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

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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.

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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 palaeogeographical reconstructions (Martel *et al.*, 1994; Betzler *et al.*, 2006; Martín *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, some 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 asses a facies-based model also for ancient tidal straits.

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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 (bioclastic) 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

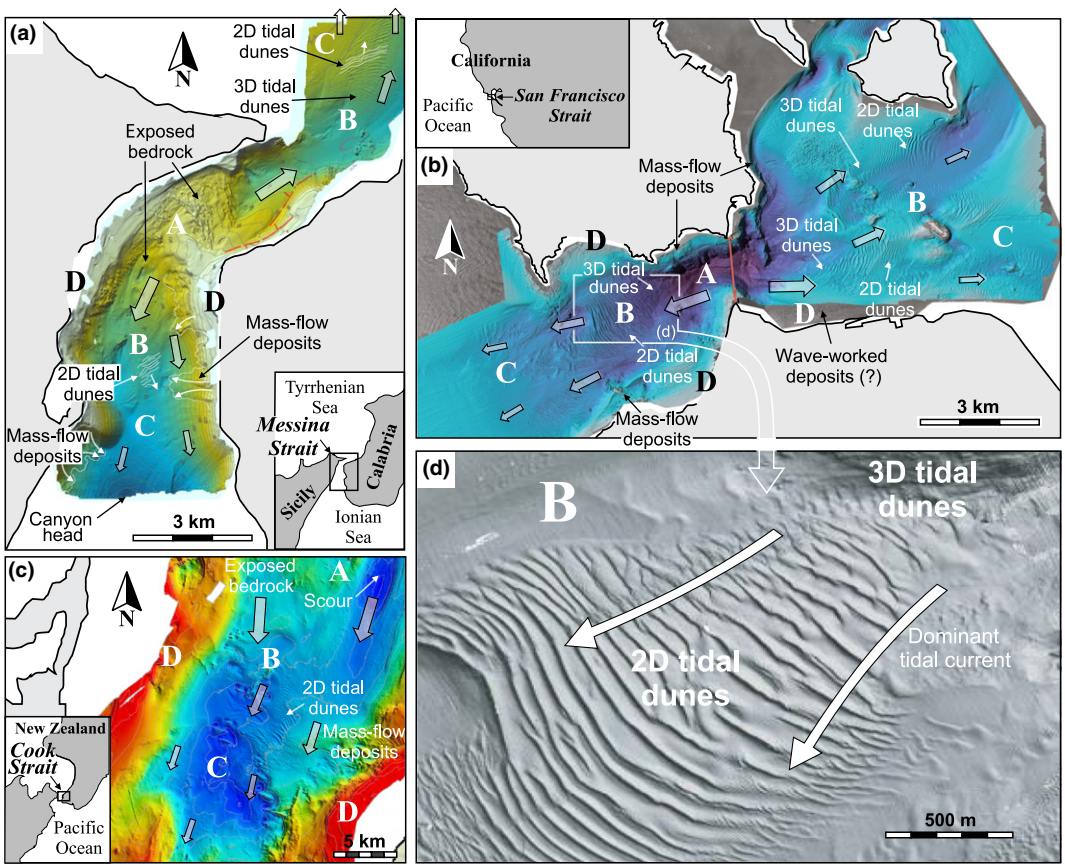

Fig. 1 Depositional zone partitioning from multibeam surveys of three modern tidal straits. (a) Messina Strait (Ferranti *et al.*, 2008), (b) San Francisco Strait (Barnard *et al.*, 2006), and (c) Cook Strait (Lamarche *et al.*, 2011). (*A = strait-centre zone*; *B = dune-bedded strait zone*; *C = strait-end zone*; *D = strait-margin zone*). (d) Detail of the zone *B* in the San Francisco Strait showing down-current 3D-to-2D tidal dune transition.

