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Relationships among bottom sediment, benthic fauna, and suspended sediment concentration at a sandy shoreline, Hamana-ko (Honshu, Japan): Implications for sediment entrainment

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Abstract: The relationships among sedimentary texture, suspended sediment concentration, and benthic community were analyzed from shallow subtidal environments at Hamana Bay, Japan. Meiofaunal communities of the upper centimeter of the bottom sediment are dominated by nematodes and harpactacoid copepods; juvenile gastropods and bivalves, ostracodes, and tardigrads are locally abundant. Sessile and slow-moving mobile macrofauna of the top few centimeters of bottom sediment are dominated by polychaetes and the gastropod *Umbonium moniliferum*, all of which are quite variable in distribution. Both macrofaunal and meiofaunal community composition are moderately correlated with sedimentary texture and depth. Sediment in all locations analyzed was fine to medium sand, with mud concentrations less than 3% of the sample by weight.

Suspended sediment concentrations (SSC) varied over two orders of magnitude, from 3.7 to 152.5 mg/ℓ. SSC does not correlate statistically significantly with any individual variable, but is best related to biotic components such as nematode abundance and mobile macrofaunal abundance. There is a relatively strong relationship between SSC and the first axes of principal components analyses of the biotic assemblages and the sedimentary textural properties, even independent of current conditions at the time of collection. That is, a linear combination of the biotic and sedimentary variables representing a high percentage of variability in the data provides the best predictor of SSC. Generally, samples with few mobile epifauna, large numbers of polychaete tubes, and large numbers of nematodes (which may produce large quantities of organic exudates) are associated with lower SSC, while the highest SSC values are found in areas with relatively large numbers of mobile macrobenthos.

Key Words: suspended sediment concentration, sediment entrainment, sediment erosion, Hamana-ko, animal-sediment relationships, benthos

INTRODUCTION

It is well-known that benthic organisms affect the sedimentary properties of the substrate in which and upon which they live, and that in turn sediment properties affect the sort of organisms that can successfully colonize it (e.g., SANDERS 1958, MCCALL & TEVESZ 1982, NOWELL *et al.* 1981, JUMARS & NOWELL 1984, AMOS *et al.* 1992). Biota may stabilize sediment by excretions that bind sedimentary particles, or destibilize sediments by increasing water content, increasing bottom roughness, or breaking physical or organic bonds between sedimentary grains (FEATHERSTONE & RISK 1977, RHOADS *et al.* 1978, LEE & SCHWARTZ 1980, ECKMAN *et al.* 1981, GRANT *et al.* 1982). One of the most fundamental properties of sediment is its stability in the face of current flow, i.e., its entrainability or erodibility, and a considerable literature exists concerning its measurement with respect to physical factors such as grain size, current strength, water content, mineralogy of the sediment, and water content (e.g., HJULSTRÖM 1935, MILLER *et al.* 1977, YALIN 1977, MEHTA 1986, 1989, MAA 1992). However, the feedback relationships between organisms and entrainability are poorly understood. Understanding these relationships will have implications both for understanding natural ecological processes and for the influence of human disturbance in coastal areas (RHOADS &

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Boyer 1982).

A number of authors have attempted to quantify the relationships between erosion and benthos by creating experiments in which the bottom velocity is controlled. Several studies have observed organism-erosion relationships using laboratory flumes, using either a block of natural sediment with the sediment-water interface preserved (Grant *et al.* 1982) or by defaunating the sediment and then observing the effects of adding individual taxa to the sediment (McCall *et al.* in prep; Davis 1993). However, it is difficult to recreate the conditions of the field in the laboratory (Young & Southard 1978, Maa *et al.* 1991), i.e., to recreate the sediment surface structure on the scale of sedimentary grains, the natural biotic communities, the benthic boundary layer flow structure, and the nature and distribution of organic molecules. Some studies been done using a flume in site in the field (e.g., Amos *et al.* 1992, Maa *et al.* 1993, Ross & Imada in prep). Flumes, however, require a great deal of equipment, making frequent deployment and thus obtaining data from numerous ecological contexts difficult; further, one still risks artificially affecting entrainment rates (e.g., during deployment of the flume or creation of unnatural bottom flow structure).

