Late Holocene stratigraphic evolution and sedimentary facies of an active to abandoned tide-dominated distributary channel and its mouth bar

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ABSTRACT
To better understand the sedimentary facies of tide-dominated deltas, a core dataset from the Ba Lai palaeochannel in the Mekong River Delta was obtained and studied. Nine sedimentary facies were identified and interpreted as representing the Late Holocene evolution of the Ba Lai palaeochannel, including its pre-abandonment and post-abandonment phases, as well as pre-channel phases. The channel formed at 2.6 ka as a distributary channel connected to the deltaic network and was abruptly abandoned and rapidly infilled with sediment at 0.7 ka. The channel deposits are up to ca 11 m thick and overlie shelfal shell layers, which, in turn, overlie Mid-Holocene and Pleistocene deposits. The active-channel fill and mouth-bar deposits consist of sand and mud with cyclical patterns, bidirectional lenses and abundant mud layers, suggesting deposition mainly driven by river and tidal processes. The abandoned-channel fill consists entirely of organic-rich mud, suggesting a predominance of tidal processes. Other sedimentary facies include tidal-flat and marsh deposits; they mostly consist of mud and formed in shallow to subaerial areas near the channel margins or on barforms. Depending on the exact location of the core in this depositional setting, three possible stratigraphic successions and facies models are presented herein. Near channel margins, the deposits show an upward gradual change from heterolithic to mud with a well-developed fining-upward trend. Away from the channel margins, the deposits show an upward sharp change from heterolithic to mud due to the channel abandonment. The mouth-bar-area facies model shows an upward gradual change from heterolithic to heterolithic/sand to mud deposits with a coarsening-upward to fining-upward trend. Although differences among systems likely exist, the authors suggest that the sedimentary facies described in this study and the resulting facies models should be used to better understand tide-dominated deltaic systems and to improve their interpretation in the geological record.

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INTRODUCTION

Tide-dominated deltas are often interpreted in the geological record from sandstone-dominated successions (e.g. Tanavsuu-Milkeviciene & Plink-Bjorklund, 2009; van Cappelle et al., 2016; Levell et al., 2020), but in modern systems they show mud-dominated or highly heterolithic sediments, although they could be sandier in the upstream river-dominated portion of their channels or in locally wave-dominated beach ridges (e.g. Harris et al., 2004; Wang et al., 2009; Tamura et al., 2012; Gugliotta et al., 2017). Based on this difference in grain size, together with other incongruences and uncertainties regarding sedimentary structures as diagnostic indicators of specific processes (e.g. Ainsworth et al., 2012; Flemming, 2016; Gugliotta et al., 2016), the interpretations of ancient tide-dominated deltas have often been questioned (e.g. Walker, 1992; Goodbred & Saito, 2012; Gugliotta et al., 2016). On the other hand, sedimentological studies on Holocene and modern tide-dominated deltas typically focus on the hydro-sedimentary dynamics, sediment budgets and Holocene coastal evolution, among others (e.g. Goodbred & Kuehl, 1999; Hori et al., 2002; Ta et al., 2002; Ogston et al., 2008; Nowacki et al., 2015; Glover et al., 2021). Although these studies provide outstanding results for their scopes, detailed description and interpretation of the sedimentary facies are seldom presented. As a consequence of these arguments, it follows that the sedimentary facies of tide-dominated deltas and their depositional elements (for example, channels, bars) remain still poorly understood, if not in broad terms (e.g. Dalrymple & Choi, 2007; Goodbred & Saito, 2012), and are a topic of recent scientific debate.

To help resolve this issue, Late Holocene successions are extremely important because, in many cases, they are still linked to their depositional environment and are more easily interpreted compared to older successions. This higher level of certainty can help to build a model of expected sedimentary facies in the various sub-environments of tide-dominated deltas. Furthermore, although studies of modern environments are also useful in this sense, core-based studies of Late Holocene successions allow better stratigraphic control compared, for example, to surface grab samples or measurements of suspended-sediment concentrations in modern environments (e.g. Nowacki et al., 2015; Gugliotta et al., 2017). Finally, if modern environments are subjected to various modifications of the hydro-sedimentary regime and morphology because of human impacts through dams, sand mining, dykes and others (see Anthony et al., 2014; Li et al., 2017), in Late Holocene successions these issues are much less relevant and more natural conditions can be expected.

This study examines a core dataset through the Late Holocene succession of the Mekong River Delta (MRD) with the aim of understanding the sedimentary facies and depositional elements of this tide-dominated system. The core sites were carefully selected within the margins of the Ba Lai palaeochannel and its associated mouth bar; this is the only major distributary channel of the MRD that was abandoned and infilled with sediment during the Late Holocene (Tamura et al., 2012; Gugliotta et al., 2021), providing a unique opportunity to investigate sedimentary facies of distributary channels and mouth bars in tide-dominated deltaic settings. Because of the general context of the core sites and the known hydro-sedimentary dynamics in the nearby present-day distributary channels and mouth areas in the MRD, the depositional environment and processes of the studied deposits are already relatively well-known or at least easier to interpret. Therefore, the sedimentary facies that will be described in this study, will provide more reliable results compared to studies of older successions and should be used as a solid base to build new facies models. The present study aims at providing, using a core dataset from the Ba Lai palaeochannel, a significant advance on facies models of tide-dominated deltas, which remain poorly understood compared to their fluvial-dominated and wave-dominated counterparts.

REGIONAL BACKGROUND

The MRD, in southern Vietnam (Fig. 1A), is fed by one of the longest rivers in the world, with a
very large drainage-basin area, delta-plain area, average annual river discharge and annual sediment yield (Syvitski & Saito, 2007; Milliman & Farnsworth, 2011). Delta progradation initiated at approximately 8 ka, together with other similar systems, in response to a deceleration in global sea-level rise (Stanley & Warne, 1994; Tamura et al., 2009). Since then, the delta has prograded more than 200 km, with the shoreline migrating from Cambodia to its present-day position (Stanley & Warne, 1994; Tamura et al., 2009). After its initiation, the MRD was a tide-dominated delta sheltered from waves by a bedrock in the north-east; however, as the deltaic shoreline prograded seaward it became increasingly exposed to waves and evolved into a tide-dominated and wave-dominated delta at approximately 3 ka (Ta et al., 2002, 2005). The present-day delta is a mixed-energy system characterized by an upstream to downstream transition from river to tide-dominated distributary channels (Nowacki et al., 2015; Gugliotta et al., 2017) and a wave and tide-dominated shoreline (Ta et al., 2002, 2005; Tamura et al., 2010). The delta area and the lower drainage basin are characterized by a tropical savannah to monsoon climate of the Köppen–Geiger classification (Peel et al., 2007) with a rainy summer generating high river discharge and a dry winter associated with low river discharge. Wind and wave direction and energy vary seasonally, with the summer monsoon generating weaker longshore currents towards the north-east and the winter monsoon causing stronger longshore currents and an overall prevailing net sediment transport towards the south-west (Fang et al., 2006; Tamura et al., 2010). The shoreline area is mesotidal, with tides observed in channels more
than 300 km upstream of the river mouths and brackish water intruding up to approximately 50 km during the dry season (Gugliotta et al., 2017). The delta plain is intersected by numerous beach ridges, seven active distributary channels and the abandoned Ba Lai palaeochannel (Fig. 1B), in addition to a dense network of smaller natural and artificial canals. The downstream tracts of the distributary channels (i.e. the final 85 to 100 km) show a distinctive morphology with low sinuosity and seaward-widening and seaward-shallowing trends, which was associated with an overall dominance of tidal processes therein (Gugliotta et al., 2017; Gugliotta & Saito, 2019). In these downstream tracts, sediments mainly consist of sand–mud alternations with relatively high and variable mud content, which were also associated with the tidal dominance (Gugliotta et al., 2017, 2018a, 2019; Jiang et al., 2020). Also, these areas are characterized by variable and relatively high suspended-sediment concentrations indicating the formation of turbidity maxima that play a major role in deposition of mud (Wolanski et al., 1998; Nowacki et al., 2015; Le et al., 2020).

