Compaction rates and paleo-sea levels along the delta complex north of Manila Bay, Luzon Island, Philippines

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ABSTRACT

Uncontrolled groundwater extraction has been proposed as the main cause of accelerated subsidence in the delta region north of Manila Bay. However, natural autocompaction of deltaic sediment and other anthropogenic factors also enhance subsidence, amplifying global sea-level rise and aggravating land loss, flooding, and tidal inundation. Here, we report how we determine the longer-term subsidence rates and paleo-sealevel history of the delta plain using sediment cores. Four sediment cores 3 to 10.7 m long taken in Bocaue and Malolos, Bulacan and Lubao, Pampanga all display shoaling-upward sequences that consist of, from bottom to top: basal shallow-marine clays comprising nearly half of each core; mangrove peat; beach sand; fluvial sand and mud; and uppermost floodplain clays. Porosities of the deltaic sediments range from 0.3 to 0.8. Peat has the highest porosities, from 0.7 to 0.8. Calculations indicate about 2 to 6 m of compaction for the whole sediment sequence. Wood fragments at 7 m and 8.4 m depths in the shallow-marine section of the Pampanga core respectively yielded radiocarbon ages of 1800 ±40 and 1730 ±40 years. If around 1,000 years ago is when the surface 10 m of sediments started compacting, they would have done so at rates of 0.2 to 0.6 cm/y. Natural compaction in similar environments such as in Po Delta, Italy and Mississippi Delta are comparable, ranging from 0.09 to 0.37 cm/y. The small values acquired in this study imply that large human-induced components may account for as much as 97 percent of the subsidence in Pampanga.

Keywords: autocompaction, subsidence, paleo-sea level, delta

INTRODUCTION

Local, relative sea-level rise from both natural and human-induced land subsidence, well recognized in other countries, can be orders of magnitude more rapid than global sea-level rise. Neither, however, has yet been understood and accepted in the Philippines. Deltaic lowlands are very vulnerable to ecological change and economic damage due to marine invasion and floods exacerbated by sea level rise. Worsening floods in the region north of Manila Bay continue to draw much attention as they affect this densely populated and highly developed agri- and aquaculture area. Studies by Siringan and Rodolfo (2003) and Rodolfo and Siringan (2006) indicate that aggravated flooding there is due to local, relative sea-level changes greatly enhanced by accelerated sediment compaction and ground subsidence caused by excessive groundwater withdrawal. Additional land subsidence can also be expected from natural compaction caused by loading of delta sediments during deposition.

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This ongoing work uses delta-plain sediment core data to establish the lateral and vertical response of the delta complex to long-term sea level fluctuations, and to determine the contribution of natural compaction to relative sea-level changes. The results provide a more complete picture, and thus a better understanding of the role of subsidence in the worsening floods, and should greatly aid in mitigating subsidence with appropriate and cost-effective measures.

Physiographic and Geologic Setting

The southern end of the Central Luzon Basin (Fig. 1a) is a broad tidal-river delta complex, formed by the sediments delivered to northern Manila Bay by the Pampanga, Angat, Bulacan-Meycauayan Rivers within the Pampanga River Basin, the largest of the 26 catchment areas (Siringan and Ringor, 1997). Covering about 2,700 km2 (Siringan and Rodolfo, 2003), the delta complex is occupied by the coastal towns of Bataan, Pampanga, Bulacan, and the KAMANAVA area of northwestern Metro Manila. The delta surface has a very gentle gradient, with elevations rising from mean sea level (msl) to 10 meter above msl 10 km to 25 km inland (Sandoval and Mamaril, 1969; NEPC, 1987). To the west, the delta is flanked by the eastern Zambales Mountains of Eocene ophiolites and the Recent Pinatubo, Natib, and Mariveles volcanoes. To the east, the delta is contained by the foothills of the southern Sierra Madre Mountains. These consist of Creteceous to Eocene metavolcanics, metasediments and ophiolites, Oligocene to Miocene carbonates, marine clastics and volcaniclastics, and Pliocene to Pleistocene shallow marine to terrestrial sedimentary and pyroclastics (BMG, 1982; BED, 1986; Encarnacion, 2004). Quaternary alluvium underlying the delta plain typically consists of consolidated silt or clay, and poorly cemented sand and gravel derived from the Pleistocene Guadalupe Formation (BMG, 1982; JICA, 1982). The young fluvio-marine deposits are highly susceptible to compaction. Borehole data in the KAMANAVA cities of Kaloocan, Malabon, Navotas and Valenzuela show the Holocene marine and river deposits vary laterally in thickness from 1-31m (CTI Engineering Co., Ltd., 2001).