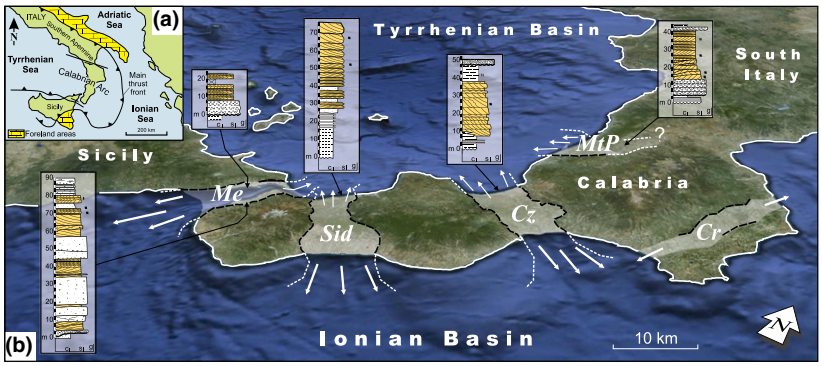

Fig. 2 (a) Regional geological setting of south Italy. (b) Satellite overview of the Calabrian Arc with the main Neogene-to-Quaternary tidal straits and relative simplified stratigraphies (white arrows indicate the inferred tidal currents flowing axially to the seaways). Letter symbols: *Me* = Messina Strait; *Sid* = Siderno Strait; *Cz* = Catanzaro Strait; *MtP* = Mt Pellegrino Strait; *Cr* = Crotone Strait.

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, *Corallia 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 Trentesaux, 2004). In these systems, the strait-centre zone represents the shallowest part of the seaway floor (depth ranges from −30 to 40 m in the Dover and Malacca straits, to −130 m in the Messina Strait; Fig. 1a). In contrast, in other tidal straits, the centre is the deepest part of the seaway, which is often scoured or channel-shaped (San Francisco and Cook straits; Fig. 1b,c).

2D/3D tidal cross-strata: the *strait dune-bedded zone*

This facies association is the volumetrically most important deposit 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)]. In the Calabrian straits, medium to very coarse siliciclastic sand, containing abundant granule-size clasts and variable amounts of bioclasts, forms complex 'sand sheets' up to 80–120 m thick (Longhitano *et al.*, 2012b) (Fig. 3c). Large scale 2D and 3D cross-strata have highly varying set thicknesses (0.5 to 9–10 m). Cross-strata can be of planar or trough types, with erosional surfaces (master bedding planes) gently dipping (5° to 10°–12°) in the direction of the general migration, forming cosets of compound cross-bedding (Fig. 3d). Internally, foresets show frequent tidal bundles of thinning- and thickening-upward lamina sets, according to repeated neap/spring siliciclastic- and bioclastic-rich intervals (Longhitano, 2011) (Fig. 3e). Palaeocurrents are weakly bidirectional with one dominant direction, depending on the strait side where these bedforms migrated. This facies association is generally deprived of mud layers or drapes, rip-up mud clasts or fluid mud intervals, and contains fragments of deep-sea corals, molluscs, brachiopods, echinoids and cirripeds, indicating a depth range of 200–450 m.

2D/3D cross-strata of the *dune-bedded strait zone* record tidal dunes, whose aggradation resulted from the attenuation of the bed shear stress exerted by decelerating tidal currents 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 (Berné *et al.*, 1988; Le Bot and Trentesaux, 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 a phase of marine transgression, due to the consequent widening of the strait width in result

