Rapid coastal subsidence in the central Ganges-Brahmaputra Delta (Bangladesh) since the 17th century deduced from submerged salt-producing kilns

Till J.J. Hanebuth[1]*, Hermann R. Kudrass[1], Jörg Linstädter[2], Badrul Islam[3], and Anja M. Zander[4]
[1]MARUM–Center for Marine Environmental Sciences, University of Bremen, Leobener Strasse, 28359 Bremen, Germany
[2]Institute of Prehistoric Archaeology, University of Cologne, Weyertal 12, 50923 Cologne, Germany
[3]Department of Geology and Mining, University of Rajshahi, Rajshahi 6205, Bangladesh
[4]Institute of Geography, University of Cologne, Albertus-Magnus-Platz, 50923 Cologne, Germany

ABSTRACT

The densely populated, low-lying Ganges-Brahmaputra Delta is highly vulnerable to global sea-level rise. In order to estimate the rate of subsidence of the delta, we examined submerged salt-producing kiln sites in the coastal Sundarbans (a huge UNESCO-protected mangrove forest). These kilns were built just above the winterly spring high-tide level of the time, but their bases are currently located ~155 cm below the corresponding modern level. According to optically stimulated luminescence (OSL) dating, the kilns were last fired ~300 yr ago, and salt production was terminated by a catastrophic event that affected the kiln sites at different levels and locations. ^{14}C ages of charcoal at the kilns' bases and associated mangrove stump horizons support the OSL dates. Based on the elevations and ages, the 300 yr average rate of sinking of the outer delta is 5.2 ± 1.2 mm/yr, which includes 0.8 mm/yr of eustatic sea-level rise. With the expectation of further acceleration of sea-level rise, the already-present problematic situation will be aggravated, and only prudent control of sediment accretion will keep southern Bangladesh above sea level.

INTRODUCTION

The huge river deltas in Asia, with their large catchment areas in a monsoonal precipitation regime, are characterized by enormous water and sediment discharge rates. Such deltas are extremely vulnerable to tectonics, flooding, changing sediment supply, and rising sea level. Also, coastal modifications, aquaculture, dam and dike construction, and groundwater extraction may cause coastal erosion and land subsidence. Thus, future global sea-level rise represents a major threat for both inhabitants and the ecosystem (Syvitski et al., 2009).

Modern deltas consist of thick Holocene depositional bodies (Stanley and Warne, 1994; Goodbred and Kuehl, 2000a). Such massive material loading is accompanied by sediment compaction and crustal sinking; i.e., subsidence experienced as a relative sea-level (RSL) rise (Syvitski et al., 2009). Accurate knowledge of the rate of subsidence is as indispensable as predictions of the rate of future sea-level rise, because both effects can lead to land lowering. However, estimating past subsidence rates is quite a challenging task because paleo–sea-level indicators, which are reliable for precise dating, are rare.

REGIONAL SETTING

The Ganges-Brahmaputra Delta (Fig. 1A) annually transports ~1 × 10^9 tons of sediment, of which ~30% accumulates in the subaerial delta and the rest is delivered to the submarine delta and the Bengal Fan (Goodbred and Kuehl, 1998). The southern central delta is occupied by a preserved natural mangrove forest called the Sundarbans. The coast shows meso-tidal variations of 2–4 m (Han and Webster, 2002) and is positioned on a major cyclone trail with disastrous storm surges (Kudrass et al., 1998; Karim and Mimura, 2008).

The outer delta is slowly sinking over geological time due to its position at the eastern edge of the northeastward-drifting Indian plate (Steckler et al., 2008). Boreholes in the coastal region indicate Holocene fine-grained sediments several tens of meters thick (Goodbred and Kuehl, 2000b) associated with significant compaction-related subsidence (Steckler et al., 2010). Previous reconstructions of land accretion rates in the lower outer delta calculated long-term Holocene subsidence rates of ≤5 mm/yr (Goodbred and Kuehl, 2000a; Stanley and Hait, 2000; Allison and Kepple, 2001). However, none were able to resolve historical subsidence rates, which must be as accurate as possible for sustainable coastal management. While a recently installed GPS network focuses on vertical movements (Steckler et al., 2010), we used submerged kilns from the Sundarbans coast as precise paleo–sea-level indicators. These kilns were used about three centuries ago for producing salt on an industrial scale for India (Hamilton, 1853; Serajuddin, 1978).

