# Deflection of the progradational axis and asymmetry in tidal seaway and strait deltas: insights from two outcrop case studies

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**Abstract:** Deltas represent the major sediment source for tectonically confined, tide-dominated seaways or straits. Modern examples show how along-shore tidal currents are able to modify the impinging delta shape, generating asymmetrical coastal plains, deflected delta fronts and elongate sandbanks. Seaway or strait deltas can become become tide-influenced or tide-dominated, assuming physical attributes that may depart from classical models. Ancient deltas in seaways and straits can also reveal unexpected facies stacking and stratigraphies, which can be misinterpreted or attributed to different depositional settings. Two ancient analogues of deltas that prograded into elongate basins dominated by amplified tidal currents are presented here. A common element in these deltas is the progressive-upwards change in the dominant process of sediment dispersion recorded in the delta facies. Early stages of progradation are dominated by river- and wave-influenced lithofacies, whereas late deltaic advancements occur with a dominance of tidal current circulation on the delta fronts and the consequent morphologies are deflected/elongated in the direction of tidal flow. This study provides the basis for a preliminary stratigraphic framework for the depositional style of these types of delta. The studied deposits also suggest analogies with the spatial distribution of many hydrocarbon reservoirs investigated along the margins of confined, narrow, linear basins, the interpretation of which is still debated.

River deltas, the main vehicle of water and sediment transport from continents to ocean basins, are among the most investigated depositional systems in the world. Their historical importance stems from their great natural and economic potential for society because of their strategic importance in land use (Syvitski *et al.* 2005; Bhattacharya 2006). In modern times, ancient deltaic deposits have revealed important georesources (Tyler & Finley 1991) and their architectural and facies elements, from outcrop to experimental studies, have been highlighted in increasing detail in the last few decades as a result of innovative investigation techniques.

For these reasons, river delta systems have benefited from an impressive number of depositional models. These are mostly based on: (1) the dominant hydrodynamic processes governing sediment delivery along the deltaic coastlines (e.g. Galloway 1975; Orton & Reading 1993); (2) their diagnostic morphologies assumed at the shoreline (Fisher *et al.* 1969; Bhattacharya & Giosan 2003); or (3) the distinctive depositional geometries that deltas generate in a cross-sectional view when they enter a standing body of water (i.e. basin) (e.g. Wescott & Ethridge 1990). Despite this proliferation of models and associated classifications, the Galloway-based terminology has rightly received preferential use among sedimentologists because it has been improved through time (e.g. Dalrymple *et al.* 1992; Orton & Reading 1993; Ainsworth *et al.* 2011).

Deltas have been described in a wide range of tectonic settings and have been used as proxies to reconstruct basinal history around the world because they are considered formidably sensitive to high-frequency sea-level changes, process regime variations and structural movements of the basin margins (Muto & Steel 2002; Yoshida *et al.* 2007; Longhitano 2008).

River deltas can depart from a classical symmetrical coastal shape as a result of the influence of channel avulsion in the delta plain area or an oblique approach of waves at the coastline (Bhattacharya & Giosan 2003). In wave-dominated coastlines, strongly asymmetrical delta morphologies result from the influence of wind-induced alongshore currents, which tend to deflect the deltaic components at the river mouth and also favour the formation of spits and bar complexes (Wright 1977; Orton & Reading 1993; Reading & Collinson 1996). Asymmetrical river mouth entrances are also attributed to autocyclic distributary switching in meandering river channels on the delta plain (Longhitano & Colella 2007). In these settings, the river mouth is often bypassed when a river flood transports sediment onto a delta mouth bar and beyond.

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Sand is mostly stored in the mouth bar and slowly reworked and re-entrained in the littoral sand stream. Fine sand, silt and clay are carried as a buoyant half-jet and rained onto the shelf floor (Swift & Thorne 1991). These studies focused on the observation of subaerial features, but paid less attention to sediment routing and distribution at the delta front, which represent a volumetrically important deltaic component.

Fewer studies have documented river deltas impinging upon, and interacting with, straits or elongate seaways (Keller & Richards 1967; Galloway 2002; Willis 2005). These deltas often prograde into confined marine settings where the effects of waves, flood and/or ebb tides and river input are subordinate to the dominant influence of tidal current patterns running parallel to the coastline, increasing in their strength as a result of the mass convergence of water (Defant 1961; Pugh 1987; Pratt 1990). As a consequence, river deltas sourcing tidal straits or seaways can assume strongly skewed or strike-elongate morphologies, departing substantially from the expected river delta morphologies (e.g. Weise 1980; Korus & Fielding 2015; Ayranci & Dashtgard 2016).

Surprisingly, a general observation along the world's coastlines reveals that >20% of modern deltas prograde into tide-dominated straits and seaways, although many of these examples are not necessarily subject to significant deflections or asymmetries in their subaerial environments (www.eoearth.org). Based on this evaluation, a significant number of ancient deltas may have been accumulated and preserved in the rock record of tidal seaways and straits, especially where tectonics shaped parts of the sedimentary basins into elongate narrow sectors (e.g. rift, thrust-top or strike-slip basins). These types of deltas have possibly assumed important morphological asymmetries and deflections of their subaqueous environments, as elongate basins usually experience an oceanographic circulation with tidal or other currents flowing axially. This is one of the main issues that has inspired the present research, which investigated the basis for a new stratigraphic model for such deltas

These general considerations point towards types of deltas that differ from 'classical' wave-, river- or tide-dominated models. Therefore the possible importance of paying more attention to river deltas sourcing tidal elongate seaways or straits can be highlighted by the following questions.

(1) What are the distinctive morphological features and sediment zonations of tide-dominated seaway/strait deltas?
(2) How can we recognize them in the rock record?
(3) What kind of vertical facies successions and stratigraphic sequences can they assume?
(4) Are tide-dominated seaway/strait deltas the possible interpretative key in unravelling sand-rich hydrocarbon reservoirs entrapped in confined settings?

We critically review two outcrop case studies in which siliciclastic-dominated, sand-rich sedimentary successions have been interpreted as the record of deltaic sequences prograding into narrow and elongate settings. Their stratigraphic and sedimentary facies stacking patterns record delta front accumulation strongly influenced by tidal currents, causing progressive sandbody and distributary channel deflection, the likely key with which to detect other ancient deltas building into a similar setting. The two field study cases derive from: (1) the Campanian of the Western Interior Seaway of southern Wyoming, USA; and (2) the Tortonian of the Calabrian Arc in southern Italy.

## Tidal seaways and straits

Tidal seaways are elongate marine passageways, thousands of kilometres wide, connecting two wider basins. The dominant hydrodynamic force in tidal seaways results from tidal currents flowing parallel to strike. Tidal straits are narrower than seaways and are governed by the convergence and amplification of tidal currents as a result of narrowing of the cross-sectional area of the water body (Pugh 1987). Recent studies on ancient tidal strait-fill successions in southern Italy have attempted to demonstrate that a critical cross-sectional area is the fundamental quantitative condition through which a strait becomes dominated by the amplification of a tidal flow (Longhitano *et al.* 2014). This condition, favourable to the onset of a tidal circulation, can be also matched during late transgressive stages, as has occurred recently along many of the world's coastal systems at the end of the post-Last Glacial Maximum relative sea-level rise (e.g. Longhitano *et al.* 2016).

Seaways and straits are mainly sourced by river deltas. Other minor sediment supply can be provided by: (1) lateral debris aprons or landslides shed from steep margins; (2) clastic sediments derived from the erosion of older lowstand deposits by strong tidal flows in the proximity of the tidal maxima at the narrowest strait zone; and (3) *in situ* carbonate factories, well adapted to high-energy conditions (Anastas *et al.* 2006; Longhitano 2013). As observable in many modern examples (e.g. the Juan de Fuca Strait, Malacca Strait, San Francisco Strait, Messina Strait, Dover Strait and Torres Strait; see Fig. 1), coaxial tidal currents strongly influence the sea bottom. They flow in reversal phases, often in opposition between the two interlinked basins, favouring the development of wide tidal bedform

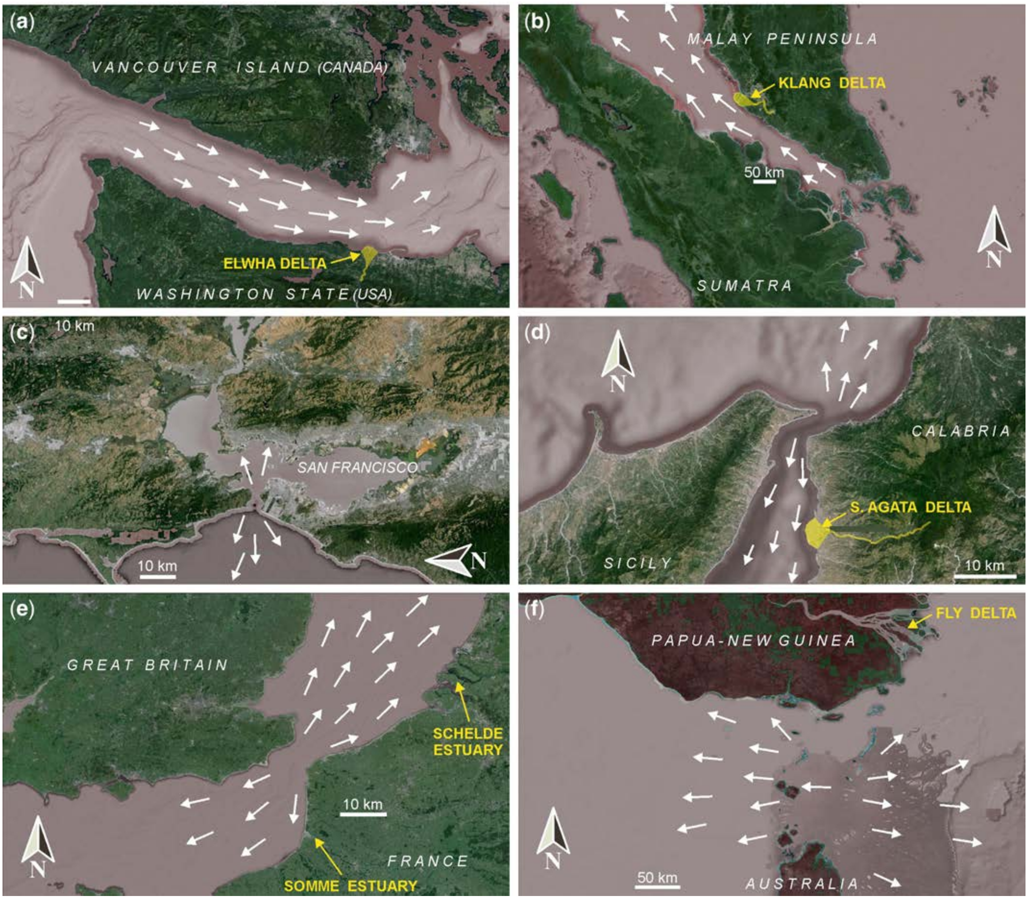


**Fig. 1.** Examples of modern tidal straits and seaways. (**a**) The Juan de Fuca Stait at the northwestern boundary of the USA, where the Elwha Delta is developing (see Fig. 19a). (**b**) The Malacca Seaway, Indonesia, with the Klang Delta prograding from the northeastern border (Fig. 19d). (**c**) The San Francisco (or Golden Gate) Strait, California. (**d**) The Messina Strait in the central Mediterranean Sea; the Sant'Agata River Delta is highlighted. (**e**) The Dover Strait, western Europe. (**f**) The Bass-Torres Strait, northern Australia. Arrows indicate the main directions of tidal currents.

fields, including two- and three-dimensional, simple and compound dunes, passing downcurrent and laterally to rippled, highly bioturbated fine-grained sheets (e.g. Dalrymple 1984, 2010; Ashley 1990; Anastas *et al.* 1997; Bastos *et al.* 2003). Tidal currents are able to produce deposition and bedform migration outwards of the seaway or strait, rather than inwards. This is mainly due to the energy condition of the opposing flow during each phase of tidal reversal, which is usually in a weaker, but increasing, stage (in the strait side from which it flows in) and is thus unable to move significant sand volumes. However, many stratigraphic sections observed in ancient tidal strait-fill successions occasionally show the occurrence of thinner cross-strata migrating in an opposing direction to the dominant palaeocurrent trend as a result of the momentary interruption of the dominant tidal flow and the consequent increasing influence of the opposite, subordinate current.

Along the margins, tidal dunes and ripples merge with shoreface and deltaic sediments (e.g. Longhitano 2012, 2013; Steel *et al.* 2012; Longhitano *et al.* 2014). The Coriolis effect can be an important additional process regulating the tidal circulation in wide seaways (e.g. the modern Taiwan Strait), whereas tidal straits, which are considered to be narrower sea branches between islands or promontories, usually generate a tidal amplification as a result of coastal narrowing and the consequent tidal current convergence (Reynaud & Dalrymple 2012).

River deltas sourcing tide-dominated passageways can be strongly influenced during their evolution by the effect of tidal currents flowing landwards and seawards through the delta channel systems and tidal currents flowing parallel to the strait coastline (Uroza 2008; Longhitano 2015; Longhitano & Steel 2015). This type of delta can be strongly skewed in its coastal morphology and asymmetrically deflected towards the dominant tidal current direction (e.g. the Klang Delta in the Malacca Strait; the Elwha Delta in the Juan de Fuca Strait). Importantly, deltas that undergo such tidal influence in their subaqueous reaches can be intensely modified on their delta front (e.g. the Fraser River Delta; Ayranci & Dashtgard 2016). Sediments that are significantly reworked under the effect of the dominant tidal current form elongate sandbodies, pseudo-spits or sand ribbons. In the case of consistent sediment supply and persistent strong tidal circulation, sand can be transported far downcurrent, forming ‘detached’ shoals and macroforms.