The Ba Lai palaeochannel, which is the objective of this study, is located within the tide-dominated area of the MRD. The palaeochannel margins, as well as the outlines of an ancient mouth bar, are visible in satellite images due to the contrast in elevation and vegetation with the surrounding areas, and because of the discontinuities of beach ridges (Fig. 1B). The palaeochannel was abandoned at 0.7 ka because of an increase in sediment supply at the regional scale that also caused other changes in the south-western part of the MRD and that was likely favoured by allogenic factors (i.e. human impact and/or climate change; Tamura et al., 2012, 2020; Gugliotta et al., 2021). After its abandonment the Ba Lai palaeochannel rapidly stored approximately 600 Mt of sediment in a time range of 45 to 263 years (Gugliotta et al., 2021), causing the almost complete infill of the channel and its preservation as a relict feature. Currently, only a minor portion of the channel remains with flowing water, and it is connected to the deltaic network through a small artificial canal.

**METHODS**

Eight cores were collected from the area of Ba Lai palaeochannel in 2019. This dataset includes the cores used by Gugliotta et al. (2021) to constrain the abandonment timing and mechanisms of the Ba Lai palaeochannel, in addition to four new cores mainly from the mouth-bar area. Two of the cores (BL1 and BL2) are 20 m long and were drilled mechanically as boreholes, whereas the remaining six cores (BL1a, BL3a, BL3b, BL3c, BL3d and BL4a) vary in length between 4.2 m and 5.3 m, and were obtained manually with a peat corer (Table 1). The surface elevations of the core sites were estimated from topographic maps and varied from 0.9 to 2.0 m. Core recovery ranged from 78.8 to 91.8%. The margins of the palaeochannel were constrained in QGIS using a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) obtained from the United States Geological Survey (https://earthexplorer.usgs.gov/) and satellite images from the Google Geological Survey.

In the laboratory, cores were split, photographed, described and sampled for X-radiography, shell identification and age dating. The description included the recording of the sediment grain size, vertical trends, sedimentary structures, as well as trace and body fossils, and was used, together with the general context of the palaeochannel, to differentiate nine sedimentary facies (Table 2). Bioturbation intensity was also recorded using the Bioturbation Index (BI) of Taylor & Goldring (1993). X-radiographs were acquired for selected intervals of the cores using 20 cm long slabs with a SOFRON SRO-i503-2 (Sofron Inc., Tokyo, Japan) instrument coupled with a digital X-ray detector NAOMI NX-04SN (RF Inc., Nagano, Japan). Mollusc species from four samples were photographed, identified and interpreted in terms of depositional environments based on ecological data of Okutani (2000).

Accelerator Mass Spectrometry radiocarbon (AMS 14C) dating was carried out at Beta Analytic Inc. on 27 samples of plant matter and shells (Table 3). The conventional ages were calibrated using the software Calib version 7.1.0 applying the curves IntCal13 for plant material samples and MARINE13 for shell samples (Stuiver & Reimer, 1993; Reimer et al., 2013; Stuiver et al., 2020). A delta R of ~60 years, which was a weighted mean of two data points near the MRD region (Southon et al., 2002; Dang et al., 2004), was used for the calibration of shell samples.

Optically-Stimulated-Luminescence (OSL) dating was conducted on eight samples of quartz silt and sand (Table 4). Samples were collected from the split section of borehole cores, wrapped with aluminium foil, and processed under controlled red light to determine the equivalent dose (De)
and the final OSL ages using the procedure outlined in detail in Collins et al. (2021). Measurements were carried out with a TL-DA-20 Risø TL/OSL reader (Risø Kagaku, Tokyo, Japan) equipped with blue LEDs for stimulation and a $^{39}$Sr/$^{90}$Y beta source for irradiation. Emitted luminescence through a Hoya U-340 filter (Hoya Corporation, Tokyo, Japan) was measured with a photomultiplier tube. The environmental dose rate was determined considering contributions of radionuclides in sediments and cosmic rays and using the Dose Rate and Age Calculator software of Durcan et al. (2015). Three sand samples from core BL1 showed OSL signals above the saturation level and thus their OSL ages could not be quantified accurately (Wintle & Murray, 2006). For these samples, $D_0$ of the single saturation exponential curve of the dose-response were determined instead of $D_e$ to estimate minimum ages.

Age–depth models and accumulation rates were calculated using the Bacon age–depth modelling software (Blaauw & Christen, 2011), with depth data every 10 to 20 cm and ages calculated to the depth of the uppermost dating sample. In this paper, both AMS $^{14}$C and OSL ages are expressed as the median value and in ka relative to 2020 CE. The ages obtained from the two different methods fit well with one another and were combined to constrain the chron stratigraphy of these deposits. Only three AMS $^{14}$C ages were inconsistent with the surrounding stratigraphy and/or showing age reversals; these ages were interpreted as the result of reworking or rooting and were not considered further.

RESULTS

Sedimentary facies

The nine sedimentary facies recognized in this study (Table 2) are herein described and interpreted from top to bottom. The first six facies represent the evolution of the Ba Lai palaeochannel, including its pre-abandonment and post-abandonment deposits, whereas the remaining three facies represent pre-channel deposits of different ages (Late Holocene, Middle Holocene and Pleistocene). This paper focuses on the Late Holocene stratigraphic evolution and sedimentary facies of the tide-dominated Ba Lai palaeochannel and therefore pre-channel deposits, especially older ones from the Middle Holocene and Pleistocene, are described and interpreted with less detail.
Table 2. Characteristics of the sedimentary facies identified in this study.

