Dear Dan,

On behalf of my co-authors and myself I submit our revised manuscript. Below are the collated responses to the comments from reviewers followed by a markedup manuscript version. We strived to address all comments carefully and to the point.

Thank you for your help in editing this work.

Sincerely,
Liviu Giosan

RESPONSE Reviewer 1

We appreciate the thorough review by Tor Törnqvist (in Arial, bold and italics) and provide our response below.

REFEREE: ***Giosan et al. present new field data from one of the least studied large deltas on the planet. As such, this is a potentially useful contribution that might serve as a launching pad for more detailed future investigations. While I appreciate the challenges of working in a relatively remote and underexplored delta, the dataset presented here is very modest in size. As a result, several of the interpretations are tenuous, as detailed further below.***

RESPONSE: Indeed we wrote this paper not to address specific problems in the Ayeyawady delta but to provide a basis for and highlight future lines of enquiry in a region little known before. In our revision we try to make this point clearer and provide interpretations with the proper degree of uncertainty suitable at this stage.

REFEREE: ***A significant portion of the study relies on geochronology, including a set of new OSL ages. OSL dating in these geologically young terranes has often proven to be challenging, as exemplified by the nearby Ganges-Brahmaputra Delta where OSL chronologies have been notoriously problematic (but see a recent paper by Chamberlain et al., 2017, QG). Conditions in the Ayeyawady drainage basin may be different, however – something that would be worth addressing. For example, the authors might consider including some OSL decay curves to illustrate the dominance of the fast component in their quartz sands. Nevertheless, without verification of the OSL ages by means of independently obtained dating results (either historical ages or from other radiometric techniques), some caution is probably in order.***

RESPONSE: We appreciate the heads up on the recent paper by Chamberlain et al. The problems raised by the reviewer may apply to the fluvial sediments that we dated (levee samples). Nevertheless, all samples dated, fluvial and bech ridge, are dominated by the fast component. We provide an example in the revised supplementary data.

REFEREE: ***Setting these concerns aside, the stratigraphic context of the two OSL samples from natural levee-deposits near the delta apex is not well documented, preventing the reader from fully assessing their interpretation. The map (Fig. 2c) shows sample locations with respect to the surface morphology (including what appears to be oxbows) and the tables indicate the depth of the samples below the land surface. What is needed here is some subsurface information (i.e., cross sections) that shows the geometry and extent of the natural-levee deposits. With the information presented, all one can infer is that overbank deposition occurred around 1.5 ka. Likewise, a 14C dated wood trunk in a point bar doesn't really constrain anything. Assuming that it is contemporaneous with the point-bar deposits (which is by no means certain), the only thing it would reveal is that the point bar was actively forming at that time. When the associated channel belt started to form is an entirely different issue. Note that a rigorous sampling strategy is needed to determine the beginning and end of activity of channel belts in such settings; this would require considerably more subsurface data than presently available. Without such data, inferring avulsions remains a guessing game.***

RESPONSE: Our sampling strategy was exploratory and suited to the field context and lack of accessibility due to habitation on delta highlands like fossil ridges and levees. But we agree with the reviewer that the presentation and interpretation can be improved on. Samples were taken from the top of levees to access the latest sediments deposited and deep enough to be undisturbed by human activity. We added text to explain this subsurface context. Indeed dating the inception of channel belt is not achievable with the strategy employed and was never our intention, as we now make clear. However, dating the activity on the youngest levee of a channel belt provides a limiting date for the abandonment of that belt. All dated sites have already been provided since the initial submission with lat-long information. We could include zoomed-in Google Earth images of the locations in the supplementary if the editor suggests it but readers can easily visualize locations at the resolution they need using information from Table 2.

REFEREE: ***On the other hand, the interpretation of the beach ridge geochronology should be a little more straightforward. The possible temporal correlation of the oldest beach ridges with those in other SE Asian deltas is an interesting phenomenon to point out, even though the interpretation of potential causes must probably remain somewhat speculative at this point.***

RESPONSE: Indeed the interpretation provided is a starting point that will be explored in detail in the future.

REFEREE: ***Within this context, I would suggest the authors consider what may be a much simpler explanation. Assuming that modern sea levels in this part of the world were approached around 5000 years ago, I wonder how one can rule out that older beach ridges exist but are simply buried in the subsurface.***

RESPONSE: We are not clear what this comment means exactly. Based on previous reconstructions in South and Southeast Asia the sea level in the region most likely had an early to mid Holocene highstand above than present level. Based on the drill record at Kyonmangay the delta already reached there at that time. If they existed, older beach ridges would have been located more inland. Based on the morphology of the delta plain significant fluvial accretion that could lead to burial is limited to meander belt regions near the two main courses of the river well upstream of Kyonmangay. With sea level since 5000 years ago falling it is hard to envision burial of ridges on the delta plain south of Kyonmangay to the latitude of Labutte where the first ridge was dated at ~4.6 ka. Published work cited by us for other deltas in the region that show ridges establishing themselves in late Holocene also do not indicate signs of burial.

REFEREE: ***Returning to the inferred avulsion, it should be noted that avulsion is fundamentally an autogenic process, even though it can sometimes be triggered by allogenic forcing. Therefore, it seems unnecessary to invoke such mechanisms to explain a single avulsion. Given the overall setting that the authors describe (one with substantial Holocene aggradation) it is to be fully expected that many avulsions have occurred in this delta.***

RESPONSE: We agree with the reviewer on this point as we fully expect that the river avulsed many times during the construction of its Holocene delta. Nevertheless we refer to its last major avulsion that is indicated by the existence of the two alluvial ridges, one of which is now abandoned as a result. However, we removed the more speculative aspects of the story on the allogenic forcing, leaving it for future work.

REFEREE: ***The inferences about subsidence rates beneath the Ayeyawady Delta based on comparison with the Lambeck et al. (2014) sea-level curve (lines 490-494) are untenable. If the authors want to compare their mangrove-based sample with a globally averaged sea-level curve in a meaningful way, they need to remove the effects of glacial isostatic adjustment that are significant virtually everywhere (see, e.g., Milne & Mitrovica, 2008, QSR). For example, hydro-isostatic effects (also known as continental levering) are potentially substantial along continental margins such as this one. In other words, accounting for these effects would require GIA modeling. Besides, inferring vertical stability in such a tectonically active setting seems like a dangerous proposition in the first***

place. And finally, the mangrove peat is unlikely to be compaction-free since it is not a basal peat (see below).

RESPONSE: The reviewer is correct. A recent paper looking at GIA component in nearby regions does suggest subsidence and show a mid Holocene highstand. On the other hand preservation of deltaic beach ridges of late Holocene age argue for relative stability. We have rewritten the text to nuance our interpretation and eliminated the mention to stability from the conclusion and abstract.

REFEREE: ***The supplementary information seems short enough that it could easily be incorporated in the main text. Otherwise, the manuscript is very long and could be shortened considerably without much loss of information.***

RESPONSE: The revised supplementary has now more info that can be accessed by readers interested in data. However, we tend to disagree with the reviewer on the length of the manuscript. We ran an informal test on other colleagues on this point and they appreciated the comprehensiveness of the paper for a region that is little studied. Given that the journal has no printed version we see no reason to significantly shorten it but we'll do so if the editor suggests it.

REFEREE: ***Lines 93-94: most readers are probably unfamiliar with these regional historic periods.***

RESPONSE: We provided more info in the revision.

REFEREE: ***Line 278: "meandering belts" should be "meander belts" (or better yet, the more generic "channel belts").***

RESPONSE: Fixed.

REFEREE: ***Lines 387-388: "lower delta plain" is a more widely used term in this context than "outer delta".***

RESPONSE: Fixed.

REFEREE: ***Lines 392-393: or, alternatively, they have simply not been active very long.***

RESPONSE: Fixed.

REFEREE: ***Lines 410-411: note that basal peat is defined as immediately overlying a consolidated (commonly Pleistocene) basement. In this case, one would assume that weakly laminated muds are Holocene in age, which makes the mangrove peat an intercalated peatbed.***

RESPONSE: We debated this among ourselves as the muds are fluvial, freshwater in nature, rather than strictly marine mudflats. The text was modified to correct it based on the point made by the reviewer.

