Bayhead deltas and shorelines: Insights from modern and ancient examples

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Bayhead deltas are important components of the rock record as well as modern estuaries, hosting important hydrocarbon reservoirs and many coastal cities, ports and large expanses of wetlands. Despite their significance, few studies have summarized their occurrence and sedimentary characteristics. In this paper we review the stratigraphic, sedimentary, and geomorphic characteristics of 68 modern and ancient bayhead deltas. Bayhead deltas are found in incised valleys, structural basins, fjords, interdistributary bays of larger open-ocean deltas, and other backbarrier environments. Except for within fjords, they generally prograde into shallower and more brackish waters than their open-ocean equivalents. As a result, 80% of modern, 68% of Quaternary, and 67% of ancient bayhead deltas have clinoform thicknesses of 10 m or less with 73% of modern bayhead deltas having clinoform thicknesses of 5 m or less. Additionally, 89% of modern, 81% of Quaternary, and 77% of ancient bayhead deltas examined are fluvial dominated. We distinguish true bayhead deltas from their genetically similar bayhead shorelines, which are not constructional features but sites of enhanced marsh or estuarine sedimentation near river mouths with inadequate rates of sediment delivery to form distributary channels and prograde into the estuary or lagoon. We also distinguish confined bayhead deltas found in incised valleys, structural basins, and fjords from unconfined bayhead deltas found as incipient lobes of larger delta complexes and other backbarrier lagoons. The architecture of confined bayhead deltas is largely influenced by the limited accommodation brought about by the walls of the flooded valleys in which they are located. As such, confined bayhead-delta ontogeny is controlled by many autogenic interactions within these valley walls. Both confined and unconfined bayhead deltas are sensitive to sea-level rise, climate-controlled changes in sediment flux, and tectonics. Their relatively small size, connection with the terrestrial system, and protected nature make them the ideal depositional system to record Earth history including sea-level and climate changes.

1. Introduction

Bayhead deltas are an important component of estuarine systems. They host expansive wetlands (Nichols et al., 1986; Pasternack and Brush, 2002) and mangroves (do Amaral et al., 2006), link watersheds with estuaries, and provide storage of nutrients, sediments, and pollutants (Abu-Saba and Flegal, 1995; Knight and Pasternack, 2000; Nikanorov et al., 2010; Springborn et al., 2011). They are also host to a number of important cities and industrial centers across the globe including Tokyo, Japan; Melbourne, Australia; Saint Petersberg, Russia; the Port of Houston, Texas; Tampa, Florida; and San Jose, California. Located at the fluvial-to-marine transition, they are sensitive to disturbances both due to anthropogenic effects such as groundwater extraction (White and Tremblay, 1995) and water and sediment supply depletion and extension (e.g., Pasternack et al., 2001; Sloss et al., 2005, 2011; Jaffe et al., 2007; Jaeger et al., 2009; Jalowska et al., 2015) and natural cycles of climate, sea-level changes, and extreme events such as tsunamis and storms (e.g., Rodriguez et al., 2010; Naruse et al., 2012; Jalowska et al., 2015). Thus, their ancient deposits provide important clues about Earth's history (e.g., Amorosi et al., 2005, 2009; Rodriguez et al., 2010).

Within modern estuaries, bayhead deltas provide the link between the fluvial and estuarine realm, and in most systems are the dominant source of sediments and freshwater to the upper portions of estuaries, backbarrier-lagoons, and interdistributary bays (Smith et al., 2013). In Holocene and modern systems with high sediment flux with respect to estuarine accommodation, they can completely fill the open-water or open-bay portions of estuaries, and transform a wave-dominated estuary into a tide-dominated estuary or open-ocean delta (Roy et al., 1980; Anthony et al., 2002; Harris and Heap, 2003; do Amaral et al., 2006), which has led to the abandonment of many ancient cities (Anthony et al., 2014). In many estuaries they provide the only

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mechanism of completely filling the open-bay environment with fluvially-derived sediment as base level in the middle bay, defined by wind-generated waves, tidal currents and sea level, causes resuspension of fine-grained sediment and prevents accretion of open-bay muds above wave base (Nichols, 1989; Roberts et al., 2005; Sloss et al., 2010; Simms and Rodriguez, 2015).

Within the rock record, they also provide important context for sequence stratigraphic models and are a key depositional environment when tracking cyclicity (e.g., McLaurin and Steel, 2000; Aschoff and Steel, 2011a, 2011b). In addition, their ancient deposits within the subsurface are host to valuable petroleum reservoirs (e.g., Terzuoli and Walker, 1997; Hubbard et al., 2002; Plint and Wadsworth, 2003; Bowen and Weimer, 2003, 2004) and provide aquifers for many populated centers. Despite this importance, few studies have focused on comparing how the depositional processes operating within bayhead deltas differs from those in more open-water conditions (Aschoff et al., 2018). In light of new insights brought about from the study of open-ocean deltas (e.g., Bhattacharya and Giosan, 2003; Olariu and Bhattacharya, 2006) and deltas in general (Edmonds et al., 2011), a review of bayhead deltas is warranted. The purpose of this study is to review the deposits and stratigraphic controls on bayhead deltas and to summarize their characteristics and behaviors as sedimentary systems. We base this review largely on our own work primarily within the Gulf of Mexico (Anderson and Rodriguez, 2008) but also upon a compilation of 68 (inclusive of our work) modern, late Quaternary, and ancient bayhead delta systems from the literature (Fig. 1, Table 1). Using this review as a foundation, we provide a template for classifying bayhead deltas based on their geomorphology and sedimentary deposits and distinguish them from another genetically-related feature, defined here as bayhead shorelines.

2. Bayhead delta compilation

We used common literature search tools (GeoRef, GoogleScholar, citations in other papers) to identify studies of bayhead deltas from a total of 68 systems (Table 1). These included 29 modern (4 of which also included descriptions of their late Pleistocene/early Holocene equivalents), 20 late Pleistocene/early Holocene (post Last Glacial Maximum, LGM), and 23 ancient (pre-LGM) examples of bayhead deltas. Within this study, we refer to those bayhead deltas that formed during the late Pleistocene/early Holocene following the LGM as “Quaternary” and those that formed prior to the LGM as “Ancient”, noting that some of the ancient bayhead deltas are technically Quaternary in age. We compiled their clinoform thickness, age, geological setting, and whether they were fluvial, tide, or wave dominated. The clinoform thicknesses of the modern bayhead deltas were assumed to be the water depth immediately offshore the delta front in the cases where the original authors did not explicitly state clinoform height. For the Quaternary and ancient examples, we assumed the clinoform thickness was equal to the thickness of the delta front deposits when not explicitly stated. No correction was made for compaction of the ancient bayhead delta deposits. We acknowledge that these assumptions as well as the limitations associated with compiling a relatively small data set from different sources with different study objectives and stratigraphic detail may bias our results, but the broader trends should still be reflected within the compilation.

3. Review of examples and deposits

3.1. Geological occurrence and setting

Bayhead deltas form in a number of geologic settings including the upper portions of wave-dominated estuaries (e.g., “barrier estuary” of Roy et al., 1980; Dalrymple et al., 1992), flooded incised valleys (Thomas and Anderson, 1994; Bowen and Weimer, 2003; Simms et al., 2006; Amorosi et al., 2003, 2013), fjords (Syvitski and Farrow, 1983; Corner et al., 1996; Corner, 2006; Eilertsen et al., 2011), structural basins (Harris, 1989; Carr et al., 2003; Schwarz et al., 2011; Osman et al., 2013), within larger delta plains (Van Heerden and Roberts, 1988; Wellner et al., 2005; Rao, 2006; Li and Bhattacharya, 2014) and other protected backbarrier environments (Semeniuk et al., 2000; Sloss et al., 2005; Joeckel and Korus, 2012; Macreadie et al., 2015) (Fig. 2). Although modern bayhead deltas are common in all of these settings, their Quaternary and ancient counterparts do not appear in as wide diversity of settings (Fig. 3). Most Quaternary examples are found within incised valleys and most ancient bayhead deltas are found within incised valleys or structural basins (Fig. 3).

Within the classic estuary models, bayhead deltas form in the upper reaches of the estuary where the river widens at its confluence with the central basin (Fig. 4A). They are most common in wave-dominated estuaries (Dalrymple et al., 1992) and usually absent in tide-dominated estuaries (Allen and Posamentier, 1993; Kitazawa, 2007). Quaternary and ancient bayhead deltas are particularly common within incised-valley systems, representing the first estuarine unit that forms above

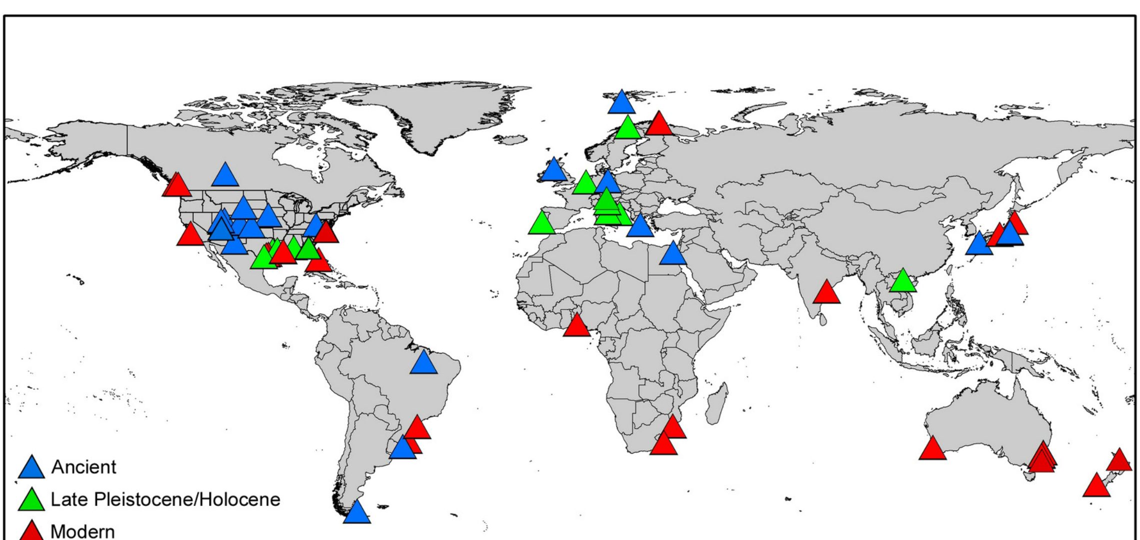

Fig. 1. Map illustrating the locations of the ancient (blue triangles), Late Pleistocene-early Holocene (green triangles), and modern (red triangles) bayhead deltas summarized in this paper.

Table 1
Summary of the characteristics of the bayhead deltas reviewed as part of this study.