| Phase               | Facies                  | Thickness (m) | Description                                      | Main features                                                                 | Trace fossils                      | Body fossils               | Sed. acc. rates (cm year\(^{-1}\)) | Age range (ka) | Interpretation                                      |
|---------------------|-------------------------|---------------|--------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------|-----------------------------|-------------------------------------|----------------|-----------------------------------------------------|
| Post-abandonment    | Soil                    | 0.1 to 1.5    | Oxidized structureless mud or sand with root traces | Oxidation, root traces, in some cases coarsening-upward                         | Root traces; BI 4–5               | –                          | –                                   | –              | Recent subaerial exposure                         |
|                     | Abandoned-channel fill  | 1.5 to 6.3    | Structureless silty clay with root traces and plant matter | Root traces, plant fragments, burrows, faint parallel lamination              | Root traces, unidentified burrows; BI 0–5                                     | –                          | 1.9 to 11.1                         | 0.73 to 0.66 | Deposition in a channel detached from deltaic network |
| Pre-abandonment     | Marsh deposits          | 0.5 to 2.0    | Structureless silty clay with root traces and plant matter | Root traces, plant fragments                                                  | Root traces, unidentified burrows; BI 1–5                                     | –                          | 0.8 to 0.9                            | 1.77 to 1.02 | Deposition in upper intertidal to supratidal marsh areas |
|                     | Tidal-flat deposits     | 1.0 to 4.1    | Clay with silt laminae and lenses and root traces   | Clay drapes, parallel (inter)lamination, cyclical patterns, lenses, burrows, root traces, fining-upward | Root traces, **Planolites**, **Annicolites**, **Polykladichnus**; BI 0–5       | –                          | 0.7 to 1.4                            | 2.57 to 1.38 | Deposition in channel attached to deltaic network   |
|                     | Active-channel fill     | 2.4 to 3.8    | Clay with silt to fine sand laminae and lenses      | Clay drapes, fluid muds, mud clasts, parallel (inter) lamination, cyclical patterns, (bidirectional) lenses, burrows, fining-upward | Root traces, **Planolites**, **Annicolites**, **Chondrites**, **Gastrochaenolites**, **Planolites**, **Polykladichnus**, **Skolithos**, **Tetenaria**, **Thalassinoides**; BI 0–4 | Potamocorbula sp., microfossils, shell fragments | 0.1 to 0.5 | 3.41 to 2.29 | Deposition on shelf, basinward of river mouth |
|                     | Mouth-bar deposits      | 1.7 to >2.2   | Clay to fine sand arranged in (inter)laminae and (inter)bedding with lenses | Clay drapes, fluid muds, mud clasts, parallel (inter) lamination, cyclical patterns, lenses, burrows, coarsening-upward | Root traces, **Planolites**, **Annicolites**, **Thalassinoides**, **Polykladichnus**; BI 0–3 | Shell fragments | 0.5 to 1.4 | 5.23 to 4.75 | Prodelta                                       |
| Pre-channel         | Shell layers            | 0.3 to 1.3    | Structureless silty clay with shells or carbonate concretions | Shells, carbonate concretions, borings into shells                          | Sedilichnus                      | –                          | 3.41 to 2.29 | Deposition on shelf, basinward of river mouth |
|                     |                        | >8.3          | Alternations of clay and silt or mottled mud       | Parallel (inter)lamination, mottling, carbonate concretions, coarsening-upward | **Skolithos**, **Planolites**, **Annicolites**; BI 0–5                       | Sponge spicules                   | 5.23 to 4.75 | 98      | Estuary                                      |
|                     | Mid-Holocene deposits   | >7.5          | Alternations of clay to fine sand, or mottled sand or mud | Clay drapes, fluid muds, mud clasts, parallel (inter) lamination, mottling, oxidation, fining-upward | **Thalassinoides**; BI 0–5                       | –                          | –                                   | >98           |                                                        |

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Table 3. Details of the AMS $^{14}$C dating.

| Core | Sample elevation (m) | Material | Conventional age (years BP) | Calibrated age: median (cal BP) | $\Delta^{13}$C (‰) | Probability (cal BP) | 2 sigma range (cal BP) | Probability (cal BP) |
|------|----------------------|----------|----------------------------|--------------------------------|------------------|---------------------|---------------------|---------------------|
| BL1  | –1.70                | Plant    | 1270 ±30                   | 1225                           | 0.968            | –28.99              | 1158–1147           | 0.013               |
|      | –4.40                | Plant    | 1660 ±30                   | 1563                           | 0.030            | –24.49              | 1689–1671           | 0.002               |
|      | –6.52                | Plant    | 1780 ±30                   | 1699                           | 0.17             | –27.99              | 1745–1616           | 0.818               |
| BL1  | –10.20               | Shell    | 3400 ±30                   | 3341                           | 1.00             | –4.02               | 3426–3242           | 0.002               |
|      | –10.35               | Shell    | 3230 ±30                   | 3124                           | 1.00             | –3.95               | 3226–3010           | 0.002               |
|      | –1.23                | Plant    | 880 ±30                    | 788                            | 0.281            | –27.99              | 908–845             | 0.017               |
|      | –2.44                | Plant    | 560 ±30                    | 593                            | 0.719            | –28.53              | 642–588             | 0.477               |
| BL2  | –4.20                | Plant    | 620 ±30                    | 601                            | 0.78             | –29.65              | 658–551             | 0.477               |
|      | –5.08                | Plant    | 640 ±30                    | 599                            | 0.041            | –29.85              | 667–621             | 0.477               |
|      | –8.15                | Shell    | 1700 ±30                   | 1307                           | 0.574            | –5.33               | 1374–1251           | 0.574               |
| BL2  | –9.53                | Plant    | 1310 ±30                   | 1253                           | 0.281            | –26.84              | 1294–1224           | 0.281               |
|      | –10.20               | Shell    | 2480 ±30                   | 2217                           | 0.006            | –27.61              | 2303–2123           | 0.006               |
| BL2  | –11.35               | Plant    | 4410 ±30                   | 4981                           | 0.003            | –27.61              | 5257–5249           | 0.003               |
| BL2  | –11.98               | Plant    | 4520 ±30                   | 5158                           | 0.337            | –28.60              | 5305–5212           | 0.337               |
| BL1a | –3.15                | Plant    | 4220 ±30                   | 4751                           | 0.451            | –29.16              | 4853–4801           | 0.451               |
| BL3a | –0.40                | Plant    | 1030 ±30                   | 946                            | 0.029            | –26.17              | 1048–1030           | 0.029               |
| BL3a | –2.70                | Plant    | 1360 ±30                   | 1290                           | 0.965            | –27.34              | 1334–1257           | 0.965               |
| BL3a | –3.20                | Shell    | 1860 ±30                   | 1467                           | 0.007            | –1.28               | 1546–1376           | 0.007               |
| BL3b | –0.42 m              | Plant    | 230 ±30                    | 213                            | 0.487            | –25.19              | 418–413             | 0.487               |
|      | –1.60 m              | Plant    | 1410 ±30                   | 1317                           | 0.422            | –26.31              | 1359–1285           | 0.422               |
|      | –2.45 m              | Plant    | 420 ±30                    | 491                            | 0.059            | –31.80              | 523–435             | 0.059               |
| BL3c | –3.15                | Plant    | 1700 ±30                   | 1603                           | 0.074            | –26.20              | 1697–1646           | 0.074               |
| BL3d | –1.80 m              | Plant    | 670 ±30                    | 641                            | 0.441            | –28.10              | 676–631             | 0.441               |
| BL3d | –2.45 m              | Plant    | 700 ±30                    | 664                            | 0.820            | –28.10              | 688–642             | 0.820               |
| BL3d | –4.15 m              | Plant    | 640 ±30                    | 599                            | 0.426            | –26.89              | 667–621             | 0.426               |
| BL4a | –1.73 m              | Plant    | 630 ±30                    | 600                            | 0.574            | –28.37              | 663–618             | 0.574               |
| BL4a | –4.10 m              | Plant    | 2050 ±30                   | 2013                           | 0.592            | –27.45              | 2113–2076           | 0.592               |

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Soil (Late Holocene to present-day)

Description. These deposits are found at the top of each core and vary in thickness between 0.1 m and 1.5 m (Figs 2 and 3). They typically overlie with a gradational contact the abandoned-channel fill or marsh deposits. The sedimentary facies consists of oxidized reddish sand and/or mud with sparse plant fragments, root traces and patches marked by colour changes (Fig. 4A). This facies is commonly structureless or shows localized parallel lamination and displays either no vertical trend or a coarsening-upward trend. Bioturbations consist of root traces and typically show BI of 4 to 5.

