

**TERRIGENOUS MATERIAL IN COASTAL ZONE SEDIMENTS
OF GUAM AND SAIPAN**

by

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ABSTRACT

Coastal sediments behind fringing and barrier reefs in Guam and Saipan were analyzed for carbonate, ash, organic matter, and concentrations of HCl-extractable iron, phosphorus, aluminum, silica, and ammonium. Stable C isotope ratios were obtained from samples of sedimentary organic and inorganic matter and macrophytes. The data are used as a first order estimate of the amount and distribution of terrestrial material in variety of sites that were chosen to represent a decreasing terrestrial impact gradient from intertidal discharge of aquifer waters and a true river estuary to an offshore lagoon.

The presence of very small amounts of terrestrial material (particularly iron, ash, and relatively isotopically light C) can easily be detected with simple methods. Muddy estuarine sediments contain less P, isotopically lighter carbon, and ca. 250 times more Fe than marine sediments. Offshore lagoons within barrier reefs may sequester some materials of apparently terrestrial origin due accumulation from chemically dilute ocean waters in areas of high biological productivity, but this process may be distinguished with the other analyses used here. Between these, an easily resolved gradient is observed that has both geochemical and biochemical causes.

Average accumulation factors (annual terrestrial flux/surface sediment contents) for individual terrigenous materials range from 0.03 to 3.8 for ash and Fe at sites not expected to be impacted by natural erosion of terrestrial material. The data are useful for engineers, developers, and regulatory personnel who need to know existing levels of terrestrial "contaminants" in coastal waters and sediments prior to major changes in land use of watersheds.

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INTRODUCTION

Runoff from land carries a variable load of terrigenous material, including detrital Al, Fe, Si, and organic matter, that can be traced for a first-order approximation of flux to the coastal zone (Hedges and Parker, 1976; Pocklington, 1976; Tan and Strain, 1976; Botello et al., 1980; Stumm and Morgan, 1981; Zolan, 1981; Mantoura and Woodward, 1983). Whereas such input to river estuaries is normal, coral reefs and marine lagoons are extremely sensitive to excessive inputs of terrestrial silt and sediment. Excessive turbidity and direct smothering of coral/algal assemblages may alter the food web structure of reefs, moats, and lagoons (Roberts and Murray, 1983; Tomascik and Sander, 1985). Nutrient inputs may cause a shift in coral community structure to a weedy algal type (Smith et al., 1981).

Rapid commercial development of Pacific islands requires the collection of baseline information on the important sedimentary environments of the coastal zone prior to major changes in watershed land use. However, biogeochemical studies of island sedimentary carbonate environments have lagged behind those of continental coastal zones (Berner, 1980). Emery (1962) surveyed most of the beaches and lagoons of Guam and provided textural and chemical data for many of them. Randall and Birkeland (1978) studied sedimentation at Fouha and Ylig Bays, but did not distinguish the allochthonous and autochthonous fractions. Birkeland (1984) proposed a land-effect rationale for differences in coastal community structure between that of high and low (atoll) tropical islands. At this writing, no reports of the nutrient biogeochemistry of Mariana sediments have been published, but a survey of the chemical content of coastal sediments has been recently initiated (Randall, Univ. of Guam, pers. comm.).

The purposes of the present study were to (1) investigate several ways to easily distinguish the terrestrial fraction in sediments of estuaries, moats, and lagoons of Guam and Saipan, and (2) then estimate the existing levels of terrestrial materials. These analyses will help identify those coastal regions that have been naturally impacted by terrigenous material and to distinguish them from others that have been impacted by development in the adjacent watersheds.

Coastal sediments of Guam and Saipan are shown here to have been impacted by different terrestrial runoff processes including intertidal aquifer discharge, sheet flow, and conservation of river load nearshore. Normal biogeochemical processes that occur in estuaries also occur, but in sites that are not usually considered to be estuaries. These include areas where aquifer water percolates into the

intertidal and subtidal areas and considerably lowers the ambient salinity. Some of the runoff processes occur at levels at which little if any effect is detectable, while others indicate the potential for future eutrophication problems.

THE STUDY SITES AND METHODS

The Study Sites

Five separate sites were chosen as models of some of the types of coastal habitats that exist in the Mariana Islands. Cocos Island, Ipan Beach, the Ylig River Estuary, and Tumon Bay (Blue Lagoon) sites were on Guam. The San Roque samples came from the northwest coast of Saipan in an area otherwise morphologically similar to Tumon Bay (Fig. 1).

Cocos Island Lagoon (CI), off the southern coast of Guam is shallow (3 to 5 m deep) with dense patches of the seagrass Halodule spp., broad sandy areas, and rain is the only freshwater input. Merizo channel (MC) separates this lagoon from mainland Guam, was created by a fault, is up to 40 m deep, and is a depositional basin for both direct runoff and for material that sloughs from shore and from the elevated platform of Cocos Lagoon. The MC site was on the Cocos Lagoon side of the channel in 10 m of water in a heavily bioturbated Callianassa (Decapoda, Crustacea) mound area.

Ipan Beach moat is shoreward of a fringing reef and is < 3 m deep. After heavy runoff, the offshore surface waters usually contain an easily distinguished layer of turbid water from the Talofofo River, 1.5 km to the south (average annual discharge = 51 cfs or $46 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ [Randall and Holloman, 1974]). Also, this was the site of a military camp and several large pieces of metallic debris (55 gal drums full of concrete) were left in the moats when the camp was abandoned. These activities have resulted in a large residual Fe and Si signal in the sediments above and beyond that of terrestrial runoff. Three separate sites were sampled at Ipan. Ipan Beach fore-reef (Offshore Ipan, OI) is a typical fringing coral fore-reef community that ranges down to several hundred meters on the sloping southeast coast of Guam. Any terrigenous sediment that is deposited at the Ipan sites must first mix with ambient seawater. Two depositional holes were sampled (at 17 and 25 m), as well as the coral rubble in turbulent areas (3 and 17 m). Ipan Lagoon (IL), the moat area (< 3 m deep) behind the fringing reef, had sparse macrophytes, moderate turbulence, and rather coarse sediments. The IB samples were from several smaller moat pools peripheral to the larger IL moat site and had relatively calm wave action, finer sediments, abundant infauna and patches of the seagrass (Enhalus, spp.).

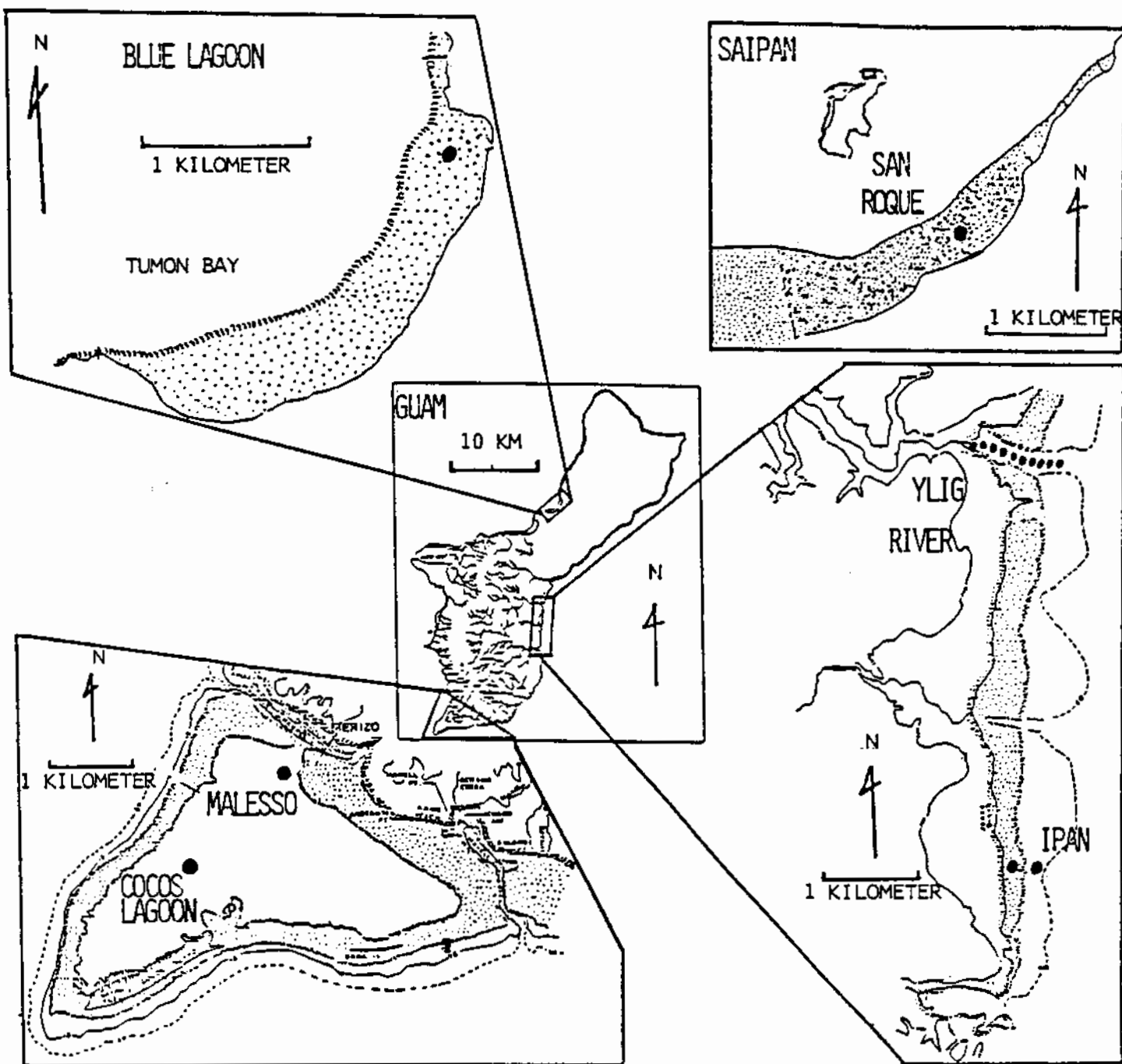


Figure 1. Study sites in Guam and Saipan.

