finer sizes. Bioclastic fractions evolve into two populations: coarse, low-diversity assemblages, dominated by reef framework particles, and finer sands composed of a more diverse mixture of smaller non-framework skeletal materials.

Introduction

Loose sediment constitutes a significant component of modern reefs in the Mariana Islands. These deposits occur above wave base, both within and immediately seaward of the reef margin, and represent dynamically shifting fluxes of predominantly locally derived materials. They survive within carbonate framework, and as meter-scale infillings between reef framework buildups; as such, they may constitute the majority by volume of the solid reef margin. Less probably, shallow reef-front detritus may survive as a separate, seaward-fining grainstone/rudestone facies.

Petrographic (thin-section) studies of Pleistocene and Holocene reef-core facies in the southern Mariana Islands (Fig. 1) (Schlanger 1964, Siegrist et al. 1984, Siegrist & Randall 1985) give testimony to the importance of the detrital component in ancient reef-core limestones. Well over sixty-percent of microscopically mounted points from several hundred thin sections of "coral reef" were in fact coarse silt (0.05 mm) to pebble-size (4–16 mm) carbonate detritus. In this respect, the modern reef systems in the Mariana Islands are both analogs as well as ideal laboratories for studying the formation of ancient reef limestones.

In earlier related studies, Cloud (1959) described the texture and taxonomy of 64 samples from 7 transects across the lagoon within Saipan's barrier reef. He included only 3 sites (Cloud's No. E6, E7, and G2) that could be considered as reef front, and these were within a channel. Sediments ranged from medium-fine (0.125 mm) to very-coarse sand (2.00 mm) and were well-sorted (Trask coefficient = 1–1.8). Size distributions were unimodal, leptokurtic, and symmetrical. Sediments were entirely biogenic and consisted, in usual order of decreasing abundance, of whole and fragmented reef corals, coralline algae, *Halimeda*, molluscs, foraminifers, echinoids, and many other locally-derived taxa.

Emery (1962) performed a similar study on Guam. Most of his samples were collected within the Cocas Lagoon on the south coast, but several off-reef samples from as deep as 355 meters were also included. Unfortunately, no samples originated from the shallow reef-front areas, obscuring any direct comparison with results from this study.

In this report we describe results from a study of shallow reef front sediments sampled off six of the Mariana Islands. Specifically, we attempted to measure and interpret textural and compositional variability in reef-front sediment deposits around Anatahan, Guguan, and Pagan, young volcanic islands of the northern arc and Aguijan, Rota, and Saipan, older limestone-capped islands to the south (Fig. 2). The northern islands are volcanically active, whereas the southern islands last experienced volcanic activity in Early Miocene time (Reagan & Meijer 1984).

With several minor exceptions on Saipan, none of the islands considered in this study has permanent stream drainage. Terrigenous sediment is mainly transported by slope processes, precluding major textural modification that normally results from fluvial transport. Carbonate development around the northern islands is primarily restricted to intermittent apron reefs, averaging perhaps 50 meters in width. Reefs around the limestone islands are more varied. A barrier reef dominates the west coast of Saipan, but both Saipan and Rota have abundant fringing reefs with shallow reef-flat platforms. In contrast, Aguijan lacks any fringing reefs.