	Delta(s)	Clinoform Thickness[a]	Fluvial/ Wave/Tide	Unconfined/ Confined	Setting	Forset/Topset	Age	Reference
Modern								
	Klinaklini, Canada	220+	F?	Con	Fjord	F	Modern	Syvitski and Farrow, 1983
	Homathko, Canada	220+	F?	Con	Fjord	F	Modern	Syvitski and Farrow, 1983
	Nueces, USA	2 m	F	Con	IV	T	Modern	Simms et al., 2008
	Guadalupe, USA	3.7 m	F	Con	IV	T	post-2 ka	Donaldson et al., 1970
	Trinity, USA	3 m	F	Con	IV	T	Modern	Thomas and Anderson, 1994; Anderson et al., 2008
	Colorado (Gulf of Mexico), USA	1.8 m	F	Un	Backbarrier	T	Modern	Kanes, 1970
	Lake Calcasieu, USA	<4 m	F	Con	IV	T	Modern	Nichol et al., 1996; Milliken et al., 2008
	Mobile, USA	3 m	F	Con	IV	T	Modern	Rodriguez et al., 2008
	Loxahatchee, USA	2 m	F?	Con	IV	T	Modern	Jaeger et al., 2009
	Atchafalaya, LA, USA	<4 m	F	Un	Interdistributary Bay	T	Modern	Van Heerden and Roberts, 1988
	Wax Lake, LA, USA	<6 m	F	Un	Interdistributary Bay	T	Modern	Majersky et al., 1997
	Morro Bay, CA, USA	<3 m	F	Un	Backbarrier-Structural	UNK	Modern	Gallagher, 1996
	Guaratuba Estuary, Brazil	<5 m	F	Con	IV	UNK	Modern	Barbosa and Suguio, 1999
	Leirpollen, Norway	30–40 m	F	Con	Fjord	F	Modern	Corner et al., 1996
	Tanafjord, Norway	175 m	UNK	Con	Fjord	F	Modern	Corner et al., 1996
	Oueme River, Benin, West Africa	<4 m	F	Con	IV/Backbarrier	T?	Modern	Anthony et al., 2002
	Maputo Bay, Mozambique	<6 m	T?	Uncon	Backbarrier	UNK	Modern	Green et al., 2015
	Mtamvuna Estuary, South Africa	<4 m	UNK	Con	IV	UNK	Modern	Cooper, 1993
	Godavari River, India	<5 m	F	Un	Interdistributary Bay	UNK	1929 (Modern)	Rao, 2006
	Hooka Creek, Australia	<2 m	F/W	Un	Backbarrier	T	post-2.9 ka	Sloss et al., 2005
	Mullet Creek, Australia	<2 m	W	Un	Backbarrier	T	Post-2.6 ka	Sloss et al., 2005
	Macquarie Rivulet, Australia	<3 m	F	Un	Backbarrier	T	post-0.35 ka	Sloss et al., 2005
	Conjola Creek, Australia	<3 m	F	Con	IV	T	post-2.0 ka	Sloss et al., 2010
	Stony Creek, Australia	<3 m	F	Con	IV	T	post 0.3 ka	Sloss et al., 2006
	Leschenault Inlet Estuary, Australia	1–2 m	F	Uncon	Backbarrier	UNK	Modern	Semeniuk et al., 2000
	Wyong River, Australia	<4 m	F	Uncon	Backbarrier	UNK	post 1.1 ka	Macreadie et al., 2015
	Ourimbah Creek, Australia	<4 m	F	Uncon	Backbarrier	UNK	post 1.1 ka	Macreadie et al., 2015
	Selwyn River, New Zealand	<2 m	F	Uncon	backbarrier	UNK	Modern	Leckie, 2003
	Fjordland (16), New Zealand	15–50+ m	F	Con	Fjord	F	Modern	Pickrill, 1980
Quaternary								
	Nueces, USA	4 m	F	Con	IV	T	post-8 ka	Simms et al., 2008
	Trinity, USA	3–8 m	F	Con	IV	T	post-8 ka	Thomas and Anderson, 1994; Anderson et al., 2008
	Lake Calcasieu, USA	<10 m	F	Con	IV	T	post-8 ka	Nichol et al., 1996; Milliken et al., 2008
	Mobile, USA	3 m	F	Con	IV	T	post-8 ka	Rodriguez et al., 2008
	Apalachicola Bay, FL, USA	2 m	F	Uncon/Con	IV/Backbarrier	UNK	post-7 ka	Osterman et al., 2009
	Roanoke, NC, USA	<4 m	F	Con	IV	UNK	Late Holocene	This Study
	Camaqua, Brazil	<7 m	F/W	Un	Backbarrier	UNK	post-8 ka	dos Santos-Fischer et al., 2016
	Malselv, Norway	3–44.5 m	F	Con	Fjord	F	post-9 ka	Eilertsen et al., 2011
	Rhine River, Netherlands	4–5 m	F?	Con	IV	UNK	8–7.3 ka	Hijma et al., 2009
	River Tagus, Portugal	8 m	T	Con	IV	T?	7–4 ka	Vis and Kasse, 2009
	Po River, Italy	<5 m	F?	Con	IV	UNK	10.5–7.5 ka	Amorosi et al., 2003
	Tiber River, Italy	5–21 m	F	Con	IV	UNK	13–7 ka	Bellotti et al., 2007; Milli et al., 2013
	Manfredonia, Italy	<15 m	F?	Con	IV	F	8–7.2 ka	Maselli and Trincardi, 2013; Maselli et al., 2014
	Arno Valley Fill, Italy	<10 m	?	Con	IV	UNK	8–3 ka	Amorosi et al., 2013
	Rikuzentakata Plain, Japan	<5 m	F	Con	IV	UNK	post-5 ka	Chida et al., 1984
	Kiso River, Japan	13 m	F	Con	IV	F?	1–6 ka	Masuda and Iwabuchi, 2003
	Yoro River, Japan	13 m	UNK	UNK	IV	UNK	post 6 ka	Kaizuka et al., 1979; Okazaki and Masuda, 1989
	Obitsu River, Japan	20 m	UNK	UNK	IV	UNK	post 6 ka	Kaizuka et al., 1979; Okazaki and Masuda, 1989
	Red River, Vietnam	~15 m	T?	Con	IV	UNK	8.5–6.5 ka	Hori et al., 2004
	Tuggerah Lake Estuary, New Zealand	<3 m	UNK	Con	IV	UNK	post 8 ka	Clement and Fuller, 2018

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Table 1 (*continued*)

	Delta(s)	Clinoform Thickness[a]	Fluvial/ Wave/Tide	Unconfined/ Confined	Setting	Forset/Topset	Age	Reference
Ancient (Pre-Holocene)								
	Bluesky Formation, Canada	10–33 m, 4–20 m,	UNK	Con	IV	UNK	K	Terzuoli and Walker, 1997
	Dunvegan Formation, Canada	4–8 m	UNK	Con	IV	UNK	K	Plint and Wadsworth, 2003
	Ferron Sandstone, Utah, USA	<4 m	UNK	Un	Interdistributary Bay	UNK	K	Li and Bhattacharya, 2014
	Book Cliffs, Utah	0.5–3 m	F	Con?	IV	UNK	K	Aschoff and Steel, 2011a, 2011b (SG)
	Straight Cliffs Formation, Utah, USA	<5 m (20–30 m)	F?	Un?	backbarrier?	UNK	K	Gallin et al., 2010
	Blackhawk Formation, Utah	<6 m	UNK	Un?	backbarrier	T	K	Flores et al., 1984
	Hueco Formation, New Mexico, USA	<7 m	UNK	Con	IV	UNK	Permian	Mack et al., 2003
	Harding Sandstone, Colorado, USA	<5 m	UNK	UNK	UNK	UNK	Ordivician	Allulee and Holland, 2005
	Fall River Formation, SD, USA	<10 m	UNK	Con	IV	UNK	K	Willis, 1997
	Rakes Creek Shale, Nebraska, USA	<10 m	F?	Un	backbarrier	UNK	Up. Penn.	Joeckel and Korus, 2012
	Morrow Sandstone, KS, USA	<5 m	UNK	Con	IV	UNK	Lo. Penn.	Buatois et al., 2002
	New River Formation, WV, USA	1–2 m	UNK	Con	Paleovalley fill	UNK	Lo. Penn.	Korus et al., 2008
	Mississippi Embayment, USA	<15 m	UNK	Con	IV	UNK	Pleistocene	Greene et al., 2007
	Rio Bonito Formation, Brazil	5–15 m	UNK	Con	Fjord/IV?	UNK	Permian	Holz, 2003
	Camita Basin, Brazil	<5 m	F?	Con	IV w/ some structural control	UNK	K	Rossetti, 2006
	Springhill Formation, Arg.	0.7–3.2 m	F?	Con	Structural	UNK	K	Schwarz et al., 2011
	Helvetiafjellet Formation, Spitsbergen	3–6 (<30) m	UNK	Con	IV	UNK	K	Midtkandal et al., 2008; Midtkandal and Nystuen, 2009
	Egol Formation, Scotland	17–25 m	F	Con	Structural	UNK	Jurassic	Harris, 1989
	Schoningen Formation, Germany	4.5–11.2 (10 m)	F	Con	Structural (Salt)	UNK	Eocene	Osman et al., 2013
	Akarta, Greece	3–5 m	F	Con	IV	UNK	Pleistocene	Gobo et al., 2014
	Akarta, Greece	8 m	W	Con	IV	UNK	Pleistocene	Gobo et al., 2014
	Akarta, Greece	8–80 m	F	Con	IV	F	Pleistocene	Gobo et al., 2014
	Nukhul Formation, Egypt	<17 m	T?	Con	Structural	F?	Miocene	Carr et al., 2003
	Himenoura Formation, Japan	<40 m	F?	Con	IV	UNK	K	Komatsu et al., 2008
	Paleo Tokyo Bay, Japan	5–12 m	W	Con	IV?	UNK	Pleistocene	Okazaki and Masuda, 1992
	Paleo Tokyo Bay, Japan	5–10 m	F	Con	IV?	UNK	Pleistocene	Okazaki and Masuda, 1992

[a] For modern examples assumed to be water depth delta prograding into. For Quaternary and ancient examples, assummed to be the thickness of the delta front deposits or sands when clinoform depth not explicitly stated.

fluvial strata and being the first indicator of an increase in accommodation thus defining the transgressive surface (Zaitlin et al., 1994). In some incised valley systems, tributaries to the main trunk incised valley provide separate but coalescing bayhead deltas (Bowen and Weimer, 2003; Maselli et al., 2014). Their numbers within structural basins are greater within the ancient record than within modern settings while their preservation within Quaternary and ancient fjords is less representative than their prevalence along modern high-latitude coastlines.

3.2. Temporal and stratigraphic occurrences

Modern bayhead deltas have been described from every continent except Antarctica and Quaternary examples have been described from almost as wide a geographic range (Fig. 1). Some of the oldest deposits interpreted as a bayhead delta date to the Ordovician (Allulee and Holland, 2005). Descriptions of bayhead delta deposits are particularly prevalent from the Cretaceous while multiple examples have also been identified in Pleistocene and Pennsylvanian sediments and rocks (Table 1, Fig. 1). Many Cretaceous examples are found within the Cretaceous Interior Seaway of North America, but this is largely a reflection of the amount of work that has been done there (Fig. 1).

Most modern bayhead deltas are forming along coasts that are experiencing relatively slow rates of sea-level rise relative to the post-LGM rate. Within the Quaternary they formed as part of the transgressive systems tract filling fluvial valleys created during the lowstand, often in a back-stepping stratigraphic succession (Thomas and Anderson, 1994; Nichol et al., 1996; Holz, 2003; Bowen and Weimer, 2003, 2004; Greene et al., 2007; Anderson et al., 2008; Simms et al., 2008; Vis and Kasse, 2009; Maselli et al., 2014). Ancient bayhead deltas are also common within the transgressive and early highstand systems tracts of incised valleys, in particular at the updip maximum sea-level shoreline before the turn-around to regression (Plink-Bjorklund and Steel, 2006; Porebski and Steel, 2006; Aschoff and Steel, 2011a, 2011b; Schwarz et al., 2011; Maselli et al., 2014; Aschoff et al., 2018) (Fig. 2A). Within the Cretaceous Interior Seaway they record periods of relatively low accommodation (Aschoff and Steel, 2011b). They can also form at any time within interdistributary bays as part of a large deltaic complex (Fig. 2D), although within the Rhine-Meuse system they are more common within the early highstand and/or falling stage systems tracts (Hijma et al., 2009).