## Geological settings of study areas

Two outcrop study areas were considered in this work with the aim of reviewing tide-influenced, deltaic successions developed across the margin of a wide seaway and in a narrower tidal strait. The two field study areas expose strata deposited in the Cretaceous Western Interior Seaway of the USA and the Tortonian Calabrian Arc. The Cretaceous Western Interior Seaway is an extensive marine passageway that connected the Gulf of Mexico to the south with the Arctic Sea to the north, where there was a tidal circulation governed by the overall oceanographic setting and by the narrowing and widening of this seaway as the relative sea-level repeatedly rose and fell. The Tortonian Calabrian Arc is a small orogen that hosted a number of tectonically controlled corridors. These corridors produced significant tidal current amplification and the consequent exchange of sediment dispersal between the interlinked Tyrrhenian and Ionian basins.

## Cretaceous Western Interior Seaway of North America

The Cretaceous Western Interior Seaway of North America was a 500–1000 km wide and *c.* 4500 km long tidal seaway that occupied a retro-arc foreland basin during the easterly migration of the Sevier fold–thrust belt towards the Colorado Plateau (Kauffman 1977; Kauffman & Caldwell 1993) (Fig. 2a). The Western Interior Seaway was characterized by relatively shallow water depths along its length, probably rarely exceeding 100 m, and with low-gradient margins (e.g. Kauffman 1977), except for localized areas in the proximity of the forebulge zone or isolated intra-basinal highs (Cole & Young 1991; Plint *et al.* 1993). The best documented aspect of the Western Interior Seaway is the repeated regressive–transgressive transits of deltas (usually on a 100–300 ka timescale) that built transversely out into the seaway from the western margin (Asquith 1970; Plint *et al.* 1986; Plint 1990, 1991; Roehler 1990; Hettinger & Kirschbaum 2002; Plint & Kreitner 2007; Aschoff & Steel 2011*a*, *b*). A notable feature of these deltas, particularly in the Campanian, was that the deltas developed during highstand periods (i.e. those sited furthest west when the seaway was wider) were generally wave-dominated on relatively linear coasts (Martinsen 2001, 2003; Hampson & Howell 2005), whereas the lowstand deltas (developed up to 150 km further east when the seaway was narrower) developed on invaginated coastlines and were more strongly tide-influenced (Mellere & Steel 1995*b*; Hampson *et al.* 2008; Aschoff & Steel 2011*a*, *b*). The large-scale effect of tidal waves entering the seaway from the Gulf of Mexico produced an overall current-dominated oceanography and significant anticlockwise tidal flow patterns that particularly affected the distal, subaqueous segments of the lowstand deltas (Klein & Ryer 1978; Dalrymple 2010) as they built into the seaway from its western margin. The width of the Western Interior Seaway changed dramatically over any relative sea-level cycle. At relative highstands of sea-level, the seaway was 500–1000 km wide, whereas it narrowed by several hundred kilometres during relative lowstands, favouring the progradation of falling-stage deltas (Fig. 2b) (Steel *et al.* 2012). This pattern of a changing shoreline process regime with seaway width was especially notable across Utah, Colorado and Wyoming during the Campanian period, the interval of the present case study (Fig. 2c).

The tendency for basinwards regime change from decreasing wave influence to increasing tide influence as the deltas migrated from highstand inner to lowstand outer reaches of the pre-existing platform of the seaway is, interestingly, the opposite of the typical trend on passive continental margins, where the strongest wave climate is commonly observed along the outermost shelf reaches (Porębski & Steel 2006; Yoshida *et al.* 2007).

A Campanian cross-section from Rock Springs to Denver (see Fig. 2c for location) illustrates this basinwards change in shoreline/delta type from west to east into the Western Interior Seaway and illustrates the series of tide-dominated lowstand deltas (e.g. the Airport, Blair, Meeker, Morapos, Kremmling, Muddy Buttes, Hygiene and Gunsight Pass sandstone units) that developed far basinwards of the updip wave-dominated deltas (Fig. 3).

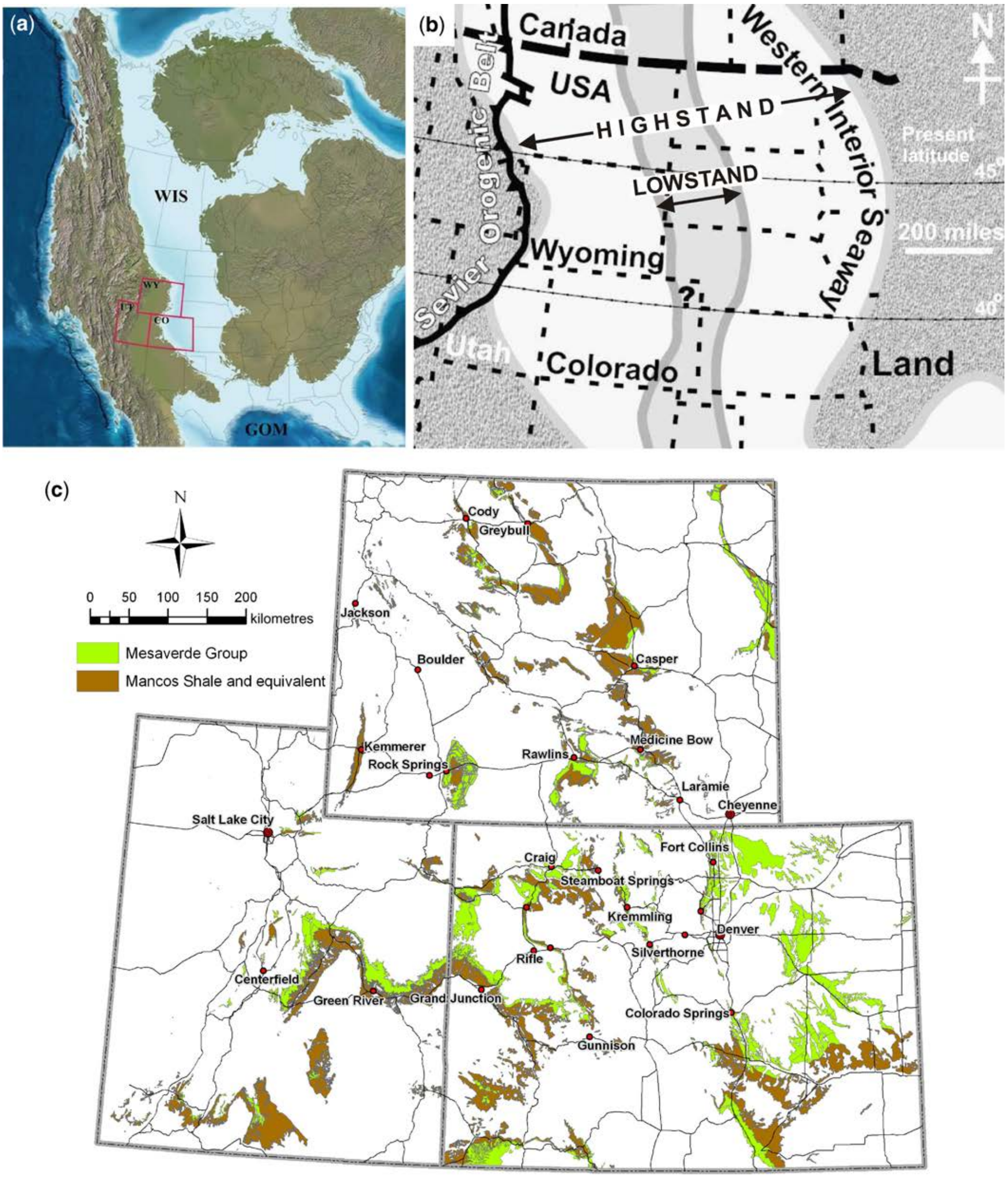


**Fig. 2.** (**a**) Reconstruction of the Western Interior Seaway (WIS) (from Blakey & Ranney 2008). The study areas of Utah, Colorado and Wyoming are highlighted. This setting represents the widest dimensions of the seaway during the sea-level highstand at 75 Ma. GOM, Gulf of Mexico. (**b**) Palaeogeographical detail of the study area (modified from Yoshida *et al.* (2007), after Kauffman (1977)). The shallow seaway changed its width significantly over each third- and fourth-order relative sea-level cycle. (**c**) Overview of the Mesaverde Group outcrops in Utah, Wyoming and Colorado, providing evidence for the eastwards and southeastwards progradation of the Campanian delta systems into the seaway over >600 km (see panel b) over 10 Ma. There was a later landwards retreat of the same extent (Fig. 3). The most distal segment of any delta system was the lowstand part and the example highlighted here is the O'Brien Spring Sandstone, documented from the Rawlins area in Wyoming.

A particular feature of many of the lowstand, tide-dominated deltaic units of the Campanian is that their palaeocurrents indicate that they prograded not eastwards, like the highstand shorelines, but southwards, i.e. they became skewed southwards to run sub-parallel to the highstand shorelines. We

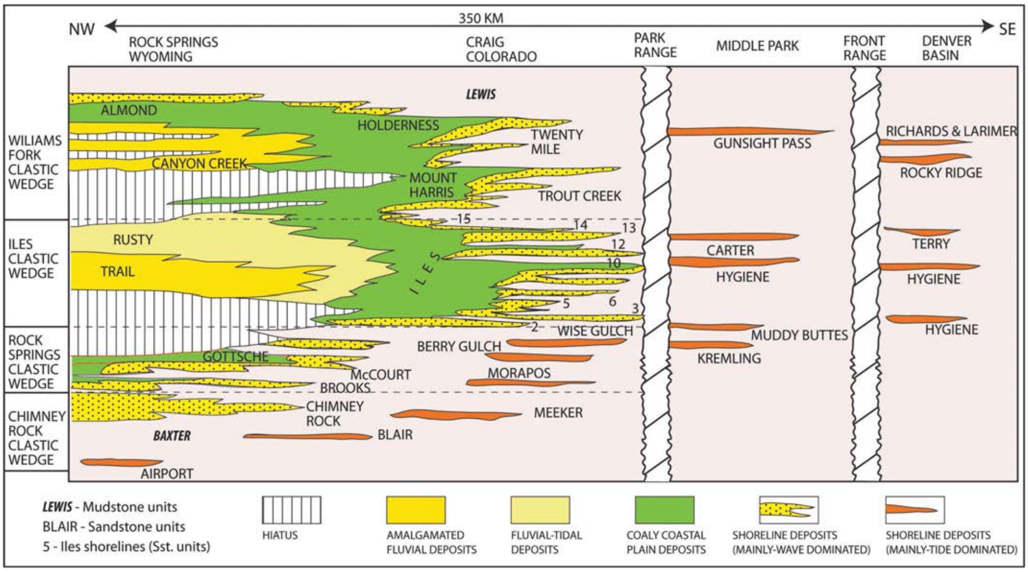


**Fig. 3.** Overview of the Campanian stratigraphy in a schematic cross-section from SW Wyoming through to the Denver Basin, Colorado. Note the systematic progradation, at all levels, of lowstand tide-dominated deltas that entered the narrowed Western Interior Seaway. These lowstand deltas swing from an eastwards to a southwards pathway as they meet the southwards-flowing tidal current gyre dominating the seaway at these times (from Steel *et al.* 2012). The lowstand O'Brien Spring Sandstone discussed here occurs northwards along-strike from this cross-section, broadly coeval with the Morapos or Berry Gulch sandstones.

have chosen a single example, the O'Brien Springs Sandstone (Fig. 4) in southern Wyoming (broadly coeval with the Brooks and Morapos sandstone units in Fig. 3) to illustrate how this happened, as the delta built out into the tide-dominated lowstand seaway.

## *O'Brien Springs Sandstone of the Haystack Mountains Formation, Wyoming*

The O'Brien Springs Sandstone is a member of the Campanian Haystack Mountains Formation (Martinsen & Tillman 1989; Mellere & Steel 1995*a*, *b*) cropping out in the Rawlins area of southern Wyoming. It was described and interpreted in detail by Uroza (2008). The sandstone unit is about 55 m thick and coarsens upwards (in two parasequences) from thin, current-rippled sandstone sets alternating with extensive mudstone layers to thicker cross-stratified sandstone sets that also alternate with thin mudstones, although the mudstones becomes thinner upwards (Fig. 5a). The dune cross-strata that dominate the sandstone succession tend to change upwards from planar to trough cross-strata, as shown in Figure 5b. The cross-strata imply that the O'Brien Springs delta front was covered by southwards-migrating subaqueous dunes, probably at times of strong reworking by the north to south tidal currents of the seaway (see Fig. 8). The mud layers, on the other hand, are likely to have been generated at times of muddy river effluent flooding down onto the delta front. The key evidence that the sandstone beds were deposited mainly by tidal currents is the presence of abundant slack water mud drapes, the tidal bundling of strata and bidirectional cross-strata (Fig. 6) (Mellere & Steel 1995*a*; Steel *et al.* 2012)

The hypothesis of mud–sand interbedding caused by the interaction of influences from muddy river flooding and from the reworking action of the sandy tidal seaway is supported by: (1) the marked bimodality of grain sizes in the measured succession, with alternating mudstones and upper fine- to medium-grained sandstones (Fig. 7a); (2) the gentle lensing and channelling of the sandstone beds (Fig. 5a), which indicates how the tidal current reworking was taking place; (3) the occasional abundance of *Ophiomorpha* traces in the clean sandstones (Fig. 7b), suggesting open marine conditions; and (4) the marked change in dominant palaeocurrent direction from easterly (in the western outcrops) to southerly (in the eastern outcrops) (Uroza 2008) (Fig. 8).

