On the Holocene Evolution of the Ayeyawady Megadelta

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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.

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) historical periods. Recent rapid development trends and population growth underline the need to understand the history and document the current state of the Ayeyawady delta.

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 it viable.

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 (Fig. 4 and 5). In the process we reassess our knowledge concerning monsoonal deltas in general by 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 upper 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 strike-slip Sagaing Fault 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-Buman 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 ~$422 \pm 41 \times 10^9$ 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 apparently decreased to the present level of $379 \pm 47 \times 10^9$ m^3/year (*Furuichi et al., 2009*). Among the delta-building Himalayan rivers, the Ayeyawady is a prodigious sediment conveyor (~$364 \pm 60 \times 10^6$

t/year), second only to the combined Ganges-Brahmaputra (*Robinson et al, 2007*). Between 40 and 50 % of the 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 from 50×10^9 m^3 to a maximum of 40 to 50×10^6 t/year by assuming sediment yields similar to the Ayeyawady's (*Milliman and Farnsworth, 2010*). Another sediment contributor to the Gulf of Mottama (~180×10^6 t/year; *Robinson et al, 2007*) is the Thanlwin River (Salween) draining the eastern Shan Plateau and eastern Tibetan Plateau. Information about the variability in Ayeyawady's sediment discharge over the Holocene lifetime of the delta is sparse, as are reconstructions for the monsoon regime 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 Early Holocene (e.g., *Ponton et al., 2012*).

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 higher 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 the western rocky Cape Maw Deng (formerly Pagoda Point), 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 Yangon River into the Sittaung estuary. Despite the large fluvial sediment load of the combined Ayeyawady and Sittaung delivered annually (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.

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 sediment suspended 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.

Waves are subordinate in importance 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. Wind currents are 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 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 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*).

The bathymetric characteristics of the shelf and the circulation system favor deposition of fine fluvial sediments in a mudbelt that widens from 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 the floodwave 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.

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-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 (core 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 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. The radiogenic composition of sediments from Sittaung River, the closest source to the delta other than Ayeyawady iyself, was measured on floodplain sample near Bago (Fig. 1). Nd and Sr chemistry was undertaken with conventional ion chromatography 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*).

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.

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.

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, located at the western and eastern edge of the delta, do not show visibly large alluvial ridges (Fig. 2a, b) suggesting 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).

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 indicating 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.

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.

Overall, optical ages on the natural levee of an oldest 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 indicate 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. However, a future systematic exploration of the meander belts subsurface architecture is needed to reconstruct their history.

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, 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. 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 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) then 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 probably 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 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) indicate that the 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 quantifiy subsidence as neighboring regions of Thailand and Malay Peninsula (Bradley et al., 2016) suggests 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 point bar and floodplain deposition. The abandonment of the western Daga meander belt not much after 1,500 years ago, suggest that the Ayeyawady started to flow on a single preferential course close to that time. 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 suggest that the advanced position of the western half of the delta was acquired early and maintained during progradation. Delta growth since 6,300 years ago, with intermediate stages delineated by successive beach ridge sets, suggest 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 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*), 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 with its western half from Cape Maw Deng to the Bogale Promontory 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, 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*) showing 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 indicated by the shelf edge position 40 to 70 meter 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, defying 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.

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 boundary between the two clinoforms. 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 more 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 it probably acted as a littoral energy fence (*sensu Swift and Thorne, 1992*) trapping a significant part of the Ayeyawady coarser 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 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 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.

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 appears to be vertically stable 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 other several deltas across the Indian monsoon domain, suggests a possible climatic control on delta morphodynamics through variability in discharge, changes in wave climate, or both.

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 contributed instead to deposition on the shelf, as did most of the load from both Ayeyawady and Sittaung.

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 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 a deep, mixed-source mid-shelf clinoform, the Ayeyawady-Sittaung-Thanlwin subaqueous delta, into the Mottama shelf depression.

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

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Table 1. Results of AMS ^{14}C dating of organic materials from drill cores IR1 (Kyonmangay) and IR2 (Ta Loke Htaw).