The Ylig River Estuary (YR) was sampled from its mouth at the Rte. 4 bridge along a transect to the edge of the fringing reef in an increasing gradient of depth from 5 to 30 m. The river bottom consisted of alternating layers of terrigenous mud and oceanic carbonate, and many tree trunks, coconuts, and bamboo stalks were present. Of the five areas studied, this site serves as the estuarine member in a continuum of river runoff. Surface water salinities in the top 20 to 50 cm brackish layer at YR Sta. 1 (the Rte. 4 Bridge, Fig.1) are always < 5 o/oo during runoff events, and > 30 o/oo bottom waters normally occur for several km upstream of the bridge.

The northern end of Guam is almost entirely carbonate (in contrast with the lateritic/argillaceous outcrops of the southern end) and there are no rivers. Instead, the aquifer (the so-called Ghyben-Herzberg lens) discharges at sealevel around the entire northern periphery. The aquifer waters are easily detectable at low tide due to their lower temperature and by the easily-observed percolation of aquifer water into the subtidal waters. Tumon Bay is in this northern carbonate regime with aquifer discharge into the intertidal zone, but with minimal natural surface runoff. The BL site in this bay was chosen, together with the CI site, as the other "marine end-member" of a runoff continuum. The moat (average depth = 0.80 m at MLW) receives a significant quantity of nitrate-rich aquifer water (Zolan, 1982; Matson, 1987) but otherwise contains little sediment or other debris associated with surface runoff.

The San Roque site (SR) in Saipan is very similar to the Tumon Bay site in its orientation to normal weather patterns, size, shape, and depth. The exception is that the adjacent land has deeper layers of lateritic soils. Also, because of poor land-use practices in the small watershed, two small engineered rivers as well as dirt roads and farms allow discharge of inordinately large amounts of eroded lateritic (not carbonate) sediment. Thus, it can be compared with the BL site for the effects of (largely anthropogenic) terrigenous runoff into an otherwise marine reef-flat moat.

The eight sites therefore range from a river estuary with substantial terrestrial influence (YR) to an essentially purely marine community (CI). Intermediate between these are marine sites where subsurface freshwater intrudes (BL), coastal erosion and little runoff (MC), marine moats (IL and IB), offshore reefs with sporadic input of river sediment (OI), and an otherwise marine moat with heavy anthropogenic input (SR). They are summarized in Table 1.

Table 1. Terrestrial impact on the eight study sites.

Site	Type of Terrestrial Effects
Cocos Island (CI)	Rainwater; carbonate island erosion
Tumon Bay (BL)	Aquifer discharge; some sheet flow
San Roque (SR)	Small river; heavy construction erosion
Malesso Ch. (MC)	Coastal erosion; small river
Ipan:	
Offshore (OI)	Fore-reef; large storm river plume
Lagoon (IL)	Iron drums; little terrigenous material
Biological (IB)	As above (IL), but highly productive
Ylig River (YR)	River estuary

Methods

Samples were obtained from surface (the top 1 to 2 cm) and deeper sediments (cores of the top 10 to 70 cm) randomly between December 1984 and June 1986, without regard to seasonality of runoff. In this respect, the evidence presented in this report for terrestrial impact on these sites represents the signal that can be detected year-round. Lower levels of terrestrial materials that only appear sporadically or seasonally are not considered here and are discussed in a subsequent report (Matson, in preparation).

Sediments were routinely dried (50° C), homogenized, and subsampled for several type of analyses, as follows:

- HCl-extracts for analysis of Al, Fe, Si, P, and NH_4^+ (> 24 h in reagent grade HCl made 20 % [vol] in deionized reverse osmosis tap water),
- Loss on ignition (LOI = 500° C > 2 h), and residual ash, and,
- Stable C isotope ratios ($\delta^{13}\text{C}$) of organic and inorganic fractions of sediment and macrophytes (chemical oxidation and mass spectrometry performed at Coastal Science Laboratories, Austin, Texas).

Samples were obtained in either Whirl-Pak (R) bags; poly-vinyl chloride (PVC), 8 cm diameter core liner (sediment cores using SCUBA); or in acid-cleaned, linear polyethylene (LPE) Nalgene bottles (river and lagoon waters). Immediately after collection, samples were either dried at 50° C or frozen for subsequent analysis after drying. Some sediment cores were sectioned in an N_2 atmosphere while Eh readings (Corning Pt electrode) were being taken.

For analysis of "labile" Al, Fe, Si, and P (operationally defined as that fraction solubilized in 20% HCl for 24 h at room temperature), ca. 2 to 10 g dried sediment was weighed into acid-cleaned Erlenmeyer flasks or in glass dissection dishes, followed by addition of 20% HCl. The particulate residue left after this carbonate digestion (% loss in HCl = % HL) was collected on precombusted, preweighed Gelman type A/E glass fiber filters, and the filtrate was stored in acid-cleaned LPE bottles. The residue on the filter was dried at 50° C, reweighed (= weight loss for calculation of % HL content, and combusted at 500° C for >2 hr for an estimate of organic matter (loss on ignition, LOI). The material remaining after ignition was considered to be ash, not to be confused with volcanic ash. The filtrate was analyzed for Al, Fe, Si, and P (Al and Fe by atomic absorption; Si and P by molybdate/tungstate and molybdate, respectively, Stainton et al., 1974). Concentrations are expressed as μmol per gram of original dry sediment, i.e., not "carbonate-free".

For stable C isotope analyses, fresh frozen or oven dried (ca. 50° C) samples were shipped directly to the contractor. There, CO₂ was released with mild acid, trapped, and purged directly through a mass spectrometer. Residual organic matter was oxidized with KMnO₄ and the resulting CO₂ was handled as above. The $\delta^{13}\text{C}$ data are reported relative to the Chicago PDB standard and are accurate to 0.2 o/oo.

Stable C isotope analysis of sedimentary carbonate and organic matter can be used to help distinguish terrestrial from marine material (Hedges and Parker, 1976; Schultz and Calder, 1976; Botello et al., 1980; Stephenson and Lyon, 1982; Fry and Sherr, 1983; Gearing et al., 1984; Smith et al., 1985; Peterson et al., 1986). Isotope discrimination by photosynthetic enzymes of algae, macrophytes, and terrestrial plants is generally of the order of 18 o/oo. The stable C isotope ratio ($\delta^{13}\text{C}$) of atmospheric CO₂ = -12 o/oo while marine CaCO₃ = ca. +3 o/oo (Friedli et al., 1986). Marine plankton fix dissolved bicarbonate that appears to have a $\delta^{13}\text{C}$ value of about + 4 o/oo. This results in terrestrial organic carbon $\delta^{13}\text{C}$ values of -28 o/oo and corresponding values around -14 o/oo, both about 18 o/oo lighter than the inorganic C source. These differences are used here to identify occurrence of terrestrial OC and freshwater CO₂ in the nearshore sites studied.

RESULTS AND DISCUSSION

Chemical Composition of The Sediments

A summary of the average chemical composition of the eight sites is given in Table 2, and the data are arranged by

Table 2. Mean ($\pm$ 1 SD) chemical composition of the sediments at the eight study sites. N ranges from 9 to 40 for each entry. The sites are listed in approximately increasing order of impact by land.

Site		Fe umol	P g ⁻¹	Si dry wt	HL %	LOI of dry	Ash wt	POC d ¹³ C - PDB	PIC
BL	X	1.3	6.0	9.9	99.5	0.39	0.093	-14.0	1.99
	1 SD	0.64	0.91	6.5	0.14	0.089	0.056	4.48	0.72
CI	X	3.5	9.8	5.0	99.1	0.74	0.15	-12.7	3.38
	1 SD	0.84	1.5	5.4	0.4	0.36	0.058	0.32	0.10
OI	X	8.4	8.0	22	98.9	0.75	0.38	-14.9	2.00
	1 SD	0.65	1.0	0.8	0.1	0.11	0.005	0.93	0.34
MC	X	27	8.2	34	98.3	0.68	0.99	-12.1	2.77
	1 SD	15	0.82	14	0.55	0.31	0.24	0.10	0.83
IL	X	33	8.4	29	97.0	1.5	1.4	-11.9	2.40
	1 SD	23	1.1	10	1.7	1.0	1.1	1.1	0.09
SR	X	23	no data		97.0	1.06	1.95	-15.0	3.48
	1 SD	20			1.96	0.59	1.40	1.36	0.41
IB	X	60	7.5	40	94.7	3.1	2.1	-13.2	3.14
	1 SD	44	0.81	14	2.4	1.6	2.0	7.74	1.44
YR	X	323	5.0	24	34	14	53	-21.3	0.83
	1 SD	74	4.8	14	12	5.5	8.3	1.71	1.28

increasing concentrations of ash and decreasing HL (*i.e.*, carbonate) contents. The stable C isotope data (d¹³C) provide independent corroboration of the occurrence of terrigenous material (Fry and Sherr, 1983; Peterson *et al.*, 1986).

