A facies-based depositional model for ancient and modern, tectonically–confined tidal straits

Sergio G. Longhitano
Department of Sciences, University of Basilicata, V.le Ateneo lucano, 10, 85100, Potenza Italy

ABSTRACT
Modern and ancient tidal straits are the least well understood of all tide-dominated depositional systems. To provide an increased understanding of these systems, a facies-based depositional model is assessed by comparing multibeam surveys of three present-day tidally dominated seaways with a number of superbly exposed Neogene-to-Quaternary strait-fill successions of Calabria (south Italy). The model points out the existence of four depositional zones, laterally adjacent from the narrowest strait centre to its terminations, distributed along symmetrical or asymmetrical seaways. These zones, whose signature is recorded in four facies associations in the Calabrian tidal straits, are as follows: (i) the strait-centre zone, associated with the tidal current maxima and where sediments are scarce or absent; (ii) the dune-bedded zone, where sediments form dune complexes due to tidal flow expansion; (iii) the strait-end zone, where currents decelerate accumulating thinly bedded, fine-grained deposits; and (iv) the strait-margin zone, where sediment massflows descend tectonically active, steep margins towards the strait axis. In ancient, tectonically confined, narrow seaways, these facies generate a distinctive deepening-upward vertical succession, where tidal currents are the dominant process in the sediment distribution.

Terra Nova, 0, 1–7, 2013

Introduction
In spite of their importance today and in the geological record, tidal straits are probably the least well understood of all tidal depositional systems. Sedimentological models have been developed for mega-, macro- and mesotidal settings (i.e. tide-dominated estuaries, deltas, salt marshes, open-coast tidal flats and shelves; see Davis and Dalrymple, 2012; Longhitano et al., 2012a), but, except for a growing number of palaeo-geographical reconstructions (Martel et al., 1994; Betzler et al., 2006; Martin et al., 2009; Olariu et al., 2012; Longhitano et al., 2012b; Reynaud et al., 2012; among others), there is only one general, albeit simplistic, model for straits provided by Anastas et al. (2006).

Recently, the economic relevance of these systems has greatly increased, because many ancient strait-fill successions have revealed significant oil and gas reservoirs (e.g. the Miocene Viking strait, between the west Norwegian and the Shetland highs, or the Middle Jurassic Garn Formation, Kristin oil field, offshore mid-Norway). Importantly, tidal straits are advantageous commercial navigation seaways and their sedimentary dynamics is essential in case of installation of plumbing or wiring for technical uses. Therefore, a depositional model summarizing the main physical elements and dynamics of such complex systems is needed.

In this study, one of the most common modern tidal seaways are divided into depositional zones where tidal currents, interacting with other minor processes, are the dominant control on sediment distribution. The predicted sedimentary product of these zones is then compared with four Neogene-Quaternary strait-fill successions of Calabria, to assess a facies-based model also for ancient tidal straits.

Tidal straits
The term ‘strait’, used as synonymous of seaway or marine passageway, indicates a narrow arm of sea comprised between emerged lands (or shallowly submerged margins) and linking two adjacent larger basins. Commonly, straits are crossed by marine currents flowing dominantly in one direction, but amplified in their strength, due to the restriction of the cross-sectional area (Defant, 1961; Pugh, 1987). When the currents are regulated by a tidal cyclicity, the strait is called ‘tidal’ or ‘tidally-dominated’ (Pratt, 1990).

In modern straits, tidal currents flow axially to the seaway, having reversal directions and phase difference between the two interlinked basins. They vary greatly in velocity, exceeding 2 m s⁻¹ along the narrowest parts of many of these systems (Malikides et al., 1988; Lindstrom et al., 1990; Santoro et al., 2002).

In a strait system, sediments derive from rivers, fan deltas, or marginal cliff collapses. When vigorous tidal currents occur, also exhumed parts of the basement rocks or fluvial/deltaic deposits that accumulate during previous lowstands, and usually exposed in the narrowest strait centre, are swept and eroded, contributing a minor proportion of the strait infill. In many modern and ancient seaways, in situ carbonate (biloclastic) production is often the dominant sediment source.

