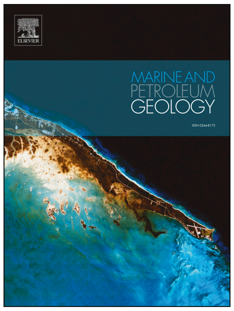

Interplay of tidal and fluvial processes in an early Pleistocene, delta-fed, strait margin (Calabria, Southern Italy)

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PII: S0264-8172(17)30067-3

DOI: 10.1016/j.marpetgeo.2017.02.021

Reference: JMPG 2828

To appear in: *Marine and Petroleum Geology*

Received Date: 16 September 2016

Revised Date: 7 February 2017

Accepted Date: 21 February 2017

Please cite this article as: Rossi, V.M., Longhitano, S.G., Mellere, D., Dalrymple, R.W., Steel, R.J., Chiarella, D., Olariu, C., Interplay of tidal and fluvial processes in an early Pleistocene, delta-fed, strait margin (Calabria, Southern Italy), *Marine and Petroleum Geology* (2017), doi: 10.1016/j.marpetgeo.2017.02.021.

INTERPLAY OF TIDAL AND FLUVIAL PROCESSES IN AN EARLY PLEISTOCENE, DELTA-FED, STRAIT MARGIN (CALABRIA, SOUTHERN ITALY).

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Abstract

The architecture and morphodynamics of modern and ancient tidal straits and in particular the deposits of strait-margin zones, have been significantly understudied compared to other marginal marine settings, even though many reservoirs in the North Sea and the Norwegian Continental Shelf are developed in narrow grabens or seaways. This paper presents a detailed sedimentological and stratigraphic analysis of an early Pleistocene marginal-marine succession deposited along the northern margin of the Siderno paleostrait (southern Italy). This area represents an excellent case study of sedimentation along a tidal strait margin, interpreted to record the interaction of fluvial and tidal processes. Here, syn-depositional tectonics produced a complex coastal morphology, significantly influencing sedimentation and hydrodynamic processes. Along the strait margin, the emplacement of an isolated tectonic high (Piano Fossati) created a ca. 3.5 km-wide local passageway. This morpho-structural element induced interplays between fluvio-deltaic processes (fed from the northern strait margin) and tidal current reworking (active within the marine strait).

The field-based facies analysis reported here documents an initial stage of non-tidal shallow-marine sedimentation across the strait. A subsequent regression caused river-generated hyperpycnal flows and the transfer of large volumes of pebbly and shelly sandstones into deeper water. Tidal currents became amplified in the strait, and, in the delta front area, they were able to rework river-derived sediments generating large dune fields. Following the local tidal transport pathway, strong tidal currents skewed the delta front (causing it to be asymmetrical) and elongated sand bodies in a direction parallel to the marine strait axis. Differently from the classical tide-influenced deltas in which onshore-offshore tidal flow predominates, coast-parallel deflection and strong asymmetry of delta-front deposits is a typical feature of deltas entering tide-dominated seaways and straits, where strong tidal currents are capable of dispersing large volumes of sand for significant distances along the coast and along the strait axis. This process became progressively enhanced during the following transgression, when tide-modulated currents reworked biocalcarenitic sands over the previous delta deposits, generating southeasterly migrating dunes. At the end of the transgression, strandplain progradation caused the closure of this marginal branch of the Siderno Stait. This last stage of sedimentation was followed by a dramatic regional-scale structural uplift, which *ended any marine circulation within the strait. This work provides new insights on sedimentation in a tide-dominated strait, and helps to predict sandbody distribution along the strait margin and axis. These findings can be applied to any other setting characterized by a narrow (possibly structurally-confined) basin dominated by tidal currents.*

Keywords: tidal strait; tidal and fluvial processes; strait margin; early Pleistocene; Calabro-Peloritani Arc

1.0 INTRODUCTION

Tidal straits are narrow marine passageways, flanked by emergent land areas, linking two adjacent basins (Pugh, 1987). Their oceanography is governed mainly by current convergence and amplification, due to the restriction of the cross-sectional area (Defant, 1961). In modern straits (e.g., the *San Francisco Strait*, *Messina Strait*, *Dover Strait* and *Torres Strait*), tidal currents commonly flow in opposite directions between the two connected basins, and exert great influence on the sediments, producing a partitioning of by-pass areas and specific depositional zones (Longhitano, 2013). Bedload parting zones and associated scour zones can be developed at flow constrictions (i.e., commonly in the narrowest point in the strait) and local bottom stress maxima, whereas sand transport paths are developed in the direction of the peak tidal current, and along two oppositely directed pathways away from the location of bedload parting (Harris et al., 1995). As a consequence, sediments in straits commonly accumulate in two main depositional zones, symmetrically located away from the local bedload parting, and occurring at both ends of the strait where flow expansion leads to deposition (Longhitano, 2013). Tidal transport pathways control the spatial distribution of tidal sedimentary facies, so that sand-rich tidal bedform fields pass down-current and laterally to finer-grained sand sheets (e.g., Belderson et al., 1982; Harris et al., 1995; Reynaud and Dalrymple, 2012). Therefore, tidal circulation and sedimentary structures would not be directly comparable to the classical tidal sedimentary structures present in other tide-dominated systems such as tidal deltas and estuaries (e.g., Martinius and Van den Berg, 2011), and, if a strait is sufficiently narrow, tidal currents would be rectilinear rather than rotary.

Existing facies models for straits (Anastas et al., 1997; Anastas et al., 2006; Longhitano, 2013) mainly deal with the redistribution of sediment already present on the sea floor or with sediment generated *in situ* by biologic activity. However, significant volumes of siliciclastic sediment can also be introduced into the strait by rivers entering the strait along its margins (Frey and Dashtgard, 2011; Longhitano et al., 2012b; Longhitano, 2013; Longhitano and Steel, 2016). Depending on the coastal gradient, strait margins can be steeply-inclined by-pass slopes, or gently-sloping depositional shelves, where shorefaces and river deltas develop, impinge upon and interact with tidal dune fields (e.g., Longhitano and Steel, 2016).

River deltas entering into such tide-dominated passageways can be strongly impacted by the effect of tidal currents, but differently than in ‘classical’, large muddy tide-dominated deltas (e.g., Dalrymple et al., 2003; Goodbred Jr and Saito, 2012; Cummings et al., 2016). Rather than simply being influenced by flood and ebb currents that flow perpendicularly to the general coastline and enter the river through the delta distributary channels, deltas in straits are confronted by tidal currents that move mainly parallel to the main coastline, causing asymmetrical deflection of the delta-front sands, and creating considerable elongation of tidally-reworked, dune-bedded sand bodies in the direction of the locally dominant tidal flow (e.g., the Klang Delta in the Malacca Strait; the Elwha Delta and the south-west coast of Vancouver Island in the Juan de Fuca Strait; Uroza, 2008; Frey and Dashtgard, 2011; Longhitano, 2015; Longhitano and Steel, 2015, 2016). In this type of system, the sediment is introduced by river floods that are capable of transporting large quantities of clastic sediments, but these sediments then become significantly reworked at the delta front by tidal currents flowing at a high angle with respect to the delta progradation direction.

This paper documents such a depositional setting along the northern margin of the late Pliocene – early Pleistocene Siderno Strait, located in the Calabro-Peloritani Arc, southern Italy (Fig. 1A).

The Siderno Strait represents a well-preserved example of an ancient tide-dominated passageway. In particular, in the eastern side of the basin (Fig. 1C), magnificent cross-stratified mixed siliciclastic-bioclastic complexes exhibiting large-scale (meter-thick) tidal foresets occur (Longhitano et al., 2012a). The northern border of the Siderno Strait was a tectonically-controlled margin during the strait’s formation and infilling, and it was characterized by the presence of an intra-strait tectonic high (Fig. 1B). The 3.5 km-wide constriction laying between this high and the northern margin of the strait generated hydraulic amplification of tidal currents flowing roughly parallel to the margin (i.e., locally dominant flow towards the SE), having great influence on the progradation of deltaic systems laterally impinging into this narrow passageway.

The objective of the present work is thus threefold: 1) to document the sedimentary facies and architectures that develop along a strait margin; 2) to investigate how sedimentation responded to the local morpho-structural constrictions; and 3) to show how tidal circulation significantly impacted the incoming deltaic wedge.

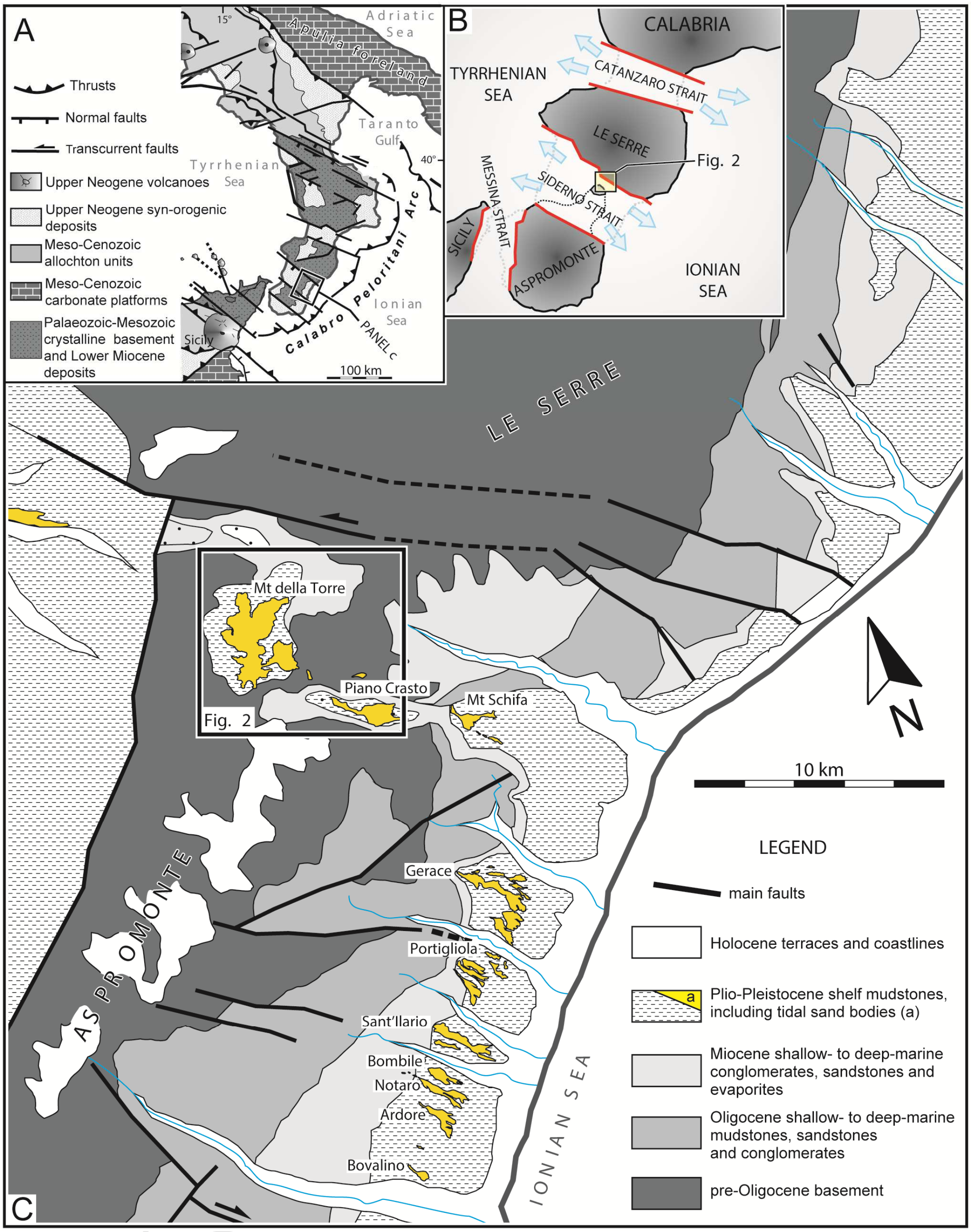

Fig. 1. (A) Regional-scale structural sketch of the Calabro-Peloritani Arc, showing the main Plio-Pleistocene shear zones responsible for the south-eastward tectonic migration towards the Ionian Basin (modified from Tansi et al., 2007). (B) Paleogeographic reconstruction of the Siderno Strait during the Pleistocene, with the studied sector indicated in the rectangle. Note the occurrence of other adjacent tidal straits. (C) Simplified geological map of the central-eastern sector of the Siderno Basin, showing the main tidal sand bodies and the area documented in this work (modified from Cavazza et al., 1997).