In this study we have measured the SSC at random points in time and space, and contrasted the measured SSC with local environmental variables. We are unaware of any previous studies that have searched for relationships among entrainment and environmental variables using natural SSC values and information on local bottom sediment and biota. The lack of previous studies on naturally occurring levels of SSC with respect to biota may be due largely to the perception that it is difficult to distinguish the effects of individual processes that work together to create the observed SSC. We believe it is worthwhile to explore the statistical relationships among variables using natural data, and to seek potentially causal relationships that could then be tested under controlled conditions.

For this study we chose 20 points essentially randomly in space and time to measure SSC and measured some of the variables that may explain variations in SSC. The number of data points is not large with respect to the number of variables investigated, and the number of variables investigated is only a subset of those that may be important, but the study illustrates the sort of work that may enable an expansion of basic knowledge about sediment transport and aquatic benthos. The purpose of this report is: to present integrated sedimentologic and faunal data from the shoreline of Hamana-ko; to discuss strategies and problems in measuring animal-sediment relationships and entrainability in natural environments; and, using the data of this study, to speculate briefly about some possible biotic factors influencing suspended sediment concentration.

Reasoning and assumptions behind this study

We have concentrated upon data that can be relatively quickly taken, to determine the feasibility of identifying relationships among erodibility and environment in natural environments, without need of extensive equipment, personnel, and time. In particular, we did not collect much data regarding the velocity of the flow impinging on the bottom, or the recent history of this flow prior to sampling. While the absence of flow data may make relationships among other environmental variables less clear, we propose that it will not make their contributions to SSC undecipherable.

Our presumption is based upon the idea that a faster current may erode little more than a slower current if both currents are below the critical velocity for most of the sediment. Moreover, the bottom sediment grain size is roughly the same among the studied sites, thus there is little difference in critical velocity among the sites, (e.g., Hjulström (1939) and later studies), therefore differences in SSC generally cannot be ascribed to either variations in mean grain size or to mean water energy (attainment of critical stress for the particular grain size). Hence other factors, such as subtle variations in sediment cohesion, may affect the amount of fines removed from sands, or biota may control the likelihood that high entrainment occurs.

There are 2 critical assumptions in the structure of this study. One is that SSC can be used as an estimator of local sediment erodibility; the second is that it is statistically plausible to use about 20 points chosen randomly in time and space to infer potential relationships among variables. Erodibility is generally defined by either the erosion threshold, i.e., critical current velocity, at which erosion begins, or the erosion rate (Amos *et al.* 1992). Though related, the erosion threshold and erosion rate are not the same, and one can imagine circumstances under which any one type of sediment may have initially a higher erosion threshold, while a second type of sediment, over time under a certain critical stress, yields a greater rate of erosion. However, both of these are very difficult to measure under natural conditions. In our case, assuming that settling velocity of the eroded sediment is high and/or that currents quickly carry away locally entrained sediment (without bringing in large quantities of suspended material from elsewhere), the suspended sediment concentration (SSC), which is relatively easily measured, should mirror the erosion rate to a sufficient degree that SSC may be used as a proxy for erosion rate.

Of course, some caution must be used concerning the extrapolation of suspended sediment concentration to local entrainability. The velocity needed to keep a grain in suspension is smaller than that for its initial erosion. Since the settling velocity of the clay-sized suspended sediment recovered from our filters may be hours or even days, nearly all the suspended material may have floated in from outside the field locations, perhaps even directly from rivers entering the bay. Arguing against that is the very large small-scale temporo-spatial variability in the SSC; sediment being transported over more than a few meters would be quickly mixed to a temporo-spatially homogeneous concentration. However, the lowest concentrations measured may represent such a background level from allochthonous sources.