The schematic reconstruction of how the deltas prograding eastwards into the narrowed lowstand seaway were markedly deflected southwards by the Western Interior Seaway tidal current circulation is given in Figure 8. Because the lowstand tidal

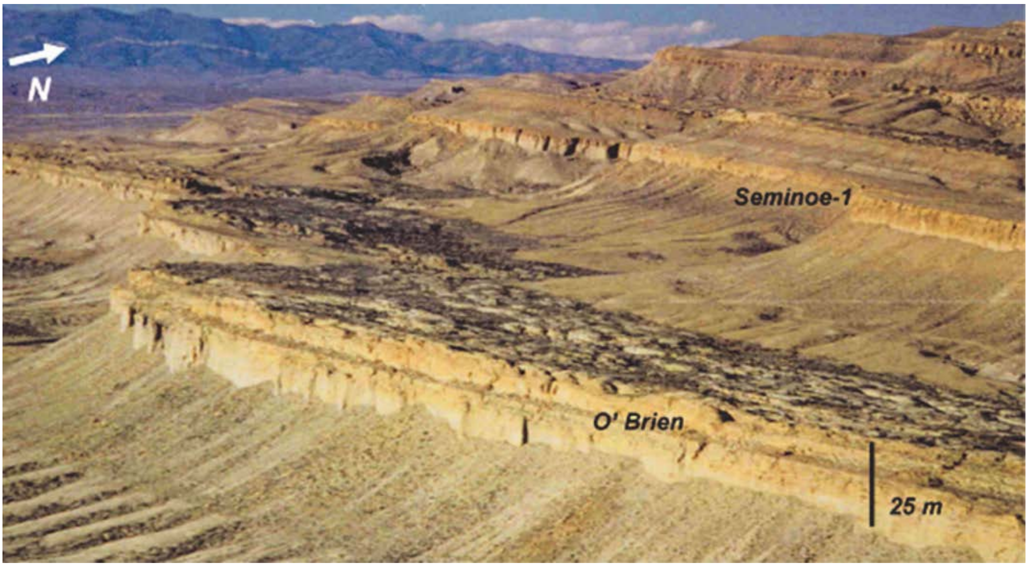


**Fig. 4.** The O'Brien Springs Sandstone (only the upper 25 m is exposed) cropping out near the North Platte River, NE of Rawlins.

sandstone units of the Haystack Mountains Formation are, in places, associated with storm wave-generated sandbodies (Mellere & Steel 1995*a*, *b*; Uroza 2008), it is possible that the deflected deltas were protected on their eastern side by wave-formed spits, as shown in Figure 8.

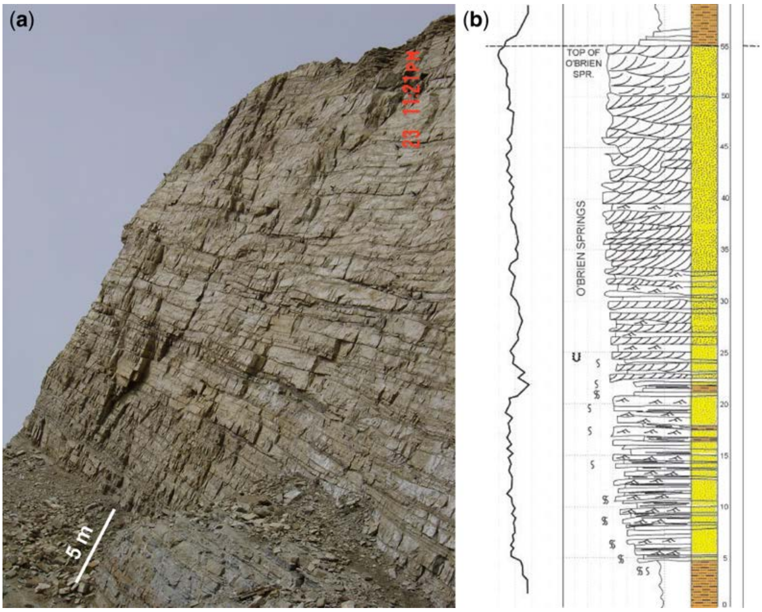


**Fig. 5.** (**a**) Outcrop of upper 35 m of O'Brien Springs Sandstone on Sinclair Road near North Platte River. The thin-bedded lower part is current rippled, whereas the thicker bedded upper part is mainly cross-stratified. Note that the sandstone beds are lensing in places and the very thin mud layers are pervasive through much of the succession. (**b**) Measured section of O'Brien Springs Sandstone, including a hand-held gamma ray profile that accentuates the presence of two parasequences.

**Fig. 6.** Clear bidirectional (herringbone) cross-strata in O'Brien Springs sandstones at the westernmost location on Haystack Mountains. A total of 117 readings on cross-stratal azimuths showed clear eastwards and westwards palaeocurrents (Fig. 8).

## Miocene to Quaternary of the Calabrian Arc, central Mediterranean, southern Italy

The Calabrian Arc is a restricted orogen, presently located in southern Italy, which originated after crustal subduction beneath the Ionian lithosphere during the middle Miocene and the opening of the Tyrrhenian back-arc basin (Malinverno & Ryan 1986; Dewey *et al.* 1989; Gueguen *et al.* 1997; Bonardi *et al.* 2001). The Calabrian Arc consists mainly of Hercynian metamorphic and intrusive rocks, tectonically superposed on ophiolite-bearing units of Tethyan affinity, in turn overlying Mesozoic carbonate platform limestones and Cenozoic clastic cover (Fig. 9) (Ogniben 1969; Amodio Morelli *et al.* 1976; Tortorici 1982).

During its tectonic translation towards the Ionian Sea due to the westwards subduction of the oceanic Ionian crust caused by convergence of Africa and Europe, the Calabrian Arc was affected by the onset of intense thrusting, as a result of the activation of regional SE- and ESE-trending strike-slip fault zones and differently oriented normal fault sets (Ghisetti 1979; Ghisetti & Vezzani 1981; Rehault *et al.* 1987; Turco *et al.* 1990; Knott & Turco 1991; Monaco & Tansi 1992; Catalano *et al.* 1993). Strike-slip and extensional tectonics, possibly related to block rotation, induced a structural fragmentation of the Calabrian Arc from the Middle Miocene onwards (Turco *et al.* 1990; Martini *et al.* 2001). This tectonic phase favoured the formation of structural highs, which separated graben and half-graben filled by alluvial, shallow water and deeper marine sediments (Monaco & Tansi 1992; Catalano *et al.* 1993). Many of these basins originated across some of the major strike-slip zones of the Calabrian Arc, forming narrow, linear, tectonically controlled marine straits (Fig. 9). They connected the Tyrrhenian and Ionian seas, generating important marine water exchanges and consequent current convergence, with an oceanographic setting very similar to that occurring along the present day Messina Strait separating Sicily from the Italian peninsula (Colella & D'Alessandro 1988; Colella 1995; Longhitano & Nemec 2005).

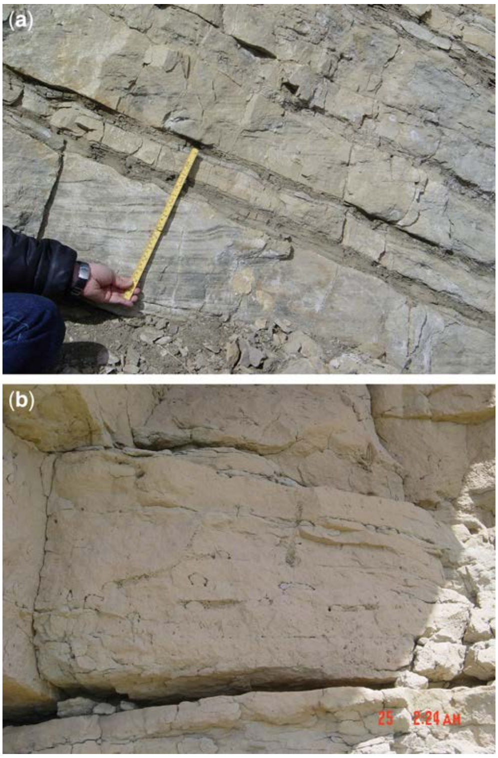


**Fig. 7.** (**a**) Marked bimodality of grain size between mudstone beds and up to medium-grained cross-stratified sandstone sets. (**b**) Some of the cross-stratified sandstone beds are thoroughly reworked by *Ophiomorpha* burrows.

These extensional basins are the Miocene Amantea Basin (Colella 1995; Longhitano & Nemec 2005) and a series of Plio-Pleistocene graben, including the Catanzaro Basin (Longhitano *et al.* 2014), the Crotone Basin (Zecchin *et al.* 2004; Zecchin 2005), the Siderno Basin (Colella & D'Alessandro 1988) and the proto-Messina Strait (Mercier *et al.* 1987; Longhitano *et al.* 2012*b*) (Fig. 9). Large sediment volumes, mostly derived from river deltas and tidal current abrasion of the sea bottom, filled these straits under the influence of amplified tidal currents (Longhitano 2012, 2013). Today, these successions commonly exhibit sandstones with recurrent large-scale (>3 m thick) cross-stratified sets (Longhitano *et al.* 2012*a*, *b*) as well as a suite of tidal sedimentary structures, such as herringbone cross-strata, tidal bundles, reactivation surfaces and heterolithic lamina sets (Longhitano 2011). Along the tectonically controlled strait margins, a number of transversely impinging deltaic successions can be detected in many of these Calabrian tidal straits, although they were not interpreted as such in the past and were more generically considered as the result of deposition along the strait margin zones (Longhitano 2012, 2013).

### *Belmonte Calabro section in the Amantea Basin*

Many intervals of these strait-fill successions are today well exposed in Calabria, including transgressive deltaic complexes. Transgressions occurred due to the high subsidence rates imparted by marginal faults that were active during sedimentation, producing coastal back-stepping, with strata lapping against block-faulted margins (Longhitano & Nemec 2005; Longhitano *et al.* 2012*b*; Longhitano 2015). For this reason, the lowermost stratigraphic intervals of many of these deltas are tectonically deformed, passing upwards to less inclined stratal sequences through a series of progressive internal unconformities.

A well-exposed example is the Belmonte Calabro section in the Miocene Amantea Basin (Fig. 10a). This is a triangular-shaped, peri-Tyrrhenian Miocene tectonic depression, presently exposed on the western coast of Calabria (Fig. 10a). The Amantea Basin formed in the Serravalian, after the extensional faulting of this part of the Calabrian Arc and consequent marine inundation (Argentieri *et al.* 1998). During the middle Tortonian to early Messinian, this basin was part of a wider tidal strait, the oceanography of which was possibly dominated by strong tidal currents flowing towards the SW (dominant) and NE (subordinate) (Colella 1995; Longhitano & Nemec 2005). The sedimentary record of this setting is preserved in a basin-scale transgressive succession (Fig. 10b) up to 260 m thick, consisting of basal, polymict conglomerates and sandstones of deltaic and shallow marine origin. A basin-wide transgressive lag separates these deposits from the overlying tidal cross-stratified mixed arenites (Longhitano *et al.* 2012*b*), which are of middle to late Tortonian age and up to 120 m thick. They are overlain by latest Tortonian to early Messinian mudstones, which are nearly 100 m thick and interbedded with calc-arenites and relics of evaporite deposits (Fig. 10b) (Di Nocera *et al.* 1974; Ortolani *et al.* 1979; Tansi 1991; Colella 1995; Argentieri *et al.* 1998; Colella & Longhitano 1998; Longhitano & Colella 1998; Mattei *et al.* 1999; Speranza *et al.* 2000; Martini *et al.* 2001; Mattei *et al.* 2002; Muto & Perri 2002).

Although the average palaeocurrent direction detectable from the foresets of the tidal cross-strata indicates a dominant direction towards the SW (e.g. Colella 1995), the Amantea Basin may have had a different orientation during the Tortonian. In fact, the tidal succession preserved today along this coastal sector of Calabria might represent only a

