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Tidal signatures in Neogene to Quaternary mixed deposits of southern Italy straits and bays

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A B S T R A C T

Some of the Neogene to Quaternary sedimentary successions cropping out in the southern Italy orogenic belt exhibit distinct stratigraphic intervals of mixed, silici-bioclastic arenites. These deposits represent bay- and strait-fill successions that accumulated during tectonically-driven, rapid transgressions in peripheral marine basins of the central Mediterranean, experiencing microtidal conditions similar to those presently existing in the Mediterranean Sea.

The Upper Miocene to Middle Pleistocene successions of Basilicata, Calabria and NE Sicily, show laterally-accreted, cross-strata of mixed composition, with the siliciclastic fraction derived from either sedimentary or metamorphic rocks and the bioclastic fraction produced by an *in situ* or near *situ* heterozoan factory.

Tidal cyclicity of semi-diurnal and diurnal to monthly and yearly periodicities has been detected in the studied deposits, where tidal bundling is revealed by the rhythmic alternation of siliciclastic and bioclastic set of laminae, repeated according to different cycles. This rhythmic signature appears to be more evident where randomly-occurring processes, such as waves, storms and currents, were mitigated by engulfed or strait palaeo-settings.

Palaeo-bays preserved short-term tidal cycles in shoreface to offshore-transition mixed deposits because hydrodynamically isolated from open marine conditions and therefore subjected to tidal influence only during fair-weather periods. On the contrary, palaeo-straits recorded tidal cyclicities of longer duration in deeper mixed deposits subjected to steady tidal currents.

1. Introduction

Tidal cycles can be easily detected in the stratigraphic record of ancient tide-dominated depositional systems, where the palaeo-range of tidal excursions is dominant (see articles in Flemming and Bartholomä, 1995 and Alexander et al., 1998). In contrast, in microtidal settings (tidal range <2 m; Hayes, 1979) the strength of tidal currents is weak compared to the influence of waves and other types of currents, and consequently a tidal signature is often undetectable or very subtle.

Exceptionally, tidal signal can be preserved in coastal embayments (e.g., Dixon et al., 1995; Yoshida et al., 2004) where the bay's length and depth cause a resonance and consequent amplification of the tidal wave (Pugh, 1987; Darlymple et al., 1990; Sztanó and de Boer, 1995), or where tidal currents are amplified along narrow passageways (e.g., Anastas et al., 1997; Mellere and Steel, 2000; Galloway, 2002) linking basins with a time-offset build-up of tidal prism (Allen, 1980, 1984a,b). The Adriatic Sea (Fig. 1A) is a modern example where the tidal range is significantly greater than in other areas of the microtidal Mediterranean Sea. Its shallow northern sector (only 40 m deep at a distance of 100 km from the coastline) increases considerably the effects of tidal waves, causing serious damages in the Lagoon of Venice and surroundings (Defant, 1961; Trincardi et al., 2004; Storms et al., 2008). Another example is the modern Messina Strait, in southern Italy, where the out-of-phase semidiurnal inversion of the tidal prism between the Tyrrhenian Sea to the north and the Ionian Sea to the south amplifies tidal currents within the strait (Vercelli, 1925; Blanc, 1954; Barrier, 1987; Mercier et al., 1987).

A number of recent sedimentological studies have documented a tidal signature in the Neogene to Quaternary successions of southern Italy (Barrier, 1987; Mercier et al., 1987; Colella and D'Alessandro, 1988; Colella, 1995; Longhitano and Nemec, 2005; Messina et al., 2007; Nemec et al., 2007; Chiarella and Longhitano, 2008; Di Stefano and Longhitano, 2009; Longhitano et al., 2010; Longhitano, 2011),

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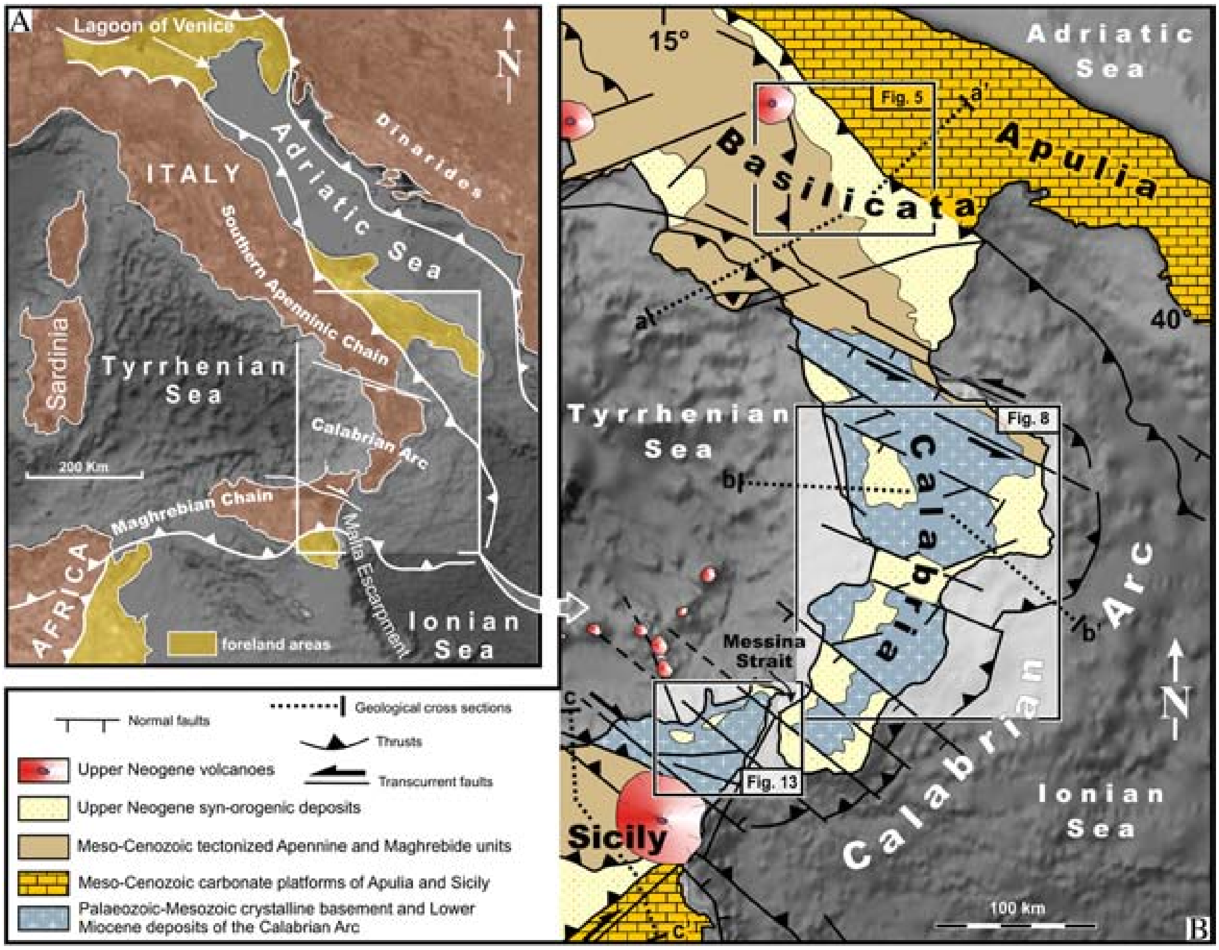


Fig. 1. (A) Geotectonic framework map of the central Mediterranean, showing the three main orogenic domains of the southern Italy belt: the Apenninic Chain, the Calabrian Arc and the Maghrebian Chain. (B) Simplified geological map of southern Italy, showing main tectonic lineaments, geodynamic domains and traces of geological cross-sections shown in Fig. 2. The study areas of this paper are in the regions of Basilicata, Calabria and Sicily (see Figs. 5, 8 and 13).

despite the regional microtidal range of ~35 cm at least from the Early Miocene onwards.

These successions consist of sediment of mixed or 'hybrid' composition (*sensu* Zuffa, 1980) showing the co-existence of an extrabasinal (siliciclastic) and an intrabasinal (bioclastic) component (*in situ* mixing *sensu* Mount, 1984). In general, in mixed sediments, the siliciclastic fraction is most likely derived from river input to the basin or from wave erosion of bedrock units (see discussion in Longhitano et al., 2010), and consists of fragments of sedimentary, metamorphic or igneous rocks. The bioclastic fraction originates from biogenic sources of *in situ* or near *situ* carbonate factories (Kamp et al., 1988; Budd and Harris, 1990; James and Clarke, 1997; Pomar and Hallock, 2008) favored by cyclical or irregular climatic optimums (Colella and Vitale, 1998; Capozzi and Picotti, 2003; Roveri and Taviani, 2003; Massari and Chiocci, 2006; Di Stefano and Longhitano, 2009).

When entrained by waves or currents, mixed sediments offer a different hydraulic response to sediment dispersal processes, because the density and the shape of bioclastic material differ markedly from that of siliciclastic material (Prager et al., 1996). Consequently, even weak tidal signal can be recorded as heterolithic segregation, especially where strong fair-weather or storm waves are absent (Longhitano, 2011).

This study revises and discusses some of the Neogene–Quaternary tidalites of mixed composition that crop out in the southern Italy. Their occurrence within a microtidal palaeo-oceanographic setting bears important implications for palaeogeographic and structural reconstructions.

2. The southern Italy orogenic belt

The southern Italy orogenic belt is an arc-shaped orogen comprising the Apenninic–Maghrebian chains and the superimposed Calabrian Arc (Fig. 1A,B) (Critelli, 1999; Grasso, 2001; Vai, 2001; Finetti et al., 2005a,b). The tidalite-bearing successions revised in this study pertain to satellite or syn-rift Neogene–Quaternary sedimentary basin fills developed on deformed substrates of different sectors of the orogenic belt (Fig. 1A). These basins were semi-enclosed areas generated by thrust-front growth or normal faulting, also bounded by lateral ramps or strike-slip faults (Fig. 1B) (e.g., Martini et al., 2001).

2.1. The Apenninic–Maghrebian orogen

The Apenninic–Maghrebian orogen (Fig. 1B) developed mostly during the Cenozoic, as the product of convergence between Europe and Africa–Adria plates (Dewey et al., 1989; Boccaletti et al., 1990; Roure et al., 1991; Monaco et al., 1998; Menardi Noguera and Rea, 2000; Grasso, 2001; Finetti et al., 2005b). The orogen consists of several tectono-stratigraphic units that derive from the superimposition of originally-adjacent palaeo-geographical domains of the Mesozoic Neotethys (Cello et al., 1989; Pescatore et al., 1999). From WSW to

ENE in Basilicata, and from WNW to ESE in Sicily, these units are represented by an internal Mesozoic ophiolitic unit with Meso-Cenozoic oceanic sedimentary cover (Ligurian Unit), Upper Triassic to Cenozoic carbonate platform domains (Apenninic and Sicanian Platform), a thick deep-water succession of Mesozoic age (the Lagonegro–Imerese units), and external Upper Triassic–Cretaceous carbonate platform (Apulian–Hyblean units) (Fig. 2A) (Grasso, 2001). The latter represents the foreland of the orogen. During the Plio-Pleistocene, the Apulian–Hyblean domains were partly thrusted and deformed (Carbone and Lentini, 1990) (Fig. 2A). A number of thrust-top basins developed close to the front of the orogen (Patacca and Scandone, 2004), leading to local marine flooding of their peripheral basinal areas (Longhitano, 2008). Quasi-confined gulfs formed in the northern sector of the Southern Apennine (Basilicata), including the Acerenza–Oppido Lucano–Tolve and Tricarico basins (Chiarella and Longhitano, 2008; Longhitano et al., 2010), (Fig. 1B).

2.2. The Calabrian Arc

The Calabrian Arc (Fig. 1B) is composed of a series of tectonic units derived from original palaeo-geographic domains of the Tethys, and overlain by basement nappes (Ogniben, 1969; Amodio Morelli et al., 1976; Tortorici, 1982). The Arc comprises remnants of the Alpine–Betic back-thrust belt superimposed onto the Apenninic Chain during the opening of the Tyrrhenian back-arc basin (Gueguen et al., 1997).

The opening of the western Tyrrhenian Sea since the Middle Miocene was associated with the onset of intense thrusting in the eastern sector of the orogen, due to the progressive migration of the Calabrian Arc toward the Ionian Basin (Fig. 2B) (Malinverno and Ryan, 1986; Dewey et al., 1989; Decandia et al., 1998). This migration occurred through the development of regional SE- and ESE-trending shear zones dissecting the pre-existing thrust sheets (Ghisetti, 1979; Ghisetti and Vezzani, 1981; Rehault et al., 1987; Turco et al., 1990; Knott and Turco, 1991; Monaco and Tansi, 1992; Catalano et al., 1993).

Strike-slip tectonics and blocks rotation induced a structural fragmentation of the Calabrian Arc from the Middle Miocene onward (Turco et al., 1990; Martini et al., 2001), and favored the formation of structural highs which separated grabens and half-grabens, such as the Amantea Basin, filled by alluvial, to shallow-water to deeper marine sediments (Colella, 1995; Mattei et al., 2002; Muto and Perri, 2002; Longhitano and Nemec, 2005; Tansi et al., 2007), (Fig. 1B).

From the Late Pliocene to Pleistocene, some parts of the back-arc zone were affected by extensional tectonics superimposed on strike–slip deformations, which resulted in the formation of narrow straits, such as the Catanzaro and Siderno palaeo-straits, linking the Ionian to the Tyrrhenian with sublittoral sedimentation (Colella and D'Alessandro, 1988; Argnani and Trincardi, 1993; Van Dijk et al., 2000), (Fig. 1B).