Temporally isolated values of SSC: The logic behind comparing the SSC at randomly chosen points in time to learn about organism-sediment relationships rests on the assumptions that the median SSC at different sites may vary and be measurable and that temporally most SSC values at one site hover relatively close to the median value — closely enough that if points are selected at random from the 2 sites, the sample with the higher SSC will have more likely come from the site with the higher median SSC.

The suspended sediment (SS) observed in this study may not be from the well-sorted fine to medium sand, but instead from finer particles from the interstices of the sand. One can see this from the median particle size of the SS collected on filters, and also from the observation that current velocities are generally under the critical velocity for the sandy grain sizes, but erosive for some part of the muddy and finest sand fractions. We make the assumption from observations of both direct measurements and turbidometer recordings that background SSC is very low and does not differ greatly between sites, and cannot explain large variations in SSC. Thus, the major difference among sites will be the susceptibility of mud-sized particles to enter into suspension at very small current speeds or biotic sedimentary disturbance, with occasional variations due to entrainment of sand-sized particles. Mud particles will not act with the high cohesion that they do in mud-dominated sediments, and thus presumably have a much lower critical stress than indicated by typical Hjulström-type figures. The amount of erosion of such fines may vary according to several conditions: the amount of fines; the nature of fines — their tendency to be bound as pellets or to be attached to other grains by organic matter; the exposure of fines to currents through bioturbation; the surface roughness; active biological transport; or the degree of activity of macrofauna. Mud suspension will also be affected by its settling rate, its tendency to stick to other grains or to aggregate, or to stick to the bottom again if direct contact is made through turbulent flow (e.g., Self *et al.* 1989, Stolzenbach *et al.* 1992).

If we choose a point at random from the temporal SSC curve at some site 'a' (equivalent to taking a sample at one site at Hamana-ko) and a point at random at another site 'b', we hope that the probability is high that the point from the curve at 'a' will in fact be higher than at 'b'. The likelihood of this will increase if the larger erosional events responsible for most of the SSC (1) are transitory and (2) are not frequent with respect to sampling time, i.e., that most sites are well into the settling phase (past the inflection point of an exponentially declining temporal SSC curve) after an erosion event. If the number of events is fairly frequent with respect to the sampling interval, then we must also consider that the probability of finding SSC(a)>SSC(b) is decreased if the number of erosional events (rises in shear velocity, u_*, to above the threshold stress) at 'b' is much higher than at 'a'. It has been shown using a turbidometer (Fig. 1) that the high SSC is a very transitory event; from video-camera observations some of the so-called "suspended" sediment during these transitory events may actually be undergoing saltation. SSC is normally at a fairly uniform level, presumably the sum of a low level of allochthonous suspended sediment transported into the local area and material remaining in suspension after a local erosion "event" (generally a wave). Based on observations from a continuously monitoring turbidometer, the number of events is small.

Thus, conditions seem to be satisfied that if entrainability at some site 'a' is sufficiently larger than that at 'b,' we will see it if we have a sufficiently large number of data points. We expect the data to have a great deal of scatter, and thus low correlations among variables, even if in nature the relationships are tight, because of the temporally random nature with respect to u_* with which the data were collected.

Observations at Hamana-ko

For this study we made preliminary observations of the relationships between sediment entrainment and benthic communities *in situ*, in shallow water sandy environments of a shallow brackish lagoonal bay known as Hamana-ko. In this paper we report simple empirical relationships between the benthic community, sedimentary texture, and suspended sediment concentration above the bottom. This paper also provides a brief review of some of the factors relevant to organism-sediment relationships in sandy sediments. In a later report (Ross & Imada, in prep), we will describe the construction of a straight flume for use in the field for controlling current velocity for performing experiments upon sediment entrainability.