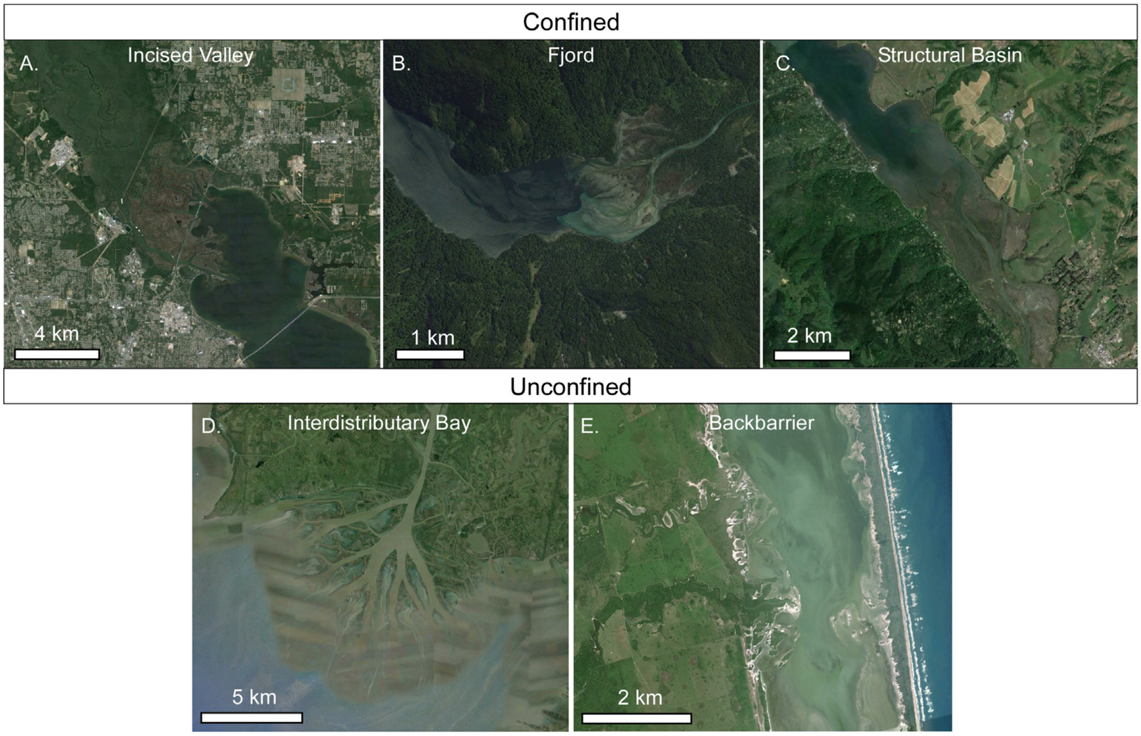

Fig. 2. Examples of confined (Pensacola Bay, Florida, USA - A, Bradshaw Sound, Fjordland, New Zealand - B, and Agunitas Creek, California, USA - C) and unconfined (Wax Lake Delta, Louisiana, USA - D, and Tenacitas, Laguna Morales, Mexico - E) bayhead deltas. Images from GoogleEarth.

3.3. Sedimentary characteristics and facies

Compared to more open-ocean deltas, few studies have examined modern and Quaternary bayhead deltas. Those that have are largely focused on bayhead deltas within incised valleys (McEwen, 1969; Donaldson et al., 1970; Nichols et al., 1991; Pasternack and Brush, 2002) and fjords (Syvitski and Farrow, 1983; Corner, 2006; Noll et al., 2009; Eilertsen et al., 2011). Only a handful of studies have described them in other backbarrier environments (Kanes, 1970; Osterman et al., 2009). Within incised valleys, the most comprehensive studies of facies within modern bayhead deltas are those of the Trinity and Guadalupe bayhead deltas of the Texas Gulf of Mexico coast by

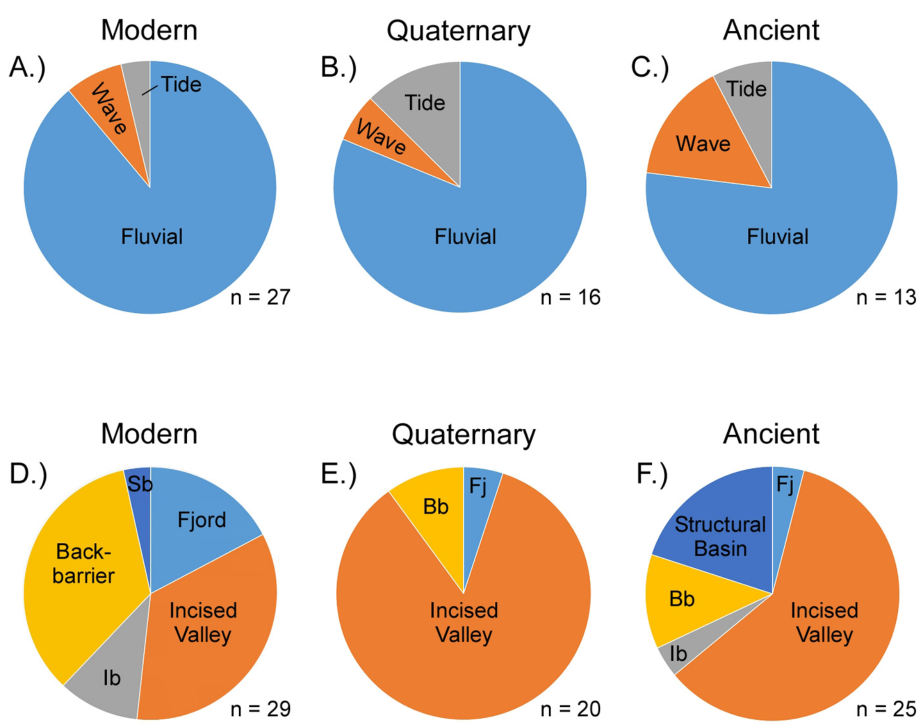

Fig. 3. The relative proportion of wave, fluvial, and tide dominated bayhead deltas in modern (A), Quaternary (B), and ancient (C) systems. Also shown are the relative proportions of modern (D), Quaternary (E), and ancient (F) bayhead deltas within incised valleys, back-barrier (Bb), fjords (Fj), interdistributary bays (Ib), and structural basins (Sb). See Table 1 for the data used for making these charts.

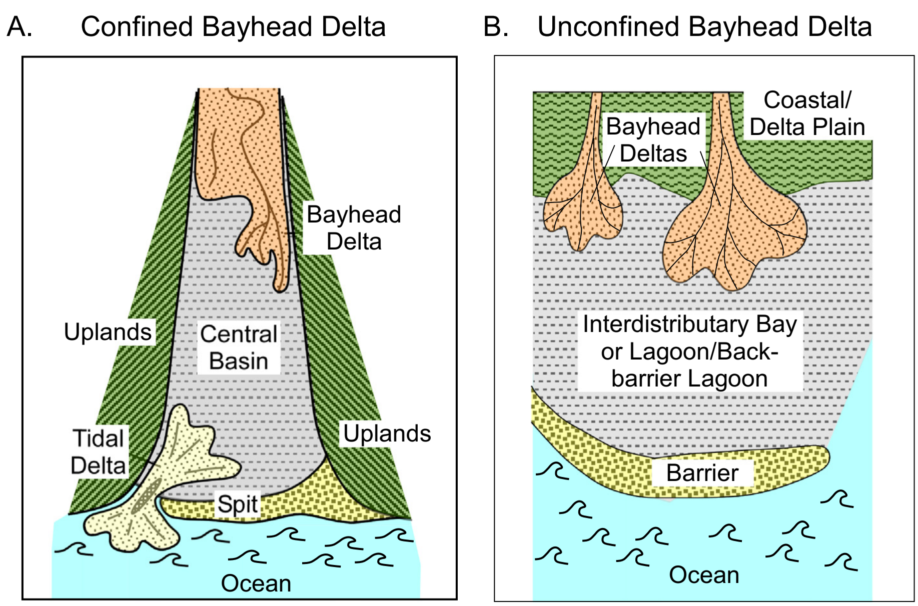

Fig. 4. (A) Model of a confined bayhead delta within a wave-dominated estuary. (B) Model of two unconfined bayhead deltas forming within an interdistributary bay of a larger delta complex.

McEwen (1969) and Donaldson et al. (1970), respectively. Outside of incised valleys, the best studied modern bayhead deltas are those of the Mississippi Delta plain such as the Atchafalaya (Van Heerden and Roberts, 1988; Wellner et al., 2005) and Wax Lake (Majersky et al., 1997; Shaw et al., 2013) bayhead deltas of the Gulf of Mexico coast and those from modern fjords (Syvitski and Farrow, 1983; Eilertsen et al., 2011).

From comparative studies of both modern and ancient bayhead deltas, some common characteristics of their deposits emerge. Interpreted ancient bayhead-delta facies are commonly heterolithic (Anthony et al., 2002; Joeckel and Korus, 2012), thinly bedded (Carr et al., 2003; Li and Bhattacharya, 2014), contain abundant flaser- and mud or clay-draped deposits and indications of tidal influence (Buatois et al., 2002; Holz, 2003), and wave and current ripples including climbing ripples (Li and Bhattacharya, 2014). All of these characteristics are found in modern bayhead deltas as well. In addition, geometrically, inclined shingled sets of sandstone are also common in ancient examples (Korus et al., 2008). Ancient, Quaternary, and modern bayhead deltas are frequently rich in wood and other carbonaceous material (Barbosa and Suguio, 1999; Anthony et al., 2002; Mack et al., 2003) (Fig. 5), particularly within their delta-plain deposits (Pasternack and Brush, 2002). They often contain an assemblage of fauna that are best adapted to brackish environments such as oysters (Carr et al., 2003) or *Rangia* spp. (Simms et al., 2008). Modern bayhead deltas within the interdistributary bays of the larger Mississippi Delta complex are sand-rich due to the resuspension of fine grained materials during the passage of fronts (e.g., Roberts et al., 2005), while contemporary bayhead deltas within the large coastal embayment of Maputo Bay in Mozambique are muddy (Green et al., 2015). Similar to the examples from the modern Mississippi delta complex, the modern Trinity bayhead delta plain of the northwestern Gulf of Mexico is composed dominantly of sand (McEwen, 1969), while the Nueces bayhead delta plain 330 km to the southwest of the Trinity delta is composed dominantly of mud (Rice, 2015).

Based in part on some of the general characteristics listed above, Aschoff and Steel (2011b) and Aschoff et al. (2018) suggest several criteria for the identification of ancient bayhead delta deposits. These include brackish-water indicators (fossils, traces, or clay minerology) within the delta front deposits and indications of shallow water depths and limited marine influence. They also are marked by the development of small-scale clinoforms with a decrease in grain-size and paleocurrent energy, and an increase in mud interbeds with increasing depth. In addition, their stratigraphic position between fluvial and central-basin deposits and coarsening upward succession or abrupt sand within a central basin deposit (Fig. 5) are also keys for their identification within ancient deposits (Aschoff and Steel, 2011b; Aschoff et al., 2018). As a

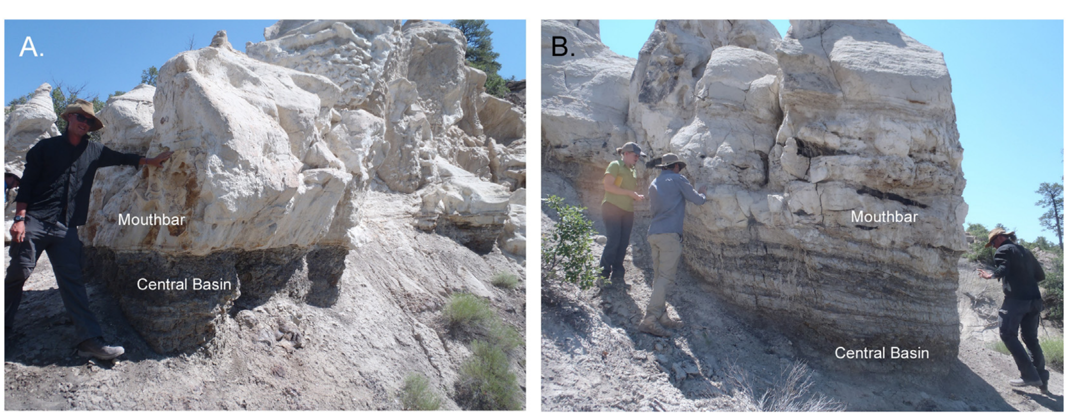

Fig. 5. Photographs of a sharp (A) and intercalated (B) contact between bayhead delta sandstones and central basin shales within the Cretaceous Menefee Formation of northern New Mexico.

whole, ancient bayhead deltas are similar to modern and Quaternary bayhead deltas in that they can be either dominated by mudstones or sandstones, depending on the characteristics of the fluvial basin (climate, slope, size, lithology, etc.).