Location	Sample	Altitude (*m bsl*)	Type	Labcode	Latitude	Longitude	Age (*years BP*)	Error (*years BP*)	d13C (*per mil*)	Calibrated Age (*years*)*	Error (*years*)	Observations
Kyonmangay	IR1-9.60	-2.9	leaf fragment	OS-132754	16°26'15N	95°08'01"E	5,590	100	-28.65	6487	213	small
Kyonmangay	IR1-20.0	-13.3	leaf fragment	OS-132658	16°26'15N	95°08'01"E	7,300	40	-26.71	8166	80	
Kyonmangay	IR1-35.0	-28.3	mangrove wood piece	OS-133490	16°26'15N	95°08'01"E	8,300	40	-27.27	9352	148	
Kyonmangay	IR1-40.0	-33.3	carbonized wood piece	OS-132659	16°26'15N	95°08'01"E	9,100	35	-26.58	10351	88.5	
Ta Loke Htaw	IR2-19.0	-0.5	wood trunk piece	OS-133606	17°39'13"N	95°26'2"E	1,320	15	-28.04	1307	53.5	
Ta Loke Htaw	IR2-33.5	-15.0	carbonized wood piece	OS-135132	17°39'13"N	95°26'2"E	8,020	30	-27.7	8959	117.5	small

*Calendar ages are relative to year 2016

Table 2. Summary of the quartz and feldspar luminescence data. (n) denotes the number of aliquots contributing to dose (De). The saturated water content (w.c.) is given as the ratio of weight of water to dry sediment weight. Feldspar IR50 and pIRIR150 ages have not been corrected for any signal instability. Radionuclide concentrations used to derive quartz and feldspar dose rates are given in Table S1. Bleaching of quartz OSL signal is assessed by comparing the quartz ages with the IR50 and pIRIR150 ages. Uncertainties represent one standard error. Age uncertainties include random and systematic components. Quartz ages should be used for interpretation; feldspar ages are only used to investigate quartz OSL bleaching.

Sample code	Site	Setting	Latitude / Longitude	Depth, cm	Quartz well-bleached?	Quartz Age, ka	$pIRIR_{150}$ Age, ka	IR_{50} Age, ka	Quartz Dose, Gy	(n)	$pIRIR_{150}$ Dose, Gy	IR_{50} Dose, Gy	(n)	Quartz Dose rate, Gy/ka	K-feldspar Dose rate, Gy/ka	w.c. %
17 72 01	I8	fluvial levee	N 17 38 36.82 / E 95 18 33.64	95	probably	**1.50 ± 0.23**	6.64 ± 0.68	1.20 ± 0.23	**3.28 ± 0.49**	**34**	20.6 ± 1.9	3.73 ± 0.69	9	**2.19 ± 0.10**	3.10 ± 0.12	**29**
17 72 02	I9	fluvial levee	N 17 36 13.5 / E 95 12 53.39	110	not certain	**1.75 ± 0.32**	15.2 ± 5.5	4.02 ± 1.85	**4.14 ± 0.73**	**35**	46 ± 16	12.0 ± 5.5	9	**2.37 ± 0.10**	2.99 ± 0.11	**35**
17 72 03	I10	beach ridge	N 16 09 03.5 / E 94 43 57.3	92	probably	**1.46 ± 0.22**	2.35 ± 0.21	1.10 ± 0.07	**2.97 ± 0.42**	**40**	6.9 ± 0.5	3.25 ± 0.17	9	**2.03 ± 0.09**	2.95 ± 0.11	**28**
17 72 04	I11	beach ridge	N 16 09.2578 / E 94 44.1843	90	confident	**4.63 ± 0.47**	4.73 ± 0.37	2.71 ± 0.17	**10.1 ± 0.9**	**36**	14.7 ± 1.0	8.42 ± 0.43	9	**2.18 ± 0.09**	3.10 ± 0.11	**32**
17 72 05	I12	beach ridge	N 15 50 10.5 / E 95 29 51	100	probably	**1.04 ± 0.09**	1.94 ± 0.19	0.79 ± 0.05	**2.64 ± 0.17**	**38**	6.7 ± 0.6	2.72 ± 0.14	9	**2.53 ± 0.13**	3.45 ± 0.15	**38**
17 72 06	I13	beach ridge	N 15 49.6494 / E 95 30.2095	132	probably	**0.86 ± 0.07**	1.86 ± 0.15	0.68 ± 0.04	**1.58 ± 0.12**	**37**	5.1 ± 0.4	1.88 ± 0.08	9	**1.84 ± 0.07**	2.75 ± 0.10	**40**
17 72 07	I14	beach ridge	N 16 24 27.5 / E 96 02 20.2	115	probably	**1.19 ± 0.11**	1.43 ± 0.12	0.76 ± 0.04	**2.64 ± 0.19**	**40**	4.5 ± 0.3	2.38 ± 0.09	9	**2.21 ± 0.10**	3.13 ± 0.12	**24**