2.0 GENERAL GEOLOGICAL SETTING OF THE SIDERNO BASIN

2.1 General Tectonic Setting

The Calabro-Peloritani Arc is a small orogen located in the central Mediterranean (Fig. 1A) consisting of Palaeozoic magmatic and crystalline basement rocks overlain by Meso-Cenozoic sedimentary cover (Amodio-Morelli et al., 1976; Tortorici, 1982; Critelli, 1999). Starting from the late Miocene onwards, the arc migrated towards the Ionian Basin, as the effect of crustal convergence of the northward moving African Plate that was subducting beneath the southward-overriding European Plate (Knott and Turco, 1991; Van Dijk et al., 2000; Tansi et al., 2007 and references therein). The south-eastward structural migration of the Calabro-Peloritani Arc towards the Ionian foreland basin occurred by means of a number of regional-scale strike-slip zones that separated the orogen into segments (Fig. 1A) with different rates of tectonic deformation (e.g., Goes et al., 2004). All of these zones became narrow, elongate marine basins separated by tectonic highs (Sylvester, 1988), which connected the Tyrrhenian to the Ionian Sea, turning into tidal straits during the early Pleistocene (i.e., the Catanzaro and the Messina straits) (Fig. 1B).

The Siderno Basin (Fig. 1C) is a WNW-ESE-elongate, *ca.* 50 km long and 20 km wide, pull-apart basin between the Serre Massif to the north and the Aspromonte Massif to the south, developed during the Neogene-Quaternary within the proximal sector of the Calabrian forearc basin-fill (Van Dijk, 1992; Cavazza et al., 1997; Van Dijk et al., 2000; Cavazza and Ingersoll, 2005). The northern boundary of the basin represents one of the regional shear zones dissecting the Calabro-Peloritani Arc with left strike-slip kinematics (Knott and Turco, 1991), separating Palaeozoic crystalline basement to the north from the sedimentary deposits filling the strait to the south. The southern boundary corresponds to a shear zone with right-lateral slip kinematics, which was probably less active compared to the northern fault (Van Dijk, 1993; Tripodi et al., 2013).

The present-day exposure of the Pliocene-Pleistocene Siderno Strait-fill deposits is markedly unequal between the Tyrrhenian and the Ionian sides of the basin (Fig. 1C), with more abundant and better exposures on the Ionian side. This is due to the effect of a late Pleistocene NW-SE-trending extensional tectonics, related to the recent evolution of the Tyrrhenian Basin (Westaway, 1993; Tortorici et al., 1995; Galli and Peronace, 2015).

2.2 Neogene-to-Quaternary stratigraphy of the Siderno Basin

The Siderno basin-fill is represented by > 2,000-m-thick, Oligocene-to-Quaternary sedimentary succession, unconformably overlying the pre-Cenozoic basement (Patterson et al., 1995; Cavazza et al., 1997; Bonardi et al., 2001) (Fig. 1C).

The study interval lies at the top of a thick succession (> 800 m thick) of shallow-marine to deep-water Oligocene to Pleistocene sediments (Cavazza and DeCelles, 1993; Bonardi et al., 2001;

Cavazza and Ingersoll, 2005). The study succession consists of mixed siliciclastic-bioclastic sediments up to 150 m thick which sharply overlie light-colored shelf marls and fine-grained sandstones (Cavazza et al., 1997). They are characterized by large-scale cross-stratification that is considered to record the onset of strong tidal currents in the Siderno Strait (Colella and D'alessandro, 1988; Cavazza et al., 1997; Longhitano et al., 2012a). The cross-stratified tidal deposits are unconformably overlain by gravels and sands belonging to different generations of marine terraces (Fig. 1C), lying up to 1,000 m above present-day sea level. These terraces record a phase of tectonic uplift that caused the emergence of the Calabro-Peloritani block during the last 700 Ky (Tortorici et al., 1995).

3.0 FACIES AND FACIES ASSOCIATIONS

This work is based on geological mapping (Fig. 2) and collection of detailed sedimentological data, coupled with detailed logging of three stratigraphic sections at key locations (Fig. 3), paleocurrent measurements in cross-bedded sets and outcrop photomosaics for bedding architecture. The studied outcrops are exposed on the Ionian side of the ancient Siderno Strait, between *Mt della Torre* (see also Colella and D'alessandro, 1988) and *Piano Fossati* (Fig. 2).

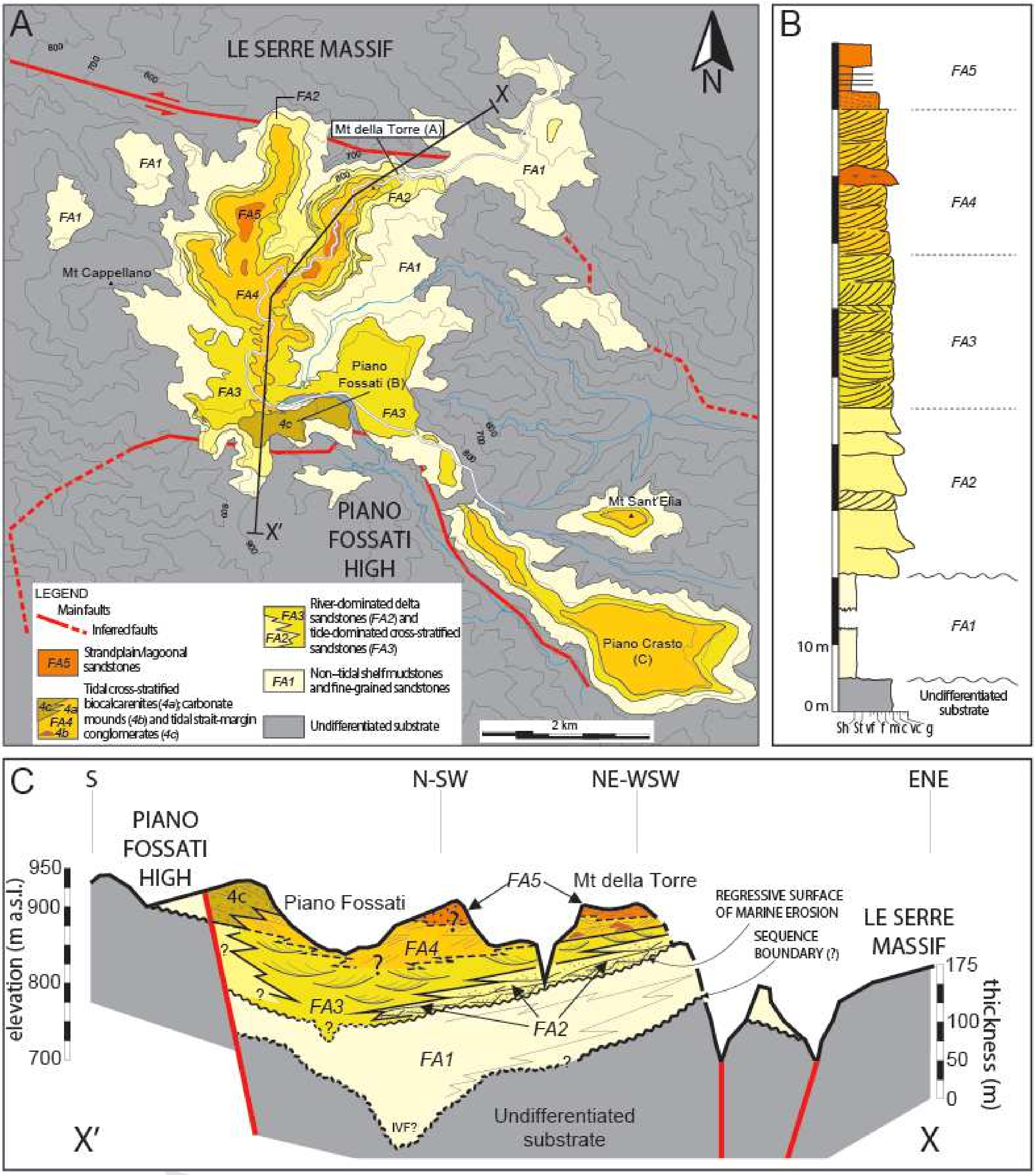

Fig. 2. (A) Detailed geological map of the studied area (see location in Fig. 1C). The present-day exposures of the lower Pleistocene succession form elongate bodies that are oriented either perpendicular or parallel to the WNW-ESE orientation of the strait. Mt della Torre (A), Piano Fossati (B), and Piano Crasto (C) show the location of the sedimentological logs shown in Fig. 3. (B) Composite section showing the vertical relationship between the main facies associations. (C) Cross-section X-X' (see location in A), stretching from Mt della Torre to Piano Fossati High.