Substantial increases in Fe, ash, and LOI (organic matter) and simultaneous decreases in carbonate (HL) occurred along the continuum of terrestrial impact. The CI and BL sites can be considered to have chemical contents that reflect natural accumulation in the marine environment while the other sites contain additional Fe, ash, LOI, and lighter C isotopes from land. However, the BL site receives intertidal aquifer input that depletes the sediments of P and supplies isotopically lighter CO₂ for carbonate formation. This relative depletion in HCl-extractable P is possibly due to diagenetic mineral concretion and P exclusion or to the presence of high (up to

450 μM) levels of nitrates in the aquifer water. Silica contents also increased along this series of sites, except for a moderate decrease in the Ylig River samples, probably due to uptake by large populations of planktonic and attached diatoms. Such populations have been observed throughout the Ylig (Matson, unpublished) and Pago Rivers (Zolan, 1980). Sedimentary P was lowest at both sites affected by freshwater runoff, either from the northern aquifer (BL) or the Ylig River (YR). This is in line with the common observation that marine systems are enriched in P relative to freshwaters (Dryssen and Wedborg, 1980; Liss, 1976).

General trends among the data are given in Figure 2 and clearly show this chemical and isotopic gradient from freshwater/estuarine samples from the Ylig to the marine "end-member" at Cocos Island. It is noteworthy that for $\delta^{13}\text{C}$ and P values, the BL site falls near the estuarine end of this trend, while for Fe, LOI and ash, this site appears to be more "marine" than the CI site. Apparently, the effect of the aquifer is significant.

Because corals are predominantly CaCO_3 , the existence of both high HL concentrations and simultaneously heavy (*i.e.*, more positive) $\delta^{13}\text{C}$ values indicates the existence of marine derived sediment. Together with Fe and Si analyses, $\delta^{13}\text{C}$ data provide a useful and easily-obtained index of terrigenous influence in the coastal zone of tropical reef systems, with high Fe and Si values and low (lighter) $\delta^{13}\text{C}$ values indicating terrestrial input. Further, terrestrial debris contains a high ash fraction, mostly due to detrital clay minerals. Conversely, the ash fraction of marine material produced in the coastal zone is low, except where diatoms (which contain high Si levels) are abundant. A graphical summary of all HL, LOI and ash data from marine sites (*i.e.*, exclusive of the Ylig River) is given in Figure 3. It is obvious that in carbonate-rich sediments (> 92 % HL), both ash and LOI contents are very predictable.

The $\delta^{13}\text{C}$ values for particulate organic carbon (POC) ranged from a mean of -21.3 o/oo (strong terrestrial/estuarine component) in the Ylig River Estuary sediments to -11.9 o/oo (strong marine component) at the IL site with coarse-grained marine carbonate debris. Three samples of POC from storm runoff in three rivers had $\delta^{13}\text{C}$ values of -23.3, -23.4, and -21.5 o/oo. The $\delta^{13}\text{C}$ values for sedimentary CaCO_3 (PIC) ranged from +0.83 in the Ylig River to +3.38 and +3.48 o/oo at the CI and SR sites, respectively. Of particular interest are the lighter PIC values for the OI and BL sites. The former intermittently receives heavy river loads of argillaceous material (mixed laterite and carbonate), while the latter is affected by the discharge of the aquifer in the intertidal zone. While both OI and SR have a detectable terrestrial OC component, the SR site has a strong marine

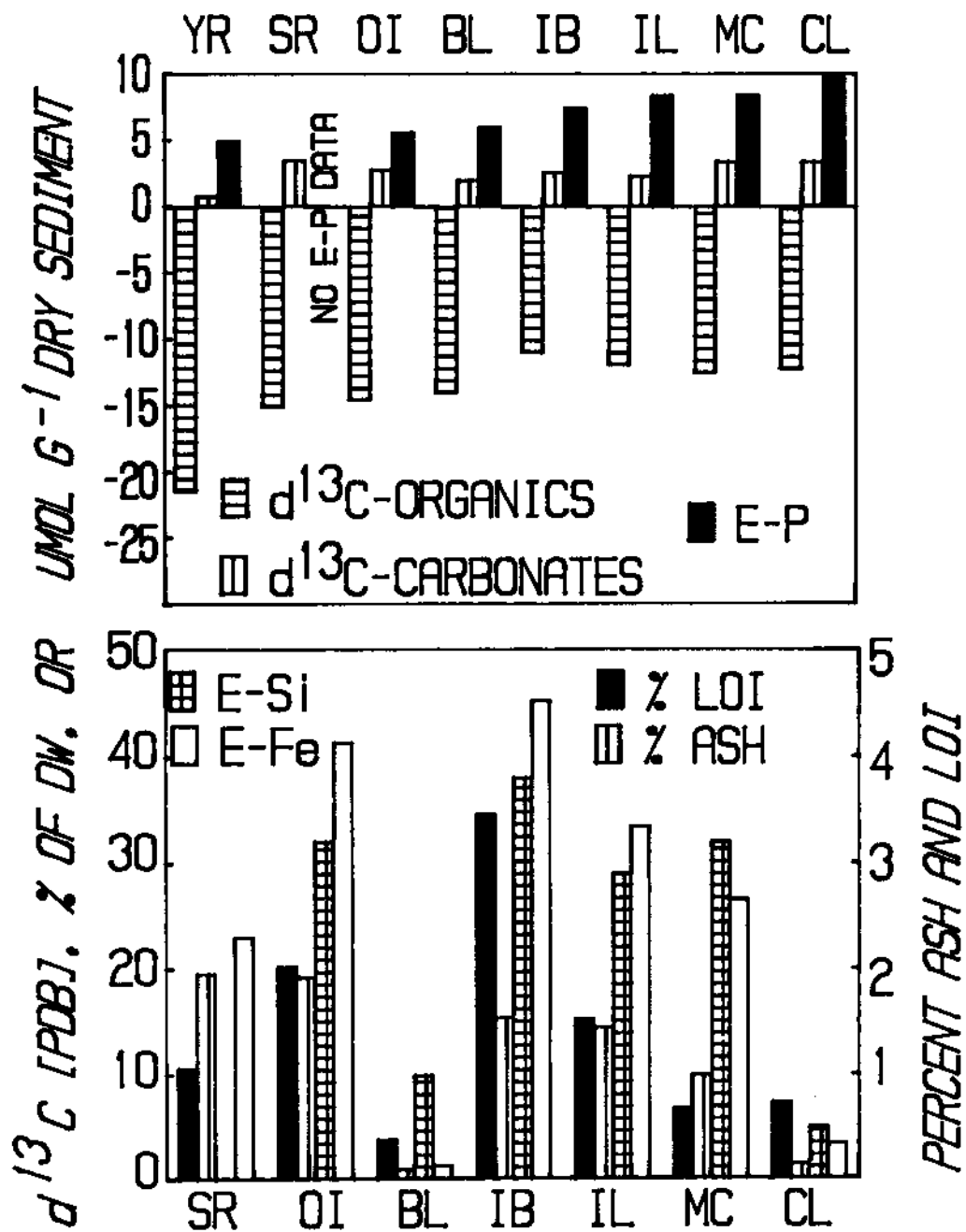


Figure 2. Mean values for extractable P, Fe, Si, and percent LOI and ash, and stable C isotope value from Guam and Saipan

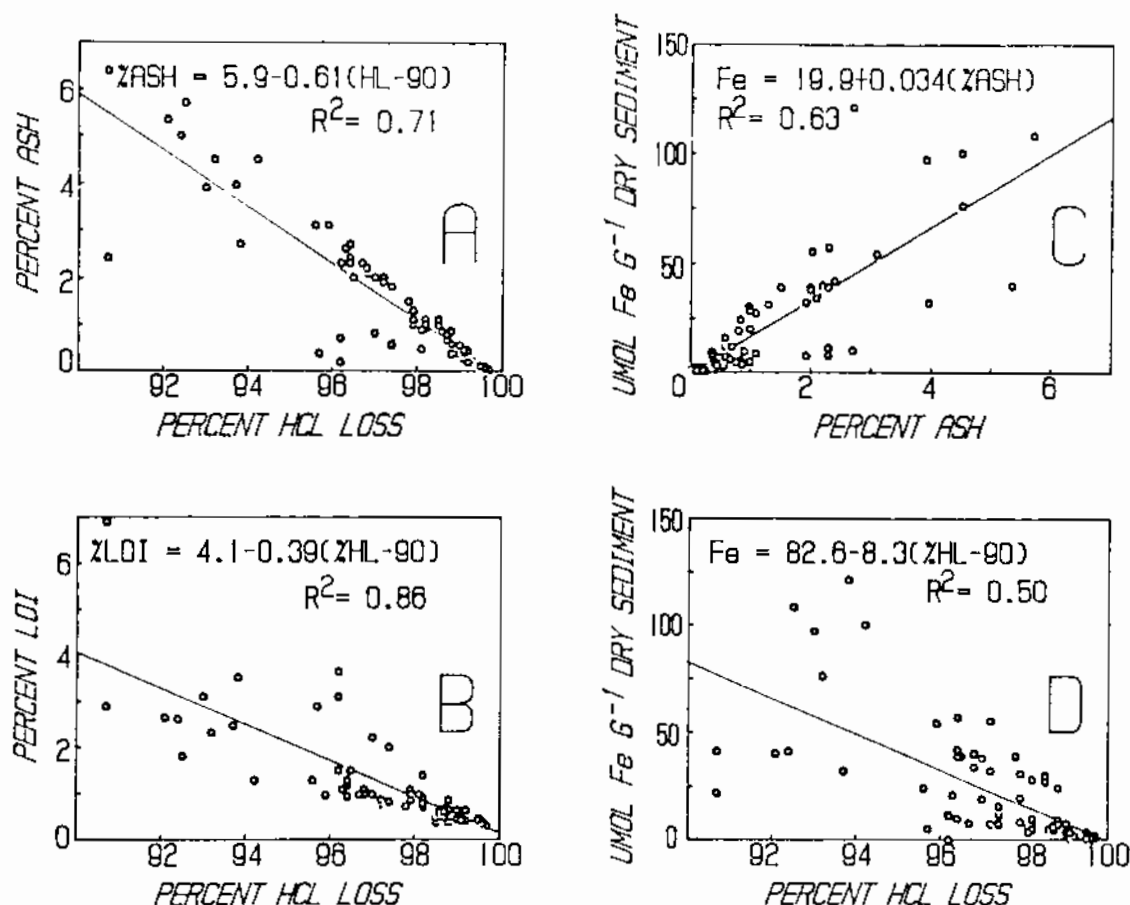


Figure 3. Linear regression analyses for % HL, LOI, ash and Fe.