In addition to these general depositional-facies characteristics, modern bayhead deltas commonly contain the same depositional subenvironments and equivalent facies as other deltas including prodelta, mudflats, delta-front, mouthbar, channel, levee, interdistributary-bay, internal spits/sandy beach ridge, and delta plain deposits (McEwen, 1969; Donaldson et al., 1970). The relative distribution and abundance of each of these subenvironments within modern bayhead deltas varies from system to system. Within the modern Atchafalaya River Delta, levees compose up to 40% of the delta deposits (Van Heerden and Roberts, 1988), while delta front sands are the largest component of the modern Trinity delta (McEwen, 1969).

3.4. Stratigraphic architecture

Eighty-three percent of modern, 81% of Quaternary, and 77% of ancient bayhead deltas compiled in this study are fluvial dominated and thus their geometries largely reflect lobe building and lobe switching (Table 1, Figs. 3, 6). Like most fluvial dominated deltas, modern and

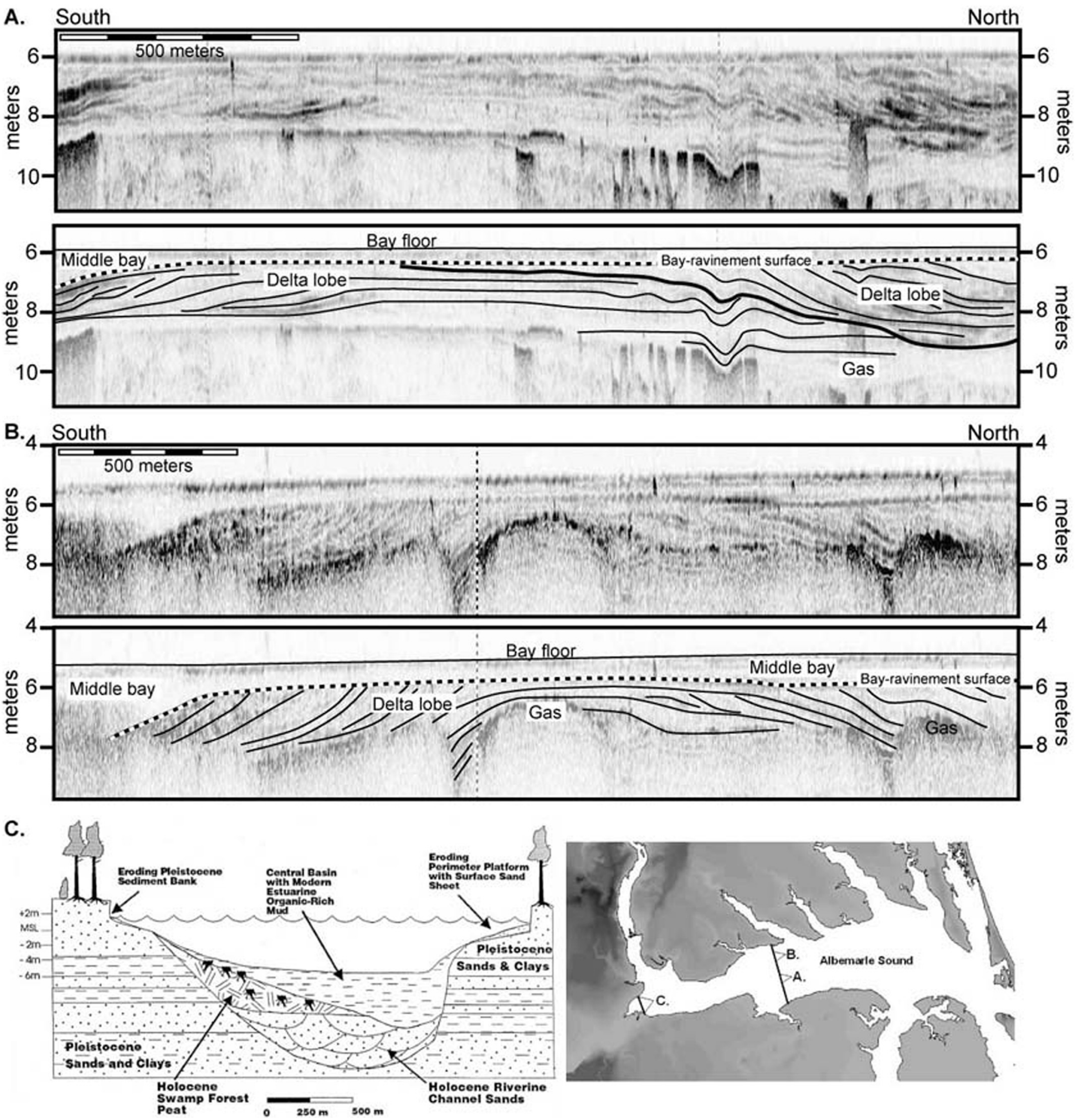

Fig. 6. Seismic profile through a late Holocene bayhead delta of the Roanoke Delta showing delta lobes and bay ravinement (A and B). (C) Cross section at the Roanoke River mouth illustrating the confined nature of the delta, after Riggs (1996).

ancient bayhead delta deposits commonly display an over-all coarsening-upward trend (e.g., Van Heerden and Roberts, 1988; Holz, 2003; Allulee and Holland, 2005; Aschoff and Steel, 2011b; Aschoff et al., 2018) (Figs. 5B, 7). Their delta fronts can be characterized by interbedded sands and muds typical of a fluvial-dominated delta. However, the lower-slopes prevalent within the estuarine basin are not as prone to produce sediment gravity flows driven by over-steepened slopes and some bayhead deltas exhibit a sharp-based sand of the mouthbar or distributary channels directly overlying finer-grained muds of the central basin (Vis and Kasse, 2009; Rice, 2015) (Fig. 5). This sharp base also reflects the relatively shallow water depths into which these deltas typically prograde, which is near the level of distributary-channel and mouth-bar deposition. These trends do not hold true for bayhead deltas in fjord settings, which may have thick clinoforms, steep slopes, and host thick sections of turbidities (Syvitski and Farrow, 1983; Corner, 2006) (Table 1) due to the generally over-deepened nature of glacial valleys. Hijma et al. (2009) found within the early Holocene Rhine-Meuse incised valley system a bayhead delta that displayed an overall fining upward succession, which they attribute to the rapid rates of sea-level rise at the time.

Edmonds et al. (2011) noted that not all deltas, including many bayhead deltas, display the well-developed forests of a Gilbert-type delta that dominate the stratigraphic record. They determined a quantifiable metric to distinguish these "topset-dominated deltas" from the classical "foreset dominated deltas" (Gilbert-delta) based on the ratio of distributary depth (h) and foreset height (f). Topset dominated deltas are defined as having an h/f ratio of >1, while foreset dominated deltas are said to have a h/f ratio much smaller than 1 (Edmonds et al., 2011). Topset dominated deltas are architecturally similar to the "shoal-water" deltas of Eilertsen et al. (2011) or Postma (1990), in which the foresets are not as well developed and the channels of the delta erode into underlying bottomsets of the older deltaic deposits (Van Heerden and Roberts, 1988). Of the three bayhead deltas mentioned by Edmonds et al. (2011), all three have h/f ratios >1 implying topset dominance. Of the 28 modern and Quaternary bayhead deltas surveyed in which data to determine topset versus foreset dominance are available, 71% of the bayhead deltas are top-set dominated. Of the 3 ancient bayhead deltas in which topset versus foreset dominance could be determined, only one is topset dominated. Of the 10 foreset-dominated deltas within our compilation, 6 occur in fjords and 1 occurs in a structural basin. The other three are found in incised valleys of active margins. Within fjords and some tectonically-controlled basins that experience high rates of accommodation creation and hence deep waters within the estuary, during the late regression, bayhead deltas can evolve from what may be a topset dominated delta into foreset-dominated forms (e.g., Eilertsen et al., 2011; Gobo et al., 2014).

3.5. Differences from open-ocean deltas

In many ways the differences between bayhead deltas and open-ocean deltas mimic those differences between "inner-shelf" and "outer-shelf" deltas as described by Porebski and Steel (2003, 2006). Except for the case of fjords (Pickrill, 1980; Eilertsen et al., 2011), modern bayhead deltas generally prograde into shallower water depths compared to most open-ocean equivalents. As a result, the clinoforms described from ancient bayhead deltas are generally not as thick (Stanley and Aschoff, 2007; Aschoff et al., 2018) (Table 1), their delta-front slopes are generally lower, and thick-bedded turbidities are commonly absent from their delta-fronts (Porebski and Steel, 2006; Aschoff and Steel, 2011b). Similar to other open-ocean "inner-shelf" deltas

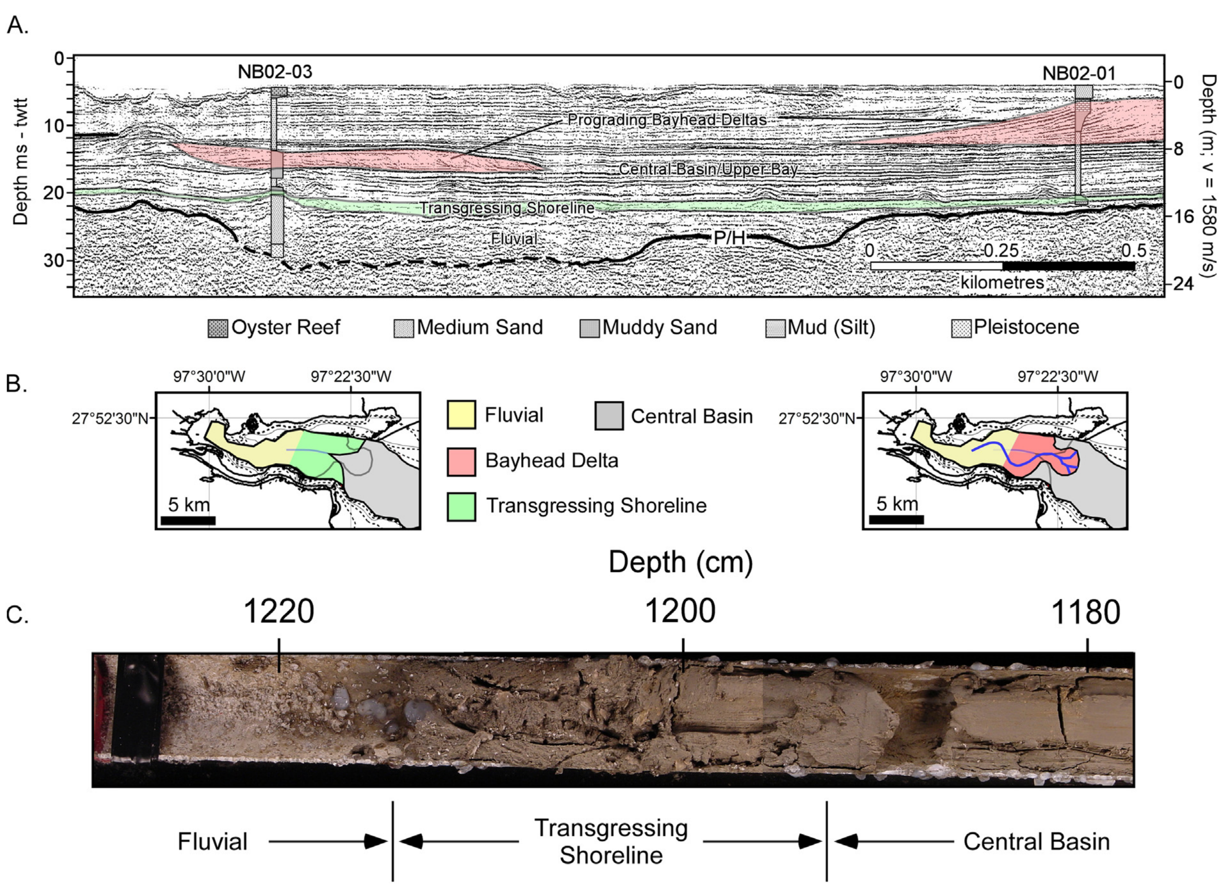

Fig. 7. (A) Seismic profile with core descriptions from Nueces Bay, Texas illustrating clinoforms built by the late Holocene Nueces Bayhead Delta (Simms et al., 2008). Note the coarsening upward package in coreNB02–01. (B) Paleogeographic maps of the Holocene history of Corpus Christi Bay, Texas. (C) Core photograph and grain-size data from the Late Pleistocene-early Holocene fill of the Nueces incised valley of the central Texas coast, USA. See Simms et al. (2008) for the original description and analysis of the core.

