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Deformed cross-stratified deposits in the Early Pleistocene tidally-dominated Catanzaro strait-fill succession, Calabrian Arc (Southern Italy): Triggering mechanisms and environmental significance

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ABSTRACT

The Early-Pleistocene Catanzaro strait-fill succession consists of large-scale tidal sets, accumulated in a tectonically confined basin during a phase of rapid relative sea-level rise. It crops out mainly in the present-day Catanzaro Trough where numerous field sections supported the characterization of the vertical and lateral facies variations and the documentation of a variety of soft-sediment deformation structures, exposed throughout their vertical and lateral extents. The soft-sediment deformation structures (SSDS) are the result of liquefaction and fluidization processes that deformed cross-laminations and other primary structures into folds, fluid-escape structures, and structureless expanses. Three different groups of SSDS have been documented in the cross-stratified deposits of the Catanzaro strait. The detailed description of these soft-sediment deformation structures in a depositional context established by facies analysis enables interpretation in terms of possible trigger mechanisms. Consistent relationships between the occurrence of distinctive SSDS and specific tidally dominated facies have been established, indicating a probable autogenic origin for the soft-sediment deformations. Liquefaction and fluidization features are interpreted as the result of increases in water pore-pressure, induced by overloading. In particular, two types of overloading agents are hypothesized, which affect the lee and stoss sides of the migrating dunes in distinct events, and inducing the deformation of foreset laminae or sets of cross-strata, respectively.

1. Introduction

Soft-sediment deformation is widespread in cross-stratified deposits since they typically show a loose and metastable texture related with the high porosity of the particles packing (Kolbuszewski, 1953; Owen and Moretti, 2011). In fact, deformed cross-strata (*sensu* Allen, 1982) are widely reported in fluvial (*e.g.* Jones, 1962; Hobday and Von Brunn, 1979; Turner, 1981; Owen, 1995; Samaila et al., 2006) and aeolian deposits (*e.g.* Rice, 1939; Robson, 1956; Steidtmann, 1974; Horowitz 1982; Glennie and Buller, 1983; Bryant and Miall, 2010). Allen and Banks (1972) and Hendry and Stauffer (1975) have grouped all kinds of soft-sediment deformation structures occurring in cross-stratified sedimentary units in three main types. Type I is represented by simple overturned foresets forming recumbent folds (with a sub-horizontal axial plane) that involve only the middle or upper part of the bed ("recumbent-folded deformed cross-bedding" of Allen and Banks, 1972; "parabolic recumbent deformed cross-bedding" of Doe and Dott, 1980). Type II shows various irregular folds that differ in scale, morphology and orientation of the axial planes occurring near the top of cross-bed set ("crumpled or buckled cross-bedding" of Wells et al., 1993). Type III includes more complex deformation showing randomly oriented folded laminae that can be faulted and, locally, primary cross-stratification can be totally obliterated ("disharmonically buckled cross-bedding with faults" of Wells et al., 1993). Types I and II seem to be more frequent in fluvial settings, with rare examples in transitional deposits, while Type III has been described only in aeolian successions and is mainly interpreted as result of seismically-induced liquefaction (Allen and Banks, 1972; Allen, 1982; Bryant and Miall, 2010). Two main genetic mechanisms have been invoked for the Type I and Type II deformation of cross-stratified deposits (see a complete review in Wells et al., 1993): (i) sliding of sediment down the frontal surface of an advancing cross-stratified sand body (Rice, 1939; Rust, 1968; Puga-Bernbabèu et al., 2010); and (ii) current drag action on the underlying liquidized cross-stratified sets (Robson, 1956; Allen and Banks, 1972; Owen, 1987, 1996). The trigger mechanism for the complete liquefaction or decrease of shear strength in the cross-stratified units is under debate too being be interpreted as result of:

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(a) earthquakes (Selley, 1969; Allen and Banks, 1972; Mazumder et al., 2006); (b) wave action (Dalrymple, 1979); (c) overloading/sand-laden flood (Coleman, 1969; Hendry and Stauffer, 1975; Yagishita and Morris, 1979); (d) flow regime changes as in the dune/plane-bed transition (Røe and Hermansen, 2006); and (e) sudden changes in the groundwater level (Williams, 1970).

Tidal deposits contain large portions of cross-stratified sand that are susceptible to liquefaction (high initial porosity/void ratio). Moreover, cross sets for their non-conformable shape, highlight any liquefaction-induced disturbances. Nevertheless, in literature, there are few examples of deformed cross-lamination in tidal deposits (Anderton, 1976; Mazumder, 2006; Longhitano et al., 2014).

In this paper, several well-exposed stratigraphic sections of the Early Pleistocene tidally dominated Catanzaro strait-fill succession (Calabrian Arc, Southern Italy) are described. Here, deformed cross-strata with different morphologies and shapes, in association with other soft-sediment deformation structures, characterize the tidal deposits at various stratigraphic intervals. Facies associations involved in the deformation processes and the SSDs have been described in agreement with the procedures suggested by Owen and Moretti (2011) and Owen et al. (2011). Main aims of this study are to (i) describe the variable morphologies of deformed cross-laminae, (ii) interpret mechanisms of deformation and trigger agents, and (iii) establish the environmental significance of soft-sediment deformation in tidal settings.