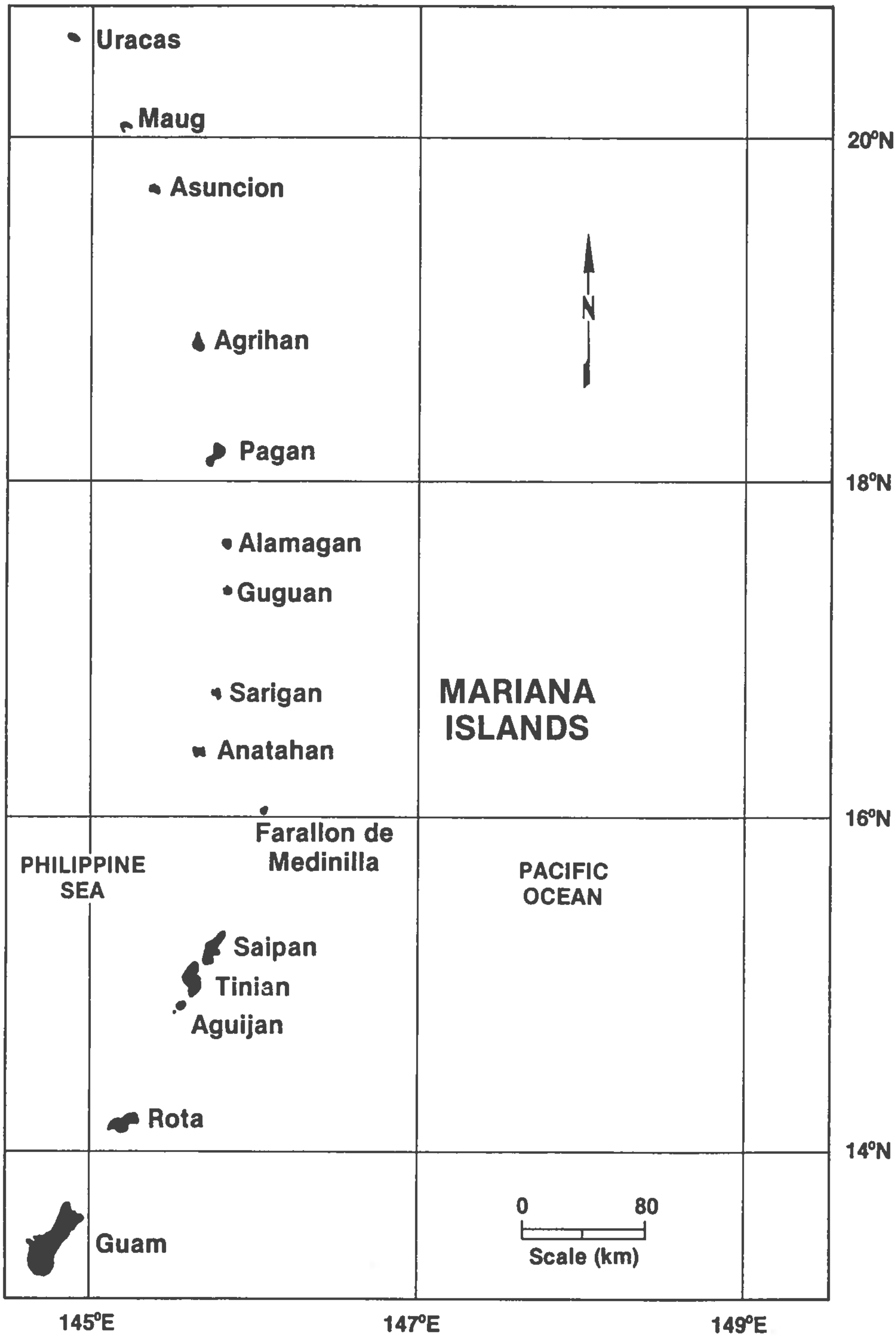

Figure 1. Mariana Islands, showing the locations of the six sampled islands: Anatahan, Guguan, Pagan, Aguijan, Rota, Saipan.

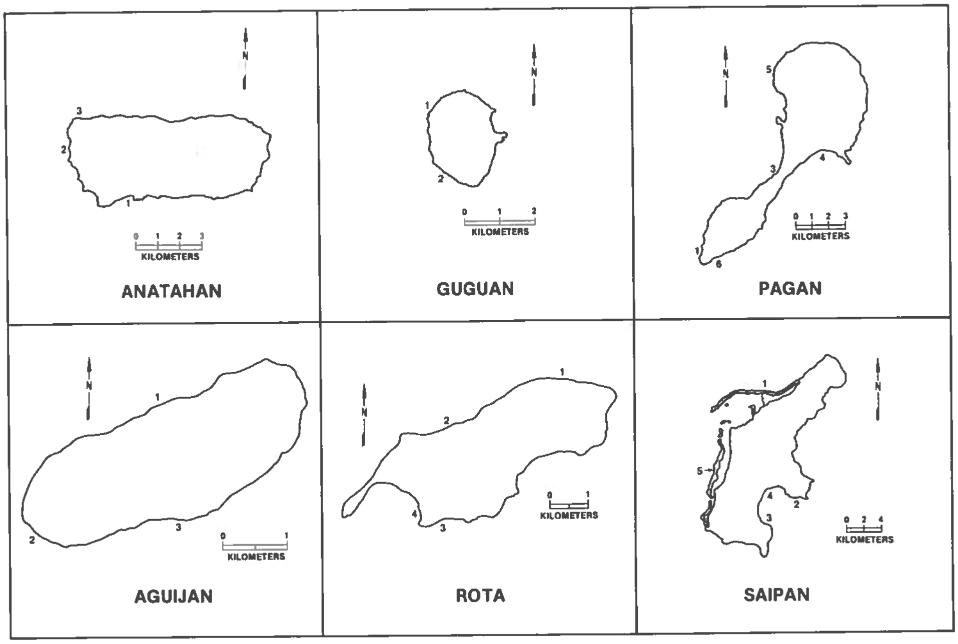

Figure 2. Sampling locations around each of the three northern volcanic islands (top) and three southern limestone islands (bottom).

Methods and Materials

FIELD SAMPLING

Samples were collected during several extensive shallow-water biologic reconnaissance studies of shallow marine environments of the Mariana Islands undertaken by the University of Guam, Marine Laboratory (Randall 1985). Sample sites (Fig. 2) were selected to cover a broad range of sedimentary environments as estimated from underwater surveys. Each site was assigned to one of four general sedimentary environments (Fig. 3) and are so designated in Table 1. Environments were classified on the bases of the degree of development of insitu reef deposits, relative amounts of loose sediment, and type of rock substratum.

At each site, at a sounding of approximately 20 feet (6.1 meters), a geologic hammer with float was hurled from the boat to define the collection point where approximately 3-kilogram samples were collected in wide-mouthed jars. Additional sites were selected around several islands to develop intra-island comparisons. Still other shallow reef-front sediment samples were included from a separate environmental study on Saipan (Sites 4 and 5). These materials were also collected at approximately 6-meter depths.

LABORATORY METHODS

Field samples were washed in fresh water, air dried, and split into subsets for analysis. One subset was wet-screened at 0.5-phi intervals to develop grain-