(Porebski and Steel, 2006), their successions are commonly thinner (Thompson et al., 2008) and smaller (Stanley and Aschoff, 2007). Of the modern deltas surveyed as part of this study, 80% are prograding into water depths less than or equal to 6 m. The 6 modern bayhead deltas prograding into deeper water (all >20 m) are found within fjords (Figs. 6, 8, Table 1). Sixty-eight percent of Quaternary bayhead deltas have clinoforms or delta front deposit thicknesses of 10 m or less (Fig. 8, Table 1). This difference in clinoform height/delta front thickness is likely in part due to the greater accommodation created during the rapidly rising sea levels of the late Pleistocene and early Holocene. Sixty-six percent of ancient bayhead deltas have clinoform or delta front thicknesses of 10 m or less; although, 81% of ancient bayhead deltas have clinoform or delta front thicknesses of 15 m or less (Fig. 8, Table 1). The greater thicknesses within ancient versus modern bayhead deltas may reflect in part the importance of tectonics in enhancing accommodation as two of the five ancient bayhead deltas with clinoform thicknesses >15 m are found in structural basins, with two of the other three located in tectonically active margins. In addition, this apparent increase in clinoform thickness may also be biased by compensational stacking with time (deposits accumulating in the same location through time thus stacking multiple aged deposits due to continuously rising sea levels or subsidence within the basin).

Despite these similarities between bayhead deltas and open-ocean "inner-shelf" deltas, there are some significant differences. Modern bayhead deltas commonly have limited fetch and associated wave exposure, although not necessarily free from the erosive influence of waves. This is reflected in the number of fluvial dominated bayhead deltas. Of the 27 modern bayhead deltas with data available, only 7% (2) are wave-dominated, while 89% are fluvial dominated (Fig. 3, Table 1). Similar trends are found in Quaternary and ancient bayhead deltas suggesting similar processes are operating within these bayhead deltas as well (Fig. 3). In some cases, this results in the near absence of littoral drift and wave action as an important process acting on their shorelines; this is most common within fjords (e.g., Pickrill, 1980; Syvitski and Farrow, 1983). However, in other settings, wave action is strong enough to rework their abandoned delta lobes but not enough to destroy the "bird's-foot" architecture of the active lobe. The southwestern flank of the modern Trinity Delta of the northwestern Gulf of Mexico has been straightened and eroded following avulsion of the main Trinity River to the north and east (McEwen, 1969) (Fig. 9A). At the other end of the spectrum, fluvial discharge can be so low in comparison to other forces, such as wave and tidal energy, that basinal processes are able to significantly rework the delta front forming a classic cuspate wave-dominated shape (Sloss et al., 2005; Mateo and Siringan, 2007) (Fig. 9B) and the deposition of hummocky cross-stratification in ancient examples (Komatsu et al., 2008) or a tide-dominated shape with multiple tidal channels (Fig. 9C) and bayhead bars (e.g., Fenies and Tastet, 1998).

Due to their rapidly fluctuating brackish- to fresh- water conditions, modern and ancient bayhead deltas are generally marked by a lower diversity and smaller-sized ichnofacies (Shepard and Moore, 1955; Buatois et al., 2002; MacEachern and Gingras, 2007; Thompson et al., 2008; Korus et al., 2008; Davison and MacEachern, 2009; Joeckel and Korus, 2012; Li and Bhattacharya, 2014) and biofacies (Barbosa and Suguio, 1999) in comparison to open-ocean equivalents, although the age of the deposits must be considered (e.g. Buatois et al., 2005). Within the estuary facies assemblage, these inhospitable conditions generally led to better preservation of primary sedimentary structures (Hauck et al., 2009). These freshwater and brackish-water dominated trace fossils commonly include Skolithos, Siphonichnus, and Tektonargus (Hauck et al., 2009) (Table 2). In addition, the brackish water nature of the estuary may contribute to more hypo and homopycnal flows at the delta mouth and unlikely development of hyperpycnal flows (Harris, 1989).

4. Classification

4.1. Bayhead deltas versus bayhead shorelines

As is the case for all deltas, different morphologies result from differences in the relative influences of waves and tidal processes versus fluvial sediment supply (Sloss et al., 2006) and the interaction between accommodation and sediment accumulation. In the case of fluvial sediment input overwhelming the creation of accommodation from erosion and/or sea-level rise, the result is a regressive bayhead delta (Figs. 2, 10B). Conversely, where sediment accommodation overwhelms sediment accumulation, the shoreline will transgress forming what we refer to as a bayhead shoreline (Figs. 10C, 11). Geomorphologically, modern transgressing bayhead shorelines have a smooth transition between the river and estuary without a distinctive set of distributary channels, mouthbars, and prograding lobes (Figs. 10, 11).

Regressive bayhead deltas display similar morphologies to their larger offshore fluvial-dominated delta counterparts, including main feeder channels that bifurcate into distributary channels and form a

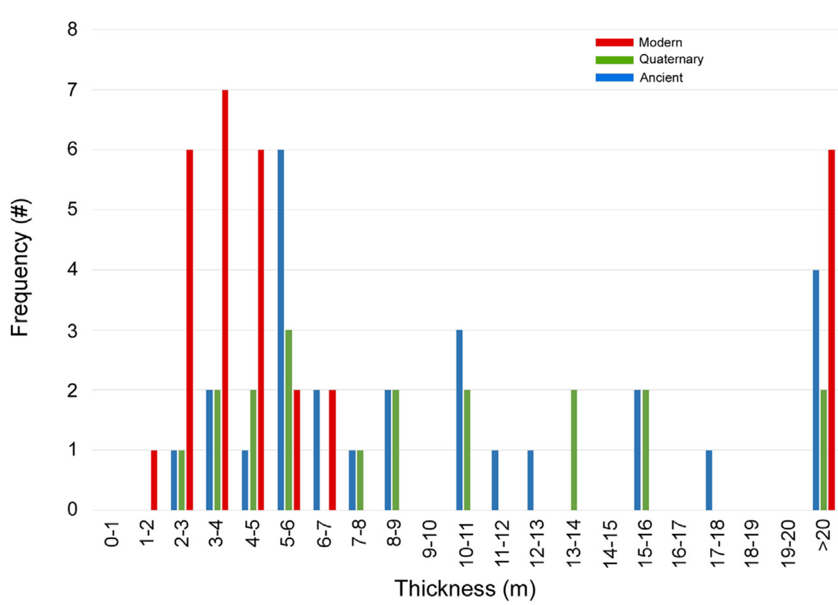

Fig. 8. Chart summarizing the thicknesses of bayhead delta clinoforms based on case studies described in the literature. See Table 1 for a list of the deltas summarized in this study.

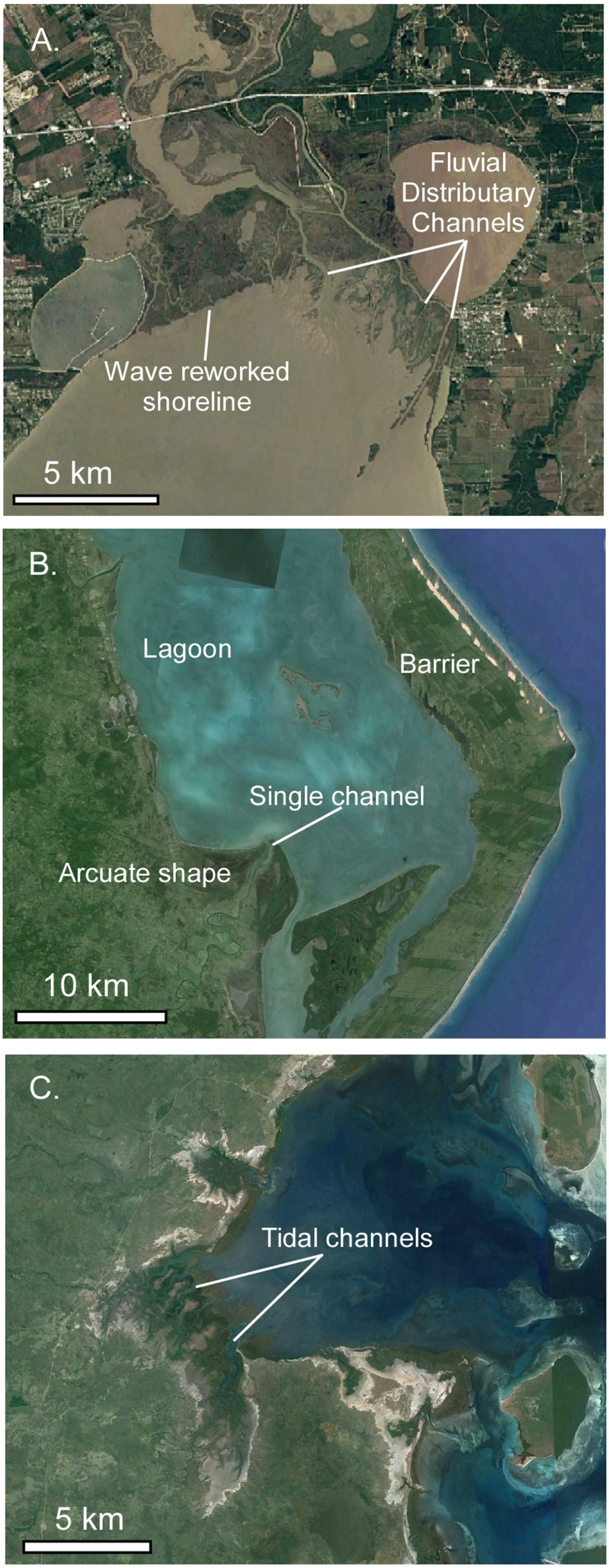

Fig. 9. (A) Aerial photograph of the Trinity Bayhead Delta illustrating the western reworked and hence flat frontal beach of its southern lobe and fluvial-dominated nature of the active eastern lobe. (B) wave-dominated shape of a bayhead delta in Laguna Tamiahua, Veracruz, Mexico. (C) tide-dominated shape of the Montepuez delta of north-eastern Mozambique. Images from GoogleEarth.

shoreline protuberance (Fig. 2). Mouthbars are well developed. In seismic profiles and well-exposed outcrops, delta growth is expressed as prograding clinoforms (Fig. 7A). These clinoforms can be well developed (Figs. 6, 7) but are generally <15 m high (Fig. 8).

Transgressive bayhead shorelines are funnel-shaped, a result of the narrow river widening into the open bay over a short distance (Fig. 12). The deposits of transgressing bayhead shorelines are generally composed of a thin veneer of muddy sand or organic-rich muds (Fig. 11) and are often interpreted as simply transgressive coastal-plain deposits (e.g., Amorosi et al., 2003) or marsh deposits (Hori et al., 2002; Mattheus and Rodriguez, 2014). The marshes and coastal mudflats of these bayhead shorelines accrete at faster rates than equivalent bay-margin marshes and coastal mudflats due to higher fluvial input. Within seismic profiles, transgressing bayhead shorelines form a chaotic to transparent sheet or a set of parallel reflections (Fig. 7B).

