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Sea-Level Rise Tipping Point of Delta Survival

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ABSTRACT

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The estimated rate of global eustatic sea-level rise (RSLR) associated with the formation of 36 of the world's coastal deltas was calculated for the last 22,000 years. These deltas are located in a variety of environmental settings with respect to tidal range, isostasy, and climate. After correcting the original uncalibrated radiocarbon age estimates to calibrated years, 90% of the deltas appear to have formed at an average age of 8109 ± 122 before present (BP) and a median age of 7967 BP. This age corresponds to a period of significant deceleration in the RSLR to between 5 mm y^{-1} and 10 mm y^{-1}, and is in agreement with two regional estimates of vegetation growth limits with respect to RSLR. This RSLR tipping point for delta formation can be used to inform forecasts of delta resiliency under conditions of climate change and concomitant SLR. The RSLR is accelerating and will likely be several times higher than the formation tipping point by the end of this century. Hence, the world's deltaic environments are likely to be lost within the same time frame.

ADDITIONAL INDEX WORDS: *River deltas, delta formation, climate change.*

INTRODUCTION

A conspicuous co-occurrence of the inception of modern deltas worldwide was a dramatic reduction in the rate of global eustatic sea-level rise (RSLR) after the abrupt climatic event of 8400–8000 calendar years ago (the "8.2-ka event"). The conditions of delta formation were further enhanced by the presence of huge accommodation spaces that had largely developed along continental trailing edge margins during the early Holocene marine transgression. A sharp global cooling started about 8247 before present (BP), and an enormous volume of freshwater entered the North Atlantic (Hijma and Cohen, 2010; Thomas *et al*., 2016). This incipient rise in delta growth was not related to global changes in rainfall, because vegetation cover and runoff were different among deltas, and there were different sediment loading rates in different watersheds. Precipitation after the 8.2-ka event, for example, was highly variable at a regional scale, with some areas in the Southwest United States, China, and Africa becoming drier (Guo, Petit-Maire, and Kröpelin, 2000; Holliday, 1989), but wetter in Europe, Lake Baikal, and northwestern China (Demskse *et al*., 2005; Kalisa, Merkt, and Wunderlich, 2003; Zhang *et al*., 2000). After the 8.2-ka event, delta formation began relatively quickly once the dynamic balance – or tipping point – between sediment supply, erosion, and RSLR shifted to favor coastal progradation (Stanley and Warne, 1994). Thereafter, deltas assumed a variety of geomorphic forms in response to regional variations in riverine sediment supply, wave and tidal conditions, and climatic regimes.

Civilizations developed along river deltas (Pennington, Bunbury, and Hovius, 2016), and today their population is >351 million, and the deltaic freshwater and sediment discharge is 39% and 50%, respectively, of the global amount (Syvitski and Saito, 2007). An extensive agricultural system has developed within deltas and many are global trade centers.

Sea levels worldwide began to accelerate after 1930, more than double the previous rate of the first decades of the century, and are predicted to accelerate in the future (Church and White, 2006). What was the RSLR when these modern deltas formed? Can this information inform us about when accelerating SLR will lead to their demise? In this investigation, the published radiocarbon ages of modern deltas were corrected to reflect isotopic fractionation, compared with contemporary RSLR, and discussed in terms of future tipping points.

METHODS

The inception of modern delta formation was estimated in the notable Smithsonian survey of >50 modern deltas by Stanley and Warne (1994). Their radiocarbon ages were not corrected to account for fractionation of carbon isotopes ^{13}C and ^{12}C because of changes in carbon cycling and cosmic ray flux and do not represent calendar years. Herein the Stanley and Warne (1994) data are corrected to reflect fractionation and the new ages are compared with contemporary SLR rates (as

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Figure 1. Location of the deltas aged by Stanley and Warne (1994).

determined by coral dating) to identify a SLR tipping point of delta initiation.

The formation ages of 36 deltas (Figure 1) compiled by Stanley and Warne (1994) were recalibrated using the online model of the Intcal.13 curve by OxCal (https://c14.arch.ox.ac.uk/oxcal/OxCal.html; Bronk Ramsey, 2008, 2009; Bronk Ramsey and Lee, 2013). This commonly-used model uses tree rings, plant macrofossils, speleothems, corals, and foraminifera to determine the conversion from uncalibrated to calibrated age. The reported dates are relative to 1950 BP. The original data and the calibrated estimates are in the Supplementary Materials. The percent frequency of deltas formed within 500-year intervals was calculated from 22,000 BP to present.

