Changes in Bathymetry and Their Implications to Sediment Dispersal and Rates of Sedimentation in Manila Bay

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ABSTRACT

The predominant sediment dispersal pathways and lateral variations in sedimentation rates in Manila Bay, specifically off Cavite, Manila, and Pampanga were determined primarily by using water depth changes over the period 1901 to 1950 and secondarily from sediment-distribution patterns. High-resolution reflection seismic profiles and piston cores have provided information on longer- term sedimentation. Off Cavite and Manila, sediments are transported predominantly to the north of the source. The zones north of the Cavite Spit and west northwest of the Pasig River mouth are major sinks for sediment accumulating at rates as high as 9 cm/yr. Shoaling rates vary across the three study areas: Pampanga Bay showing the least amount of shallowing and the Pasig River area, the greatest. Apparently low rates of sedimentation in the Pampanga Bay could be due to rapid subsidence. A general increase of sedimentation rate in the offshore direction is also indicated by the bathymetric changes. This trend implies low retention of sediments near the coast, which might be due primarily to a relative sea level rise in the bay. The high-resolution reflection seismic data indicate that the relatively high sedimentation rates along the deeper central portions are not a recent trend. However, this long-term trend is probably controlled by the bay's morphology rather than by sea level fluctuations.

Key words: bathymetric changes, sedimentation rates

INTRODUCTION

Sediment dispersal patterns can be determined in different ways that depend on the specific information needed. Transport of sediment can be measured directly with detailed current measurements, sampling of sediment in transport, and the use of a variety of tracer materials. These methods are costly and tend to be local in their extent. Tracing of sediment plumes from remotely sensed data can also be employed, but like direct measurements, remote sensing has its drawbacks. The synoptic view afforded by these data is very useful in delineating the sources and dispersion of sediments. However, the defined pathways apply only to the uppermost portions of the water column and there is no direct information regarding the final fate of the sediments. Numerical simulation of water circulation may also be conducted. More importantly, these monitoring programs do not deal adequately with the problem of appropriate time scale which is sufficient to integrate the processes responsible for net erosion, transport, and deposition of sediments (Gao &Collins, 1994).

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In Siringan and Ringor (1997), we presented the coastal morphology and nearshore net sediment drift patterns around the Manila Bay. In this paper, we present the changes in bathymetry and the sediment distribution in selected portions of Manila Bay, from which the predominant sources, pathways, and sites of deposition of sediments entering the bay were deduced. Also, the changes in bathymetry were used to estimate rates of sedimentation and show the lateral variation in the rates. High-resolution reflection seismic data and piston cores were used to examine the longer-term (several hundreds to a few thousand years) sedimentation in the bay, specifically in the variation in thickness of the sediment cover.

Estimates of sedimentation rates in Manila Bay

Santos and Villamater (1986) estimated sedimentation rates based on the ^{137}Cs profiles of cores taken at three different locations in Manila Bay (Fig. 1). A core from a 7 m water depth in Bacoor Bay yielded a rate of 4.3 cm/y, one taken off Meycauayan River at a depth of 7 m gave 3.2 cm/y, and one from Pampanga Bay, taken at a 10 m water depth, yielded 5.5 cm/y.

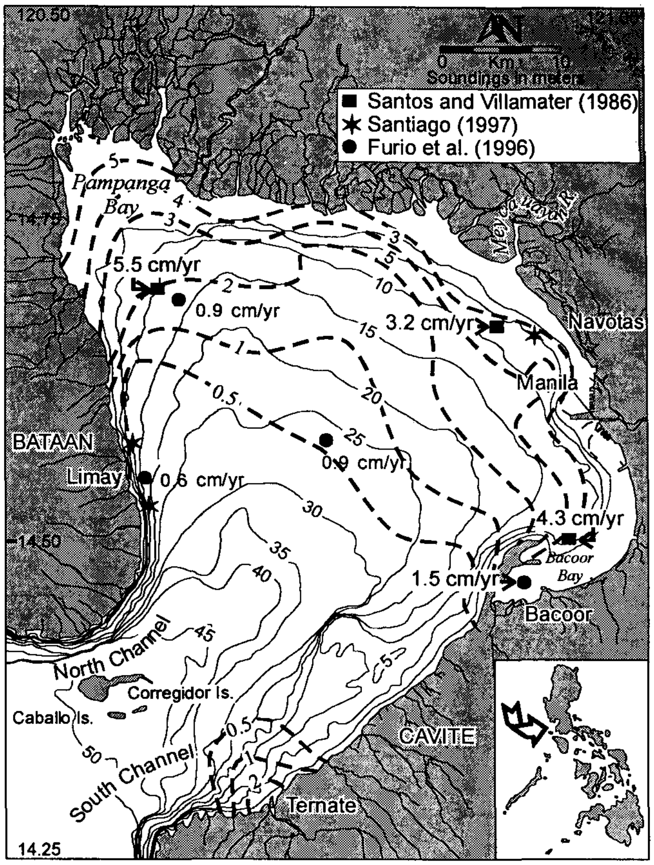

Fig. 1. General morphology and bathymetry of Manila Bay (bathymetric data from USDMA 1982). Also shown are estimates of radionuclide-derived sedimentation rates and the location of cores where they were derived. Furio et al. (1996) reported rates ranging from 0.64 to 1.5 cm/y. The 1.5 cm/y is derived from a core within Bacoor Bay. Dashed lines represent the isopleths of annual sedimentation rates (cm/y) derived by de las Alas (1990) through numerical modeling.

Through numerical modeling, de las Alas (1990) estimated the spatial variation of sedimentation rates in the bay. Rates greater than 3 cm/y were predicted for the coastal regions along the northeastern half of the bay and less than 1 cm/y on the central and southern parts of the bay (Fig. 1).

Furio et al., (1996) and Santiago (1997) reported sedimentation rates of less than 1 cm/y based on ^{210}Pb profiles (Fig. 1). One of the Bacoor Bay cores studied by Furio et al. (1996) yielded a sedimentation rate of 1.5 cm/y.

Circulation models of Manila Bay

De las Alas and Sodusta (1985) simulated the response of Manila Bay to the quasi-steady forcing by prevailing winds (Fig. 2). Northeasterly winds, with speeds averaging about 5 m/s from October to January, produce a counterclockwise gyre in Pampanga Bay and a clockwise gyre at the southwest coast of the Cavite area (Fig. 2a). Southeasterly winds, with speeds ranging from 3 to 6 m/s from February to May, generate a single counterclockwise gyre in the bay (Fig. 2b). Southwesterly winds, with speeds of 5 to 7 m/s from June to September, produce a clockwise gyre in Pampanga Bay and a counterclockwise gyre off the southwest coast of Cavite (Fig. 2c). Convergence occurs off Pasig River, and the flow heads towards the central parts of the bay then towards the mouth.