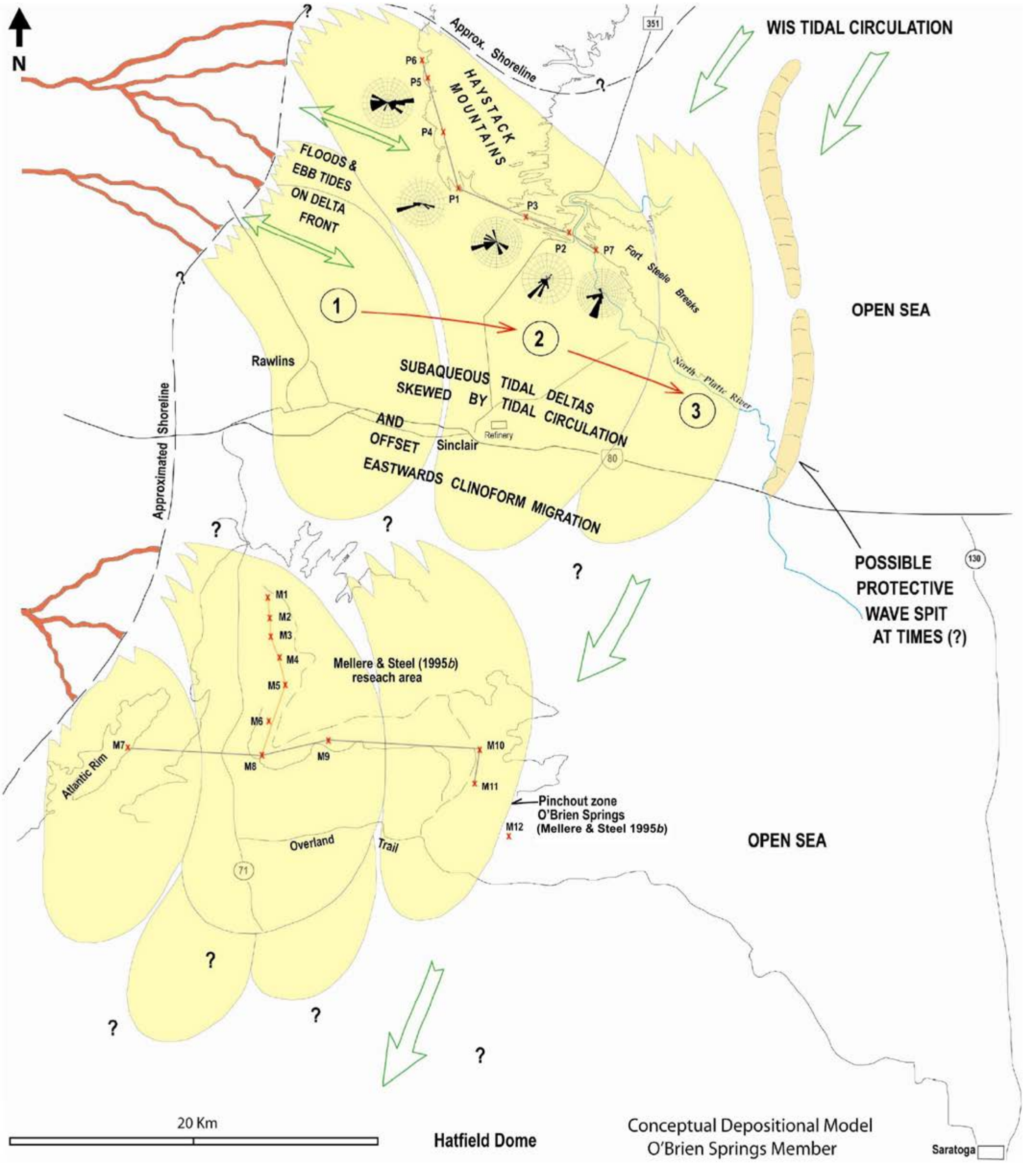


**Fig. 8.** Palaeogeographical reconstruction of the O'Brien Springs Member, Haystack Mountains Formation, SW Wyoming during the Cretaceous. The palaeocurrents measured at five sites along the front of the Haystack Mountains clearly show a change from bimodal west–east directions in the west to southerly directed currents further east, indicating that the deltas impinging into the tidal seaway were preferentially deflected to the south (modified from Uroza 2008).

marginal portion of a wider tidal strait system, the main strait centre deposits of which would presently be tectonically downthrown to the west after Plio-Pleistocene faulting of the Tyrrhenian Sea margin (Catalano *et al.* 1993). As a consequence, the original orientation and shape of the Amantea tidal strait still remains uncertain.

The Belmonte Calabro section is a 500 m long and 200 m thick, north–east-oriented cliff adjacent to the northwestern margin of the Amantea Basin (Fig. 11a). It exposes a stratified succession exhibiting evident synsedimentary tectonic deformation attributed to the active faulting of the margin during the middle Tortonian (Fig. 11b) (Turco *et al.* 1990;

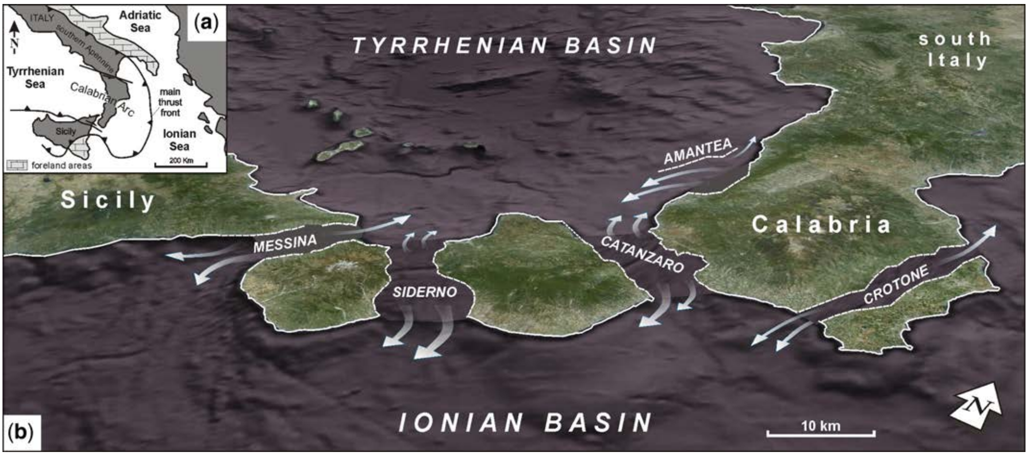


**Fig. 9.** Reconstruction of the palaeogeographical setting of the Calabrian Arc in southern Italy during the Neogene–Quaternary. This small orogen experienced a strike-slip tectonic fragmentation, which favoured the opening of a number of block-faulted narrow basins. These basins acted as tidal straits linking the Tyrrhenian and the Ionian seas and were filled by thick, cross-stratified deposits (modified from Longhitano 2013).

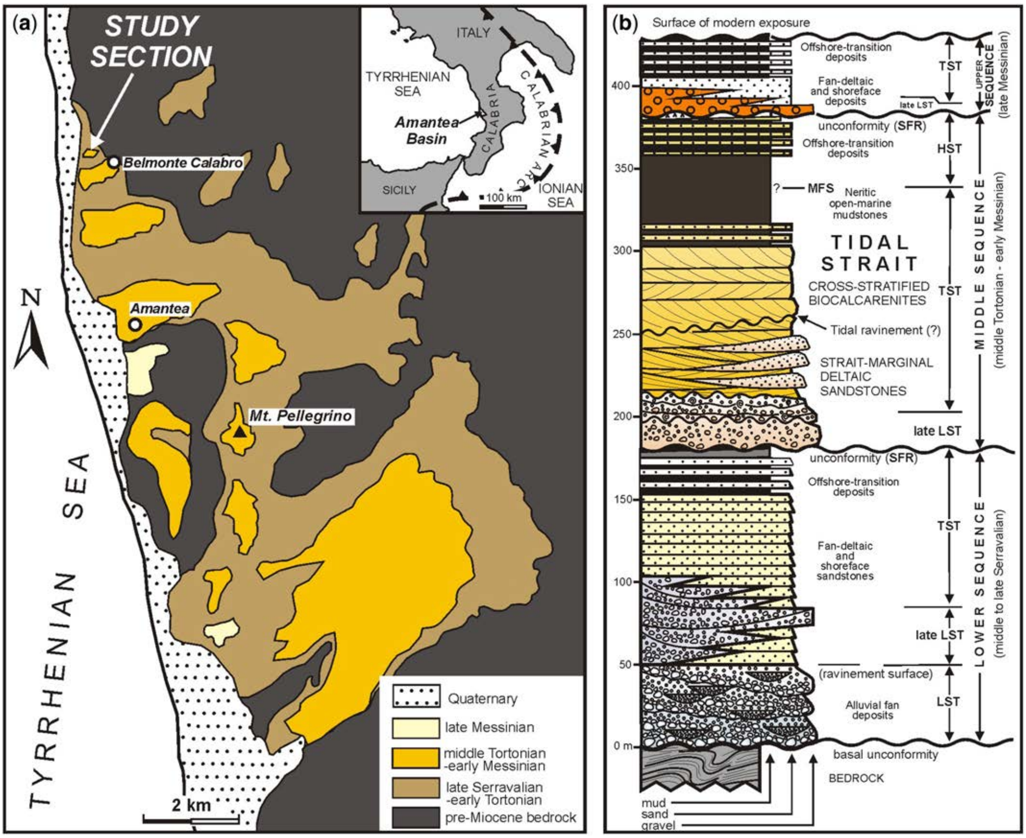


**Fig. 10.** (**a**) Simplified geological map of the Amantea Basin. (**b**) Stratigraphy of the Amantea basin-fill succession. The studied interval corresponds to part of the intermediate upper Tortonian–lower Messinian depositional sequence (modified from Longhitano & Nemec 2005).

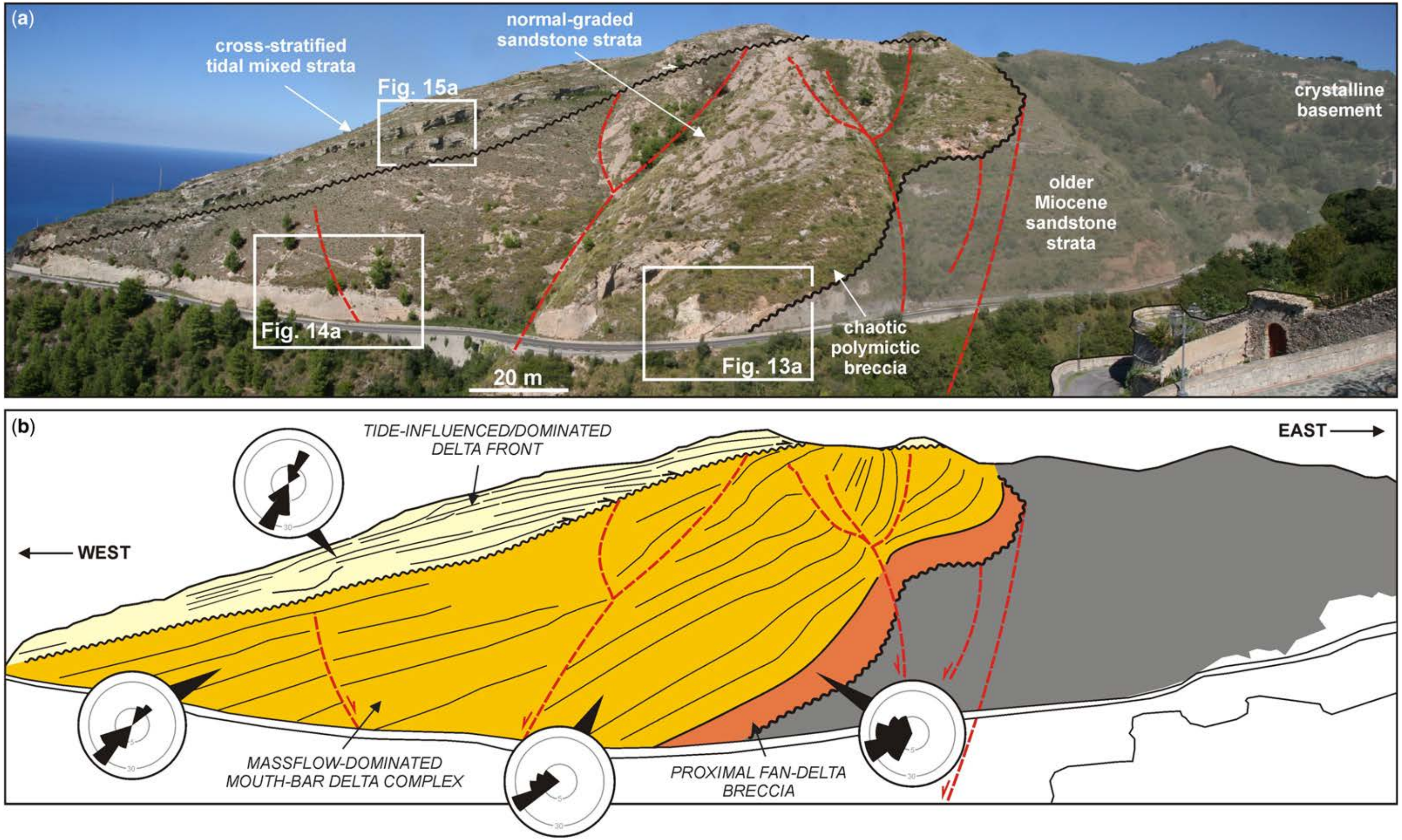


**Fig. 11.** (**a**) Photomosaic and (**b**) interpreted line drawing of the Belmonte Calabro section, north of the Amantea Basin. The succession, interpreted as a deltaic transgressive unit, shows the basal coarse-grained sediments strongly deformed as a result of synsedimentary normal faults and the occurrence of the overlying tide-dominated cross-stratified sandbodies that lie erosionally on the older deposits. The overall progradation of the deltaic body is to the west. Rectangles indicate details shown in the following figures.

Martini *et al.* 2001). The succession included in this section is bounded by a basin-scale basal angular unconformity, incised into an older marine sequence (Colella 1995). In general, from the bottom to the top, sediments consist of basal fossiliferous breccias, rapidly passing upwards to normally graded, indistinctly laminated sandstones and a series of vertically stacked sets of tidal cross-stratified mixed arenites with different stratal thicknesses and internal foreset architectures (Longhitano & Nemec 2005; Longhitano *et al.* 2012*b*). These deposits can be grouped into three main facies associations, which are vertically and laterally stacked (Fig. 12).

*Coarse-grained breccia and conglomerate (proximal fan delta).* The lowermost stratigraphic interval exposed at the Belmonte Calabro section is *c.* 25 m thick and lies on the basal unconformity, which separates this middle Tortonian sequence from the underlying Serravallian sequence (Fig. 13a) (Di Nocera *et al.* 1974; Ortolani *et al.* 1979; Colella 1995; Colella & Longhitano 1998; Longhitano & Colella 1998; Muto & Perri 2002; Longhitano & Nemec 2005). This deposit is organized into a series of vertically stacked, 4–5 m thick, normal-graded strata, the inclination of which is a combination of an original depositional dip enhanced by a syn- to post-depositional tectonic tilt. Sediments consist of monomict and polymict breccias, including dominant granitic and metamorphic angular clasts, associated with subordinate well-rounded sandstone and limestone clasts, in many places interspersed in a sandy matrix containing fragments of bivalves, bryozoans, echinoids and serpulids (Fig. 13b). Palaeocurrents detected from imbricated clasts indicate an average eastwards sediment transport direction. Upwards, this coarse-grained facies passes abruptly to a 40–50 cm thick interval of mixed siliciclastic and/or bioclastic coarse-grained sandstone containing low-angle cross-lamination with N 260° E palaeocurrents, capped by remnants of a highly bioturbated mudstone interval (Fig. 13c).