Fig. 1. (a) Physiography and (b) geology of the Ayeyawady Basin and adjacent regions.

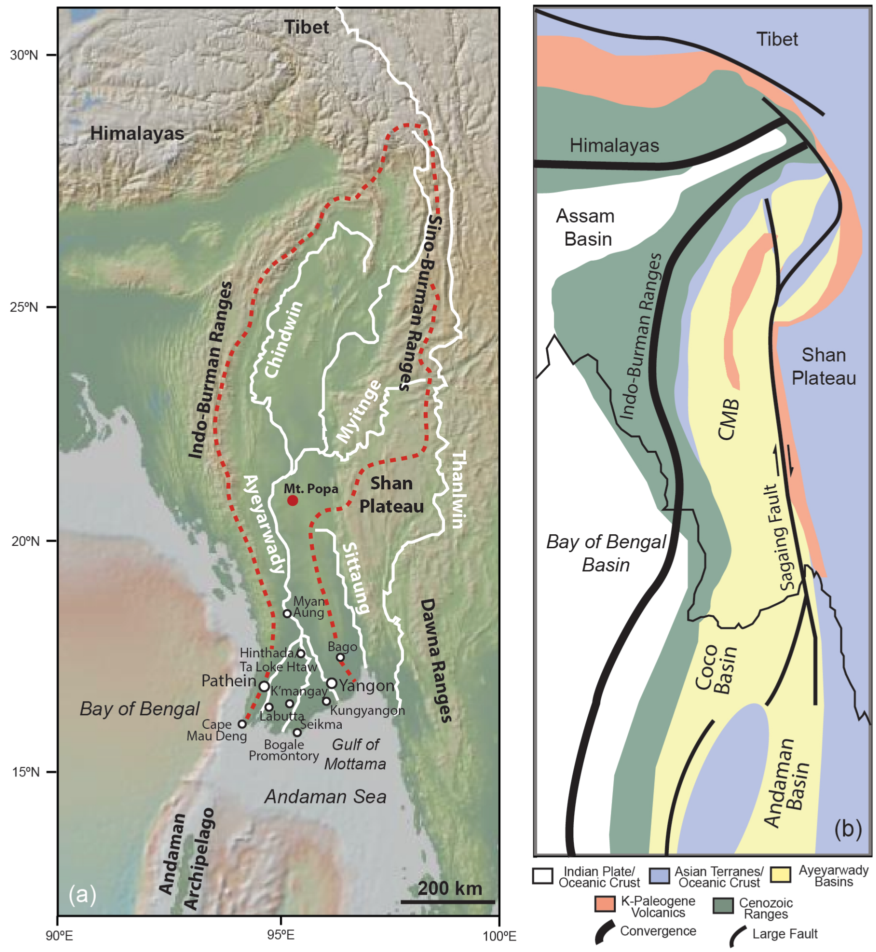

Fig. 2. (a) SRTM-derived DEM for the Ayeyawady delta region (pattern of colors repeats every 10 m to 300 m in height; higher landscape in black); (b) large scale features of the Ayeyawady delta region with identified river and distributary courses and mouths as well as beach ridges shown on an ASTER satellite photo ; (c) sample locations and chronology on the meander belts documenting the avulsion near the delta apex (meander belts as white lines delimited from ASTER and Google Earth images); (d) preliminary model of the Ayeyawady delta evolution with sampling locations and types with chronological information on the youngest fluvial deposits and beach ridges.