MATERIALS AND METHODS

Three sites with partly submerged kilns were investigated in A.D. 2010: Gawbonia (21°51′30″N, 89°44′53″E), Katka-A (21°51′14″N,

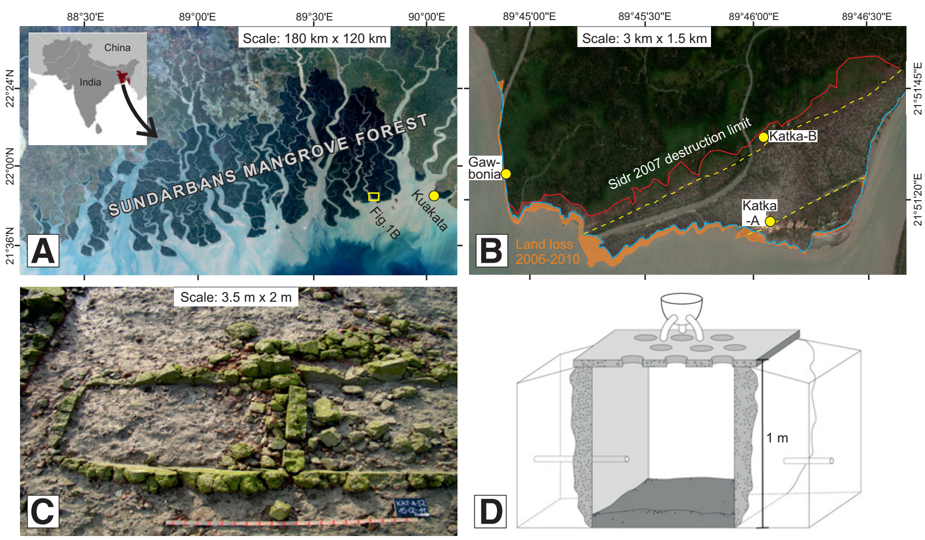

Figure 1. A: Satellite image (NASA) of the Sundarbans (India and Bangladesh) with the Katka, Gawbonia, and Kuakata study sites. B: Low-tide satellite image (from Google Earth™) showing the three Katka and Gawbonia sites. Blue line—modern shoreline; orange area—land loss during A.D. 2006–2010; red line—A.D. 2007 cyclone Sidr destruction limit; yellow lines—former vegetation boundaries. C: A typical double-chamber salt kiln remnant at Katka-A, showing fired outer walls of irregular thickness. D: Reconstruction of a kiln according to field observations.

*E-mail: thanebuth@uni-bremen.de.

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89°46′01″E), and Katka-B (21°51′35″N, 89°46′03″E) (Fig. 1B). Coastal erosion at all sites leads to increasing kiln exposure. A fourth site, 35 km further east, near Kuakata (21°49′N, 90°06′E), was sampled in 1999, but has been completely eroded since. The elevations of 20 kiln bases in Katka-A, Katka-B, and nearby Gawbonia, as well as two successive ancient in situ mangrove stump horizons, were measured in relation to the winter spring high-tide level (see the GSA Data Repository[1]). The fired walls (up to 20 cm thick) of seven kilns were sampled at their lowermost parts (where the fire was hottest) for dating the last thermal resetting by fire, using optical stimulated luminescence (OSL; see the Data Repository). In addition, five in situ kiln charcoal layers and two in situ mangrove stumps were dated by accelerator mass spectrometry ^{14}C (Katka, Gawbonia) and conventional ^{14}C dating (Kuakata).