carbonate component. Therefore, it appears that terrestrial organic matter can accumulate, especially as a result of erosion after large storms, in otherwise marine habitats that contain typical marine carbonates. The SR isotope data thus imply a different type of impact. The SR terrestrial material contains little carbonate that could alter the marine carbonate (HL) signature, while at the BL site very little, if any, terrestrial organic matter occurs, but the carbonate signature is detectably altered by mixing of freshwater CO_2 from the aquifer.

Of particular interest is the apparent lack of agreement between the "impact gradient" given for sediment chemical composition (above) and $\delta^{13}C$ values. The main reason for this, especially at the BL site, is the type of CO_2 that is fixed into $CaCO_3$. The BL site is impacted by aquifer discharge that contains some CO_2 in equilibrium with the atmosphere, while sites with no freshwater input (CL, MC, OI) have CO_2 supplies that are in equilibrium with marine carbonates. Therefore, the latter are several o/oo heavier

than samples from sites impacted by freshwater. The extreme example is the Ylig River PIC that averages 0.83, or 2.65 o/oo lighter (more "atmospheric") than marine samples (CL, MC, OI). Also, the $\delta^{13}\text{C}$ values for CO_2 in the interstitial pore waters of the Ylig River sediments were much heavier (-11.7 to -17.2, and averaged -13.8 o/oo, data not shown) than the sedimentary organic matter (-21.3) from which they were generated. This may indicate that either heavy marine OC was oxidized (and it constituted a minor fraction of the sediment) or that the lighter CO_2 that was produced from -21.3 OC was removed by autotrophic organisms (Whelan, 1972; Matson *et al.*, 1983; Matson and Brinson, 1985). These excursions from the normal marine data clusters are more evident in Figure 4. Very light organic carbon (*i.e.*, < -24 o/oo) was produced at several sites, including that by cyanobacteria at Ipan and by *Enteromorpha* in the "estuary" at the Blue Lagoon.

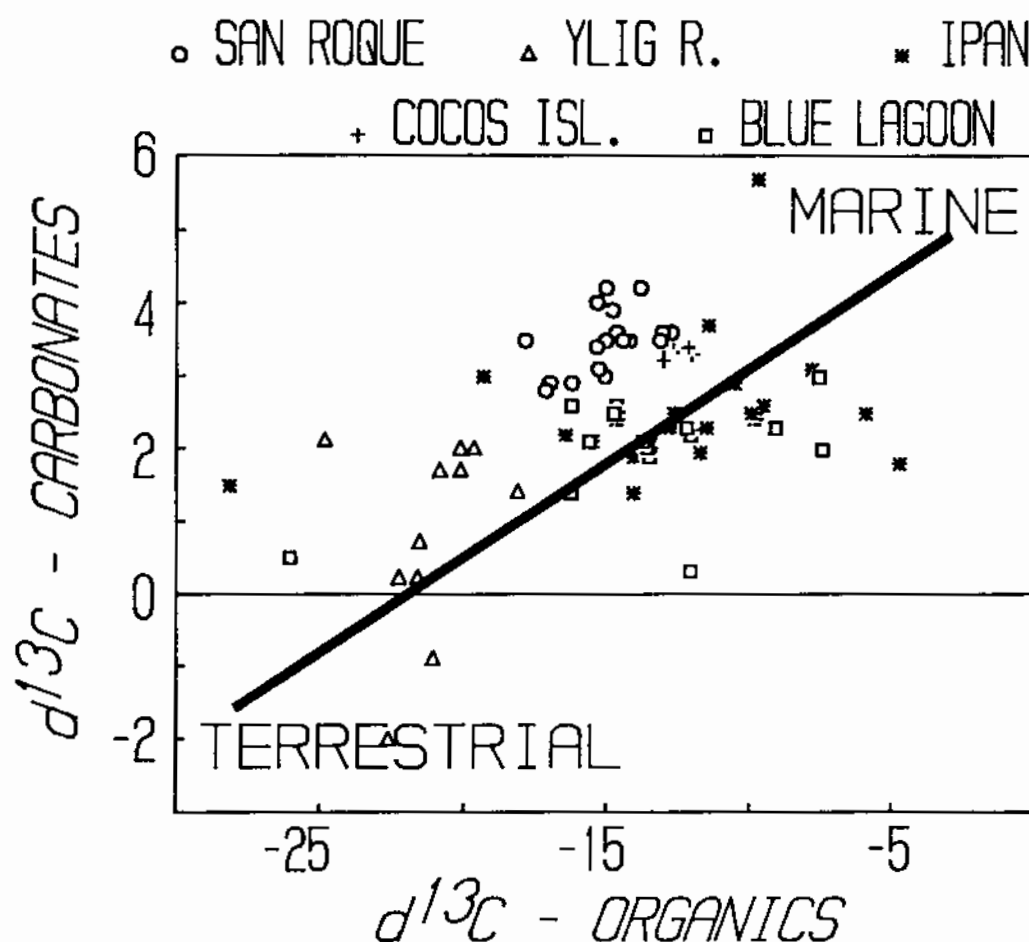


Figure 4. Stable C isotope data. The symbol is larger than the analytical error.

The large variability among the $\delta^{13}\text{C}$ data may also be due to the recently described existence of both C-3 and C-4 plants in the marine realm, as well as to mixed modes of metabolism among them (McMillan *et al.*, 1983). Thus, some marine plants, such as *Thalassia* and *Enhalus* may have very different $\delta^{13}\text{C}$ values for organic carbon depending upon season, location of the sample (root, stem, leaf blade), and even the location of the sampled plant within a bed. Further, estuarine plants, such as *Enteromorpha* (which is a major producer at the BL site within the aquifer discharge delta), have $\delta^{13}\text{C}$ -POC values as low as -26 o/oo. This value is several o/oo lighter than the POC in freshwater runoff. Further, decomposed *Enteromorpha* had a $\delta^{13}\text{C}$ -POC value of -21.7, which indicates substantial leaching and removal of the light isotopes during diagenesis (Matson, in press). Nonetheless, the means for these sites clearly shows the difference between river/ estuarine transitions (YR; -21.8 o/oo) and marine POC (-10 to -15 o/oo). The previously described heterogeneity of Ylig River sediments is evident from the isotope data in Figure 5, discussed below.

The stable C isotope data presented here are quite similar to those of Smith *et al.* (1985) from Kaneohe Bay on Oahu, in the Line Islands, and from the Great Barrier Reef. However, their $\delta^{13}\text{C}$ -PIC values are systematically lighter than those for carbonate sediments on Guam and Saipan. Their inorganic C data cluster around +1.0 (+/- 0.8; N = 60) regardless of whether the sediment was from an oceanic atoll (*e.g.*, Fanning or Christmas Isl.) or from a fringing reef near runoff (three sites on the Great Barrier Reef). The Mariana Isl. means (except the Ylig River data) are systematically 1.7 o/oo heavier than the pooled data from the study of Smith *et al.* Most of the samples from both studies were processed by the same contractor, so this cannot be a reason for the difference between the data. Perhaps the Mariana Islands, in proximity to deep ocean trenches, receives a supply of isotopically heavier bicarbonate from upwelling (Kroopnick, 1985). Alternately, the reefs studied by Smith *et al.* (1985) may be less productive than the Mariana reefs. High rates of photosynthesis can result in less discrimination against the heavier isotope that results in heavier carbonate sediment. However, in spite of this difference in inorganic C isotope values, their organic C values were quite similar to those found here. Their average for the organic fraction was -15.6 (+/- 2.7; N = 65) which includes some lighter material (-22.4; N = 5) from reefs nearshore in Australia.