The opening of the Tyrrhenian Sea as a back-arc basin (Malinverno and Ryan, 1986; Boccaletti et al., 1990; Knott and Turco, 1991; Robertson and Grasso, 1995) leads to block-faulting of the inner margin of the Apennine orogen, generating extensive deformations and subsidence (Fig. 2C). This favored the marine flooding and consequent marine sedimentation in confined embayments and gulfs of northern Sicily, such as the Barcellona Pozzo di Gotto Basin and the Rometta palaeo-bay (Di Stefano et al., 2007; Messina et al., 2007).

From Middle Pleistocene, the western side of the Calabrian Arc and the eastern side of Sicily were affected by intense WNW–ESE extension related to the Calabrian–Sicilian Rift Zone (Cello et al., 1982; Gasparini et al., 1982; Tortorici et al., 1995; Monaco et al., 1997; Monaco and Tortorici, 2000; Van Dijk et al., 2000; Tansi et al., 2007), which generated the formation of the Messina Strait (Di Stefano and Longhitano, 2009).

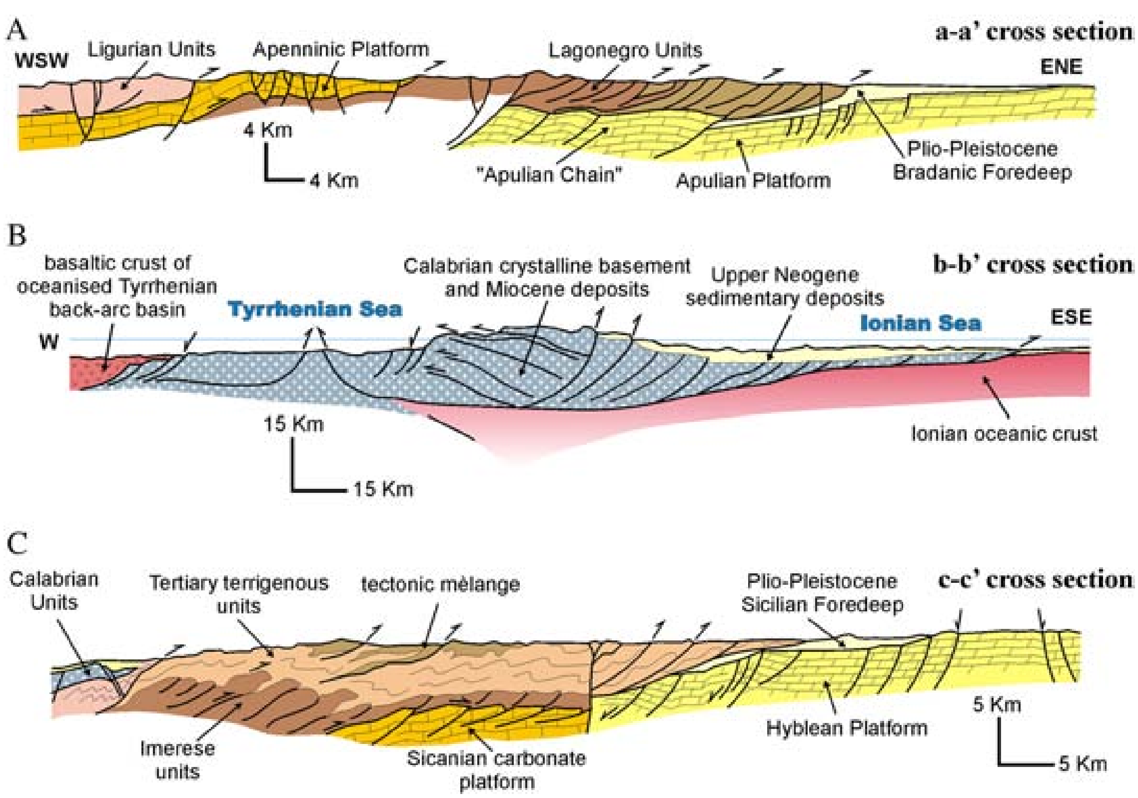
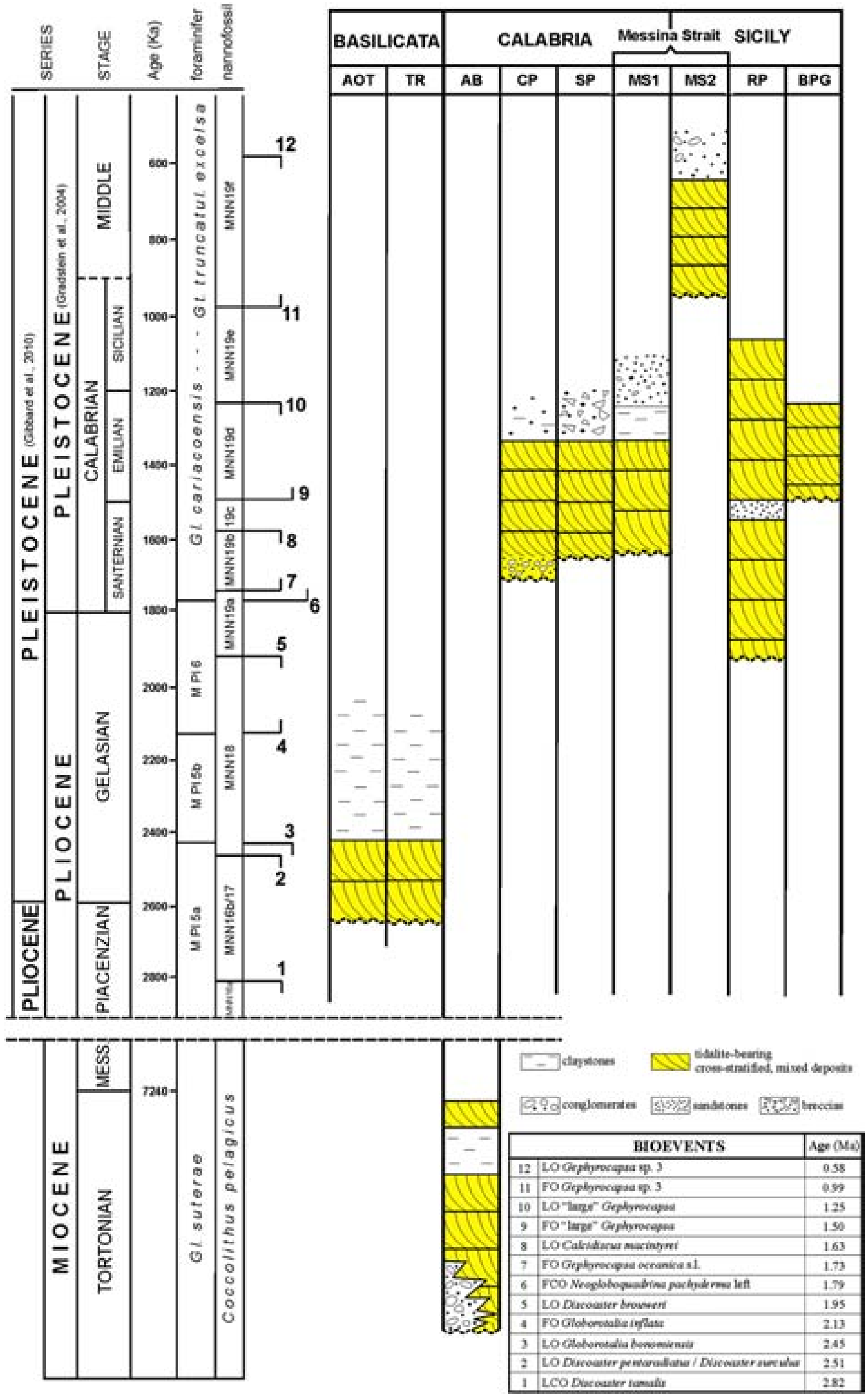


Fig. 2. Geological cross-sections through the study areas (see profile lines in Fig. 1B). The cross-sections show: (A) the Southern Apennine, (B) the Calabrian Arc and (C) the Sicilian segment of the Maghrebian Chain.
Sections compiled and modified from Piedilato and Prosser (2005), Tansi et al. (2007) and Grasso (2001), respectively.



	BIOEVENTS	Age (Ma)
12	LO *Gephyrocapsa* sp. 3	0.58
11	FO *Gephyrocapsa* sp. 3	0.99
10	LO "large" *Gephyrocapsa*	1.25
9	FO "large" *Gephyrocapsa*	1.50
8	LO *Calcidiscus macintyrei*	1.63
7	FO *Gephyrocapsa oceanica* s.l.	1.73
6	FCO *Neogloboquadrina pachyderma* left	1.79
5	LO *Discoaster brouweri*	1.95
4	FO *Globorotalia inflata*	2.13
3	LO *Globorotalia bononiensis*	2.45
2	LO *Discoaster pentaradiatus* / *Discoaster surculus*	2.51
1	LCO *Discoaster tamalis*	2.82

Fig. 3. Bio-chronostratigraphic framework of the studied successions. Two alternative placements of the Pliocene/Pleistocene boundary are illustrated, representing the most recent (Gibbard et al., 2010) and previous (Gradstein et al., 2004) convention. Plio-Pleistocene foraminifer biozones after Cita (1975) em. Sprovieri (1992); Plio-Pleistocene nannofossil biozones after Rio et al. (1990); ages of bioevents (1–12) are after Sprovieri et al. (1998); Miocene nannofossil scheme after Theodoridis (1984) and Miocene foraminifer scheme after Iaccarino (1985). (AOT = Acerenza–Oppido Lucano–Tolve Basin; TR = Tricarico flood-tidal delta; AB = Amantea Basin; CP = Catanzaro palaeo-strait; SP = Siderno palaeo-strait; MS1 = Calabrian Messina Strait; MS2 = Sicilian Messina Strait; RP = Rometta palaeo-bay; BPG = Barcellona Pozzo di Gotto Basin).

3. Tidalite-bearing mixed deposits in Neogene to Quaternary basins of southern Italy

Most of the basins present in southern Italy were filled by Miocene to the Pleistocene sedimentary successions of mixed silici-bioclastic arenites (Fig. 3). These deposits vary in thicknesses, lithosome geometries and internal architectures. Many show a complex suite of meter-scale cross-stratification and cross-lamination attributed to a tidal origin (Fig. 4) (Longhitano, 2011).

The frequent preservation of tide-influenced deposits in the regionally microtidal Mediterranean Sea has been explained by the identification of straits and embayments, where tidal currents were hydraulically amplified or enhanced in their strength (Colella and D'Alessandro, 1988; Colella, 1995; Longhitano and Colella, 1998;

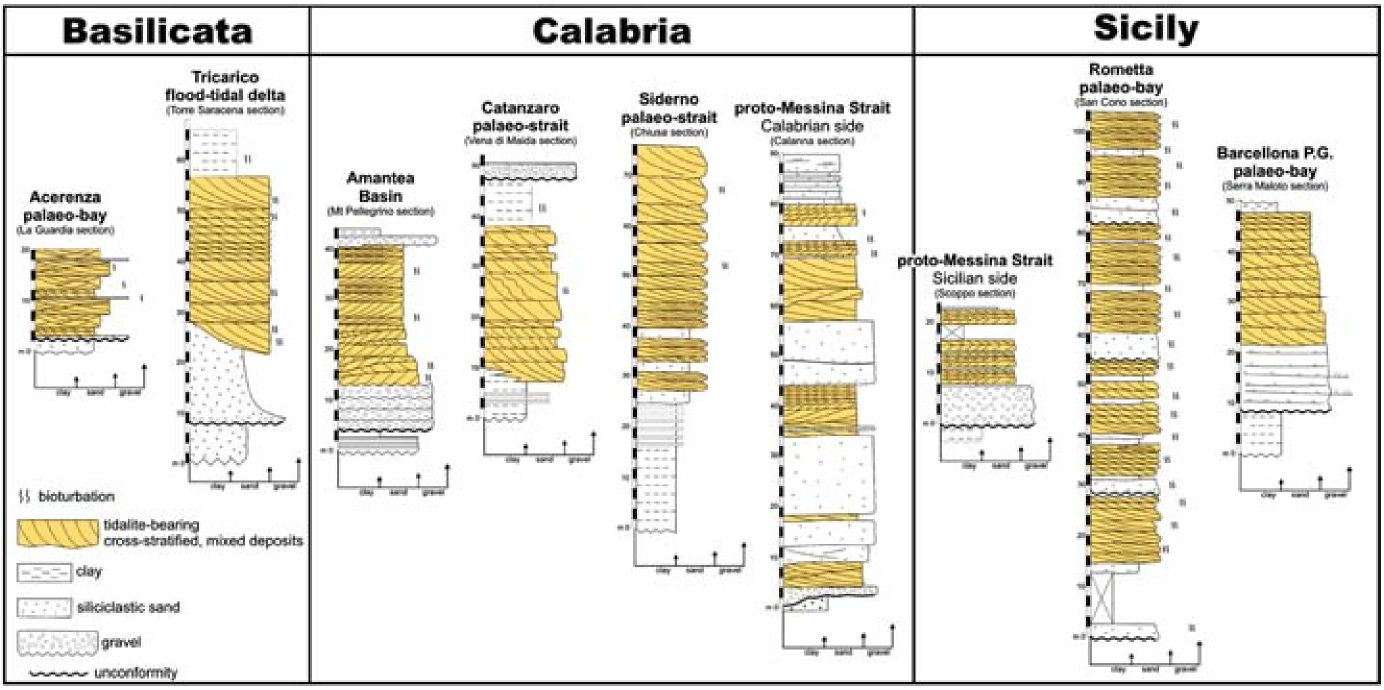


Fig. 4. Sedimentological logs of the stratigraphic sections studied across Basilicata, Calabria and NE Sicily. Tidalite-bearing mixed deposits are in yellow. Data from Tricarico are redrawn from Longhitano et al. (2010); data from Amantea are from Longhitano and Nemec (2005); data from Siderno are from Colella and D'Alessandro (1988); data from the Calanna section are re-drawn from Mercier et al. (1987); data from the Scoppo section are from Di Stefano and Longhitano (2009); data from Rometta are from Di Stefano et al. (2007); data from Barcellona P.G. are from Messina et al. (2007).