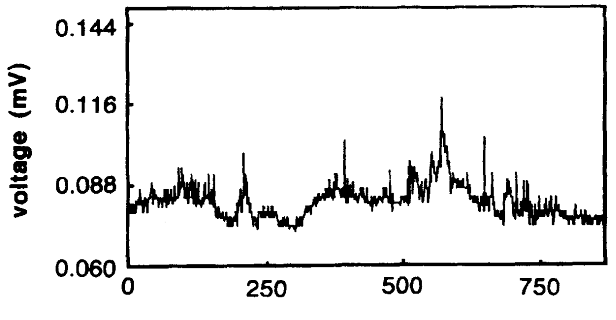

Fig. 1 Turbidometer data, showing voltage every second for about 15 minutes, reflecting suspended sediment concentration (SSC) in ambient water. The data was taken at about 15:20 to 15:35 on 28 July 1994. Note that suspended sediment concentration peaks only during brief events, and quickly returns to a lower level. The voltage was not properly calibrated to SSC, thus the actual magnitude of the SSC is not shown.

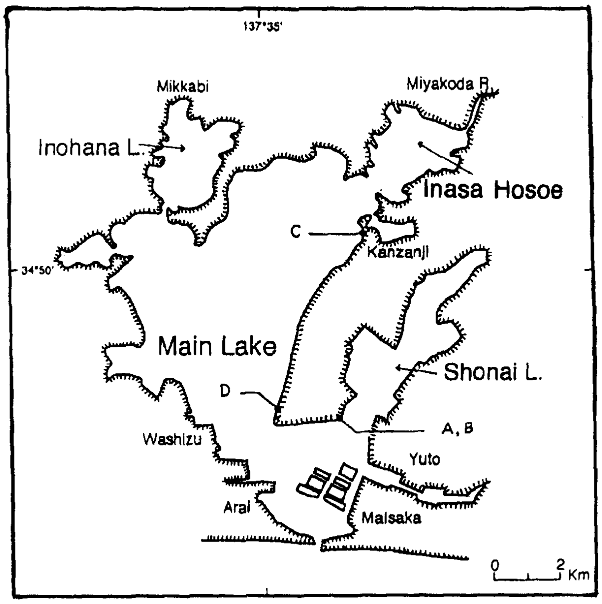

Fig. 2 Map of Hamana-ko. The bay opens at the southern end, between Arai and Maisaka, into the Pacific Ocean.

Field sites

We observed sediment entrainment and biotic assemblages at Hamana-ko, literally translated from Japanese, Lake Hamana. Hamana is actually a brackish-water bay with a very narrow opening to the Pacific Ocean on the central eastern coast of Honshu, Japan (Fig. 2). The depth of the mouth is only about 1 m deep, with a deeper canal for boat traffic, creating a lagoon with water circulation dependent largely on tidal flow. The waves at Hamana-ko are gentler than those along the open sea coast, making working conditions feasible.

The bay varies spatially in its salinity and water energy, and thus in its sedimentary and biotic characteristics. The bay has a sandy bottom near the shores along the half of Hamana-ko closest to the inlet; the central areas of the bay, and upper reaches of the bay, have a mud bottom (Ikeya & Handa 1972, Sanukida & Matsushita 1986). The studies we performed were in the shallow subtidal and intertidal parts of sandy beaches facing the largest parts of the bay. The Hamana-ko bottom environment is significantly modified by aquiculture, fishing and shell-fish collecting, swimming, and boating. We made our observations at three locations that are accessible by road vehicle, and which vary slightly in salinity, sediment texture, biota, and frequency of human disturbance. The locations will be referred to here as locations A, B, C, and D.