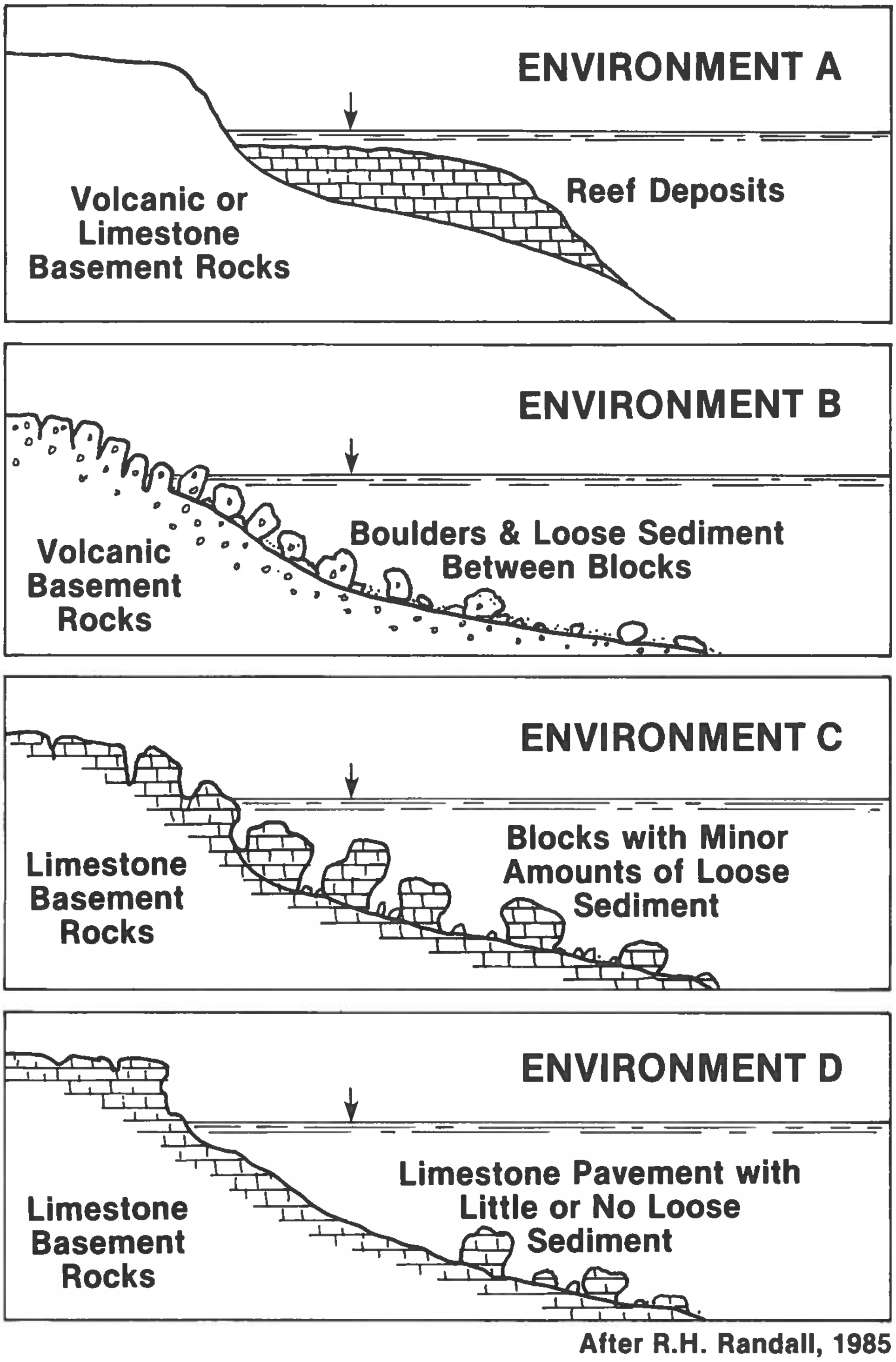

Figure 3. Schematic vertical profiles of sedimentary environments sampled in this study. (Modified from Randall 1985).

Table 1. Sample sites classified according to sedimentary environments illustrated in Figure 3.

Island	Site Number	Classification	Island	Site Number	Classification
Anatahan	1	B	Aguijan	1	A
	2	A		2	C
	3	A		3	C
Guguan	1	B	Rota	1	D
	2	B		2	A
Pagan	1	A		3	D
	2	B		4	A
	3	B	Saipan	1	A
	4	A		2	D
	5	B		3	A
				4	A
				5	A

size frequency distributions, where phi = $-\log_2(\text{mm})$. This log-transformed scale is preferred over linear SI measurements by sedimentologists because it helps to bring size frequencies of most natural sediment populations closer to Normal Distributions. Weighed size fractions were treated for 24 hours with 0.1N HCl to determine carbonate and non-carbonate proportions in each fraction. A second split (approximately 100 grams) was wet-screened to collect a coarse fraction (+10 mesh, or coarser than −1 phi or 2.0 mm), a fine fraction (−60 mesh, or finer than 2 phi or 0.25 mm), and a modal-size fraction from which to make comparative estimates of composition. The modal-size fraction ranged from as coarse as +5 mesh (−2 phi or 4 mm) on Anatahan samples to +35 mesh (1 phi or 0.5 mm). In words, −10 mesh represents the cut between coarse sand and granule; +60 mesh represents the cut between medium and fine sand.

The −60 mesh fraction from the limestone islands (especially Saipan Site 4) included particles as small as coarse silt and they were analyzed with a petrographic (polarizing optics) microscope at up to 150× magnification. Four microscope slides for each size fraction per sample were point-counted with this instrument. Modal and coarse fractions were counted at low magnifications with a reflecting binocular (biological) microscope, from loose grain mounts glued onto black index cards. The following categories were recognized:

Terrigenous (fresh): unweathered, though often altered, volcaniclastic grains including single crystals of plagioclase, pyroxenes, olivine, and magnetite; composite grains of volcanic materials; chert; chlorite and serpentine; zeolites.

Terrigenous (weathered): same as above, but showing greater than 20% weathering to oxide-hydroxides or clay minerals.

Soil minerals: iron, aluminum, and/or manganese oxides and hydroxides; clay minerals except chlorite and serpentine.

Pollen.

Reef-derived (fragmented): skeletal fragments of benthic reef organisms including, in general order of abundance, corals, coralline (red) algae, molluscs (split into bivalves, snails and vermetids), foraminifers, green algae (*Halimeda*), echinoid plates and spines, bryozoans, sponge chips from a variety of materials, miscellaneous spicules (holothurian, sponge, tunicate, etc.), unclassified calcareous fragments, crustacea, polycheates, barnacles, diatoms, ostracodes.