Longhitano and Nemec, 2005; Messina et al., 2007; Di Stefano and Longhitano, 2009; Longhitano et al., 2010; Longhitano, 2011).

3.1. The successions of Basilicata (Acerenza–Oppido Lucano–Tolve and Tricarico)

The north–central segment of the Southern Apennine in Basilicata, known as the Lucanian Apennine, includes tidally-influenced Pliocene shallow-marine deposits. The best outcrops are those Acerenza, Oppido Lucano, Tolve and Tricarico (Fig. 5). The Pliocene succession generally consists of two shallow-marine sedimentary cycles, 200–300 m thick (Ippolito et al., 1975; Bonardi et al., 1988), separated by an angular unconformity well displayed in the frontal part of the Apennine (Pieri et al., 2004). The younger Middle–Upper Pliocene cycle is the best preserved (Sabato and Marino, 1994). In the studied localities, the lowermost part of this cycle consists of some tens of meters thick transgressive gravels and sandstones, passing upwards to 60 m thick littoral–sublittoral mixed deposits and to some tens of meters thick mudstones (Fig. 4). The terrigenous fraction of mixed deposits predominantly consists of medium to coarse siliciclastic sand, with mono-crystalline quartz and subordinate feldspars (Chiarella and Longhitano, 2008). The bioclastic fraction consists of coarse sand- to granule-grained fragments of red algae, bivalves, bryozoans, echinoids, and *Balanus* sp. fragments. The common benthic foraminifera content includes *Textularia*, *Rotalia*, *Cibicides*, *Elphidium*, and *Lenticulina* (Sabato and Marino, 1994).

Mixed deposits are internally organized into coarsening-upward parasequences induced by high-frequency variations in relative sea level; lateral thickness variations are attributed to local tectonics while internal facies variability is interpreted to record changes in hydrodynamics (Chiarella and Longhitano, 2008; Longhitano et al., 2010; Chiarella, 2011). In the sites of Acerenza, Oppido Lucano and Tolve (Fig. 4), vertical facies tracts suggest shoreface to offshore-transition environments, while in the Tricarico area (Fig. 4), sediments accumulated in a sublittoral flood-tidal delta system (Longhitano et al., 2007; Sabato et al., 2007; Chiarella and Longhitano, 2008; Longhitano et al., 2010).

The mixed deposits in the parasequences consist of tabular planar cross-strata sets, 10–30 cm thick, showing mainly unidirectional foresets that are attributed to the migration of small 2D dunes driven by oblique and downwelling currents (cf., Di Stefano et al., 2007; Mateu-Vicens et al., 2008; Di Stefano and Longhitano, 2009; Puga-Bernabéu et al., 2010). The dune foresets show a rhythmic alternation of silici-bioclastic strata, with thicknesses varying according to harmonic phases of tidal periodicities (Longhitano, 2011).

3.1.1. The Acerenza–Oppido Lucano–Tolve (AOT) basin

The deposits of the AOT basin consist of remnants of a Pliocene succession (Pieri et al., 2004) filling a series of thrust-top depressions elongated roughly parallel to the main frontal thrusts of the Lucanian Apennine (Chiarella and Longhitano, 2008). Some of these small basins were 2–3 km wide and 5–10 km long (Fig. 5), and were most likely characterized by shallow submerged margins and sublittoral to moderately deeper environments, where a series of prograding coastal wedges formed (Fig. 4). The bioclastic fraction mainly derives from an *in situ* or near *situ* cool-water carbonate factory, while the siliciclastic fraction represents the product of submarine abrasion of pre-Pliocene sedimentary units exposed to wave erosion (Chiarella and Longhitano, 2008; Chiarella, 2011).

Sediments of the AOT basin (Fig. 5) form a ~200 m thick succession that comprises two cycles bounded by an angular unconformity (Maggiore and Walsh, 1975; Labriola et al., 2008; Labriola and Onofrio, 2008). The lowermost cycle is Early Pliocene, 150–160 m thick and consists of alluvial to transitional deltaic conglomerates and sandstones, passing upwards to marine sands and clays (Pepe, 2008). The uppermost cycle is 30–40 m thick and consists of a few meter-thick basal layer of pebbly sandstones with abundant shell debris, overlain by a 20–25 m-thick succession consisting of sand- to gravel-sized carbonate debris mixed with siliciclastic quartz-rich sand (Fig. 6A). The mixed interval passes rapidly upwards to a thick succession of open marine

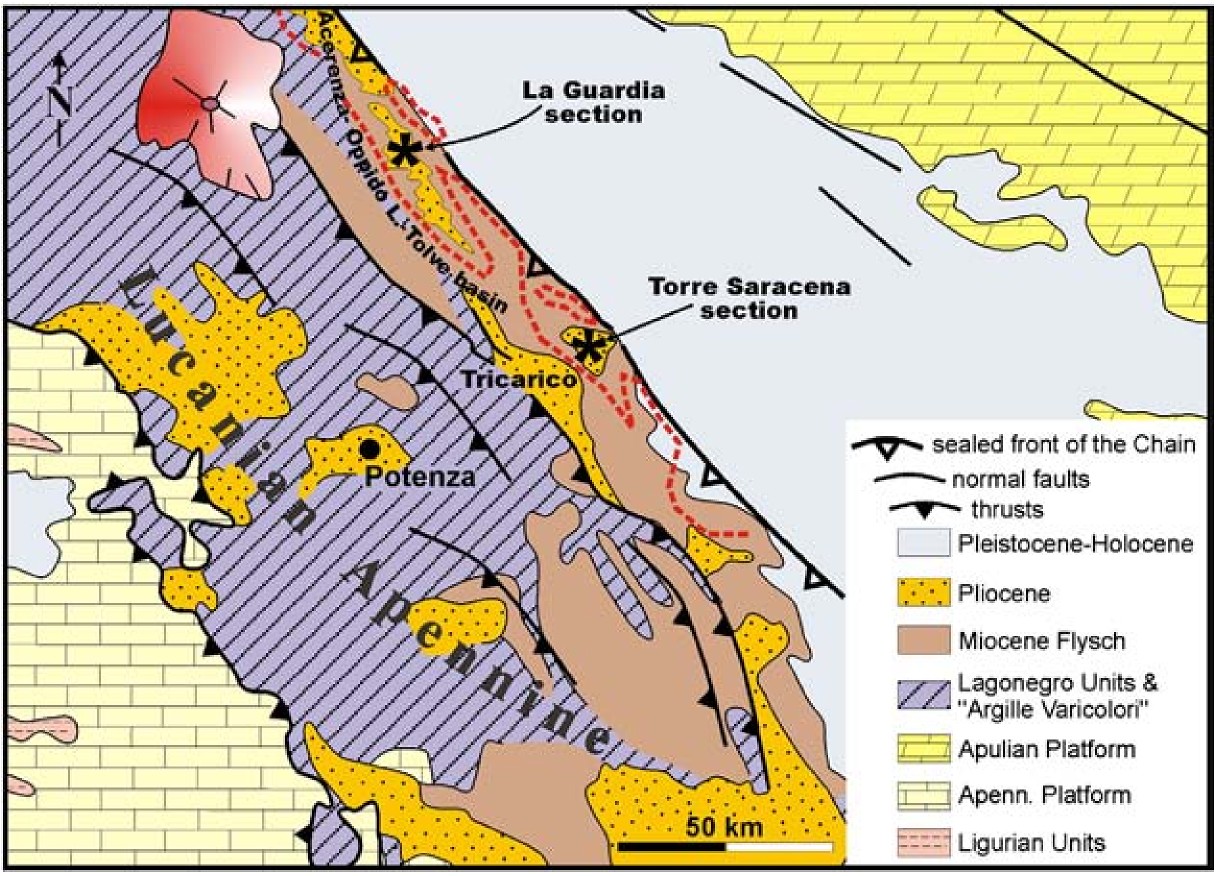


Fig. 5. Simplified geological map of the Lucanian Apennine showing main outcrop localities. The Middle to Upper Pliocene studied successions containing tidalite-bearing mixed deposits are mostly confined in the external sector of the thrust front, where they represent the infill of elongated small basins, oriented roughly parallel to the main thrust front (the dashed line indicates the inferred palaeo-coastline).
Modified, from Longhitano et al., 2010.

mudstones (Chiarella and Longhitano, 2008), containing abundant diatoms and a nannofossil assemblage of *Helicosphaera sellii*, *Pseudoemiliania lacunosa*, *Geminithella rotula*, *Pontosphaera* spp., *Calcidiscus macintyrei*, small-sized *Gephyrocapsa* spp., and rare *Discoaster brouweri*, of the Rio et al.'s (1990) MNN18 biozone, Gelasian in age. However, additional biostratigraphic data sampled in other sections of this basin (Pieri et al., 2011) may indicate the Middle Pliocene for the base of these deposits (MNN16b/17 biozone; Rio et al., 1990) (Fig. 3).

Mixed sediments observed at the La Guardia section (Fig. 5) form aggrading to prograding wedge-shaped bodies (Fig. 6A) whose present-day distribution roughly indicates the complex palaeo-physiography of a gently-inclined shelf. Each wedge, 5 to 15 m thick, consists of three 2–8 m thick bed sets bounded by slightly angular unconformities (Fig. 6A) (Chiarella and Longhitano, 2008). Bed sets are formed by well-sorted hybrid arenites (Fig. 6B). They display ~0.5–1 m thick unidirectional foresets (Fig. 6C) that pass upwards to multidirectional foresets and to hummocky and swaley cross-strata (Chiarella, 2011).

Sediments show a characteristic segregation of the siliciclastic and bioclastic fractions in form of heterolithic foreset lamination (Longhitano and Chiarella, 2008; Longhitano, 2011). Heterolithic segregation progressively decreases upwards until it is completely absent in the upper interval of the bed sets. This pattern is interpreted as the result of an 'interference zone' along a vertical shoaling-up sequence between current-dominated and wave-dominated subtidal environments (Chiarella, 2011). In the deeper depositional zones, the marked segregation occurring between siliciclastic and bioclastic foreset laminae (Fig. 6D) is attributed to the influence of wave-driven unidirectional currents modulated by the influence of short-term tidal cycles acting on a water column confined in narrowly engulfed embayments (Longhitano, 2011).

3.1.2. The Tricarico (TR) flood-tidal delta

The Lower to Upper Pliocene Tricarico succession (Sabato and Marino, 1994; Pieri et al., 2004; Tropeano et al., 2006; Longhitano et al., 2010; Pieri et al., 2011) fills a small thrust-top basin lying unconformably on a series of tectonically deformed Cretaceous to Miocene Apennine units (Fig. 5). The outcrops lie on two E-trending, asymmetric synclines dissected by minor, transtensional faults (Gallicchio and Sabato, 2008).

The TR succession consists of two Pliocene cycles separated by an angular unconformity (Sabato and Marino, 1994; Gallicchio and Sabato, 2008; Pieri et al., 2011). The younger, middle to upper Pliocene (Piacenzian–Gelasian) cycle is up to ~140 m thick and lies unconformably on to deposits of the Lower Pliocene or on older Apennine units. The cycle consists mostly of conglomerates, arenites and mudstones (Pieri et al., 2004; Pieri et al., 2011). The uppermost part contains 30 m thick mixed deposits passing upward to a 30 m thick mudstone succession. Silici-bioclastic sediments occur in 0.1 m to 6 m thick beds, dominantly tabular, angular to tangential cross-stratification and subordinate plane-parallel and trough cross-stratification (Fig. 7A). Cross strata, locally very intensely bioturbated, form stacked packages generated by SSW-migrating large dunes (Fig. 7B). Cross sets are internally characterized by herringbone structures (Fig. 7C) and bundles of alternating thicker and thinner foreset laminae forming cycles of coarser- and finer-grained strata (Fig. 7D and E). Bundle cross lamination consists of bioclastic and siliciclastic intervals, whose regular alternance is consistent with semi-diurnal to monthly tidal cycles (Longhitano, 2011). These cross-stratified facies are interpreted as the result of the hydraulic amplification of strong tidal currents forced to flow across narrow,