Lineaments in satellite images of the region are most likely active faults that might be responsible for some

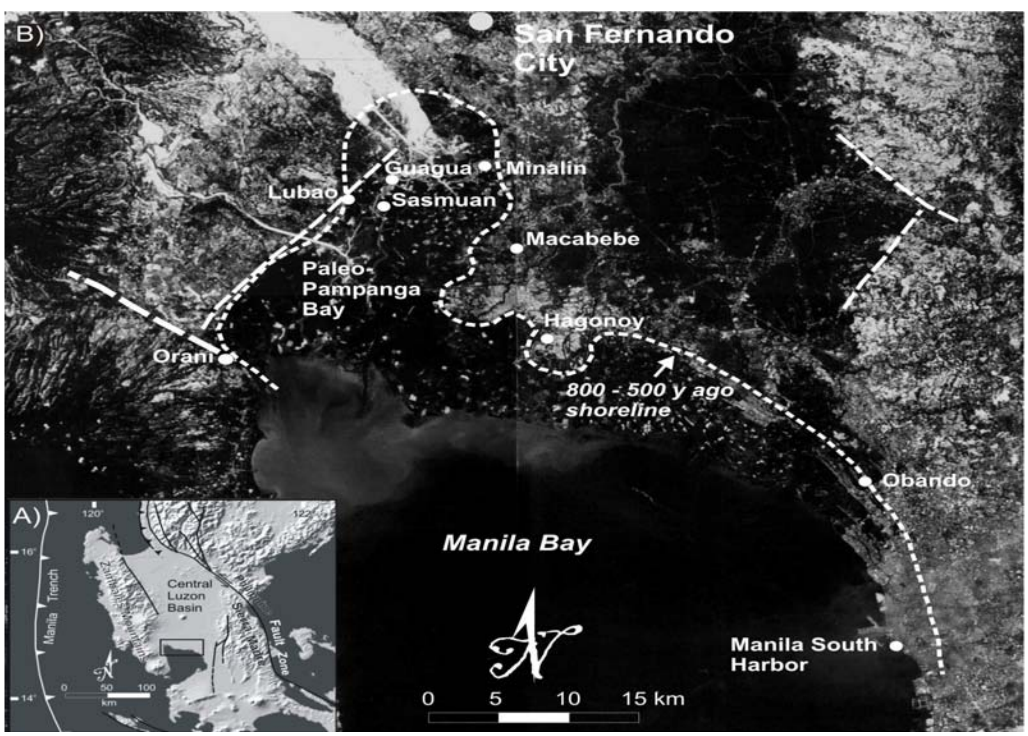

Figure 1 A) Major geologic structures of Central Luzon Basin modified from Maleterre (1989) and Nelson et al., (2000).
B) Coastal morphology and local tectonic features

of the vertical motions (Siringan and Rodolfo, 2003). The most prominent lineament passes northeastward through Hermosa, Bataan to Bacolor, Pampanga and bounds wetlands to the southeast and dry alluvial plains to the southwest (Fig. 1b).

Paleoshoreline Positions

At least nine chenier ridges in a 1991 radar image along the Navotas-Obando coastal plain are sand accumulations heaped by waves on a muddy substrate along former shorelines. The most inland and oldest of these ridges, near the Bulacan River, is approximately 7 km north of the present shoreline (Siringan and Ringor, 1997). Chenier ridges are absent, however, along the western coast. Instead the landward limit of wetlands in Hagonoy, Bulacan and Macabebe, Pampanga are marked by paleo-delta lobes 5 to 10 km inland. Gaillard, et al. (2005) defined the ca. 500 - 800 y BP paleo-shoreline by using core data and the landward limit of wetlands. Apparently, the area on which the Pampanga towns Lubao, Sasmuan, Guagua, and Minalin are situated (Fig. b) was an embayment until it was rapidly filled with volcaniclastic Pinatubo sediments generated by the eruptive episode of 500-800 y BP (the *Buag* event of Newhall et al., 1996).

Precipitation and Tides

The region has two pronounced seasons, dry from November to April and wet during the rest of the year. Precipitation records of the Philippine Atmospheric, Geophysical and Astronomical Administration (PAGASA) from 1961 to 1997 document that southwest monsoon winds and typhoons deliver approximately 1,000-3,000 mm of annual rainfall, about 325 to 425 mm during the wettest months of July to September. Tides in the bay are predominantly diurnal, with a microtidal range of 1.25 m along the Metro Manila coast (Siringan and Ringor, 1997).