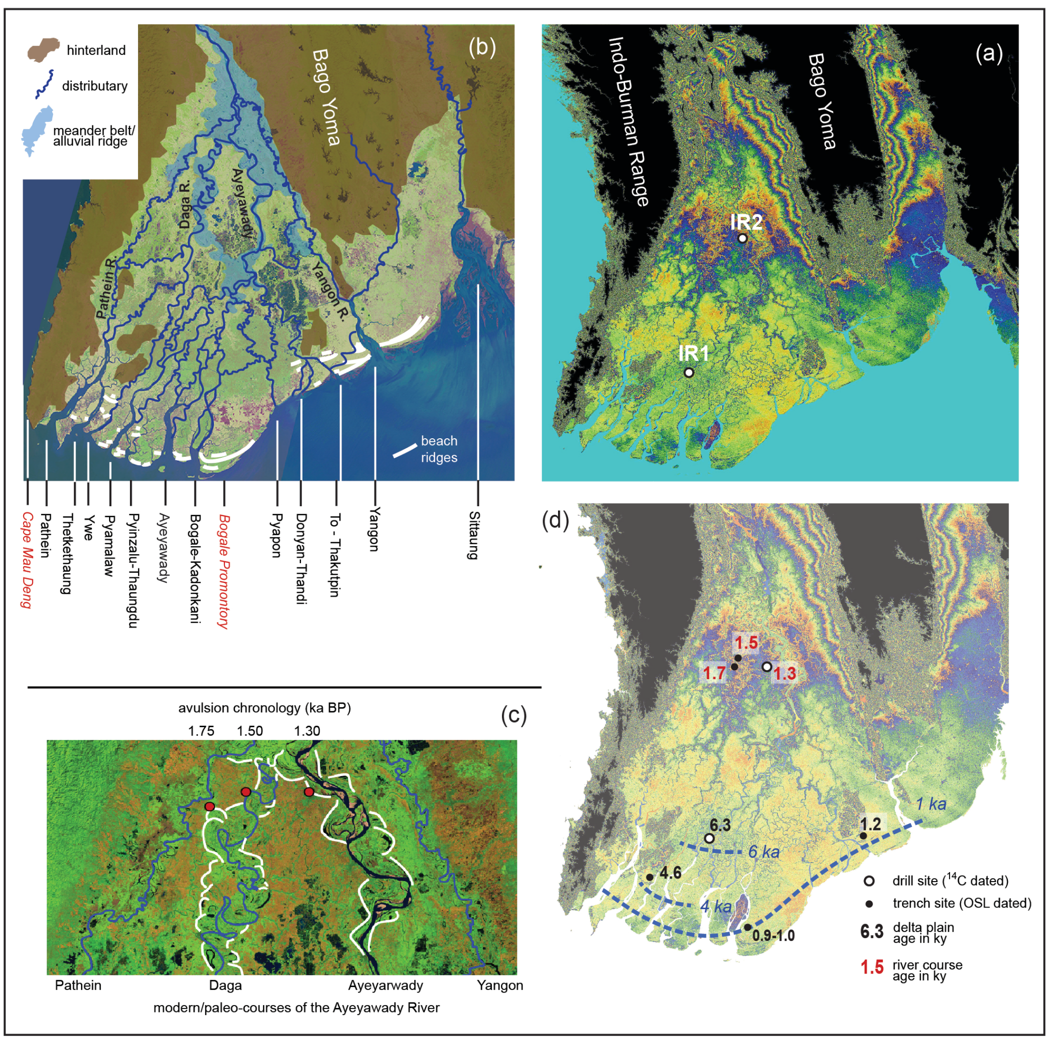

Fig. 3. (a) Depositional environments interpreted from litho- and chemo-stratigraphy with radiocarbon chronology for drill cores in the Ayeyawady delta; (b) interpreted Ayeyawady delta stratigraphy and evolution along the Ayeyawady's main course.