Sedimentary bedforms develop along the strait bottom. These features, described as tidal (compound) dunes (Dalrymple, 1984, 2010; Ashley, 1990), exhibit complex lateral/vertical relationships and internal architectures (e.g. Anastas et al., 1997; Bastos et al., 2003), as they result from the bed shear stress exerted on to the sediments by reversal tidal currents interacting with occasional wind-driven storm waves.
Tidal currents distribute sediments producing a ‘bedload parting’, which promotes the transport of bed material from the central (erosional) part towards either sides of the strait after flow expansion (Harris et al., 1995; Reynaud and Dalrymple, 2012). Bedload parting depends on the tidal phase dominance along the strait (e.g. the more symmetrical the reversal currents, the more volumetrically equivalent the depositional areas).

**Depositional zone partitioning in modern tidal straits**

Detailed multibeam images of modern tidal straits allow the identification of depositional zones, each characterized by common hydrodynamics, sediment grain sizes, bedforms and morpho-bathymetric features (Fig. 1a–c). These zones are as follows: (i) the strait-centre zone, equivalent to the narrowest axial sector of a tidal strait, which is generally associated with bedload parting, tidal current maxima and sediment by-pass, with erosion or net deposition close to zero due to the highest bed shear stress; (ii) the dune-bedded strait zone, adjacent to the centre zone, but characterized by a widening cross-sectional area, is the zone of maximum sediment accumulation rate due to the initial deceleration of the tidal currents; here, medium to very large 3D and 2D tidal sand dunes form, associated with ripple-scale bedforms with a reversed or transverse direction of migration; (iii) the strait-end zone, which represents the distal part of a tidal strait, is commonly characterized by decelerating tidal currents and deposition of fines, due to the definitive enlargement of the strait cross-section; and (iv) the strait-margin zone, corresponding to the flanks of a tidal strait, is influenced by wave reworking processes in gently sloping strait margins (e.g. the Torres Strait), or gravity-driven, sediment mass flows in straits with steeper margins (e.g. the Messina Strait). The deepest part of this zone is also influenced by tidal currents flowing along the axis of the seaway.

**Dataset of ancient examples**

The strait-fill successions used to test the above concepts of strait partitioning belong to a number of extensional basins located across the Calabrian Arc (Fig. 2a). The Calabrian Arc is a small orogen, which was strongly affected by strike-slip tectonics and block rotation during middle Miocene (Knott and Turco, 1991). This tectonic development produced a structural fragmentation of the arc and favoured the formation of narrow grabens, including the Tortonian Mte Pellegrino Strait, and...
the Plio-Pleistocene Catanzaro, Siderno and Messina straits (Fig. 2b). These seaways were filled by 80- to 200-m-thick deepening-upward successions during dramatic phases of tectonic-driven marine transgressions (Colella and D’Alessandro, 1988; Longhitano and Nemec, 2005; Longhitano et al., 2012b). Tidal currents were amplified flowing in phase opposition from one basin to the other, like the modern Messina Strait (Figs. 1a and 2b) where flows range in velocity from 0.1 to 0.35 m s\(^{-1}\) in the strait reaches, up to 2 m s\(^{-1}\) in the sill (Santoro et al., 2002).

### Facies-based depositional model for ancient tidal straits

Four main facies associations were recognized in all the study areas. These deposits are considered the record of the depositional zones detected in the modern tidal straits (Fig. 1a–c).

**Gravel/shell lags: the strait-centre zone**

These condensed deposits lie directly on top of isolated faulted basement blocks, often located in the central sector of the basins, forming laterally discontinuous lags 1–2 m thick (Fig. 3a). Sediment consists of structureless assemblages of fossil fragments, pebbles and cobbles, immersed in a siliciclastic gravel-size matrix very rich in glaucony (Fig. 3b). In other straits, this sector can be highly depositional. As reconstructed in the Tortonian Mt Pellegrino Strait (Longhitano and Nemec, 2005), the strait-centre zone may be a very narrow area (1–2 km wide) and the scoured sea bed can be rapidly filled by coarse-grained sediments derived from the strait margins (Fig. 3c). Faunal associations are represented by disarticulated mollusc shells associated with highly weathered fragments of red algae, Corallina errinecea and Laminaria, indicating high-energy environments subjected to vigorous currents.