Interpretation. This sedimentary facies is interpreted as soil developed under subaerial conditions. The soil formed due to pedogenesis of pre-existing deposits likely similar to the underlying facies (abandoned-channel fill or marsh deposits); however, the soil with a coarsening-upward trend might have formed from incipient levee deposits of the palaeochannel. Similar coarsening-upward levees are present and better developed in the upstream part of the Mekong River in Cambodia (Gugliotta et al., 2018b). No dating is available from this facies, but its stratigraphic context clearly suggests a sub-recent to recent age (for example, last few centuries to decades).

Abandoned-channel deposits (post-abandonment channel phase – Late Holocene)

Description. These deposits are found in cores BL1a, BL2, BL3d and BL4a and vary in thickness between 1.5 m and 6.3 m (Figs 2 and 3). They typically overlie with a sharp contact the active-channel fill or, in one case, tidal-flat deposits. The sedimentary facies consists of grey to brown, organic-rich, silty clay with abundant plant fragments and root traces (Figs 4B and 5A). This facies is structureless or shows a faint horizontal lamination marked by millimetre-scale layers of plant fragments. No clear vertical grain-size trend is visible. Bioturbation mainly consists of root traces with rare unidentified small burrows, with BI varying from 0 to 5. Seven of the eight AMS 14C ages from this facies indicate consistent values of 0.73 to 0.66 ka (Table 3). The remaining age in core BL2 is 0.86 ka but defines an age reversal as it is older than three underlying ages consistently within the range of 0.66 to 0.67 ka in cluster (Fig. 2). Sediment accumulation rates of this facies are typically high with values ranging from 1.9 cm

| Sample | Core elevation (m) | Material | Grain size (µm) | K (%) | U (ppm) | Th (ppm) | Rb (ppm) | Water content (%) | Dose rate (Gy) | D_e (Gy) | Age (ka) | No. aliquots |
|--------|-------------------|----------|----------------|-------|---------|----------|----------|------------------|----------------|----------|-----------|--------------|
| BL1a   | -2.90             | Quartz   | 4–11           | 1.95  | 1.62    | 2.83     | 142.0    | 138.0            | 63             | 3.62 ± 0.14 | 3.62 ± 0.07 | 1.38 ± 0.08 | 6 (6)       |
|        | -5.10             | Quartz   | 4–11           | 1.86  | 2.65    | 138.0    | 137.0    | 60               | 2.54 ± 0.13 | 3.68 ± 0.05 | 1.45 ± 0.08 | 6 (5)       |
|        | -8.80             | Quartz   | 4–11           | 1.86  | 2.65    | 138.0    | 137.0    | 45               | 2.54 ± 0.13 | 3.68 ± 0.05 | 1.45 ± 0.08 | 6 (5)       |
|        | -10.90            | Quartz   | 4–11           | 1.94  | 3.26    | 156.0    | 150.0    | 71               | 2.58 ± 0.13 | 8.27 ± 0.11 | 3.21 ± 0.17 | 6 (5)       |
|        | -13.25            | Quartz   | 120–180        | 0.79  | 1.11    | 110.0    | 106.0    | 21               | 1.57 ± 0.12 | > 100      | > 100     | > 100       |
|        | -16.40            | Quartz   | 120–180        | 1.23  | 1.11    | 74.5     | 72.5     | 71               | 1.69 ± 0.13 | > 182      | > 182     | > 182       |
|        | -18.36            | Quartz   | 120–180        | 1.43  | 1.25    | 81.1     | 80.1     | 80               | 1.88 ± 0.15 | > 185      | > 185     | > 185       |
|        | -18.40            | Quartz   | 120–180        | 1.76  | 2.60    | 13.10    | 13.10    | 46               | 2.62 ± 0.15 | 12.47 ± 0.17 | 4.75 ± 0.28 | 6 (6)       |

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year$^{-1}$ to 3.1 cm year$^{-1}$ in core BL2 and reaching up to 11.1 cm year$^{-1}$ in core BL3d (Fig. 6).

**Interpretation.** This sedimentary facies is interpreted as abandoned-channel fill, representing sediment accumulation in a channel likely detached from the deltaic network where the sediment supply from upstream had been cut-off or highly reduced. It is also possible that a partial connection to the deltaic system was still present, but this had likely been reduced to the point that only the mud fraction was being supplied from upstream. Instead, it is suggested that most of the sediment infilling this abandoned channel would be supplied from its mouth by the action of tidal currents, after being transported to the shelf mainly by channels located north-eastward of the Ba Lai palaeochannel (Tamura *et al.*, 2012; Gugliotta *et al.*, 2021). This is consistent with the general dynamics of the present-day MRD, with sediment being exported by the channels during high flow and partially reimported from the shelf during low flow (Nowacki *et al.*, 2015; Gugliotta & Saito, 2019; Jiang *et al.*, 2020), and with a longshore net sediment transport towards the south-west (Fang *et al.*, 2006; Tamura *et al.*, 2010). The consistent ages and high sediment accumulation rates for the abandoned-channel fill suggest that the channel was abandoned abruptly at approximately 0.7 ka and infilled rapidly in the order of decades to a few centuries (Gugliotta *et al.*, 2021).

**Marsh deposits (pre-abandonment channel phase – Late Holocene)**

**Description.** These deposits are found in cores BL1, BL3a, BL3b and BL3c, and vary in thickness between 0.5 m and 2.0 m (Figs 2 and 3). They typically overlie with a gradual contact tidal-flat deposits. The sedimentary facies consists of grey to brown, organic-rich, silty clay with abundant plant fragments and root traces (Fig. 4C). This facies is structureless and shows no clear vertical grain-size trend. Bioturbation mainly consists of root traces and rare unidentified small burrows, with BI varying from 1 to 5. The only AMS $^{14}$C age from this facies in core BL1 indicates a value of 1.30 ka (Table 3), whereas sediment accumulation rates vary between 0.8 cm year$^{-1}$ and 0.9 cm year$^{-1}$ (Fig. 6).

**Interpretation.** This facies is interpreted as marsh deposits representing an upper intertidal to supratidal environment located near channel margins or on bar tops. Marsh deposits and the abandoned-channel fill show similar sedimentological features, but the two facies were differentiated based on the stratigraphic context and other differences. Marsh deposits show a more gradual contact with the underlying deposits, lower accumulation rates and are thinner and older compared to the abandoned-channel fill. The general context of the cores highlights that marsh deposits are found either near channel margins (for example, core BL1) or overlying barforms (for example, BL3a, BL3b and BL3c). This, together with their older age, suggests that marsh deposits accumulated in areas that were more elevated than the adjacent channel bed and became subaerial before the channel abandonment.

**Tidal-flat deposits (pre-abandonment channel phase – Late Holocene)**

**Description.** These deposits are found in cores BL1, BL1a, BL3a, BL3b and BL3c and vary in thickness between 1.0 m and 4.1 m (Figs 2 and 3). They typically overlie with a gradual contact the active-channel fill or mouth-bar deposits or, in one case, pre-channel deposits. The sedimentary facies consists of grey to brown clay with silt laminae and lenses forming millimetre-scale interlaminations (Figs 4D, 5B and 5C). These alternations commonly show apparent cyclical patterns in the distribution and thickness of the laminae (for example, Fig. 5C). The deposits of this facies show a general fining-upward trend. Plant fragments and root traces are common (Fig. 7A) and the trace-fossil assemblage also includes Planolites, Arenicolites and Polyk-ladichnus (Fig. 7B). Traces show variable intensity and distribution, with BI varying from 0 to 5. Three of the four AMS $^{14}$C ages and two OSL ages from this facies indicate values between 1.77 ka and 1.02 ka (Tables 3 and 4), whereas the remaining AMS $^{14}$C age in core BL3b indicates a value of 0.28 ka, but was inconsistent with the surrounding stratigraphy. Sediment accumulation rates of this facies, calculated mainly for core BL1, vary between 0.7 cm year$^{-1}$ and 1.4 cm year$^{-1}$ (Fig. 6).