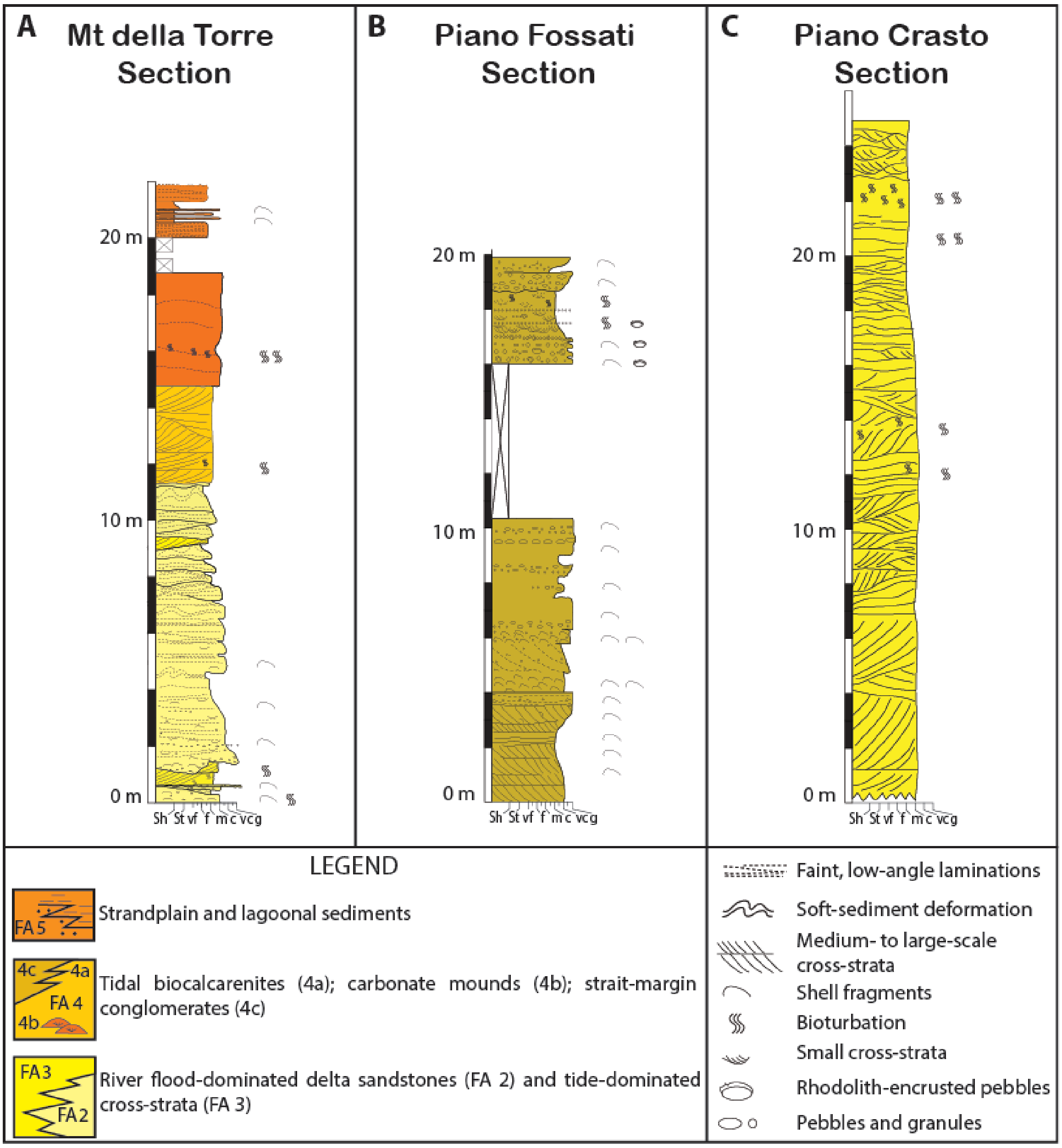

Fig. 3. Stratigraphic logs measured in the studied succession. The location of each log (A, B, and C) is shown in Fig. 2.

The sedimentological analysis has documented 12 sedimentary facies, which have been grouped into 5 facies associations (Table 1).

3.1. Facies association 1 (Shelf mudstones and marlstones)

Description. This facies association (*FA1*) includes the deposits in the lowermost stratigraphic interval of the study area, at the base of the hills and along modern incised valleys (Fig. 2). The deposits consist of a 60-70 m-thick monotonous coarsening-upward succession of light-colored mudstones and marlstones that consist of tabular, structureless beds about 1 m thick (facies *1a*)

(Fig. 4A), with common intercalations of thinner bedded mudstone and fine-grained, structureless and faintly laminated, sandstone towards the top (facies *1b*) (Figs. 4B and 4C). These deposits do not show any sign of tidal influence. The base of the succession lies on the Zanclean Trubi Fm. and older substrates, forming a paraconformity surface (Cavazza et al., 1997), whereas the top of the succession is sharp and in places erosional. *FA1* deposits are commonly associated with *Zoophycos* ichnofacies, and have abundant planktonic Foraminifera dominated by *Sphaerodinellopsis* spp. and *Globorotalia margaritae* (Colella and D'alessandro, 1988).

Interpretation. Sediment textures, paucity of bedding and lamination, and the micro-palaeontological content of *FA1* deposits indicate hemi-pelagic and pelagic suspension fall-out in an open shelf environment. The calcareous nature of these sediments implies a general low rate of siliciclastic input in the basin and/or a distal (shelf) environment. However, the coarsening-upward trend, represented by progressively more abundant sandstone intercalations towards the top, suggests a shallowing trend. The fine-grained deposits of *FA1* appear to infill pre-existent topography, consisting of narrow valleys and interfluves (Fig. 2) that originated during a previous sea-level lowstand, which was responsible for the formation of the regional-scale unconformity documented at the base of these deposits (Cavazza et al., 1997).

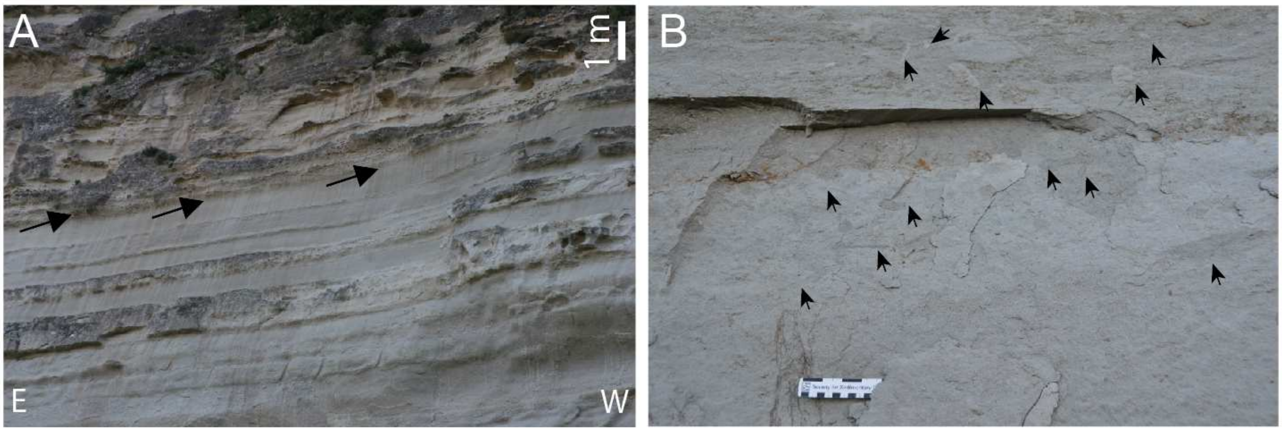

Fig. 4. (A) Shelf mudstones and marlstones belonging to *FA1*; note the tabular bedding and overall structureless nature of *FA1* deposits. Arrows point to the surface separating *FA1* from the overlying *FA2-FA3* tidal cross-stratified sandstones. (B) Detail of *FA1*, showing the structureless and bioturbated (B.I. 5) nature of the deposits (black arrows point at bioturbations).

3.2 Facies Association 2 (River-dominated, tide-influenced proximal deltaic deposits)

Description. The deposits of *FA2* comprise two facies: *2a* and *2b* (Table 1).

Facies *2a* consists of coarse- to medium-grained sandstones with subordinate conglomerates, organized into lenticular bodies, ranging in thickness from 0.4 m to 5-6 m (Fig. 5A). The base of each body commonly scours deeply (up to a few meters) into the underlying deposits. Towards the top of this succession, body-bounding surfaces display undulate geometries with a wavelength of several meters (*ca.* 5-6 m; Fig. 5B). Granules and small pebbles, composed of sub-angular lithic fragments, mud chips and shell fragments, commonly mark the basal erosional surfaces. The individual bodies show a subtle fining-upward trend, from conglomerate or very coarse/coarse-grained sandstones, to coarse- and medium-grained sandstones (Fig. 5A). Sandstones consist of moderately to poorly sorted siliciclastic grains (rich in mica), commonly containing abundant shell and bioclastic fragments (10-20%) concentrated at the base of beds. The shell fragments are usually sub-horizontal, and not in a hydrodynamically stable position, although near the base of the beds they can be convex upwards and slightly imbricated (in small pockets). The bodies are largely structureless, but indistinct plane-parallel and faint low-angle laminations associated with gently undulating laminations occur. Soft-sediment deformation structures (SSDS) are usually present in the uppermost part of each bed (Fig. 5A) as contorted bedding.

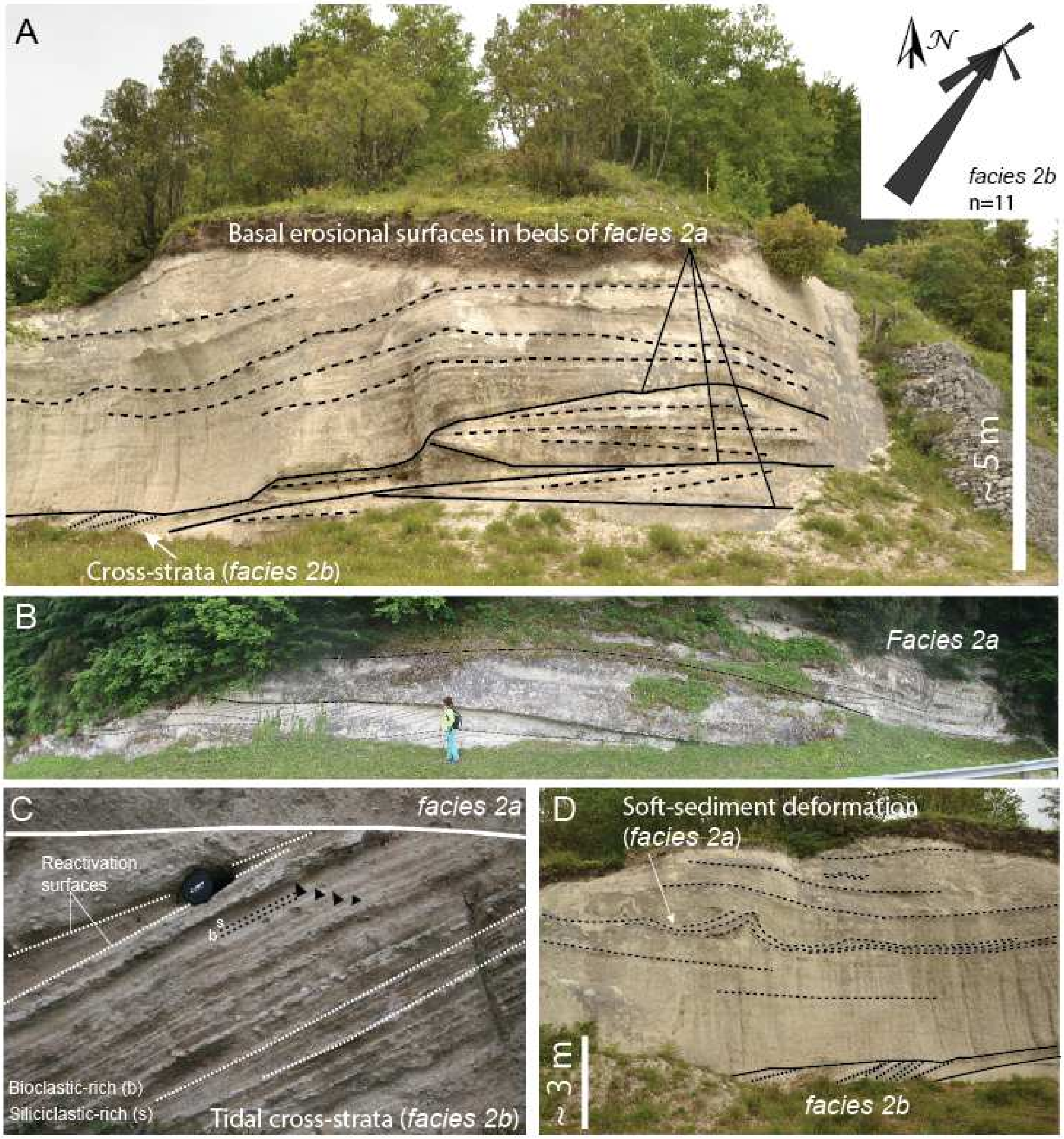

Fig. 5. Overview of *FA2* deposits at Mt della Torre. (A) Typical erosional surfaces of *facies 2a*; note how *facies 2b* is eroded by *facies 2a*. The rose diagram shows paleocurrent measurements obtained from the cross-strata of *facies 2b*. (B) Undulate erosional surfaces. (C) Tidal foreset lamination within *Facies 2b*, erosionally overlain by the deposits of *facies 2a*. The triangles show packages of bioclastic and siliciclastic laminae. (D) Soft sediment deformation in *facies 2a*; outcrop cliff is the same as shown in A.