Villanoy and Martin (1997) used a two-dimensional circulation model to determine the relative importance of wind and tide forcing. Their tide-driven circulation

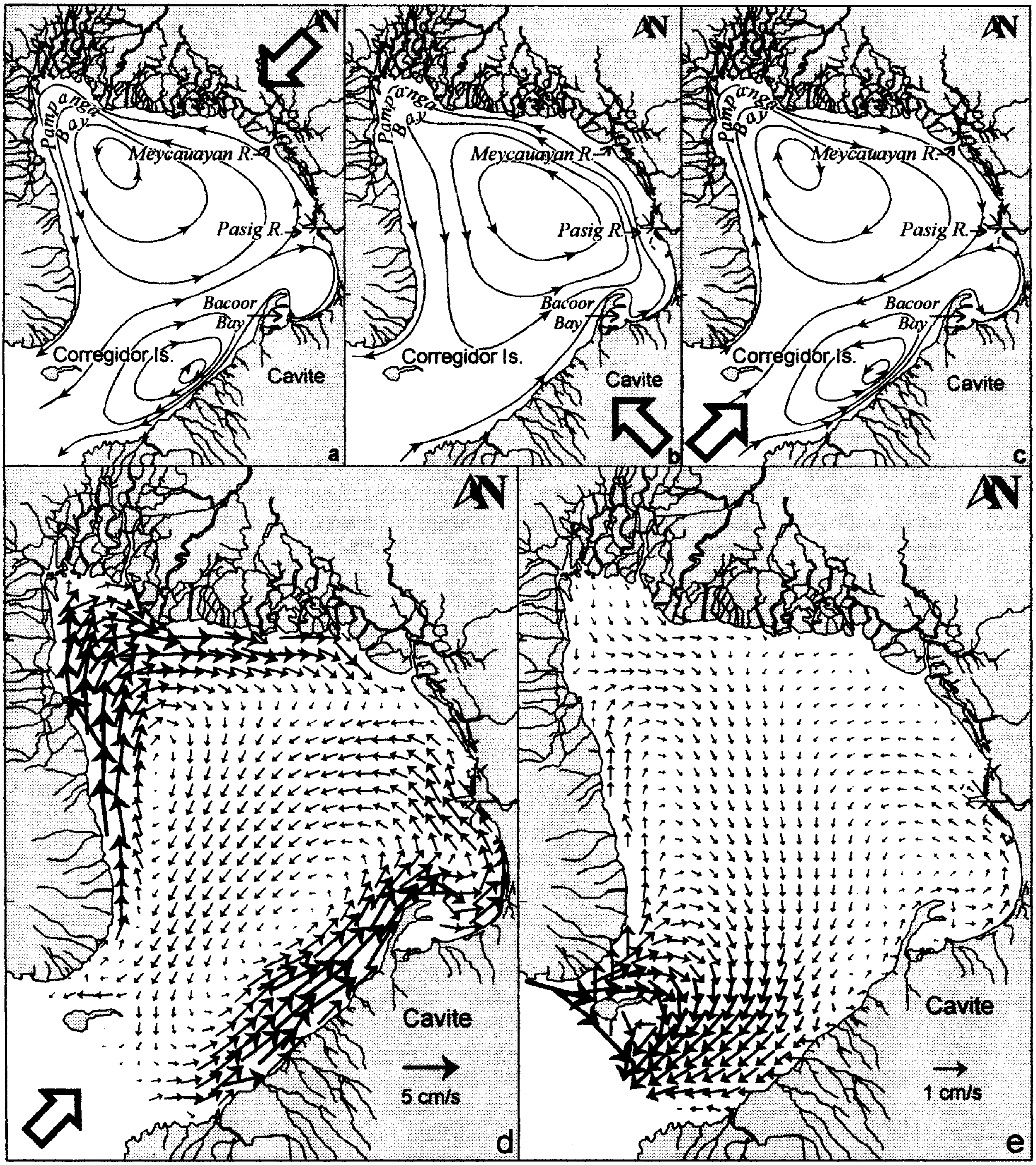

Fig. 2. Wind- (a-d) and tide-driven (e) circulation models of Manila Bay after de las Alas and Sodusta (1985; a-c), and Villanoy and Martin (1997; d-e). Large arrows indicate wind direction.

model indicates that the residual tidal velocities are strongest at the mouth where it enters the bay north of Corregidor and exits to the south (Fig. 2e). Their wind-driven circulation model, which uses the mean September 1995 wind data, shows the generation of two asymmetrical counter-rotating gyres similar to the de las Alas and Sodusta (1985) model for the southwesterly winds, except that their convergence is placed off the Meycauayan River (Fig. 2d).

Siringan and Ringor (1997) delineated the net nearshore sediment drift patterns in Manila Bay by combining the coastal geomorphology with changes in shoreline position and predominant longshore current directions derived from the interaction of locally generated waves and bay morphology. They identified that sediment drift directions are predominantly to the northeast along Cavite, to the northwest along Manila and Bulacan, and to the north along Bataan. The greater importance of tide-driven onshore-offshore sediment transport, relative to alongshore movement, along the northern coast of Manila Bay was suggested.

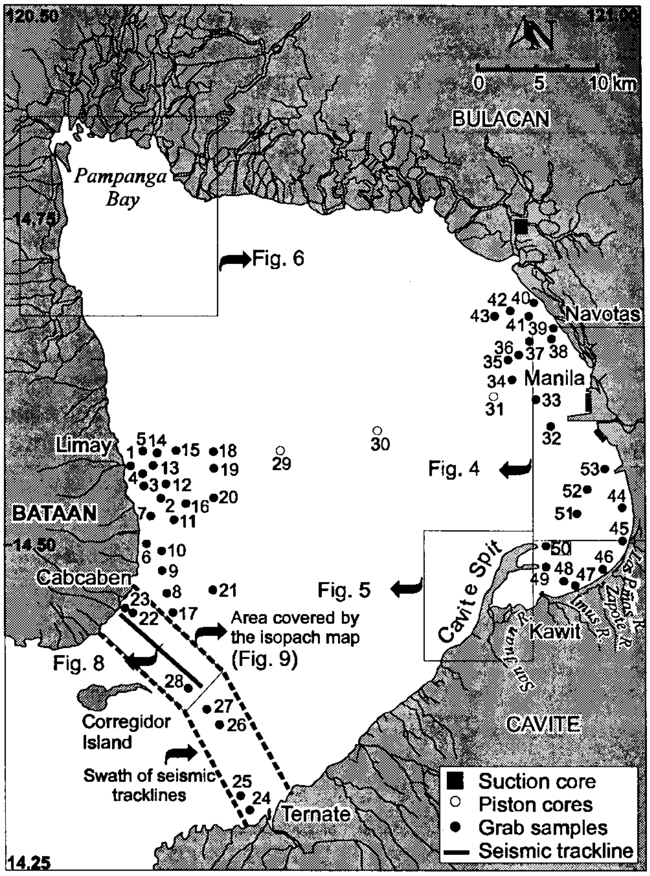

Fig. 3. Primary data set used in this study. Also shown is the location of subsequent figures.

MATERIALS AND METHODS

Table 1 presents data from two sets of bathymetric maps, dated 1944 and 1961, used in this study. Available maps printed after 1961 do not contain updated bathymetric information, and so no later comparison was possible. Changes in shoreline position and bathymetry were determined by overlaying the maps. The shorelines were traced manually. Changes in bathymetry were established by comparing the raw water-depth values on the maps. Map coverage restricted the work on only three sectors in the Manila Bay: Cavite, Pasig River, and Pampanga Bay areas.

The upper 10-15 cm of the bottom sediments in the vicinity of Cavite-Pasay, Navotas, and Limay, Bataan were sampled using a grab sampler (Fig. 3). Samples were spaced more closely near the coast and river mouths where changes can be expected to occur over shorter distances. Gravel, sand, and silt-clay fractions of the sediments were determined by wet-sieving. To establish vertical variations in sediment type, three piston cores, each slightly shorter than three meters, were acquired in 1995 (Fig. 3).