**Interpretation.** This facies is interpreted as tidal-flat deposits representing a subtidal to intertidal environment located near channel margins or on bar tops. Sand–mud alternations and cyclical patterns suggest a dominance of tidal processes, whereas the low diversity suite of traces is indicative of a stressed environment with varying salinity. Tidal-flat deposits are
typically associated with marsh deposits, and together accumulated near channel margins (for example, core BL1) or overlying barforms (for example, BL3a, BL3b and BL3c). The context and ages suggest that tidal-flat deposits accumulated in areas that were more elevated than the adjacent channel bed and became shallow to subaerial before the channel abandonment.

**Active-channel fill (pre-abandonment channel phase – Late Holocene)**

*Description.* These deposits are found in cores BL1, BL2 and BL4a and vary in thickness between 2.4 m and 3.8 m (Figs 2 and 3). They typically overlie with a gradational contact the mouth-bar deposits or with a sharp contact a shell layer. The sedimentary facies consists of grey to brown clay with silt to fine sand laminae and lenses forming millimetre to centimetre-scale alternations, although a few sand layers containing mud clasts are up to 20 cm thick (Figs 4E and 5D to F). Apparent cyclical patterns in the distribution and thickness of the laminae are sometimes present (for example, Fig. 5E) and, in a few cases, sand lenses show bidirectional patterns. Millimetre to centimetre-thick mud layers are ubiquitous. The average content of sand for this facies is approximately 25%, making the deposits heterolithic and overall mud-dominated. The deposits of this facies also show general thinning-upward and fining-upward trends. Root traces are present, but rarer compared with all the other facies described above. The trace-fossil assemblage includes *Arenicolites, Chondrites, Gastrochaenolites, Planolites, Polykladichnus, Skolithos, Taenidium* and *Thalassinoides* (Fig. 7C to E). Traces are mainly found in the mud and they are either sand or mud filled; they show variable intensity and distribution and are often concentrated in certain intervals that occur irregularly (for example, Fig. 5D). The BI varies from 0 to 4. Shells are sometimes found and include the mollusc *Potamocorbula* sp. (Fig. 8A), shell fragments and unidentified microfossils. Three AMS 14C ages and one OSL age from this facies indicate values between 2.57 ka and 1.32 ka (Tables 3 and 4). Sediment accumulation rates are generally low with values ranging between 0.1 cm year\(^{-1}\) and 0.5 cm year\(^{-1}\) in all cores where this facies is present (Fig. 6).

**Interpretation.** This sedimentary facies is interpreted as active-channel fill, representing sediment accumulation in a distributary channel connected to the deltaic network and with significant sediment supply from upstream. This facies shows similar sand—mud proportions and sedimentary structures to the sediments of the present-day tide-dominated distributary channels of the MRD (Gugliotta et al., 2017, 2018a, 2019; Jiang et al., 2020) suggesting, together with the general context of the Ba Lai palaeochannel, similar hydro-sedimentary dynamics. Sand—mud alternations, cyclical patterns and bidirectional lenses generally suggest a dominance of tidal currents. Mud clasts are similar to those identified along the present-day distributary channels by Gugliotta et al. (2018a), and likely generated through deposition—erosion cycles due to tidal and river processes. The large amount of mud present in this facies is interpreted to represent mud drapes and fluid muds that are likely associated with the presence of a turbidity maximum and import and/or in-channel storage of fine-grained sediments that is typical of tide-dominated distributary channels (Gugliotta & Saito, 2019). Field measurements in the present-day distributary channels of the MRD show that the suspended-sediment concentrations often exceed the threshold of 400 mg l\(^{-1}\) beyond which fluid mud can form, and can even exceed 1000 mg l\(^{-1}\) (Nowacki et al., 2015; Le et al., 2020). Although river-derived sedimentary structures were not recognized, the authors suggest that this sediment was supplied mostly by the river from upstream and the presence of the coarser fraction itself (up to fine sand) is evidence of river processes. The relatively high trace fossil diversity suggests more persistent and higher water salinity compared to other facies above (cf. La Croix et al., 2015), whereas *Potamocorbula* sp. also suggests subtidal to intertidal brackish waters (Okutani, 2000). The concentration of traces in certain intervals might indicate times of little or no deposition likely related to the variability of the river discharge at the seasonal scale (cf. Gingras

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**Fig. 2.** Sedimentological logs of the long cores BL1 and BL2 with information about sedimentary features, trace and body fossils, ages and interpretations. Grain-size scale: cl = clay; si = silt; vfs = very-fine sand; fs = fine sand; ms = medium sand. From Gugliotta et al. (2021).
Fig. 3. Sedimentological logs of the short cores BL1a, BL3a, BL3b, BL3c, BL3d and BL4a with information about sedimentary features, trace and body fossils, ages and interpretations. Grain-size scale: cl = clay; si = silt; vfs = very-fine sand; fs = fine sand; ms = medium sand. See Fig. 2 for legend. Logs of cores BL3d and BL4a are modified from Gugliotta et al. (2021).

Fig. 4. Selected photographs of the sedimentary facies recognized in this study. (A) Soil consisting of oxidized reddish silty clay (core BL4a, 1.00 m to 0.85 m). (B) Abandoned-channel fill consisting of grey to brown structureless silty clay with plant fragments and root traces (core BL4a, −0.45 m to −0.60 m). (C) Marsh deposits consisting of grey to brown structureless silty clay with plant fragments and root traces (core BL3b, 1.00 m to 0.85 m). (D) Tidal-flat deposits consisting of grey to brown clay and silt interlaminations with root traces (core BL1, −4.55 m to −4.70 m). (E) Active-channel fill consisting of grey to brown clay with fine sand laminae and lenses (core BL1, −6.80 m to −6.95 m). (F) Mouth-bar deposits consisting of grey to brown clay with sand layers (core BL3c, −3.73 m to −3.88 m). (G) Shell layer consisting of grey silty clay with abundant shells (core BL1, −10.20 m to −10.35 m). (H) Mid-Holocene deposits consisting of grey mottled mud (core BL2, −14.20 m to −14.35 m). (I) Pleistocene deposits consisting of reddish oxidized mottled mud (core BL1, −12.85 m to −13.00 m).
et al., 2002); nonetheless, due to the irregular distribution of the bioturbated intervals, a clear seasonal bedding was not identified, likely because of the intense tidal reworking in this area.