REFEREE: ***Line 484: while it is conceivable that there is such a thing as a paleovalley in the subsurface, it is a bit uneasy to just state this with no supporting evidence. I suggest some rewording, here and elsewhere.***

RESPONSE: We disagree with this view: our drill sites indicate the base of the Holocene below the present sea level. Based on what is know about the geodynamics and climate of the region we see no reason for a sediment-rich river like Irrawaddy not to have built a delta at any time during Pleistocene highstands most of which were higher than the present sea level. Pleistocene sediments have been described in oil exploration boreholes across the delta at greater depths than the present sea level. They are not differentiated at higher resolution age intervals in an attempt to delineate the valley at this time as we would have liked.

REFEREE: ***Line 500: this looks like simple autogenic channel scour to me. Note that "erosion event" might be misconstrued by the reader to reflect floodplain degradation on a wider scale.***

RESPONSE: Fixed.

REFEREE: ***Line 519: since these are said to be rates, I suppose this should be m/yr or something of the like?***

RESPONSE: Fixed.

REFEREE: ***Fig. 1: please indicate the drainage basin of the Ayeyawady River; this is important, among others, in view of the comments above about OSL dating. A scale bar would be helpful too.***

RESPONSE: Fixed.

REFEREE: ***Fig. 3: the interpreted depositional environments include terms that are not mutually exclusive (e.g., floodplains are fluvial).***

RESPONSE: Fixed.

RESPONSE Reviewer 2

We appreciate very much the pioneering context provided by Dr. Rodolfo as well as his thorough review (in Arial, red) and provide our response below.

REFEREE: ***The paper is a valuable analysis of the evolution of the Ayeyarwady and deserves publication after major revision. It is too long, and in need of editorial polish; for example, some references give the publication year after the author name(s), others give the year at the very end. The text and figures also need to be better coordinated.***

RESPONSE: Like in our response for Reviewer 1 we rather disagree with the reviewer on the length of the manuscript. An informal test on colleagues on this point suggest that readers appreciated its comprehensiveness with the context of a relative lack of information for the region. Given that the journal has no print version we see no strong reason to significantly shorten the text but we'll do so if the editor suggests it. We did try to streamline the text in the revised version but addition of new information kept it as long as before.

Editorial comments are appreciated and we will make sure that references will be in perfect order when we submit the final manuscript for publication.

REFEREE: ***Line 1 ff.: In the recent literature, the Irrawaddy has been variously renamed the Ayeyawady, as in this paper, but, more commonly, the Ayeyarwady, (e.g, cf. references in this paper: Brakenridge 2017; Damodararao 2016; Furuichi et al. 2009; Ramaswami et al. 2004; and Rao et al. 2005). Perhaps, to be internally consistent, can this paper use "Ayeyarwady, which is phonetically closer to "Irrawaddy" anyway?***

RESPONSE: We used the official name for the river in Myanmar while identifying its previous name (Irrawaddy) at the beginning of the text. We now identify Ayeyarwady at the same location as well.

REFEREE: ***80 Change "coagulate" to "congregate".***

RESPONSE: Done.

REFEREE: ***83 economic***

RESPONSE: Fixed.

REFEREE: ***93-9 Pyu, Bagan, and Ava historical periods are not defined and not well-known. Perhaps give the time spans of each in parentheses?***

RESPONSE: Done.

REFEREE: ***124-137 and Figure 1: A string of prominent Quaternary basaltic to basaltic-andesite volcanoes and associated volcanic plugs longitudinally bisects the Central Myanmar Basin, from Mt. Loimye at Lat. 26N in the north to Mt. Popa at about Lat. 21N. (see Lee et al., 2016, Late Cenozoic volcanism in central Myanmar: Geochemical characteristics and geodynamic significance, Lithos 245 p. 174-190). Popa rises more than 1.5 km above sea level and experienced Strombolian eruptions. At the very least, the volcanoes are tectonically significant enough to deserve inclusion in Figure 1, especially given that the figure shows the older volcanic rocks along the east of the CMB. Might these younger volcanoes have sedimentologic and geochemical significance as well?***

RESPONSE: The Cretaceous-Paleogene volcanics in the CMB were indeed missing in Fig 1. We have now added them, indicated the location of Mount Popa on the physiographic map and also added info in the text.

REFEREE: ***125 Oligocene/Early Miocene time***

RESPONSE: Fixed.

REFEREE: ***135 and Figures 1 and 5: The control of the Sagaing Fault on both tectonics and sedimentation requires that it be plotted more accurately, especially offshore. This is especially true in Figure 5. Figure 1 of Rao et al. (2005) plots the fault offshore, well to the west of where Figure 5 of Giosan et al. does, showing how strongly it divides sedimentation style. Plotted this way will give Figure 5 much more sense.***

RESPONSE: We used the most detailed depiction available of the offshore faults from Morley (2017). The splays from the Sagaing fault do indeed divide the shelf sedimentation styles.

REFEREE: ***(Lines 535- 585 probably need to emphasize the role of the fault as well.)***

RESPONSE: Done.

REFEREE: ***162: “sync” is not a valid word. Instead of “in sync” say “synchronously”***

RESPONSE: Fixed.

REFEREE: ***200-203 “Despite the large fluvial sediment load of the combined Ayeyawady and Sittaung delivered annually (350–201 480 106 t), shoreline changes have been puzzlingly minor along the Ayeyawady delta coast since 1850 (Hedley et al., 2010).” Perhaps the main reason is because most of the sediment, driven eastward into the Gulf of Mottama by the prevailing***

westerly currents during the southwest monsoon of maximum runoff and sediment discharge, does not stay there, but moves southward to depositional sites on the outer delta shelf, 60 to 100 km south of the Gulf of Mottama (Rodolfo, 1975). The role of contrasting tidal currents off the eastern and western delta, described in lines 559 ff. of Giosan et al. is very instructive.

RESPONSE: That is very good point that we intended but failed to make. The sediment dynamics on the shelf is certainly complex and should make the subject of future studies. We added now the suggestion in text

REFEREE: ***Taking the opportunity to cite a researcher even older than I am: H. L. Chhibber (1934, The Geology of Burma. Macmillan, London, 538 pp) compared bathymetric charts of the Marine Survey of India compiled from 1854-1859 and 1903-1910 to calculate miles of seaward advance of the 3, 5, 10, and 20 fathom isobaths off the western lobe and in the Gulf of Martaban. (Table 2A of Rodolfo 1975 gives his data with their metric equivalents.) Off the western delta he reported about 4 km/100y with no consistent trend with depth. In contrast, rates of advance in the Gulf of Mottama increased steadily with offshore distance and depth, from 8 km/100y for the 5-fathom (9.1 m) isobath to 56 km/100y for the 20 fathom (36.6 m) isobath. Unfortunately, he had no deeper data, for none were necessary for most marine traffic at the time. I also compared the 1854-1859 survey with the bathymetry measured by the PIONEER and the survey ship USN SERRANO from 1960 to 1964, and by the OCEANOGRAPHER in 1967. Again, starting 60 to 140 km off the Gulf of Mottama coast, isobaths advanced increasingly more rapidly seaward, from 24 km/100y closer to shore to as fast as 56 km/100y offshore. The corresponding net shoaling in that zone ranges seaward from 5 to 60 m during the century between data sets.***

RESPONSE: We have explored this interesting avenue during our study but unfortunately found that the reconstruction by Chhibber is likely incorrect due to the poor coverage of the earlier survey. Data available from the Pioneer, Serrano, and Oceanographer is also limited to a few of lines on the inner and mid shelf compared to the outer shelf and do not allow for a good comparison. The only core on the Mottama clinoform that has been dated (we added this info in the text) does not support such extreme rates of accretion. As a result we prefer to refrain at the moment in speculating about this issue and leave that for future studies.

REFEREE: ***South of this zone of depositional shoaling, the Mottama Depression is an area of more than 11, 000 km2 of essentially no accumulation, incised with a dendritic complex of shallow, poorly defined channels that lead to the Martaban Canyon. Its impressive 100- km length, average 045' gradient, 6-km width and 600 m of relief testify to the major, long-term role of the canyon, and the channels that feed sediment into it, in***

funnelling great quantities of Ayeyarwady sediment to the deep Andaman Basin floor. Given its importance, it merits greater mention, and inclusion in Figs. 4&5.