RESULTS

Kiln Sites

The Katka and Gawbonia kiln sites are affected by severe coastal erosion. At Katka, the mangrove forest covers the coastal strip, containing the typical Sundari tree (*Heritiera fomes*) with its reddish wood and buttress roots. At the shore, a 75-m-wide erosional ramp consisting of grooved stiff mud with numerous in situ roots slopes gently toward the modern tidal mud flat (Fig. 2). Innumerable broken mangrove stems concentrated near the top shore, and a washover fan of fine sands reaching hundreds of meters inshore, are the remains of the destruction of Cyclone Sidr in 2007 (Figs. 1B and 2; Badarinath et al., 2009). The modern root network of the Sundari trees at the study sites is restricted to a level 10 cm above winter spring high-tide level (see the Data Repository). We used this local mangrove land level as a reference (see the Data Repository) for all our elevation data (below modern land level [bmll]). One ancient Sundari mangrove stump horizon spreads at 230 cm bmll over the entire Katka-A area, and another appears at 135 cm bmll in local patches. The stumps at the lower level stick out of the modern tidal flat, and the still–red-colored wood hints to very recent exposure from the anoxic muds.

At Gawbonia, a 15-m-wide coastal ramp covered by soft mud ends at a 0.5-m-high scarp along the edge of a dense mangrove forest. One kiln was exposed along the scarp and several others were barely covered with soft mud on the erosional ramp.

The situation at Kuakata is different, as the original mangrove forest has been changed to rice fields, protected by a 6-m-high dike. In 1999, five kilns were exposed ~2 m bmll on a 30-m-wide muddy erosional surface associated with in situ stumps at the same elevation (the 1999 shoreface and dike have since been eroded).

Kiln Construction and Sea-Level Indications

The kilns were constructed at two particular elevation levels. The 4 × 1 m box kilns consist of two chambers with a common wall along the shorter side (Fig. 1C). The original kiln height of 1 m is preserved at Katka-B. The kilns are embedded in stiff mud and filled with mud interspersed with fired kiln fragments and shards of ornamented brine clay pots. The inner base of each kiln was marked by a 2-cm-thick layer of white sticky ash overlying a prominent charcoal bed (Fig. 1D). The inner sides of the kiln walls are smooth, whereas the outer sides are highly irregular, with decreasing thickness downward. The kiln chambers were originally built by excavating 1-m-high artificial mounds, and the kiln walls were then produced by firing (Fig. 1D). Fifty (50) clay pots with brine were then placed on a systematically perforated clay roof. According to British administration reports (Hamilton, 1853), these kilns were placed just above the winter (i.e., dry season) spring high-tide level, to protect them against seawater inundation. The kilns were surrounded by shallow salt ponds used for solar brine formation, which were flooded only during the few days of winter spring tide. Thus, the kiln bases can be considered as reliable paleo–sea-level indicators, and coincide with the upper ancient mangrove stump horizon (Fig. 2).

Levels of Kiln Bases

At Katka-A, the 13 kilns investigated are located in a 50 × 50 m area. The kiln bases appear at 155 ± 15 cm bmll (Fig. 2). About 650 m north, four Katka-B kilns are located at a spot that is 30 cm higher than the Katka-A reference land level. Their bases occur at 75 cm bmll; i.e., ~80 cm above the coastal Katka-A kilns (Fig. 2). In addition, at Gawbonia, 2 km west of Katka-A, the charcoal base of one kiln occurs at 165 cm bmll, and the other at 70 cm bmll, coinciding with the two Katka kiln base levels. The elevations of the five Kuakata kilns could not be correlated to the Katka sites, but their bases were located between 2.07 m and 1.89 m below the coastal land surface in 1999. Thus, their position seems to be slightly deeper than those at Katka-A.

Dating the Last Kiln Firing, Charcoal, and Mangrove Horizons

Kiln-wall OSL dating of the lower kiln set (Katka-A) reveals a most probable age of the last kiln firing in the range of A.D. 1640–1750, with an average age of A.D. 1705 ± 35 (Table 1).