Human induced compaction

A number of aquifers 15 to 30 meters deep in the delta plain sediments are tapped by shallow water wells for domestic, agri- and aquacultural uses (Sandoval and Mamaril, 1969). Fishponds use large volumes of groundwater to replace water fouled by overfeeding. In addition, the near-surface sediments are rapidly dewatered when the ponds are dried up twice a year to prepare for the next cropping. To some extent, this practice is similar to the drainage practices in the peat lands of Netherlands that accelerate natural compaction

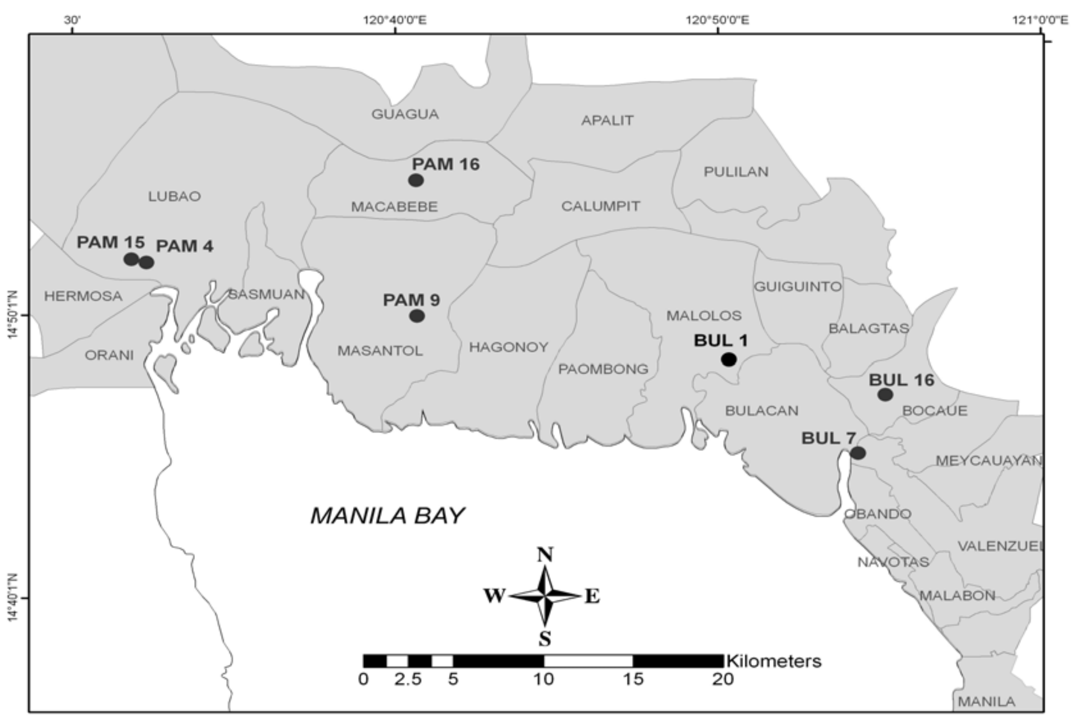

Figure 2. Core sites location across the delta complex.

rates of 1.7 to 6 mm/yr to several centimeters or more (Stephens, et al., 1984). There, however, the enhanced rates eventually decrease to a constant rate equal to or even lower than the pre-disturbance values. Both surface and shallow dewatering processes enhance compaction of the deltaic sediments due to loss of original volumes of pore waters trapped in clays and organic-rich soils such as peat. Enhanced compaction in the deeper sections of the delta plain can be attributed to withdrawal from wells as deep as 110 m (Siringan and Rodolfo, 2003).

METHODS

Seven sediment cores ranging in lengths from 3.0 to 10.7 m (Fig. 2) were taken using a manual mud corer at locations associated with paleo-shoreline features such as beach ridges and paleo-deltas delineated from a satellite image. Data acquired from four of these cores (PAM 4, BUL 1, BUL 7, and BUL 16) are presented in this report. Color and grain size were logged, and paleoenvironments were deduced from lithologies, sedimentary structures, and organic matter and molluscan contents. Porosities and compaction ratios were calculated by measuring water contents and bulk densities. Subsamples from the peat layers are currently being processed for radiocarbon dating. Previous age dates of wood fragments at 7 m and 8.4 m depths in the shallow-marine section of core Pam 4 yielded radiocarbon ages of 1800 ± 40 and 1730 ± 40 y BP, respectively (Gaillard et al., 2005). Precise elevations of each core site still need to be determined.