Locations A and B, at Marakushi Gate, are just east of a bridge connecting the "back" (north) of the bay with the land spit that mostly closes the mouth of the bay. The concrete stilts of the bridge form a wave block from the center of the bay so that sediments shoreward of the block (B) are sightly finer than several tens of meters downshore from the bridge (A). This area has abundant edible bivalves that are collected with a rake-like tool at low tide, thus there is severe human disturbance that occurs nearly daily, at low tide, along the intertidal part of the shoreline. There had been, however, little or no human disturbance since the previous low tide at the times and sites sampled. In addition, motorboats pass within about 50 m of the shore, increasing wave energy and throwing up entrained sediment.

Location D, at Marakushi Beach, is a sand beach several hundred meters further into the bay from site A. It is likely frequently disturbed in summer by swimmers, but was disturbed only patchily by wind surfers at the time of our study. Location C, at Kanzanji Beach, is a sand beach toward the inside of the bay, in front of a hotel. This beach is frequently disturbed in summer, but was probably little disturbed at the time of our study. Locations C and D may be strongly affected by waves induced by westerly winds in winter.

With one exception, all samples were taken within a one-week period from 25 October to 2 November 1994; the exception is one sample from Murakushi Gate from July 28. Most samples were taken on 25 and 26 October. The others were taken in association with an *in situ* flume study, indicated by the suffix "f" attached to sample numbers in the tables. At Hamana-ko there is seasonality in water temperature and salinity, wave conditions, stratification of the lake, and fresh water and particulate input, and consequent effects upon the biota and likelihood of human activities. Thus these results are particularly time dependent (cf. Maa 1993). Oguri (1995 MS) reviewed the seasonality in sediment properties and sedimentary flux toward the center of the basin.

METHODS — FIELD STUDIES

At each site suspended sediment concentration and suspended sediment grain size distribution were measured. In addition, five possible forcing factors were estimated: depth, water velocity, macrofauna, meiofauna, and bottom sediment grain size distribution. Water temperature was measured using a standard mercury thermometer; salinity was determined indirectly by measuring water density using an Akanuma gravitometer and then factoring out the effect of temperature.

Suspended sediment concentration was measured by drawing 50 ml of water into a plastic syringe with a mouth opening of 3 mm. Time for extraction of one sample was about 20 seconds. The samples were taken about 5 cm above the sediment surface. The samples was brought back to the laboratory in 50 ml bottles and filtered, and the filters were weighed.

Suspended sediment concentration was also measured using an optical (infrared) backscatter turbidometer (model OBS-1, manufactured by the D & A Instrument Co., Washington State, U.S.A. [Downing *et al.* 1981, Maa *et al.* 1992], integrated with software as the "Microlite" instrument system by Coastal Leasing, Inc., Massachusetts, U.S.A.), which measured sediment concentration continuously (once per second) by an infrared light ray sensor. However, mechanical and calibration problems made some of this data unreliable.

Suspended sediment grain size distribution was estimated by cutting 1 cm squares from the interior of the filters (avoiding both the center and the edge, which tend to have higher concentrations) and observing them by scanning electron microscopy. A part of the filter was chosen at random under the SEM, and grains at selected points along a transect across the monitor were chosen for measurement. Only grains with a major axis length greater than 0.5 μm were measured, because others should have passed through the filter.