This coarse-grained basal interval shows the classical sedimentary assemblage of a base of slope deposit, produced by sediment accumulation

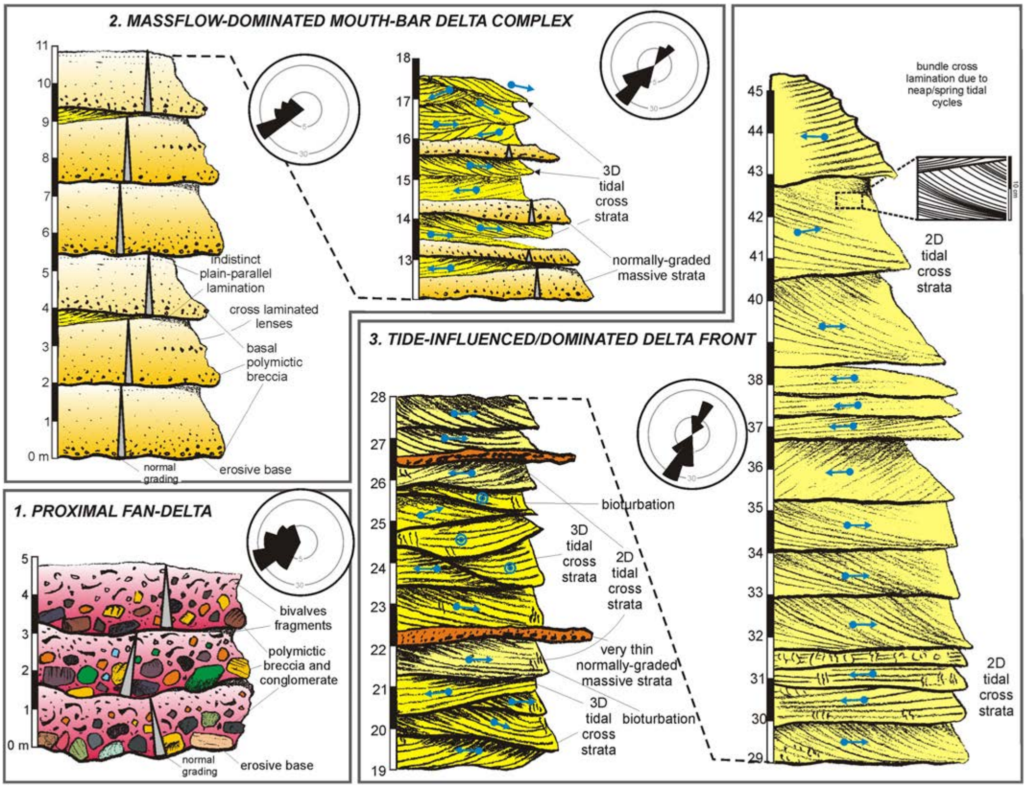


**Fig. 12.** Schematic framework of the main facies associations recognized in the studied succession. Numbers 1–3 indicate the progressive occurrence of these deposits, from older (1) to younger (2). Note the progressive-upwards rotation of palaeocurrent patterns.

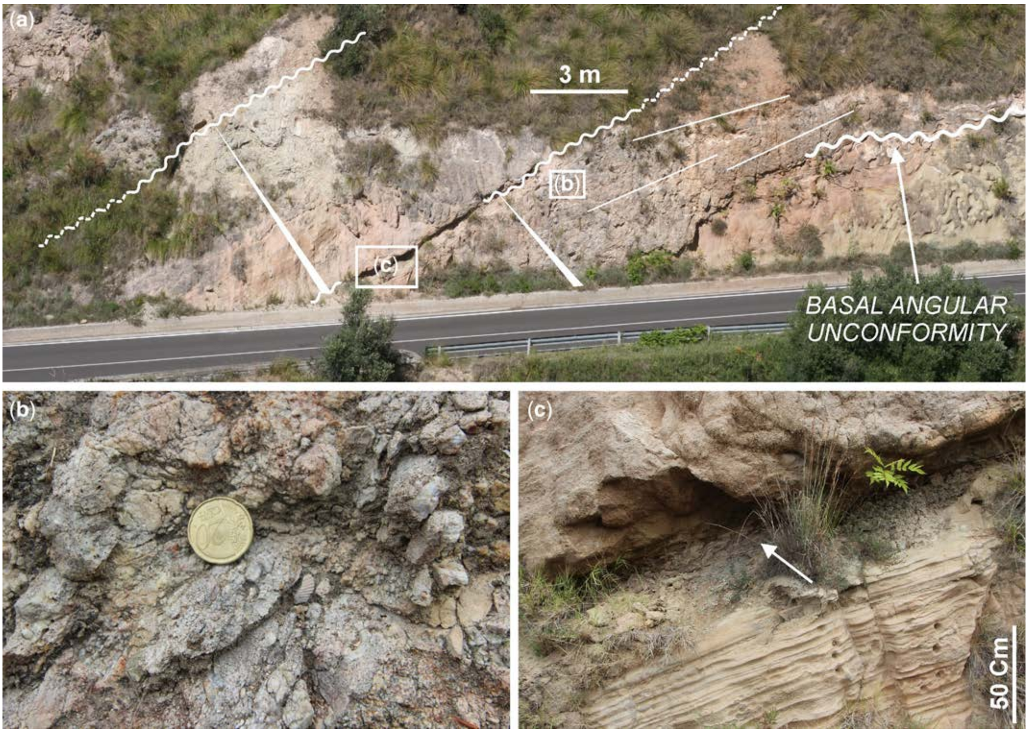


**Fig. 13.** (**a**) Outcrop showing the deltaic basal interval of the studied succession lying unconformably on older open marine sediments. (**b**) Details of the fossiliferous breccia. (**c**) Fine-grained, laminated intervals and muddy horizons (arrow) are often preserved on top of these strata.

at the toe of the subaqueous slope, against a tectonically active, faulted basin margin (see Fig. 16a). Angular monomict clasts showing encrusting submarine organisms suggest that these deposits had a brief period under the water table before being incorporated into seacliff collapses. However, there are also well-rounded polymict clasts, which possibly indicate derivation from a marginal alluvial fan. Sediments included in this interval thus indicate mass transport by rockfall and debris flow processes, recording the subaqueous toe of a cliff-attached fan delta system dominated, at that time, by repeated gravitational mass flow events (see Fig. 16a).

*Normally graded sandstones (mouth bar).* The overlying, conformable stratigraphic interval is *c.* 100 m in thickness. Sediments are mainly siliciclastic and form a monotonous succession of normally graded, 6–7 m thick units, the erosional bases of which appear planar to slightly undulating in an along-dip cross-sectional view (Fig. 14a). These units contain three main intervals. The first of these is a basal microbreccia and conglomeratic interval up to 1 m thick (Fig. 14b), passing upwards into a *c.* 4 m thick structureless coarse-grained sandstone with scattered granules and pebbles and scarce, undifferentiated fossil fragments. In the uppermost part of these intervals, indistinct cross-lamination can be seen, associated with bioturbation and rare fluid escape soft sediment deformation (Fig. 14c). The third (topmost) interval of the units can be occupied by 1–2 m thick sets of tidal cross-strata consisting of coarse- to medium-grained arenites and exhibiting evident siliciclastic/bioclastic tidal bundles and reactivation surfaces (Fig. 14d). Palaeocurrent directions show N 260° E to N 240° E trends. Upwards, the thickness of the second massive interval decreases, being progressively replaced by the tidal cross-stratified deposits with a counter-clockwise progressive change of the palaeocurrent directions.

This unit is interpreted as a deltaic mouth bar complex (see Fig. 16b). A basal erosion surface suggests an initial river jet, followed by a rapidly accumulated, siliciclastic sandy interval with normally graded beds and fluid escape structures. During the waning of energy in this initial growth stage of the mouth bars, the sand accumulated near the river mouth was tidally reworked. At the end of

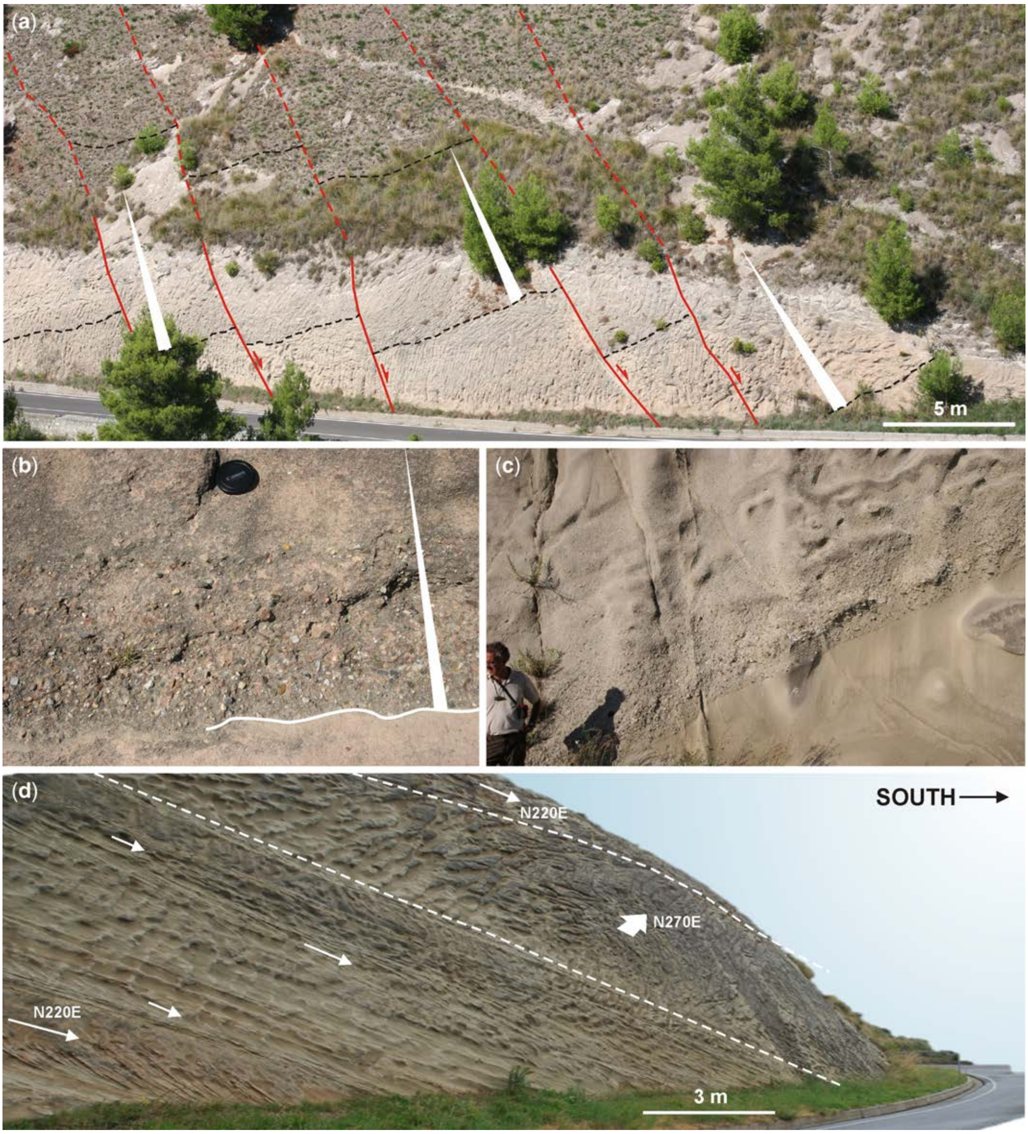


**Fig. 14.** (**a**) Vertically stacked, normally graded sandstone strata, interpreted as a deltaic mouth bar complex. These strata are intensely dissected by a system of normal faults related to the development of this margin of the Amantea Basin after deposition. (**b**) Detail of the basal micro-conglomerate lying above an erosional surface. (**c**) Soft sediment deformation structures also occur in this facies. (**d**) Along-strike view of these deposits showing alternating normally graded and cross-stratified intervals with different palaeocurrent directions.

deposition, the top of the mouth bars became occupied by small- to medium-sized tidal dunes, as this part of the basin had become tidally influenced (see Fig. 16b). The mouth bars thus developed after a first important step of tectonically induced marine transgression, which changed the main sedimentary processes into river-dominated, but also tidally influenced (see Fig. 16b).

*Large cross-stratified mixed arenites (delta front).* At the very top of the Belmonte Calabro section, a *c.* 40 m thick tabular succession erosionally overlies the rest of the previously described deposits. The erosional surface can be traced laterally throughout the entire Amantea Basin for several kilometres and is interpreted as a ravinement surface as it recorded the regional-scale onset of a dominant tidal circulation during the middle Tortonian (Longhitano & Nemec 2005) (Figs 10b & 11a). Mixed siliciclastic/bioclastic arenites overlie the erosional surface and are composed of >65% polycrystalline quartz fragments, mica and glauconitic crystals, with fragments of bivalves, corals, red algae and echinoids comprising the remaining percentage. The bioclastic content increases upwards to as much as 70%. This succession consists of five to six vertically stacked, retrogradational wedge-shaped units, separated by discontinuity surfaces marked by shell and pebble lags. The wedges, which include thinning-upwards strata sets (Fig. 15a), pinch-out towards the west–SW (basinwards) and lap against the underlying strata (landwards) (Fig. 11b). They mostly include two main facies. In the first facies, faintly laminated sandstone strata form 2–3 m thick and 30–40 m wide lenticular beds, including siliciclastic-dominated deposits, which commonly show normal grading, soft sediment deformation and cross-stratification, but lack other small-scale tidal signatures. In places, these lenses are encased within, or alternate with, the second facies of tidally cross-stratified, 3–4 m thick tabular bedsets, in which the content of the bioclastic fraction increases dramatically compared with the other lithofacies. Cross-sets exhibit two- and three-dimensional geometries (Fig. 15b), dominantly unidirectional

**Fig. 15.** (**a**) Topmost stratigraphic interval observable in the Belmonte Calabro section showing vertically stacked, thinning-upwards cross-stratified units, interpreted as delta front wedges prograding towards the west (left in the photo). (**b**) Detail of tidal trough cross-strata observable in an along-strike view of the section. (**c**) Tabular tidal cross-strata, forming simple and compound foresets.

foresets dipping towards N 220° E, and numerous tidal structures such as herringbone cross-strata, neap–spring tidal bundles, heterolithic lamina sets and reactivation surfaces (Fig. 15c).