Facies 2b occurs as localized intercalations within *facies 2a*. It is characterized by a lenticular geometry, commonly infilling pre-existing scours, and is erosionally bounded at the top (Fig. 5C). *Facies 2b* is cross-stratified, forming sigmoidal, angular and tangential foresets up to 2 m thick (Fig. 5C). These sediments are composed of upper medium-lower coarse and lower medium-upper fine sandstones with sparse sub-angular pebbles, granules and shell fragments. The cross-strata typically display segregation of bioclastic-siliciclastic laminae and set-climber ripples (ripples climbing up the foresets), cyclic alternation of angular and tangential toesets, and reactivation surfaces. The overlying deposits belonging to *facies 2a* truncate the upper part of the foresets (Fig. 5C). SSDS are absent in *facies 2b*. In places, *facies 2b* is intensely bioturbated, displaying abundant poorly preserved meniscate *Scolicia* traces (Fig. 5D). Paleocurrent measurements of f*acies 2b* cross-strata indicate a dominant direction towards the SW (Fig. 5A).

Interpretation. *FA2* deposits are interpreted to represent fluvially-derived sediments entering a shallow-marine area in a proximal deltaic setting, based on the sediment texture, sorting, occurrence of shell fragments, bed geometries and sedimentary structures.

Facies 2a deposits are interpreted as the result of river flood-generated hyperpycnal flows (Mutti et al., 1996; Mutti et al., 2000; Mutti et al., 2003). Sedimentation may have occurred through an initial phase of scouring of the underlying deposits which is usually characteristic of high-energy river floods (Nemec and Muszynski, 1982; Sohn et al., 1999), as occurs nowadays along the Messina Strait margin (Casalbore et al., 2011). The coarse-grained, poorly sorted and mainly structureless lower portion of *facies 2a* strata would represent the basal hyperconcentrated flow produced when sediment-laden flows entered seawater during a river-flood event (Mutti et al., 1996; Mutti et al., 2000). Bed scouring, with associated rip-ups and shell debris, is very common in this type of flow (Mutti et al., 2000; Rossi and Craig, 2016). The presence of shells not in hydrodynamically stable position further supports the lack of traction currents, but rather the presence of very high depositional rates or high sediment concentrations. The mostly structureless nature of *FA2* beds also supports the inference of high deposition rates. The finer-grained and finely laminated upper part of each body can represent the waning stage of the river-flood event or a decrease in sediment concentration (i.e., more dilute turbulent flows; Mutti et al., 2000). Alternatively, the laminations within each bed can be interpreted as internal scour surfaces or as antidunes (Southard and Boguchwal, 1990; Ito, 2010), related to the passage and deposition of sediment surges. The SSDSs may have been caused by allogenic triggers (e.g., earthquakes) linked to the fault activity along the basin margins, or autogenic triggers related to rapid deposition and/or high sediment concentrations.

Facies 2b cross-strata have been deposited or reworked under the influence of currents, possibly tidal in origin, based on the alternations of siliciclastic and bioclastic laminae (Longhitano, 2011), reactivation surfaces, cyclic alternation of angular and tangential toeset geometry and set-climber ripples (e.g., Longhitano, 2011; Chiarella, 2016). We argue that f*acies 2b* cross-strata were formed in interflood periods, when tidal currents had enough time to rework the sediments emplaced during the previous river-flood event. The lack of SSDSs in *facies 2b* suggests that deposition of *facies 2a* occurred when the sediments were already dewatered (Chiarella et al., 2016). *Facies 2b* cross-strata are only sporadically preserved and truncated by *facies 2a* deposits, suggesting that each high-energy flood event was able to remove tidally-reworked interflood deposits in the most proximal areas.

In summary, *FA2* sediments suggest accumulation in a river-flood-dominated, tide-influenced proximal deltaic setting, that most likely is inter-gradational between a river-delta system and a fan-delta system (cf. Mutti et al., 1996; Mutti et al., 2000), characterized by high-energy scouring and deposition associated with river-flood generated hyperpycnal flows. Tidal currents were present in the marine strait, but were only able to rework the fluvially-derived sediments during interflood periods. The preservation potential of tidally-reworked sediments in this proximal deltaic setting is fairly low, due to the high degree of erosion occurring during river-flood events.

3.1.3 Facies Association 3 (Tide-dominated delta-front and passageway axis)

Description. FA3 is volumetrically the most important part of the study succession, comprising up to *ca.* 70 m of moderately- to well-sorted medium- to coarse-grained siliciclastic sandstones, with biocalcarenitic intervals (Figs. 6 and 7). *FA3* forms vertically-stacked packages (up to 24 m thick) separated by wide and undulatory major erosion surfaces (Fig. 6). Each package is characterized by stacked cross-strata. Cross-stratal sets have tabular to lenticular geometries and range in thickness from 1 to 6 m. Both trough (facies *3a*) and planar-tabular (facies *3b*) cross-strata are present, with paleocurrent directions ranging from 45°N to 100° N. However, moving from Mt della Torre (in the northwest) to Piano Crasto (in the southeast, i.e., down-flow; Fig. 2), cross-strata geometries change from mainly 3D to 2D. Foresets exhibit reactivation surfaces, thinning-thickening foreset bundles, alternation of angular and tangential toesets, and segregated (siliciclastic-bioclastic) laminae (Fig. 7). Trace fossils are meniscate forms both parallel to and cross-cutting the foresets, whereas the biocalcarenitic intercalations are dominated by bivalves, bryozoans and less abundant barnacles, small brachiopods and corals.

In cliff exposures, *FA3* cross-strata appear to alternate and interfinger with *FA2* deposits, and *FA3* packages become thicker and more abundant towards the top (Fig. 7D).

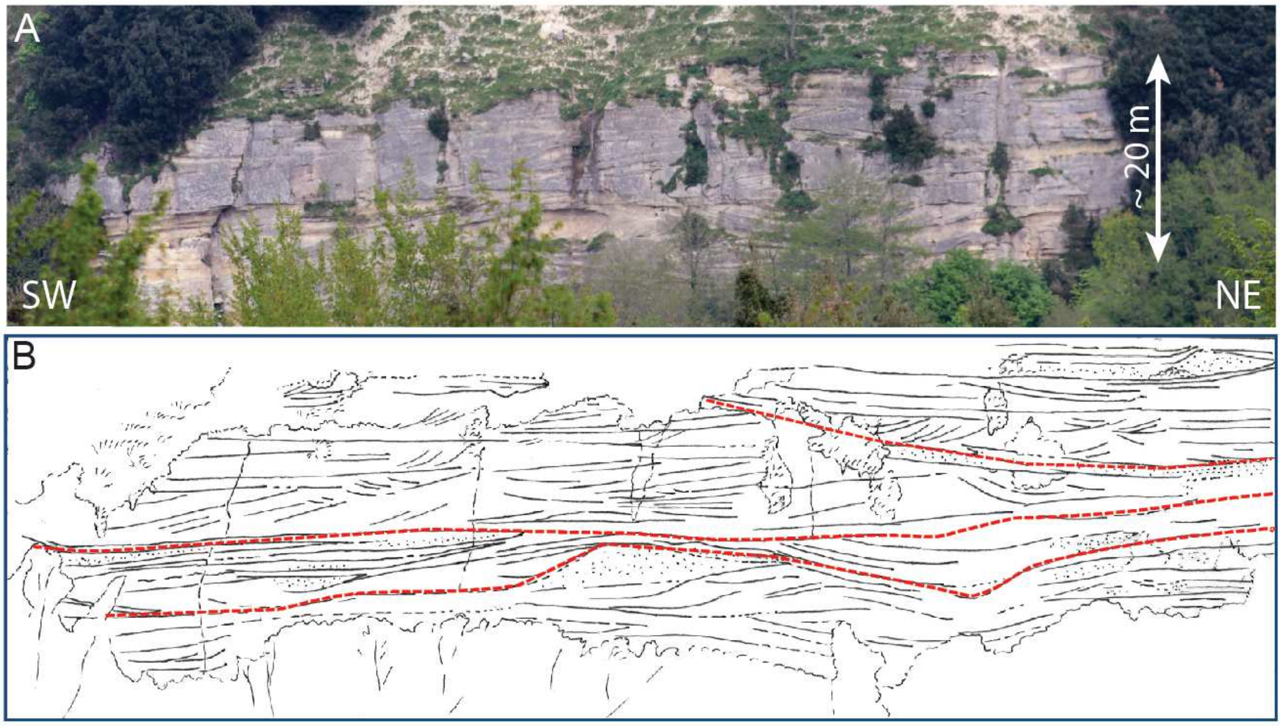

Fig. 6. Outcrop photographs of *FA3*. (A) Piano Fossati section showing large-scale cross-stratification with abundant three-dimensional cross-strata. (B) Line-drawing of the photograph in A. Red surfaces represent major erosion surfaces. Note cross-cutting sets and the dominant foreset dip towards the left (E-SE).