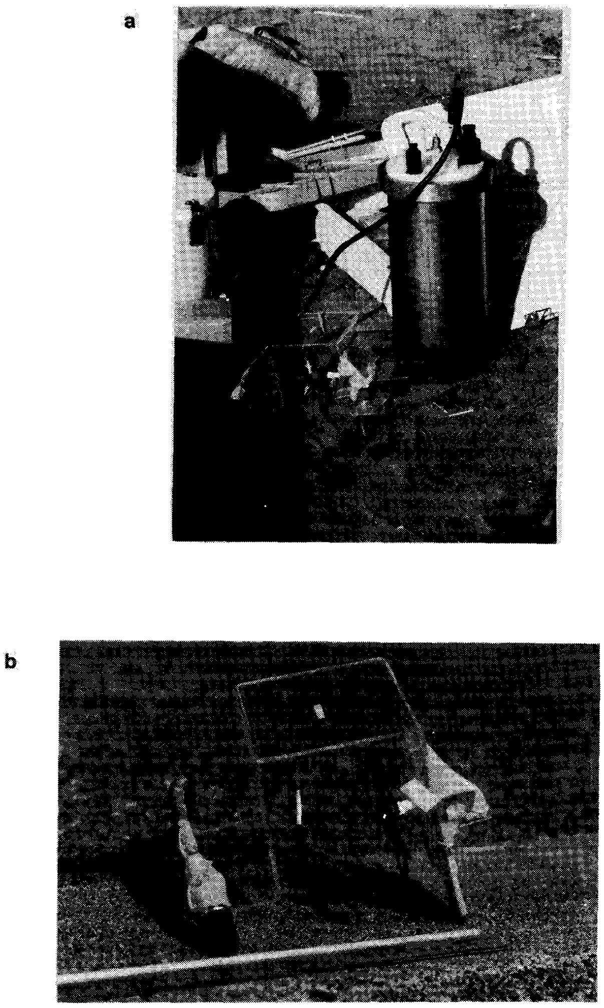

Fig. 3 Video-camera support. (a) Turbidometer (upright metal cannister) attached to camera support. (b) The turbidometer sensor is attached to a flap so that it sits about 5 cm above the bottom. The black bead hanging from fishing line from the camera support was used to observe current flow and wave motion. The pinwheel was also intended for observing current flow. The longer right limb of the support is placed into the sediment for stability. The video camera housing is placed directly above the support, and an underwater light is shone through the right side.

Water velocity was measured by observing the movement of a black plastic ball 5 mm in diameter hung from a nylon string under a clear acrylic stand, such that he ball hung 5 cm above the bottom (Fig. 3). The ball density was slightly greater than sea water, so that it sunk in still water but was highly sensitive to moving water. The movement of the ball was recorded by placing an underwater video camera upon the top of the acrylic stand, and video recording for about one minute, covering the time that the suspended sediment sample was taken. The relationship between current velocity and movement of the ball in a horizontal field was determined empirically by timing the speed of particles traveling across the field of view. The "velocity" of the tidal flow was weak during the experiment, but flow was also caused by the circular orbit of waves; while this motion is different than that of a true current, it apparently has similar erosional characteristics (Nowell & Jumars 1987), and it was considered that the similarity in water movement between wave orbits and currents is sufficiently high to obtain at least a qualitative estimation of the relationship between water movement and sediment entrainment. Technical difficulties with the video camera resulted in only 8 measurements of water movement. It is actually u_* that is important for sedimentary processes at the sediment surface (e.g., Yalin 1977). u_*, however, is nearly linearly related to u,

Table 1 Salinity and water temperature of the 3 locations.

Location	Date	Salinity ‰	Water temperature ℃
Murakushi gate	10/25/1994	30.50	22.0
	11/2/1994	29.38	23.0
Kanzanji beach	10/26/1994	31.70	23.2
	10/31/1994	28.73	22.6
Murakushi beach	10/26/1994	31.76	21.8
	11/1/1994	30.54	21.1

Table 2 Water depth of the samples at each site. Depth with respect to mean sea level is a rough estimate. LT=low tide, HT=high tide; plateau refers period within 1 hour, before and after, tidal extreme.