The corrected dates of formation were compared with the late Quaternary submergence history represented by three sea-level curves. The first curve used is a reconstructed sea level created by R.A. Rohde (http://www.globalwarmingart.com/wiki/File:Post-Glacial_Sea_Level_png). The data displayed in this graph are from the well-cited synthesis of calibrated dating of coral samples by Fleming *et al.* (1998). Fleming *et al.* (1998) quantified global eustatic SLR after correcting for glaciohydro-isostatic contributions using ice distribution and models that included earth rheology. This graph was used to quantify the RSLR (mm y^{-1}) over four time intervals for before and after the peak in global delta formation. The intervals are on the original source: 7500 to 7000 BP (3.2-m difference), 7000 to 4000 BP (2.6-m difference), 7000 to 0 BP (4-m difference), and 8000 to 11,000 BP (50-m difference). The 11,000 BP date is identifiable as the beginning of the last rapid rise in sea level, preceding the slowdown around 7500 to 7000 BP.

The second sea-level curve was established using ^{14}C and thermal ionization mass spectrometric U-Th methods to date 145 coral and intertidal peat samples collected from the Caribbean (table 4 from Toscano and Macintyre [2003]).

The third sea-level curve is from Sloss, Murray-Wallace, and Jones (2007), and is based upon data from tectonically stable regions of New South Wales, Australia.

The RSLR was determined for each of these data sets and plotted against the estimated age of delta formation to assess potential relationships.

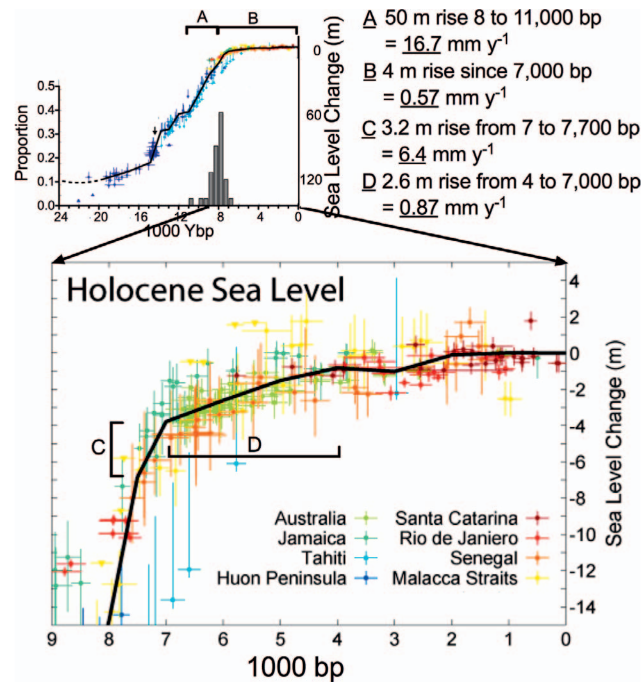

Figure 2. Initiation ages for the world's river deltas and sea level. The proportion of 33 deltas formed in 500-y intervals (gray, binned data) overlie sea-level height from 24,000 BP to present. The average age of all deltas is 8109 ± 122 y (calibrated to a 1950 baseline). Sea level at four intervals is shown: (A) From 8000 to 11,000 BP; (B) from 7000 BP to present; (C) from 7000 to 7700 BP; (D) from 7000 to 4000 BP. The initiation age is at the hinge point where sea-level rise slowed dramatically between (A) and (B) in the top figure, or (C) and (D) in the bottom figure. The colored figure of sea level is from http://www.globalwarmingart.com/wiki/File:Post-Glacial_Sea_Level_png.

RESULTS

The corrected estimate of radiocarbon ages of modern delta formation yielded a mean of 8109 ± 122 BP ago ($n = 36$; $\mu \pm 1$ SEM), and a median age of 7967 BP. The formation of 33 of the 36 deltas included in this assessment began between 9000 and 7000 BP (Figure 2). The most precise estimate of the SLR in the Atlantic Ocean at the time of delta formation is from Toscano and Macintyre (2003), who provided data suitable for estimating RSLR for just before and after delta formation: 5.5 and 4.8 mm y^{-1}, respectively (Figure 3). Their estimate is lower than that from the less-detailed SLR estimates of Sloss, Murray-Wallace, and Jones (2007) for the slightly younger Pacific Ocean deltas of 10 mm y^{-1} during delta formation, and is less than 6 mm y^{-1} for the 500-year binned data. These formation ages are coincidental with the deacceleration of RSLR observed in all three curves (Figures 2 and 3). As estimated, worldwide deltaic formation initiated when the RSLR decelerated by 50% (10 mm y^{-1}) to 75% (5 mm y^{-1}) during the early Holocene.