Mouth-bar deposits (pre-abandonment channel phase – Late Holocene)

Description. These deposits are found in cores BL2, BL3a, BL3b and BL3c and vary in thickness between 1.7 m and 2.2 m, although in the
Fig. 6. Age–depth models and accumulation rates for five of the cores based on AMS $^{14}$C and OSL (Optically-Stimulated-Luminescence) ages. Model of core BL2 is modified from Gugliotta et al. (2021).
majority of cases they were cored only partially and thus are probably thicker (Figs 2 and 3). In the only case where the lower contact was intersected (core BL2), these deposits overlie relatively sharply a shell layer. The sedimentary facies consists of grey to brown clay to fine sand arranged in millimetre to decimetre-scale interlamination and interbedding (Figs 4F, 5G and 5H). Millimetre to centimetre-thick mud layers are ubiquitous. Apparent cyclical patterns in the distribution and thickness of the laminae are sometimes present for thinner layers (for example, Fig. 4F), but thicker sand layers seem to be distributed randomly. Sandier intervals are also present and may reach a thickness up to approximately 1 m (core BL3a), although they still show abundant mud drapes, thicker mud layers (i.e. fluid muds) and mud clasts. The average content of sand for this facies is 41% and generally increases basinward from core BL2 (18%), through cores BL3c (49%) and BL3b (44%), to core BL3a (55%). The deposits of this facies show a general coarsening-

Fig. 7. Selected photographs and X-radiographs of trace fossils. (A) Root traces in tidal-flat deposits (core BL1, ca –3.90 m). (B) Polykladichnus (Py) and Arenicolites (Ar) in tidal-flat deposits (core BL1, ca –5.75 m). (C) Gastrochaenolites (Ga) and Arenicolites in active-channel fill (core BL2, ca –6.60 m). (D) Taenidium (Ta) and Arenicolites in active-channel fill (core BL1, ca –7.30 m). (E) Chondrites (Ch) in active-channel fill (core BL1, ca –9.20 m). (F) Thalassinoides (Th) and Arenicolites in mouth-bar deposits (core BL2, ca –9.80 m).
upward trend. The trace-fossil assemblage includes Arenicolites, Polykladichnus and Thalassinoides (Fig. 7F). Traces are mainly found in the mud and they are either sand or mud filled; they show variable intensity and distribution, and are often concentrated in certain intervals that occur irregularly (for example, Fig. 5G). The BI varies from 0 to 3. Shell fragments are sometimes found. Five of the six AMS $^{14}$C ages from this facies indicate values between 1.67 ka and 1.32 ka, whereas the remaining age in core BL3b indicates a value of 0.56 ka, but was inconsistent with the surrounding stratigraphy. Sediment accumulation rates, calculated for this facies in cores BL2 and BL3a, show values ranging from 0.5 cm year$^{-1}$ to 1.4 cm year$^{-1}$ (Fig. 6).

Interpretation. This sedimentary facies is interpreted as mouth-bar deposits representing sediment accumulation near the river mouth and associated with the general progradation of the system. This facies is similar to the active-channel fill but shows higher proportion of sand, higher sediment accumulation rates and a different vertical trend (i.e. coarsening-upward). Also, the presence of this mouth bar is evident as this is clearly visible in aerial view around the locations of the cores displaying this facies (Fig. 1B). The ages of this facies, combined with the shoreline chronology of Tamura et al. (2012), also confirm that these deposits accumulated basinward of the channel, near its mouth. Similar mouth bars are seen at the mouth of the present-day distributary channels of the MRD (e.g. Tanaka et al., 2016). As for the active-channel fill, the sand–mud proportions, sedimentary structures and general context suggest a combination of river and tidal processes. The higher concentrations of sand and its increase towards the most basinward core (BL3a) may be due to the wave processes that resuspended mud and increased sand concentrations in these deposits (Tamura et al., 2010; Kanai et al., 2013a,b; Fricke et al., 2017; Stephens et al., 2017). The trace-fossil assemblage is not as diverse as for the active channel fill, perhaps because of the higher sedimentation rates and the additional stress generated by wave processes.

Fig. 8. Selected photographs of the mollusc shells. (A) Potamocorbula sp. in the active-channel fill (core BL2, −8.15 m). (B) Talonostrea talonata Li & Qi in a shell layer (core BL2, −10.20 m). (C) Crassostrea sp. in a shell layer (core BL1, −10.20 m). (D) Moerella jedoensis (Lischke) in a shell layer, also showing the boring Sedilichnus (core BL2, −10.20 m). (E) Anomia chinensis Philippi in a shell layer (core BL2, −10.20 m).
processes in the river-mouth area. Nonetheless, it should also be noted that mouth-bar deposits are less represented in the two longest cores and/or intervals with X-radiographs, where trace fossils were more easily identifiable, and this could also explain the difference amongst the two facies. Due to the general context, the authors suggest that, as for the active-channel fill, mouth-bar deposits also formed in conditions with relatively persistent and high salinity. As for the active-channel fill, the concentration of traces in irregular intervals might indicate times of little or no deposition likely related to the variability of river discharge at the seasonal scale, associated with additional tidal reworking.

Shell layers (pre-channel phase – Late Holocene)

Description. These deposits are found in cores BL1 and BL2 and vary in thickness between 0.3 m and 1.3 m (Fig. 2). They overlie with a sharp contact Pleistocene or Mid-Holocene deposits. The sedimentary facies consists of structureless, grey, silty clay with abundant shells and/or carbonate concretions (Fig. 4G). Mollusc shells consist of Crassostrea sp., Ostrea sp., Talonostrea talonata Li & Qi, Moerella jedoensis (Lischke) and Anomia chinensis Philippi (Fig. 8B to E). In BL2 core, corals were also found, as well as the boring Sedilichnus into a shell (Fig. 8D). Three AMS $^{14}$C ages and one OSL age from this facies indicate values between 3.41 ka and 3.19 ka in core BL1 and of 2.29 ka in core BL2 (Tables 3 and 4).

Interpretation. This sedimentary facies is interpreted as shell layers forming in a shelf environment basinward of the river mouth and with limited terrigenous sediment supply. This shelf environment represents a phase prior to the full establishment of the Ba Lai channel. The ages of this facies, combined with the shoreline chronology of Tamura et al. (2012), also confirm that these deposits accumulated basinward of the channel, in a shelf environment. The different ages in cores BL1 and BL2 suggest that this shelf environment migrated basinward when the Ba Lai channel formed and with the continuation of the deltaic progradation. The shell assemblage suggests an environment in water depths of less than 20 m, brackish to fully marine salinity, and hard to soft substrate (Okutani, 2000). An analogue environment can be expected on the modern Sunda Shelf southeastward of the MRD (Szczuciński et al., 2013).

Prodelta deposits (pre-channel phase – Middle Holocene)

Description. These deposits are found in cores BL1a and BL2 and are up to 8.3 m thick, although they were cored only partially and thus are probably thicker (Figs 2 and 3). The sedimentary facies consists of alternations of grey clay and silt or mottled mud, with abundant carbonate concretions. The facies is structureless or shows parallel lamination and interlamination at the millimetre scale. The deposits of this facies show a general coarsening-upward trend. The trace-fossil assemblage includes Arenicolites, Planolites and Skolithos, with BI ranging from 0 to 5 that generally increases upward. Sponge spicules were also found. Three AMS $^{14}$C ages and one OSL age from this facies indicate values between 5.23 ka and 4.75 ka, and therefore within the Middle Holocene (Tables 3 and 4).

Interpretation. This sedimentary facies is interpreted as a prodelta environment formed prior to the establishment of the Ba Lai channel. The presence of this facies in only some of the cores suggests that these deposits accumulated in low-relief areas filling an existing topography. The sponge spicule and carbonate concretions suggest a marine environment with relatively high salinity.