Location	Date	Sample number	time of measurement	measured depth (cm)	depth with respect to MSL (cm)	tidal state
Marakushi Gate	94-07-28	A1f	14:30	32	36	LT, plateau
	94-10-25	A2	14:21	2	0	LT, plateau
		A3	15:39	35	30	rising
		A4	14:50	44	40	rising
		A5	15:07	47	43	rising
		A6	15:26	30	25	rising
		A7	15:53	15	9	rising
	94-11-02	A8f	12:50	29	22	rising
Under bridge	94-10-25	B1	16:14	15	8	rising
		B2	16:22	22	15	rising
		B3	16:33	38	31	rising
Kanzanji Beach	94-10-26	C1	11:47	40	36	falling
		C2	12:14	56	53	falling
		C3	12:36	61	59	falling
		C4	12:56	65	63	falling
	94-10-31	C5f	13:39	37	26	HT, plateau
Marakushi Beach	94-10-26	D1	15:40	30	26	rising
		D2	16:02	37	33	rising
		D3	16:19	34	29	rising
		D4	16:32	15	10	rising
	94-11-01	D5f	15:36	54	47	rising

at a point x in the benthic boundary layer; since this study is concerned merely with identifying (potentially causative) correlations among variables, we simple use u_x instead of u_* in our analyses.

Depth was measured using a meter stick at the time of sampling (Table 2). Depth with respect to local mean sea level was estimated by linearly interpolating between tidal extremes. Tides at Kanzanji are delayed about 2 hours from those of the open ocean around Maisaka, and tides at Murakushi are delayed about 90 minutes (Nonaka *et al.* 1973). Also, the magnitude of the tidal range within Hamana-ko is considerably damped, to roughly 25 to 30% of the open-ocean range. Because of uncertainties in the exact timing and magnitude of tidal ranges at our sites, estimates of depth with respect to mean sea level are only approximate, but are probably within ± 10 cm. All sites were subtidal, less than 1 m deep.

Sediment at each site was cored using a plastic (PVC) corer 4.4 cm in diameter. The core was divided into half cm sections in the top centimeter, and divided into one centimeter sections down to five centimeters. This sediment was fixed in formalin at the site, and changed to alcohol and stained with rose bengal in the laboratory.

The first half centimeter was used for the meiofaunal and grain size analyses. This sediment was first wet sieved over a 0.063 mm sieve. The water residue, containing particles 63 μm, was saved; its volume was measured, it was well mixed, and approximately one half liter was removed and filtered over a 0.45 μm filter. The mud remaining on the filter was weighed, and the weight was divided by the fraction of the water residue volume that had been filtered, in order to find the total weight of mud in the sample.

To extract meiofauna from the sediment, sandy sediment was poured into a 1 liter graduated cylinder filled with tap water. The mixture was tipped upside down several times, and less dense material was immediately decanted into the 63 μm sieve and then poured into an acrylic tray for observation. This process was repeated several times. The meiofauna, foraminifera, diatoms, and biologic shell debris were counted and indentified to the class or phylum level. After observation, the decanted residue was stored in alcohol.

The sand-sized sediment was dried and passed through sieves of 1, 0.5, 0.25, 0.125, and 0.063 mm and each size fraction weighed.

The macrofauna data is only semi-quantitative, in that the depth and weight of the samples were not measured, but were estimated by eye. Macrofaunal density was estimated by submerging a garden trowel (semi-horizontally) to a sediment depth of about 3 cm and washing this heaping trowelful of sediment over a 1.44 mm sieve. At most sites three trowel samples were taken; the data represents the average number of macrofauna and tubes contained in the samples. At the 4 "f" sites, 10 samples were taken, from the site to 3 m oceanward of the site. The summarized data for this site represents a weighted average, the weights inversely proportional to the distance from the site (for example, the 10th sample, farthest from the site, counts 1/10th that of the sample directly at the site). The number of empty shells and amount of shell debris and other gravel were also recorded. All material recovered in the sieve was identified in the field and immediately returned to the water.

Rapidly moving macrofauna such as decapod crustaceans were frequently observed near the strandline, but were not seen within the sampling sites and not recorded. A moderate number of small holothurians were present at Kanzanji Beach, but were not within our area of sampling.

Results: Physical measurements

Suspended sediment concentrations vary over nearly two orders of magnitude, from 3.7 to 1525 mg/ℓ and vary greatly even at sites from the same location (Table 9). The variation in concentration is as much a function of timing as of