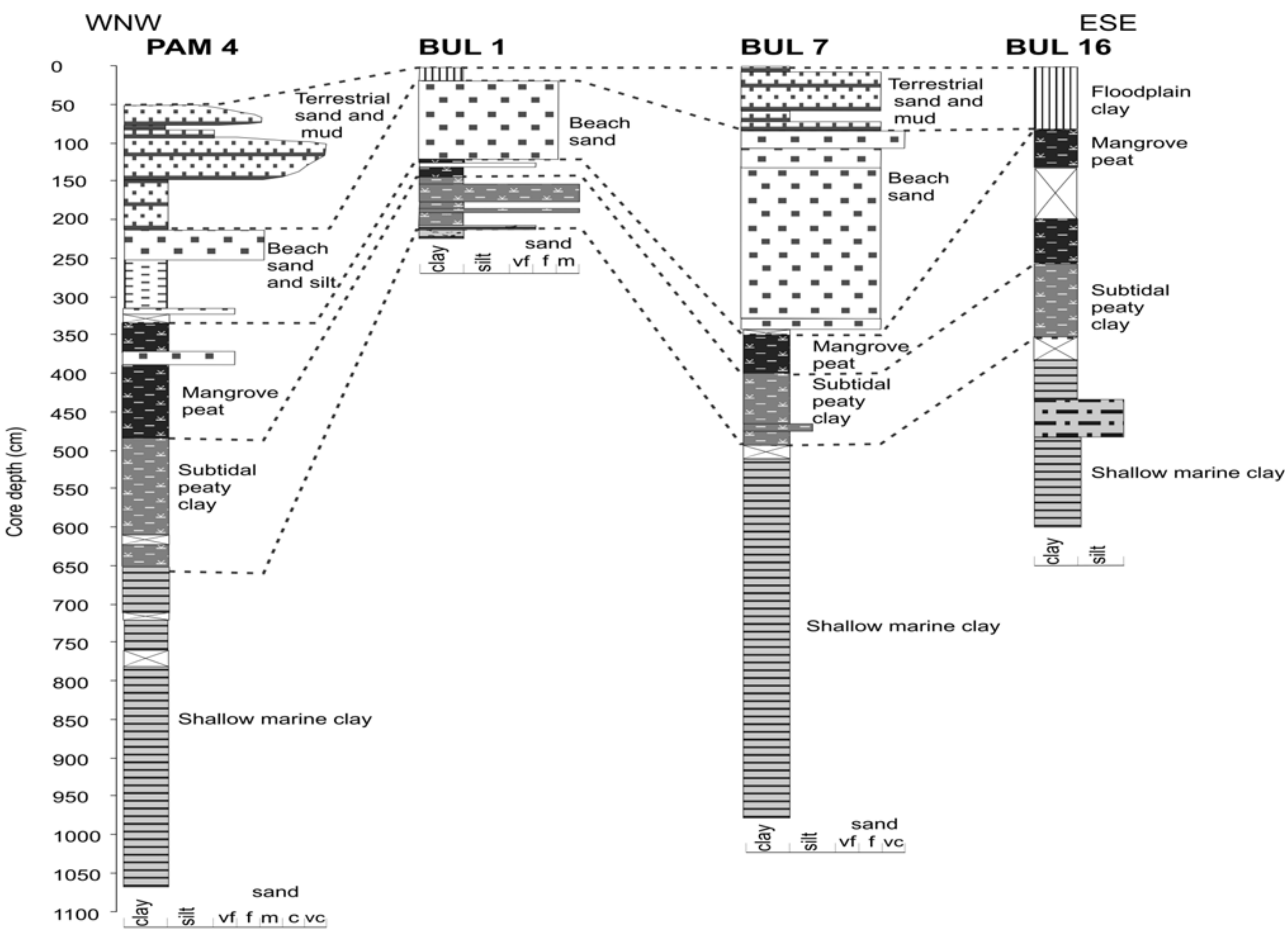

Figure 3. Shallow subsurface stratigraphy of the delta complex north of Manila Bay.

Table 1. Magnitudes of compaction of the sediments in Pampanga and Bulacan.