For use in this study, the National Power Corporation (NPC) provided high-resolution reflection seismic data that was acquired in 1994 to assess the feasibility of laying a submarine cable system across Manila Bay to connect the northern and southern Luzon power grids. These data are located within an area delimited by dashed lines in Fig. 3. An isopach map of the bay sediments was constructed based on these seismic profiles. An average interval velocity of 1,525 m/s was used to convert two-way travel time to sediment thickness.

Table 1. 1944-45 and 1961 bathymetric maps used in this study

Year	Map and Scale	Source	Remarks
1944	Balanga NW (Pampanga) 1:25,000	US Army Map Service (USAMS)	Compiled in 1944 from Luzon, 1:25,000, AMS S812, 1944, which are based on: USC&GS Topographic Field Survey Sheets, 1:20,000 1916-17; Luzon, 1: 31,680, Office Dept. Engr., Phil. Dept., No. 31 E, 1940. (Rd. and bridge revision 1939, Trail revision, 1942); Vol. I, Commission of Census, Commonwealth of Phil., 1939; USC&GS Chart 4255, 1940, (Special Printing 44-4/21); P. Is., 1:200,000, USC&GS, No. 7, 1941; Communication Map of P. Is., 1:400,000, Hq. M. I., Phil. Dept., No. CM 14-2, 1927 (Tel. and Tel. corrected to 1940, AMS); Mobiloil Road Map of the P. Is., 1:1,100,000, Standard vacuum oil Co., P. Is., 1942. Revisions from miscellaneous large scale vertical photography, 1940; Stereo compilation by USGS from oblique photography, 1944. Hydrography compiled from 1916-1917 surveys by USC&GS, 1944.
1944	Balanga NE (Pampanga) 1:25,000	USAMS	-do-
1944	Balanga SW (Pampanga) 1:25,000	USAMS	-do-
1945	Manila 1:50,000	USAMS	Topography compiled from 1:50,000 Series Luzon AMS 712 with revisions from large scale photography, Dec. 1944. Additional information from Terrain Study 94, Oct. 1944, Terrain Handbook 41, Nov. 1944, & Road Folder for Luzon Nov. 1944 AGS SWPA. Place named from AMS 1:25,000 Series Luzon. Controlled in position from field surveys of USC&GS 1901 to 1927.
1944	Cavite NW 1:25,000	USAMS	Compiled from USC&GS charts 4236, 1940 (Special Printing 42-3/23); Luzon, 1:5,280, Office Dept. Engr., Phil. Dept., Nos. 34 Cb 4, 34 Cb 8 & 34 Cb 12, 1917; Vol. I, Commission of Census, Commonwealth of Phil., 1939; USC&GS Topographic Field Survey Sheets, 1:5,000, 1:20,000, 1921-1931; Communication Map of P. Is., 1:400,000, Hq. M. I., Phil. Dept., No. CM 14-2, 1927 (Tel. and Tel. corrected to 1940, AMS); Revisions from miscellaneous oblique & vertical photography, 1930-1938; Stereo compilation by USGS from vertical & oblique photography, May 1944. Hydrography compiled from 1917-1941 surveys by USC&GS, 1944.
1944	Amaya SE (Cavite) 1:25,000	USAMS	Compiled in 1944 from oblique & vertical photography dated 1944 by stereophotogrammetric methods, & from Luzon, 1: 31,680, Office Dept. Engr., Phil. Dept., No. 34 C, 1940. (Rd. and bridge revision 1939); Vol. I, Commission of Census , Commonwealth of Phil., 1939; USC&GS Chart 4255, 1940, (Special Printing 44-1/21); Communication Map of P. Is., 1:400,000, Hq. M. I., Phil. Dept., No. CM 14-2, 1927 (Tel. and Tel. corrected to 1940, AMS); Hydrography compiled from 1904-1916 surveys by USC&GS, 1944.
1961	Balanga (Pampanga) 1:50,000	Board of Technical Surveys and Maps (BTSM)	US Army Map Series 711 compiled in 1956 by photogrammetric methods: 1947-1953 photographs and others.
1961	Manila 1:50,000	BTSM	US Army Map Series 711 compiled in 1956 by photogrammetric methods: 1947-1953 photographs and others.
1961	Cavite 1:50,000	BTSM	US Army Map Series 711 compiled in 1956 by photogrammetric methods: 1947-1953 photographs and others.

RESULTS

Changes in shoreline position and bathymetry

Pasig River area

The bathymetry off Manila indicates that the sub-tidal component of the Pasig River Delta extends approximately 4 km from the river mouth to a depth of 12 m (Fig. 4). A sub-tidal channel that trends south-southwest off the river mouth is maintained through dredging. In this area, changes in water depth in the interval between aquisition periods of the bathymetric data used in the 1944 and 1961 charts indicate overall shoaling, which increases away from the coast (Fig. 4). The area west-northwest of the Pasig River mouth has shoaled approximately 4 m. Minimal deepening was restricted to a few, very small areas.

Changes in the position of the shoreline along Manila are due mainly to land reclamation. As much as 600 m has been reclaimed off Tondo, immediately north of the North Harbor (Fig. 4). Coastal retreat is documented in only a few places. Likewise, erosion has been artificially limited by the numerous seawalls and breakers in the area.

Cavite area

Coastal retreat of as much as 100 m may have occurred along the western coast of the Cavite Spit in the interval between aquisition periods of the shoreline data used in the 1944 and 1961 maps (Fig. 5). An exception is the shoreline between Cañacao and Sangley Point, where progradation is due to reclamation for the Sangley Point airstrip. Along the northwest-facing coastlines behind