RESPONSE: At this moment we prefer to restrict ourselves to the shelf as the original papers by the reviewer (Rodolfo) and the Ramaswamy, Rao and colleagues series have good discussions on existing data about the canyon and continental margin. However, we did identify the canyon in Fig. 5.

REFEREE: ***Line 248ff: A discussion of human impacts on the delta that exacerbate flooding needs to include the impact of land subsidence due to excessive groundwater withdrawal. See Syvitski et al. (including Giosan), 2009, Sinking deltas due to human activities: www.nature.com/articles/ngeo629. This article reports that the Ayeryawady is aggrading 1.4 mm/y, much slower than relative sea level rise of 3.4-6 mm/y. The problem is especially serious in many coastal East Asian metropolitan areas. Many of them are experiencing centimeters per year of subsidence, resulting in worsening floods and tidal encroachment (see Rodolfo and Siringan, 1996, https://www.researchgate.net/publication/ 7264797flooding from subsidence is ignored_around northern Manila B, Philippines). These include Tokyo and Osaka in Japan, 14 of China's 36 coastal and deltaic cities, six of which are sinking at rates of 4 cm/y or more; Taipei, Taiwan; Hanoi, Viet nam; Manila, Philippines; Bankok, Thailand; and Jakarta, Indonesia. Yangon, with its rapidly growing population (5.21 million in 2014) is apparently no exception. In "Sinking Yangon: Detection of subsidence caused by groundwater extraction using SAR interferometry and PSI time-series analysis for Sentinel-1 data" Van der Horst (2017) (https://www.myanmarwaterportal.com/repository/281-sinkingyangon.html), reports that about 2 million of the metropolitan population get their water from household wells; additional, undetermined quantities are withdrawn by industry; and initial SAR results indicate parts of the city are subsiding more than 9 cm/y. Excessive pumpage and the resulting subsidence surely are not limited to Yangon. Given the monsoonal seasonality of rainfall, does not agri- and aquaculture on the delta rely substantially on groundwater during the dry season as well? That certainly is the case on Pampanga Delta north of Manila in the Philippines, which shares Myanmar's monsoonal seasonal rainfall.***

RESPONSE: This is an important problem but we feel we do not have adequate data to address it. Nevertheless we added text to mention it.

REFEREE: ***Lines 295 ff: For better reference, IR1 and IR2 should be plotted on Figure 2 (d), and the caption for Figure 3 should refer to that.***

RESPONSE: Drill sites are identified on Fig. 2d but names are not as it would require that all dates be identified by name, which would clutter the figure. We added them in Fig. 2a instead and modified the caption for Figure 3 as suggested.

REFEREE: ***358 ff: Plate 1, the outsized bathymetric chart for Rodolfo 1969a pocketed in the back cover of its issue, included data gathered by OSS OCEANOGRAPHER, which used satellite navigation otherwise restricted to the U.S. military. Those data were used to control the tracks of the PIONEER; USN SERRANO was probably equipped with satellite navigation as well. The bathymetry of the shelf and adjacent sea floor was reasonably accurate.***

RESPONSE: See above.

REFEREE: ***592 One "be" too many.***

RESPONSE: Fixed.

REFEREE: ***659 ff (References): Perhaps one co-author should systematically go through each, check punctuations, and rigorously follow all the journal's References format: author surname [comma] author initials [for each author] colon Title [first letter capitalized] [comma] Journal title [comma] volume number [comma] first page [comma] last page [comma] url if provided [comma] year [period]. The journal copy editors will be pleased:***

RESPONSE: We will certainly do that when the final version of the manuscript is submitted.

REFEREE: ***Minor edits: 694: : : :Prades, L.: Design: : : 702: Description 728: Blount, C. D., 733: Garzanti, E., Wang: : : 760 (Myanmar). 789: Ramaswamy, V., and Rao, P. S. The Myanmar 798: Turney, C. S. M., 809: Rodolfo, K. S., 1975: [by date, this should be the third Rodolfo reference, not the first, and the year should end the citation] 812: Rodolfo, K .S., 1969a: Bathymetry [move date to end of citation] 816: Scher, H. D. and Delaney, M. L. Breaking the glass ceiling 817: paleoceanography. Chemical Geology 820: Shi, W. and Wang, M.: 828: paleoceanography. Chemical 832: Nakamura, T.,***

RESPONSE: Fixed except for citation style that will be attended to in the final version.

REFEREE: ***Figure 4. The precision and accuracy of the DEM-derived bathymetry are not impressive. Also: why are the horizontal and vertical scales of Profile 3 different from those of the other profiles, and why is it presented to the left of Profile 4?***

RESPONSE: The bathymetry to ~90 m is as good as it gets at the moment (6442 sounding points). In deeper regions, which is not the focus of our work, we agree that the GEBCO data is of less quality mainly due to its resolution. The scale changes for profile 3 is needed to visualize the channel-drift couplet and its position was chosen for figure symmetry reasons. However, all profiles are easy to identify on the associated map and the scale change is noticeable to the reader.

REFEREE: ***Figure 5. Top panel: The two-head red arrow is not explained in the figure caption, or in the text. Middle panel: It is interesting that the orange hydrologic "shear front" is so similarly positioned with the offshore Sagaing Fault as plotted by Rao et al. (2005).***

RESPONSE: Fixed. About the Sagaing fault see above.

On the Holocene Evolution of the Ayeyawady Megadelta

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*submitted to *Earth Surface Dynamics*

Abstract:

The Ayeyawady delta is the last Asian megadelta whose evolution has remained essentially unexplored so far. Unlike most other deltas across the world, the Ayeyawady has not yet been affected by dam construction providing a unique view on largely natural deltaic processes benefiting from abundant sediment loads affected by tectonics and monsoon hydroclimate. To alleviate the information gap and provide a baseline for future work, here we provide a first model for the Holocene development of this megadelta based on radiocarbon and optically stimulated luminescence-dated trench and drill core sediments collected in 2016 and 2017, together with a re-evaluation of published maps, charts and scientific literature. Altogether, this data indicates that Ayeyawady is a mud-dominated delta with tidal and wave influences. The sediment-rich Ayeyawady River built meander belt alluvial ridges with avulsive characters. A more advanced coast in the western half of delta (i.e., the Pathein lobe) was probably favored by the more western location of the early course of the river. Radiogenic isotopic fingerprinting of the sediment suggest that the Pathein lobe coast does not receive significant sediment from neighboring rivers. However, the eastern region of the delta (i.e., Yangon lobe) is offset inland and extends east into the mudflats of the Sittaung estuary. Wave-built beach ridge construction during the late Holocene, similar to other several deltas across the Indian monsoon domain, suggests a common climatic control on monsoonal delta morphodynamics through variability in discharge, changes in wave climate, or both. Correlation of the delta morphological and stratigraphic architecture information onland with the shelf bathymetry, as well as its tectonic, sedimentary and hydrodynamic characteristics provide insight on the peculiar growth style of the Ayeyawady delta. The offset between the western Pathein lobe and the eastern deltaic coast appears to be driven by tectonic-hydrodynamic feedbacks as the extensionally lowered shelf block of the Gulf of Mottama amplifies tidal currents relative to the western part of the shelf. This situation probably activates a perennial shear front between the two regions that acts as a leaky energy fence. Just as importantly, the strong currents in the Gulf of Mottama act as an offshore-directed tidal pump that help build the deep mid-shelf Mottama clinoform with mixed sediments from Ayeyawady, Sittaung, and Thanlwin rivers. The highly energetic tidal, wind and wave regime of the northern Andaman Sea thus exports most sediment offshore despite the large load of the Ayeyawady river.