Reef-derived (whole): entire skeletons or skeletal components of reef organisms including foraminifers, *Halimeda*, small gastropods, unclassified calcareous organisms (especially in the finer fractions), holothurian ossicles, diatoms, and otoliths.

Probable pelagic foraminifers.

Miscellaneous: rhodoliths, oncolites, phosphatic pellets, beachrock and older recrystallized limestone clasts, and particles of unknown origin.

STATISTICAL METHODS

All statistics were calculated using SYSTAT software (SYSTAT 1985). Point-count data were summarized in histogram form for visual comparisons of distributions. Inter- and intra-island differences in sediment composition, diversity, and texture were then developed using standard analysis of variance (ANOVA) and multivariate analysis of variance techniques (MANOVA) (Sokal & Rohlf 1987).

Multiple linear regressions (Davis 1986) were employed in an attempt to identify environmental variables that might be driving the system and controlling the makeup and texture of the sediments, and at the same time, to define other variables and combinations of variables whose measurement does not contribute significant information about sediment variation. Selection of these variables (Table 2) generally followed earlier work by Grigg (1983) and Randall (1985); several variables can be considered extrabasinal in a geologic sense ($X_1 - X_4$), while others reflect within local, reef-margin conditions ($X_5 - X_6$). With the exception of the arbitrary volcanic activity index, all variables were measured in the field or estimated from maps.

Finally, factor analysis was invoked to frame out the shallow reef-front sedimentary system. This procedures aims at simplifying variation patterns (in our

Table 2. Environmental variables used in analysis.

Variable	Variable Range
x_1 = Volcanic Activity Index	1 (Aguijan, Rota, Saipan; 5 (Anatahan); (Guguan); 10 (Pagan)
x_2 = Island Area	4.2 (Guguan) to 121 km^2 (Saipan)
x_3 = Volcanic (erodable) terrain	100% (Guguan, Anatahan, and Pagan) to 0% (Aguijan)
x_4 = Reef exposure direction (seaward exposure)	0 to 360 degrees in polar coordinates, normal to modern reef margin
x_5 = Percent coral coverage	0.4–88.9%
x_6 = Coral coverage density	1.1–48.2 corals/sq. meter

case compositional variation) and identifying underlying (environmental) factors constraining those patterns. Correlation matrices of variables X_1 through X_6 were factor analyzed using the method of principal components (Davis 1986).

Results and Discussion

SEDIMENT COMPOSITION

The overall composition of each of the +10, −60, and modal size fractions (averaged for each island are given) in Tables 3 and 4. Raw bioclastic count data may be requested from the senior author. It is evident that pelagic contributions to these sediment reservoirs are negligible. It is equally evident that reef-front deposits are effectively a binary system of siliciclastics and reef carbonates except at a few sites around limestone islands. However, only in coarse and modal fractions from the volcanic islands do the two end-members approach equal proportions. In fine fractions especially, composition tends to reflect the type of island: terrigenous-dominated if volcanic, or reef-derived if non-volcanic. The data further indicate that siliciclastic grains are concentrated in finer size fractions, a circumstance that will be discussed below.

Shannon-Weaver Diversity Indices (Lloyd & Ghelardi 1964) were calculated from bioclastic compositional data in the +10, −60 and modal size fractions and averaged results are shown at the bottom of Tables 3 and 4. This measurement describes the average degree of uncertainty in predicting a clast category counted at random on a microscope slide. Uncertainty increases both as the number of different categories increases and as individual particles are distributed more uniformly among categories already present. A comparison of this diversity measurement between islands and island groups is discussed below.

Individual bioclastic component percentages (not shown) suggest distinct differences in the makeup of biogenic fractions between volcanic and limestone islands. Whole and fragmented corals, coralline algae, and molluscs comprise at least 80% of both fine and coarse fractions from the volcanic islands. In contrast, *Halimeda* and benthic foraminifers are additional major components in the sediment collected from limestone islands. This is especially evident in the −60 fraction where *Halimeda* and foraminifer clasts constitute between 33% and 43% of the bioclastic sediment.

MANOVA: We tested whether bioclastic sediment compositional differences between volcanic and limestone island groups were significant by using MANOVA (SYSTAT 1985). From F-Test probabilities listed in Table 5 we note that, in coarser fractions, coralline algae, bryozoan, and foraminifers show significant differences between the island groups. However, in finer fractions, corals, *Halimeda*, molluscs, and foraminifers vary significantly between island groups. The greatest island group differences in the modal sizes appear to occur between populations of foraminifers, mollusks, *Halimeda*, and coralline algae. The multivariate Wilks-Lambda value (Sokal & Rohlf 1987) implies that, considering all taxa simultaneously, volcanic islands differ significantly from limestone islands

Table 3. Sediment composition in +10, −60 and modal[1] sieve sizes averaged over each volcanic island.

Count Categories	Anatahan				Guguan			Pagan		
	+10 mesh	+5 mesh	+18 mesh	−60 mesh	+10 mesh	+18 mesh	−60 mesh	+10 mesh	+35 mesh	−60 mesh
Terrigeneous (fresh)	2.0	4.2	5.8	6.2	4.6	6.4	14.7	19.4	57.3	70.3
Terrigeneous (weath.)	60.0	49.5	48.7	52.4	32.4	39.4	44.1	28.0	16.0	9.4
Soil Minerals	6.1	4.8	11.3	27.6	4.6	8.8	18.2	—	4.0	5.2
Pollen	—	0.6	—	0.9	—	—	3.5	—	—	—
Reef-derived (fragm.)	28.2	31.4	13.8	8.5	49.6	40.3	11.2	51.0	18.7	12.3
Reef-derived (whole)	1.8	8.4	10.8	2.9	4.9	5.0	5.9	1.0	1.1	0.3
Pelagic	—	—	—	0.8	—	—	0.4	—	0.8	1.6
Miscellaneous	1.8	1.1	—	0.2	4.0	0.1	1.8	0.6	2.1	1.0
Shannon-Weaver Diversity Index	1.47	1.45	1.53	1.67	1.48	1.54	1.65	1.49	1.56	1.56

[1] Two distinct modal size classes characterize shallow reef-front detrites in Anatahan samples.