This facies association represents the condensed deposits of an at times, erosional by-pass area that, usually, occupies the narrowest strait-centre zone (Fig. 4a). Modern examples are provided from the Dover and Messina straits where accelerating currents, as they converge in the strait centre, prevent the deposition and accumulation of sand (Santoro et al., 2002; Le Bot and Trenteaux, 2004). In these systems, the strait-centre zone represents the shallowest part of the seaway floor (depth ranges from 200 to 450 m). Cross-strata can be 2D and 3D tidal cross-strata of the dune-bedded zone record tidal dunes, whose aggradation resulted from tidal current flowing in a widening cross-sectional strait area (Fig. 4a). The complex internal architecture of two- and three-dimensional tidal dunes depends on the symmetry of the two opposite tidal currents (Dalrymple and Rhodes, 1995) and on the eventual interaction with waves that may occur in such confined basins during high-energy events (Benn et al., 1988; Le Bot and Trenteaux, 2004). In the Calabrian straits, 3D tidal dunes frequently evolve upwards to 2D dunes. This facies transition is considered as the vertical record of the decrease in the tidal current energy during the phase of marine transgression, due to the consequent widening of the strait width in result of the investigated Calabrian straits, as well as in many other Tertiary tidal seaways (e.g. the North-Betic Strait (south Spain), the Bonifacio Strait (south Corsica), the Te Kuiti Strait (Australia), the Rhone-Alp Strait (northern Alps)).
Fig. 3 (a) Gravel/shell lag in the strait-centre zone (zone A) of the lower Pleistocene central Catanzaro Strait. The deposit is transgressed by tidal cross-strata of the dune-bedded strait zone (zone B). (b) Detail of a similar deposit, showing the chaotic assemblage of pebbles and coral fragments in a reddish, coarse-sand matrix. (c) Vertically stacked tidal cross-strata with unidirectional foresets in the dune-bedded strait zone (zone B) in the Tortonian Mt Pellegrino Strait. Note their transgressive feature on to the underlying coarse-grained deposit of the strait-centre zone (zone A). (d) Detail of a cross-strata set from the dune-bedded strait zone (zone B) of the lower Pleistocene Siderno Strait. (e) Bioclastic/siliciclastic segregation in cross-stratified sandstone (Siderno Strait). (f) Thinly bedded fine sandstone and siltstone recording the strait-end zone (zone C) in the Catanzaro Strait. (g) Detail of the previous outcrop, showing a pervasive bioturbation. (h) Tidal cross-strata incised by channelized mass-flow deposits in the strait-margin zone (zone D) of the lower Pleistocene northern Messina Strait. (i) Equivalent association exposed in the southern Messina Strait. Note multi-storey channel-fills and neap(n)/spring(s) tidal cycles in the tidal foreset.
to tectonically driven subsidence (Chiarella, 2011). This interpretation assumes that the 3D-to-2D tidal dune transition, also obtained in flume experiment (Southard and Boguchwal, 1990), observed in the late Precambrian Scottish Dalradian tidal shelf (Anderton, 1976) and in the modern San Francisco Strait (Fig. 1d), results from the hydraulic change across an energy profile, where the progressive down-current decrease in the tidal current strength may change bedforms from three- to two-dimensional.

**Ripple-bedded, highly bioturbated fine-grained strata: the strait-end zone**

In the studied successions, large-scale tidal cross-strata pass laterally and vertically to sporadic dune-scale coarse sandstone strata with dominant ripple-bedded fine sandstone strata, alternating with thinly bedded siltstone strata (Fig. 3f). Internally, unidirectional small dunes contain bundled cross-lamination and reactivation surfaces (Fig. 3g). Bioturbation can be dominantly observed in large diameter (> 1 cm) vertical to inclined shafts, and in J- or U-shaped burrows, suggesting *Skolithos*, *Thalassinoides*, *Psilonichnus* and *Arenicolites* trace fossils (Fig. 3g).

This facies association records the strait-end zone (Fig. 4a), which represents the widening distal reaches of the seaway where the tidal currents declines due to the enlarged cross-section. Tidal flows are capable to transport fine sand only during high-energy tidal phases (e.g. during storms enhancing the strength of the tidal currents or during spring tidal cycles). Siltstone interstrata record fallout deposition from fine-grained suspended load.