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Introduction

Asian megadeltas (*Woodroffe et al., 2006*) have a long history of human habitation and anthropogenic impact. With large populations, which increasingly congregate in sprawling megacities, these vast low-lying and ecologically-rich regions are under threat from environmental degradation, climate change and sea level rise. The Ayeyawady (formerly known as Irrawaddy or Ayeyarwady) is the least studied of these megadeltas despite its scientific, social and economic importance (*Hedley et al., 2010*). Located in the larger India-Asia collision zone, the Ayeyawady delta (Fig. 1) bears the imprint of uniquely complex tectonic processes in a region of oblique subduction (*Morley et al., 2017*) and is a repository for unusually large sediment yields under an erosion-prone monsoon climate (e.g., *Giosan et al., 2017*). Sediment redistribution within the delta and on the shelf fronting it is affected by strong tides amplified by the geomorphology of the region (*Ramasawamy and Rao, 2014*). In contrast to other Asian megadeltas, the Ayeyawady river basin is arguably less transformed by post-World War II anthropogenic impacts, although humans have probably affected delta development since at least the Iron Age as agriculture expanded along the river (*Moore, 2007*) and later intensified during the Pyu (~200 BC to 1050 AD), Bagan (~850 to 1300 AD), and Ava (~1350 to 1550 AD) periods. Recent rapid development trends and population growth underline the need to understand the history and document the current state of the Ayeyawady delta.

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Although the Ayeyawady River is less regulated compared to other large rivers, plans are afoot to construct several dams across it and this may change the water and sediment regimes, as well as fluxes reaching its low-lying delta plain (*Brakenridge et al., 2017*). Inundation of the Ayeyawady delta region during cyclone Nargis in 2008 was one of the costliest and deadliest natural disasters ever recorded (*Fritz et al., 2009; Seekins, 2009*). Catastrophic monsoon-driven river floods are also common and devastating (*Brakenridge et al., 2017*). The Ayeyawady delta may already be sediment deficient (*Hedley et al., 2010*) and the anticipated sediment deficit after damming could increase its vulnerability to such transient events as well as to long term sea level rise (*Giosan et al., 2014*). Strong tidal currents in the northern Andaman Sea (*Rizal et al., 2012*) amplify some aspects of delta vulnerability, such as salinization (*Taft and Evers, 2016*) whereas other aspects may be attenuated such as sediment redistribution along the coast or sediment trapping within the subaerial delta (e.g., *Hoitink et al., 2017*). Better knowledge on how the delta has formed and functioned will help future efforts to maintain its viability.

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To alleviate the information gap and provide a baseline for future work we sketch here a first model for the Holocene evolution of the Ayeyawady delta based on new field data collected in two expeditions in 2016 and 2017 (Figs. 2 and 3; see Fig. S1 for site locations and names) together with a re-evaluation of published maps, charts and scientific literature (Figs. 4 and 5). In the process we reassess our knowledge concerning monsoonal deltas in general by

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advancing new ideas on how morphodynamics and sedimentary architecture can be controlled by feedbacks between tectonics and tides, as well as by the balance between fluvial discharge and wave climate.

Background

The Ayeyawady River is a major fluvial system that became individualized in Oligocene/Early Miocene time (Fig. 1; *Licht et al., 2016*; *Morley, 2017* and references therein). The Late Cretaceous subduction of the Neotethys Ocean followed by the collision between India and Asia first led to an Andean-type margin comprised of the Wuntho-Popa Volcanic Arc and associated forearc and backarc basins (e.g., *Racey and Ridd, 2015; Liu et al., 2016*). The uplift of the Indo-Burman Ranges accretionary prism since early Paleogene completed the separation of the Central Myanmar Basin (CMB) from the Bay of Bengal. The complex of basins forming the CMB were further segmented by compression and inversion (e.g., *Bender, 1983*). These basins include the Ayeyawady Valley separated by the Bago Yoma (Pegu Yoma) from the Sittaung (Sittang) Valley flowing along the Shan Plateau. The Ayeyawady River infilled this ~900 km long shallow marine area toward the Andaman Sea, a Cenozoic backarc/strike-slip basin induced by oblique subduction of the Indian plate under Eurasia (e.g., *Curray, 2005*). A southern shift in Ayeyawady deposition was evident in the Miocene after the major strike-slip fault, the Sagaing, activated along Bago Yoma. The Holocene delta is the last realization in a series of deltas comprising this southward-moving Ayeyawady depocenter.

Myanmar's hydroclimate that is responsible for Ayeyawady flow is spatially complex owing to its varied topography and compound influences from both the Indian and East Asian monsoon systems (*Brakenridge et al., 2017*). Orographic precipitation occurs along the northeastern Himalayas and Indo-Burman Ranges (*Xie et al., 2006*), as well as the Shan Plateau feeding the upper Ayeyawady and the Chindwin, whereas Central Myanmar, in the lee of these ranges, remains drier. The upper basin of the Ayeyawady also receives snow and glacier meltwater in the spring. Over 90% of the discharge at the delta occurs between May and October with small but significant interannual variability (*Furuichi et al., 2009*) linked to the El Nino-Southern Oscillation, Indian Ocean Dipole, and Pacific Decadal Oscillation (*D'Arigo and Ummenhofer, 2014* and references therein).

In historical times the Ayeyawady River has transported ~422 ± 41 × 10^9 m^3 of freshwater every year to the ocean (*Robinson et al, 2007*), watering Myanmar from north to south along the way (Fig. 1). The water discharge has now apparently decreased to the present level of 379 ± 47 × 10^9 m^3/year (*Furuichi et al., 2009*). Among the delta-building Himalayan rivers, the Ayeyawady is a prodigious sediment conveyor (~364 ± 60 × 10^6 t/year), second only to the combined Ganges-Brahmaputra (*Robinson et al, 2007*). Between 40 and 50% of the

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sediment comes from the upper Ayeyawady, with the rest supplied by its main tributary, the Chindwin (*Garzanti et al., 2016*). Sediments transported by the Upper Ayeyawady River come primarily from erosion of gneisses and granitoids of the Himalayan Eastern Syntaxis region and the Sino-Burman Ranges. Although draining less steep terrain, the Chindwin contributes more sediment than the Upper Ayeyawady from the easily erodible flysch and low-grade metasedimentary rocks of the Indo-Burman Ranges. Both water and sediment discharge vary synchronously at interannual time scales as a function of monsoon intensity (*Furuichi et al., 2009*), but they changed little since the late 19th century when *Gordon (1893)* measured them systematically for the first time. In addition to the Ayeyawady, the Sittaung River supplies sediment to the northern shore of the Gulf of Mottama (*aka* Gulf of Martaban) where its estuary merges with the Ayeyawady delta coast (Fig. 1). The sediment discharge from the Sittaung is unknown but can be estimated based on its annual water discharge range of 50×10^9 m^3/year to a maximum of 40 to 50×10^6 t/year by assuming sediment yields similar to the Ayeyawady (*Milliman and Farnsworth, 2010*). Another sediment contributor to the Gulf of Mottama (~180×10^6 t/year) is the Thanlwin River (Salween) draining the eastern Shan Plateau and eastern Tibetan Plateau (*Robinson et al, 2007*). Information about the variability in Ayeyawady's sediment discharge over the Holocene lifetime of the delta is sparse, as are reconstructions for the monsoon variability in its basin. Assuming the modern direct correlation between water discharge and sediment load one may qualitatively infer an increase in sediment delivery since 10,000 years ago with a peak in around 5000 years ago when the Andaman Sea was at its freshest (*Gebregeorgis et al., 2016*), followed by a decrease to the present values, as the Indian monsoon has weakened since the mid Holocene (e.g., *Ponton* et al., *2012; Dixit et al., 2014*).

The Ayeyawady delta is a mud-dominated delta that exhibits mainly tidal and secondarily wave influences (Figs. 2 and 5; *Kravtsova et al., 2009*). Ayeyawady's single braided channel starts to show avulsive behaviour near the town of Myan Aung (~18.2°N) where the tidal influence is still felt ~290 km from the Andaman Sea (Fig. 1). The apex of the delta, defined as the region of deltaic distributary bifurcation, is north of the town of Hinthada (18°N) around 270 km from the coast. Multiple branches are active in the delta, splitting and rejoining to form a network of lower order distributary channels and reaching the coast through eleven tidally-enlarged estuaries (Fig. 2). Most of the water discharge (76%) is delivered to the Andaman Sea through three main mouths: Pyamalaw, Ayeyawady and To-Thakutpin from west to east (*Kravtsova et al., 2009*).