Table 4. Sediment composition in +10, −60 and modal[1] sieve sizes averaged over each limestone island.

Count Categories	Aguijan			Rota				Saipan		
	+10	+35 mesh	−60	+10	+14	+35 mesh	−60	+10	+18 mesh	−60
Terrigeneous (fresh)	—	—	—	—	—	—	—	—	—	0.1
Terrigeneous (weath.)	—	—	—	2.2	2.02	2.3	2.4	2.7	2.9	2.0
Soil Minerals	—	—	0.1	0.3	0.1	2.0	2.7	0.3	0.8	2.9
Pollen	—	—	—	—	—	—	0.3	—	0.3	0.4
Reef-derived (fragm.)	92.1	94.4	86.1	93.2	87.3	86.4	84.4	92.1	87.9	86.5
Reef-derived (whole)	6.9	2.9	9.7	1.9	8.9	7.4	6.4	2.8	5.5	5.5
Pelagic	—	0.3	1.1	—	—	—	0.5	—	—	0.4
Miscellaneous	0.9	2.4	3.1	2.4	1.7	1.9	3.3	2.0	2.6	2.3
Shannon-Weaver Diversity Index	1.52	1.63	1.80	1.54	1.55	1.63	1.71	1.75	1.74	1.83

[1] Two of several size modes listed for Rota samples.

Table 5. Probabilities associated with MANOVA testing of differences in biogenic sediment between island groups (degrees of freedom = 1, 16).

	Probabilities		
	+10 mesh	Modal	−60 mesh
corals	.262	.061	.004
coral. algae	.009	.013	.057
Halimeda	.104	.008	.001
molluscs	.057	.001	.000
foraminifers	.008	.000	.000
echinoids	1.000	.680	.425
bryozoans	.003	.101	.152
miscell.	.913	.096	.111
Shannon-Weaver	.008	.004	.002
Wilks-Lambda (df = 40,42)	.091	.053	.002

in −60 mesh and modal fractions (P = .002 and .053), and marginally in +10 mesh size (P = .091).

MANOVA results also indicate that the Shannon-Weaver Diversity Index is significantly greater in limestone than volcanic islands and as is the case with individual taxon, differences are magnified in finer grain sizes. Thus, our analyses of variance of compositional data strongly suggest that, when compared to intra-island variability, bioclastic sediments differ significantly between island groups and those differences are most clearly indicated in finer-size fractions. This situation implies fundamental differences between the two island groups in their reef community structures, or in the physical-biological processes of sediment comminution or both.

Regression Analysis: Table 6 lists those independent variables that contributed significantly to predicting variation in different dependent variables. The fraction of total variation accounted for by the regression function is listed as R-square. It is evident that the variables controlling composition of coarse fractions are similar, but not identical to those involved with the finer textured materials. The variables, volcanic activity, island area, percentage of erodable volcanic terrain, and coastal exposure direction are obviously influential. However, because volcanic activity increases northward along the arc, some of this influence may be a latitudinal effect rather than one related directly to volcanism. Surprisingly, included basinal variables are only marginally involved in influencing sediment composition.

Multiple regression analysis was able to "explain" no more than 74% of the variation in any one major classified taxon in the sediment (i.e., coralline algae in the −60 mesh). Indeed, it failed to account for most of the variation in corals, *Halimeda*, molluscs, echinoids, bryozoans and the miscellaneous category. One possible explanation may lie in the lack of one or more regression variables in our experimental design that measures activity or diversity of the bioeroder pop-

Table 6. Multiple regression analysis: bioclastic sediment composition vs. environmental variables ($X_1 - X_6$).

	Significant Independent Variables					
Dependent Variable	−10 mesh	R^2	Modal	R^2	−60 mesh	R^2
corals	X_1X_2	.51	X_1X_2	.47	X_5	.22
coralline algae	X_1X_4	.63	$X_1X_2X_4$	.70	$X_1X_2X_3X_4$	.74
Halimeda	none	.01	none	.14	none	.13
molluscs	X_1X_3	.59	X_1	.49	X_1	.35
foraminifers	$X_1X_2X_4$	.69	X_1X_2	.67	$X_1X_2X_3$	.69
echinoids	X_1	.18	none	.20	none	.17
bryozoans	none	.01	none	.15	none	.10
misc.	X_2	.38	X_3	.41	X_3X_4	.45
Shannon-Weaver	X_1X_4	.36	X_1	.39	X_1X_5	.57

Table 7. Factor analysis: factor loadings on first three principal components: I, II, III.

	+ 10 mesh			Modal			−60 mesh		
	I	II	III	I	II	III	I	II	III
coral	.844	−.422	.021	−.451	+.693	.099	−.580	.603	.103
coral. algae	−.865	−.062	−.325	−.379	−.793	−.228	−.179	−.866	−.055
Halimeda	.554	.453	−.569	.676	.091	.221	.866	.061	.194
molluscs	−.852	−.252	.154	−.883	−.083	−.036	−.879	.056	.035
foraminifers	.227	.477	.749	.774	−.213	.286	.893	−.153	−.136
echinoids	−.368	.773	−.243	.701	−.117	−.291	.801	.221	−.380
bryozoans	.827	.359	−.057	.444	.481	.163	.286	.741	.293
misc.	−.400	.711	.229	.328	−.383	−.140	.398	−.135	−.868
% Variation accounted for	49.1	20.8	14.1	48.6	24.0	12.8	48.0	23.5	13.2

ulations. Alternatively, the relationship between the reef variables and the variation of individual taxon may be more complex than the linear model assumed.