Sediment Type	Present Thickness, m		Initial Thickness, m		Decrease in Thickness, m	
	PAM 4	BUL 16	PAM 4	BUL 16	PAM 4	BUL 16
Fluvial sand	0.95	-	1.07 - 1.30	-	0.12 - 0.35	-
Beach sand	0.65	-	0.74	-	0.1	-
Mangrove peat	1.75	1.05	2.00 - 4.17	1.66 - 3.33	0.25 - 2.42	0.61 - 2.28
Subtidal peaty clay	1.70	0.95	2.19 - 3.06	1.36 - 1.90	0.49 - 1.36	0.41 - 0.95
Shallow marine clay	4.20	2.20	4.88 - 5.60	2.44 - 2.84	0.68 - 1.40	0.24 - 1.06
Total	**9.25**	**4.20**	**10.88 - 14.87**	**5.46 - 8.07**	**1.64 - 5.63**	**1.26 - 4.29**

RESULTS AND DISCUSSION

Paleoenvironments and paleo-sea levels

Most of the cores are complete upward sequences consisting of basal shallow-marine clay, transitioning into a mangrove-peat that in turn is overlain by beach sand capped by fluvial sand and mud transitioning to floodplain clays (Fig. 3). Such sequences represent deposition in successively shallower environments; the beach sand on top of the peat documents deepening by relative sea level rise, followed by fluvial progradation.

The shoaling upward sequence from marine clay to mangrove peat indicates shoreline progradation. Subsequently, as evidenced by beach sand overlying peat layers, the coastline retreated, possibly due to either regional sea-level rise or a local seismic event affecting the entire delta plain. The Buag eruption of Mt. Pinatubo, or fault movements along one or more of the many lineaments in the delta plain may have caused co-seismic subsidence. Finally, natural and human-induced compaction lowered the beach sands to their present depths. Importantly, the peat deposits overlain by beach sand in other core sites indicate a baywide event, not localized erosion caused by delta shifts. The beach sands deposited soon after the eruption of Pinatubo 500 to 800 years ago record a pre-eruption shoreline more landward than the present one. High sediment input after the eruption rapidly filled the paleo- Pampanga Bay (Gaillard et al., 2005), prograding fluvial sediments translating the shoreline seaward close to its present position.

Porosity and natural compaction

Natural compaction, caused by the squeezing out of pore water by the accumulating weight of overlying sediments, is recorded in the loss of porosity with depth. In the uppermost 10 m of deltaic sediments, porosities range from 0.3 to 0.8. Peats have the highest values of 0.7 to 0.8, and sands are the least porous, at only 0.3 to 0.4. To reconstruct the initial thickness of each sedimentary layer, these porosity values were compared to initial porosities of recent deltaic sediments along Manila Bay, as well as from Atkins and McBride (1992). Compaction ratios were determined with the equation

$$CR= h_1/h_2= 1\text{-}n_2/1\text{-}n_1$$

where h1= initial thickness, h2 = present thickness, n1 = initial porosity, n2 = present porosity (Einsele, 1992). Each compaction ratio yields a magnitude of the reduction in sediment thickness (Table 1) due to loss in porosity owing to natural and or anthropogenic causes.

In Lubao, the 10-m surface sedimentary sequence has been compacted about 1.6 to 5.6 m; about 0.25-2.42 and 0.49-1.36 m respectively for the peat and peaty clay layers, sediment types easily compacted due to their very high water and organic contents. As in the Thessaloniki delta plain in Greece (Stiros, 2001), oxidation of peat soils in the vadose zone may also contribute to subsidence.

Assuming that the top of the core is at present mean sea level (msl), 1.6 to 5.6 m of compaction indicates that the peat layer presently 3.5 m below msl was deposited in the depth zone from 1.9 below to 2.1 m above present msl. If co-seismicity caused the sudden deepening represented by the peat being overlain by beach sand, an even higher elevation is required. Reconstructions of regional paleosealevel by Berdin and others (2003) and Siringan and others (2003) indicate that sea level reached it present position in the Philippines about 1,000 years BP. This implies that the middle value of estimated compaction is more realistic.

Assuming that compaction started about 1,000 years ago, the deltaic sediments could have been compacted at rates of 0.16-0.56 cm/yr, 0.36 cm/yr on the average, accounting for 2 to 8 percent of the estimated 2 to 8 cm/yr typical subsidence rates from 1991 – 2001 (Rodolfo and Siringan, 2006). The difference between the calculated compaction rates and the observed subsidence is most probably due to compaction of the sediments below the sampled surface sections, but other factors yet to be recognized may be lowering the deltaic surface. Our natural compaction rates are higher than the 0.09 to 0.37 cm/yr calculated by Kuecher and others (1993) in a similar Mississippi Delta environment, and the 0.1 cm/yr in Po Delta, Italy (Pirazzoli, 1996) but longer durations and sequences there might account for the difference.

CONCLUSION

The compaction ratio of near-surface sediments indicate that of the 2 – 8 cm/yr of subsidence, about 2 to 8 percent can be attributed to natural compaction of the near surface sediments. This implies that enhanced dewatering of the upper 30 m of the sediment column can potentially account for almost 98 % of the subsidence rates during the past decade.

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