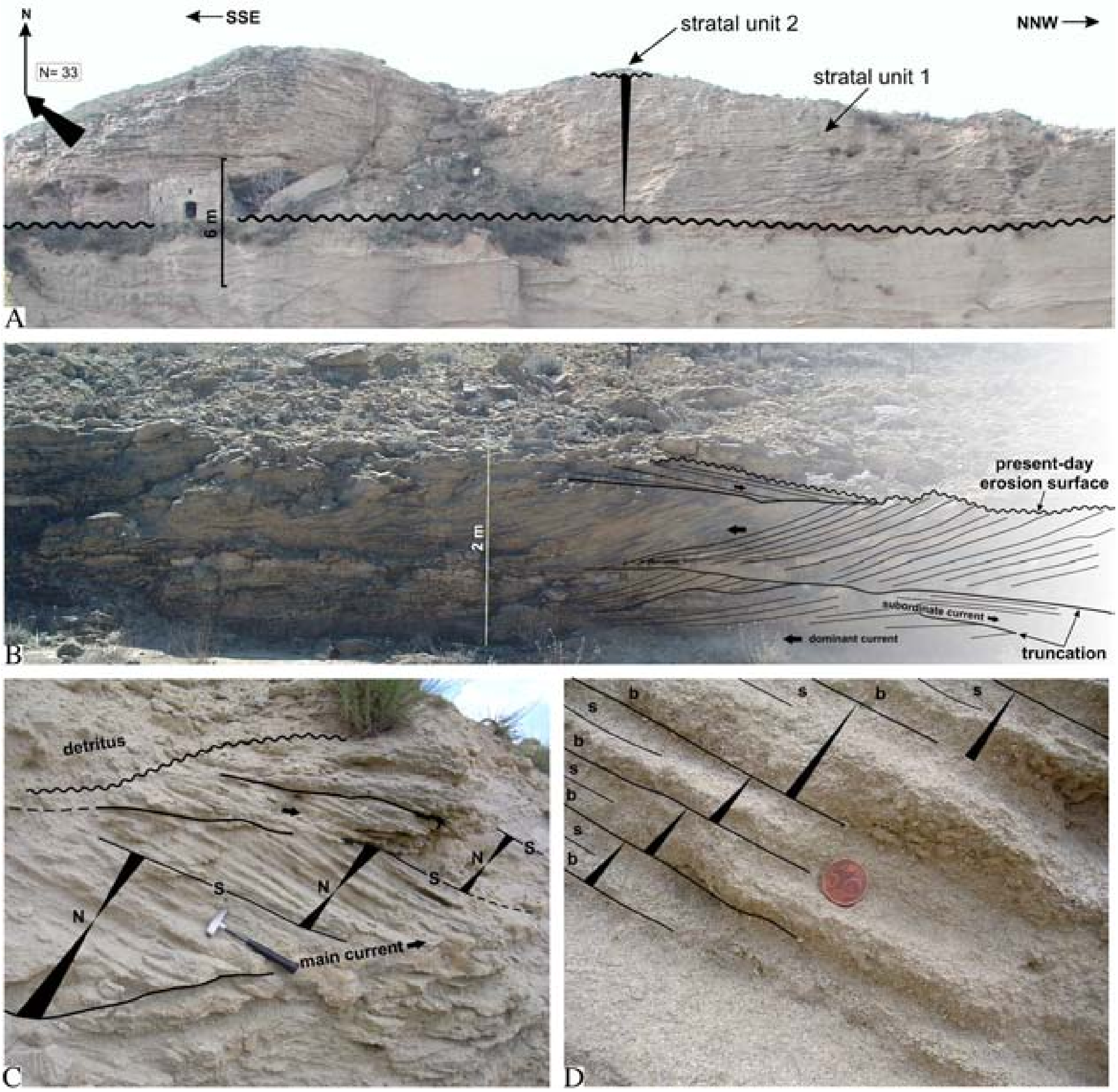


Fig. 6. La Guardia section (see Fig. 5 for location). (A) View of the section. The Middle-Upper Pliocene silici-bioclastic deposits are organized into three stratal units (here only the first two units are exposed), separated by unconformities and showing a shoaling-upward trend (palaeocurrents in the top-left corner). (B) Mixed deposits pertaining to the 2nd stratal unit show bidirectional cross-stratification (the main palaeo-direction is from the right to the left of the photo). (C) Tidal cross sets containing fining- to coarsening-upward lamina-sets indicate neap/spring (*N*/*P*) tidal cycles (hammer 35 cm long). (D) Close-up of Fig. 6 C showing tidal bundles (arrows) that consist of bioclastic (*b*) and siliciclastic (*s*) pairs of laminae (coin 2 cm of diameter).

tectonically-constrained passageway (Sabato et al., 2007; Longhitano et al., 2010). Sedimentation occurred in a semi-confined small basin, isolated from the open sea by a wide anticline. The crest of the anticline hosted a carbonate factory producing skeletal grains (Longhitano et al., 2010). Undulations on the anticline hinge originated the ‘strait passageway’ across which flood deltas developed (Sabato et al., 2007; Longhitano et al., 2008; Longhitano et al., 2010).

3.2. The successions of Calabria (Amantea, Catanzaro and Siderno) and the Messina Strait

The Neogene to Quaternary tectonic evolution of the Calabrian Arc leads to the formation of several half-grabens and narrow linear basins, including the Amantea Basin, the Siderno and the Catanzaro palaeo-straits, and the present-day Messina Strait (Fig. 8). Along these natural corridors tidal currents were amplified (Mercier et al., 1987), generating the best developed and preserved tidalites of southern Italy. Mixed deposits consist of a siliciclastic fraction dominated by metamorphic rock fragments (mostly schists and gneiss) and a bioclastic fraction deriving mainly from heterozoan associations. The deposits are commonly characterized by large scale (>1 m thick) cross-stratification.

3.2.1. The Amantea Basin (AB)

The ~120 m thick mixed arenites of the AB are of middle to late Tortonian age and, jointly with the neighboring Mendicino and Grimaldi areas (Mastandrea et al., 2002) (Fig. 8), represent the oldest tidalite-bearing sediments known in the Neogene of southern Italy. The AB (Di Nocera et al., 1974; Ortolani et al., 1979; Tansi, 1991; Colella, 1995; Muto and Perri, 2002; Longhitano and Nemec, 2005; Notaro, 2007) formed during Serravalian by the coalescence and marine inundation of fault-bounded coastal depressions (Argentieri et al., 1998; Mattei et al., 1999; Speranza et al., 2000) and is filled by upper Serravalian to Messinian deposits (Colella, 1995; Colella and Longhitano, 1998; Longhitano and

Fig. 7. Torre Saracena section (see Fig. 5 for location). (A) Interval of mixed deposits characterized by large scale cross stratification (migration is from right to left; palaeocurrents in the top-left corner) organized into vertically-stacked packages of tabular beds separated by marked truncation surfaces (B). (C) Locally, the cross sets show bidirectional cross-stratification that suggests flood/ebb tidal currents. Close-up views of these deposits reveal tidal bundles referable to neap/spring (*N*/*S*) and semi-diurnal tidal cycles formed by coarsening- to fining-upward packages of laminae (D) and bioclastic (*b*) and siliciclastic (*s*) couplets of laminae (E).

Colella, 1998; Martini et al., 2001; Muto and Perri, 2002) divided into three main depositional sequences (Colella, 1995).

The younger sequence (middle Tortonian to lower Messinian) consists of a transgressive succession up to 80 m thick, formed by polymict conglomeratic alluvial and deltaic deposits passing upwards to massive, shallow-marine sandstones. A transgressive lag horizon separates these deposits from the overlying mixed, silici-bioclastic deposits. Depending on the local source areas, the terrigenous component can be represented by either limestone or metamorphic fragments, whereas the bioclastic fraction consists of medium- to very coarse-grained shell detritus. Mixed deposits are late Tortonian based on the presence of foraminifer assemblages referable to the Iaccarino's (1985) *Globorotalia suterae* biozone (Rao et al., 2006). The deposits occur throughout the AB, but they are best developed and exposed in the central sector (Mt Pellegrino section, Figs. 4, 8, 9). Here, a south-trending palaeo-strait formed as a tectonic graben, 1.5–2 km wide and 4 km long, with shallowly submerged margins and a southward-sloping floor.

Large-scale planar cross-stratification records migration of straight- to sinuous-crested 2D dunes (*sensu* Harms et al., 1982). Most cross-sets are 0.2–6 m thick, exceptionally up to 9 m (Fig. 9B), with a dominant southward palaeocurrent direction and show rhythmic alternation of thicker/coarser and thinner/finer strata (Fig. 9C). Segregated siliciclastic and bioclastic sets of laminae are often present within the foresets (Fig. 9D). These laterally-accreted heterolithic bundles are organized into cyclically repeated coarsening- and fining-upward lamina sets that arguably indicate the occurrence of semi-diurnal to monthly tidal periodicities (Longhitano and Nemec, 2005). The evidence of lunar apsides and nodal cycles (Pugh, 1987; Archer et al., 1991) has been also recognized along uninterrupted, laterally continuous large-scale dunes.

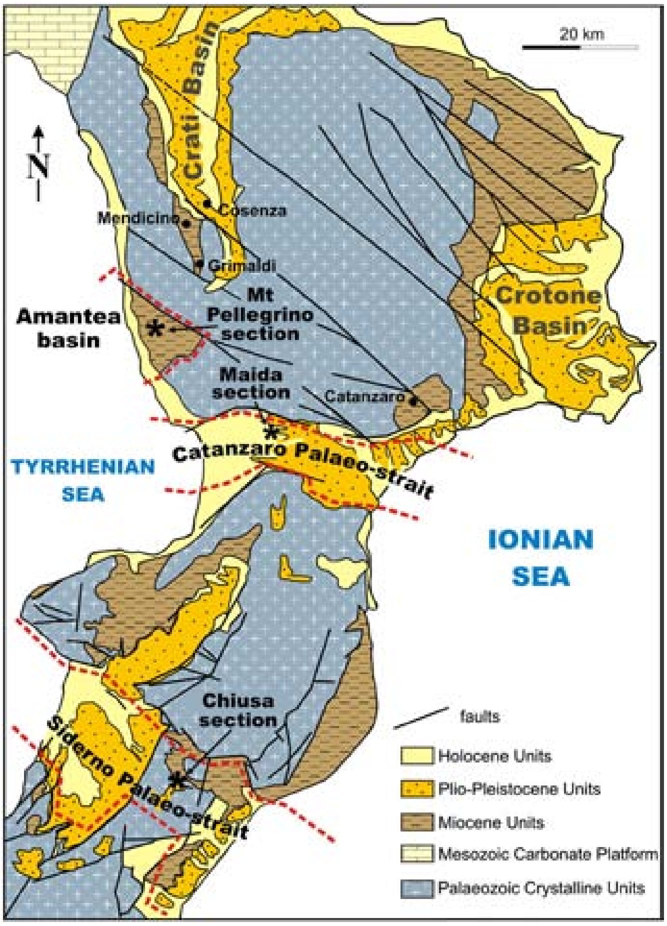


Fig. 8. Simplified geological map of Calabria showing the three main sites where tidalite-bearing deposits were studied. Mixed sediments are of Tortonian age in the Amantea Basin, and of Early Pleistocene age in the Catanzaro and Siderno palaeo-straits. Dashed lines indicate the inferred palaeo-margins of the main sedimentation areas. Modified from Tansi et al., 2007.

3.2.2. The Catanzaro and Siderno palaeo-straits

The Catanzaro (CP) and Siderno basins (SP) are WNW–ESE oriented palaeo-straits of Calabria (Fig. 8) and were fault-bounded, tide-dominated seaways where Lower Pleistocene mixed deposits accumulated (Colella and D'Alessandro, 1988; Colella, 1995; Cavazza et al., 1997; Cavazza and Colella, 2001). The narrow seaways linked the Tyrrhenian Sea to the west with the Ionian Sea to the east and were characterized by sublittoral to bathyal environments with strongly amplified tidal currents (Colella and D'Alessandro, 1988; Colella and Longhitano, 1997).

The Lower Pliocene to Middle Pleistocene infill of the CP forms a ~200 m thick regressive to transgressive succession: the lower regressive interval consists of deep-water mudstones passing upward to sublittoral siltstones; the upper transgressive interval is represented by mixed arenites grading upwards into open-marine siltstones. At the base of this latter interval, moderately preserved nannofossil assemblages of *H. sellii*, medium-sized *Gephyrocapsa* (=*G. oceanica* s.l.), small-sized *Gephyrocapsa*, *P. lacunosa*, *G. rotula*, *Syracosphaera pulchra*, *Pontosphaera* spp., *Calcidiscus leptoporus*, *C. macintyrei* of the MNN19b–c biozones of Calabrian stage, Santernian substage, were found (Fig. 3).

Silici-bioclastic deposits show metamorphic fragments mixed with skeletal fragments of a heterozoan assemblage and are organized into vertically-stacked cross strata, forming sets up to 4 m thick (Fig. 10A and B). The tidal dunes display bundle cross-lamination with a marked tidal cyclicity (Fig. 10C and D). Dunes migrated toward WNW in the western sector, and toward ESE in the eastern sector of the CP. Mixed sediments are capped by a transgressive condensed shell bed and by a muddy–silty, intensely bioturbated succession. The entire succession is erosively overlain by Upper Pleistocene continental to marine deposits (Chiarella et al., 2009; Chiarella, 2011).

The sedimentary succession of the SP consists of two depositional sequences separated by an angular unconformity and ranging in age from Early Pliocene to Early Pleistocene (Colella and D'Alessandro, 1988). The lowermost sequence contains Lower Pliocene 30–40 m thick bathyal mudstones passing upward to 20–30 m thick siltstones, that yield nannofossil assemblages of *G. rotula*, *H. sellii*, *Pontosphaera* spp., *P. lacunosa*, *C. leptoporus*, *C. macintyrei*, small-sized *Gephyrocapsa*, medium-sized *Gephyrocapsa* (=*G. oceanica* s.l.) of the MNN19b–c biozones of Calabrian stage, Santernian substage. This interval is overlain by siliciclastic–bioclastic sand facies organized into vertically-stacked trough and tabular cross-strata (Fig. 11A), with thickness ranging from 0.3 m (lower part) to 2.5 m (upper part). Cross strata form unidirectional sets mostly oriented E–SE, with a lower amount of bedforms showing opposite direction (W–NW) (Fig. 11B–D). Thickening-upward beds generally indicate deepening conditions (Rubin and McCulloch, 1980; Dalrymple and Rhodes, 1995), thus mixed deposits are inferred to record a transgressive episode.

In both the CP and SP examples, dunes are characterized by strata bundles attributed to neap-spring tidal cycles (Colella and D'Alessandro, 1988; Cavazza and Colella, 2001; Longhitano, 2011). Each bundle consists of rhythmically repeated couplets of alternating siliciclastic and bioclastic strata (Figs. 10E and 11E) with cyclic thickness changes attributed to the semi-diurnal tidal cycles (Longhitano, 2011).