This third stratigraphic interval caps a transgressive sedimentary succession, which records the development of a steep margin fan delta that prograded onto the eastern margin of the Amantea Strait. Deposits belonging to this uppermost unit developed above the deltaic mouth bar complex after a significant change in the coastal setting of this area, possibly related to the evolution of the block-faulted basin margin. Tidal cross-stratified wedges accumulated on this surface record a more mature stage of a fan delta system and a backstepping against the basin margin. After this further dramatic flooding of the coastal area, the delta had become tidally dominated (Fig. 16c). Tidal wedges are interpreted as part of the delta front that prograded into a strait margin zone where tidal currents flowing axially to the strait were the dominant hydrodynamic force (Fig. 16c). They are stacked in a back-stepped fashion, possibly recording steps of normal regression that punctuated the overall relative sea-level rise. Internally, the wedges indicate tidal dominance, but also an intermittent river influence. The indistinctly laminated sandstone intercalations indicate brief river flood influxes and the deposition of siliciclastic-rich plumes entering the delta front too rapidly to be completely reworked by tidal currents. The cross-stratal sets, the volumetrically dominant element in these sandbodies, represent two- and three-dimensional tidal dunes in the delta front environment (Fig. 16c). Palaeocurrents suggest that the main progradation of this fan delta was rapidly ‘adjusted’ to the dominant tidal current trend. Thus the thinning-upwards observed in the delta front wedges might reflect a progressive deflection of this part of the delta and a wider sand distribution into elongated sandbodies towards the strait axis (Fig. 16c).

## Discussion

The field examples documented in the previous sections indicate that deltas prograding into tidal seaways or straits diverge slightly from classical deltaic models because they leave different diagnostic signatures in the rock record. The recognition of such deltas in ancient stratigraphic successions may have significant potential in palaeogeographical reconstructions of past scenarios and can be of crucial importance in clastic reservoir characterizations of subsurface sandstone-rich deposits accumulated in tectonically confined settings or elongate marine basins.

### *Deltas sourcing tidal straits and elongate seaways: sedimentary signature and diagnostic features*

River deltas impinging tidal elongate seaways or straits are marginal depositional systems, the dimensions, features and processes of which are strictly dependent on the coastal gradient of the seaway borders (Fig. 17). Tectonically active, steep margin straits are commonly characterized by isolated, rare fan–deltaic deposits, often associated with debris aprons, as a result of the high gradient of their coastal areas, which prevents significant sediment accumulation on the shelf and favours the direct transfer of the river discharge towards the deeper zones of the straits (e.g. the modern Messina Strait). Conversely, river deltas can extend much further across gently sloping seaway margins because tectonically stable borders favour clinoform progradation and long-lived deltaic sequences (e.g. the modern Klang Delta in the Malacca Strait) (Fig. 17).

The gradient of the margins may interplay with the tidal oceanography in shaping deltas impinging seaways and straits. It is well known that the morpho-tectonic setting of the basin borders governs the type of the delta nucleated from that margin, especially with respect to its internal architecture, facies distribution and sediment calibre (e.g. Orton & Reading 1993). A possible reconstruction of how deflected deltas differ between steep and gently sloping seaway/strait margins is summarized in Figure 18.

One recurrent aspect of structurally controlled steep margins on a seaway is that deltas can be coarse-grained and of small dimensions (with 1–5 km wide and 2–3 km long delta plains) (Fig. 18a). The geological record indicates that such deltas are short-lived and/or deposit multiple vertically stacked sequences because of the continuous change in the morphological configuration of the coastline (e.g. Colella 1988). These deltas often originate in single units separated by internal unconformities recording tectonic pulses (e.g. Longhitano 2008). Consequently, tidal currents oriented along-shore may be able to rework only the distal environments of these deltas, where fine-grained deposits are delivered (Fig. 18a). As the result, tidal seaways or straits that have tectonically active margins may potentially generate deltas that are sensitive to the local tidal circulation only in their sandstone-dominated delta front areas or during episodes of transgression, as the delta documented in the Amantea Basin demonstrates.

Tidal seaways characterized by more tectonically stable margins often exhibit gently sloping shelves (Fig. 18b). In such settings, deltas form more extensive systems (with 10–50 km wide and 50–100 km long delta plains), but, importantly, they

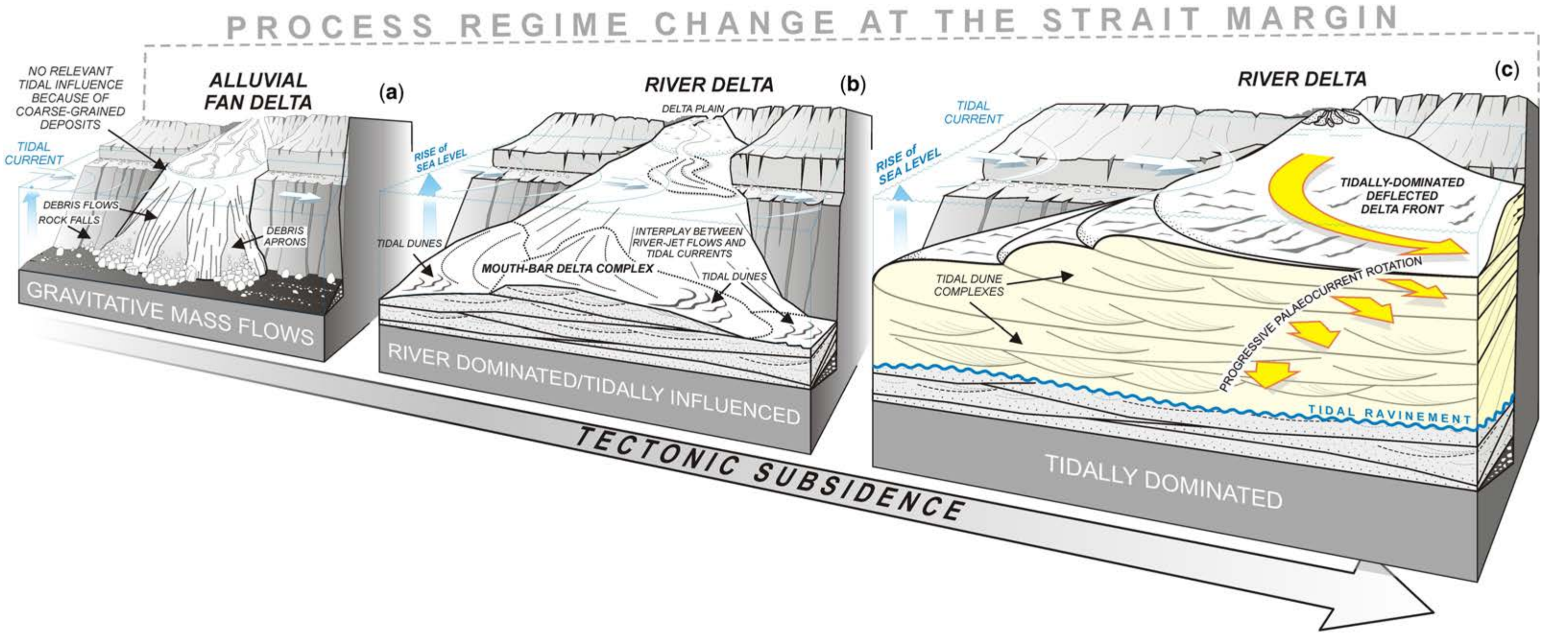


**Fig. 16.** Block diagram showing the inferred evolution of the Belmonte Calabro fan delta. (**a**) An early stage of delta progradation occurred through the emplacement of gravity-dominated mass flows, accumulating coarse-grained deposits. (**b**) A tectonically induced transgression generated back-stepping of the delta and a more mature deltaic stage, through the development of a tide-influenced mouth bar delta complex. (**c**) The late stage of progradation produced tide-dominated sandbanks in the delta front, with deflected morphologies and tidal dunes.

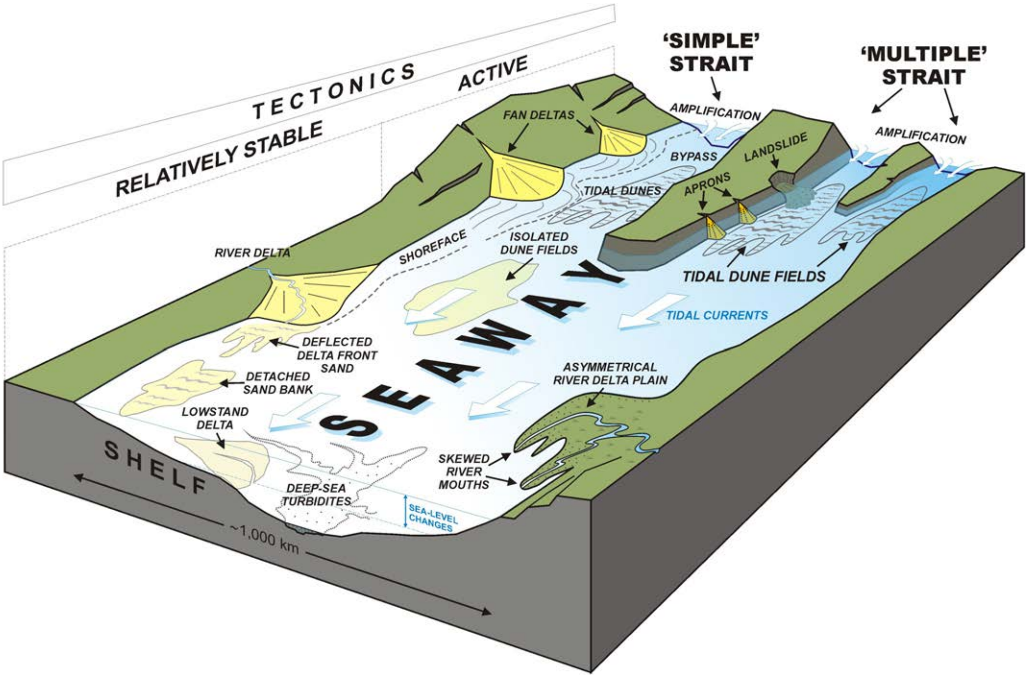


**Fig. 17.** Schematic representation of a tidal seaway including single and multiple narrower straits. Tidal currents are the major hydrodynamic controlling factor on the processes of sediment distribution. Deltas prograding into the seaway can be related to steep, tectonically active margins or gently sloping shelves. In both cases, tidal currents are able to rework and deflect delta front deposits, forming elongate subaqueous sandbodies and detached sandbanks, including large tidal dunes. In some cases, the delta plain area is also skewed in the sense of the dominant tidal flow.

form long-lived systems that are recorded in extensive, laterally continuous clinoform sets, including abundant volumes of sandstone-dominated delta front deposits (Uroza 2008). Under these conditions, tidal currents may interact to different degrees with the prograding deltas, interplaying with waves and generating facies belts with different attributes (Steel *et al.* 2012) (Fig. 18b). The outcrop example documented in the Western Interior Seaway indicates that these deltas are very sensitive to tidal

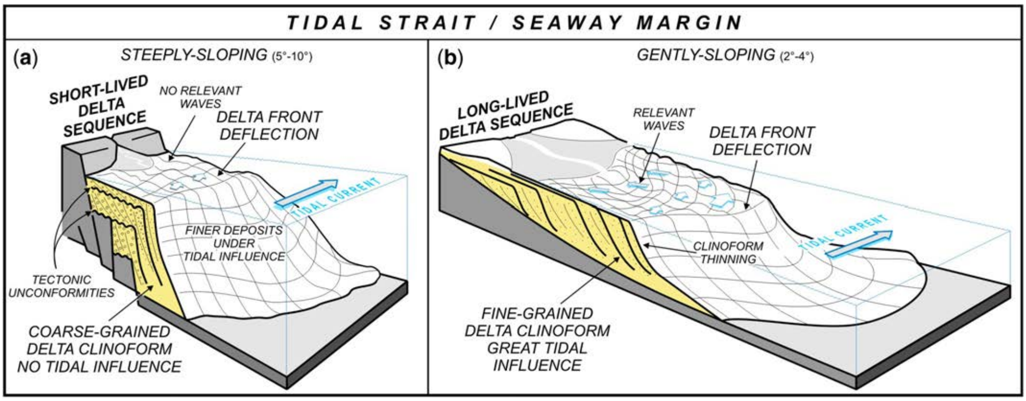


**Fig. 18.** Morpho-sedimentary models reconstructing deltaic deposition over (**a**) a steeply and (**b**) a gently sloping margin of a seaway/strait governed by tidal currents.

deflection and are also able to preserve the signature of the increasing tidal flow energy as the seaway is progressively narrowed by their progradation.

### *Deflection in the progradational axis and asymmetry of the delta front sand distribution*

Although reconstruction of the plan view shape of deltas at the shoreline is often a rather speculative aspect of ancient stratigraphic analysis, the primary coastal morphology of tidal strait deltas is one of their most distinctive elements.