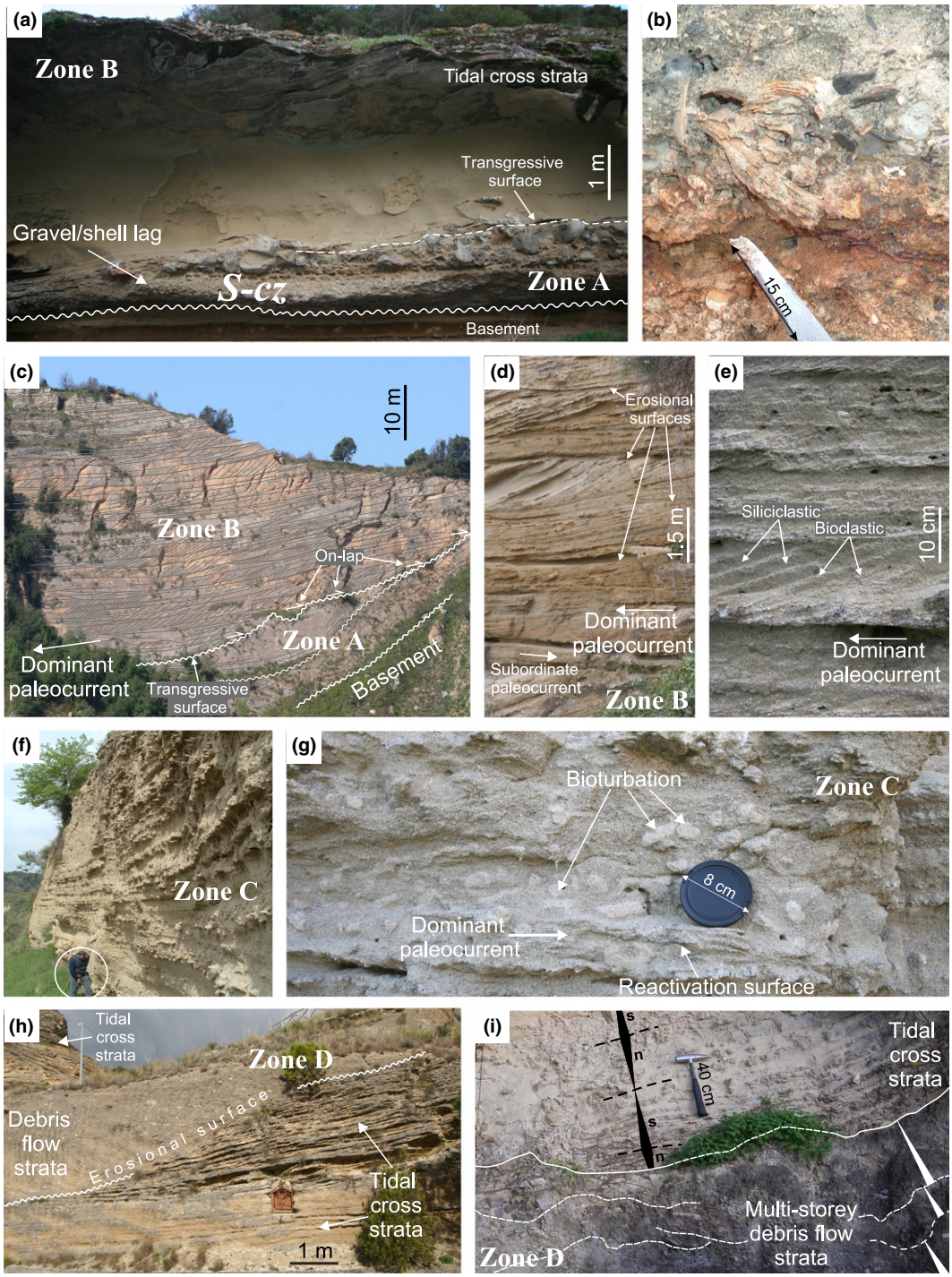

Fig. 3 (a) Gravel/shell lag in the *strait-centre zone* (zone A) of the lower Pleistocene central Catanzaro Strait. The deposit is transgressed by tidal cross-strata of the *dune-bedded strait zone* (zone B). (b) Detail of a similar deposit, showing the chaotic assemblage of pebbles and coral fragments 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.