In natural conditions when the delta was covered by tropical forests and mangroves (*Adas, 2011*), sedimentation on the delta plain occurred within active and abandoned channels, on channel levees and inter-distributary basins (*Stamp, 1940; Kravtsova et al., 2009*). The coast prograded via shoal/bar emergence and wave-built beach ridges with associated interridge swales (*Kravtsova et al., 2009*). The coastline for the Ayeyawady delta proper stretches from

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the western rocky Cape Maw Deng, adjacent to the Pathein River, to the Yangon River in the east (Fig. 1). However, this conventional definition does not capture the fact that the accumulative coast with sediment input from the Ayeyawady continues east of the Yangon River into the Sittaung estuary. Despite the large annual fluvial sediment load of the combined Ayeyawady and Sittaung (350–480 × 10^6 t), shoreline changes have been puzzlingly minor along the Ayeyawady delta coast since 1850 (*Hedley et al., 2010*). Sea level change data is sparse and unreliable for the delta and no data on subsidence/uplift exists.

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The shelf morphology in front of the Ayeyawady delta is complex due to its tectonic structure and the nature of Holocene sedimentation (*Rodolfo, 1969a,b, 1975; Ramaswamy and Rao, 2014*). The width of the shelf is ~170 km wide off the Ayeyawady River mouths, widening to more than 250 km in the Gulf of Mottama (Figs. 1 and 5). The shelf edge exhibits a flat, platform-like indentation in the Gulf of Mottama between 140 and 180 m deep (i.e., the Martaban Depression - *Ramaswamy and Rao,* 2014) that features a dendritic network of channels feeding the Martaban Canyon (*Rodolfo, 1975).* Most of the large Ayeyawady suspended sediment load is redistributed by the strong tidal currents (Fig. 5) and seasonally-reversing wind-currents to be deposited on the wide northern Andaman shelf (*Ramaswamy and Rao, 2014*) where it mixes with sediment from the Sittaung, Thanlwin and other smaller rivers (*Damodararao et al., 2016*). Semi-diurnal tides vary between 2 and 3 m from the Pathein River to the Bogale River, reaching higher stages inside distributaries. The tidal range is gradually amplified to macrotidal conditions on the shallow (<30 m) shelf of the Gulf of Mottama from the Bogale Promontory toward the Sittaung estuary where it reaches above 7 m during spring tides (*British Admiralty, 1935*). Associated tidal currents also vary accordingly to over 3.5 m/s near the Sittaung mouth.

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Waves are subordinate in importance for sediment transport to tides, with average heights less than 1 m in winter to 1–2 m in summer (*Kravtsova et al., 2009*). Tidal currents combine with the wind-driven circulation that is clockwise during the summer monsoon and reversed during the winter monsoon (*Rizal et al., 2012*). The macrotidal regime maintains turbid conditions year-round with the turbidity front oscillating ~150 km offshore in the Gulf of Mottama in phase with the spring-neap tidal cycle (*Ramaswamy et al. 2004*). Annual turbidity levels and suspended sediment distribution are modulated by the monsoonal-driven winds, currents and river discharge (*Ramaswamy et al. 2004; Matamin et al, 2015*) with the most extensive and compact turbid waters occurring in the boreal winter. During the summer the turbidity region shrinks to the Gulf of Mottama and nearshore regions where river plumes are active and dispersed eastward. Turbidity profiles show an increase with depth during fair-weather and uniform concentrations during major storms or cyclones (*Ramaswamy et al. 2004; Shi and Wang 2008*). Bottom nepheloid layers and possibly hyperpycnal flows occur in the Gulf of Mottama and flow into the interior of the Andaman Sea as mid-water nepheloid layers (*Ramaswamy et al., 2004*).

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The bathymetric characteristics of the shelf and the circulation system favor deposition of finer fluvial sediments in a mudbelt that widens from the western edge of the Ayeyawady coast into the Gulf of Mottama that more or less coincides in extent with the high turbidity region (*Ramaswamy and Rao, 2014*). The outer shelf, including the Martaban Depression, is a zone of low to non-deposition, and exhibits a relict morphology with topographic irregularities that host relict coarse-grained carbonate-rich sediment and fauna with patchy Holocene muds (*Ramaswamy and Rao, 2014*).

In terms of human impacts on the delta it is important to note that the population of Myanmar increased from 4–5 million in the late 19th century to ~51 million in 2014 with 30% residing in the Ayeyawady delta region. This large increase in population led to a rapid rate of deforestation in the basin, but also to destruction of mangroves for agriculture and fuel in the delta (*Taft and Evers, 2016*). An earlier large migration wave to the delta occurred in the latter half of the 19th century when the British colonial authorities cleared much of the delta forests and mangroves for rice agriculture (*Adas, 2011*). Construction of dikes to protect agricultural lands in the delta began in 1861 and continued aggressively until the 1920s. These dikes are generally of a horseshoe type protecting delta islands in the upstream and sides from floodwaves but recently poldering with diking entire islands was employed. Most channels remain natural with no extensive system of dredged canals. However, all dikes limit overbank flooding and deposition of sediment (*Volker 1966; Stamp 1940*) and the entire agricultural system favors salinization of soils in the delta. The model for the Holocene evolution of the Ayeyawady delta that we provide below allows us to assess first order relationships to the complex regional tectonics, climate, and shelf circulation as a baseline for the future development and management of the delta.

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Methods

The large scale morphology of the Ayeyawady delta, together with the adjoining regions (Fig. 2), were assessed and studied using satellite data and old maps of the region. High-resolution (90-m) digital elevation data were derived from NASA’s Shuttle Radar Topography Mission (SRTM; *Farr et al., 2007*). Digital elevation models (DEMs) were constructed at 300 m resolution and were used in combination with Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Google Earth to identify geomorphic features that provide insight into fluvial morphodynamics. The delta and upstream floodplain was delimited from adjacent hinterlands with associated marginal alluvial fans, as were remnant inselberg-like pre-deltaic terrains inside the delta. We identified active and abandoned river courses and delta distributaries and their meander belts. Finally, we identified fossil beach ridges denoting former delta shorelines. Guided by this assessment, in two field expeditions in the Ayeyawady delta in 2016 and 2017, we collected sedimentary records from shallow hand-

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dug trenches and cores with mechanized pneumatic and percussion drilling (Figs. 2 and 3; see also Fig. S1).

Fossil wave-built beach ridges were targeted by trenching in order to obtain a chronology for the delta coast advance (Figs. 1 and 2; see also Fig. S1). Samples for Optically Stimulated Luminescence (OSL) dating were collected where possible from within the beach-foreshore facies in water tight opaque tubes (site I-11 at Labutta in the western side of the delta; sites I-12 and I-13 at Seikma near the central delta coast; and site I-14 at Kungyangon near the eastern delta coast). A sample was collected in the anthropogenic overburden to date habitation on a Labutta beach ridge (Site I-10). In addition, two levee samples were collected on meanders of the now defunct western major branch of the Ayeyawady (Figs. 1 and 2; Table 2) near the apex of the delta (i.e., sites I-8 near Ta Loke Htaw and I-9 near Lemyethna bordering the last abandoned course and an earlier-formed oxbow lake, respectively). Levee samples were collected in trenches at the top of each levee, below the overburden.

Drill coring was designed to recover continuous sediment records to the pre-deltaic Pleistocene sediments (Figs. 2 and 3; see also Fig. S1; Table 1). Drill sites were located in the middle and near the apex of the delta (site IR1 to 70.4 m depth at Kyonmangay located 6.7 m above sea level and core IR2 to 43 m depth at Ta Loke Htaw located at 18 m above sea level, respectively) to assess the deltaic architecture and, in particular, how far the post-glacial transgression reached inside the suspected Pleistocene Ayeyawady incised valley. Facies analysis was based on the visual description of lithology, sedimentary structures, textures and benthic foraminifera presence. In addition, XRF-scanning-based high resolution chemostratigraphy was employed for the drill cores to identify depositional environments using Woods Hole Oceanographic Institution's (WHOI) ITRAX XRF scanner (see methodology in *Croudace et al., 2006*). From the suite of measured elements we used [Si]/[Rb] ratio to characterize the sand content (i.e., Si-rich sand relative to fine grained muds, rich in Rb; *Croudace and Rothwell, 2015*), the [Br]/[total XRF counts] ratio or Br* to characterize the organic matter (i.e., with Br enriched in marine organic matter; *McHugh et al., 2008*), and [S]/[Rb] ratio to characterize redox conditions in fine-grained muds (i.e., with S in excess of terrigenous values in reducing conditions; *Croudace and Rothwell, 2015*).