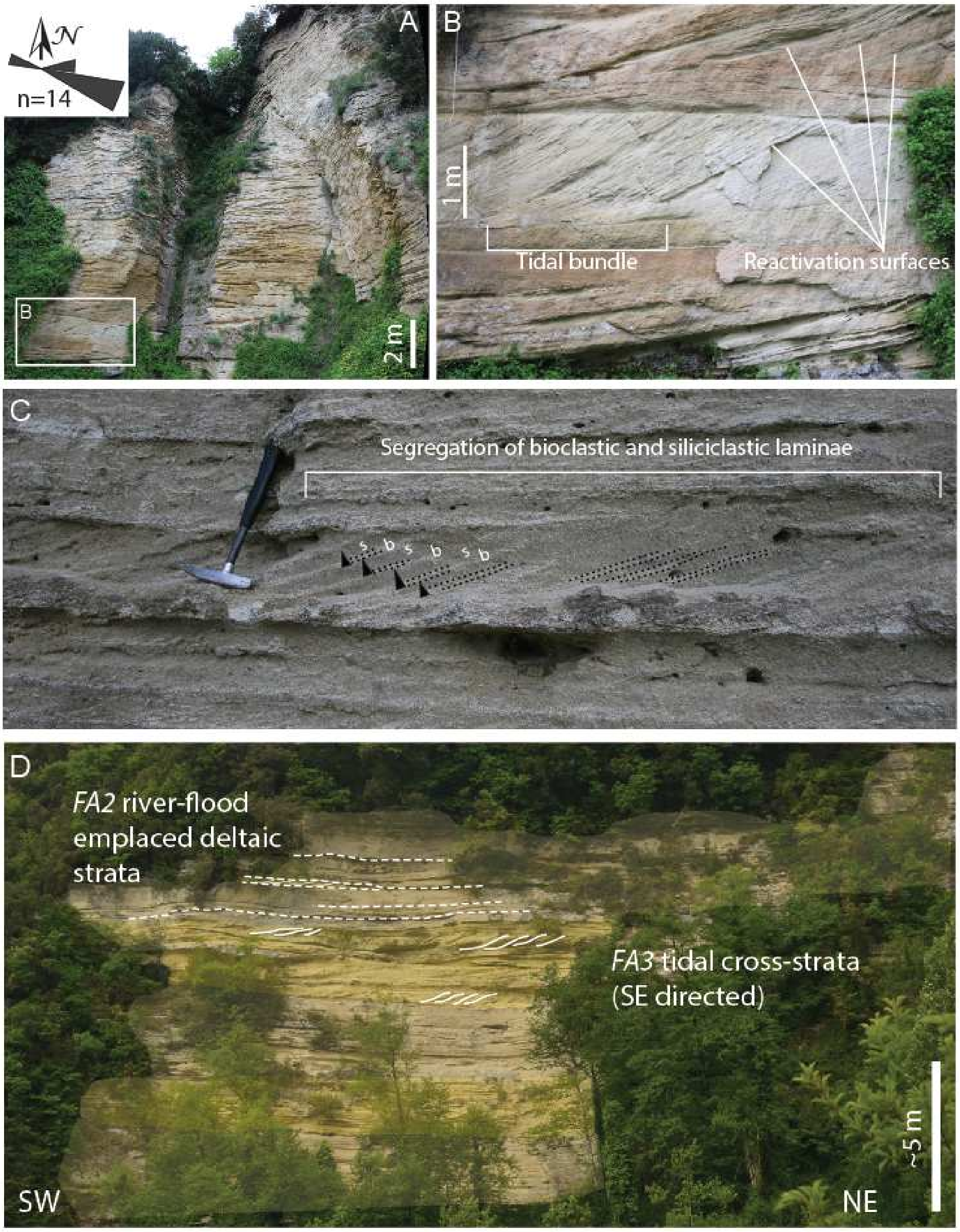

Fig. 7. Outcrop photographs of *FA3*. (A) Piano Crasto section, which lies down-current from the section shown in Fig. 6 (see Fig. 2), shows dominant two-dimensional cross-strata; inset shows paleocurrent measurements. (B) Details of the photo in panel A showing internal features of the tidal cross strata. (C) Cross-strata of *FA3* showing a marked segregation between biocalstic (b) and siliciclastic (s) laminae. Hammer for scale is 32.5 cm long. (D) Cliff exposure in Mt della Torre area, showing the interfingering and alternation between *FA2* and *FA3*.

Interpretation. The *FA3* cross-stratified sandstone succession is interpreted as a series of superimposed dune fields, derived from tidal reworking of distal delta-front deposits and delta-fed sediments within the passageway axis. *FA3* cross-strata are interpreted as generated by tractional tidal currents flowing within the strait at a high angle with respect to the main deltaic progradational axis (see also Longhitano and Steel, 2016). Tidal structures lack distinct mud drapes and the set-climbing ripples that characterize some estuarine environments (e.g., the Eastern Scheldt; Martinius and Van den Berg, 2011), as the system is mud-poor and the sand is overall coarser grained; they show more similarities with the deposits present in the Miocene of southern France (James et al., 2014). Additionally, because of the narrowness of the Mt della Torre passageway, we believe that the tidal currents were rectilinear rather than rotary.

This reconstruction suggests that the distal delta front was exposed to the action of the tidal currents that were flowing within the passageway. This interplay is recorded in the greater abundance of tidal cross-strata (*FA3*) relative to river-dominated facies (*FA2*). Strong tidal currents in this part of the basin were responsible for the deflection of the delta front progressively in the direction of the locally dominant tidal current, roughly parallel to the local margin of the strait. Deflected delta-front deposits are thought to be characterized by a gradual upward swing of paleocurrents, from perpendicular to roughly parallel to the coastline (Longhitano and Steel, 2016). Even though the present study is lacking a complete paleocurrent dataset due to discontinuous outcrop exposures, other evidence supports this interpretation: the direction of outbuilding of the delta in relation to the source area (1); paleocurrent data collected on *FA3* cross-strata, documenting highly oblique (in relation to the delta) direction of the tidal strait currents (towards the ESE).

Within the passageway, tidal current strength probably decreased down-current (i.e., from Mt della Torre to Piano Crasto), due to the progressive enlargement of the passageway cross-section, generating a downcurrent transition from three- to two-dimensional tidal dunes, as observed in other modern and ancient tidal straits (e.g., Chiarella et al., 2012; Longhitano, 2013; Longhitano et al., 2014).

The major erosion surfaces within the basal part of this association a slightly inclined in the main sediment transport direction, indicating a low-angle downcurrent-dipping slope, a geometry that also contributes to the flow expansion that generated the down-current decrease in tidal-current speeds. The thickness of these strata is also probably the result of a certain confinement exerted by the previous topography and the presence of the Piano Fossati tectonic high (Fig. 2).

Colella and D'alessandro (1988) interpreted these sediments as having accumulated in a bathyal setting. Their interpretation is not necessarily in disagreement with the one presented in this paper. Bathyal depths can be as shallow as 150-200 m, and it can be possible (given the active tectonic setting) that the slope onto which the delta was building was steeper than normal shelf gradients, allowing for tidal current reworking in deeper waters. In the modern Messina Strait, tidal currents are sufficiently strong to be able to rework sediment into large dune fields at bathyal depths. Additionally, it is possible that tidal currents accelerating over the strait sill transported deeper-water organisms into shallower water. Furthermore, Colella and D'alessandro (1988) interpretation is in part based on the absence of wave-related sedimentary structures. This absence, however, does not necessarily means bathyal depths, but rather that the sediments were deposited below wave base and/or that tidal and fluvial currents have not allowed the preservation of wave-related structures. In this particular setting, the strait margin was not fully exposed to open sea and wave base could have been relatively shallow.

3.4 Facies Association 4 (Strait-margin complex)

Description. FA4 includes three main facies *4a*, *4b* and *4c*.

At Mt della Torre, *facies 4a* forms a *ca.* 30 m-thick succession of coarse-grained biocalcarenitic sandstones, composed of fragments of bivalves, bryozoans, echinoids and corals mixed with a variable amount (10-30%) of quartz-rich siliciclastic material. The biocalcarenites sharply overly the deltaic siliciclastic deposits, recording an abrupt enrichment in the carbonate content of the deposits (Fig. 8A). *FA4* deposits are cross-stratified, forming individual sets of trough (3D) and planar-tabular (2D) cross-strata up to 2 m thick (Fig. 8B). Paleocurrents suggest a general direction towards 125°N, although the dataset is limited due to poor outcrop accessibility.

Facies 4b represents isolated carbonate mounds, 10 m-wide and *ca.* 3-4 m thick (Fig. 8C). Mounds include clusters of large *Megabalanus tulipiformis* (Colella and D'alessandro, 1988), associated with abundant barnacles, bryozoans and brachiopods. However, solitary cm-size corals represent the recurrent species. In places, the mounds show intense bioturbation, especially close to their base.

At Piano Fossati, the correlative deposits are represented by *facies 4c* (Figs. 8D and 8E), consisting of conglomerates and mixed siliciclastic-bioclastic sandstones, organized into three vertically-stacked, coarsening-upward lenticular units, with a thickness ranging from 5 to 10 m. These coarsening-upward units exhibit several scour surfaces and extensive, low-angle accretionary surfaces that pass into distal fine-grained deposits towards the southeast (parallel to the passageway axis). Discoidal, sub-angular to well-rounded conglomerate clasts of *facies 4c* are up to 10 cm in diameter, derived from granitoid basement rocks and are commonly encrusted by algal rhodoliths. Some layers are rich in serpulids, bivalves, and rhodoliths (Fig. 8E). Most of the strata are normally or inversely graded, contain abundant shells and barnacles, and a medium-grained arenite matrix enriched in echinoids, bivalves and bryozoans. Cross-stratification occurs in places, forming 9 to 20 cm thick sets. Bioturbation is sparse, but can be quite pervasive (B.I. 4) in certain intervals where only ghosts of cross-strata are preserved.

Interpretation. The biocalcarenites of *FA4* (*facies 4a*) are characterized by two- and three-dimensional cross-strata very similar to those observed in the *FA3*, and similar cross-stratified biocalcarenites pervasively occur in a number of other stratigraphic sections in the Siderno Strait.

They are also present in other correlative basins of southern Italy, and they have been interpreted in previous studies as tidal cross-strata produced by the superimposition of trains of migrating tidal dunes (Longhitano et al., 2012a). The presence in *facies 4a* of cross-strata (rich in bioclasts) oriented parallel to the strait margin seems to indicate that tidal currents (flowing axially to the passageway between Mt della Torre and Piano Fossati) controlled the deposition of *FA4* biocalcarenites as well.

Within *facies 4a*, carbonate mounds (*facies 4b*) occur. The presence in the carbonate mounds of solitary corals of small dimensions can indicate a relatively deep environment (James and Lukasik, 2010) which in this case can be related to a rapid rise of relative sea level (Colella and D'alessandro, 1988). Another possibility is that the small size of the corals is not related to water depth, but rather to a temperature limitation (James and Lukasik, 2010). These deposits merged laterally and across the outcrop localities into the coarse-grained deposits of facies *4c*, that are interpreted as beach sediments reworked by currents and storms in an upper shoreface setting along the flank of the Piano Fossati tectonic high.

Compared to *FA2* and *FA3*, the abrupt enrichment in bioclasts and the occurrence of localized carbonate mounds in *FA4* point towards a reduction of siliciclastic (deltaic) input in the basin and relative sediment starvation, which in turn allowed favorable conditions for the development of faunal communities. Siliciclastic starvation in the basin could have occurred for two main reasons: 1) climatic change and reduction in water and sediment supply to the basin (i.e. deactivation of fluvial systems); and/or 2) relative sea-level rise and consequent deepening of the Siderno Strait, and back-stepping of the fluvio-deltaic systems.