3.2.3. The Calabrian side of the proto-Messina Strait (MS1)

The Messina Strait (MS) is a narrow linear basin (Zelilidis, 2003) presently located between Calabria and Sicily (Fig. 1). It formed in the Late Pliocene by normal faulting in a belt extending from western Calabria to southern Sicily (Ghisetti, 1984,1992; Monaco et al., 1996; Guarnieri et al., 2005). This NE–SW-oriented fault system is known as "Siculo-Calabrian Rift Zone" (Monaco and Tortorici, 2000; Finetti et al., 2005a; Catalano et al., 2008) and is associated with minor quasi-perpendicular faults, which control the present-day setting of the Sicilian Ionian coast (Tortorici et al., 1995; Finetti et al., 1996; Lentini et al., 1996; Jacques et al., 2001; Catalano et al., 2003).

From the Early–Middle Pleistocene onwards, Calabria and north-eastern Sicily were affected by strong uplift, the amount of which decreased laterally toward the north and the west (Ghisetti, 1981; Dumas et al., 1982; Westaway, 1993; De Guidi et al., 2002; Antonioli et al., 2006). This uplift was caused by displacement along extensional faults that controlled local domains of subsidence, including the Messina Strait (Ghisetti, 1981; 1992; Valensise and Pantosti, 1992; Monaco and Tortorici, 2000; Catalano et al., 2003).

The MS is presently characterized by sea-floor erosion in its narrowest sector, whereas sediments accumulate farther along the strait axis, as it enlarges. Here, strong currents generate coarse-grained dunes that migrate from north to south and *vice versa* (Ryan and Heezen, 1965; Selli et al., 1978). Currents, ranging in velocity from 1 to 3 m/s (Santoro et al., 2002), are generated by amplification of out-of-phase tidal cycles that occur every 6 h (Selli et al., 1978). These currents form dunes of medium to coarse sand to gravel up to 12 m high in a sublittoral to bathyal environment (Barrier, 1984; Montenat et al., 1987).

Similar deposits crop out along the uplifted Calabrian and Sicilian present-day margins of the strait, as discontinuous sandstone ridges roughly elongated along the original extension of the proto-Messina Strait. At the Calanna site (Fig. 12A), these ridges consist of vertically-stacked packages of dunes composed of mixed silici-bioclastic sandstones that yield *H. sellii*, *Pontosphaera* spp., *P. lacunosa*, small-sized *Gephyrocapsa*, medium-sized *Gephyrocapsa* (=*G. oceanica* s.l) of the MNN19b biozone (Calabrian stage, Santernian substage) (Fig. 3). The direction of migration of the cross sets suggests that the

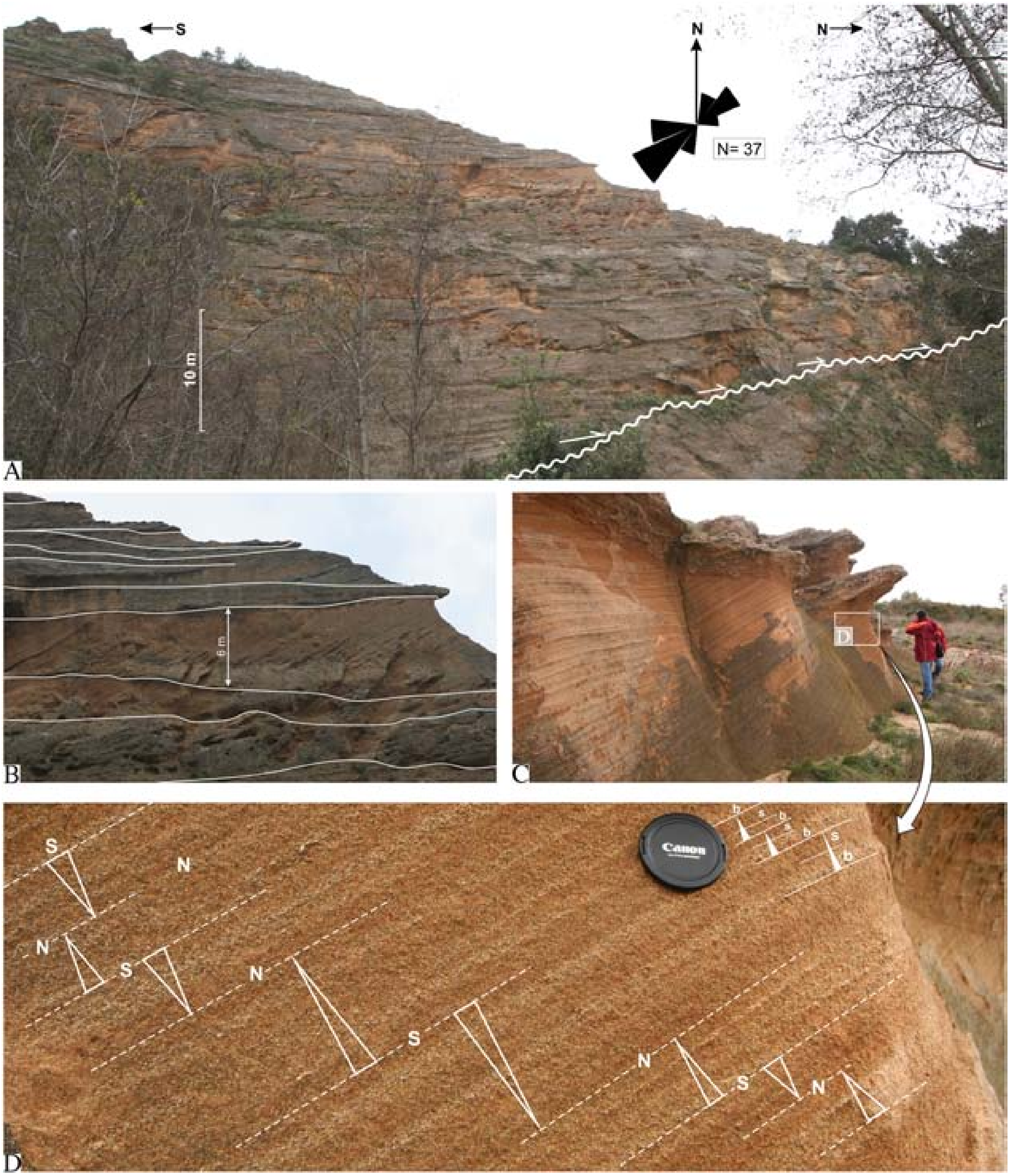


Fig. 9. Mt Pellegrino section in the Amantea Basin. (A) Vertically-stacked packages of cross sets generated by 2D large scale dunes developed in transgression over fan deltaic, coarse grained deposits (palaeocurrents are also shown). (B) 2D dunes onlap (white arrows) an unconformity surface (undulated white line), are up to 6 m high and characterized by a good lateral continuity (C). (D) Internally, cross lamination reveals exceptionally continue intervals of semi-diurnal silici-bioclastic bundles (*s*/*b*) and neap/spring (*N*/*S*) tidal cycles (lenscap 8 cm of diameter).

tidal flows migrated axially through the proto-strait and produced dunes of mixed sediment (Fig. 12A and B) organized into bundles of segregated bioclastic and siliciclastic particles (Fig. 12C–E), recording a tidal cyclicity of semi-diurnal to longer periodicity.

3.3. The successions of NE Sicily (Messina, Rometta and Barcellona Pozzo di Gotto)

Pliocene to Pleistocene successions of NE Sicily are relics of 100–200 m thick shallow to deeper marine uplifted deposits (Fig. 13) (Di Stefano et al., 2007; Di Stefano and Longhitano, 2009). These deposits record repeated episodes of marine flooding of engulfed coastal depressions affected by local tidal amplification (Messina et al., 2007; Di Stefano and Longhitano, 2009). These basins are related to the onset of the opening of the Messina Strait along the Ionian side of NE Sicily and to the opening of the Tyrrhenian Sea in the northern sector (Figs. 1A and 2C).

The overall Upper Oligocene to Pleistocene sedimentary succession of NE Sicily is subdivided into several unconformity-bounded depositional cycles, resulted from compressional to extensional

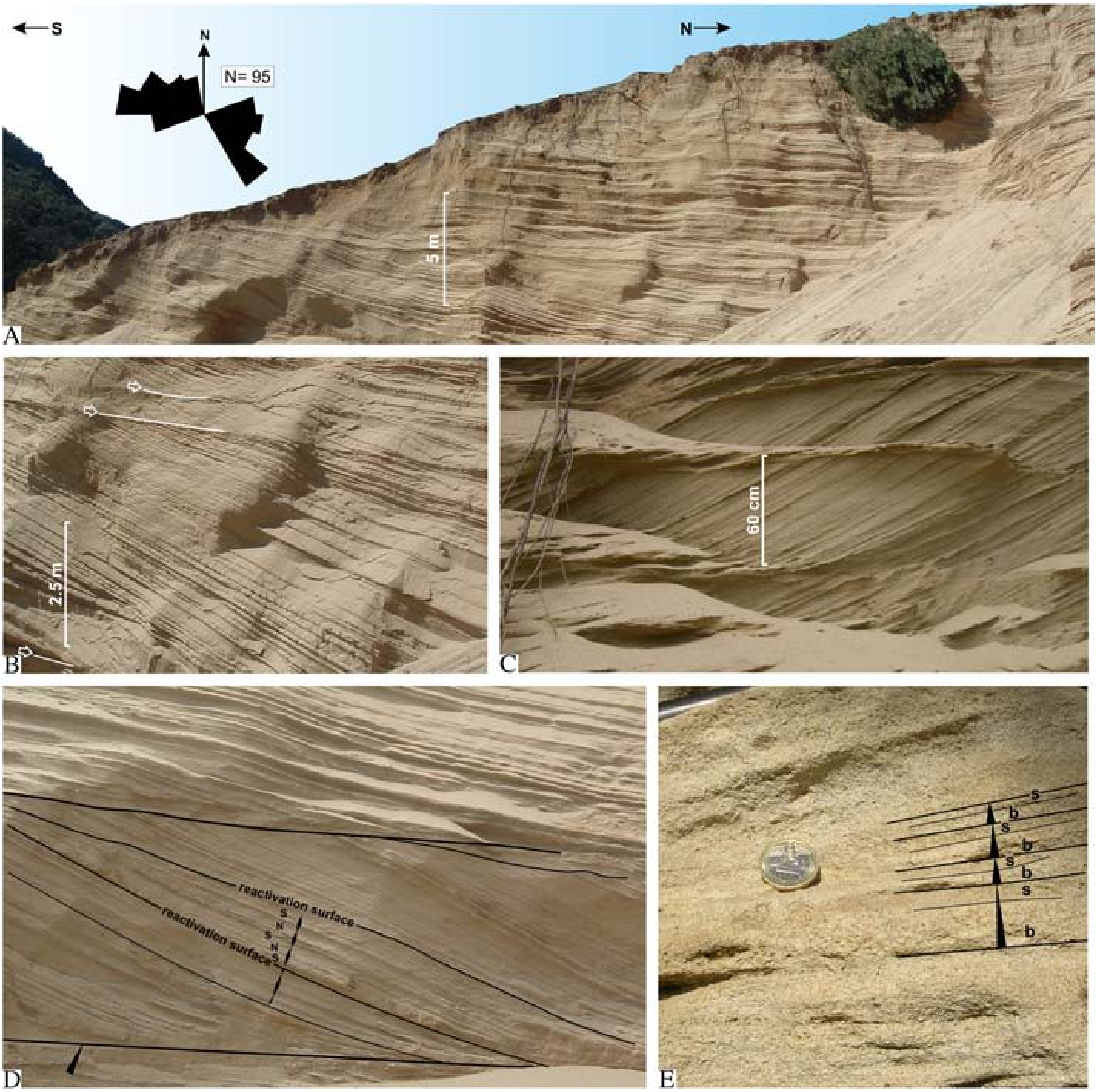


Fig. 10. (A) The Maida section studied in the Catanzaro palaeo-strait. (B) Large scale 2D cross sets are up to 3 m thick and mostly unidirectional (toward the right of the photo) (white arrows indicate discontinuity surfaces; palaeocurrents are also shown). (C) Close-up observations reveal cross sets locally interrupted by reactivation surfaces and coarsening- and fining-upward bundling of laminae of neap/spring origin (*N*/*S*) (D). (E) Lamina sets consist of bioclastic (*b*) and siliciclastic (*s*) bundles.

tectonic phases preceding the opening of the Tyrrhenian Basin (Lentini et al., 1995; Monaco et al., 1996; Guarnieri et al., 2005 and references therein). The extensional faulting fragmented the orogen into structural highs and subsiding local basins (Monaco et al., 1996), leading to the formation of a number of peripheral sub-basins (Seguenza, 1873–1877; Ogniben, 1960; Catalano and Cinque, 1995; Di Stefano and Lentini, 1995; Catalano and Di Stefano, 1997; Lentini et al., 2000; Finetti et al., 2005a; Di Stefano et al., 2007; Messina et al., 2007; Di Stefano and Longhitano, 2009).

The Middle–Upper Pliocene to the Middle Pleistocene successions cropping out between the sites of Messina, Rometta and Barcellona Pozzo di Gotto on the Tyrrhenian coast of NE Sicily (Fig. 13), were subdivided by Di Stefano et al. (2007) and Messina et al. (2007) into different depositional sequences on the basis of stratigraphic organization and biostratigraphic data. These depositional sequences are equivalent to the Lower to Middle Pleistocene succession of the Ionian coast of NE Sicily (Di Stefano and Longhitano, 2009). The deposits of the Upper Pliocene to Lower Pleistocene interval are mixed in composition, with a siliciclastic fraction that varies greatly, from schist- to quartz-dominated, depending on the nature of the neighboring source area. Sediments are organized into ripple- to dune-sized cross-bed sets.

3.3.1. The Sicilian side of the proto-Messina Strait (MS2)

A sedimentary succession similar and time-equivalent to the deposits observed along the Calabrian flank of the Messina Strait

Fig. 11. The Chiusa section in the Siderno palaeo-strait. (A) View of the main outcrop (palaeocurrents in the top-right corner). The succession is characterized by large scale, mostly unidirectional dunes (B) and ripples (C) that exhibit foresets of markedly segregated bioclasts and siliciclastic grains. (D) Foresets also reveal cycles of neap/spring (*N*/*S*) (hammer 35 cm long) and couplets of bioclastic–siliciclastic (*b*/*s*) pairs of laminae of tidal origin (F) (coin 2.5 cm of diameter).