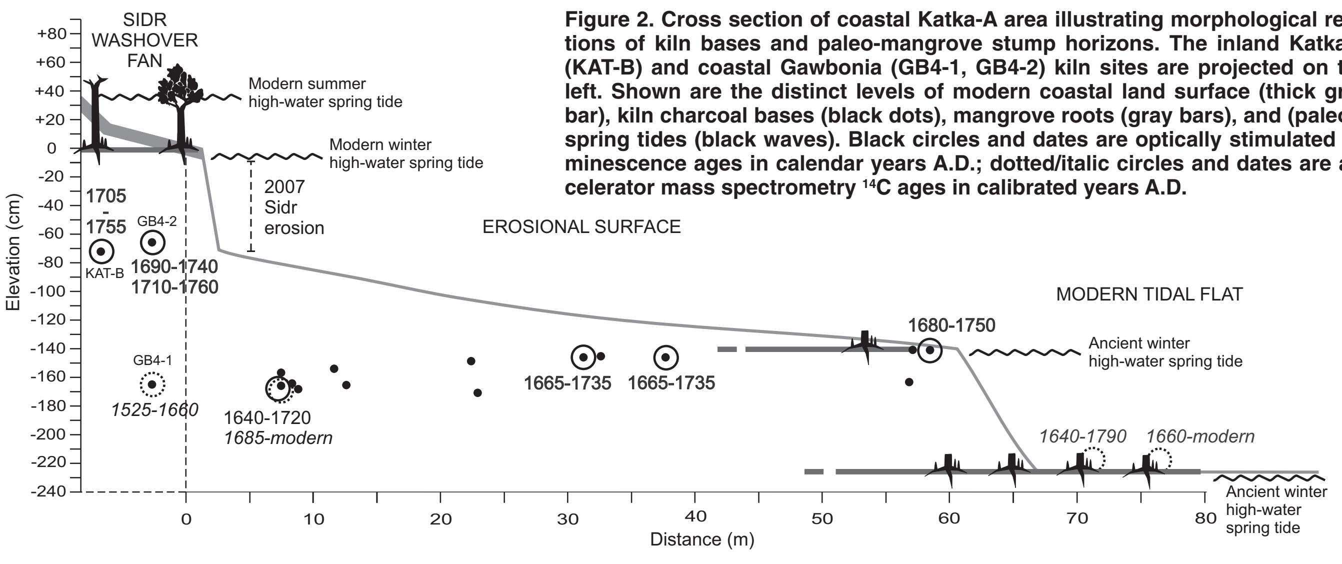

Figure 2. Cross section of coastal Katka-A area illustrating morphological relations of kiln bases and paleo-mangrove stump horizons. The inland Katka-B (KAT-B) and coastal Gawbonia (GB4-1, GB4-2) kiln sites are projected on the left. Shown are the distinct levels of modern coastal land surface (thick gray bar), kiln charcoal bases (black dots), mangrove roots (gray bars), and (paleo–) spring tides (black waves). Black circles and dates are optically stimulated luminescence ages in calendar years A.D.; dotted/italic circles and dates are accelerator mass spectrometry ^{14}C ages in calibrated years A.D.

[1]GSA Data Repository item 2013276, elevation measurement methods, and OSL dating details, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

The Katka-B and the upper Gawbonia kilns, at a higher elevation, show comparable OSL ages. Also, the charcoal at Kuakata has a similar ^{14}C age. The widespread mangrove stump horizon, which is 80 cm under the kiln horizon at Katka-A, produced ^{14}C ages of A.D. 1640–1790 and A.D. 1660 to modern (Table 2). The two stump-^{14}C ages support the OSL ages of the last firing of the kiln. Thus, the last salt production most probably occurred near the transition from the 17th to the 18th century.

TABLE 1. OSL DATING RESULTS FOR FIRED KILN WALLS

Lab code	Sample ID	Elevation of kiln bases (cm bmll)	OSL age (yr)	OSL age transferred to calendar age (yr A.D.)
C-L3050	Kat A-2	146	315 ± 40	1655–1735
C-L3052	Kat A-9	166	330 ± 40	1640–1720
C-L3053	Kat A-11	138	295 ± 35	1680–1750
C-L3054	Kat A-13	147	310 ± 35	1665–1735
C-L3055	Kat B-1	72	280 ± 25	1705–1755
C-L3058	GB 4-2/3	67	270 ± 25	1690–1740
C-L3059	GB 4-2/4a	67	250 ± 25	1710–1760

Note: OSL—optically stimulated luminescence; bmll—below modern land level. All analyses were made on quartz extracts (technical details are available in the Data Repository [see text footnote 1]). Dates were measured at the Cologne Luminescence Laboratory, Institute of Geography at the University of Cologne, Germany.