Factor Analysis: Factor analysis of the correlation matrices for the coarse (+10 mesh) sediments (Table 7) indicates that the highest loadings on the first principal component arise from variation in reef-framework organisms: corals, coralline algae, molluscs, and bryozoans. For both the modal and fine (−60) fractions, high loadings on the first component are from non-framework organisms; *Halimeda*, foraminifers, echinoids as well as molluscs again. An inverse relationship holds for the second principal component. Because over eighty-percent of the total variation in all size classes tested is accounted for by principal components I and II, compositional variability within the carbonate fraction can be simplified into two operational end-members: coarser detritus enriched in reef-framework organisms and finer materials that include higher concentrations of smaller, non-framework organisms.

The notion of compositional-textural end-members in reef-front sediments is based on an assumption that size separation by sieving models natural particle-size attenuation processes. Preliminary conclusions from a companion study on Guam (Siegrist, Randall & Dwyer, in prep.) involving multiple sampling (various depths) at each reef-front site support this assumption. Should it hold, it would mean that carbonate sediment on the reef front evolves in much the same manner as does terrigenous sediment in comparable high energy regimes (e.g. beach, rivers): non-uniform starting material (texturally and/or compositionally immature) is comminuted and winnowed into several lithofacies, subpopulations with distinctive textural and compositional properties.

SEDIMENT TEXTURE

Volcanic Islands: Figure 4 displays grain-size frequency histograms of material sampled from the three volcanic islands. Summary statistics appear in Table 8. Aside from the clear domination of terrigenous material, an obvious aspect of these distributions is their strong centrosymmetric character and general impoverishment in silt-sized particles (finer than +3 phi). Both of these characteristics may be a reflection of grain-size distributions of original silicate starting material and prevailing hydrodynamic regimes, but lack of silt-size bioclastic material may be related to absence of bioeroders producing that specific size of material.

It is also evident that there is a tendency for carbonate bioclastics at each site to be both coarser and to be more poorly sorted than associated siliciclastics. This feature is particularly well demonstrated at Sites 2 and 3 on Anatahan where mixed populations of sediment have resulted in decidedly bimodal frequency histograms, a reflection of the hydraulic equivalence of particles of two different mineral compositions; reef-derived bioclastics are being transported and deposited with terrigenous particles that average several phi intervals finer in grain size.

Another departure from a symmetric distribution is indicated for Site 4 on Pagan, where the 1981 base surge eruption reached the sea. A strong positive skewness in the grain-size distribution at that site indicates a disproportionate amount of fine material in the sediment.

Limestone Islands: Figure 5 shows grain-size frequency distributions derived for the limestone islands. Histograms stress the subordinate role of terrigenous influx in reef systems surrounding those islands. Grain-size distributions notably lack a strong central tendency, but instead are polymodal or follow the rectangular distribution (Mood 1950), implying that bioclastic materials are less influenced by hydrodynamics than are siliciclastic grains. Rather, we hypothesize that size distributions of bioclasts appear to be responding to inherent sizes of live organisms modified by subsequent attrition and bioerosion. These histograms (Fig. 5) also imply that skeletal debris may undergo selective winnowing as shown by the truncated fine-tails of the distributions from Aguijan (Site 1); Rota (Sites 1 and 2); and Saipan (Sites 1, 2, 3, and 5).

Overall sorting of the reef front sediments as defined by s, the standard deviations of grain size (Table 8), ranged from poor to very-well sorted (Folk

1974). Terrigenous components invariably are better sorted than associated carbonate material.

Multiple regression analyses of size and sorting (Table 9) indicate that terrigenous fractions vary in response to extrabasinal variables. In contrast, grain size and sorting of carbonate sediments are not associated with extrabasinal variables; even coastal exposure direction is not important. They are, however, correlated with basinal characteristics related to reef productivity, $X_5 - X_6$. Overall, regression analysis was more successful in explaining size and sorting than it was in describing the variation in composition.

CONCLUSIONS

We put forth the following conclusions concerning the composition of shallow reef-front sediments in the Mariana Islands.

Binary system: The detritus is a binary system of terrigenous siliciclastics and reef-derived carbonate skeletal materials. Dominance of either end-member is a function of island type. Pelagic contributions are negligible at the depth sampled.

Major contributors: Certain taxa persist through the range of sizes from all sample sites: corals, coralline algae, molluscs (predominantly snails and vermetid gastropods), benthic foraminifers, and *Halimeda.* Corals and molluscs dominate the sediments from volcanic islands, whereas no taxon stands out in the more diverse assemblages from the limestone islands.

Controlling variables: Extrabasinal environmental variables exert more influence on the overall composition and diversity of the bioclastics than do two reef productivity variables considered. The largest contributor to sediment variability is the so-called volcanic activity index, but this is confounded with latitude, as volcanic activity increases northward along the arc. In many cases regression functions failed to account for appreciable variation in individual taxon in the sediments, indicating a need to either re-evaluate the linear model or to consider additional sediment-modification variables, perhaps those related to bioeroder activity.

Concerning textural variability in reef-front sediments, we offer the following conclusions:

Frequency distributions: Terrigenous grain size distributions (phi-scale) are centrosymmetric and only nominally skewed, reflecting a hydrodynamic influence. Bioclastic grain size distributions are more complex, fitting either rectangular distributions, or just as often being polymodal.