(Calanna section; *c.f.*: par. 3.2.3) occurs west of the city of Messina (Scoppo section) (Figs. 4, 13 and 14A). These deposits bear nannofossil assemblages of the Middle Pleistocene MNN19f biozone, and are the remnants of the sedimentary succession filling the Sicilian side of the proto-Messina Strait (see Di Stefano and Longhitano, 2009 for a detailed list). This unit mainly consists of monotonous alternation of mixed sandstone and siltstone strata, made up of a bioclastic fraction of fragments of corals, serpulids and sponges, mixed with a siliciclastic fraction of quartz grains recycled from older sedimentary units. Skeletal material is moderately to highly degraded. It appears ubiquitously disarticulated, fragmented and commonly rounded and polished, due to both biological and physical processes of degradation. Sediments are dominated by tabular cross strata up to 1 m thick, with palaeo-flow directions ranging from N95°E to N300°E, alternating with massive to normally-graded beds up to 2.5 m thick (Fig. 14B). Cross strata are organized into vertically-stacked bidirectional cross-laminated sets, containing bundles of coarsening- and fining-upward intervals of laminae (Fig. 14C and D). A close up view reveals bioclasts and siliciclastic grains markedly segregated into couplets of laminae (Fig. 14E). This association is interpreted to represent proximal (marginal) strait deposit, where tidal dunes were incised by debris flows (Di Stefano and Longhitano, 2009). Cross strata bundles suggest neap/spring tidal cycles, while bidirectional cross-laminated sets indicate bundles of semi-diurnal tidal periodicities.

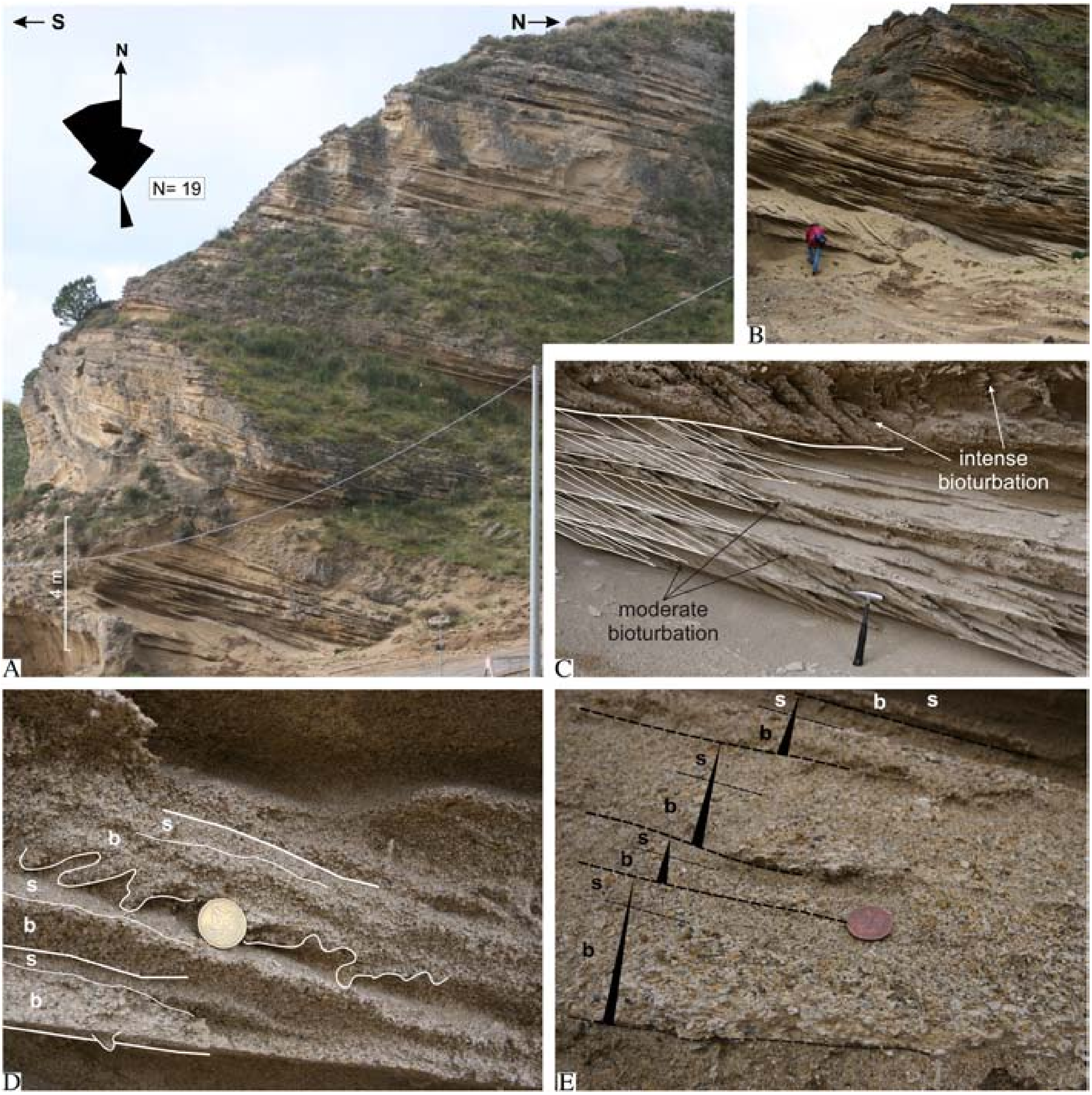


Fig. 12. (A) The Calanna section in southernmost Calabria preserves Lower Pleistocene deposits of the proto-Messina Strait (palaeocurrents in the top-left corner). (B) A closer view reveals cross sets generated by mostly unidirectional dunes and ripples. (C) Bioturbations is concentrated in discrete intervals and at the base of bioclastic laminae of mixed silici-bioclastic sediments (D) (hammer 35 cm long; coin 2.5 cm of diameter). Foreset lamination is characterized by bundles of segregated heterolithic particles (*b*/*s*) that reflect semi-diurnal to neap-spring tidal cycles (E) (coin 2 cm of diameter).

3.3.2. The Rometta Palaeo-bay (RP)

Along the Tyrrhenian coast of NE Sicily, 15–20 km W of the Messina Strait, a 160 m thick Middle Pliocene to Middle Pleistocene succession crops out near Rometta (Fig. 13). The succession which comprises shallow water to deeper marine environments, was studied in the San Cono section (Fig. 13). Di Stefano et al. (2007) identified three unconformity-bounded units overlying deformed bedrock. They partly correlate to the sequences documented in NE Sicily (*c.f.*: par. 3.3.1) (Di Stefano and Longhitano, 2009). The intermediate unit (R_2*Auct.*) contains calcareous nannofossil assemblages of the Rio et al.'s (1990) biozones from MNN19a (Gelasian) to MNN19e (Calabrian, Sicilian sub-stage) (see Di Stefano et al., 2007 for a detailed nannofossil list). Sediments are characterized by a terrigenous fraction made up of sedimentary- and metamorphic-derived rock fragments, mixed with bioclastic fragments that show sedimentological features very similar to the deposits documented by Messina et al. (2007) in the westernmost sector of this area. Mixed deposits observed in the San Cono section form vertically-stacked tabular to gently-undulated 0.5 to 1.2 m thick cross-sets (Fig. 15A), dominated by unidirectional palaeocurrents (Fig. 15B). Cross sets are internally organized into bundle cross lamination of alternating coarsening- and fining-upward intervals, cyclically bounded by reactivation surfaces (Fig. 15C). In turn, each bundle consists of rhythmic alternations of siliciclastic- and bioclastic-rich laminae organized into cycles of 20–25

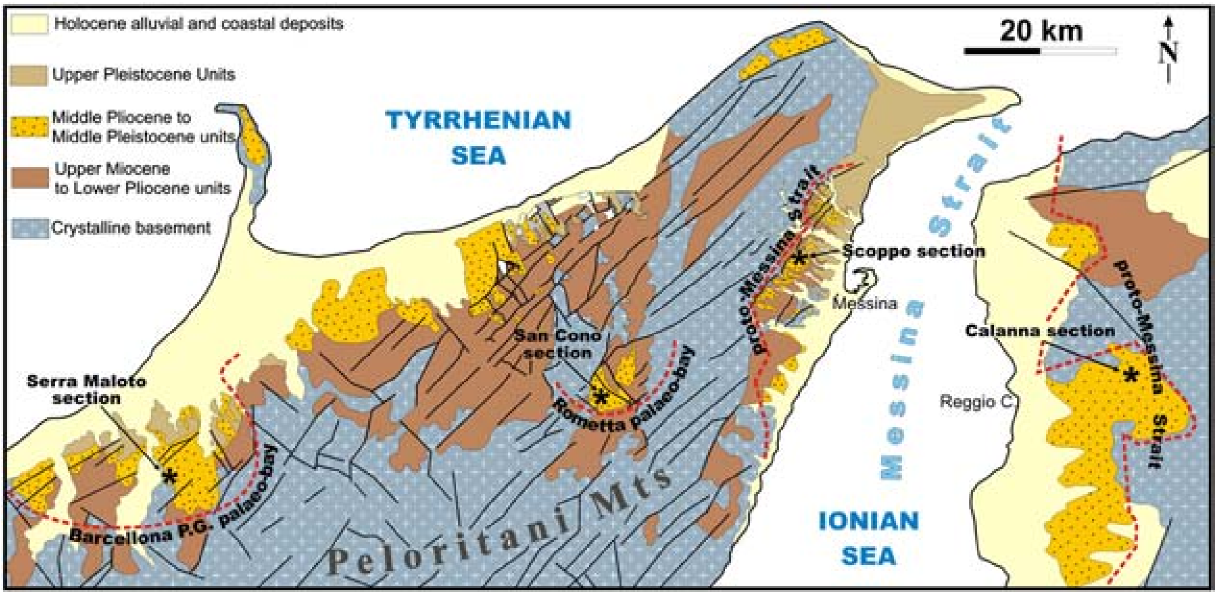


Fig. 13. Geological map of the NE Sicily and SW Calabria forming the present-day Messina Strait. Here, the studied sections of Calanna (in the Calabrian side) and Scoppo (in the Sicilian side) bear tide-influenced mixed deposits pertaining to the Lower Pleistocene proto-Messina Strait. Along the Tyrrhenian coast of NE Sicily, the other correlative successions of the Rometta (San Cono section) and Barcellona P.G. (Serra Maloto section) palaeo-bays were studied.
Modified, from Lentini et al., 2000.

laminasets (Fig. 15D). The direction of dune migration is towards the offshore and was interpreted as the result of basinward-directed powerful currents (*i.e.*: Mateu-Vicens et al., 2008; Puga-Bernabéu et al., 2010). Also for the Rometta succession, the occurrence of mixed deposits that were subjected to a tidal influence suggests the existence of an engulfed coastal palaeo-geography, where the tidal range may have been enhanced by diurnal to monthly resonances of the tidal wave with the bay length (Pugh, 1987; Messina et al., 2007).

3.3.3. The Barcellona Pozzo di Gotto Palaeo-bay (BPG)

The Plio-Pleistocene Barcellona Pozzo di Gotto (BPG) basin was studied by Barrier (1987), Kezirian (1993), Di Geronimo et al. (2002, 2005), and by Messina (2003) and Messina et al. (2007). The BPG basin represents a shelf embayment comprising two adjoining palaeo-bays formed by the flooding of bedrock fault-blocks in response to general tectonic extension (Messina et al., 2007) (Fig. 13). The basin-fill succession exceeds 200 m in thickness and comprises marine deposits of terrigenous to mixed silici-bioclastic composition recording different marine sedimentary environments affected by waves, storms, and tidal currents. Deposits were subdivided into two Plio-Pleistocene depositional sequences separated by an erosional unconformity (Messina, 2003; Messina et al., 2007). The transgressive interval of the upper sequence bears *G. rotula*, *Helicosphaera carteri*, *Pontosphaera spp*., *P. lacunosa*, *C. leptoporus*, small-sized *Gephyrocapsa*, "large" *Gephyrocapsa*, medium-sized *Gephyrocapsa* (=*G. oceanica* s.l.) of the MNN19d zone of Calabrian, Emilian substage. Mixed sediments of the lower sequence exhibit a compound tidal dune complex interpreted to be deposited in a mid-bay setting (Messina, 2003) (Fig. 16A) and overlain by open marine mudstones of the upper depositional sequence (Fig. 4).

Mixed sediments consist of fossiliferous marine sandstones up to 25 m thick that vary from silici-bioclastic in the lower part, to predominantly bioclastic in the uppermost part. The siliciclastic fraction shows a general fining upward trend and consists of quartz and other metamorphic fragments. The bioclastic content includes fragments of brachiopods, bryozoans, pectinid bivalves and subordinate fragments of crinoids and polychaetes recording an upward deepening trend (Di Geronimo et al., 2002; Messina, 2003). Deposits consist mainly of planar cross-stratified facies (Fig. 16B), showing rare burrows of *Skolithos* ichnofacies (Fig. 16C). Planar cross-strata sets are 0.25–1.4 m thick and are stacked upon one another defining cosets several meters thick (Fig. 16B and D). Foresets are generally composed of fining- or coarsening-upward siliciclast-rich strata alternating structureless bioclast-rich strata (Fig. 16E). Paleocurrent data indicate dune transport mainly towards the NNE (Messina, 2003).