DISCUSSION

On the basis of the data reviewed in this study, the world's deltas formed in association with the 8.2-ka event when the RSLR slowed to between 5 and 10 mm y^{-1}. An exact coincidence

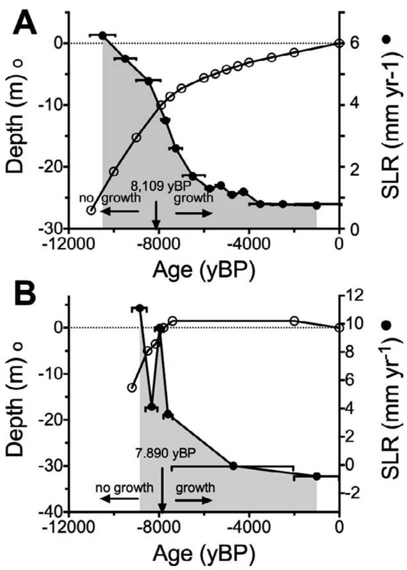

Figure 3. The sea level (m) and rise (mm y^{-1}) for two data sets. (A) The age vs. depth (m) curve for 145 Caribbean coral and peat samples calculated with ^{14}C dates for the last 11,000 y for 14 intervals (left *y*-axis; from Toscano and Macintyre, 2003, table 4). The calculated sea-level rise (right *y*-axis; mm y^{-1}) is the shaded area. (B) The age vs. depth (m) curve for 151 radiocarbon and 50 amino acid racemization-derived ages on fossil molluscs, peat, mangrove roots, and organic-rich facies in New South Wales, Australia (from data in Sloss, Murray-Wallace, and Jones, 2007). The calculated sea-level rise (right *y*-axis; mm y^{-1}) is the shaded area. The vertical arrow is the average formation date for only Pacific Ocean deltas represented in the recalibrated Stanley and Warne (1994) data set.

of a decelerating RSLR and the initiation of all deltas is not expected, if only because of measurement error or sampling variations. There appears to be, for example, a 100-year delay in SLR between delta growth in the Rhine and Mississippi river deltas (Hijma and Cohen, 2010). However, the concurrence of a slowing RSLR and delta formation is close enough to suggest a strong causal significance.

If most modern deltas initiated when the RSLR fell below a critical value or tipping point, then the reverse is likely true; the world's marine deltas, broadly speaking, will begin to collapse when the forecasted RSLR exceeds this tipping point. There is evidence that this will occur when the RSLR reaches between 5 and 10 mm y^{-1}. Morris *et al*. (2016), for example, conducted an empirically based modern modeling analysis of 5075 samples from 33 salt marshes; they estimated that the maximum combined mineral and organic accretion rate for salt marshes before failure was about 5 mm y^{-1}. Their upper threshold is similar to the $>$5–6 mm y^{-1} tipping point suggested in Figures 2 and 3. Also, Fujimoto *et al*. (1996) estimated that the limit of organic accretion for Pacific mangroves was between 2 and 10 mm y^{-1}, and Watson *et al*. (2017) declared that the future of RSLR had already arrived in New England salt marshes where recent SLR rates over the last 19 years were 4 to 6 mm y^{-1} and salt marsh losses over the last 3 to 4 decades were 0.4 to 0.44% y^{-1}. The rate of delta collapse later this century may be much faster than that of delta initiation during the mid-Holocene. The Nile Delta has retrograded more quickly than it likely prograded, spawning barrier and spit growth from longshore transport at its flanks (Smith and Abdel-Kader, 1988). The shape of the accommodation space and its fill rate was determined by winds, current, waves, shelf slope, and sediment supply, and will surely affect the geomorphology and rate during any inland retreat.

Predicting the effect of contemporary stressors and future RSLR variations on tidal characteristics is challenging (Hoitink and Jay, 2016). Ongoing dune formation and overwash from erosion of the delta front and recycling and reworking of the remaining sands could slow the retreat rate by dampening waves from offshore winds. In any case, the evolution of macrotidal estuaries with SLR, increased fluvial sediment inflow, and river damming is expected to be measured in decades, not centuries (Wolanksi, 2006). One example of what happens with reduced sediment supply is the 40–50-year growth phase after European colonial land clearing increased sediment loading in the Mississippi River. Once clearing was complete, the rate of sedimentation fell because of soil conservation measures and sediment trapping behind newly constructed dams (Tweel and Turner, 2012). Plants that had established in shallow depths over decades disappeared in fewer years than it took to establish them. The retreat of the river deltas along the sea-level curve in Figure 2 will not be a mirror image of the ascent (land gain/progradation) because of differences in soil organic content. Caribbean mangrove wetlands have persisted for thousands of years with only trace amounts of inorganics in them (McKee, Cahoon, and Feller, 2017).