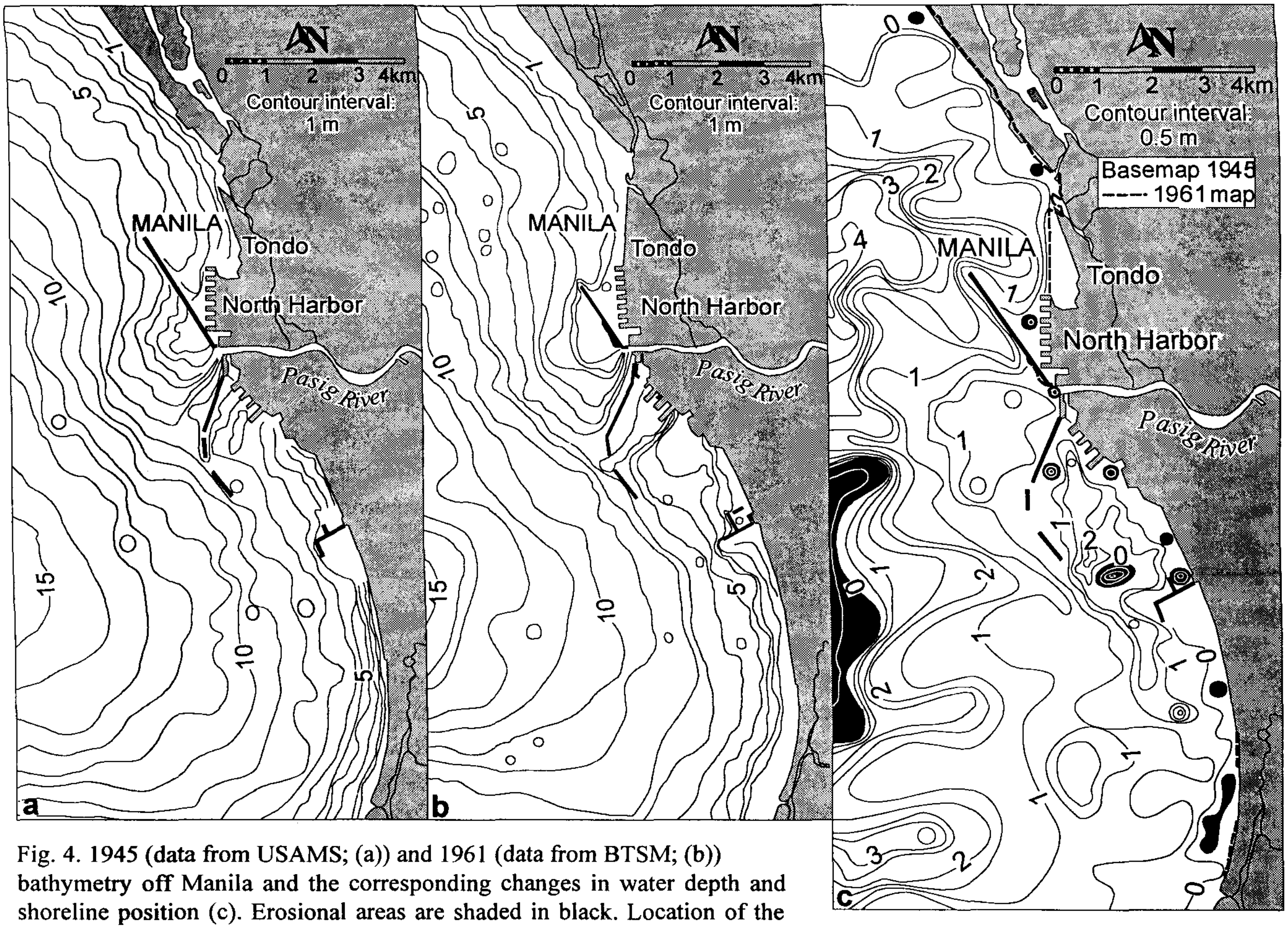

Fig. 4. 1945 (data from USAMS; (a)) and 1961 (data from BTSM; (b)) bathymetry off Manila and the corresponding changes in water depth and shoreline position (c). Erosional areas are shaded in black. Location of the shoreline segment is indicated in Fig. 3.

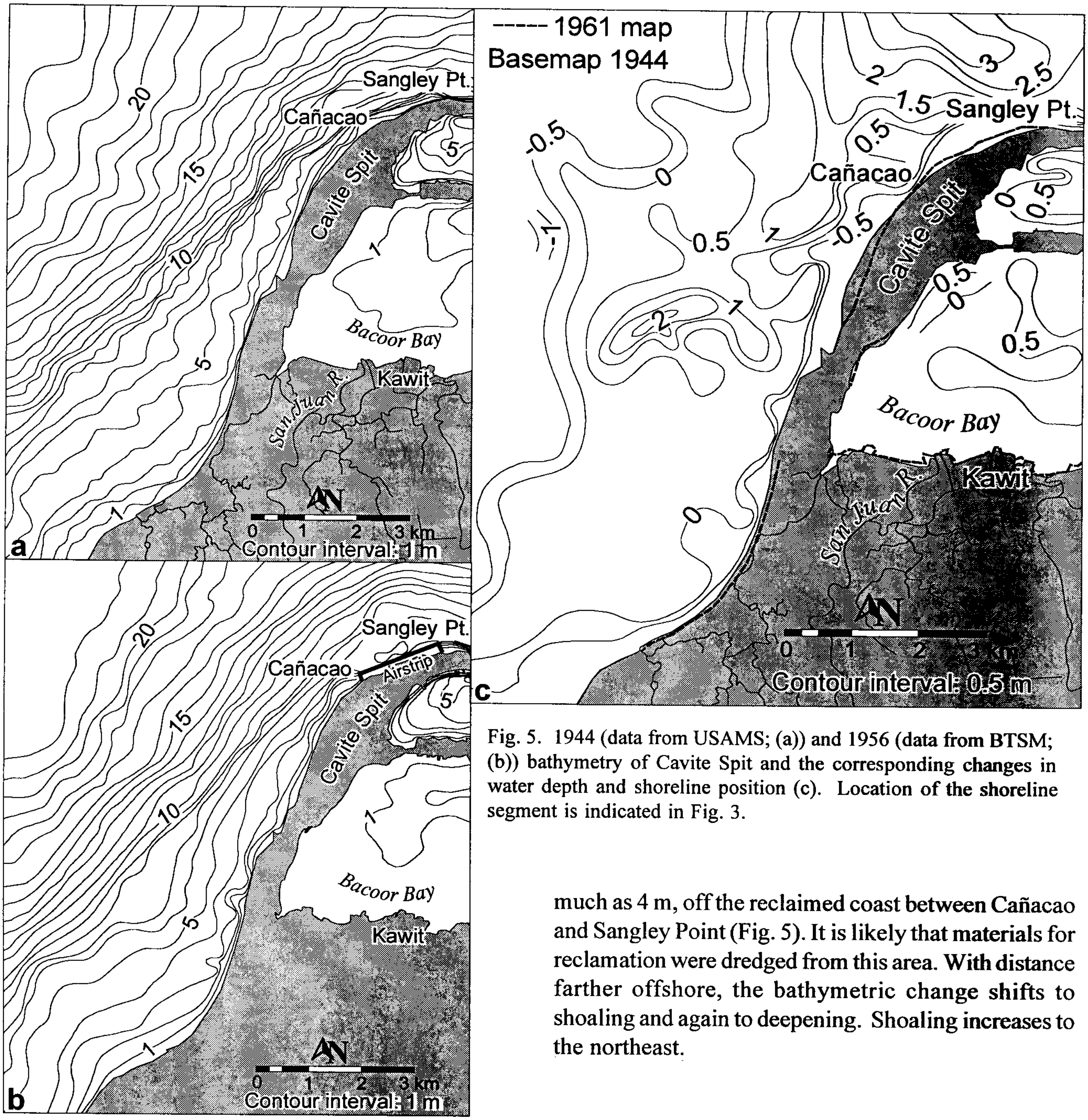

Fig. 5. 1944 (data from USAMS; (a)) and 1956 (data from BTSM; (b)) bathymetry of Cavite Spit and the corresponding changes in water depth and shoreline position (c). Location of the shoreline segment is indicated in Fig. 3.

the spit, mostly natural progradation seems to have occurred, coupled with a general shoaling of less than a meter within the Bacoor Bay area. On the other hand, erosion along the western coast of the Cavite Spit is coupled with deepening along the immediate offshore area. Interestingly, deepening is greatest, as much as 4 m, off the reclaimed coast between Cañacao and Sangley Point (Fig. 5). It is likely that materials for reclamation were dredged from this area. With distance farther offshore, the bathymetric change shifts to shoaling and again to deepening. Shoaling increases to the northeast.

Pampanga Bay

A large portion of the shoreline from Balanga to Orani, Bataan retreated in the interval between aquisition periods of the shoreline data used in the 1944 and 1961 charts (Fig. 6). In contrast, the adjacent northeastern coast underwent mainly progradation associated with a general westward shift of the mouths of fluvial-tidal channels.