Sediment sources for the pre-modern delta were estimated using radiogenic isotopes (Nd and Sr) on a bulk sediment sample from the delta apex trench (I-8 taken as representative for Ayeyawady fluvial sediment). To assess any potential addition of non-Ayeyawady sediment sources (e.g., littoral drift, marine biogenic carbonates) another pre-modern sample from the youngest dated fossil beach ridge trench near the coast (I-12) was measured both as bulk and decarbonated sediment. The radiogenic composition of sediments from the Sittaung River, the closest source to the delta other than Ayeyawady iyself, was measured on a floodplain sample (Fig. ***). Nd and Sr chemistry was undertaken with conventional ion chromatography

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following the method of *Bayon et al. (2002)*. Strontium was separated and purified from samples using Sr-Spec (Eichrom) resin. Nd chemistry was performed with LN resin (Eichrom) following method described in *Scher and Delaney (2010)*. Sr and Nd analyses were conducted on the NEPTUNE multi-collector ICP-MS at WHOI with the internal precision around 10–20 ppm (2σ); external precision, after adjusting ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd values by 0.710240 and 0.511847 for the SRM987 and La Jolla Nd standards respectively, is estimated to be 15–25 ppm (2σ). ^{143}Nd/^{144}Nd isotopic composition is expressed further as εNd (*DePaolo and Wasserburg, 1976*) units relative to (^{143}Nd/^{144}Nd)CHUR= 0.512638 (*Hamilton et al., 1983*).

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Plant and wood pieces were radiocarbon-dated to derive a chronology for the deltaic sediment succession and the pre-deltaic base (Table 1). Accelerator mass spectrometry (AMS) radiocarbon dating was performed at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at the WHOI. The methodology for AMS radiocarbon dating is presented on the NOSAMS site (www.whoi.edu/nosams) and discussed in *McNichol et al. (1995)*. All dates have been converted to calendar ages using CalPal 4.3 (*Bronk Ramsey, 2009*) and the IntCal13 calibration dataset (*Reimer et al., 2013*).

Seven samples were collected for OSL dating. Samples were collected using light-tight metal tubes hammered horizontally into cleaned sediment surfaces. The tubes were opened under subdued orange light at the Nordic Laboratory for Luminescence Dating (Aarhus University) located at Risø (DTU Nutech) in Denmark. Using standard sample preparation techniques (wet sieving, acid treatment, heavy liquids) purified quartz and K-feldspar-rich extracts in the 180–250 µm grain size range were obtained (except sample 177202 for which it was 90-180 µm). Multi-grain aliquots of quartz and K-feldspar were measured using a SAR protocol (*Murray and Wintle, 2000*) suitable for young samples. The purity of the quartz OSL signal was confirmed using OSL IR depletion ratio test (*Duller, 2003*; all aliquots within 10% of unity). For quartz OSL preheating for dose and test dose was 200°C/10s and 160°C, respectively and K-feldspar rich extracts were measured using a post-infrared (IR) Infrared Stimulated Luminescence (IRSL) (pIRIR150) protocol based on *Madsen et al.* (2011). Early and late background subtraction was used for quartz OSL and feldspar pIRIR dose calculations respectively. Total dose rates to quartz and K-feldspar were calculated from radionuclide concentrations measured on the outer material from the tubes using high resolution gamma ray spectrometry (*Murray et al., 1987*). Samples were assumed to have been saturated with water throughout the entire burial lifetime.

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The morphology of the subaqueous extension of the Ayeyawady delta was studied using the only available detailed bathymetric chart of the region that was based on surveys from 1850 to 1929 with small corrections until 1935 (*British Admiralty, 1935*). Newer navigation charts of the region report only small corrections afterwards. The final DEM (Figs. 4 and 5) consists of

6442 individual soundings reduced to the original datum at Elephant Point at the entrance in Yangon River; to these we added the digitized bathymetric contours of the original chart. To extend the bathymetry offshore beyond the coverage of the original chart we used GEBCO 2014 Grid (General Bathymetric Charts of the Oceans, a global 30 arc-second interval grid). Prior to digitizing, all charts and satellite photos used in this study were georeferenced and transformed to a common UTM projection (Zone 46 N) with Global Mapper 18.0 (http://www.globalmapper.com/) using 16 control points for each chart or photo. DEMs at a 250 m spatial resolution were generated from digitized soundings with Surfer 12.0 software (Golden Software, Inc.). The ‘‘natural neighbor’’ algorithm was chosen for interpolation because it is suitable for a variable density of data across the interpolation domain and does not extrapolate depth values beyond the range of existing data.

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Results

In concert with satellite photos, our SRTM digital elevation model (Fig. 2a) reveals that the morphologically-defined Ayeyawady delta plain starts immediately after the river emerges from its mountainous valley at Myan Aung, bound on the western side by the Indo-Burma Range and massive alluvial fans originating in the Bago Yoma on the eastern side. Several inselberg-like pre-deltaic high terrains occur close to the coast on the western side of Pathein River and on both sides of Yangon River. Two alluvial ridges, 5 to 7 m high relative to their adjacent delta plain, with visible meander belts and rare crevasse splays, were constructed by large trunk channels (Fig. 2a, b, c). The western alluvial ridge along the Daga course is largely fossil, whereas the eastern ridge is being built along the present course of the river (Fig. 2c). Both ridges taper off in the mid-delta as the trunk channels start to bifurcate into distributaries that split and rejoin on the lower delta (Fig. 2a,b). After the bifurcation zone the delta plain is uniformly low in altitude (<5 m) with the exception of the higher mudflats near the entrance in the Sittaung estuary (Fig. 2a). Although possessing meander belts of their own in their upper reaches, the Pathein and Yangon Rivers, which are located at the western and eastern edge of the delta, do not show visibly large alluvial ridges (Fig. 2a, b). This suggests that they were not preferential routes for the main trunk Ayeyawady but secondary courses or have not been active for very long. Near the coast, several generations of wave-built beach ridges are evident in the lower part of the delta, bundling occasionally into beach ridge plains on the Bogale Promontory and on the sides on Yangon River (Fig. 2b).

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Sediment in our trenches on the Ayeyawady beach ridges exhibited weakly stratified, mud-rich, fine sand lithologies. Fluvial deposits trenched near the apex showed a typical levee facies exhibiting weakly laminated, amalgamated fine sands and muds below the bioturbated and human-disturbed overburden. The IR1 drill core (Fig. 3) at Kyonmangay (Fig. 2; see also Fig. S1) shows a succession of delta plain bioturbated soils and delta plain muds overlaying amalgamated fine to medium sand and muds of the delta front and prodelta/estuarine clayey muds with intercalated organic-rich detritus layers. Marine influences are documented in the prodelta/estuarine and delta front deposits by high Br* and rare benthic foraminifers. Tidal influence is indicated by thick-thin and sand-mud alternations in the delta front deposits. Flooding is suggested by occasional clean sandy layers in the prodelta facies. Both the delta plain and prodelta/estuarine deposits show increased S/Rb values indicative of poorly oxic conditions. The transition to delta front advance at Kyonmangay occurred at 13.5 m below sea level (mbsl) ~8,100 years ago, as documented by the radiocarbon content of a leaf fragment. The deltaic succession stands on a 9,300 years old mangrove peat at 28.5 mbsl near the base of the deltaic Holocene deposits. Pre-Holocene fluvial deposits older than 10,200 years BP occur below, consisting of structureless medium to coarse sands with clayey mud intercalations, gravels, and fine-grained weakly laminated channel infills.

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The IR2 drill core (Fig. 3) at Ta Loke Htaw (Fig. 2; see also Fig. S1) near the delta apex on the modern alluvial ridge exhibits a succession of delta plain sandy muds topping structureless medium sands with rare intercalated thin muds of channel/point bar type. They overlie fine-grained, weakly laminated channel infill deposits and floodplain fine sands with intercalated thin muds that started to accumulate ~8,900 years BP (radiocarbon dated wood piece). Below ~25 mbsl structureless fine to medium sands of channel/point bar and gravel layers occur to the base of the drill core. Organic material is rare in all facies at Ta Loke Htaw except for occasional wood branches and a tree trunk in the upper point bar facies. Marine influence is absent as foraminifers are not encountered and Br* levels are consistently low.