The question is then: when might the modern deltas collapse? Projections by the U.S. National Research Council (2010) suggested an "intermediate low" and "high" level of RSLR during the 21st century to be between 5.6 and 16 mm y^{-1}, respectively. Church *et al*. (2014), the authors of the Intergovernmental Panel on Climate Change Working Group I Fifth Assessment Report (IPCC WGI AR5) chapter on "Sea-Level Change," projected that the RSLR would "likely" be 8 to 16 mm y^{-1} for 2080 to 2100. They noted, "In the calibrated uncertainty language of the IPCC, this assessed likelihood means that there is roughly a one-third probability that sea-level rise by 2100 may lie outside of the 'likely' range, whose minimum is about 50% above the rate before the deltas formed. The AR5 did not exclude the possibility of higher sea levels." The report also stated: "The upper boundary of the AR5 'likely range should not be misconstrued as a worst-case upper limit." A recent update projects an intermediate, high, and extreme SLR of 10, 20, and 25 mm y^{-1}, respectively, by 2050, and 15, 35, and 44 mm y^{-1}, respectively, by the end of the century (Sweet *et al*., 2017).

The range of factors influencing the worldwide RSLR is only beginning to be accurately quantified. It is prudent to acknowledge, for example, that the IPCC estimates of RSLR and temperature change likely underestimate what might eventually occur (Horton *et al*., 2014). The "likely" range from the IPCC AR5 chapter did not include the melting of the Twaite ice sheet in Antarctica. It now seems, on the basis of the estimates from two different teams of scientists, that the long-feared collapse of the Antarctica Ice Sheet has started, beginning what will be a centuries-long "unstoppable" process that could raise sea levels further (Joughin, Smith, and Medley, 2014; Rignot *et al*., 2014).

For perspective, note that the average global rate of RSLR from 1993 to 2010 was $\sim$3 mm y^{-1} (Cazenave and Llovel, 2010; Hay *et al*., 2015; Holgate, 2007; NOAA, 2010). Note also that the variability in decadal sea-level changes is increasing (Holgate, 2007). The U.S. Northeast Atlantic Coast, for example, experienced a 1-in-850-year sea-level high stand during 2009–2010 when sea levels jumped 128 mm (Goddard *et al*., 2014). Any worst-case scenario forecast for the sea-level future – and delta survival – could, therefore, be a gross underestimate if multiple RSLR-increasing factors were to co-occur. Quantifying the likelihood of such a convergence is daunting. Even if a given sea-level phenomenon (*e.g*., exceptional sea-level high stands) were to occur more regularly, it will not be certain that each occurrence is a response to the same factors, or that the same factors will again occur under different futures.

It may be too late to stop an acceleration in the rate of global SLR, and the thermal inertia of the oceans might exceed any potential mitigation measures. Moreover, if the present is any guide, then the future of global sea-level change will likely not be monotonic. Tessler *et al*. (2015) recently mapped the "risk space" for the world's major marine deltas using information and forecasts from physical, human, and socioeconomic contexts. The authors acknowledge that gaps remain in understanding the geophysical factors underpinning global and regional relative sea-level trends, but suggest that leveraging economic and engineering resources will eventually determine delta sustainability.

Coastal construction works best when the process to be ameliorated is defined both in magnitude and frequency, and the needed resources are allocated and applied in a framework of national consensus. The long struggle of the Dutch in confronting RSLR is testimony that an unrelenting focus of will and material can temporarily sustain low-elevation deltaic landscapes (in this case the Rhine–Meuse–Scheldt delta complex). Whatever were the impacts of the Little Ice Age on the shores of The Netherlands from increased storminess in the North Sea, centuries of low global RSLR gave the Dutch time to develop solutions and deploy them – a luxury that will not come again soon. The process of deltaic decay may exceed the adaptation rate of human societies.

CONCLUSIONS

Geologic data suggest that the tipping point between modern delta resilience and collapse will likely occur in the next 50 years as the RSLR reaches between 5 and 10 mm y^{-1}. These changes to the existing coastal geomorphology will have regional, national, and international repercussions, occur nearly concurrently, and will compromise existing trade networks, settlements, and ecosystems. "There are better options for policy-makers than to play wait-and-see (Oppenheimer and Alley, 2016)."

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