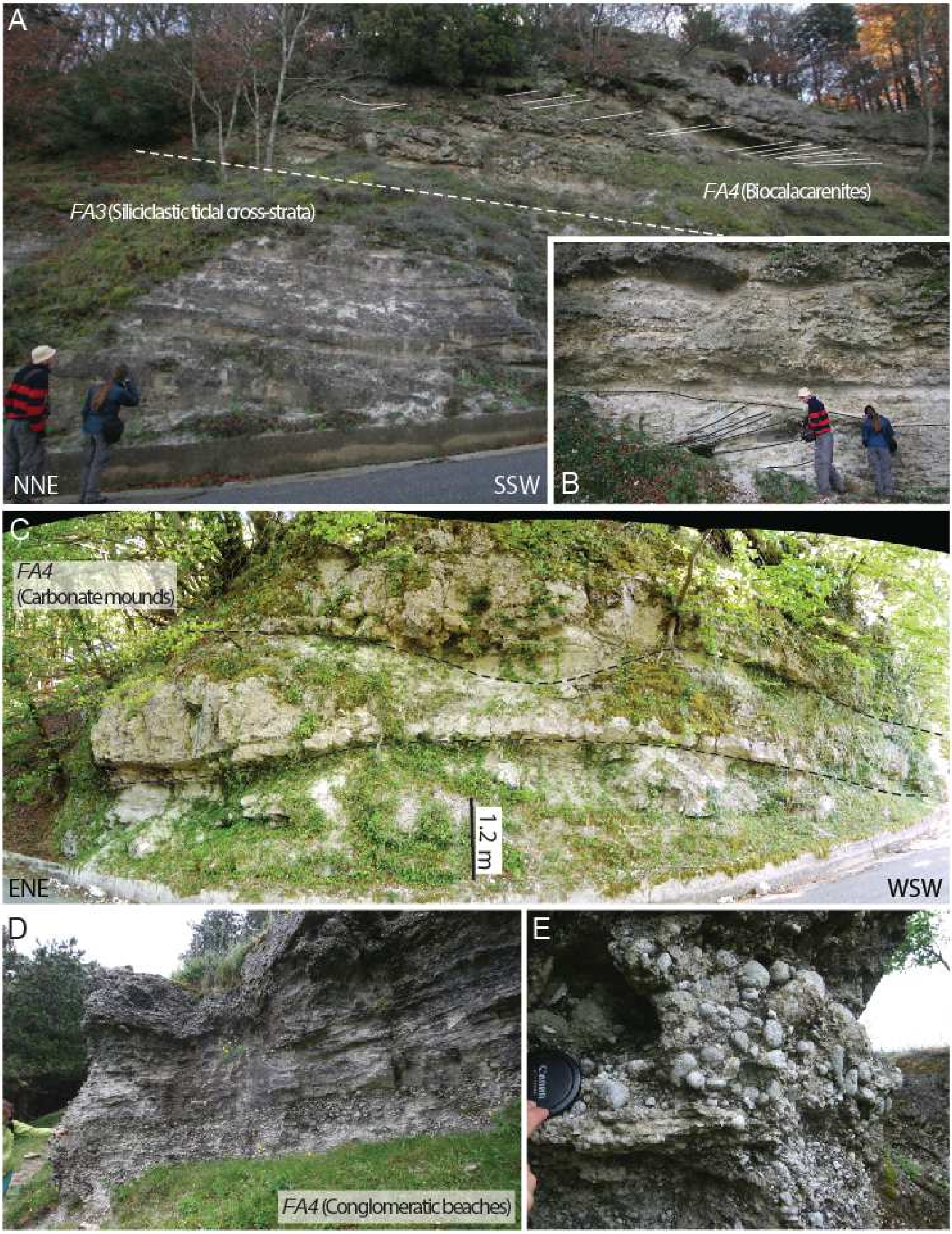

Fig. 8. Outcrops of *FA4*. (A) Vertical transition at the Monte della Torre section between *FA3* and *FA4* (dotted line). (B) Detail of cross-stratified biocalcarenites of *facies 4a*. (C) Carbonate mounds of *facies 4b*. (D) Conglomerates and sandstones of *facies 4c* at Piano Fossati. (E) Detail of panel D, showing the rounded pebbles of *facies 4c*, some of which are encrusted by algal rhodoliths. Lens cap is 8 cm.

3.5 Facies Association 5 (Strandplain and lagoon complex)

Description. The deposits of *FA5* represent the uppermost stratigraphic interval of the investigated succession (Barrier et al., 1993). They have been subdivided into three facies: *5a*, *5b* and *5c*.

Facies *5a* consists of light colored upper-fine to lower-medium-grained sandstones (Fig. 9A), that are well sorted, with sub-rounded grains and containing few bioclasts. These deposits are characterized by low-angle laminae and normally-graded beds. The bed thickness is of the order of a few centimeters.

Facies 5b overlies *facies 5a* and forms an alternation of mudstones and coarse sandstone beds, including bioclastic-rich beds, 1 to 10 cm thick (Fig. 9B). The bioclastic intervals mostly contain bivalve and gastropod fragments, ranging from shell hash, to larger fragments (Fig. 9C).

Facies *5c* has been recognized at the very top of the succession, and consists of 5-6 m-thick, lower medium-grained, very well sorted sandstones with ghosts of low-angle laminations (Fig. 9D), forming an elongate sand body stretching perpendicularly (north-south oriented) with respect to the passageway (see Fig. 2).

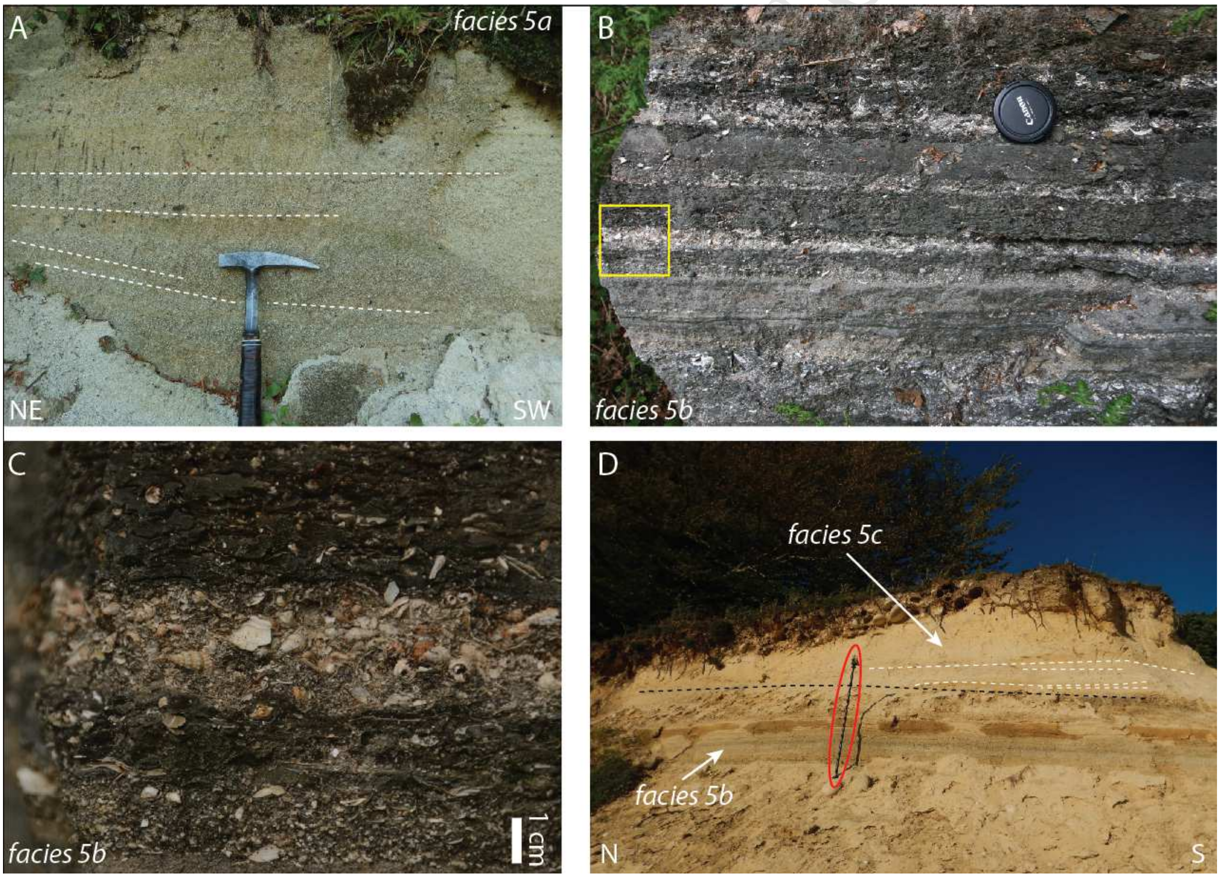

Fig. 9. Deposits belonging to *FA5*. (A) Low-angle laminated foreshore sandstones (*facies 5a*). (B) Alternation of mudstones and bioclastic sandstones interpreted as lagoonal deposits of *facies 5b* (yellow rectangle indicates the detail in panel C). Lens cap is 8 cm. (C) Bioclastic-rich interval encased in muddy sediments (*facies 5b*). For location, see rectangle in (B). (D) Laminated, fine-grained sandstones of *facies 5c* interpreted as aeolian deposits overlying *facies 5b* (Jacob staff in the red ellipse for scale is 1.1 m tall).

Interpretation. FA5 is interpreted as a shoreface–strandplain system (*facies 5a*), including a lagoonal environment (*facies 5b*) (cf. Boothroyd et al., 1985; Ashley and Grizzle, 1988; Nichols, 1989). Barrier et al. (1993) interpreted these sediments as being deposited in a restricted (lagoonal) environment based on the abundance of *Gobius* sp., a genus of fish in the family Gobiidae native to fresh, brackish and marine waters (Nelson, 2006). The shoreface–strandplain system may have been the barrier bar inherited from the preceding transgression (that occurred during deposition of *FA 4*), but became now a regressive shoreface or strandplain (possibly marking the turn-around from transgression to regression at the beginning of the relative sea-level highstand). The coarse-grained sandstone layers and bioclastic-rich layers could represent sediments reworked by waves/storms. *Facies 5c* could possibly represent small aeolian dunes (backshore environment), which could be part of a spit or a tombolo. The deposits of *FA5* are significantly shallower and more proximal than the underlying deposits belonging to *FA4*, indicating an overall shallowing trend. The change from tidal facies (*FA3* and *FA4*) to the wave-influenced facies (*FA5*) can be related to an overall change in the water circulation of the basin (as suggested by Barrier et al., 1993), or it could represent the change from tide-dominated sedimentation in deeper water to wave-dominate sedimentation along the shoreline as presently seen in the English Channel.

4.0 DISCUSSION: MARGINAL-MARINE SEDIMENTATION ALONG THE SIDERNO STRAIT NORTHERN MARGIN

The sedimentary succession exposed along the northern margin of the Siderno Strait shows a regressive-transgressive-regressive, vertical facies trend, from shelf mudstones, to deltaic and passageway-axis tide-influenced cross-bedded sandstones, to tidal cross-bedded biocalcarenites, up to regressive paralic non-tidal sandstones (Fig. 2). This trend has been interpreted as the result of sedimentation across a strait-margin zone during a complete cycle of relative base level fluctuation. The northern margin of the Siderno Strait was characterized by a highly irregular morphology, due to the emplacement of an isolated tectonic high (i.e. *Piano Fossati*), which further narrowed the strait to form a *ca.* 3.5 km-wide local passageway. This narrowing induced a strong amplification of tidal currents, because it created the optimal conditions of water depth and local morphology (e.g., cross-sectional area) for peak tidal current strength (Anastas et al., 2006; Longhitano et al., 2014), creating a (tidal) current-dominated passageway. The findings presented in this work can therefore be applied to any strait or seaway that develops strong tidal currents. The deposits of the northern margin of the Siderno Strait show that tidal currents dominated sediment transport throughout the regressive and transgressive (LST and TST) part of the relative sea-level cycle; this means that during both lowstand and transgressive system tracts the cross-sectional area of the passageway was optimal for amplification of tidal currents, and only during HST conditions was the passageway too wide (*FA 1*) or too shallow (*FA 5*) to allow currents to be amplified (see also Anastas et al., 2006).