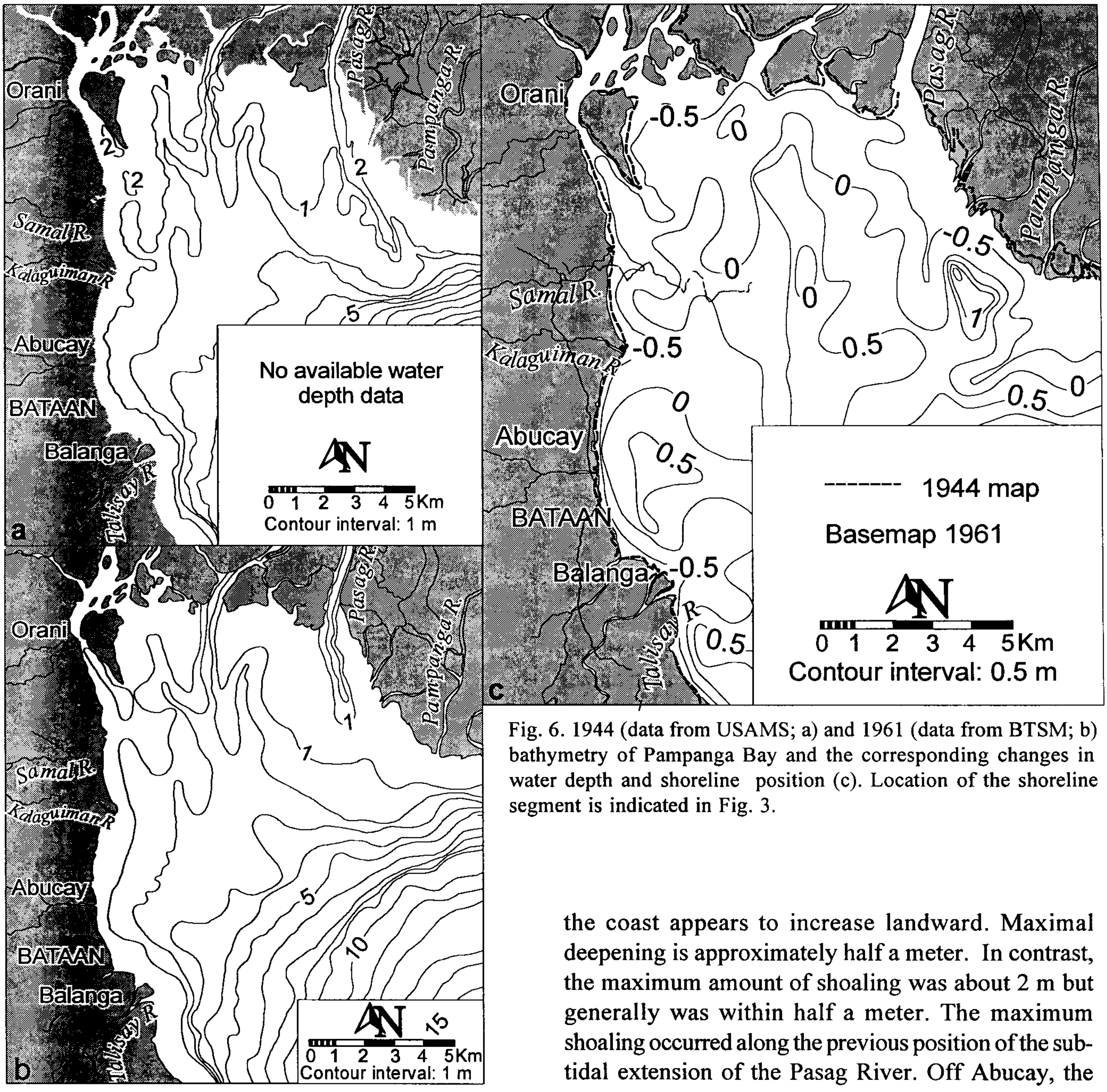

Fig. 6. 1944 (data from USAMS; a) and 1961 (data from BTSM; b) bathymetry of Pampanga Bay and the corresponding changes in water depth and shoreline position (c). Location of the shoreline segment is indicated in Fig. 3.

Offshore, the most noticeable change is displayed by the distal-portion of the subtidal channel of the Pasag River, which retreated almost 3 km and shifted approximately 0.5 km westward (Fig. 6). Comparison of the maps also indicates general deepening along the western and northern nearshore zones of Pampanga Bay. Deepening is relatively more widespread off the Samal and Talisay river deltas than elsewhere along the coast. Generally, the amount of deepening all along the coast appears to increase landward. Maximal deepening is approximately half a meter. In contrast, the maximum amount of shoaling was about 2 m but generally was within half a meter. The maximum shoaling occurred along the previous position of the sub-tidal extension of the Pasag River. Off Abucay, the shoaled area is fringed by zones where deepening has occurred. Shoaling in the central parts of Pampanga Bay defines a north-south trending swath that appears to open up to the south.

The general pattern of shoaling near the coast and deepening offshore is, in general, consistent with the changes in shoreline position during the same period. Deepening occurred where the shoreline retreats and shoaling is associated with prograded shorelines. Thus, deepening can be attributed to erosion, shoaling to deposition.

Bay-wide sediment distribution

The bottom sediments off the Cavite-Bacoor, Pasig River-Caloocan, and Bataan areas consist predominantly of mud (<0.063 mm) (Table 2). Sand fractions (2 mm-0.063 mm) are mostly fine- to very fine-grained, in concentrations that are typically lower than 5%, with the highest offshore abundances occurring off Cavite. The gravel fractions (>2 mm) in these samples are mainly shells and shell fragments. Along a transect across the mouth of Manila Bay, from Cavite to Bataan, amounts of sand are consistently high, but generally decrease towards the middle of the bay.

A bay-wide sediment distribution map compiled from data contained in NAMRIA bathymetric maps indicates that the sandy substrate off Cavite extends towards Batangas and outside of the bay (Fig. 7). Furthermore, the other sandy substrates are at or close to the shoreline. Coastal sediment from Balanga, Bataan to Malabon, Bulacan is sandy mud or muddy sand. Rocky substrates occur off Cavite and south of Limay, Bataan. A similar bay-wide sediment distribution map of Duyanen (1995), based on 164 surface sediment samples, shows a similar pattern. Duyanen's (1995) grain size analysis, using the Atterberg-cylinder (Mueller 1967), shows that silt-sized (0.063 mm-0.002 mm) fragments dominate the mud-rich portions of the bay.

Vertical variation in sediment type and lateral variation in sediment thickness

The three piston cores taken off Manila and in the middle of the bay (Fig. 3), each almost 3 m long, consist of muddy, dark greenish gray, slightly mottled sediments with a few discrete sandy mud laminations. No distinct vertical or core to core variation was recognized.

In the seismic profiles, the muddy sediments are expressed as a seismically transparent surface package overlying a highly irregular, possibly polygenetic surface (Fig. 8). Near the coasts, minor reflectors in this transparent unit indicate sandy intercalations. From the center of the bay towards Cavite, the transparent package thins out; towards Bataan, it initially thins and then thickens again, defining a wedge that progrades into the bay. An isopach map of the seismically

Table 2. Summary of grain size analysis (in weight percent)