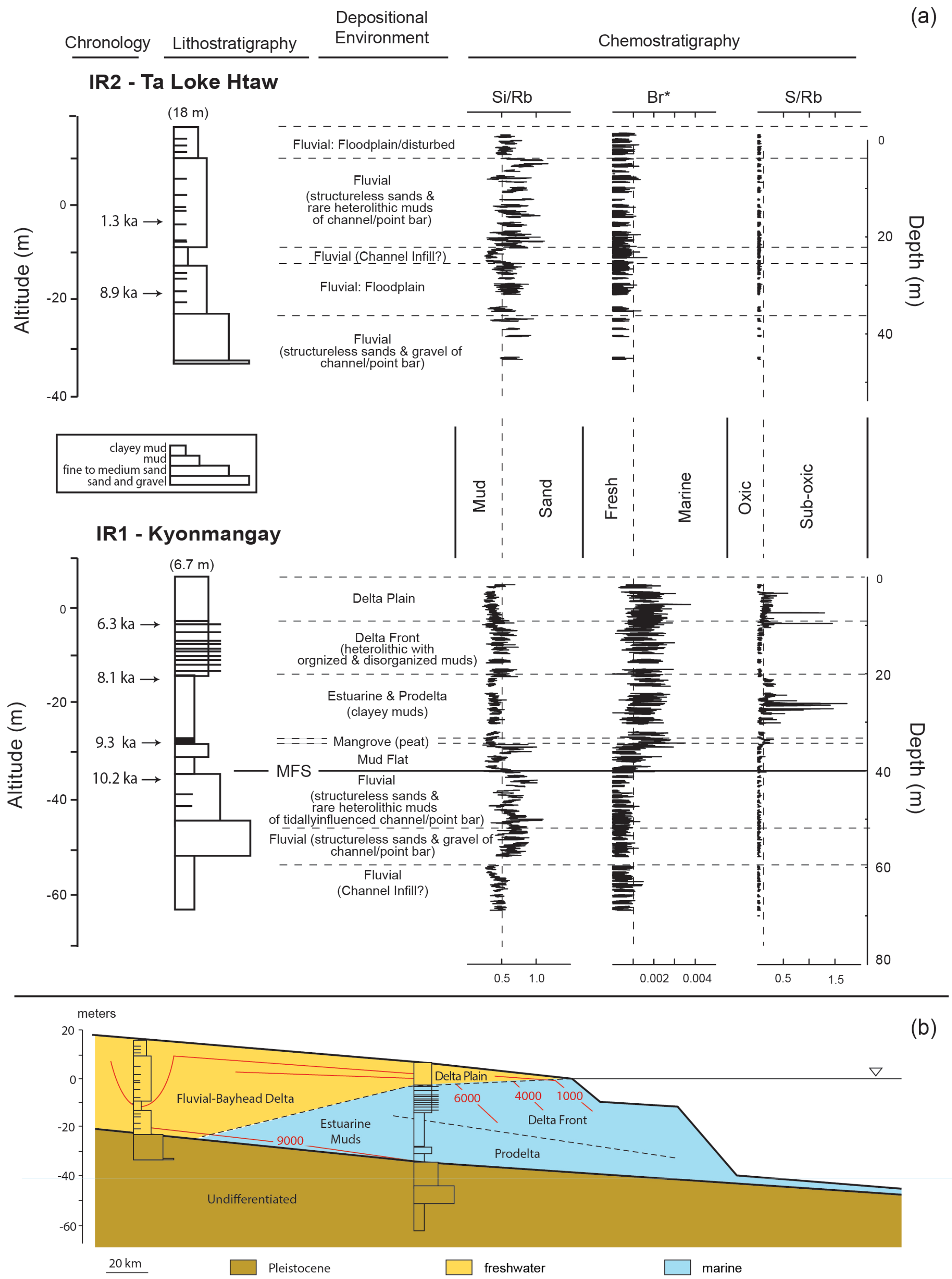

Fig. 4. Interpreted bathymetric profiles across the northern Andaman Sea shelf (bathymetric profiles identified on map). Dashed line on map indicates the approximate limit of consistent fine-grained sediment deposition on the shelf farthest from shore. The SRTM-derived DEM for the Ayeyawady delta region is shown onland.