Controlling variables: Grain size distribution of biogenic material appears to be a function of original skeletal geometry, availability of the organism, and comminution/winnowing processes.

Texture-composition interaction: Biologic compositional differences between volcanic and limestone islands and biologic diversity are more apparent in finer size fractions. Compositional evolution occurs by comminution of clasts and

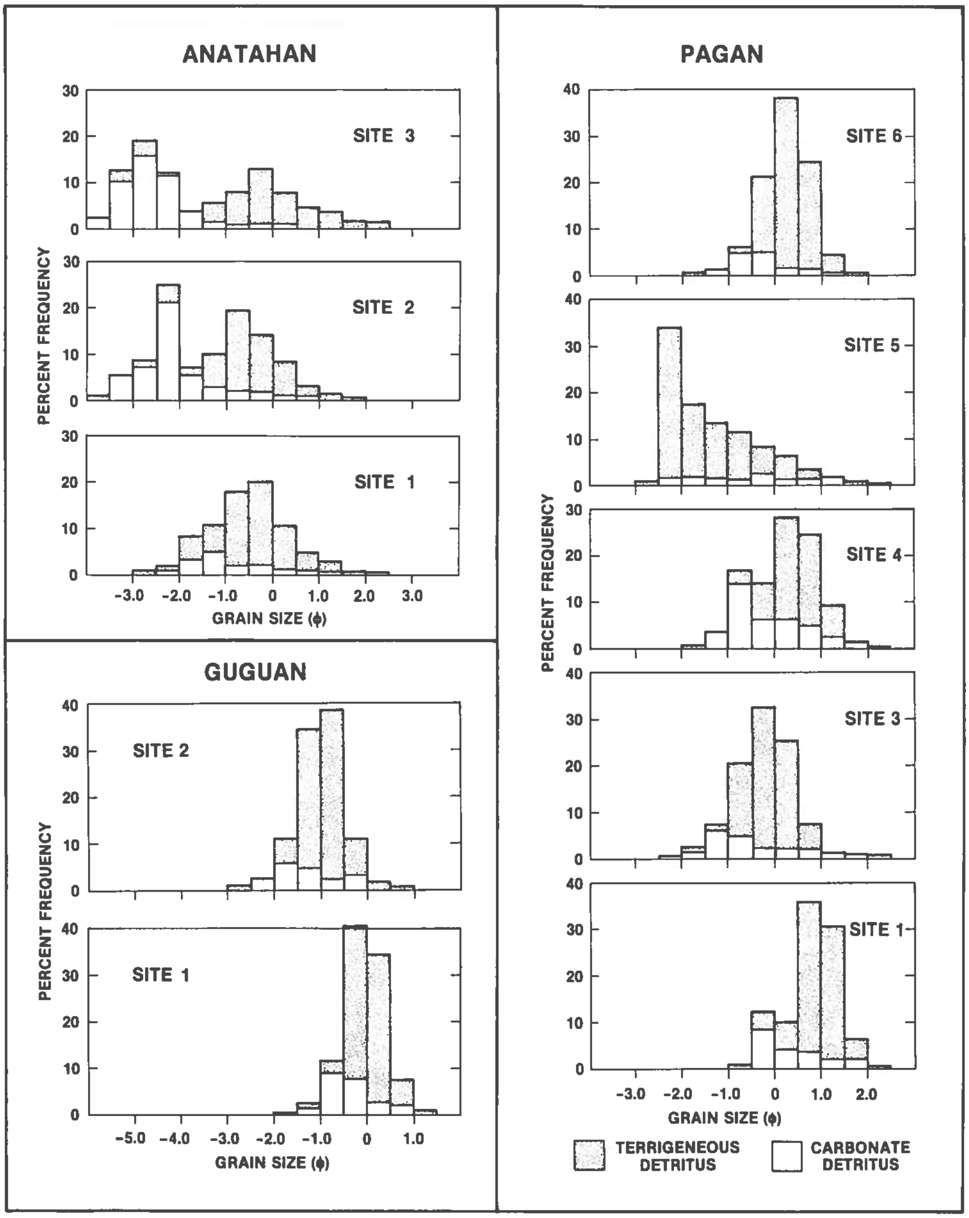

Figure 4. Size-frequency distributions of siliciclastic and bioclastic components in reef-front sediments around volcanic islands.

winnowing of fines. Assuming that laboratory sieving models grain size attenuation on the reef front, then bioclastic sediment clearly evolves from a heterogeneous source of reef-carbonate materials into (a): coarse-grained, low-diversity

Table 8. Summary statistics of sediment texture by island and sample sites.

		Mean Size (phi)		Sorting (s)	
Island	Site	Terrigenous	Carbonate	Terrigenous	Carbonate
Anatahan	1	−0.48	−0.97	0.78	0.98
	2	−0.41	−2.10	0.81	0.96
	3	0.00	−2.62	1.17	0.91
Guguan	1	−0.01	−0.48	0.48	0.83
	2	−1.00	−1.33	0.53	0.80
Pagan	1	0.88	0.39	0.67	0.87
	2	0.13	−0.28	0.83	1.11
	3	0.55	−0.15	0.86	1.00
	4	−1.13	−1.01	1.31	1.16
	5	0.33	−0.37	0.66	0.91
Aguijan	1	—	−0.81	—	1.38
	2	—	−0.47	—	1.47
	3	—	−0.38	—	1.29
Rota	1	—	1.46	—	1.18
	2	—	0.61	—	1.31
	3	0.57	−0.28	0.96	1.20
	4	—	0.15	—	0.94
Saipan	1	—	−0.16	—	1.33
	2	−0.24	−0.79	0.83	1.14
	3	−0.36	−0.72	0.80	1.02
	4	1.09	0.01	0.98	1.43
	5	—	−0.01	—	1.28

mixtures of winnowed, reef-framework fragments and (b): finer-grained, taxonomically diverse assemblages of carbonate sediment that include both comminuted particles and grains of whole organisms.