Sample No.	Gravel	Sand	Silt-clay
Bataan			
1	1.14	0.82	98.04
2	0.59	7.15	92.25
3	1.59	13.67	84.73
4	0.12	1.57	98.31
5	0.15	1.01	98.83
6	2.90	93.72	3.38
7	3.97	35.48	60.55
8	0.33	1.61	98.06
9	0.17	9.30	90.53
10	0.00	4.55	95.45
11	1.66	5.31	93.03
12	0.76	4.85	94.39
13	0.76	4.86	94.38
14	0.73	2.72	96.55
15	1.87	7.67	90.46
16	0.27	5.99	93.74
17	0.00	4.11	95.89
18	1.06	12.74	86.20
19	0.14	2.28	97.58
20	0.00	3.16	96.84
21	0.05	4.08	95.87
Cavite-Bataan			
22	0.00	30.08	69.92
23	0.28	71.37	28.35
24	0.02	98.46	1.51
25	51.24	46.72	2.04
26	24.36	64.56	11.08
27	1.44	16.24	82.32
28	0.00	22.10	77.90
Cores			
29	0.17	2.75	97.08
30	0.28	1.69	98.03
31	0.12	3.17	96.72
Pasig River-Caloocan			
32	0.00	1.20	98.80
33	0.09	2.18	97.73
34	0.94	4.97	94.10
35	0.05	1.16	98.79
36	0.00	1.40	98.60
37	0.00	1.29	98.71
38	6.01	92.84	1.15
39	0.00	3.78	96.22
40	0.22	4.13	95.65
41	0.05	2.74	97.21
42	0.00	2.76	97.24
43	0.00	2.42	97.58
Cavite-Bacoor			
44	5.25	54.26	40.49
45	0.75	8.08	91.17
46	0.00	3.86	96.14
47	0.64	6.60	97.38
48	0.03	2.59	0.70
49	0.00	0.70	99.30
50	0.13	5.77	94.09
51	0.04	2.00	97.56
52	0.00	2.49	97.51
53	1.48	4.47	94.05

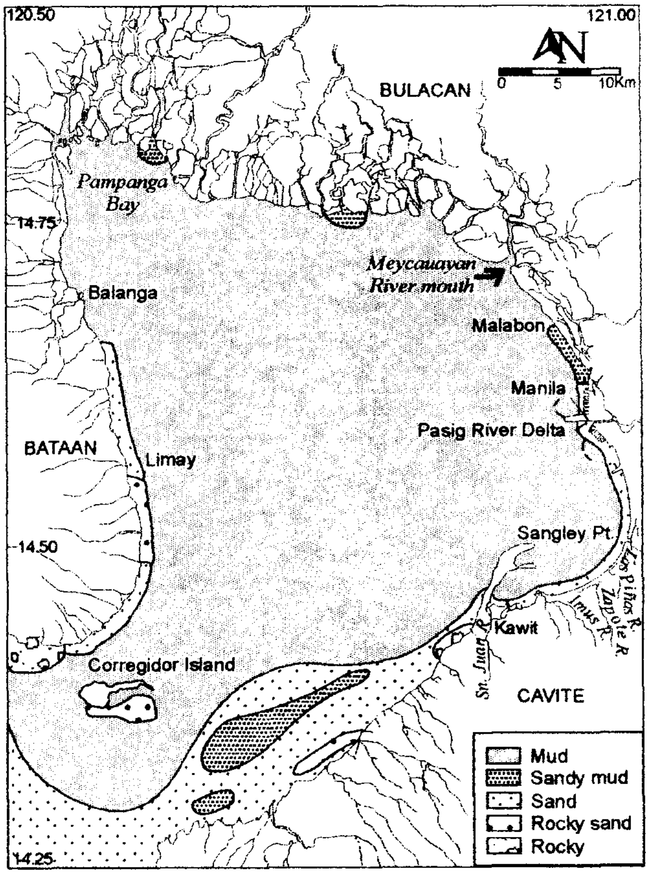

Fig. 7. Bay-wide sediment distribution based on NAMRIA data

transparent package and its lateral equivalents indicate a general thickening of the sediment fill towards the deeper center of the bay (Fig. 9).

DISCUSSION

Sediment dispersal from bathymetry and bathymetric changes

Pasig River area

Deposition of a fraction of the sediment load of the Pasig River is represented by the subtidal delta lobe in front of it (Fig. 4). The sediments here are very muddy (Table 2), reflecting the prominence of very fine-grained fractions in the Pasig River's sediment load. The morphology of the subtidal delta, skewed to the northwest, suggests greater sediment transport in that direction. The greater amount of shoaling on this side of the Pasig River Delta, interpreted as due to deposition, also points to northerly sediment transport. Shoaling south of the Pasig River mouth, in the area behind the southernmost jetty, is likely due to the trapping of sediments coming around the jetty. Some of the accumulated sediments behind the jetty may have also come from south of the Pasig River.

Based on river discharge data, Pasig River is likely to have high sediment loads from July to December (Fig. 10). These months are characterized by the predominance of southwesterly and northeasterly winds. In the wind-driven circulation model of de las Alas and Sodusta (1985), sediment plumes from the Pasig River would be displaced northward by northeasterly and southeasterly winds. Part of the sediment plume may also be transported to the south with the northeasterly winds. With southwest winds, the convergence of the wind-driven currents nearshore of Pasig River and its eventual veering offshore, sediment plumes from Pasig River can possibly be driven directly offshore. Villanoy and Martin's (1997) circulation model, also wind-driven, suggests that southwesterly winds would still result in a northerly veering of Pasig River sediment plumes. The return flow is located off the Bulacan River. The bathymetry and bathymetric changes suggest the dominance of a northerly sediment transport.

Cavite area

At the northern tip of the Cavite Spit (Fig. 5), the northeastward shoaling and the relatively high silt concentrations in the surface sediment indicate predominantly northward sediment transport. The silt is likely derived from the sandy platform off the western coast of Cavite.

Deposition north of the Cavite Spit is probably due to flow retardation brought about by deepening and widening. A vertically uniform wind-driven northeastward flow off the Cavite coast would undergo both horizontal and vertical flow separation, thus causing a decrease in velocity and the settling of the silt in the