The quartz OSL and feldspar pIRIR150 luminescence dating results are summarized in Table 2 and Table S1. The quartz OSL signal is dominated by the fast component and the average dose recovery ratio is 1.00±0.02 (4 samples, 11-12 aliquots per sample) suggesting that our quartz De values measured using SAR are reliable. One prerequisite for accurate age estimation is that the quartz OSL signal was sufficiently bleached prior to burial in the sediment sequence. In this study we use the feldspar IR50 and pIRIR150 age data to provide insights into the completeness of bleaching of the quartz OSL signal (e.g., *Murray et al., 2012; Rémillard et al., 2016*). This is based on the observation that feldspar signals bleach much more slowly than quartz OSL (*Godfrey-Smith et al., 1988; Thomsen et al., 2008*): IR50 signals bleach approximately one order of magnitude slower than quartz OSL and pIRIR signals bleach even more slowly than IR50 signals (e.g., *Kars et al., 2014; Colarossi et al., 2015*). We are confident that the quartz signal is well-bleached when the pIRIR150 age agrees within uncertainty with the quartz age; this is the case for sample 177204. We consider that the quartz OSL signal is very likely to be completely bleached when the IR50 age agrees or is slightly lower (due to fading) than the quartz age. This is the case for all samples except for sample 177202 for which the IR50 age may be slightly older. Nevertheless, this does not mean the quartz OSL age for this particular sample is affected by partial bleaching; we just cannot be certain it is not.

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Overall, optical ages on the natural levee of an old meander series of the fossil eastern alluvial ridge indicate full activity by ~1,750±320 years ago. Sedimentation on the top of the natural levee bordering the last Daga course indicates that its abandonment took place no earlier than 1,500±230 years ago (Fig. 2; see also Fig. S1). A radiocarbon date calibrated to ~1,300 years ago on a large wood trunk from the point bar facies drilled at Ta Loke Htaw indicates that the present eastern course of the Ayeyawady was active at the time. The fresh appearance of the wood make it unlikely that it is remobilized fossil wood. Future systematic exploration of the meander belts subsurface architecture is needed to reconstruct their history.

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Our combined chronology indicates the Ayeyawady delta reached as far south as the latitude of the cities of Yangon and Pathein around 6,300 years ago, as documented by a radiocarbon content of a leaf fragment from the delta plain facies at Kyonmangay. Optical dating shows that the least advanced beach ridge bundle found on the western side of the delta near Labutta is also the oldest (~4,600 years old; Fig. 2 and Fig. S1). The beach ridge plain at the Bogale Promontory started ~1,000 years ago, soon after beach ridges started to form at the Yangon River mouth (~1,200 years ago; Fig. 2 and Fig. S1).

Radiogenic provenance fingerprinting of the bulk river sediment (Table S2) on the Ta Loke Htaw levee shows that ^{143}Nd/^{144}Nd (εNd) and ^{87}Sr/^{86}Sr values of 0.512263 (-7.3) and 0.7120 respectively, lie close to the beach ridge sediment composition: 0.512285 (-6.9) and 0.7118 for bulk sediment and 0.512287 (-6.8) and 0.7119 for bulk decarbonated sediment. The identical ^{87}Sr/^{86}Sr values for the bulk and decarbonated beach ridge sample suggest that marine biogenic carbonates are a minor sediment component at the coast. However, previous measurements on Ayeyawady sediments (Table S2 with data from *Allen et al., 2008* – 150 km upstream of the delta; *Colin et al., 1999* – at an unspecified location) show a larger variability in εNd with values of -8.3 and -10.7. The closest sediment source along the coast, the Sittaung River that drains Bago Yoma and the Shan Plateau shows ^{143}Nd/^{144}Nd (εNd) and ^{87}Sr/^{86}Sr values of 0.512105 (-10.4) and 0.7168 respectively. The Yangon River, the largely abandoned easternmost branch of the Ayeyawady close to Bago Yoma has εNd and ^{87}Sr/^{86}Sr of -12.2 and 0.7080 respectively (*Damodararao et al., 2016*), which suggest mixing with a source similar to the Sittaung.

Our reassessment of the late 19th – early 20th century bathymetry with the high-resolution digital elevation model produced several surprises (Figs. 3 and 4a). First, the edge of the shelf (Fig. 4) was found to be significantly deeper in front of the Mottama Depression (>150 m) than west of it (100–120 m deep). Second, the mud belt along the Ayeyawady delta exhibits a clinoform attached to the shore and likely composed of sandy muds (*Rao et al., 2005*) and extending to depths of 35–40 m. In contrast, the Gulf of Mottama exhibits a thick mid-shelf clinoform comprised of finer muds (*Rao et al., 2005*) with the steep frontal region extending from 40 to 90 m water depth. The transition between the western and eastern clinoforms is

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marked by a transversal channel that is 10 km wide and 5 m deep on average and is flanked on the deeper eastern side by a drift-like elongated feature of similar average dimensions. Third, a flatter area of the outer shelf in front of the western Ayeyawady delta coast stands out from the typical outer shelf chaotic relief, suggesting potential preservation of a relict pre-Holocene delta region at water depths between 35 and 45 m.

Discussion

Our new drill core information (Fig. 3) indicates that the Holocene Ayeyawady delta advanced into an incised valley estuarine embayment that extended north of Kyonmangay (~80 km from the current coast) but did not reach as far as the current delta apex at Ta Loke Htaw (270 km from the coast). The Pleistocene deposits of the incised valley intercepted in our cores are fluvial, generally much coarser than the delta deposits but heterolithic with indications of increasing tidal influence nearer to the Andaman Sea at Kyonmangay. The overlying peats atop mudflat sediments sampled at Kyonmangay indicate the presence of a muddy coast with mangroves at the time of their transgression ~9,300 years ago. Given that the contemporaneous ice-volume equivalent global sea level was between -29 and -31 mbsl (*Lambeck et al., 2014*), the altitude of the mangrove peat (-28.3 mbsl) on the largely incompressible Pleistocene deposits below indicate that the delta is vertically stable. However, glacial isostatic adjustment modeling is needed to quantify subsidence as neighboring regions of Thailand and Malay Peninsula (*Bradley et al., 2016*) suggest that relative sea level reached higher earlier during the deglaciation. After the mangrove coast was flooded, the marine embayment accumulated estuarine/prodelta muds afterwards. At 8,100 years ago the Ayeyawady bayhead delta front reached the southern Kyonmangay site and by ~6,300 years ago delta plain deposition started.

Deposits at the delta apex in the drill core at Ta Loke Htaw indicate a dynamic fluvial environment with channel erosion (i.e., scouring) followed by point bar and floodplain deposition. The abandonment of the western Daga meander belt after 1,500 years ago, left the Ayeyawady flowing along a single preferential course. Meander belt construction on the old and new course of the river, leading to the formation of alluvial ridges, appears to be an efficient type of aggradation on the upper delta plain before the river starts to bifurcate.

Near the coast, the quasi-contemporary beach ridge development on the Bogale Promontory and Yangon River mouth argue for the advanced position of the western half of the delta being acquired early and maintained during progradation. Delta growth since 6,300 years ago, with intermediate stages delineated by successive beach ridge sets, point to decreasing rates of advance of ~25 m/year until ~4,600 years ago and 8 to 10 m/year afterwards. The latter are still higher than the average progradation value of 3.4 m/year calculated by *Hedley et al. (2010)* for the last century or so. Furthermore, the recent progradation occurred primarily on the coast adjacent to both sides of the Yangon River, while the shoreline of the rest of the

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delta has been largely immobile. It is important to note that, like the Ayeyawady, many large river deltas developing under the Asian monsoon regime, such as Mekong (*Ta et al., 2002*), Red River (*Tanabe et al., 2003*), or Godavari (*Cui et al., 2017*) started to form wave-built beach ridges between 5000 and 4000 years ago changing from river-dominated morphologies to show stronger wave-influenced characteristics. Given that these deltas were at various stages of advance from within their incised valleys onto the shelf it is more likely that their morphological evolution was climatically driven rather than controlled by local factors as previously proposed. As the late Holocene monsoon aridification started at that time (*Ponton et al., 2012; Dixit et al., 2014*), fluvial discharge variability at centennial timescales increased setting the stage for periodic wave-dominance of deltaic coasts during more arid intervals.