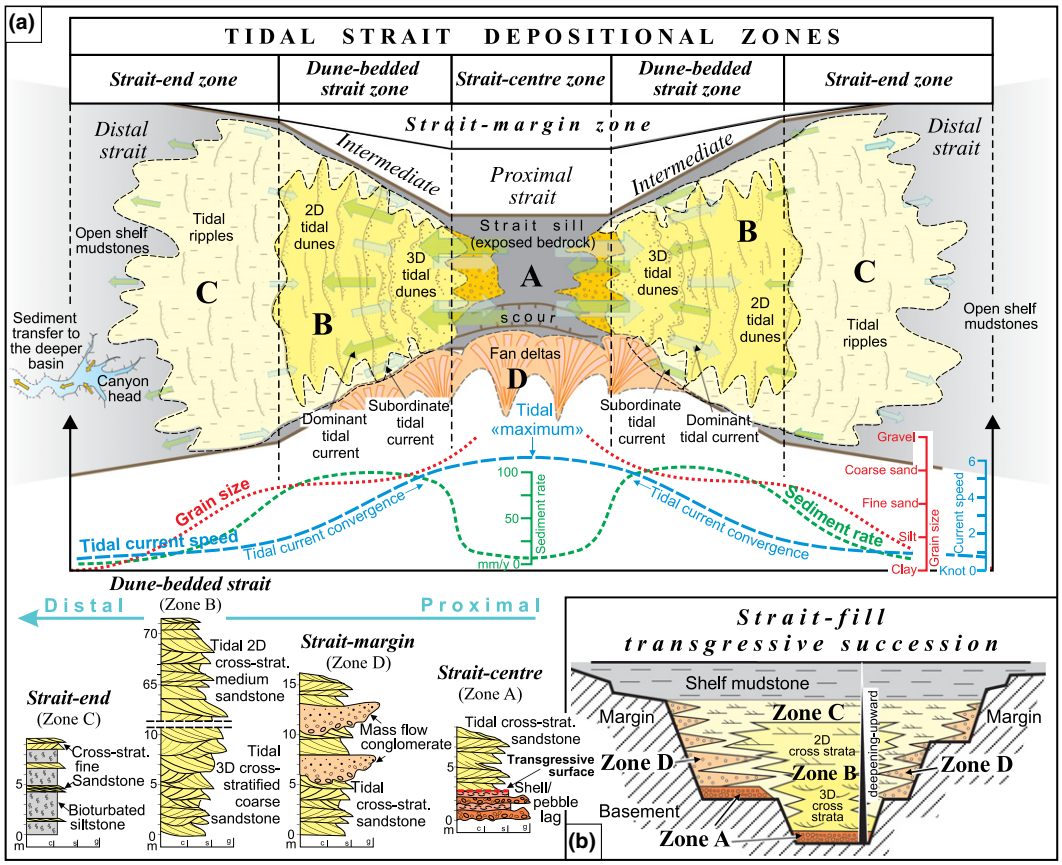

Fig. 4 (a) Depositional model for tectonically controlled, narrow tidal straits. The system is partitioned into depositional zones, which are symmetrically distributed with respect to the strait centre. Bedforms, sediment grain size and sediment deposition rate vary according to the tidal current strength distribution across the seaway. Each zone has a distinctive vertical facies tract, passing laterally to each other, from the proximal, to the intermediate, to the distal strait. (b) Strait-fill transgressive succession showing lateral/vertical facies association relationships.

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 straits 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 debrisflows 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 centre, whereas the Malacca Strait is asymmetrical (its south-eastern side rapidly descends into an abyssal plain). This configuration, which is mostly governed by the tectonic evolution of the seaway, is key in the reconstruction of ancient tidal straits, because symmetrical or asymmetrical systems generate very different volumes and distributions of dune-bedded, sand-prone deposits.

Tidal strait partitioning in modern systems can be defined by the progressive decrease in the tidal current strength laterally away from the strait axis and distally, as the strait becomes wider at both ends (Fig. 4a). In the narrowest *strait-centre zone,* tidal currents converge, and the tidal maxima prevents significant sediment accumulation due to the highest bed shear stress. The stratigraphic expression of this zone is an interval of erosion or sediment condensation (merely interpreted as 'transgressive lags' in the past literature; see Anastas *et al*., 2006; Betzler *et al*., 2006; Martín *et al*., 2009), which appears rapidly buried by cross-stratified tidal deposits, accumulated during subsequent and rapid relative sea-level rises (Fig. 3a,c). In the *dune-bedded strait zone* (Fig. 4a), tidal dunes change down-current from 3D to 2D (Fig. 1d), because of a progressive decrease in the flow strength, as 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.

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