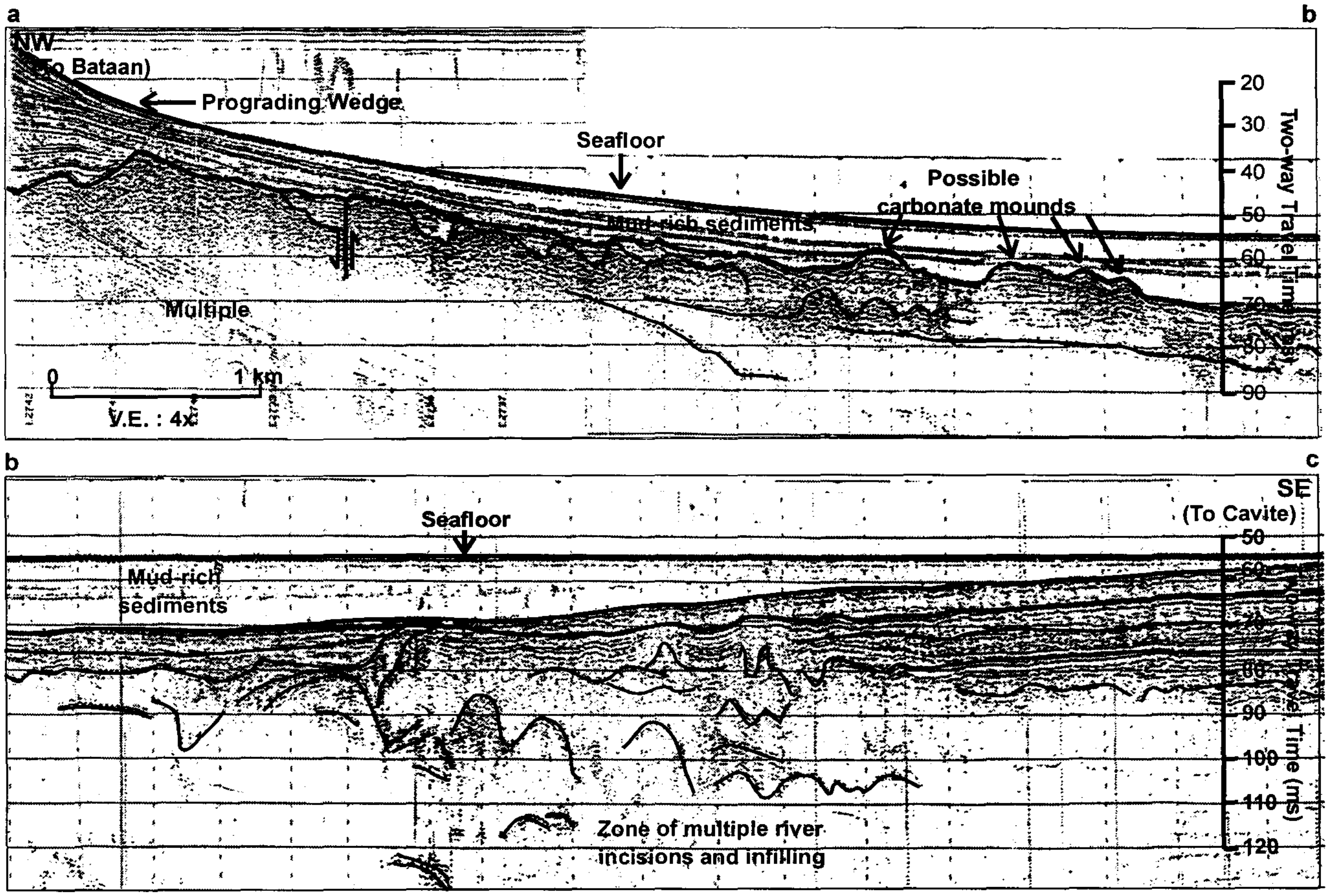

Fig. 8. Segment of a continuous seismic reflection profile across the baymouth. The thickness of the mud-rich sediment is shown in isopach in Fig. 9. Location of line is indicated in Fig. 3.

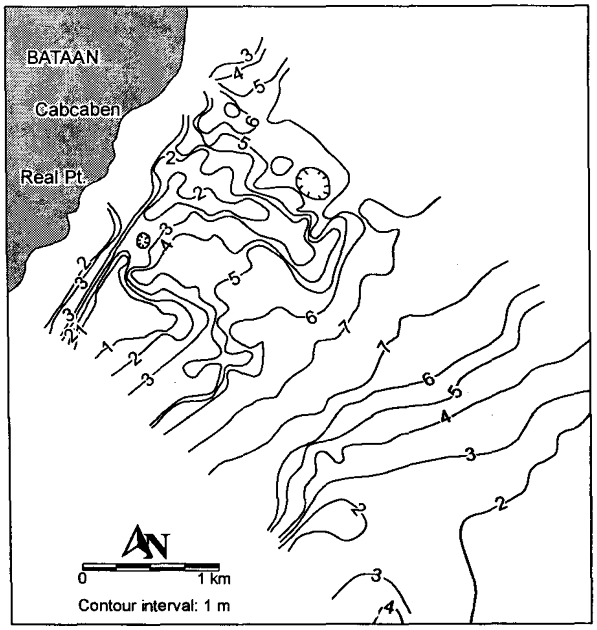

Fig. 9. Isopach map of muddy sediment cover across the baymouth. The area covered in the figure is indicated in Fig. 3.

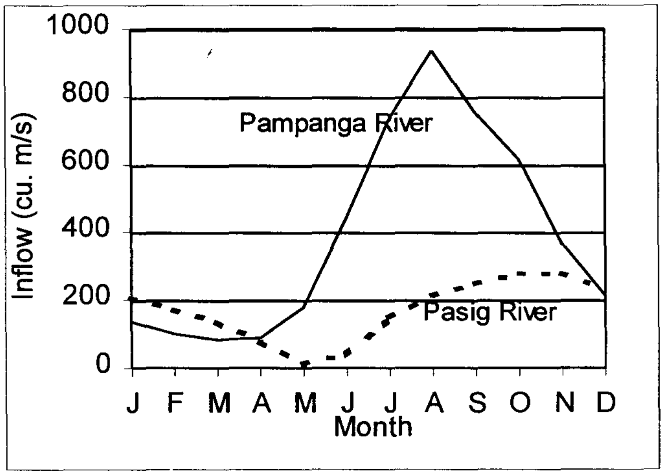

Fig. 10. Discharge of Pasig and Pampanga river basins (data from EMB)

sediment load. The other finer-grained components may continue being entrained by the flow.

Bacoor Bay (Fig. 5) has experienced relatively minimal shoaling, despite its protected nature and the potential multiple sources of sediment represented by the San Juan, Imus, Zapote, and Las Piñas Rivers, as well as the currents moving around the spit from the northwest side. The progradational nature of the coastline attests to a surplus of sediment supply. It is likely that the generally low sedimentation rates within Bacoor Bay are due to flushing of sediments. The strip fringing the Las Piñas-Kawit coast is relatively sandy despite being protected, and thus, must have lost fine-grained materials. Flushing can be due to the passage of strong wind-driven currents through Bacoor Bay as suggested by the circulation models of de las Alas and Sodusta (1985) and Villanoy and Martin (1997). Tidal currents may also be a contributing factor—Villanoy and Martin's (1997) tide-driven circulation model of the Manila Bay indicates the occurrence of fairly strong tidal currents in Bacoor Bay relative to other coastal areas in the bay.

Pampanga Bay

In Pampanga Bay, river mouths do not have associated sub-tidal delta lobes, even for Pampanga River, which has a very high sediment load in the order of 119 x 10^5 tons/y (JICA 1982), two orders of magnitude greater than the solid discharge of the Pasig River approximately 1.25 x 10^5 tons/y (SOGREAH 1974; Fig. 6). Instead of a subtidal delta lobe, the channels have subtidal continuations. This incompatibility of the absence of a subtidal delta lobe at the mouth of a river with a high sediment load is interpreted to be due to offshore flushing of sediments. This is consistent with the perceived dominance of onshore-offshore over alongshore sediment transport along the coast of the Pampanga Bay (Siringan and Ringor, 1997). Furthermore, Villanoy and Martin's (1997) simulation of tide-generated currents in the Pampanga Bay shows that the velocities are non-trivial and that the residuals are offshore-directed. Offshore flushing may also be aided by wind-driven currents. The wind-driven circulation models suggest the presence of strong currents in Pampanga Bay (de las Alas and Sodusta, 1985; Villanoy and Martin, 1997).

River discharge data for the Pampanga River system indicate that high sediment discharge are occurring from June to November, corresponding to the times when southwesterly winds predominate.

The accumulation between the Talisay and Kalaguiman River Deltas is probably due to offshore transport of sediment induced by the convergence of nearshore currents, as suggested by Siringan and Ringor (1997).

Bathymetric changes and sedimentation rates

Variation in the magnitude of shoaling occurs across the three study areas. Pampanga Bay shows the least amount of shoaling, the Pasig River area, the greatest. The variation appears not to be an artifact of different spans of time when the changes occurred in the different areas. The dates as to when the hydrographic data used in the maps were generated show (see Table 1) that the bathymetric changes cover the period 1901 to 1950 (span of 50 years) for the Manila area. The bathymetric changes for the Cavite area cover the period 1917 to 1950 (span of 34 years). For the Pampanga Bay, the period covered is probably from 1916 to 1950 (span of 35 years). The 1950 date is based on the period during which the surveys for Cavite and Manila were made. To estimate the typical magnitude of bathymetric changes for the three sites, take these estimates at face value, and divide them with the span of time represented by the maps. Pampanga Bay yields the lowest rates of sedimentation and the Pasig River area the highest. A rate of sedimentation as high as 9.4 cm/y may be occurring in the depocenter northwest of the Pasig River. A similar rate, at 8.8 cm/y, may occur northwest of the tip of the Cavite Spit. In Pampanga Bay, the highest rate found in the filled subtidal channel is only 4.3 cm/y. Correction for relative sea level rise to the bathymetric changes will increase the rates a little bit more as will be discussed later.