4.1 Deltaic *vs*. tidal strait processes

The sedimentary deposits documented in the present study are interpreted as depositional environments belonging to an ancient delta impinging onto a narrow tidal passageway. As observed in cliff exposures (Fig.7D), *FA2* and *FA3* alternate, pointing towards an interplay between fluvial and tidal processes (Fig. 10).

4.1.1
River-flood deposits in straits

The fluvial system feeding the documented delta was most likely draining the tectonically active Serre Massif (Fig. 2), providing the siliciclastic source for the gravel- and sand-size material shed into the strait. Within *FA2*, cross-strata produced by tidal current reworking (*facies 2b*) are preserved in places (Fig. 10). The uncommon occurrence of tidal cross-beds within fluvially-emplaced sediments in *FA2* indicates that fluvial processes were dominant over marine (tidal) reworking in more proximal areas close to the river mouth and during river floods. Tidal reworking occurred during interflood periods (see also Dalrymple et al., 2015; Gugliotta et al., 2016); the uncommon occurrence of *facies 2b* can therefore be related also to the erosion of tidally-reworked sediments occurring during subsequent river floods. On the other hand, *FA3* is characterized by a predominance of medium- to large-scale tidal cross-strata, which are well developed in Mt della Torre and Piano Fossati areas, as well as further downcurrent in the Piano Crasto area (see Figs. 2 and 3). *FA3* is interpreted as the product of a strong tidal reworking of sediments by tidal currents, flowing axially within the strait (i.e., south-eastward-directed dominant flow). Therefore, based on facies characteristics and on the lateral and vertical relationships between facies associations, we argue that fluvially-derived sediments were feeding a deltaic system that built transversely out from the northern margin of the Siderno Strait, and that this delta entered a narrow and confined setting caused by the presence of the Piano Fossati structural high (Fig. 10). *FA2* river-emplaced deposits point towards a river system characterized by catastrophic floods that delivered large amounts of sediment in a short period of time, similar to what occurs in the modern Messina Strait (Casalbore et al., 2011). The alternation between river-dominated and tidally-reworked sediments is arguably present in all straits where there is a lateral river input (e.g., Longhitano and Steel, 2016; Olariu et al., 2012). However, it will be particularly prominent in systems where the fluvial discharge is strongly seasonal and/or flashy, because the interflood periods would allow the tidal currents to rework more river-derived sediments (see also Dalrymple et al., 2015). In this sense, straits formed by active faults, like the ones developed in southern Italy (Longhitano et al., 2012a), would be more prone to develop fluvial systems with small, steep catchments and shelves that were narrow or absent, as opposed to straits not developed in an active tectonic setting (e.g., the Malacca Strait between Sumatra and the Malay peninsula or the Torres Strait in northern Australia; Keller and Richards, 1967; Harris, 1988).

4.1.2 Intensity of tidal current reworking

Tidal currents in straits tend to be stronger in the axial part of the passageway and weaker along the margins, due to frictional dissipation (Frey and Dashtgard, 2011; Longhitano, 2013). This energy variation may have favored a better preservation of fluvially-derived sediments (i.e., *FA2*) in the proximal delta-front environment, and widespread accumulation of tide-influenced facies (i.e., *FA3*) in the distal delta front and passageway axis. River currents would have been stronger in the proximal areas (allowing poor preservation of tidal facies), and weaker towards the passageway axis, a trend accentuating the facies differentiation generated by the spatial variation in tidal current strength.

The hydrodynamics of the tidal flow in narrow straits or passageways can exert a considerable influence in shaping sand accumulations at the bottom, forming elongate bodies oriented roughly parallel to the dominant tidal flows, as well as to the strait margins. This phenomenon has been observed in a number of modern and ancient river deltas impinging tidal straits, where delta-front sands transported at essentially right angles relative to the main deltaic progradational direction are asymmetrically distributed for considerable distances along the coast, even eventually producing detached sand banks or isolated tidal dune fields (e.g., Longhitano and Steel, 2016). This process of delta-front deflection is thought to be recorded in the study area as the cartographic distribution of *FA3* deposits in a downcurrent direction (from Mt della Torre area to Piano Crasto area) (Fig. 2).

Tidal reworking of sediments is well-documented from transgressive shallow-marine shelf settings (e.g., Trentesaux et al., 1999; Tinterri, 2007; Olariu et al., 2012b; Reynaud and Dalrymple, 2012; Leva López et al., 2016; Michaud and Dalrymple, 2016). Among these examples, the Roda Formation (Tremp-Graus Basin) and the Baronia Formation (Ager Basin) show some remarkable similarities with the study succession, as they were deposited in an elongated marine corridor in a tectonically active basin, where tidal currents were amplified and deltaic systems were present along the basin margins. According to Olariu et al. (2012b) and Michaud and Dalrymple (2016), in the Roda Formation tidal currents were able to rework delta-fed sediments only during transgressive phases, and only in deltaic parasequences that significantly protruded into the basin

(Michaud and Dalrymple, 2016). Olariu et al. (2012a) show that in the Ager Basin compound dunes of the Baronia Formation were migrating axially along the strait, parallel to the strait margin; these authors also suggest that the source of siliciclastic material could have been derived, at least partially, by lateral fluvial systems.

In our example tidal currents were amplified and further enhanced along the northern margin of the Siderno Strait, producing peak tidal current conditions during both regressive and transgressive phases. Therefore, tidal currents were able to rework delta-fed sediments even during deltaic progradation.

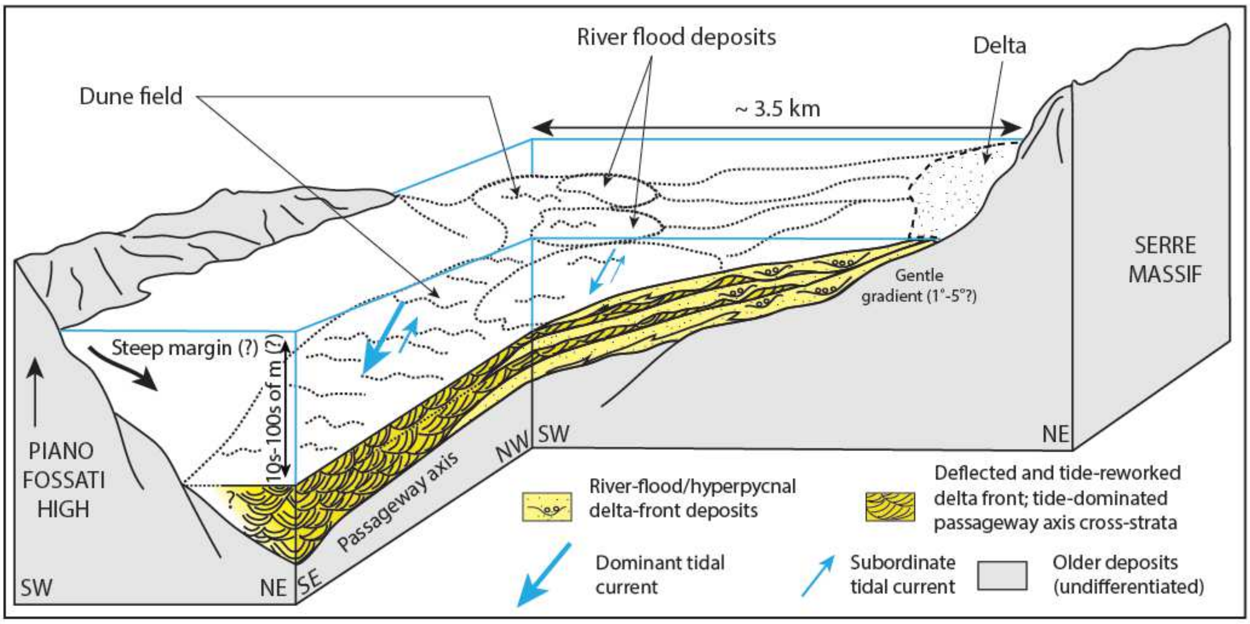

Fig. 10. Conceptual depositional model showing the relationships between river-dominated deltaic deposits and tidal cross-strata interpreted in the present work.

4.2 The Pliocene-Pleistocene Siderno strait-margin evolution

The non-tidal shelfal mudstones (*FA1*) occurring at the base of the studied succession represent a widespread stratigraphic unit in the Siderno Basin (Fig. 11A). They form aggrading tabular strata made up of mudstones, marlstones and fine sandstones containing open-marine micro-fauna. The overlying deltaic tidally-influenced cross-bedded sandstones (*FA2-FA3*) lie erosionally on top of the shelf mudstones (Figs. 2 and 3). The contact between them can be interpreted as a regressive surface of marine erosion (Plint, 1988; Helland-Hansen and Martinsen, 1996; Zecchin et al., 2015). This surface, which is a conformity surface in the southern correlative successions, presumably originated during a virtually continuous phase of relative sea-level lowering induced by the activation of the structurally-controlled northern margin of the Siderno Strait, and further scoured by strong tidal currents. From this stage onwards, the Siderno Basin records the action of tidal currents, turning from a non-tidal shelf passageway into a tidal strait (Fig. 11B) (Longhitano et al., 2012a). This change was probably related to either (1) the creation of an optimal cross-sectional area (see Anastas et al., 2006; Longhitano et al., 2014) that allowed the amplification of tidal currents, or (2) tectonic movements that opened (for the first time) the connection between the Tyrrhenian and Ionian seas. Additionally, at this time, the deposits record the first input of coarse siliciclastic material into the strait, which can possibly be related to the aforementioned tectonic movements.

During deposition of *FA4*, the marginal passageway of the northern Siderno Strait was still affected by strong tidal currents (Fig. 11C). As the siliciclastic input in the basin progressively decreased, due to either climatic change or relative sea-level rise, local carbonate mounds developed (*FA4*, *facies 4b*), enriching the tidal-reworked sands with abundant bioclastic hash.

As the rate of relative sea level rise slowed or stabilized, sediments along the strait margin in Mt della Torre area accumulated in a shallower environment, characterized by shoreface and lagoonal setting (*FA5*). The absence of any tidal signature in the deposits of *FA5* suggests that: (1) at this time there was little or no tidal circulation maintained in this sector of the basin (due to tectonic uplift and closure of the connection between the Ionian and Tyrrhenian seas; Barrier et al., 1993), or (2) that *FA5* deposits record wave-dominated conditions on the shallow strait margin, whereas the deeper part of the passageway was still tide-dominated (as occurs nowadays in the English Channel). At the last stage of deposition, before the tectonic event that rapidly uplifted the area, *FA5* sediments probably merged southwards with the conglomeratic shoreface deposits shed from the steep-sloping cliffs of the *Piano Fossati* high (Fig. 11D), based on the cartographic distribution of *FA5.* This very last stage of sedimentation resulted from the likely severe decrease of the tidal circulation, prior to the definitive closure of the passageway (Barrier et al., 1993). This, in turn would suggest that the passageway had shallowed to the point that friction was too great and tidal flow was greatly reduced or stopped (Anastas et al., 2006). This last episode of sedimentation preceded an important phase of regional tectonic uplift, the demise of any marine circulation in the rest of the Siderno Strait and a break in the oceanographic linkage between the Tyrrhenian and Ionian basins.