The incised-valley fills of the late Quaternary northwestern Gulf of Mexico have extensive portions where a relatively thin, a few tens of cm thick, bed of carbonaceous muddy sand or sandy mud separates underlying lowstand fluvial sands and overlying transgressive central-basin muds (Figs. 7C, 11, 13). In seismic profiles, this thin unit is characterized by a few wavy parallel or weakly chaotic seismic reflections (Fig. 7A). Detailed chronostratigraphies of several incised valleys in the region revealed that these relatively thin bayhead shoreline deposits formed at times when rates of sea-level rise were relatively fast (5–9 mm/yr; Milliken et al., 2008), such as during the early Holocene (Simms et al., 2008; Rodriguez et al., 2008, 2010; Anderson et al., 2008; Troiani et al., 2011). Similar bayhead shoreline deposits have been described within other incised valleys including those of the Scuppemong River of North Carolina (Mattheus and Rodriguez, 2014) (Fig. 11), the Manawata Valley of New Zealand (Clement and Fuller, 2018), Red River of Vietnam (Hori et al., 2004), the Yangse River of China (Hori et al., 2002), and the Rhine-Meuse River of northern Europe (Hijma et al., 2009). Ancient bayhead-shoreline deposits likely formed during Icehouse times, but have yet to be recognized in the rock record.

4.2. Confined versus unconfined deltas

The vast majority of modern, late Quaternary, and ancient bayhead deltas occur either within incised valleys, fjords or structural basins; the remainder are found within interdistributary bays (Fig. 3, Table 1). These settings have very different boundary conditions in that bayhead deltas within incised valleys, fjords and structural basins are largely confined to the valley. The geometry of these confined bayhead deltas is mainly controlled by the morphology of the valleys or basins, which influence wave and tidal energy. Bayhead deltas that occur within interdistributary bays are part of larger deltaic complexes and prograde into an open, unconfined, and shallow bay. Antecedent geology is an important influence on stratigraphic architecture (Belknap and Kraft, 1985; Riggs et al., 1995; Rodriguez et al., 2005; Simms and Rodriguez, 2014, 2015) and thus categorizing bayhead deltas by their boundary conditions allows for a broader discussion of their controlling mechanisms. We suggest grouping bayhead deltas into two different classes: unconfined and confined (Figs. 2, 4).

In addition to interdistributary bays of larger deltaic complexes (Flores et al., 1984; Van Heerden and Roberts, 1988; Tye and Coleman, 1989a, 1989b; Bos, 2010; Li and Bhattacharya, 2014), unconfined bayhead deltas are commonly found behind modern and ancient barrier islands and peninsulas (e.g., Figs. 2E, 6B; those of Semeniuk et al., 2000; Leckie, 2003; Joeckel and Korus, 2012). These deltas are largely unaffected by valley walls or basin margins that may influence their architecture. Unconfined bayhead deltas within large delta complexes are most common in the distal delta plain as incipient lobes of the larger delta (Bos and Stouthamer, 2011). They tend to have more lobate delta fronts as they are not confined.

Table 2
Selected common trace fossils reported in bayhead deltas.

Unit/Delta	Bioturbation Index	Most abundant Trace Fossils	Source
Rakes Creek Shale	0–6	fugichnia, Chondrites, planolites, teichichnus Palaophycus, asterosoma	Joeckel and Korus, 2012
Springhill Formation	low to very low	Planolites	Schwarz et al., 2011
Festningen Member		Skolithos	Midtkandal et al., 2008; Midtkandal and Nystuen, 2009
Nukhul Formation	1–6	Planolites, Skolithos	Carr et al., 2003
Hueco Formation		Skolithos	Mack et al., 2003
Harding Sandstone	2–3	Arenicolites, Teichichnus	Allulee and Holland, 2005
Dunvegan Formation		Planolites, Ophiomorpha	Plint and Wadsworth, 2003
Ferron Sandstone	2–5	Planolites, Chondrites, and Palaeophycus	Li and Bhattacharya, 2014
New River Formation	minor	Lockeia, Planolites, Teichichnus, Palaeophycus	Korus et al., 2008
Elgol Formation		Planolites	Harris, 1989

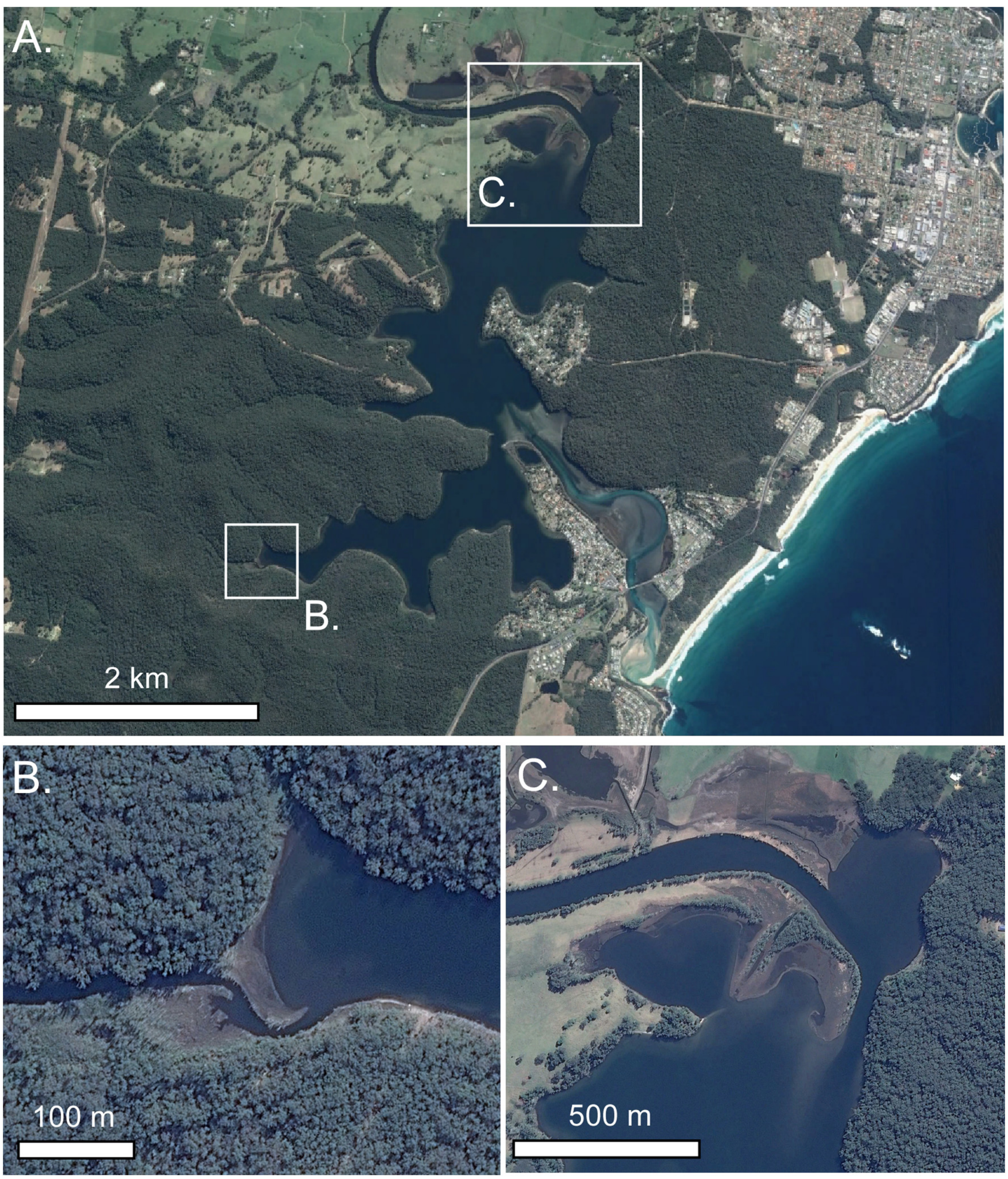

Fig. 10. (A) Aerial photograph image of Lake Burrell, New South Wales, Australia. (B) Aerial photograph of the Southern Limb of Lake Burrell illustrating a transgressive shoreline. (C) Aerial photograph of the Stony Creek Bayhead Delta illustrating a prograding bayhead delta. See Sloss et al. (2006) for a description of the facies and evolution of this system.

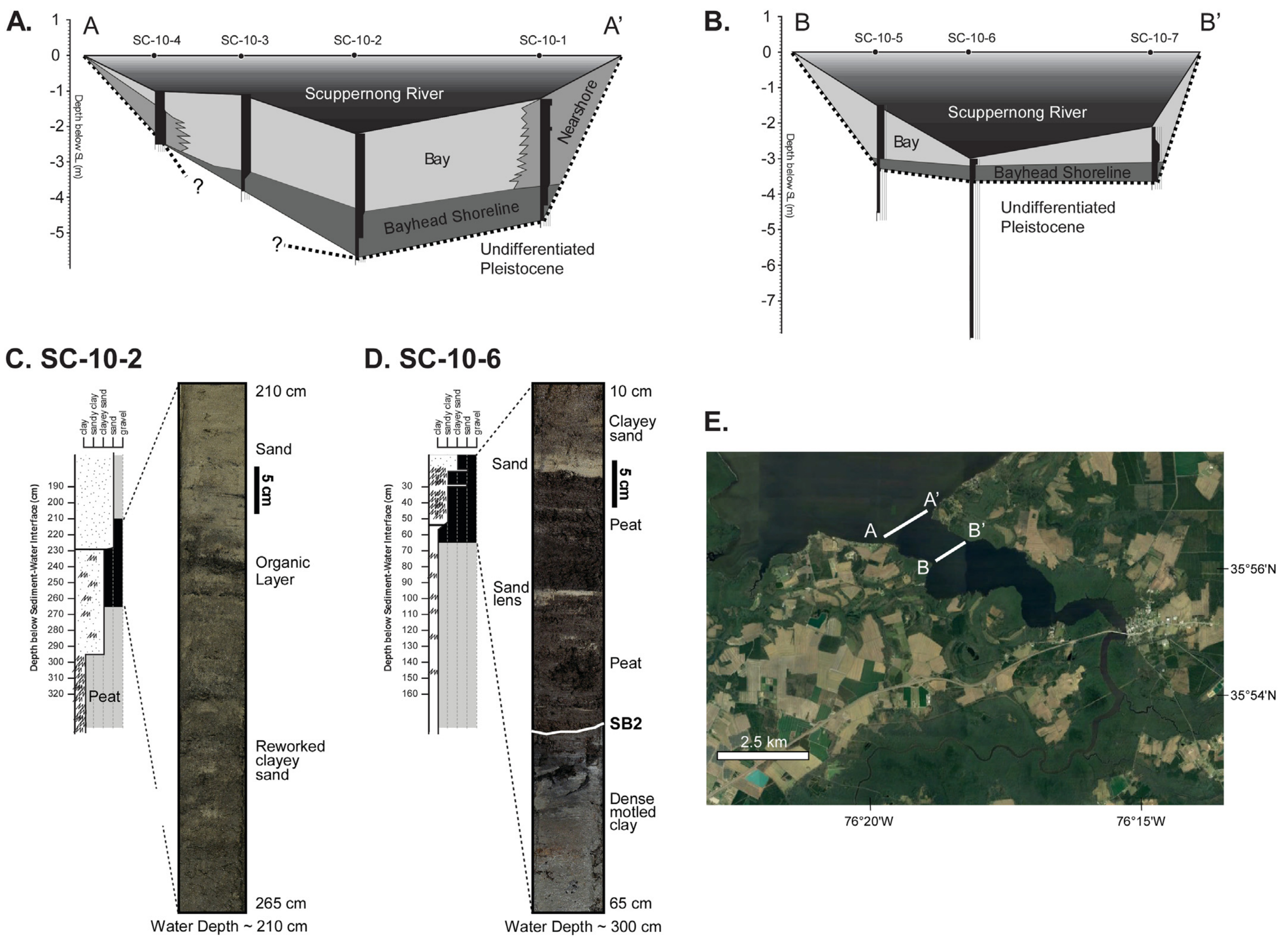

Fig. 11. Core-based cross sections (A and B) and core photographs with lithologic descriptions (C and D) of selected cores in the Scuppernong estuary (E) of North Carolina. The cores and cross sections illustrate the sedimentary deposits of transgressing bayhead shorelines (after Mattheus and Rodriguez, 2014).