Modern examples of deltas prograding into seaways or straits in which tidal currents are the dominant hydrodynamic process show that the tides act differently from those in 'classical' tidal-dominated deltas – for example, those in macro- to mega-tidal oceanographic settings (Table 1) (e.g. Longhitano *et al.* 2012*a*). In these latter well-documented systems, the repeated influence of flood- and ebb-directed tidal currents acting at the coastline usually reshapes the delta plain and delta front ('delta platform') environments, forming sandbodies striking perpendicular to the shoreline (Table 1) (e.g. Swenson *et al.* 2005; Willis 2005; Wright & Friedrichs 2006; Fagherazzi & Overeem 2007; Slingerland *et al.* 2008; Goodbred & Saito 2012; Plink-Björklund 2012). In very general terms, tide-dominated deltas are usually subject to a landwards-directed incoming ocean tide, which first interacts with the clinoformal delta front. Modern examples, such as the Changjiang River Delta or the Ganges–Brahmaputra River Delta, show shallow water settings, from 20–90 m at the bottomsets to 5–30 m at the topset/foreset transition (Goodbred *et al.* 2003). Tidal currents thus accelerate across this zone, producing an important morphodynamic influence on the compound clinoform typical of most tide-dominated delta systems (Goodbred & Saito 2012). After crossing the delta front, the tidal prism becomes compressed through the channelized distributary mouths and can be subject to upstream amplification, generating a second phase of increase in the strength of the tidal current and consequently an enhanced bed shear stress. This phenomenon, known as a 'hyper-synchronous' condition (Dalrymple & Choi 2007), produces a general upstream increase in the tidal range and current velocities, although also a subsequent decline as the tidal energy becomes gradually attenuated by bottom frictional forces (Dalrymple *et al.* 1992).

Recent decades have provided a growing body of documentation on tide-dominated and tide-influenced deltas in the ancient record (e.g. Mutti *et al.* 1985; Maguregui & Tyler 1991; Mellere & Steel 1995*a*, *b*; Willis *et al.* 1999; Bhattacharya & Willis 2001; Martinius *et al.* 2001; Willis & Gabel 2001, 2003; Willis 2005; Pontén & Plink-Björklund 2007, 2009; Tänavsuu-Milkeviciene & Plink-Björklund 2009; Plink-Björklund 2012). In contrast with these systems, river deltas prograding into seaways or straits are usually subject to a strong tidal influence as a result of the narrowing of marine passageways and a significant tidal current convergence and amplification (Longhitano 2013). Importantly, these deltas may prograde into microtidal oceanographic settings. The dominance of the tidal hydrodynamics on the deltaic systems thus occurs with very different modalities compared with the systems described previously (Table 1). Tidal currents usually flow with a general direction parallel to the coastline, very similar to along-shore current circulation (Reading & Collinson 1996). Although characterized by high velocities and strengths, tidal currents passing through straits or seaways can have less influence on the coastal and shoreline morphology of these basins, favouring the development of symmetrical delta plain geometries and near-linear shorelines. Rather, they seem to exert a more dominant effect across the subaqueous areas of the seaway margins (e.g. Chiocci *et al.* 2008; Walsh & Nittrouer 2009; Ayranci & Dashtgard 2016).

### *Modern analogues of deltas entering tidal seaways and straits*

The Elwha River Delta, along the southern margin of the Juan de Fuca Strait, separating the state of Washington from the Vancouver Island (USA), represents one of the most noticeable modern examples of a delta impinging a tidal strait (Foreman *et al.* 2004; Gelfenbaum *et al.* 2015). The delta coastline exhibits a quasi-symmetrical protuberance (Fig. 19a), despite the influence of eastwards-directed tidal currents that flow parallel to the strait margin. This tide-induced littoral drift is also responsible for the building of the Ediz Hook, which is a *c.* 5 km long, coast-attached sandy spit developed a short distance from the subaerial Elwha Delta. However, the most impressive geometric response to the dominant tidal current pattern on this delta system is the geometry assumed by the submerged delta, the most volumetrically important part of the entire system, which is strongly and asymmetrically deflected in a direction parallel to the coastline (Fig. 19a). At the easternmost periphery of the Elwha delta front, sediment accumulations assume a digitate shape, forming multiple subaqueous sandbodies attached to the main deltaic body, but elongate for several hundreds of metres (Fig. 19a). This seafloor morphology possibly reflects a long-term along-shore accretion of the subaqueous delta after various episodes of Pleistocene glaciation and, in particular, the latest Wisconsinan phase, known locally as the Fraser Stade.

Another modern example is represented by the Fraser River Delta, prograding into the Strait of Georgia in southwestern British Columbia, Canada (Fig. 19b). The Fraser River Delta has been investigated by Ayranci & Dashtgard (2016) who, based on a wide core and grab dataset of sediment samples, detected a distinct asymmetry in the sedimentological and ichnological characteristics of the updrift (south) and downdrift (north) sides of the main distributary channel in water depths below storm wave base. These researchers attributed the asymmetry in the subaqueous delta environments to the strong influence of the net north-directed tidal flow acting along the coastlines (Ayranci & Dashtgard 2016).

An interesting modern analogue of extremely deflected and elongate subaqueous deltas is the Po Delta, which enters the northern Adriatic Sea on the Italian coastline (Fig. 19c). Although the Adriatic Sea does not represent a tidal strait, because it is closed in its northern border the tides exert a relevant influence along the northern coastlines. A semidiurnal tidal prism is, in fact, considerably amplified in the northern part of the basin, promoting enhanced tidal ranges and secondary thermohaline currents (Bondesan *et al.* 1995). In the southern Adriatic Sea, 350 km south of the Po River delta, high-resolution seismic data have revealed the occurrence of a mud-prone clinoform system, which is retained as the expression of downcurrent along-shore transport of the sediment debouched by the Po River and other additional source points (Cattaneo *et al.* 2003). Sediment drift is governed by shore-parallel bottom currents, the transport capacity of which is possibly enhanced by the narrowing of the Adriatic Sea and by the tidal influx amplified by the northern engulfed basin (Fig. 19c). This recent example demonstrates an extreme, current-driven deflection in delta front or prodelta deposits that may influence sediment accumulation over large distances from the main sediment point source.

A more mature stage of delta front deflection due to amplified tidal currents may be seen in the subaqueous Klang Delta in the Malacca Strait, a segment of the Sunda shelf sea lying between Sumatra and the Malay Peninsula (Fig. 19d). Keller & Richards (1967), Emery (1971) and, subsequently, Galloway (2002) identified this as a tide-dominated delta front platform, which actively supplies sediment to the strait, occurs in a strike-elongate fashion downcurrent of the delta coastline, and is remarkably re-aligned parallel to the northern border (Coleman *et al.* 1970). This area consists of an axial sandy shoal complex, about 150 × 100 km in extent, located where the narrow southern strait opens into the relatively broad central strait, creating a 50–80 m deep shelf. Sediments of the shoal complex are reworked into large tidal bars separated by deep oval to elongate scour troughs and hollows (Fig. 19d). Tidal bars have amplitudes of 15–25 m and form elongate ridges 0.3–1 km wide and 15–70 km long. As the Malacca Strait widens northwestwards, another wide sand bank occurs detached from the main Klang deltaic body (Fig. 19d). This additional sandbank can be interpreted to result from the persistent bed shear stress imparted by the dominant tidal circulation and the consequent long-term reworking of the delta front deposits in an offset location with respect to the main delta.

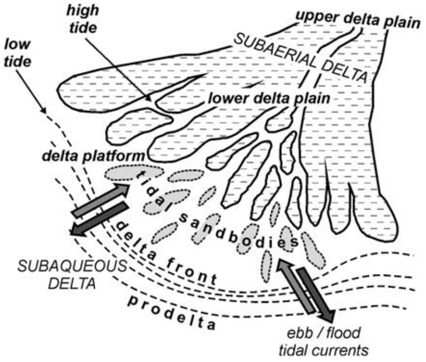
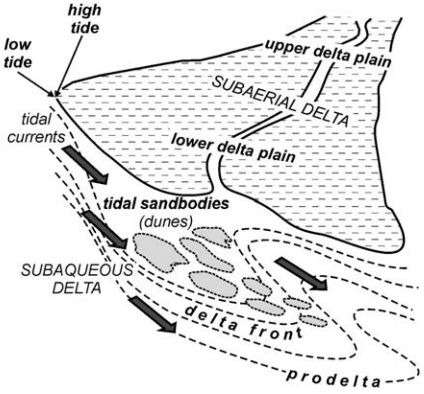
### *Diagnostic elements in ancient deflected tide-dominated strait/seaway deltas*

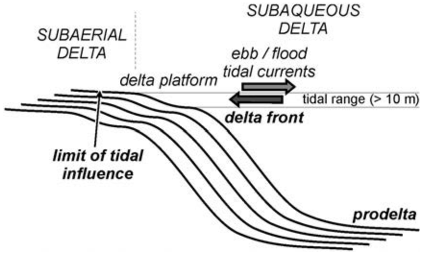
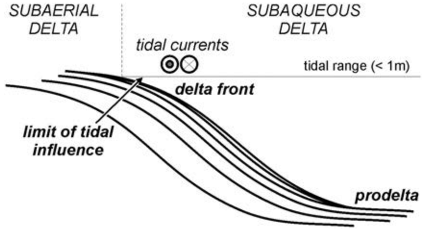
Deflection of the progadational axis and asymmetry in the delta front sand distribution (Fig. 20) is a feature that can be detected in ancient tidal seaway deltas based on the following diagnostic elements.

(i) The systematic measurement of palaeocurrent directions across the stratigraphic succession that records the delta front progradation. In tide-dominated deltas this character is usually detectable in large-scale cross-stratified complexes, which represent the result of the migration of tidal dunes across the delta front area. Smaller structures, including medium and small tidal cross-strata, and tidal bars filling distributary channels and their axes are also suitable for palaeocurrent measurements (Rahmani 1988; Nio & Yang 1991; Dalrymple 1992; Shanley *et al.* 1992; Fenies *et al.* 1999; Willis 2005; Dalrymple 2010; Steel *et al.* 2012). In deltas subject to a strong tidal deflection during progradation, the palaeocurrent patterns record a progressive upwards-rotatory trend, changing from an initial shore-perpendicular direction to a shore-parallel direction, according to the dominant tidal current. This change can be detectable within a single deltaic succession, such as the O'Brien Spring Sandstone and the Belmonte Calabro delta facies described here.

(ii) The general absence of volumetrically significant prodelta mudstone deposits in the distal deltaic environments. This feature is more common in deltas prograding into tidal straits rather than into seaways. This is because straits generally reproduce conditions of stronger tidal current amplification as a result of the restriction of the cross-sectional area in the narrowest strait centre and consequent water mass convergence (Pugh 1987; Longhitano 2013). Accordingly, deltas entering straits dominated by tidal currents encounter a high-energy oceanographic setting and thus the fine-grained suspended load is transported away for several

**Table 1.** *Comparison between the main morpho-sedimentological features among ‘classic’ tide-dominated deltas and deflected deltas prograding in seaways and/or straits developed under the influence of along-shore tidal currents*

| Delta features | Tide-dominated deltas | | Tidal seaway/strait-deflected deltas | |
|---|---|---|---|---|
| In plan | | Modern examples | | Modern examples |
| Delta plain width/length | 3:4 | Changjiang Delta (Goodbred *et al.* 2003) | 4:3 to 2:1 | • **Elwha Delta**, Juan de Fuca Strait (Foreman *et al.* 2004; Gelfenbaum *et al.* 2015) |
| Delta front platform width/length | 5:2 | Ganges–Brahmaputra Delta (Goodbred & Kuehl 1999; Kuehl *et al.* 2005) | 2:1 to 3:1 | • **Fraser Delta**, Strait of Georgia (Ayranci & Dashtgard 2016) |
| Prodelta width/length | 4:1 to 6:1 | Fly Delta (Wolanski *et al.* 1995; Harris *et al.* 1996)<br>Colorado Delta (Thompson 1968; Carriquiry & Sanchez 1999) | Up to 7:2 | • **Klang Delta**, Malacca Seaway (Keller & Richards 1967; Emery 1971; Galloway 2002)<br>• **Sant’Andrea Delta**, Messina Strait (Chiocci *et al.* 2008) |
| Delta front sandbodies | Dip elongated, seawards diverging (parallel to ebb/flood tidal currents) |  <br>Redrawn, after Goodbred & Saito (2012) | From oblique to the coastline to strike-elongated |  |

| *Cross-section* | *Ancient examples* | | *Ancient examples* | |
|---|---|---|---|---|
| Palaeocurrent trend | Perpendicular to the coastline or seawards diverging | • Maracaibo Basin, Venezuela Middle Eocene Lagunullas Formation (Maguregui & Tyler 1991)<br>• Central Wyoming, USA Mid-Cretaceous Frontier Formation (Willis *et al.* 1999)<br>• Halten Terrace, offshore Norway, Early Jurassic,Tilje Formation (Martinius *et al.* 2001)<br>• Baltic Basin, Estonia, Latvia, Lithuania, Middle Devonian Kernave–Aruküla Formation (Plink-Björklund 2012) | Rotating from oblique to the coastline to parallel to the coastline (or to the seaway/strait axis) | • **Amantea Basin**, southern Italy, Tortonian Belmonte Calabro section (Longhitano & Nemec 2005; Longhitano *et al.* 2012*a*, *b*; this work)<br>• **Messina Strait**, southern Italy, Lower Pleistocene Calanna section (Barrier 1987; Mercier *et al.* 1987; Longhitano *et al.* 2012*a*, *b*)<br>• **Southern Wyoming**, USA Campanian Haystack Mountains (Martinsen & Tillman 1989; Mellere & Steel 1995*a*, *b*; this work) |
| | | | Wave influence at the delta coastline | |
| Dominant process regime | Ebb/flood tidal currents |  | Along-shore tidal current dominance at the delta front/prodelta |  |
| Clinoform thickness/geometry | Thick topsets because of tidal reworking on the delta platform | Redrawn, after Goodbred & Saito (2012) | Thinning-upwards, in case of strong deflection | |

Examples are based on modern and ancient case studies.