Estuarine deposits (pre-channel phase – Pleistocene)

Description. These deposits are found in core BL1 and are 7.5 m thick, although they were cored only partially and thus are probably thicker (Fig. 2). The sedimentary facies consists of alternations of yellow, brown and reddish clay and fine sand passing upward to mottled sand and then to mottled mud (Fig. 4H). Signs of oxidation are present throughout but are particularly concentrated towards the top. The facies is structureless or shows parallel lamination, interlamination and interbedding at the millimetre to decimetre scale. The deposits of this facies show a general fining-upward trend. The trace-fossil assemblage mainly consists of Thalassinoides, with BI ranging from 0 to 5 that generally increases upward. Three OSL ages from this facies indicate ages >98 ka and therefore within the Pleistocene (Table 4).
Interpretation. This sedimentary facies is interpreted as an estuarine environment formed during the Pleistocene prior to the establishment of the MRD. The oxidation suggests subaerial exposure subsequent to this estuarine phase and prior to the development of the modern deltaic phase, possibly during the Last Glacial Maximum. During the early phase of development of the MRD, these deposits would represent the bedrock in a high-relief topography; nonetheless, this topography had possibly been flattened during the accumulation of the Mid-Holocene deposits and was not necessarily present when the Bai Lai channel formed.

DISCUSSION

Architecture of the Ba Lai palaeochannel

The palaeochannel was estimated to be up to 11 m thick, approximately 3 km wide and 50 km long, with a volume of 1.3 km$^3$ (Gugliotta et al., 2021). The channel base was intersected in the two longest cores (BL1 and BL2) at elevations of approximately −10 m (Fig. 9) and show a sharp contact with the underlying shell layers. Nonetheless, the preservation of the shelfal shell layers and the relatively limited age gap between shell layers and channel deposits suggest that the channel base is not particularly erosional, as could be expected in other channelized environments. At the same time, the ages of the shell layers clearly indicate that these did not form as ‘channel lags’ at the base of the channel deposits, but in a shelf environment prior to the formation of the Ba Lai palaeochannel. The channel deposits generally show fining-upward and thinning-upward trends with either a gradual transition from active-channel fill to tidal-flat and marsh deposits near the palaeochannel margins (for example, core BL1) or an abrupt change from active to abandoned-channel fill in the rest of the palaeochannel (for example, core BL2; Fig. 9). Instead, the mouth-bar deposits were estimated to be up to 9 m thick, more than 7 km long, approximately 2 km wide, and having a volume of 0.07 km$^3$ and a length to width ratio >3.5. This ratio is consistent with other tidal bars, that commonly tend to be elongated and oriented perpendicular to the shoreline in tide-dominated estuaries and deltas (Dalrymple et al., 2003; Dalrymple & Choi, 2007; Chaumillon et al., 2013). Nonetheless, it is also possible that the mouth-bar deposits described herein may represent multiple bars (i.e. a mouth-bar complex) although the relatively uniform ages from these deposits would imply that the entire mouth-bar complex formed in a relatively short time. Mouth-bar deposits show a lateral relationship with the active-channel fill and a general coarsening-upward trend (Fig. 10). In the majority of cases, mouth-bar deposits show an upward transition to tidal-flat and marsh deposits with a fining-upward trend following the coarsening-upward one of the mouth bar itself (for example, BLa–c; Fig. 10).

Evolution of the Ba Lai palaeochannel

The present dataset constrains the evolution of the ancient Ba Lai palaeochannel and its mouth and surrounding area in the Mekong River Delta (MRD). At 3.4 ka, the area consisted of a shelf environment with shell banks forming near the location of core BL1, but with no sedimentation in distal areas near core BL2 (Fig. 11A). The channel formed at 2.6 ka, with active-channel fill accumulating near core BL1 (Fig. 11B). This was a distributary channel connected to the deltaic network and with acting river and tidal processes. Due to the south-eastward progradation of the shoreline, the location of core BL4a was incorporated within the channel at around 2.1 ka, while shell-bank accumulation migrated from the location of core BL1 to that of core BL2 (Fig. 11C). At 1.4 ka, the shoreline had reached the location of core BL2, with a mouth bar forming between 1.7 ka and 1.3 ka near cores BL2, BL3a, BL3b and BL3c (Fig. 11D). This mouth bar was controlled by a combination of river, tidal and wave processes. Eventually, the mouth bar and other shallower areas near the channel margins (for example, core BL1) accumulated enough sediment to transition into tidal flats and subaerial marshes before the channel abandonment. Also, with the continuation of progradation the mouth bar was gradually incorporated within the channel. This process is well-known in deltas, and when persistent can lead to the formation of channel bifurcations due to the shallowing and expansion of these bars to form islands (Edmonds & Slingerland, 2007). Similar bifurcations are seen in the present-day MRD near the mouths of the Bassac, Co Chien and My Tho distributary channels, whereas the Ham Luong distributary channel shows an incipient bifurcation (Fig. 1B; Gugliotta et al., 2017). Also, a similar process with mouth bars becoming subaerial and forming new bifurcations is also visible in the present-day tide-dominated Yangtze River Delta.
in eastern China (Zhu et al., 2019). The bar/island at the mouth of the Ba Lai palaeochannel had likely not produced a full bifurcation yet, similar to the present-day Ham Luong channel. The preservation of the mouth bar was possible because this was already subaerial and incorporated in the channel when this latter was abandoned; this implies that the mouth bar was only partially buried by mud, making it possible to still see its outlines in satellite images. At 0.7 ka, the channel was abruptly abandoned and rapidly infilled with sediment (Fig. 11E) as suggested by the nearly coeval ages and high accumulation rates from the abandoned-channel fill (Gugliotta et al., 2021). During this phase, the channel became disconnected or only partly connected to the deltaic network and mainly with acting tidal processes, whereas river processes...
were absent or strongly reduced (Gugliotta et al., 2021). It is suggested that most of the sediment infilling this abandoned channel was supplied by tides from its mouth, after being transported to the shelf mainly by channels located northeastward of the Ba Lai palaeochannel (Tamura et al., 2012; Gugliotta et al., 2021). Since the abandonment, the shoreline prograded asymmetrically, reaching the present-day configuration of the area (Fig. 11F).