The reported radionuclide-based sedimentation rates in Pampanga Bay, off Malabon, and Bacoor Bay are in general agreement with the bathymetry-derived estimates (Fig. 1). In Pampanga Bay, the ^{137}Cs-based sedimentation rate of 5.5 cm/yr, seems to strengthen the argument for the increase of sedimentation rates towards the offshore. How far this trend can be carried offshore is unknown. ^{210}Pb-based estimates of sedimentation rates (Furio et al., 1996; Santiago, 1997) indicate a decrease to less than 1 cm/y towards the deeper and central parts of the bay. The general trend of low sedimentation to erosion near the coast and increasing sedimentation in the offshore direction could be due to the relative sea level rise, discussed later, that is occurring in Manila Bay. Bruun (1962) predicts, based on the concept of equilibrium profile, that a rise in sea level will translate the shoreface upward and landward, resulting in shore erosion and deposition offshore (Fig. 11).

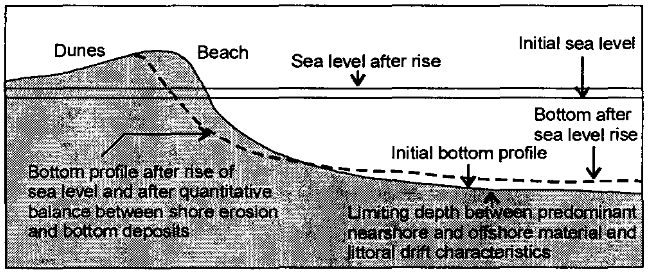

Fig. 11. Effect of relative sea level rise to coastal sedimentation as predicted by Brunn (1962)

In the baymouth area, seismic profiles and the resulting isopach map suggest that sedimentation rates are higher in the deeper central parts of the bay relative to the adjacent slopes (Figs. 8 and 9). The seismic lines also attest that this relatively high sedimentation rate is not a recent trend. This long-term sedimentation trend across the baymouth is probably controlled by the bay's morphology rather than by sea level fluctuations.

Low sedimentation rates and subsidence

The minimal shoaling in Pampanga Bay is surprising because of all the rivers emptying into Manila Bay, Pampanga River, which discharges directly into Pampanga Bay, has the highest sediment load. This apparent low sedimentation rates in Pampanga Bay might be due to an efficient flushing of sediments farther offshore, as discussed earlier. The general increase of sedimentation rates towards the offshore seems to be consistent with offshore flushing. However, subsidence could be the greater cause of the apparent low sedimentation rates in Pampanga Bay.

An overall relative sea level rise of approximately 0.40 cm/y from 1901 to 1950 (Fig. 12), the period during which the bathymeric changes occurred, is indicated by the Manila South Harbor tidal gauge record. A drastic increase in the rate of rise to approximately 2.35 cm/y occurred between 1963 to 1980 (Fig. 12). In comparison, estimates of mean global eustatic sea level rise during the last century range from 0.12 cm/y (Gornitz and Lebedeff, 1987) to 0.18 cm/y (Douglas, 1991). We attribute the higher rate of sea level rise in Manila Bay, relative to the estimates for global eustatic rise, to subsidence. The South Harbor is situated atop the deltaic deposits of Pasig River. Compaction of the deltaic sediments, under their own accumulating weight, may explain the relative sea level rise during the period 1901 to 1950. The drastic increase in the rate of relative sea level rise during the period 1963 to 1980 could be attributed to groundwater withdrawal. The trend of groundwater withdrawal in Metro Manila (NEPC, 1987; Fig. 12) shows an abrupt increase in the late 40's and acceleration in the early 70's. These trends correlate

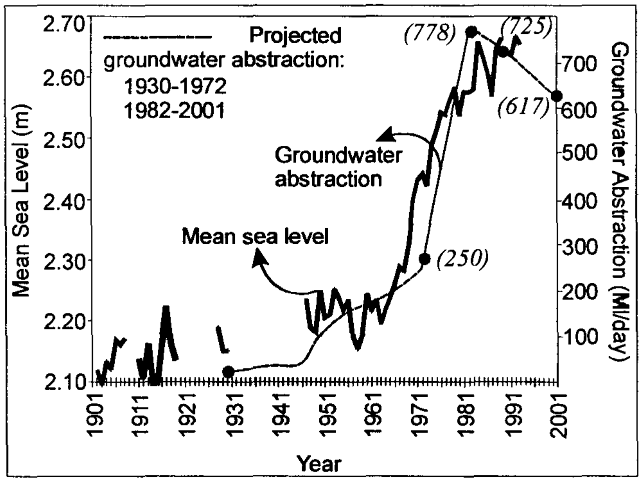

Fig. 12. Mean sea level (data from NAMRIA) and groundwater abstraction in the Metro Manila (data from NEPC 1987)

well with the trends of relative sea level change indicated by the South Harbor tidal gauge record.

We believe that the Pampanga Bay, being also deltaic, was likewise experiencing subsidence with a rate, during the period 1901 to 1950, probably exceeding that in the South Harbor. This is suggested by the greater abundance of finer-grained sediments and rapid progradation that characterize the Pampanga Delta plain (Siringan and Ringor, 1997). Logs of water wells indicate that the Pampanga Delta plain is underlain by a thick accumulation of muddy sediments (NEPC, 1987). An isopach map of the alluvial cover along the Las Piñas to Bulacan coast, constructed by Daligdig and Besana (1993), suggests a general thickening of the Holocene fluvio-marine deposits towards the Bulacan-Pampanga area. Since thick accumulations of fine-grained sediments deposited at rapid rates are highly susceptible to subsidence due to compaction, it is very likely that subsidence in the Pampanga Bay area is greater than that in the South Harbor. Besides compaction, tectonics may be contributing to the subsidence in the Pampanga Delta area. Remotely-sensed images of the delta plain, such as SAR and Landsat, indicate the presence of regional lineaments. Some of these lineaments might be faults experiencing creep with great vertical displacement. Certainly, deltaic accumulations could contribute gravitationally to such motion.

CONCLUSIONS

Off Cavite and Manila, sediments are transported predominantly to the north of their source. Relative sea level rise in the bay resulted in the low retention of sediments near the coast. Sedimentation rates of as high as 9 cm/yr could have occurred in Manila Bay. Efficient offshore flushing of sediments in Pampanga Bay may explain the apparent low sedimentation rates in this area. However, high rates of subsidence could be the greater cause.

In this study, changes in bathymetry yielded important information on the pathways, sources, and potential for the reworking of sediments and the rates of and lateral variability of sedimentation. Thus, examination of bathymetric changes, in combination with surface sediment distribution and known movements of water, would be very useful in environmental monitoring. A caveat, however: it is important to consider the local relative sea level changes since they may play a major role in determining the trends of the bathymetric changes.

ACKNOWLEDGMENTS

Funding for this project was provided by the Office of Research Coordination of the University of the Philippines Diliman to F. P. Siringan (Project No. 09505 Ns). The authors would also like to thank the National Institute of Geological Sciences for laboratory and field support. Appreciation is likewise extended to Kelvin Rodolfo and Laura David for their review and helpful comments.

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