Statistical Summaries

Linear regression analyses (least squares) of pooled data from all sites indicate that greater than 75 % of the variance (R^2) among the data is explained by regression, except for the C isotopes (Table 3). Carbonate content (%)

Table 3. Statistical summaries : linear regression analyses

Samples	X	Y	Slope	R2	N	SE
All	% HL	% LOI	- 0.21	0.89	99	1.43
		% ASH	- 0.79	0.99		1.44
		Fe	- 4.67	0.90		30.6
	% LOI	% ASH	3.30	0.83		6.52
		Fe	19.5	0.75		48.6
	% ASH	Fe	5.90	0.91		29.3
	d ¹³ C POC	PIC	0.12	0.22		1.06
Cocos	% HL	% LOI	- 0.47	0.54	9	0.25
		% ASH	- 0.56	0.45		0.35
		Fe	-30.4	0.74		10.2
	% LOI	% ASH	0.48	0.14 NS		0.43
		Fe	36.3	0.44		14.9
	% ASH	Fe	34.5	0.66		11.7
Ipan	% HL	% LOI	- 0.49	0.62	18	1.01
		% ASH	- 0.50	0.62		1.04
		Fe	-10.6	0.53		26.4
	% LOI	% ASH	0.25	0.06 NS		1.64
		Fe	6.21	0.07 NS		37.1
	% ASH	Fe	20.2	0.79		17.8
Blue L.	% HL	% LOI	- 0.59	0.86	22	0.03
		% ASH	- 0.37	0.85		0.02
		Fe	0.58	0.02 NS		0.67
	% LOI	% ASH	0.50	0.64		0.04
		Fe	- 2.15	0.09 NS		0.65
	% ASH	Fe	0.28	0.00 NS		0.68
Ylig R.	% HL	% LOI	- 0.36	0.57	10	3.99
		% ASH	- 0.65	0.81		4.00
		Fe	- 2.17	0.11 NS		77.9
	% LOI	% ASH	0.60	0.16 NS		8.48
		Fe	0.90	0.00 NS		82.6
	% ASH	Fe	3.86	0.19 NS		74.7
Saipan	% HL	% LOI	- 0.29	0.9240		0.17
		% ASH	- 0.71	0.99		0.17
		Fe	- 5.56	0.28		17.8
	% LOI	% ASH	2.17	0.84		0.57
		Fe	14.1	0.17 NS		19.2
	% ASH	Fe	8.3	0.32		17.3
		Al	0.73	0.32		22.1

HL) is inversely related to ash, organic matter (LOI), and Fe. All of the latter are generally derived from land and the regressions are heavily weighted by the end-member marine (CI, BL) and estuarine (YR) data (Table 2). Accordingly, LOI, ash, and Fe covary strongly. While there are substantial differences in R^2 and slopes within each of the eight sites, these have definite biogeochemical explanations.

For example, at Cocos Island (the marine "end-member") organic matter (LOI) and ash do not covary significantly and the relationships between HL and ash, and LOI and Fe are relatively weak. This is probably due to the fact that the organic matter comes from Halodule decomposition products that leave variable amounts of little ash and small amounts of Fe. Further, high HL concentrations show that terrigenous influence (and the corresponding occurrence of Fe, Si, and ash) is minimal.

At the other extreme, there is no significant relationship between LOI and ash or between LOI and Fe in the Ylig River sediments. This is because so much organic matter accumulates in this estuary that anoxic conditions exist within the top few mm of sediment. Under these conditions, LOI (organic matter) is conserved and Fe is precipitated into pyrite (FeS_2 ; Howarth, 1979; Pyzik and Sommer, 1982) which was not measured in this study. Further, low salinity reactions upstream of the sampling sites (Eckert and Scholkovitz, 1976; Scholkovitz *et al.*, 1978; Eaton, 1979; Morris *et al.*, 1981) remove different terrestrial fractions from solution at different rates. This results in essentially non-conservative behavior during mixing of river with sea water (Liss, 1976; Mantoura and Woodward, 1983; note that Si is relatively low in this estuary, Table 2). Geochemical fractionation and segregation of weathered clay mineral components along the salinity gradient may produce these trends (Dryssen and Wedborg, 1980; Stumm and Morgan, 1981).

For further description of the Ylig River, the values from each station are given in Figure 5. The only real trend among the data exists for silica, which decreases markedly in the center reaches of the river bottom. This is attributed to the abundant growth of phytoplankton (especially diatoms) within the estuary and on the of the border reef-flats. Phosphorus and Si increase to the highest values at the mouth of the estuary at the fore-reef border. The d^{13}C values for these sites also indicate the existence of both heterogeneous distribution and mixtures of marine, estuarine, and terrestrial material. If increasingly "marine" sediments occurred over this transect, then d^{13}C values, P, and TIC would increase and Fe, ash, and LOI would decrease with distance from the Rte 4 bridge. What appears to occur is that some marine sediment is transported upriver (Meade,

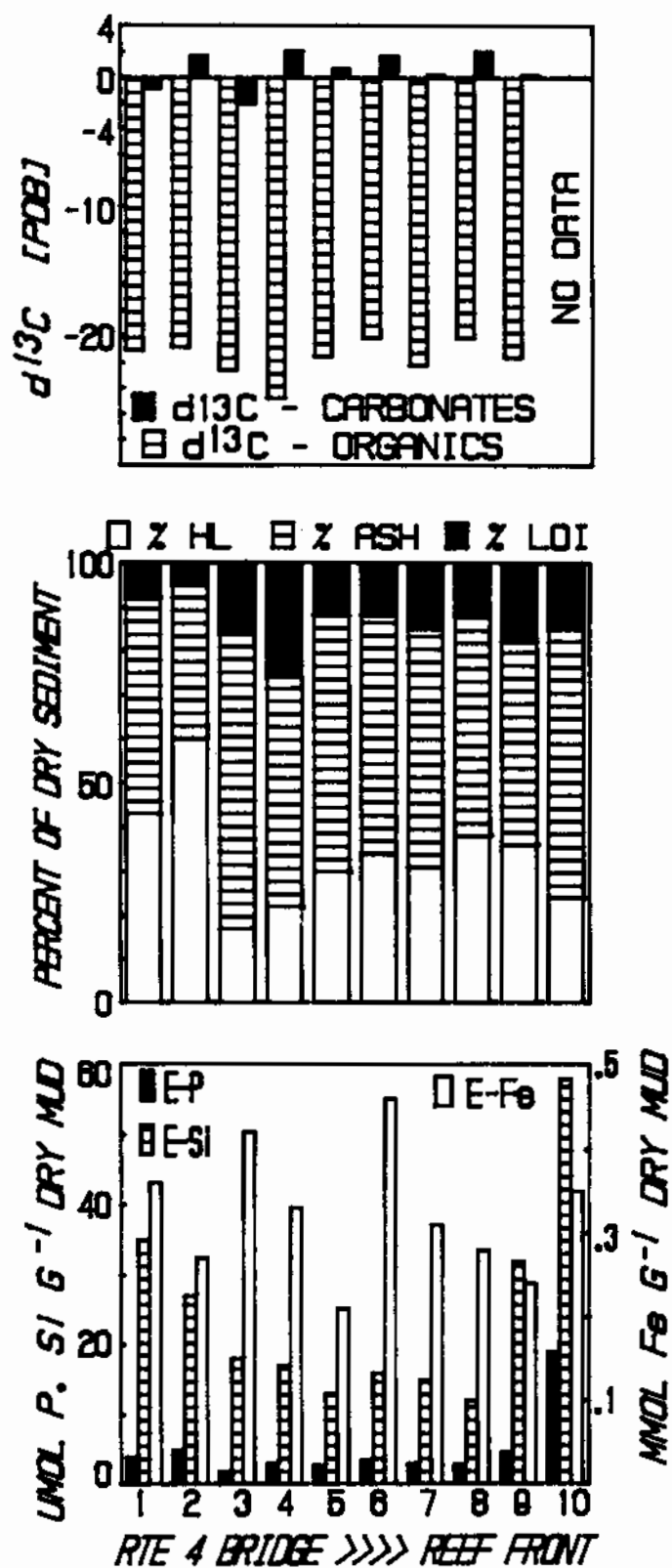


Figure 5. Ylig River Estuary nutrient and isotope data.

1972; Matson and Brinson, 1984) along the bottom of the Ylig (especially during storms) and entrains P within it. This might also explain why Fe and LOI are both related to ash, organic matter (LOI), and Fe. Also, since P increased dramatically at the most seaward station, it might be the only truly "marine" sample taken on this transect. Observations with SCUBA reveal a distinct and abrupt margin at the mouth of the estuary (between stations 9 and 10, Fig. 5) where brown river mud is replaced by marine carbonate in the surface sediments. Mixing within this estuarine system is therefore complex and poorly understood, especially in light of recent data (not shown) that indicates that linear mixing of surface waters occurs during storms (Matson, in preparation). In contrast, samples from other stations were all taken from essentially marine waters where spatial variability of the surface sediment composition is low (in comparison with the Ylig) but where vertical gradients reveal historical events, such as at San Roque in Saipan.

The deep core data from the San Roque site are shown in Fig. 6 and are all from within a 1 ha area within 50 m of the beach berm. The sampling area was chosen equidistant between two culverts that had been constructed to accelerate runoff from a village area after a main highway had been placed along the shoreline. A farm and several dirt roads on the shoreline slope supply large amounts of predominantly red clay that turn the bay brown after even small storms. Fortunately, tidal flushing is sufficient to redistribute much of this material: the tidal prism is about 75% of the bay volume. At these sites, aluminum and ammonium were measured instead of P and Si in order to better corroborate the occurrence of terrestrial admixtures in discrete sedimentary horizons. Although Al is weathered out of terrestrial laterites slower than Fe (Stumm and Morgan, 1981), its behavior is biochemically conservative: it is not affected by redox processes in sediments and does not precipitate into refractory forms as does Fe during pyritization. Therefore, it can be used as an essentially conservative tracer of terrestrial material in the coastal zone.