**Mass-flow/tidal deposit: the strait-margin zone**

Many of the studied sections exhibit structureless or normal-graded, 2- to 9-m-thick strata interbedded with 4- to 8-m-thick cross-stratified tidal deposits (Fig. 3h). Structureless strata have erosional bases cutting the underlying cross-strata and form multi-storey, often amalgamated channel-fills (Fig. 3i). Sediments consist of basal pebble-size, angular clasts, associated with broken shells, corals and bryozoans, grading upward to very coarse and medium-fine sand. In other strata with low-gradient margins, this zone is expressed by shoreface deposits or...
wave-dominated deltas (e.g. Frey and Dashtgard, 2012).

This facies association represents the sedimentary expression of the strait-margin zone (Fig. 4a) located along the side flanks of the seaway. In both ancient and modern examples used in this study, the strait flanks are tectonically active, emerged or shallowly submerged margins, composed of basement rocks and capable to generate huge flux of clastic sediments. Sedimentary processes are debrisfalls and debris-flows descending perpendicularly to the seaway axis, where tidal currents occur. This is thus a zone of interference between gravitative and tractive processes. These latter are momentary deactivated in case of debris avalanches, which may occur during earthquakes, submarine landslides or climate-driven, catastrophic flash floods. At the end of these events, tidal currents return to flow, generating bedforms that rework the top of the mass-flow deposits (Fig. 3h,i).

Discussion and conclusions

Tidal straits are current-dominated, elongated marine systems, site of tidal current amplification due to a restricted cross-sectional marine passageway. Importantly, the tidal amplification occurs independently from the tidal regime of the area (Mitchell et al., 2011).

Modern tidal straits can be either symmetrical or asymmetrical. Examples of symmetrical seaways are the Messina, San Francisco and Cook straits, where the depositional zones are mirrored with respect to the seaway cross-section enlarges towards the distal strait-end zone. Here, tidal currents slacken accumulating the finest sediment fraction (Fig. 4a). In some case (e.g. southern Messina and Cook straits), this zone is linked to a deep-marine canyon system, which transfers significant sediment volumes towards the deeper basin, preventing substantial accumulation in this area. Diagnostic components of a tidal strait are the strait-margin zones, where sediments are wave-worked in gently sloping strait margins, or accumulate intermittently under tractive and gravitative processes in straits with steeper margins. The distinctive facies association is key in identifying the strait lateral boundaries, especially in case of later structural deformations (Fig. 4a).

Tectonics plays a fundamental role, particularly in narrow, deep ancient tidal seaways. The structural extension that creates the strait tends to generate strong subsidence and consequent dramatic transgressions, generating deepening-upward successions (Fig. 4b). Common element of ancient tidal seaways is thus this recurrent vertical stratigraphic trend (Fig. 3c), where the volumetrically most important deposits are tidal cross-stratified sand-rich strata, laterally and vertically confined by bioturbated, fine-grained strata. When preserved, these transgressive successions are capped by shelf mudstones (Fig. 4b). Other ancient examples can exhibit more complex vertical successions, due to the intervention of relative sea-level fluctuations and consequent water-depth changes that force tidal currents to be or not amplified (Anastas et al., 2006).

This facies-based depositional model can be applied also to other ancient tidalite-bearing successions of dubious or difficult interpretations. It can also be useful for basin analysis reconstructions and for clastic reservoir characterizations, where predictions on the spatial facies changes or positions are of key importance.

Acknowledgements

This study summarizes data collected in ca. fifteen years of field studies. Many colleagues and friends should be thanked for the helpful and stimulating discussions on sedimentation in tidal straits, either on the field or during international conferences. My gratitude goes to the two reviewers, Bob Dalrymple (Queen’s University, CA) and Ron Steel (Texas University, US), as well as to the Scientific Editor Max Coleman and the Associate Editor, whose insightful and constructive comments helped me to improve the final model presented in this paper. Finally, I would like to dedicate this study to my new-born twins, Aurora & Gaia.

References


Received 14 February 2013; revised version accepted 8 May 2013.

© 2013 John Wiley & Sons Ltd