TABLE 2. RADIOCARBON DATING OF CHARCOAL AND IN SITU MANGROVE STUMPS*

Lab code	Sample ID	Material dated	Elevation (cm bmll)	^{14}C age (yr B.P.)	1σ calibrated age (cal yr A.D)
Hv-23531	Lower kiln Kuakata	Charcoal	2070	120 ± 55	1670–2010
Hv-23532	Upper kiln Kuakata	Charcoal	1890	170 ± 55	1665–2010
Pos-42212	Kat A-9	Charcoal	166	125 ± 30	1685–2010
Pos-42213	GB 4-1	Charcoal	167	275 ± 30	1525–1660
Pos-42214	TT-6	Mangrove stump	226	255 ± 25	1640–1790
Pos-44150	TT-4	Mangrove stump	225	190 ± 40	1660–2010

Note: *Measured at the Poznan Radiocarbon Laboratory, Poland, calibrated with CALIB 6.1.1 (Reimer et al., 2009). bmll—below modern land level; cal—calibrated.

DISCUSSION

Abrupt Flooding of the Former Mangrove Forest and the Salt-Production Sites

The coastline of the Ganges-Brahmaputra Delta is highly dynamic, with general coastal erosion in the west during the past 50 yr (Rahman et al., 2011) and pronounced aggradation in the east during the past 300 yr (Allison 1998). These erosion and accretion patterns are not solely related to vertical movement, but are typical for the rapid coastal reconfigurations occurring in such a fluvial-deltaic environment. Differential subsidence by compaction along the coast, due to variable Holocene sediment thickness and composition, might also be a major local driver, as observed in the Nile Delta (Marriner et al., 2012; Becker and Sultan, 2009).

However, the sudden, simultaneous end of salt production at all kilns, and the successive preservation of the two in situ mangrove stump horizons, cannot be attributed only to the slow, continuous subsidence and sediment aggradation.

In analogy to the dying of the modern mangrove forest between Katka-A and Katka-B caused by the recent cyclonic washover fan, the two former mangrove horizons developed in a stable sedimentary coastal environment, and may have been consequently buried and killed under the sandy washover sediments of tropical cyclones. However, because the stumps were buried by mud, which led to good preservation, and because there is no clean sand filling the kilns, this scenario is not likely. An alternative and more plausible explanation would be a rapid earthquake-related subsidence event with subsequent rapid mud aggradation. Two major regional earthquakes at A.D. 1676 and A.D. 1762 (Iyengar et al., 1999; Cummins, 2007; Steckler et al., 2008; Michels et al., 1998) are potential subsidence events bracketing the death dates of the mangrove forest.

The two kiln levels in Katka-A, Katka-B, and Gawbonia, with a difference of 80 cm in height, have the same last OSL firing date of A.D. 1705 ± 35 AD (Table 1). The two ^{14}C ages of charcoal in the Kuakata kilns indicate that these kilns could also have been last used at this same time. The older range of ^{14}C ages from the kiln charcoal at Katka, Gawbonia, and Kuakata generally confirms the OSL ultimate kiln firing date, as the wood used for the charcoal could only have grown well before this date; i.e., a few decades before A.D. 1705 (drying the wood and producing charcoal might also have added a few years). Furthermore, the fires in all the kilns had been abruptly extinguished, because considerable charcoal layers are preserved near the kiln hearth. The ash accumulation in one kiln corner might hint at a rapid flooding of the kilns. The collapse of the salt-producing industry was probably caused by a major catastrophic cyclone storm surge, which destroyed the kilns and brine ponds and killed people. The closest event coinciding with the kiln extinction around A.D. 1705 (in its uncertainties) is a tropical cyclone reported for the eastern Sundarbans at A.D. 1699, which had at least 50,000 casualties (SMRC, 1998).

Summing up, the field evidence and age data can be plausibly explained by a succession of earthquake-related abrupt subsidence and cyclonic flooding events. However, the effects and the exact timing of these two different mechanisms cannot be reliably differentiated. In addition, long-term continuous land lowering due to compaction and subsidence effects must be assumed, but the amount of such lowering cannot be extracted from our data.