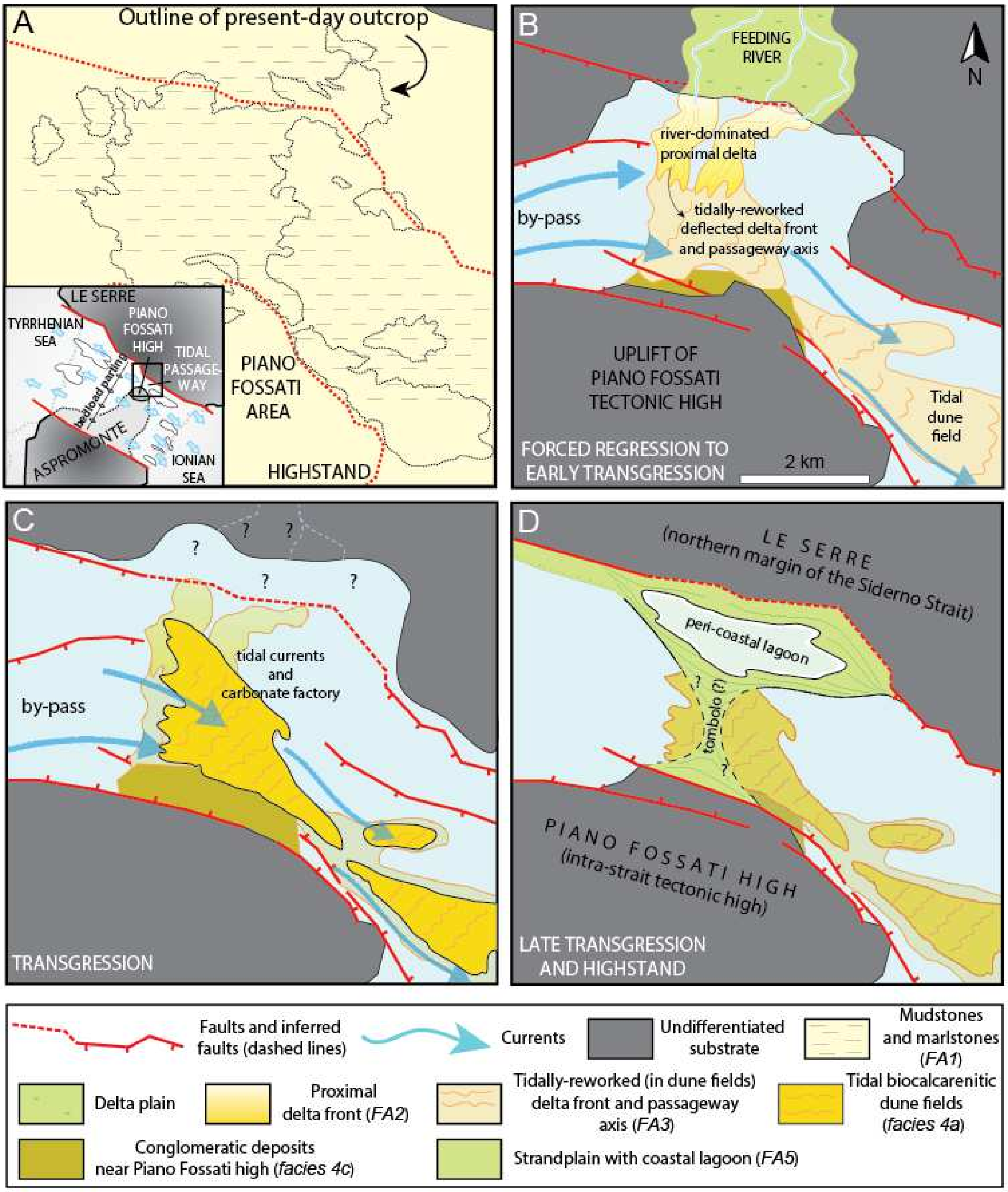

Fig. 11. Palaeogeographic reconstructions showing the evolution of the northern margin of the Siderno Strait (inset), and the associated tide-dominated passageway during the early Pleistocene. The small rectangle in the inset shows the location of the study area (shown in panels B, C, D), between the structural high of Piano Fossati and the northern margin of the basin. (A) At the end of the transgression (upper Pliocene), non-tidal open-shelf mudstones filled an inherited topography incised into older deposits that accumulated during a previous stage of relative sea-level fall. (B) A subsequent phase of regional-scale tectonic activity (early Pleistocene) in this part of the Calabro-Peloritani Arc was probably the cause of the onset of tide-modulated current exchange between the Tyrrhenian and the Ionian seas in the Siderno Strait (see reconstruction in Fig. 1C).Tidal currents were flowing from the bedload parting zone towards the SE (i.e., towards the Ionian Sea) in this sector of the Siderno Strait. Strike-slip fault movements in this part of the Siderno

Strait margin caused the uplift of the *Piano Fossati* high, creating a 3.5 km-wide passageway that became dominated by strong tidal currents with a dominant SE-directed flow. Deltas prograded into this narrow corridor from the Serre Massif, but due to the presence of strong tidal currents, the delta front deposits became reworked toward the SE (asymmetrical delta front). (C) Continued transgression or a reduction in fluvial input due to climate change caused the delta to back-step, and deposition became dominated by bioclastic tidal dunes and *in-situ* carbonate factories. (D) Highstand sedimentation caused coastal progradation and, possibly, the closure of this sector of the Siderno Strait margin.

5. Conclusions

This paper documents the sedimentology and stratigraphy of a Pliocene-Pleistocene succession deposited along the northern margin of the Siderno tide-dominated paleostrait. Deltas impinging tide-dominated straits or seaways are significantly affected by strong currents flowing parallel to the coastline, and capable of dispersing large volumes of sand for significant distances along the coast and along the strait axis. Therefore, the findings of this work can help to predict sandbody distribution and the findings can be applied to any other setting characterized by a narrow (possibly structurally-confined) basin dominated by tidal currents.

The northern margin of the Siderno paleostrait records sedimentary architectures along a morphologically complex margin, due to the presence of a structural high, which created a localized 3.5 km-wide passageway, in which tidal and fluvial processes interacted. Fluvially-fed sediments were shed from the northern margin during river-flood events, accumulating river-dominated deltaic deposits. Tidal currents flowing roughly parallel to the strait margin reworked the delta-front sediments into southeastward migrating tidal dunes, oriented at a high angle with respect to the deltaic progradation direction, generating a deflected and asymmetric delta front. Tidal reworking was stronger in the more distal deltaic locations and in the passageway axis, and weaker in the proximal sectors, so that the thickest cross-strata are located near the passageway axis, whereas deltaic deposits were dominated by river currents closer to the strait margin. Tidal reworking continued to affect sediment transport and deposition even when the siliciclastic input to the basin was shut off and sediments were mainly fed from parauthochthonous carbonate factories. During the latest stage of strait-margin filling, the sediments record the progradation of coastal strandplain deposits that progressively closed the narrow passageway. This change can be related to an overall reduction in tidal influence or to the segregation of tidal and wave dominance between deeper water and the shoreline. The regional-scale tectonic uplift that affected this segment of the Calabro-Peloritani Arc during the late Pleistocene marked the definitive deactivation of any tidal influence in the passageway, as well as in the whole Siderno Strait.

Acknowledgments

This study represents the results of a field-based research module of the first author’s PhD project, based at the University of Texas at Austin, financially supported by the University of Basilicata, UT

Austin and GSA Research Grant (10724-14), and spent in southern Italy during Spring 2015. The authors would like to thank guest editor Louis Pomar, reviewer Allard Martinius and an anonymous reviewer for the constructive comments that have greatly improved the paper. The authors would also like to thank Marta Cosma and Marcello Tropeano for the help in the field.

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Facies associations	Facies	Description of the sedimentary facies	Interpretation of the depositional processes and environments	System tract
FA5	*5c*	Medium-grained and very well sorted sandstones with ghosts of low-angle laminations. The sand body is up to 5-6 m-thick.	***Strandplain- lagoon complex*** Shoreface-strandplain system, including a lagoonal environment. It possibly marks the turn-around from transgression to regression at the beginning of the relative sea-level highstand.	HST
	5b	Alternation of mudstones and coarse sandstone beds, including also bioclastic-rich and silty interlayers, ranging in thickness from a few centimeters to *ca.* 10 cm, with bivalve and gastropod fragments.		
	5a	Light-colored upper-fine to lower-medium sandstones, well-sorted with sub-rounded grains, and containing few bioclasts. Characterized by low-angle laminae and normally-graded beds.		
FA4	*4c*	Cross-stratified, clast-supported, well-rounded conglomerates and sandstones, associated with algal rhodoliths, serpulids, bivalves, and rhodoliths.	***Strait-margin complex*** Tide-dominated dune fields developed under the influence of tidal currents flowing axially within the passageway. Laterally, on the strait-margin zone flanked by a tectonic basement high, pocket gravel beaches were present.	late TST
	4b	Isolated carbonate mounds, 10 m-wide and *ca.* 3-4 m-thick, associated with large-size balanides, barnacles, bryozoans, brachiopods, and abundant solitary cm-size corals.		
	4a	Cross-stratified, coarse-grained biocalcarenites composed of bivalves, bryozoans, echinoids and corals mixed with 10-30% of siliciclastic, sand-size fraction. They form two- and three-dimensional cross-strata up to 4 m thick, with paleocurrents pointing towards 125°N.		
FA3	*3b*	Three-dimensional large-scale cross-stratified sandstones and biocalcarenites up to 6 m thick.	***Tide-dominated delta-front and passageway axis*** Series of superimposed dune fields developed on a delta-front environment and passageway axis, reworked by powerful tidal currents flowing parallel to the strait margin.	LST - early TST
	3a	Two-dimensional cross-stratified sandstones up to 6 m thick, with paleocurrents ranging from 45°N to 100° N. They include meniscate forms and biocalcarenitic intervals (with bivalves, bryozoans, barnacles, brachiopods and corals).		
FA2	*2b*	Cross-stratified lenticular sandstones bounded by erosional surfaces, showing sigmoidal, angular or tangential foresets up to 2 m thick. In places very bioturbated (meniscate *Scolicia* traces).	***River-dominated, tide-influenced deltaic regressive complex*** River-dominated deltaic deposits, dominated by hyperpycnal and hyper-concentrated flows occurring during river floods and entering a tide influenced shallow-marine setting.	RST + LST(?)
	2a	Moderately- to poorly-sorted, normally-graded sandstones and subordinate conglomerates, forming lenticular strata, 0.4 to 5-6 m thick. Erosional basal surfaces marked by mud chips and lithic/shell fragments.		
FA1	*1b*	Thin mudstone and fine-grained sandstone intercalations.	***Shelf mudstones and marlstones*** Sedimentation in an open shelf setting.	HST
	1a	Light-colored mudstones and marlstones. Tabular strata each *ca.* 1 m thick, associated with *Zoophycos* ichnofacies, and with abundant planktonic Foraminifera dominated by *Sphaerodinellopsis* spp. and *Globorotalia margaritae*.		

INTERPLAY OF TIDAL AND FLUVIAL PROCESSES IN AN EARLY PLEISTOCENE, DELTA-FED, STRAIT MARGIN (CALABRIA, SOUTHERN ITALY)

- Sedimentation along strait margin significantly controlled by inherited topography;
- Strong interaction between fluvially-emplaced sediments and tidal currents flowing parallel to the strait margin and at a high angle with the respect to the delta progradation direction;
- Stronger tidal reworking in the most distal deltaic locations, weaker in the proximal sectors;
- Thickest cross-strata are located near the passageway axis, deltaic deposits are more river-dominated closer to the strait margin.