Analysis of the composition of reef-front sediments in the Mariana Islands indicates that there are basic differences in composition along the arc, that these differences are more pronounced in the finer-grain sizes, and that they are associated with parameters external to the reef proper. Multivariate analysis leads to the conclusion that fundamental changes in bulk composition and texture of reef-front sediment occur during comminution and winnowing processes.

Acknowledgments

This project was made possible through the kind assistance of staff members of the Marine Laboratory, University of Guam, who undertook the shallow-water reconnaissance and sampling in the Northern Marianas during the summer of 1983. They include S. Amesbury, B. Best, C. Birkeland, L. Eldredge and S. Nelson. We also thank P. Stifel and students for microscopic identifications, and A. Siegrist for computer guidance. We are indebted to A. Siegrist, M. Reaka and E. Yochelson for significant improvements in the manuscript. This study was partially supported by a grant from the University of Maryland, Graduate School Research Support Board.

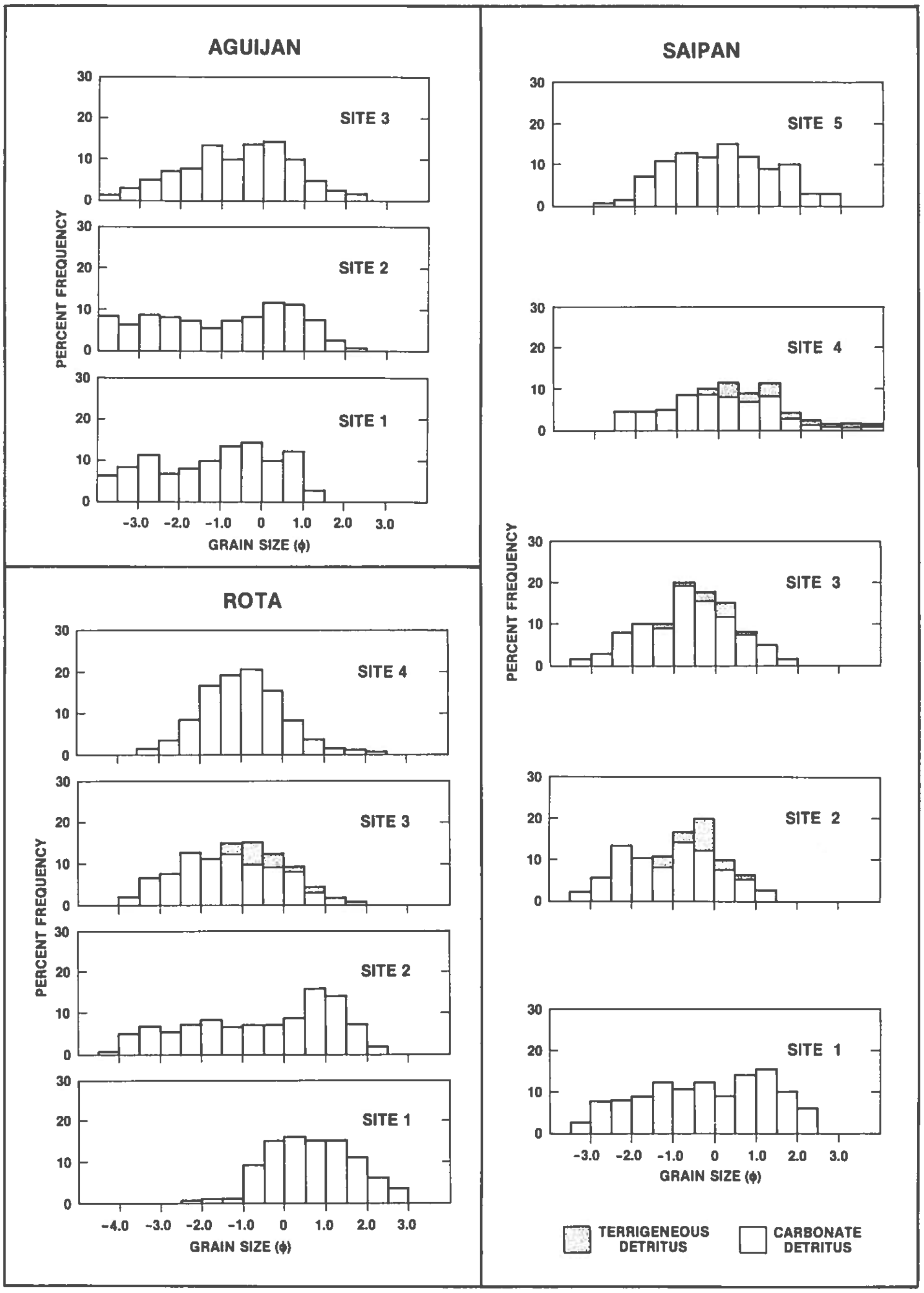

Figure 5. Size frequency distributions of siliciclastic and bioclastic components in reef-front sediments around limestone islands.

Table 9. Sediment texture multiple regression analysis summary

Dependent Variable	Significant Independent Variables	R^2
Terrigeneous Grain Size	X_1, X_3, X_4	0.74
Terrigeneous Sorting	X_3, X_4	0.51
Carbonate Grain Size	X_6	0.38
Carbonate Sorting	X_5, X_6	0.70

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Received 25 Jan. 1989, revised 20 May 1991.