Modern and ancient confined bayhead deltas are found in two other settings in addition to incised valleys: structural basins (e.g., Heap and Nichol, 1997; Carr et al., 2003; Schwarz et al., 2011; Osman et al., 2013) and fjords (Syvitski and Farrow, 1983; Corner, 2006), although very few ancient fjord successions have been described (Fig. 3). As noted by Heap and Nichol (1997), these systems will be influenced by limited lateral accommodation. Specifically, the morphology of the confining valley (whether structurally or erosionally controlled) is an important control on sediment accommodation as well as the hydrodynamic processes governing deposition (Heap and Nichol, 1997). For example, narrower valleys may result in stronger tidal flow while wider valleys may result in attenuated flow (Roy, 1984; Dalrymple et al., 1992; Heap and Nichol, 1997), but the number and nature of the tidal inlets may also impact the tidal flow structure (Panda et al., 2013). In addition, the relative balance between sediment supply and accommodation will largely be controlled by the interactions of confining morphology and relative sea-level changes (Heap and Nichol, 1997) rather than exclusively on subsidence and other components of relative sea-level change. In the case of the Weiti River estuary of New Zealand, the confined nature of the estuary resulted in inadequate accommodation for the development of a central basin within the estuary which, in turn, caused the bayhead delta within the system to be largely expressed as a point-bar (Heap and Nichol, 1997). A similar situation exists for the Hawkesbury estuary of Australia (Nichol et al., 1997). Bayhead deltas prograding into structural basins or fjords encounter greater accommodation due to the deep nature of the bays or fjords and are thus characterized by thick successions of not only bayhead-delta deposits and associated clinoforms, but also thick central-basin deposits (Eilertsen et al., 2006). The delta fronts and shorelines of confined bayhead deltas are generally less lobate and cuspate due to their confinement within the valley (Fig. 2).

5. Stratigraphic controls

5.1. Controls on preservation

Confined bayhead deltas are commonly preserved below the transgressive ravinement surface within incised valleys. Their preservation is enhanced by added accommodation due to earlier fluvial incision but filled with overlying open-bay deposits (Thomas and Anderson, 1994). This enhanced preservation may explain why most ancient examples (15/25) of bayhead deltas are described from incised valleys despite a much more balanced number of settings represented by modern bayhead deltas (10/29) (Fig. 3). Icehouse times marked by rapid sea-level changes likely exacerbate these biases as within the Quaternary 17 of 20 bayhead deltas are found in incised valleys (Fig. 3). The enhanced preservation also explains their common target as reservoirs within incised-valleys (Terzuoli and Walker, 1997; Ardies et al., 2002; Hubbard et al., 2002; Bowen and Weimer, 2003, 2004). However, part of this bias in the high number of bayhead deltas within incised valleys may be their prominent position within common incised valley facies models and hence their wider recognition (Zaitlin et al.,

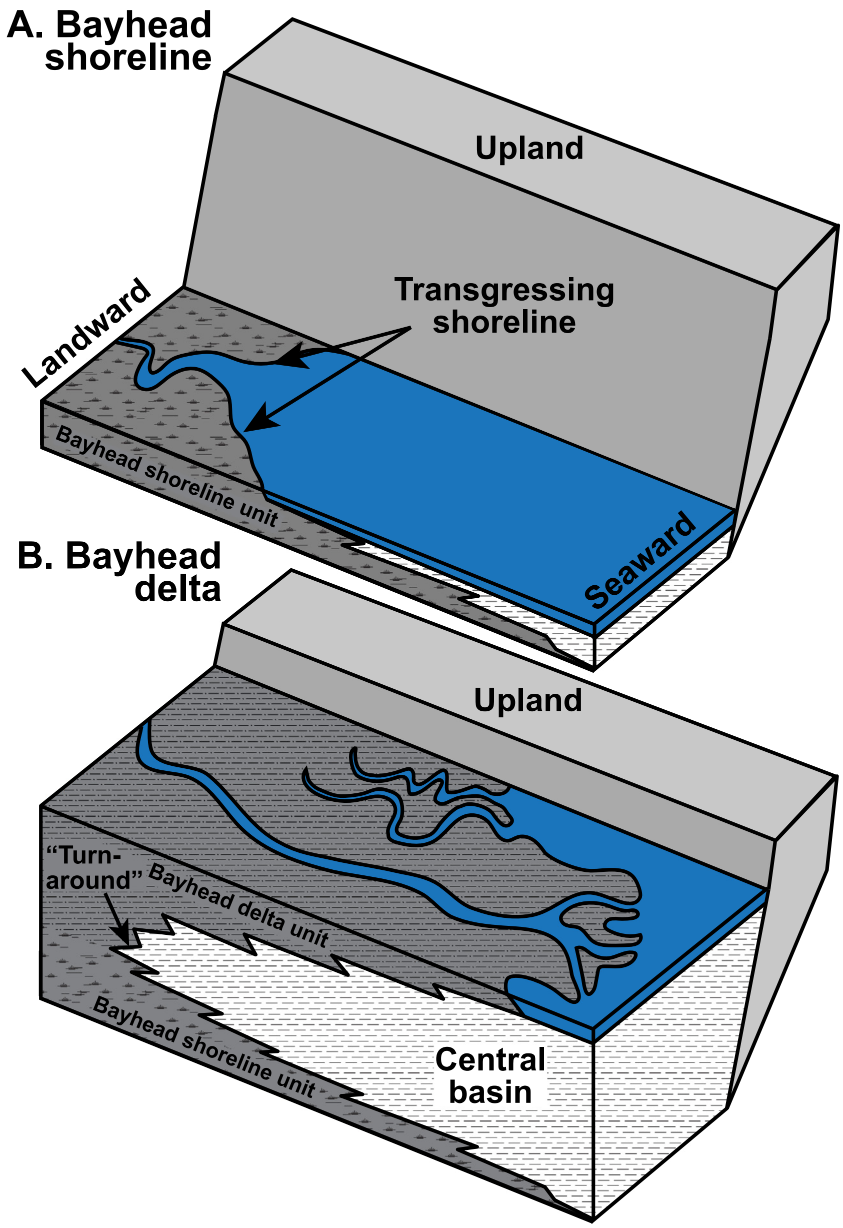

Fig. 12. Model of a depositional system changing from a transgressing bayhead shoreline to a regressing bayhead delta.

1994). Preservation potential may also be a key driver for the higher number of bayhead deltas in ancient structural basins as the added accommodation due to tectonic subsidence likely enhances their preservation potential.

Unconfined bayhead deltas are usually preserved within large deltaic complexes or directly above the maximum flooding surface. Transgressive unconfined bayhead deltas not associated with large deltaic complexes (Figs. 2E, 9B) generally have a low preservation potential due to their relatively thin nature and high potential for erosion by ravinement processes during relative sea-level rise (Joeckel and Korus, 2012). Thus their numbers within the Quaternary and ancient are less than their prevalence along modern coastlines (Fig. 3).

5.2. Allogenic controls

Controls on bayhead delta architecture include allogenic mechanisms such as relative sea-level changes, including the influence of subsidence, or climatically- or tectonically- driven changes in sediment supply as well as autogenic controls. Bayhead deltas, perhaps more than any other depositional environment, are highly sensitive to the interplay between relative sea-level rise and sediment supply due to their relatively small size and typically limited accommodation, which facilitates the ability to distinguish allogenic from autogenic processes (e.g., Li et al., 2016).

5.2.1. Sea-level changes

Like all coastal systems, relative sea-level change plays a dominant role in bayhead delta evolution and preservation. In addition, bayhead deltas appear to be more sensitive to sea-level changes than their larger open-ocean equivalents. A large part of this sensitivity to sea-level changes is their smaller size, confinement to a valley (in the case of confined incised valleys), and more closely balanced rates of accommodation creation (driven by relative sea-level changes) and sediment supply. This is particularly true for times when ice sheets regulate sea-level change (ice-house conditions), and sea-level rise tends to be more episodic and punctuated by episodes of rise that exceed the capacity of rivers to fill accommodation. For example, approximately 8200 years ago, sea-level rose along the northern Gulf of Mexico

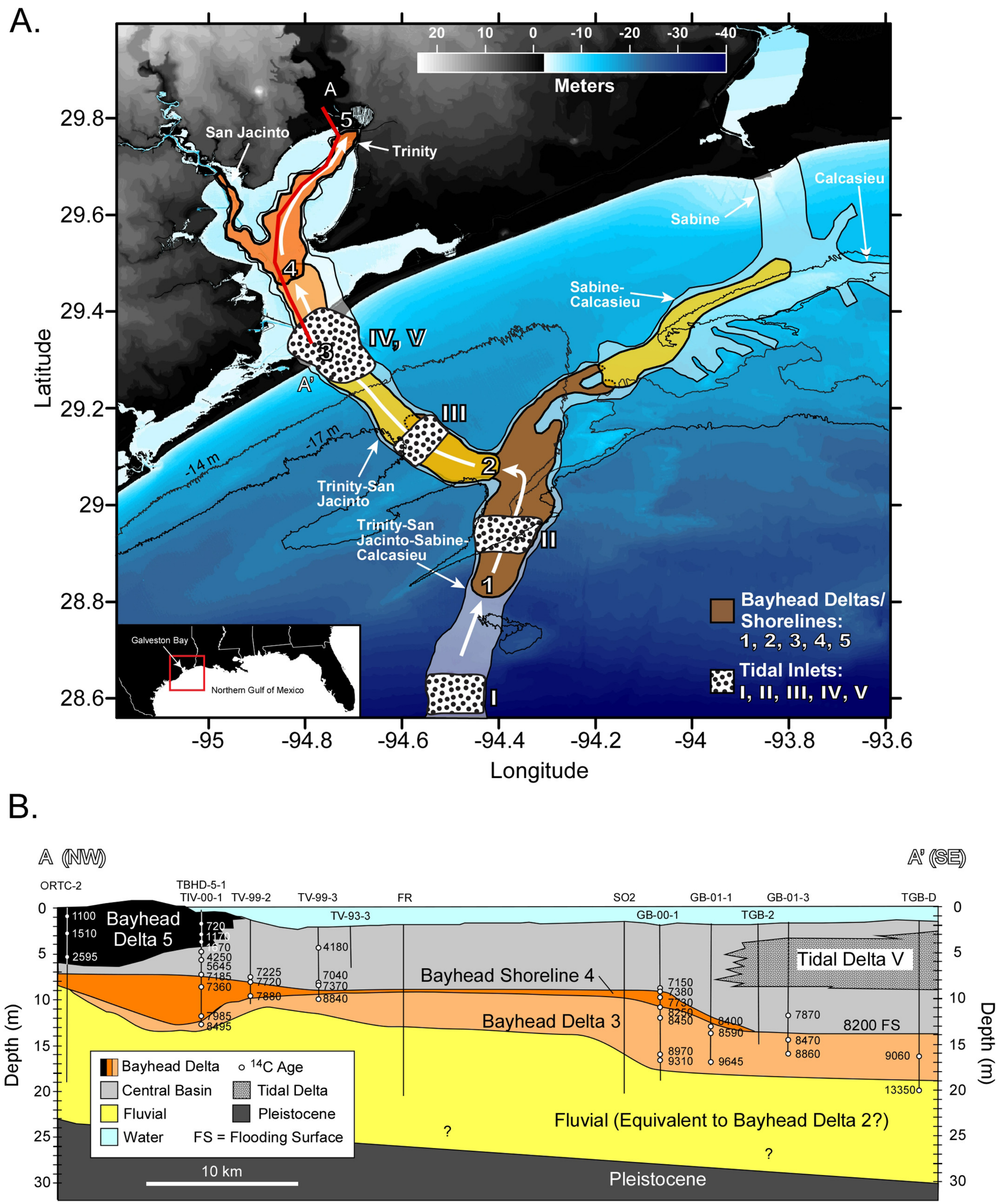

Fig. 13. (A) Map illustrating the location of the Trinity bayhead delta (shoreline) and associated estuarine environments as they backstepped within the Trinity Incised Valley through the last transgression since the Last Glacial Maximum (LGM) ~20 ka (modified from Thomas and Anderson, 1994; Anderson et al., 2016). (B) Cross-section of the Trinity Incised Valley based on cores taken within Galveston Bay showing the location and timing of the bayhead delta backstepping events during the middle to late Holocene (modified from Anderson et al., 2008).