In core HNLC-1 (Fig. 6) there is a distinct clay layer in the 20 to 30 cm sediment horizon. Here, carbonates decrease and % H₂O, Fe, Al, ash, and LOI all increase in association with this clay layer. The deeper layers of this core have been heavily bioturbated by infaunal shrimp (*Callinassa* spp.: Decapoda, Crustacea) and by large worms such as *Arenicola* spp. Thus, the inert ash fraction has been reworked into the deeper layers and accumulates to higher levels. In contrast, the LOI and NH₄⁺ concentrations decrease back to the levels in the upper sediments, presumably due to irrigation with oxygenated surface waters by infauna (Aller, 1978, 1980; Waslenchuk *et al.*, 1983), and

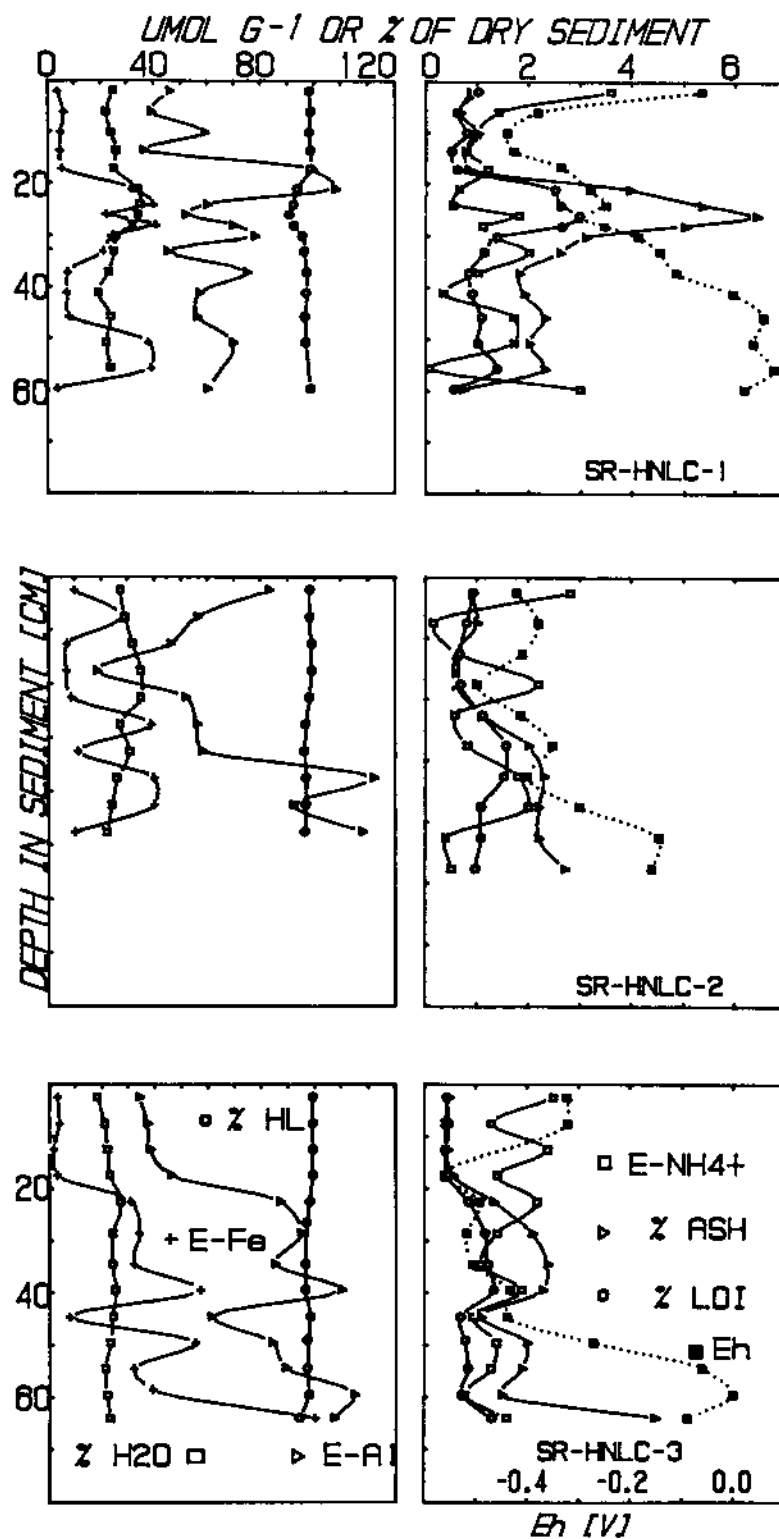


Figure 6. San Roque cores HNLC-1, 2 and 3.

subsequent consumption of NH_4^+ and organic matter.

The effects of infaunal bioturbation are more evident in cores HNLC-2 and 3 by the "smearing" of the peaks seen in core HNLC-1. In these latter two cores, terrestrial material increases rather gradually with depth in the sediment below the 20 cm layer. A broad peak of Fe, Al, and ash is evident between the 20 and 50 cm horizons of core HNLC-3. These San Roque cores indicate the presence of an historical terrestrial deposition event. Possibly, due to the absence of large, identifiable, terrestrial plant material that indicates the occurrence of a typhoon, the occurrence of these terrestrial materials are due to road construction and the resulting erosion of road bed and farm soil adjacent to it. Subsequent construction of the culverts to divert accelerated runoff would exacerbate these erosional conditions. After this event, normal marine carbonates could then again be laid down, especially from the seaward side of the lagoon during storms from the northeast. In support of this, the $\delta^{13}\text{C}$ values for the San Roque surface sediments (top 15 cm, Table 2) are representative of marine carbonate, even though there is a detectable fraction of terrestrial organic material. Unfortunately, $\delta^{13}\text{C}$ data from the deeper layers were not obtained.

From these data alone, purely oceanic end members are easily identified as the CL and BL sites. This is because neither site contains more than 1% of the amount of Fe that appears in the Ylig River:Fe from "oceanic" sources (normal biological accumulation) would be virtually undetectable in Ylig River muds. The OI site contains about 2.6 % of the amount of Fe at YR, and, together with another indicator of terrigenous material, such as Al, the terrestrial fraction might be detectable. Also, the ash content of the oceanic end-member (CL and BL) is < 0.15 %, while the Ylig samples had up to 67% ash (average of 53 %).

Flux of Material to The Coastal Zone of Southern Guam

River flux estimates were constructed from extant annual discharge and average concentration data and are compared with standing stocks in the top 1 cm of sediment at all sites (Table 4). This analysis is used to determine whether material deposited from rivers is retained within the coastal zone or whether a significant fraction is exported offshore. It also allows for estimation of the accumulation of apparently terrestrial material that accumulates in essentially marine habitats due to in situ biological production.

The "marine end-member" BL and CI sites both contain less ash and Fe than do the other sites. However, these sites

Table 4. Sediment contents (top 1 cm) and average flux to the southern coastal zone (shore to fore-reef) of Guam.

Site	Fe	P	Si	Ash	LOI	Accumulation Factor		
	mmol m ⁻²			g m ⁻²		Ash	LOI	Fe
BL	26	120	200	4.7	20	0.031	0.48	0.081
CI	70	200	100	7.5	37	0.050	0.88	0.22
OI	170	160	440	19	38	0.13	0.90	0.53
MC	540	160	680	50	34	0.33	0.81	1.7
IL	660	170	580	70	75	0.47	1.8	2.1
IB	1200	150	800	110	160	0.70	3.8	3.8
YR	6460	100	480	2650	700	18	17	20
Flux	320	68	16800	148	42	1	1	1

Average flux (m⁻² yr⁻¹) is calculated from total river runoff (16 X 10⁷ m³ yr⁻¹; Randall and Holloman, 1974) divided by the area of the southern coastal zone (ca. 80 linear km times an average 0.5 km to the fore reef) times average concentrations of Fe (8 µM), ash (3.7 mg l⁻¹), and LOI (22 % of total dry weight), all from Ellis-Neill (1986), and mean river Si and P concentrations of 420 (+/- 210) and 1.7 (+/- 0.31) µM, respectively (Zolan, 1981).

Average accumulation factor = site contents/average flux

have accumulated comparable amounts of organic matter (LOI) because of biological production. At the BL site, microalgae such as diatoms commonly occur in blooms on the sediment and in the water column. Hence, the BL site contains more silica than the CI site offshore of Guam. The offshore CI site contains more iron than BL because of accumulation of FeS in anoxic sediments within the extensive beds of the eelgrass *Halodule*. Accordingly, the silica contents at CI are low relative to BL because of the predominance of macrophyte production over that of microalgae such as diatoms. Deeper waters at the CI site allow for the development of eelgrass beds, while the shallower BL site does not.

Marine plants produce organic matter that contains essential amounts of Fe and P, and will leave a residual ash upon combustion. For example, the average TIC, ash, and LOI values for two samples of *Halimeda* were 96, 3.35 and 0.30 %, respectively, while the Fe, P, and Si contents were 3.5, 1.2, and 33 µmol g⁻¹ dry weight. This calcareous green alga is one of the more important sediment sources, especially at the OI site. At Ipan, sediments within an eelgrass (*Enhalus*) bed had 121, 7.3, and 42 µmol Fe, P, and Si g⁻¹ and 94 % TIC, 3.5 % LOI, and 2.7 % ash. In contrast, the coarser sediments outside the eelgrass bed had similar P and Si levels, but only 20 µmol Fe g⁻¹, and had 98 % TIC, 1.1 % LOI, and 1.0 %

ash. Thus, local biological effects need to be considered during both sampling and data interpretation.

At the other extreme, the Ylig River Estuary samples contain > 17 times the ash, LOI, and Fe than the "average deposition area" that was defined for the flux calculations. The YR phosphorus contents are not as great as in any of the other "marine" sites: P flux from land is quite low in comparison with storage in marine sediments.