Our re-evaluation of the shelf morphology in the context of the new data onland reveals important information for understanding the peculiar, irregular growth of the Ayeyawady delta. Its western half from Cape Maw Deng to the Bogale Promontory is well advanced into the Andaman Sea in comparison to its eastern half. First, the shelf DEM suggests that the western Ayeyawady delta continues offshore into a shallow, coarser-grained shore-attached clinoform, which is not completely unexpected given the relatively low tidal range of 2–3 m (e.g., *Goodbred and Saito, 2012*) and the perennial loss of sediment advected to the Gulf of Mottama (*Ramaswamy and Rao, 2014*). The Nd and Sr fingerprint of the river sediment is almost identical to the beach ridge at Bogale indicating that essentially no sediment from the Gulf of Mottama bearing the radiogenic imprint of Sittaung (see above) and especially Thanlwin (*Damodararao et al., 2016*) is feeding this part of the coast. The shore-attached sandy clinoform tapers off after 40 mbsl (Fig. 2b). In contrast, the Gulf of Mottama exhibits a mid-shelf mud clinoform with the roll-over at 40 m and toe depth of 80–90 m. The internal architecture of this distinctive feature was imaged previously (*Ramaswamy and Rao, 2014*) and showed seismic characteristics typical of a clinoform topset and foreset. High rates of progradation/aggradation for the Mottama clinoform have been suggested previously but a core collected on its lower foreset has an average sedimentation rate of ~1 cm/year since ~1450 AD (Ota et al., 2017), which is one order of magnitude less than proposed before (Chhibber, 1934; Rodolfo, 1975). Given the depressed character of the Mottama shelf, as indicated by the shelf edge position 40 to 70 m lower than in front of the western Ayeyawady delta, perhaps, it is not surprising that infilling of this region is still ongoing. What is surprising instead is why and how the Ayeyawady River built its delta on the eastern raised shelf block rather than in advancing preferentially into the Gulf of Mottama. Such behavior defies theoretical and modeling expectations of a more advanced deltaic coast toward the subsided block (e.g., *Liang et al., 2016*). The key to this problem appears to be again suggested by the shelf morphology.

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The distinctive transition between clinoforms exhibiting a wide elongated channel and what appears to be an attached sediment drift-like feature suggests intense current activity at the common clinoform boundary. Indeed tidal modeling suggests that a tidal shear front (e.g., *Wang et al., 2017*) may be present in this region that shows a drastic change from weak and isotropic tidal currents west of Bogale Promontory to highly oriented strong currents in the Gulf of Mottama (*Rizal et al., 2012*). Such a shear front would explain both the unusual channel-drift couplet, but also the fact the Ayeyawady was able to build its delta west of the gulf. If the tidal shear front has been a long-lived feature of the shelf circulation then it probably acted as a littoral energy fence (*sensu Swift and Thorne, 1992*) trapping a significant part of the Ayeyawady sediment on the raised western shelf block. However, such an energy fence may be broken by prevailing westerly currents during the summer monsoon when water and sediment discharge peaks from the Ayeyarwady to provide finer suspended sediment to the Mottama clinoform. Given the depressed character of the Mottama shelf block, the front must have existed since the beginning of the deglacial transgression of the northern Andaman shelf. Industrial seismic reflection profiles imaged a region of strike-slip extension in the Gulf of Mottama expressed as horsetail extensional splays linked to the Sagaing Fault system (*Morley, 2017*) that can explain the height differential between the western and eastern shelves. Furthermore, the shear front must have gradually intensified through positive feedback with the morphology as the shore-attached clinoform west of it grew larger. In contrast, the amplified tidal currents in the Gulf of Mottama efficiently redistributed the significantly larger amount of Ayeyawady sediments that escaped beyond the energy fence together with sediments from the Sittaung and Thanlwin to form the midshelf clinoform there. The offshore-directed tidal pumping leading to the formation of the Mottama clinoform is reminiscent of the situation on the eastern Indus shelf where strong tidal currents from the Gulf of Kutch built a mid-shelf clinoform with Indus sediments escaping eastward (*Giosan et al., 2006*). Such clinoforms, which are of purely tidal origin, and do not front a subaerial deltaic counterpart *per se* may have been more common in sediment-rich macrotidal environments during faster transgressive conditions in the past.

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Conclusions

The Ayeyawady delta in Myanmar is the last realization in a long series of depocenters that gradually moved southward within the tectonically dynamic intra-mountainous landscape extending from the Central Myanmar Basin in the north to the northern Andaman Sea in the south (Figs. 1 and 2). The delta developed within the incised valley dug by the Ayeyawady River during the last lowstand (Fig. 3). The Pleistocene valley was flooded at least 80 km inland from the present coast during the deglacial sea level rise. Holocene progradation into this paleo-Ayeyawady bay proceeded in the form of a fluvial- and tide-dominated delta until late Holocene wave action began to build isolated and clustered beach ridges at the contemporaneous coasts (Fig. 2). However, beach ridges are rather rare and underdeveloped, testifying to the enormous sediment load discharged by the Ayeyawady and tidal dispersal and reworking. Ridge construction during the late Holocene, similar to several other deltas across

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the Indian monsoon domain, argues for a possible climatic control on delta morphodynamics through variability in discharge, changes in wave climate, or both.

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The landscape near the delta apex exhibits active and fossil late Holocene meander belts that terminate in the mid-delta where the discharge is split to lower order distributary channels (Fig. 2). The meander belts stand as alluvial ridges above the floodplain along the active river course, as well as its antecedent paleo-course documenting the Ayeyawady's avulsive character. Construction of a more advanced coast in the western half of the delta could be seen as a quasi-independent region, the Pathein lobe (Fig. 5), which was probably favored by the more western location of the early course of the river (but see below). The eastern region of the delta (the Yangon lobe) is offset inland (Fig. 5) and exhibits a more wave-dominated morphology, largely built with Ayeyawady-derived sediment escaping alongshore. Further east, the Yangon lobe merges with the mudflats fringing the Sittaung estuary (Fig. 5). Despite its large sediment load the Thanlwin River has only built a bayhead delta, barely prograding outside its incised valley, probably due to extreme macrotidal conditions at its mouth (Fig. 5). However, its sediment instead contributed to deposition on the shelf, as did part of the load from both Ayeyawady and Sittaung.

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Correlation of the delta morphological and stratigraphic architecture information onland to the shelf bathymetry and hydrodynamics, as well as its tectonic and sedimentary characteristics, provides insight on the peculiar growth style of the Ayeyawady delta (Figs. 2–5). The offset between the western Pathein lobe and the eastern deltaic coast appears to be driven by tectonic-hydrodynamic feedbacks as the extensionally lowered shelf block of the Gulf of Mottama amplifies tidal currents relative to the eastern part of the shelf. This situation probably activates a perennial shear front between the two regions that behaves as a leaky energy fence. Just as importantly, the strong currents in the Gulf of Mottama act as an offshore-directed tidal pump that help build a deep, mixed-source mid-shelf clinoform, the Ayeyawady-Sittaung-Thanlwin subaqueous delta, into the Mottama shelf depression.

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Our study takes a first look at the evolution of the Holocene Ayeyawady delta to provide a basis for more detailed work and context to present and future management plans for this ecologically and economically important, but vulnerable region. A first conclusion for the future of the region comes by comparing the Ayeyawady to other deltas across the world. Uniquely for deltas of its size the Ayeyawady delta has not suffered a sediment deficit from damming, yet it has been barely growing. The reason is the highly energetic tidal, wind and wave regime of the northern Andaman Sea that exports most sediments offshore despite the large load of the river as envisioned by *Ramswamy et al., (2004)* and *Hedley et al. (2010)*. In addition to their effects upstream (*Brakenridge et al., 2017*), the expected sediment deficit after dams are constructed on the river and tributaries may significantly impact the delta fragile sedimentary equilibrium (*Giosan et al., 2014*). This could make it more vulnerable to

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the accelerating sea level rise (*Syvitski et al., 2009*) or changes in frequency and intensity of cyclones hitting the coast (*Darby et al., 2016*) that compound with increased subsidence linked to the rapid development of the region (e.g., Van der Horst, 2017).

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