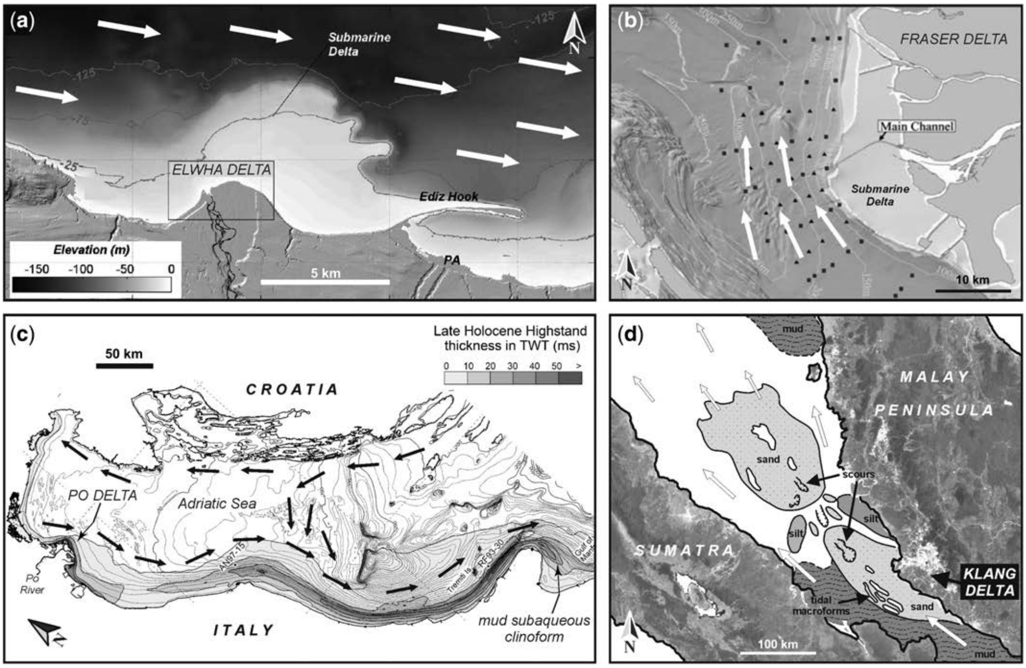


**Fig. 19.** (**a**) The Elwha Delta in the state of Washington, at the northwestern border of the USA, represents a modern example of deflected river delta prograding into the Juan de Fuca tidal strait (Fig. 1a). Although its coastal plain has no evident skewed profile, the subaqueous delta shows multiple elongate sand ridges as a result of the influence of along-shore transport due to the dominant east-directed tidal current (modified from Gelfenbaum *et al.* 2015). (**b**) The Fraser Delta prograded over the eastern margin of the same tidal strait as the previous example (i.e. the Strait of Georgia) and assumes an asymmetrical shape due to the north-directed tidal prism (modified from Ayranci & Dashtgard 2016). (**c**) The Po Delta in the northern Adriatic Sea undergoes an impressive deflection and detachment for over 350 km of prodelta muds, which feed a subaqueous clinoform in the southern Adriatic Sea (modified from Cattaneo *et al.* 2003). (**d**) Sediment pattern distribution in the subaqueous Klang Delta of the Malacca Strait (modified from Galloway 2002). Delta front sands are strongly deflected according to the dominant tidal current. Sediments are detached downcurrent from the main deltaic body to form an isolated sandbank that contains scours and tidal macroforms.

kilometres before accumulating in protected or sheltered adjacent coastal areas. Modern examples documenting an analogous process are observable in the Sant'Agata River Delta, which represents a small system prograding along the southwestern margin of the Messina Strait (Fig. 1d) in southern Italy. In the rock record, strait deltas can thus exhibit tidal cross-stratification motifs that generally lack fine-grained sediment, being deprived of 'mud-bearing' tidal structures such as double mud drapes, flaser bedding or fluid mud drapes (Longhitano 2011; Longhitano *et al.* 2012*a*).

(iii) An upwards change in the dominant process regime acting on the deltas. This feature is common in many ancient deltaic successions accumulated in basins that changed their oceanographic setting – for example, due to phases of relative sea-level rise (e.g. Porębski & Steel 2003, 2006; Yoshida *et al.* 2007; Plink-Björklund 2008). Transgressive coastlines commonly tend to be more tide-influenced than regressive coastlines (e.g. Dalrymple 1992; Dalrymple *et al.* 1992; Shanley *et al.* 1992; Allen & Posamentier 1993; Dalrymple & Zaitlin 1994; Shanley & McCabe 1994; Shennan & Andrews 2000; Yoshida 2000) and the effects of tidal processes in delta front deposits is more easily detectable in successions accumulated in incised valleys or embayed coastal areas flooded after relative sea-level rise. Ancient tidal straits documented from very different geological settings often experienced tectonically controlled transgressions (e.g. Allen & Bass 1993; Colella 1995; Mellere & Steel 1996; Anastas *et al.* 1997;

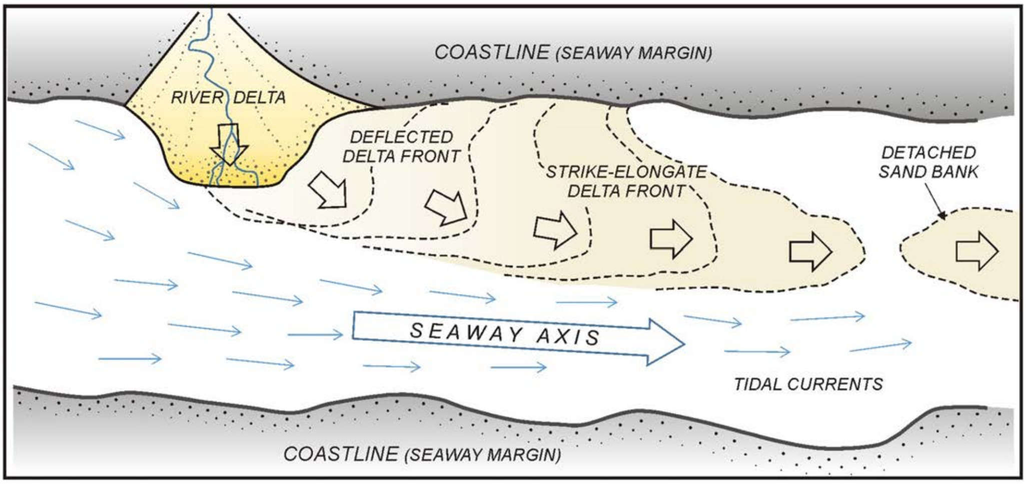


**Fig. 20.** Theoretical model explaining the process and the possible evolution through time of a river delta impinging a tidal strait or seaway. The deposits can assume deflected morphologies during an initial stage of progradation, but they may evolve into strike-elongate bodies and, finally, into detached sandbanks.

Longhitano & Nemec 2005; Olariu *et al.* 2012; Longhitano *et al.* 2012*b*, 2014; Longhitano 2013; Reynaud *et al.* 2013). In case of deltas prograding into these settings, their early transgressive stage was possibly characterized by the dominance of gravity-driven mass wasting processes or river flood jets superimposed onto other local marine influences. As the strait enlarged and tidal circulation was more pronounced at the basinal scale, deltas became even more tidally influenced/dominated in their vertical successions (Fig. 12) (Longhitano & Nemec 2005).

(iv) As documented in the Belmonte Calabro delta in the Tortonian Amantea Strait (Fig. 11), strait/seaway deltas often exhibit vertically stacked, thinning-upwards delta front units. This architectural arrangement was also described in current-deflected deltaic wedges of the Brazos, Danube, Fraser, Ganges–Brahmaputra, Kura, Po and many other deltas (see review in Korus & Fielding 2015). As observed in other case studies of coastal systems documented during the last 20 000 years (e.g. Longhitano *et al.* 2016), tidal influence has been enhanced during the late post-Last Glacial Maximum transgression in response to the deceleration of the rate of relative sea-level rise, which results in decreased accommodation space in the receiving basin (e.g. Cattaneo & Steel 2003) and the amplification of tidal processes at coastlines. However, in the observed sections, as well as in many documented deflected modern deltas, the progressive-upwards reduction in the thickness of cross-stratified wedges can be interpreted as the dip-oriented cross-sectional expression of the deflection of the delta front units and the consequent vertical juxtaposition of downcurrent locations in successive wedges. This effect and the related geometrical configurations have been documented for a number of Holocene deltas by Korus & Fielding (2015), who quantified delta front and prodelta deflection as consequence of discharge partitioning, wave reworking, plume deflection and variable subsidence (e.g. the Brazos, Danube, Fraser and Ganges–Brahmaputra deltas) or due to changing progradation rates and irregular palaeobathymetry (e.g. the Ba Lat, Kura, Llobregat, Mekong and Po deltas).

However, although recent studies have quantified delta deflection due to oceanic interference with the deltaic depositional processes, information is still lacking in our comprehension of river deltas that are tidally deflected because of their seaway and strait settings. For example, it is not fully clear whether delta deflection occurs simultaneously with sediment distribution (i.e. delta accretion) or is a secondary effect of tidal reworking of the frontal sectors of such deltas during periods of sediment starvation. Moreover, ichnofacies studies of the deltaic component of these systems are today very scarce. A systematic characterization of the distribution of the lifestyles of the organisms populating tidally deflected deltaic environments would reveal important insights into the dynamics of seaway/strait deltas and also into the interplay between subordinate factors such as turbidity, waves and occasional high-energy storm events.

## Conclusions

This study defines the main diagnostic sedimentological and stratigraphic elements of river deltas impinging tide-dominated seaways and straits. As these deltas prograde into confined marine settings, the effects of waves, flood/ebb tides and river input are usually less important than the dominant influence of tidal current patterns running parallel to the coastline. These currents represent the major hydrodynamics in tidal seaways and straits and originate from tidal reversals between two interconnected wider basins. As a consequence of the restriction, the tidal prism increases noticeably in strength due to water mass convergence, exerting a strong influence along the seaway/strait margin and related depositional systems.

Many modern examples of marine passageways governed by tidal currents were described in this work as present day analogues, including the Juan de Fuca, Malacca, San Francisco, Messina, Dover and Torres straits, because they often show that river deltas prograding from their margins can assume strongly skewed or strike-elongate morphologies, departing substantially from the expected river delta settings. Outcrop examples from two ancient basins were identified as comparable ancient models for tidal seaway/strait deltas: the Cretaceous Western Interior Seaway of the USA and the Tortonian Calabrian Arc of southern Italy. These two areas represent, respectively, an ancient extensive marine passageway connecting the Gulf of Mexico to the south with the Arctic Sea to the north in which there was a tidal circulation governed by the overall oceanographic setting, and a small orogen that hosted a number of tectonically controlled corridors, which produced significant tidal current amplification and consequent sediment dispersal exchange between the interlinked Tyrrhenian and Ionian basins.

The stratigraphic sections described from these two areas demonstrated that river deltas can generate different stratal architectures depending on the gradient of the margin they prograded from. In the case of gently sloping borders, deltas may be characterized by long-lived sequences, with clinoforms prograding for large distances and assuming a progressive change in their dip direction according to the dominant tidal current pattern. Conversely, tidal straits with steep margins tend to generate single, short-lived deltas, which are usually involved in active tectonics and form unconformity-bounded sequences with a single, uniform direction of progradation.

Both these examples indicate that the delta front is the sector of the delta system most sensitive to the short-term influence of tidal currents. Here, tidal currents are able to rework sand to create wide tidal dune fields, preserved as thick cross-stratified complexes in the deltaic stratigraphic record. Although there is no clear field evidence in either of our two ancient case studies, modern tidally deflected deltas prograding into straits, such as the Elwha, Fraser and Klang deltas, show that prodelta fines can form elongate depositional features until they are detached from the main deltaic body and may assume the connotations of different systems.

Therefore we suggest some key diagnostic elements with which to detect ancient deflected tide-dominated seaway/strait deltas in the stratigraphic record.

(1) The palaeocurrent patterns record gradual upwards-rotatory trends, changing direction from initially shore-perpendicular to progressively shore-parallel, following the dominant tidal current direction.

(2) Prodeltaic fines are scarcely preserved in tide-dominated straits because the deltas advance rapidly into a high-energy setting where mud is perennially transported in suspension. In seaway deltas, fine-grained prodelta deposits tend to be strike-elongated, oriented parallel to the dominant tidal current and can be transported for large distances across the shelf, as in the case of the modern Po River delta in the Adriatic Sea.

(3) Seaway/strait deltas can experience an upwards change in the dominant process regime, transiting from river- or wave-dominated during early progradation, progressively to tide-influenced and, during their late stages of progradation, tide-dominated. This variance results in an asymmetrically deflected delta front and (where present) prodelta deposits and tidal sandbodies elongated in the direction of the dominant tidal current. In cross-section, this process can be reflected by the accretion of thinning-upwards clinoform units, reflecting a progressive downcurrent shift of the delta front sandbodies.

These considerations establish a basis to promote further studies and reinterpretations of the elongate, coastline-attached sandbodies detected in a number of narrow confined settings in many petroliferous basins of economic significance around the world (e.g. around the margins of many tectonic highs recognized offshore the North Atlantic Ocean). The results of these analyses are crucial in predicting and modelling sandbody distributions and in reviewing many environmental interpretations of ancient settings that may be related to tide-dominated seaways or straits.

This study resulted from the convergence of two initially separate research programmes, which were contemporaneously pointing towards common observations and conclusions. The authors express their gratitude to all the collaborators and colleagues who assisted them in the field and with whom they exchanged fruitful discussions that have allowed the writing of this paper. The authors are also grateful to Allard Martinius, an anonymous reviewer and Gary Hampson for their constructive criticisms of the content of this work.

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