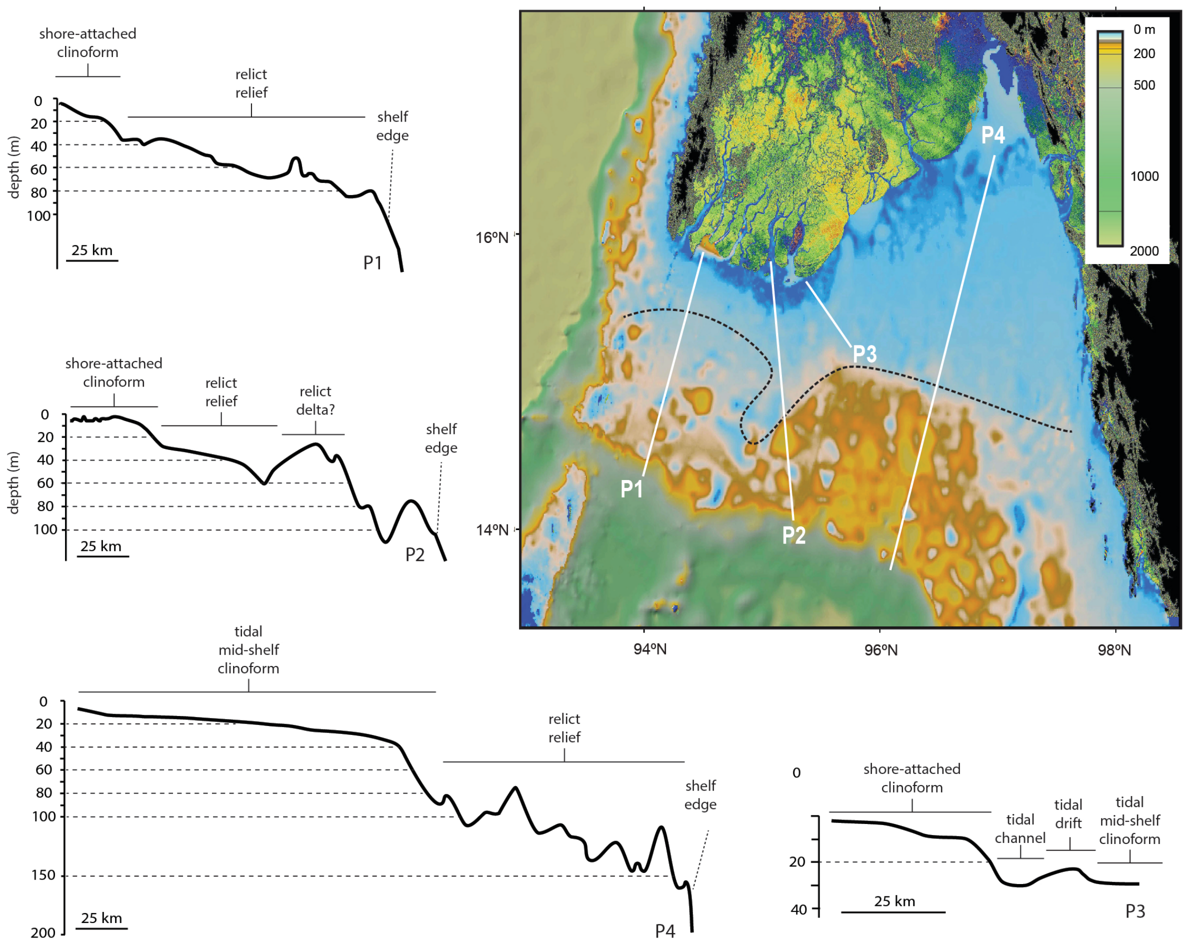

Fig. 5. (a) Bathymetry of the northern Andaman Sea shelf and SRTM-derived DEM for the Ayeyawady delta region onland with regional faults and associated splay faults (Morley, 2017); arrow pairs indicate regional compression (white) or extension (red); (b) tidal range lines (black), co-tidal lines (white) and tidal current magnitudes (ellipses) for the dominant M2 tide component (Rizal et al., 2012); (c) sketch he Ayeyawady delta plain evolution phases and associated subaqueous deltas.