somewhere between 0.4 and 2 m in <200 years (Tornqvist et al., 2004; Kendall et al., 2008; Hijma and Cohen, 2010), well within the range of some future projections in the rate of sea-level rise (Church et al., 2013). At this time, every bayhead delta studied to date along the northwestern US Gulf Coast backstepped up to 20 km (Rodriguez et al., 2010; Troiani et al., 2011). During other periods of rapid late Pleistocene and early Holocene sea-level rise, even very large rivers such as the Yangtse (Hori et al., 2002), Red (Hori et al., 2004; Tanabe et al., 2006) and Rhine-Meuse (Hijma et al., 2009) produced bayhead shorelines within their incised valleys. The rates of relative sea-level rise can be additionally enhanced by compaction-induced subsidence within incised valleys due to their relatively thick but spatially-restricted succession of underlying, often fine-grained, transgressive deposits. Along the western Gulf Coast, rates of subsidence measured by long-term tide gauges are in the range of 2–4 mm/yr, which makes relative sea-level rise approximately double the eustatic rate (Kolker et al., 2011).

Within confined systems such as incised valleys, fjords, or structurally-controlled valleys of the Late Pleistocene and early Holocene, the upper reaches of wave-dominated estuaries change at the beginning of regression from transgressing bayhead shorelines to regressing bayhead deltas (Fig. 12). For many Holocene deltas within the Northern Hemisphere, this change occurred between 7000 and 5000 years ago (Anderson et al., 2008; Simms et al., 2008; Maselli and Trincardi, 2013). This was about the same time the modern large open-ocean deltas first started to form as the rate of sea sea-level rise decreased, marking the final stage of significant melting of Earth's ice sheets (Stanley and Warne, 1994). The timing of this transition likely reflects a combination of local sea levels and sediment supplies. As the rate of sea-level rise decreased across much of the northern Hemisphere around 5000 years ago, many bayhead deltas such as the Trinity and Nueces Deltas of the northwestern Gulf of Mexico experienced significant growth (Anderson et al., 2008; Simms et al., 2008) (Figs. 7, 13). A similar pattern of a turnaround from transgression to regression is interpreted to represent a change in sea level driving ancient bayhead delta changes in the Cretaceous Interior Seaway of the US (Plink-Bjorklund, 2008; Aschoff et al., 2018).

The current highstand is the longest period of bayhead delta stability since the post-glacial sea-level rise began. It is also the time when the hosting incised valleys have been mostly enclosed by coastal barriers, which has resulted in an increase in the relative proportion of bay mud within many incised valleys (Anderson et al., 2016). During the rapid sea-level rise (~4–7 mm/yr) of the Late Pleistocene and early Holocene, the Trinity delta back-stepped within its valley, with minimal delta formation leaving only bayhead shoreline deposits behind during back-stepping events and large bayhead deltas forming during pauses (Thomas and Anderson, 1994) (Fig. 13). During back-stepping, the estuary is an open mouthed bay and tidal influence should be greater. During pauses, barriers developed (indicated by large tidal delta complexes) and larger, thicker bayhead deltas formed (Thomas and Anderson, 1994) (Fig. 13).

5.2.2. Sensitivity to climate changes

Bayhead deltas are most commonly associated with smaller fluvial systems, which can be very sensitive to climate changes. Simms et al. (2008) showed that the Holocene Nueces Bayhead delta of the Texas coast underwent four major backstepping events during its history. The first two of these were likely related to increases in the rate of sea-level rise, but the latter two at 4.8 ka and 2.6 ka occurred during a period of no known rapid increases in the rate of sea-level rise but did occur at the same time as global-scale changes in climate (Livsey and Simms, 2016). The magnitude of these backstepping events during dry periods resulted in almost 20 km of delta-front retreat (Simms et al., 2008) while a return to wetter periods brought about similar magnitudes of progradation (Rice, 2015). Climate changes during the middle-Holocene of southern Texas resulted in the former bayhead deltas of the Baffin Bay system transitioning into mud flats resembling a transgressing bayhead shoreline as the discharge of fluvial systems feeding its bayhead deltas decreased (Simms et al., 2010; Buzas-Stephens et al., 2014; Livsey and Simms, 2016).

5.2.3. Tectonics

Tectonics can influence the development and behavior of bayhead deltas via three mechanisms: confinement by fault-defined valley walls, changes in local rates of vertical motion (either via subsidence or tectonic uplift), and increases in sediment supply. The growth of active or inherited structures creates embayments that can host bayhead deltas (Dunne and Hempton, 1984; Carr et al., 2003). The importance of vertical motion on bayhead delta evolution depends on the timing and duration of bayhead delta development relative to tectonic motion. Under greenhouse conditions, such as during the Mesozoic, rates of eustatic change occurred at magnitudes and rates that were more in tune with rates of tectonic activity, hence bayhead delta evolution was likely more influenced by tectonic activity (Schwarz et al., 2011).

Modern bayhead deltas formed over time intervals of a few thousand years in response to decreasing rates of sea-level rise. Hence, tectonic influence was minimal. There are, however, exceptions. The Isumi delta of Japan underwent rapid progradation as a result of increased sediment supply following uplift in the hinterland despite rapid rates of eustatic sea-level rise at the time (Sakai et al., 2006). Similarly, Mateo and Siringan (2007) argue that movement along two alluvial-plan bounding faults in the Philippines increased sediment supply and resulted in the avulsion of the deltas within the Lingayen Gulf.

5.3. Autogenic controls

Autogenic or internal mechanisms also play an important role in controlling bayhead delta stratigraphic architecture. The same processes such as auto-retreat (e.g., Muto and Steel, 1992) that drive all deltas likely influence bayhead deltas. However, within confined bayhead deltas, the boundary conditions imposed by the valley walls (whether structurally controlled or erosionally controlled) provide an additional source of autogenic controls. These boundary conditions include valley shape, which plays a major control on confined bayhead delta evolution, and the confluence of tributary valleys. Valley shape is largely controlled by basin relief and tectonic setting. Narrow, generally deep incised valleys, such as Chesapeake Bay, occur in areas of relatively high relief. These are typically open-mouthed bays, resulting from limited barrier development. Consequently, they commonly have a greater tidal influence on the fluvial/marine transition and sediment bypass will be more efficient resulting in limited bayhead delta development. Mobile Bay is an example of an intermediate system. The valley is surrounded by steep valley walls but the mouth of the bay is enclosed by barriers resulting in reduced tidal influence. These confining valley margins forced the bayhead deltas to prograde bayward more than unconfined systems (Rodriguez et al., 2008). The Mobile bayhead delta has experienced minimal delta lobe shifting and pronounced bayward progradation due to its relatively narrow valley compared to Trinity Bay (Rodriguez et al., 2008). The modern Trinity bayhead delta is an example of a system that forms in a broad, shallow bay where lobe shifting is common (Fig. 9A). The delta has remained roughly in the same location throughout the late Holocene highstand, which has resulted in a greater proportion of sand relative to its transgressive deltas (Anderson et al., 2008). Given these geomorphological controls on bayhead delta evolution, it is important to consider changes in valley shape that will likely occur during transgression as more landward segments of the valley are flooded and as the bayhead delta shifts its stratigraphic position from the lower, narrower part of the valley to the upper, broader portions of the valley.

As part of incised-valley systems, individual parasequences can develop due to the flooding of relict topography (Heap and Nichol, 1997; Rodriguez et al., 2005). Rodriguez et al. (2005) showed in Holocene examples that the flooding of relict fluvial terraces that developed within an incised valley during the previous Late Pleistocene fall in sea level resulted in rapid increases in accommodation and thus the backstepping of the estuarine environments including bayhead deltas. Similarly, Heap and Nichol (1997) suggested that the development of the bayhead delta within a structurally controlled incised valley was limited in part to a time period after the flooding of a relict fluvial terrace, which also represented a time period of rapid environmental change within the estuary, and after the time in which a barrier formed at the head of the estuary.

In addition, tributary junctions within the incised valley flooded to form an estuary also play an important role in governing the location of bayhead-delta development (Simms and Rodriguez, 2014, 2015). During transgression, tributary junctions act as pinning points for bayhead-delta stabilization due to the predictive nature of accommodation creation within valley systems leading to a 12–35% reduction in rate of transgression in the case of a Texas-sized river (e.g., 40,000 km^2 drainage basin; Simms and Rodriguez, 2014). As such, the rate of shoreline retreat within bayhead deltas decreases independent of changes in sediment supply and relative sea levels at tributary junctions. Similarly, during regression, tributary junctions provide spots of "auto-acceleration" to bayhead delta progradation marked by an increase in the rate of shoreline progradation independent of changes in the rate of sea-level fall or sediment supply. Two similar-sized systems' bayhead deltas increase their rates of progradation by 17% when they coalesce (Simms and Rodriguez, 2015).

The presence of a barrier island in the seaward reaches of the estuary may be a prerequisite to the formation of a bayhead delta due to the overpowering influences of waves and tides (e.g., Heap and Nichol, 1997). Within the Late Pleistocene/early Holocene offshore Trinity Incised Valley of the northwestern Gulf of Mexico, bayhead deltas backstepped up to 40 km at the same time as the barrier/tidal inlet systems (Thomas and Anderson, 1994) (Fig. 13). Their reestablishment at the same time as the barrier island systems suggests a link between barrier and bayhead delta dynamics within wave-dominated estuaries. Similarly, when Mustang Island of central Texas collapsed during a period of rapid sea-level rise 8200 years ago, the Nueces Bayhead delta within the bay behind it retreated (Ferguson et al., 2018), although untangling the relative importance of the rapid sea-level rise and the collapse of the barrier island is difficult. This implies that tidal influence on the bay and its bayhead delta varied through time, being greater at times when barriers did not exist and/or the valley was narrower resulting in greater tidal amplification due to the wedge-shaped morphology of the bay. Further implied is the concept that the bay was a more efficient sediment trap once barriers formed.

6. Concluding remarks

The relatively small size and limited preservation potential (outside of incised valleys and structural basins) of bayhead deltas has likely resulted in their being overlooked and underreported within coastal deposits. Unconfined bayhead deltas are more likely to be overlooked than confined bayhead deltas due to the latter's prominence in general incised-valley fill facies models. However, this oversight may be leaving behind many underappreciated insights into Earth history that could be gleaned from the stratigraphic architecture of bayhead deltas. The high sensitivity of bayhead deltas to changes in the balance between rates of sediment supply and relative sea level make them an ideal location for reconstructing records of past sea-level and climate changes, particularly in the case of confined bayhead deltas. In the correct setting, they also record important tectonic events. Stratigraphically, they make an ideal marker for identifying the turnaround from transgression to early highstand and their buried ancient deposits are the site of petroleum reservoirs. Their hosting of many large cities makes an understanding of the processes impacting them critical for future management. Like other deltas, their low elevation makes them vulnerable to future sea-level rise. If their past responses to sea-level and climate changes are representative of future behavior then those cities and ports built on them should prepare for large and rapid changes. In the case of confined bayhead deltas, these responses may be quite variable due to the important interactions between the deltas and their confining valley walls. Because of these important characteristics, bayhead deltas should be targeted as sentinels of change when studying modern coastlines or interpreting and describing ancient stratigraphic successions.

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