The cross-stratified units are interpreted to represent tractional transport of mixed sand as straight- or sinuous-crested dunes (Harms et al., 1982), occasionally with superimposed ripples. The evidence of flow reversal, such as back-flow ripples, reactivation surfaces (Fig. 16D) and inter-stratal fine sand drapes indicate deposition by tidal currents (Reineck and Singh, 1975; Nio and Yang, 1991). The alternation of siliciclastic- and bioclastic-rich strata is interpreted as a result of the varying tidal current velocity.

The tidal signature documented in the BPG bay-fill sequence suggests existence of an embayment where tidal currents moved as long-period internal waves, possibly coming into resonance with the bay length (Pugh, 1987; Messina, 2003; Messina et al., 2007).

4. Discussion

4.1. The role of mixed silici-bioclastic sedimentation in tide-influenced microtidal settings

In the studied successions of southern Italy, mixed deposits exhibit different hierarchies of cross-stratification. Detailed observations reveal that ripple- and dune-sized units contain a tidal signature that can be recognized in the form of cycles of different periodicities.

The presence of mixtures of siliciclastic and bioclastic fractions allows to record subtler hydrodynamic processes than those detected in fully carbonate or terrigenous deposits.

The skeletal and non-skeletal components offer a different response to the same hydrodynamic processes (such as currents and waves). As the shear stress to the bottom or the velocity of a fluid flow cause grain motion, sedimentary particles respond depending on their specific density or morphometry (Mantz, 1977; Miller et al., 1977; Nelson, 1977; Allen, 1984c; Clifton and Dingler, 1984; Komar and Clemens, 1986). For instance, owing to their lower density and often platy or irregular shape, skeletal sands require a lower shear

Fig. 14. (A) The Scoppo section, on the Ionian side of NE Sicily, comprises tide-influenced mixed deposits pertaining to the succession of the Lower Pleistocene proto-Messina Strait (the upper unconformity marks the abrupt passage to Pleistocene coarse-grained deposits; palaeocurrents in the bottom-right corner). (B) Cross-stratified tidal dunes alternate with packages of multiple debris flow channelfills representing typical facies of strait margin. White arrows indicate the migration directions of dunes, while black arrows indicate fining-upwards trends within the channelized deposits. (C) Close-up view of the previous photograph showing the detail of tide-influenced cross stratification composed of bundles of coarsening- and fining-upwards foresets (migration direction is approximately normal to the outcrop surface), and recording repeated neap/spring (*N*/*S*) tidal cycles (hammer 35 cm long). (D) Tabular cross-strata sets with bidirectional foreset directions, representing flood-ebb tidal cycles in the sublittoral zone of the Lower Pleistocene proto-Messina strait. (E) Close-up detail of the same outcrop, showing the alternation of siliciclastic (*s*) and bioclastic (*b*) foreset laminae (coin 2.5 cm of diameter).

stress to initiate transport if compared to siliciclastic grains (Maiklem, 1968; Braithwaite, 1973; Clifton and Dingler, 1984; Prager et al., 1996). For this reason, heterolithic sediments provide a different petrophysical response if entrained by a fluid in motion (Collins and Rigler, 1982; Komar and Clemens, 1986), generating a specific internal segregation of bioclastic and siliciclastic particles (Longhitano, 2011).

This significant diversity, which until recently has drawn relatively little consideration and has not been documented with respect to tide-influenced environments, may affect transport rates, cause differential sediment entrainment and lead to the formation of specific stratification varieties in mixed deposits (Meyer and Krauser, 1998; Longhitano, 2011).

The tidal structures recognized are those most common in tidalites (Klein, 1971; Kvale et al., 1989; Kvale and Archer, 1990; Archer, 1991; Nio and Yang, 1991; Archer, 1996). However, additional features can be identified.

Firstly, tidalites in mixed sediments show a highly varied percentage in the silici-/bioclastic ratio. Their respective content depends on several

Fig. 15. (A) Gelasian–Calabrian mixed interval of the bay-fill succession cropping out nearby Rometta (the unconformity marks the base of the succession; palaeocurrents in the top-right corner). (B) In the San Cono section, this interval is made up of coarse siliciclastic sand admixed to granule-sized bioclasts, forming vertically-stacked succession of cross sets, generated by mostly unidirectional dune and ripple migration. (C) Detail of a package of cross-stratified tabular to undulated cross sets. Note the presence of reactivation surfaces comprising foreset intervals of tidal bundles in the lowermost cross set (hammer 35 cm long). (D) Close-up view of the previous photograph showing fining- to coarsening-upward foreset laminae that reflect neap/spring (*N*/*S*) tidal cycles.

factors, including: (i) the relative abundance of carbonate-shelly organisms within the tide-influenced environments; (ii) the relative distance of the carbonate factory from the terrigenous input or from the accumulation area; (iii) the intensity of winnowing processes that, in turn, depend on the hydrodynamic zonation of the sublittoral zone; and (iv) the energy of the hydrodynamic processes, that can be responsible for sorting of heterolithic material of different specific density.

Secondly, recent observations have demonstrated that the bioclastic fraction is constituted mostly of heterozoan skeletal associations (*sensu* James and Clarke, 1997), including bryozoans, bivalves, echinoids, brachiopods, coralline red algae and benthic foraminifera. In contrast, the siliciclastic content varies greatly among different areas. For instance, in Basilicata, in the areas of Acerenza, Oppido Lucano, Tolve and Tricarico, the siliciclastic fraction derives from sedimentary rocks, whereas, in the mixed interval of the Amantea Basin, as well as in the tidal deposits of the Siderno and Catanzaro palaeo-straits, it consists predominantly of metamorphic and calcareous fragments, derived from the crystalline basement and carbonate Mesozoic successions of the Calabrian Arc (Chiarella and Longhitano, 2008; Chiarella et al., 2009; Longhitano et al., 2010).

4.2. Tidal cycles of different periodicity recorded in mixed deposits

Astronomical tidal cycles are characterized by different periodicities, including: (i) semi-diurnal or diurnal flood-ebb cycles; (ii) half-monthly neap-spring cycles; (iii) semi-annual equinoctial cycles;

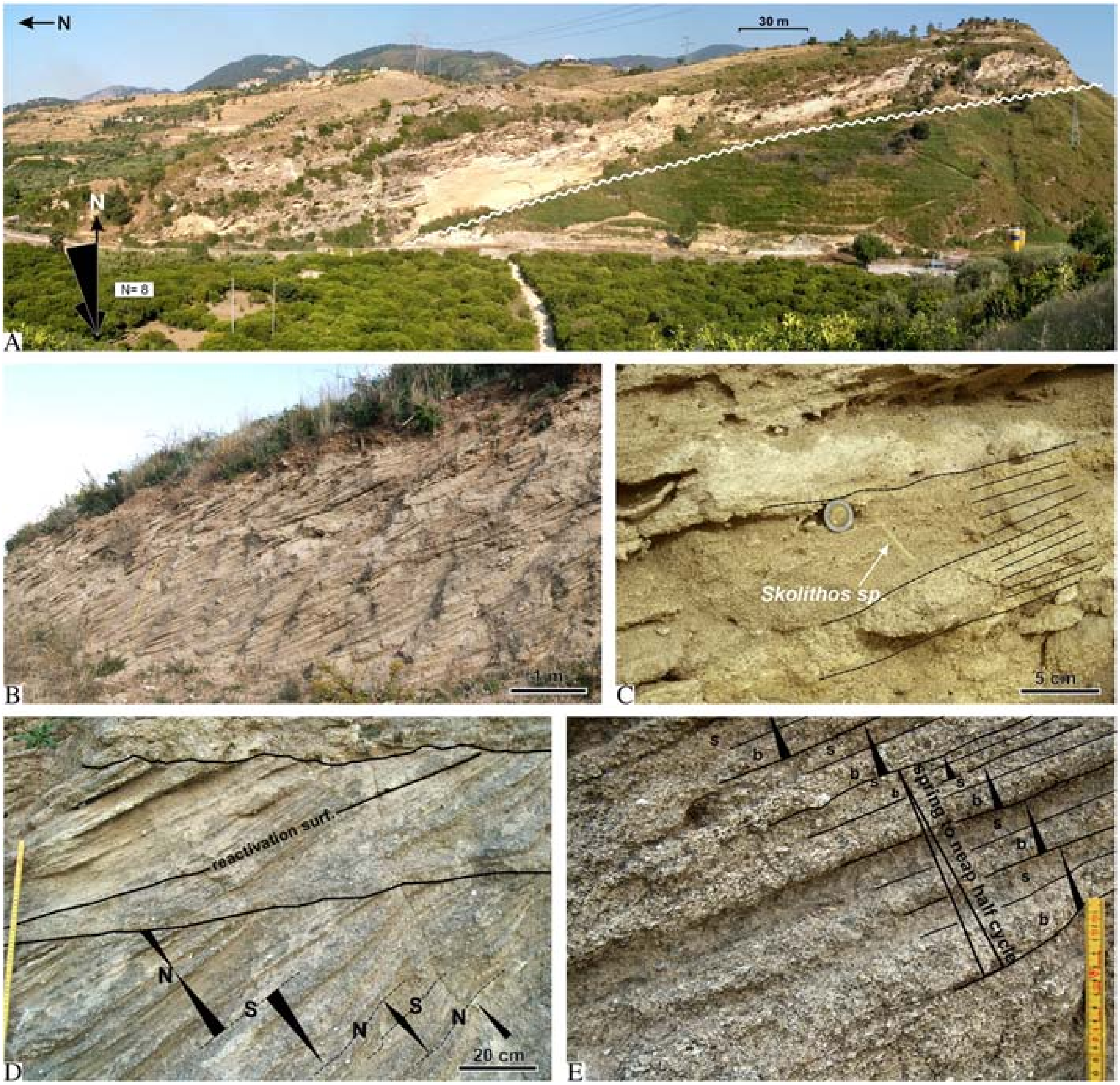


Fig. 16. Outcrops of the Serra Maloto section, from the Barcellona P.G. Basin. (A) The mixed interval of the succession is locally organized into a compound tidal dune complex, locally affected by synsedimentary tectonics (the unconformity marks the base of the succession; palaeocurrents in the bottom-left corner). (B) Sediments exhibit mostly unidirectional small scale cross sets, locally affected by intense bioturbation (C). (D) Foresets are characterized by reactivation surfaces, neap/spring (*N*/*S*) tidal cycles and by bundles of segregated bioclastic (*b*) and siliciclastic (*s*) laminae, observed at a close-up view (E).

(iv) 8.8-year lunar apside cycles, and (v) 18.6-year nodal cycles (Pugh, 1987; de Boer et al., 1989; Archer et al., 1991; Kvale et al., 1995). Each of these cycles can potentially be included in the rock record, depending on the characteristics of the depositional system and on the relative magnitude of the individual forcing factors (Archer et al., 1991; Yoshida et al., 2007).

The observations of the present study suggest that the tidal signal recognized in the Neogene to Quaternary mixed deposits of southern Italy occurs with different cyclicities. The dominance of short- *versus* longer-term tidal cyclicity appears to be mostly dependent from the palaeo-geographic setting, bay or strait, in which the mixed deposits accumulated.

4.2.1. Tide-influenced bay successions

Mixed deposits of Basilicata were interpreted as originated from coastal wedges prograding along gently-inclined sublittoral shelves of complex engulfed shorelines (Chiarella and Longhitano, 2008). These sediments were subjected mostly to the influence of waves, except for protected areas (i.e., confined gulfs or embayments). In such settings (e.g., Dixon et al., 1995; Leckie and Rumpel, 2003; Yoshida et al., 2004), semi-diurnal and/or diurnal tidal cycles may have been amplified in their range, producing tide-modulated downwelling currents characterized by slight but cyclical changes in their velocity (Fig. 17). These repeated variations in the current energy may have generated the migration of ripples and small-scale dunes (up to 0.7 m

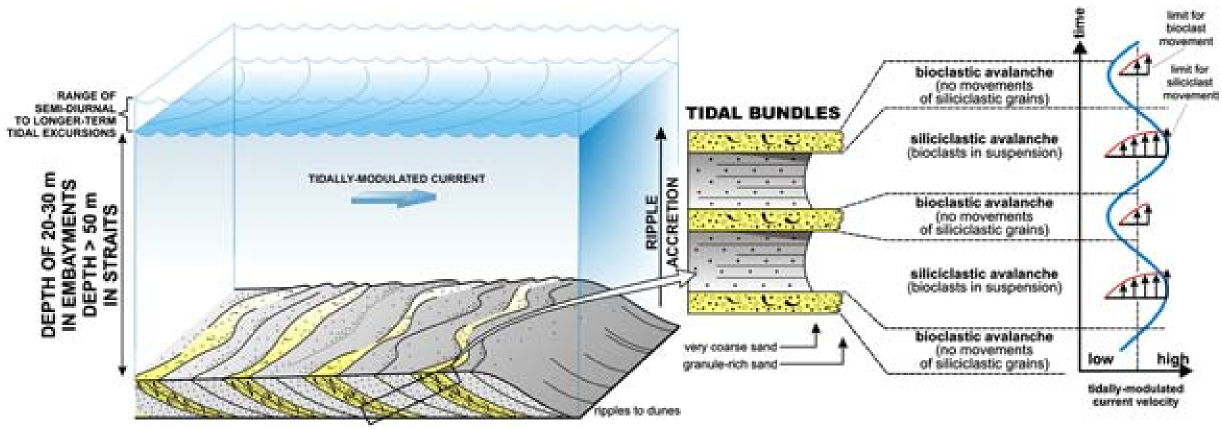


Fig. 17. Tide-influenced, mixed deposits accumulated in shallow to deeper marine environments, where tidal currents encountered favorable conditions for tidal amplification in microtidal settings. The resulting tidal facies consists of alternating siliciclastic and bioclastic cross-strata, the former reflecting the dominant tidal current and the latter recording the transition to the ensuing slack water stage. The consequent heterolithic cross-stratification may be considered as the result of a tide-modulated current, characterized by cyclical variations of current competence consistent with tidal periodicities of different duration.
Modified, after Longhitano, 2011.

thick) with a marked segregation of bioclast- and siliciclast-rich foreset laminae. Accordingly, currents with higher velocity occurred during the transition from high to low tide accumulating siliciclastic foresets, maintained the bioclastic fraction in suspension. Successively, as the current energy decreased during the ensuing variation from low to high tide, the bioclastic fraction was included in the avalanches, producing carbonate skeletal-rich foresets (Longhitano and Chiarella, 2008; Longhitano et al., 2010; Longhitano, 2011). Only the shorter-term, diurnal and monthly tidal cycles were preserved in the rock record (Figs. 6, 7, 15 and 16). High energy storms entering the most engulfed parts of these basins generated unsteady conditions, disrupting the tide-modulated cross-stratified deposits. Consequently, longer-term periodicities were most likely obliterated or possibly unrecorded. Therefore, gulfs and bays are most likely to record short-term periodicity tidal cycles in microtidal settings.