These accumulation factors can be used as a general index of both the average effect expected from runoff to the average reef area, as well as to define the contents of "marine end-members" that are not affected by surface runoff. However, subsurface runoff (aquifer discharge at the BL site), old military hardware in moats (Fe and Si at the Ipan sites), all have a pronounced effect that can be separated from both terrestrial runoff and from normal, marine, biological production. In special cases, such as the strongly (and naturally) anoxic sediments of the Ylig River, some materials, such as pyrite and organic matter may accumulate to even greater concentrations.

Then how may the terrigenous fraction be defined? For these sediments, HCl-extractable Fe contents greater than 1 to 3 $\mu\text{mol g}^{-1}$ and/or ash contents higher than about 0.5 % would indicate that some terrestrial material had been deposited. Further, in the presence of interflow, groundwater, or other non-surface freshwater runoff, low values for both P and $\delta^{13}\text{C}$ of sedimentary CaCO_3 would indicate the presence of freshwater effects. Aluminum contents also indicate the presence of terrigenous inputs. From the San Roque data, we can estimate that greater than approximately 10 to 20 $\mu\text{mol HCl-extractable Al g}^{-1}$ dry sediment shows a terrigenous input.

The simple observation of river plumes in the coastal zone or runoff from a particular source does not, by itself demonstrate the accumulation of land debris in the coastal zone: often these plumes drift out to sea and are deposited in deep water, especially after typhoons. This is evident in the Ipan samples, where some depositional holes a half mile into the sea off the fore-reef had higher Fe contents than some sediments near shore. These are not necessarily harmful offshore. At other times, plumes driven offshore by discharge are later carried back to the coast by winds and tides and the transported load can be deposited closer to shore than implied by offshore excursion of the plume. Nonetheless, the smaller, shallower area between the land and the reef is especially sensitive to these materials because of a lack of simple dilution.

Diagenetic Considerations

In the coastal zone of continents and high islands, aluminum, iron and silica are almost wholly derived from land, although Si exists at low concentrations in oceanic waters due to upwelling of waters that contain the end products of diatom dissolution. Generally, the weathering sequence is $\text{Fe} > \text{Si} > \text{Al}$, such that terrestrial materials become relatively iron-poor and aluminum-rich over time (Stumm and Morgan, 1981). In the absence of biochemical activity, these materials would be subject to only geochemical segregation (due to selective weathering) and to fractionation in the low salinity zones of estuaries where materials may flocculate, coagulate, or otherwise form different phases that result in non-conservative mixing behavior (Dryssen and Wedborg, 1980; Liss, 1976). Truly conservative behavior actually occurs only for water, heat, and a few salts such as NaCl. Therefore, both the geochemical and biochemical effects must be appreciated before any of the materials of interest may be used to imply terrigenous impact on the coastal zone.

For example, Fe can be sequestered in anoxic sediments as FeS and FeS_2 due to the production of S^{2-} during bacterial sulfate reduction and as Fe-organic-P complexes in the low salinity zones of estuaries (Krom and Berner, 1980; Pyzik and Sommer, 1982). However, as for Al and Si, its major source is land. Silica may be removed biochemically in estuaries (see the Ylig R. data, Figure 5), but Al is neither removed nor precipitated in estuarine sediment. Aluminum may therefore be a better tracer of terrigenous material, especially clays, in the coastal zone. There is some evidence that kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) forms authigenically in some marine sediments, but it is probably not a major factor in the analysis presented here.

On the other hand, P is generally in greater abundance in oceanic than in fresh waters and an average Fe/P ratio for marine sediments would usually be < 1 (e.g., CI and BL). Phosphorus frequently forms organic-silicate-Fe complexes in the aerobic coastal surface sediments (Krom and Berner, 1980) and is often found in a 1:1 ratio with Fe, as long as the sediments are aerobic and an Fe source exists (Matson *et al.*, 1983). If the sediments become anoxic, S^{2-} usually reduces and then precipitates with Fe, and releases the P to diffuse along a concentration gradient back to the oxic surface sediment. This increases the Fe/P ratio in the solid sediment phase. In these cases, it would be wise to measure FeS_2 (pyrite; Howarth, 1979) as well as the HCl-extractable fraction because Fe/P ratios might appear artifactually low.

All of these post-depositional events must be considered prior to any assumption of conservative behavior of terres-

trial material upon arrival in saline waters. Normal biogeochemical processes alter the form, speciation, and behavior of these materials. It is largely for these reasons that coastal waters and estuaries are so productive.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The material discussed above shows that terrigenous sediment does not get very far from land at any of the sites. Even the station in the Malesso Channel, when observed with SCUBA, clearly shows a rapid gradient from coastal muds near the southern rivers to almost pure carbonate within the channel and up into Cocos Lagoon. Several samples from depositional "holes" at the OI sites (at 17 and 25 m depth) contained comparatively high levels of terrigenous organic material, ash, and Fe from the plume of the Talofoto River. However, sedimentation rates should be determined for many of these sites in order to estimate the natural rate of input prior to a major change in watershed land use. Away from direct sources of runoff, the nearshore sediments of lagoons, channels, and bays have clear chemical and isotopic signatures indicative of marine origin, with minimal accumulation of terrestrial material. Thus, it is implied that input of these materials to relatively pristine marine habitats, such as CI and BL, would stimulate production and possibly change the community structure.

Specific sites with identifiable nutrient inputs, such as Fe from 55 gal drums at Ipan and nitrate in aquifer waters in Tumon Bay, are easily distinguished. Relatively pristine marine sites such as Cocos Island Lagoon and Tumon Bay can be used as a reference for natural levels of these materials. For example, Fe and the $\delta^{13}\text{C}$ values can be used to identify the addition of a little as 1% terrigenous material to CI and BL sediments. Likewise, occurrence of marine sediments in estuarine areas can be identified by accumulation of P and an increase in the stable C isotope ratio of the sedimentary carbonate. Levels above this in Mariana coastal sites can be expected to stimulate high rates of productivity that may be associated with sedimentary anoxia and eutrophication.

While this report demonstrates the potential for entrainment of terrigenous material very close to shore, each particular site should be evaluated so as to identify special habitats that either promote or preclude the deposition of terrigenous sediment. Otherwise the introduction of materials that promote nutrient enrichment, such as clay minerals, Fe and Si could have substantial effects on the community structure of the coastal zone.

On a broader scale, while much has been made of the input of terrestrial material to the world's ocean, actually very little unequivocal information has been supplied to show that the land is a major source of material for the deep ocean. It appears that most material is entrained within the coastal zone, however defined. Thus it remains to be shown that the material either accumulates within the coastal zone or is geo- and/or biochemically modified into a different form (usually dissolved) for export out to sea.

Recommendations

A thorough study of the associated nutrient chemistry of the coastal waters is recommended in order to assess whether those terrestrial materials that have accumulated in high concentrations are also beginning to cause eutrophication. A study such as this should be done for a more diverse suite of sites and should include more than just one year. To date, no other sediment nutrient studies have been done in the Mariana Islands, and, as the immediate sources of nutrients to the water column, the sediments contain crucial information.

Specific recommendations include :

- (1) routine monitoring of point sources of potential pollution,
- (2) diversion of storm drains and sewer pipes away from fragile coastal land forms such as beaches and moats,
- (3) repair of broken storm and sewer pipes,
- (4) removal of metal debris from enclosed moats and lagoons,
- (5) routine monitoring of sediment redox potential (which is easily done with inexpensive field equipment) in lagoons and moats as a sign of increasing eutrophication, and
- (6) strict enforcement of construction-related erosion regulations

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APPENDICES

Appendix I. Sediment chemistry data from Guam

Appendix II. Sediment chemistry data from Saipan

Appendix III. Stable C isotope data

APPENDIX I. SEDIMENT CHEMISTRY DATA FROM GUAM

Sample	DEPTH (cm)	PERCENT % HL	OF DRY SEDIMENT % LOI	% ASH	UMOL G ⁻¹ E-Fe	DRY SEDIMENT E-P	E-Si
BLUE LAGOON							
A-85/7/2	1	99.5	0.43	0.120	0.72	4.9	5.1
B	3	99.6	0.34	0.073	0.70	5.5	3.6
C	5	99.5	0.44	0.091	1.40	5.6	4.7
D	11	99.6	0.34	0.100	1.00	8.5	7.7
A/85/7/3	1	99.6	0.40	0.046	0.66	5.3	3.3
B	3	99.2	0.64	0.210	0.91	5.3	2.7
C	5	99.1	0.61	0.250	0.72	7.5	2.2
D	11	99.5	0.44	0.088	1.10	5.6	3.4
A/85/7/4	1	99.5	0.37	0.088	1.5	5.3	6.1
B	3	99.5	0.38	0.098	1.0	5.7	2.2
C	5	99.6	0.35	0.053	1.1	6.2	4.5
D	11	99.7	0.30	0.029	0.7	6.5	4.1
A/85/8/1	1	99.6	0.28	0.083	2.0	7.0	18
B	3	99.6	0.29	0.100	1.6	6.8	17
C	5	99.5	0.37	0.160	2.3	7.6	21
D	11	99.5	0.37	0.120	3.5	5.7	17
E	21	99.5	0.39	0.130	1.5	4.9	13
A/85/8/2	1	99.7	0.29	0.019	1.8	5.9	15
B	3	99.5	0.38	0.080	1.5	5.8	17
C	5	99.6	0.37	0.058	1.2	6.3	17
D	11	99.6	0.33	0.030	1.1	5.5	16
E	21	99.7	0.31	0.028	1.6	5.4	17
MALESSO CHANNEL							
CI85/6/2A	1	98.6	0.57	0.86	24	8.6	39
B	3	98.2	0.72	1.10	18	7.4	41
C	5	98.7	0.46	0.86	16	7.7	33
D	11	98.8	0.47	0.78	20	7.8	51
E	21	98.3	0.58	1.10	16	7.2	38
CI84/12/A	3				36	9.3	10
B	6				29	8.3	9
BURROW WALL					25	10.0	9
CI85/8CWT	5	97.1	1.40	1.50	66	9.8	43
SS	0	98.7	0.54	0.76	15	7.9	45
COCOS ISLAND LAGOON							
EWT	5	98.7	1.10	0.21	4	10.0	14
SS	0	98.5	0.38	0.09	2	8.5	11
HALODULE ROOT	10				3	13.0	1
" SEDIMENT	10				4	8.0	1
SEA CUKE FECES	0				4	9.0	2
SURFACE MUD	0				3	10.0	1