**Sedimentary facies and processes**

This study describes the sedimentary facies and process sedimentology of a tide-dominated distributary channel and its associated mouth bar. The active-channel fill and mouth-bar deposits show alternations of sand and mud, similar to what is reported from the present-day distributary channels of the MRD (Gugliotta et al., 2017, 2018a, 2019; Jiang et al., 2020). Cyclical patterns
Fig. 11. (A) to (F) Palaeogeographic reconstructions showing several phases of the channel evolution from its early development through its abandonment and to the present-day configuration. Beach ridges were identified using the Digital Elevation Model (DEM) and Tamura et al. (2012). The palaeogeographies also show the general progradation of the shoreline. White parts indicate areas of uncertainty regarding the evolution of the neighbouring channels. Palaeogeographies in (D) to (F) are modified from Gugliotta et al. (2021).
in the sand–mud alternations, bidirectional sand lenses and mud layers highlight the dominance of tidal processes. Compared to grab samples from the modern channels, the cores allowed to better identify the general vertical trends, which was fining-upward for the active-channel fill and coarsening-upward for mouth-bar deposits (Fig. 12). Evidence of seasonal variations in sedimentation was given by the concentration of trace fossils in certain intervals; however, due to the irregular distribution of these bioturbated intervals, a clear seasonal bedding, such as that reported from the river-dominated, tide-influenced Fraser River Delta (Sisulak & Dashtgard, 2012; Johnson & Dashtgard, 2014; Dashtgard & Croix, 2015; La Croix & Dashtgard, 2015) or ancient river-dominated, tide-influenced deltas (e.g. Gugliotta et al., 2016; Jablonski & Dalrymple, 2016; La Croix et al., 2019; van Yperen et al., 2019), was not identified. In the Mekong, a seasonal bedding was also observed in the sandier, point-bar deposits from the purely fluvial portion of the river in Cambodia (Gugliotta et al., 2018b). It is herein suggested that the absence of a seasonal bedding in the Bai Lai palaeochannel may be related to the intense sediment reworking caused by tidal currents in this depositional environment. In addition, it is also possible that the higher proportions of mud in the studied deposits compared to the above-mentioned river-dominated deposits, could make it more difficult to recognize the seasonal bedding. The large amount of mud present in the active-channel fill is herein associated with the presence of a turbidity maximum and import and/or in-channel storage of fine-grained sediments that is typical of tide-dominated distributary channels (Gugliotta & Saito, 2019). On the other hand, although river-derived sedimentary structures were not recognized, it is suggested that the presence of the coarser fraction (up to fine sand) in the active-channel fill and mouth-bar deposits is itself evidence of river processes. For example, the downstream area of the adjacent present-day Dong Nai River System, which has a much lower river discharge compared with the MRD, shows mostly mud with rare sand–mud alternations (Gugliotta et al., 2020); cores from this system also show mostly mud in the Late Holocene succession (Collins et al., 2021). Instead, the MRD, which has a much greater river discharge, shows common sand–mud alternations. This highlights that, with similar tidal conditions among the two systems, the sand–mud alternations are better developed in the system with a higher river discharge, because of the availability of sand supplied by the river. Instead, the higher sand content in mouth-bar deposits compared to the active-channel fill and its basinward increase were attributed to stronger wave processes that resuspended mud increasing the sand concentration in the river-mouth area. In the Ba Lai palaeochannel, the abrupt disappearance of the sand fraction would mark the abandonment of the channel and the reduction or absence of river processes therein (Gugliotta et al., 2021). In fact, the abandoned-channel fill is typically made of mud rather than heterolithic. The abandoned Ba Lai or other similar abandoned tide-dominated deltaic channels, such as those in the Mahakam River Delta, are usually considered as locally transgressive estuaries (e.g. Dalrymple & Choi, 2007). Nonetheless, a differentiation with ‘proper estuaries’ should be made as, in contrast with overall transgressive systems, abandoned deltaic channels seem unable to import a significant amount of sand fraction (Salahuddin & Lambiase, 2013; this study). On the other hand, ‘proper estuaries’ and their nearby shelf environments are part of coastal areas that have been transgressive for longer periods and can be sandier, but a large portion of this sand is reworked from older sediments due to the transgression (Eisma, 1988; Berne et al., 1998; Reynaud et al., 2018).

Facies models

The present dataset shows three possible scenarios of stratigraphic evolution and facies models for the tide-dominated distributary channel and its mouth bar, which occur depending on the exact location of the core in this depositional setting (Fig. 12). Near channel margins (for example, core BL1), the active channel evolved into tidal flats and marshes because of channel-margin accretion. Tide-dominated distributary channels are relatively stable and straight and, therefore, channel-margin accretion as expected in other fluvial and tidal environments (e.g. Cosma et al., 2019; Ghinassi et al., 2019; Sylvester et al., 2019) is limited; however, some amount of accretion still occurs because the section of the channel supported by the river-tidal hydrodynamics at a specific location decreases through time with the continuation of the deltaic progradation (Gugliotta & Saito, 2019). The facies model of channel margin deposits shows an upward change from heterolithic to mud...
deposits with well-developed fining-upward and thinning-upward trends and gradual transitions between the different sedimentary facies, from the active-channel fill, through tidal-flat deposits and to marsh deposits (Fig. 12). Away from the channel margins, the channel was still relatively deep when the abandonment occurred, recording the abrupt change from active-channel fill to abandoned-channel fill (for example, core BL2). This second facies model of channel deposits shows an upward change from heterolithic to mud deposits with fining-upward and thinning-upward trends still present but less well-developed because the transition between the different sedimentary facies is sharp and the upward trends are interrupted (Fig. 12). In both of these channel facies models, a general concave-up lenticular architecture with a sharp or erosional base can be expected. In the mouth-bar area (for example, BL3a to BL3c), mouth-bar deposits evolved into tidal flats and marshes because of the accumulation of the barform. The
mouth-bar-area facies model shows an upward change from heterolithic to heterolithic/sand to mud deposits with a coarsening to fining-upward trend and gradual transitions between different sedimentary facies (Fig. 12). For the mouth-bar facies model a convex-up lenticular elongated architecture can be expected. Similar coarsening to fining-upward trends have been already indicated for the delta fronts of tide-dominated deltas (Hori et al., 2002; Ta et al., 2002; Goodbred & Saito, 2012). Although not a tide-dominated delta, the river-dominated, tide-influenced Fraser River Delta also shows similar general facies models (La Croix & Dashtgard, 2014), with fining-upward trends often observed near the channel margins (for example, bars 2-5 and 2-7 in that study) and a coarsening-upward trend at the river mouth (for example, bar 1-3). Although differences among systems likely exist and should still be constrained, it is suggested that the sedimentary facies described in this study and the resulting facies models should be used to better understand tide-dominated deltaic systems and to improve their interpretations in the geological record.

CONCLUSIONS

The present core dataset of the Holocene succession of the Ba Lai palaeochannel in the Mekong River Delta helps constraining the sedimentary facies of distributary channels and mouth bars in tide-dominated deltaic settings. Nine sedimentary facies were identified and interpreted as representing the Late Holocene evolution of the Ba Lai palaeochannel, including its pre-abandonment and post-abandonment phases, as well as pre-channel phases of different ages (Late Holocene, Middle Holocene and Pleistocene).

The channel formed at 2.6 ka as a distributary channel connected to the deltaic network and with acting river and tidal processes. Due to the south-eastward progradation of the shoreline, the channel gradually extended seaward and a mouth bar formed between 1.7 ka and 1.3 ka. At 0.7 ka, the channel was abruptly abandoned, rapidly infilled with sediment and preserved as a relict feature. The channel deposits are up to approximately 11 m thick and overlie shelfal shell layers, which, in turn, overlie older deposits.

The active-channel fill and mouth-bar deposits consist of sand and mud with cyclical patterns, bidirectional lenses and abundant mud layers (i.e. mud drapes, fluid muds), suggesting deposition driven by river and tidal processes, with additional wave processes near the river mouth. The abandoned-channel fill consists entirely of organic-rich mud, suggesting the reduction or absence of river processes after abandonment and the predominance of tidal processes. Other sedimentary facies include tidal-flat and marsh deposits, which mostly consist of mud and formed in shallow to subaerial areas near the channel margins or on barforms.

Depending on the exact location of the core in this depositional setting, three possible stratigraphic evolutions and facies models are presented herein for the tide-dominated distributary channel and its mouth bar. Near channel margins, the deposits show an upward change from heterolithic to mud with well-developed fining-upward and thinning-upward trends and gradual transitions between the different sedimentary facies. Away from the channel margins, the deposits show an upward change from heterolithic to mud with sharp contacts between the different sedimentary facies and an interrupted fining-upward trend. The mouth-bar-area facies model shows an upward change from heterolithic to heterolithic/sand to mud deposits with a coarsening to fining-upward trend and gradual transitions between different sedimentary facies.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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