4.2.2. Tide-influenced strait successions

Tidalites detected in mixed deposits of palaeo-straits generally exhibit additional tidal cycles of longer periodicities, if compared to the previously described tidal facies. Marine passageways that commonly characterized the Calabrian Arc during Neogene to Quaternary times, were associated with energic unidirectional or bidirectional currents capable of transporting sand and gravel through the migration of large dunes up to 10 m thick (Colella, 1995; Cavazza and Colella, 2001; Longhitano and Nemec, 2005). These high-energy environments mostly recorded half-monthly neap/spring to semi-annual equinoctial cycles and 8.8-year lunar apside tidal cycles, in addition to diurnal cycles. This conclusion is suggested from the abundance of bundles of thickening- to fining-upward packages of laminae that characterize the cross-stratified deposits. For instance, in the area of the Catanzaro Basin, where the terrigenous fraction of mixed deposits is represented by fragments of metamorphic rocks (Chiarella et al., 2009), the chromatic contrast between the dark crystalline particles and the light bioclastic particles allows to recognize a mutual segregation of grains of different specific density (Fig. 17). Bundles are formed by a gradual decrease of grain size accompanied by an enrichment of bioclasts, which conforms to the decreasing energy of a spring-to-neap half-cycle. Here, bioturbation is concentrated along the foreset interval accumulated during the lower energy stages of tidal cyclicity. Conversely, increase in clast size is accompanied by a gradual increase in abundance of fragments of crystalline rocks. Very similar sedimentological evidence has been recognized in the other strait successions reported in this study, including the Amantea Basin, the Siderno and the Messina palaeo-straits (Figs. 9–12).

5. Implications for palaeogeographic reconstructions

Mixed sequences exposed in southern Italy form lithosomes of variable geometries and architectures that, in the vast majority of the studied examples, exhibit cross-stratification of different dimensions and hierarchies. Mixed deposits indicate shallow water to sublittoral conditions that often evolve upward into deeper-marine, outer-shelf environments forming transgressive sedimentary sequences (e.g., Colella and Vitale, 1998; Tropeano and Sabato, 2000; Pomar and Tropeano, 2001; Massari and Chiocci, 2006; Di Stefano and Longhitano, 2007; 2009; Longhitano et al., 2010). The presence of overlying open marine mudstones preserved the tidal cycles, except where tectonics was very active (e.g., Messina Strait).

Tidal influence is documented in modern microtidal settings along engulfed or funnel-shaped coastlines, where the tidal wave enters in resonance with the length of the bay (e.g., Pugh, 1987; Sztanó and de Boer, 1995). The tidal wave may also be significantly increased if forced to flow through a shallow or narrow inshore profile. These conditions favor semi-diurnal or diurnal tidal oscillations to be recorded in the sediments. These coastal areas are also subjected to storm waves that may generate erosion rather than deposition of sediments, producing interruption of the sedimentary record and the impossibility to preserve tidal cycles of longer periodicity in the bay.

In strait settings, cross-stratified deposits influenced by tidal processes occupied sectors characterized by sublittoral to bathyal environments (Barrier, 1987; Martinsen, 2003a,b; Le Bot and Trentesaux, 2004). For this reason, fair-weather or storm waves were unable to influence the tidal circulation, producing a certain steadiness in the tidal currents and, therefore, the possibility of a most continuous sedimentary record within the dune foresets in case of longer-term tidal cycles.

In modern examples of Mediterranean straits, such as the present-day Messina Strait, tide-generated traction currents flow at velocity ranging from 1 to 3 m/s (Santoro et al., 2002) producing gravelly, rather than sandy, dunes that migrate along the bottom. These velocities are too strong for finer (sandy) sediment accumulation and, when present, they produce erosion rather than deposition in the central and narrowest part of a strait (Longhitano, 2011). When tide-influenced cross-stratified sandy deposits occur in ancient examples, they may indicate lower current energy (Nelson, 1977). This is particularly true in the case of mixed silici-bioclastic sediments, because heterolithic particles are differently subjected to hydraulic forces, depending on their density and shape (Prager et al., 1996).

The thickness of a cross bed is expected to vary consistently with the flow strength (Stride, 1982; Allen, 1984a). Accordingly, large dunes are

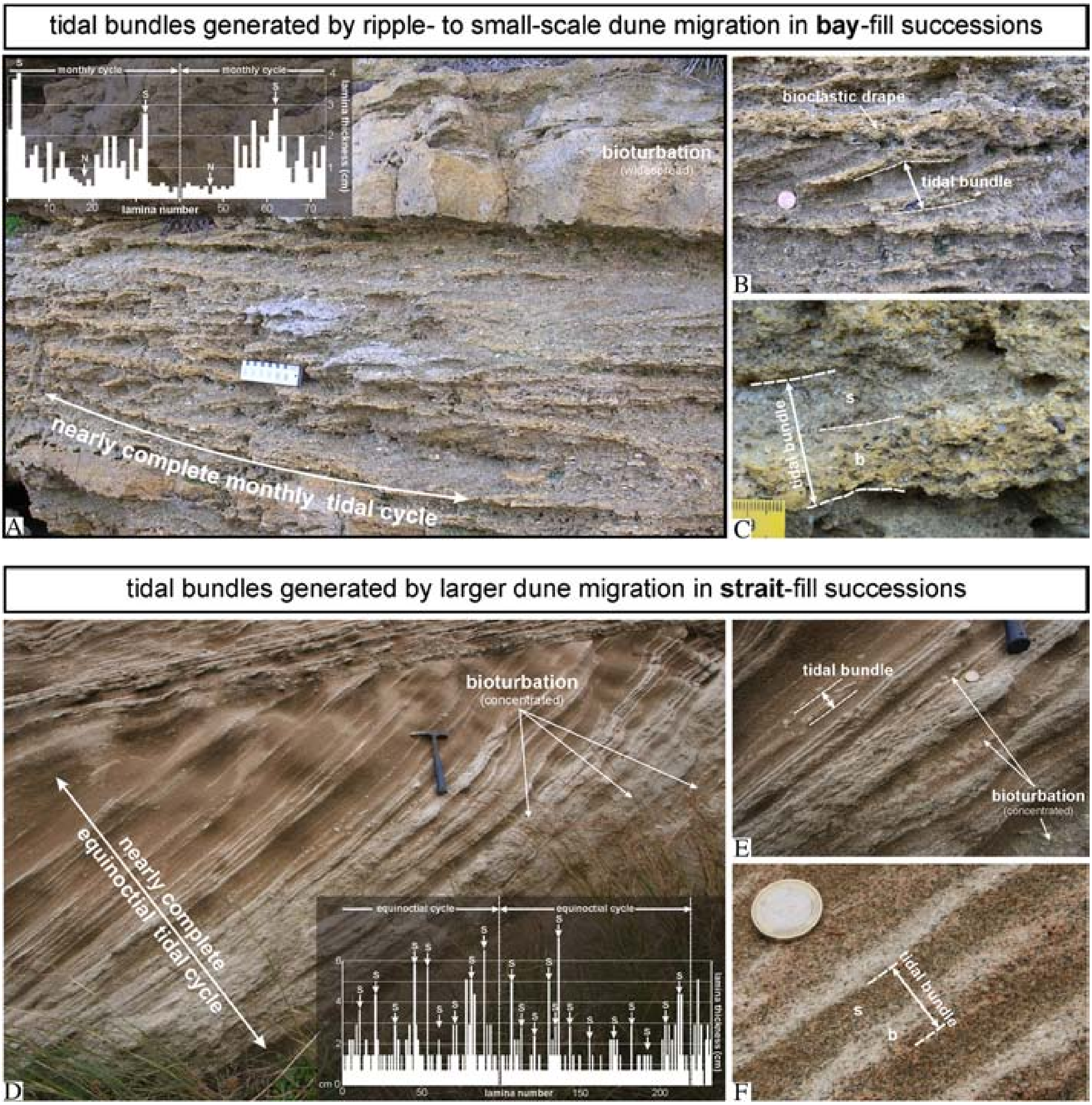


Fig. 18. Comparison between the two main types of tidal facies detected in the present study. (A) Bay-fill, tide-influenced mixed successions show dominantly ripple- to small-dune scale cross-strata (grain size comparator 12 cm long). The histogram shows semi-diurnal to monthly tidal cycles counted from lamina thickness (s = spring; n = neap). (B) The tidal facies consists of a repetition of bioclast- (*b*) and siliciclast- (*s*) rich foresets, characterized by frequent reactivation surfaces, where a pair of laminae corresponds to a single tidal bundle (C). Semi-diurnal to neap/spring cycles are the most frequent short-term tidal periodicities recorded in this facies. Bioturbation is widespread. (D) Strait-fill, tide-influenced mixed deposits are characterized by dunes of larger dimension which record longer-term tidal periodicities, from semi-diurnal to monthly to equinoctial cycles [see histogram; only spring (s) picks are indicated]. (E) Also in this case, a single tidal bundle consists of a bioclastic (*b*) and siliciclastic (*s*) pair of laminae (F). Bioturbation is concentrated in horizons where the stronger tidal currents declined, producing a temporary optimum for biological activity record.

commonly generated by powerful traction currents, whereas smaller dunes or ripples record flows of minor energy (Allen, 1984b).

The field examples documented for the mixed cross-stratified deposits of the Neogene–Quaternary of southern Italy reveal that ripple-sized bedforms observed in palaeo-bays or embayments, including the Acerenza–Oppido Lucano–Tolve, Rometta and the Barcellona P.G. basins (Fig. 18A), are very abundant in bioclasts and frequently interbedded with drapes made of skeletal particles that suggest momentary arrests of traction currents and consequent settling of suspended bioclastic material (Fig. 18B and C). Therefore, deposits of palaeobays may possibly be enriched in bioclasts independently from the amount of carbonate factory. Conversely, bedforms of larger dimension, such as the large-scale dunes observed in the Amantea Basin or in the Catanzaro and Siderno palaeo-straits (Fig. 18D) which are up to 7–8 m thick, are formed by terrigenous-dominated mixed sediments, with a siliciclastic fraction >65% (Fig. 18E and F). This component may become preponderant if the dune field was not directly influenced by the vicinity of an active carbonate factory.

Therefore, different tidal cyclicities and varying heterolithic sediment composition in cross-stratified tide-influenced mixed deposits may be related to very different palaeo-geographic scenarios, where these sediments accumulated. This is of crucial importance in palaeo-geographic reconstructions supported by facies analysis studies on mixed tide-influenced sediments that may be, as in the present case, intensely deformed and discontinuous because of subsequent tectonic events. Additionally, studies of reservoir modeling of ancient mixed deposits dominated or influenced by tides, may be better constrained if supported by observations on the dominance of a specific type of tidal cycle or the percentage of siliciclastic *versus* bioclastic fraction in the sediment.

6. Conclusions

The stratigraphic intervals examined in this study derive from Neogene to Quaternary basin-fill successions of the southern Italy orogenic belt. These deposits commonly consist of mixed, silici-bioclastic arenites, characterized by a diffused presence of cross-stratification at different scales. All the observed examples indicate that sediment accumulation occurred during rapid, tectonically-driven transgressions of parts of open to confined marine basins developed in the central Mediterranean, which was subjected to a microtidal regime from the Neogene to Present.

Specific types of facies documented in some of the best-exposed Upper Miocene to Middle Pleistocene successions, from Basilicata, to Calabria, to NE Sicily, have been interpreted as the result of the influence of tidal processes. Tidal influence or dominance on sedimentation in microtidal basins can be justified if related to specific geomorphological settings of semi-confined coastal embayment or straits, where semi-diurnal to longer-term tides can be variously amplified.

Mixed deposits observed across southern Italy are characteristically composed of an extrabasinal terrigenous fraction admixed to an intrabasinal bioclastic fraction, deriving respectively from the consumption of older bedrock units and from an *in situ* or near *situ* heterozoan carbonate factory. Tidal cycles have been detected in laterally-accreted, cross-stratified deposits of mixed composition, where repeated rhythmic alternations of siliciclastic and bioclastic laminae vary consistently with semi-diurnal to monthly and yearly tidal periodicities.

Two main tidal facies have been documented among the several localities where mixed, tide-influenced deposits have been studied: (i) short-term tidal periodicities recorded within ripple-scale and small (<1 m thick) dune-scale foresets, have diffusely been detected in shoreface mixed successions of palaeo-bays; (ii) contrarily, longer-term tidal cycles have been recognized in large-scale cross sets (>6 m thick), accumulated in deeper environments of palaeo-straits. The occurrence of tidal cycles of short duration (semi-diurnal to neap/spring) in small-scale bedforms is attributed to the specific conditions of sublittoral environments sufficiently isolated from the open marine and subjected to the tidal amplification only during fair-weather periods. In contrast, tidal cycles of longer duration (neap/spring to equinoctial) may have been recorded in palaeo-straits, where large-scale bedforms migrated under *quasi*-steady conditions of current propagation.

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