APPENDIX I., continued

Sample	DEPTH	PERCENT	OF DRY SEDIMENT		UMOL G ⁻¹	DRY SEDIMENT	
	(cm)	% HL	% LOI	% ASH	E-Fe	E-P	E-Si
IPAN BEACH LAGOON							
A/86-4	1.2	98.5	0.48	0.98	30.0	7.7	34.0
B/86/4	3.5	98.5	0.39	1.10	27.0	8.0	31.0
C/86/4	10-12	98.8	0.39	0.85	24.0	9.0	25.0
A/84/12	3				41.0	8.7	12.0
B/84/12	10				27.0	9.4	7.7
EELG/OUT	0	97.9	1.10	1.00	20.0	11.0	44.0
EELG/IN	0	93.8	3.50	2.70	121.0	7.3	42.0
koski	0	95.9	0.97	3.10	54.0	6.8	37.0
cruz	0	93.0	3.10	3.90	97.0	7.7	37.0
WT/5m	5	98.1	1.40	0.47	6.7	5.9	16.0
WT/25M	5	97.4	2.00	0.58	12.0	8.4	30.0
WT/50m	5	90.7	6.90	2.40	41.0	8.2	63.0
SS/5m	0	97.4	2.00	0.58	16.0	8.0	28.0
SS/25M	0	97.0	2.20	0.81	19.0	8.1	27.0
SS/50m	0	96.2	3.10	0.70	12.0	7.6	36.0
HALIM-2	0	95.7	2.90	0.39	5.5	2.0	19.0
HALIM-1	0	96.2	3.60	0.21		0.4	45.0
FRNTTRGH	0	99.0	0.64	0.38	7.7	7.3	21.0
RIP50FT	0	98.8	0.85	0.37	9.3	8.6	23.0
HOLE50	0	93.2	2.30	4.50	76.0	7.6	49.0
HOLE75	0	92.5	1.80	5.70	108.0	7.5	36.0
YLLIG RIVER							
Sta. 1	TOP 2-3	43	8.1	49	360	4.0	35
2	TOP 2-3	60	4.8	35	270	4.9	27
3	TOP 2-3	17	16.0	67	420	1.9	18
4	TOP 2-3	22	26.0	52	330	3.0	17
5	TOP 2-3	30	12.0	58	210	2.8	13
6	TOP 2-3	34	12.0	54	460	3.5	16
7	TOP 2-3	31	15.0	54	310	3.0	15
8	TOP 2-3	38	12.0	50	280	2.9	12
9	TOP 2-3	36	18.0	46	240	4.6	32
10	TOP 2-3	24	15.0	61	350	19.0	58

APPENDIX II. SEDIMENT CHEMISTRY DATA FROM SAN ROQUE BAY, SAIPAN

Sample	Z. cm	PERCENT OF DRY SEDIMENT			UMOL G ⁻¹ DRY SEDIMENT		
		% HL	% LOI	% ASH	E-Fe	E-Al	E-NH4
HNLC-1							
A	4	98.1	1.00	0.87	3.7	46	3.60
B	8	98.7	0.61	0.66	6.2	39	1.40
C	12	98.2	0.79	1.00	4.9	59	0.97
D	15	98.7	0.49	0.77	4.7	36	0.78
E	19	98.6	0.60	0.84	5.5	98	1.20
F	23	93.7	2.40	3.95	32.0	108	0.64
G	25	92.1	2.60	5.35	40.0	60	0.52
H	27	90.7	2.90	6.40	22.0	52	1.80
I	29	92.4	2.60	5.00	41.0	70	1.10
J	31	95.6	1.30	3.10	24.0	78	1.30
K	35	96.3	1.10	2.60	21.0	45	2.00
L	39	97.4	0.83	1.80	7.7	75	1.00
M	43	97.2	0.88	1.90	7.5	57	0.34
N	48	96.7	1.00	2.30	8.1	56	1.70
O	53	97.0	1.00	2.00	38.0	70	1.70
P	58	96.4	1.30	2.30	39.0	60	0.08
Q	61	98.7	0.54	0.72	3.8	83	3.00
HNLC-2							
A	5	98.2	0.91	0.91	9.7	83	2.80
B	10	98.2	0.79	1.00	28.0	56	0.16
C	15	98.8	0.65	0.59	7.1	46	0.63
D	20	98.7	0.67	0.60	6.8	18	2.20
E	25	97.9	1.00	1.10	8.6	52	0.57
F	30	96.5	1.50	2.00	39.0	56	0.82
G	35	96.2	1.50	2.30	11.0	58	1.80
H	40	96.8	1.00	2.20	40.0	122	2.00
I	45	96.8	1.00	2.20	40.0	92	0.41
J	50	96.4	0.95	2.70	10.0	118	0.51
HNLC-3							
A	5	99.1	0.42	0.46	3.2	34	2.50
B	10	99.1	0.47	0.41	3.9	37	1.30
C	15	99.2	0.42	0.43	1.7	38	2.40
D	20	99.0	0.45	0.56	3.2	46	1.40
E	25	97.9	0.85	1.30	31.0	87	2.20
F	32	96.8	1.10	2.10	34.0	95	1.40
G	37	96.4	1.20	2.40	42.0	85	1.10
H	42	96.4	1.30	2.30	57.0	110	1.90
I	47	98.2	0.71	1.10	7.6	61	0.93
J	52	97.2	0.79	2.00	55.0	84	1.40
K	57	97.2	0.86	1.90	32.0	89	1.30
L	62	97.8	0.72	1.50	39.0	115	0.80
M	66	94.2	1.30	4.50	100.0	107	1.60

E-NH4+ refers to NH4+ released into 2 M KCl after 2 hours (Rosenfeld, 1979), and is operationally defined as exchangeable ammonium.

APPENDIX II. SEDIMENT CHEMISTRY DATA FROM SAN ROQUE BAY, SAIPAN

Sample	Z. cm	PERCENT OF DRY SEDIMENT			UMOL G ⁻¹	DRY SEDIMENT	
		% HL	% LOI	% ASH	E-Fe	E-Al	E-NH4
HNLC-1							
A	4	98.1	1.00	0.87	3.7	46	3.60
B	8	98.7	0.61	0.66	6.2	39	1.40
C	12	98.2	0.79	1.00	4.9	59	0.97
D	15	98.7	0.49	0.77	4.7	36	0.78
E	19	98.6	0.60	0.84	5.5	98	1.20
F	23	93.7	2.40	3.95	32.0	108	0.64
G	25	92.1	2.60	5.35	40.0	60	0.52
H	27	90.7	2.90	6.40	22.0	52	1.80
I	29	92.4	2.60	5.00	41.0	70	1.10
J	31	95.6	1.30	3.10	24.0	78	1.30
K	35	96.3	1.10	2.60	21.0	45	2.00
L	39	97.4	0.83	1.80	7.7	75	1.00
M	43	97.2	0.88	1.90	7.5	57	0.34
N	48	96.7	1.00	2.30	8.1	56	1.70
O	53	97.0	1.00	2.00	38.0	70	1.70
P	58	96.4	1.30	2.30	39.0	60	0.08
Q	61	98.7	0.54	0.72	3.8	83	3.00
HNLC-2							
A	5	98.2	0.91	0.91	9.7	83	2.80
B	10	98.2	0.79	1.00	28.0	56	0.16
C	15	98.8	0.65	0.59	7.1	46	0.63
D	20	98.7	0.67	0.60	6.8	18	2.20
E	25	97.9	1.00	1.10	8.6	52	0.57
F	30	96.5	1.50	2.00	39.0	56	0.82
G	35	96.2	1.50	2.30	11.0	58	1.80
H	40	96.8	1.00	2.20	40.0	122	2.00
I	45	96.8	1.00	2.20	40.0	92	0.41
J	50	96.4	0.95	2.70	10.0	118	0.51
HNLC-3							
A	5	99.1	0.42	0.46	3.2	34	2.50
B	10	99.1	0.47	0.41	3.9	37	1.30
C	15	99.2	0.42	0.43	1.7	38	2.40
D	20	99.0	0.45	0.56	3.2	46	1.40
E	25	97.9	0.85	1.30	31.0	87	2.20
F	32	96.8	1.10	2.10	34.0	95	1.40
G	37	96.4	1.20	2.40	42.0	85	1.10
H	42	96.4	1.30	2.30	57.0	110	1.90
I	47	98.2	0.71	1.10	7.6	61	0.93
J	52	97.2	0.79	2.00	55.0	84	1.40
K	57	97.2	0.86	1.90	32.0	89	1.30
L	62	97.8	0.72	1.50	39.0	115	0.80
M	66	94.2	1.30	4.50	100.0	107	1.60

E-NH4+ refers to NH4+ released into 2 M KCl after 2 hours (Rosenfeld, 1979), and is operationally defined as exchangeable ammonium.