Calculating the Subsidence Rate for the Past 300 Years

Independent of the sinking scenario, our new data allow for a precise subsidence calculation. The lower kiln base level subsided by 155 ± 20 cm in 305 ± 35 yr (A.D. 1705 ± 35) resulting in an SL_{Ind} (sinking of paleo–sea-level indicator level) rate of 5.2 ± 1.2 mm/yr. The lower mangrove root horizon subsided by 230 ± 10 cm in a maximum of 360 yr (A.D. 1650), resulting in a minimum subsidence rate of ~6.4 mm/yr. The S_{land} (land subsidence) is a combination of (1) long-term tectonic subsidence, (2) a component linked to sediment compaction and decay of peat (extraction of groundwater can be excluded here), and (3) a component that is caused by eustatic sea-level (ESL) rise. Previous studies have shown that significant subsidence or a RSL rise has taken place over the entire Holocene based on sediment accumulation rates of 2–4 mm/yr for the central delta plain (Goodbred and Kuehl, 2000a), 1–4 mm/yr for the eastern Sundarbans outer delta plain (Allison and Kepple, 2001), and ≤5 mm/yr for the western Sundarbans (Stanley and Hait, 2000). Modern GPS data (A.D. 2003–2008) suggest higher subsidence rates of up to 12.2 mm/yr for the Dhaka area, although an anthropogenic effect from massive groundwater extraction is probable here (Steckler et al., 2010). Subsidence rates seem to vary remarkably on the local scale, but all studies indicate persistent sinking. Our paleo–sea-level indicators for the past 300 yr are complementary to the onshore sediment aggradation rates, which are interpolated over time scales of several thousand years. By applying the equation $S_{land} = SL_{Ind} - ESL$, the land subsidence can be estimated.

Global sea level is considered to have been stable during the 18th century, while an overall eustatic rise of 60 mm in the 19th century and 190 mm in the 20th century is assumed (Church and White, 2006; Jevrejeva et al., 2008). Thus, an ESL rise of 250 mm needs to be subtracted from the coastal Sundarbans S_{Ind}. Accordingly, an S_{land} rate of 4.1 ± 1.1 mm/yr for the lower kiln base level, and a minimum of 5.7 mm/yr for the lower mangrove root horizon, are calculated for the past 300 and 360 yr, respectively.

CONCLUSIONS

Reasonably postulating that the S_{land} rate will not change during the next few decades, and accepting the estimates of current sea-level rise of 1.8–3.0 mm/yr (Church and White, 2006) or 2.7–7.1 mm/yr (Syvitski et al., 2009), a RSL rise of 6.4 ± 1.7 mm/yr or 8.9 ± 3.3 mm/yr, respectively, must be assumed along the Sundarbans coasts.

Modern ^{137}Cs-based sediment accumulation rates of ~3.7 mm/yr on average (locally ranging from 0.0 to 11.3 mm/yr; Allison and Kepple, 2001) are comparable to Holocene average accumulation rates of 2–5 mm/yr (1.3–7.0 mm/yr maximum range; Goodbred and Kuehl, 2000a; Stanley and Hait, 2000; Allison and Kepple, 2001). This long-term aggradation process was obviously in overall balance with land subsidence. Our new land-lowering rates for the central coasts of Bangladesh plus the present and future ESL rise of similar range, in combination with adverse anthropogenic damming and dike effects (Syvitski et al., 2009), suggest that the future defense of the lower delta plain will be a great challenge.

The southern Ganges-Brahmaputra Delta is densely populated (143 million inhabitants in the entire delta, 2.5 million in the Sundarbans surroundings, and 2.2 million in the two coastal districts Barguna and Patuakhali located east of the Sundarbans). Subsidence of this specific coastal area by 5–6 mm/yr in combination with future sea-level rise will lead to enhanced saltwater intrusion, worsen the effects of storm surges, and reduce the arable areas, as well as reduce the drainage during monsoon flooding (cf. Han and Webster, 2002; Karim and Mimura, 2008).

This study has documented the rapid burial and abrupt abandonment of a former large industrial coastal complex. The present protection of the coastal delta zones (except the Sundarbans) by dikes has almost completely stopped new land aggradation inside the polders, whereas the land continues to aggrade in the undiked Sundarbans (Allison and Kepple, 2001). In areas of high subsidence rates, such as the study area, and on time scales of hundreds of years, it will be increasingly difficult to drain the polders, as well as protect them against storm surges. Thus, a controlled sedimentation system is needed to keep the southern part of Bangladesh above sea level and in habitable form.

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