2. Geological setting

The Calabrian Arc connects the NNW-trending Southern Apennine Chain with the Maghrebian Chain of Sicily (Bonardi et al., 2001) (Fig. 1). This small orogen mainly consists of Hercynian metamorphic and intrusive rocks, tectonically superposed on ophiolite-bearing units of Tethyan affinity, in turn overlying Mesozoic carbonate platform limestone of Apennine affinity (Tortorici, 1982). The Arc comprises remnants of a former belt of Late Cretaceous(?)–Eocene age superimposed onto the Apennine Chain during the opening of the Tyrrhenian back-arc basin, which occurred during the middle Miocene (Gueguen et al., 1997). The opening of the western Tyrrhenian Sea was associated with the onset of intense thrusting in the Apennine chain, in relation with the progressive migration of the Calabrian Arc over the subducting Ionian lithosphere (Malinverno and Ryan, 1986; Critelli et al., 2013; Maffione et al., 2013). This migration resulted from the development of regional SE- and ESE-trending strike-slip fault zones and differently oriented normal fault sets (Knott and Turco, 1991; Tansi et al., 2007; Zecchin et al., 2015).

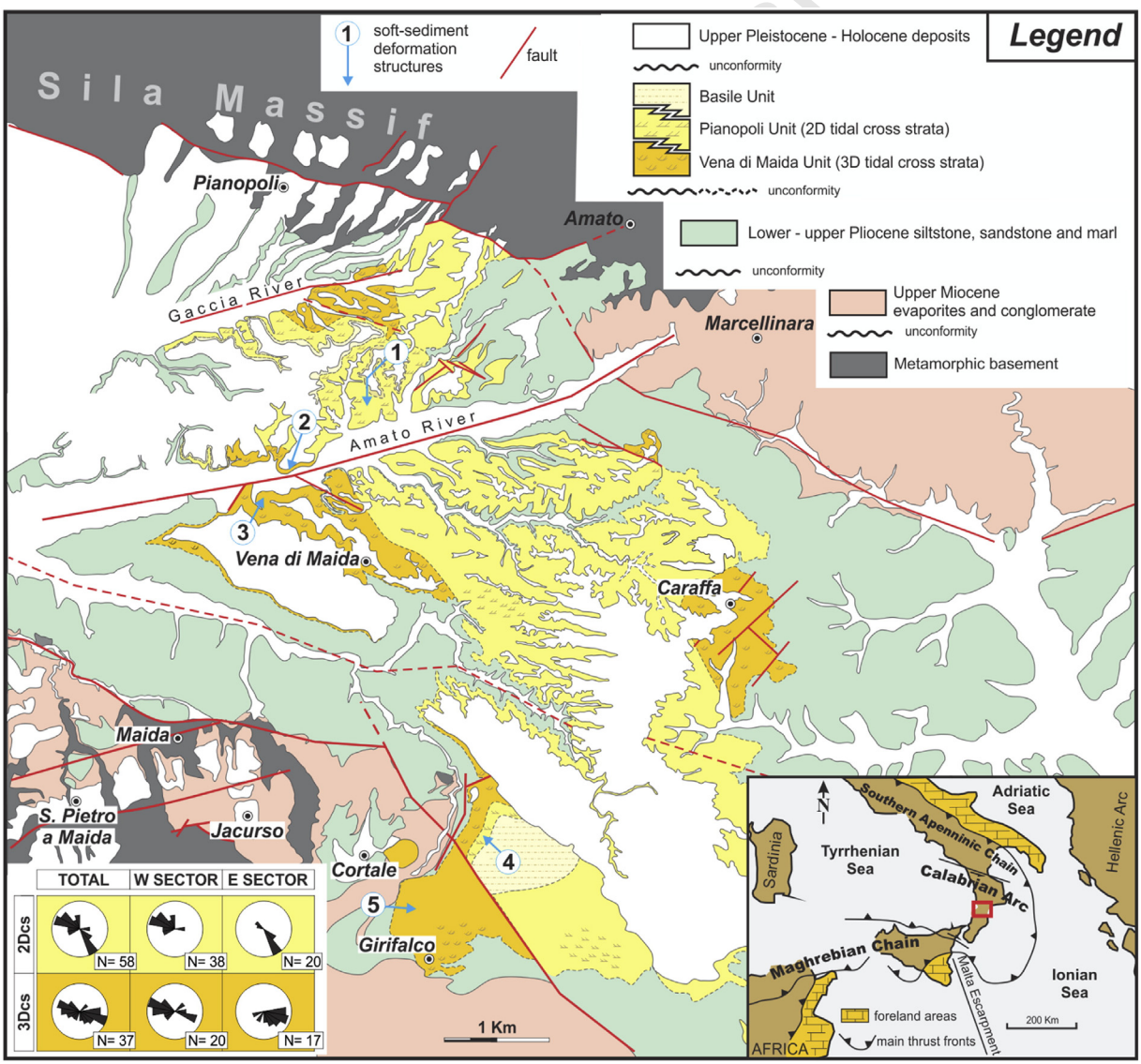

Fig. 1. Geological map of the central Catanzaro Strait, showing the aerial distribution of 3D and 2D tidal cross-strata. The inset shows the location of the study area within the Calabrian Arc (modified after Chiarella, 2011 and Longhitano et al., 2014).

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From the Late Pliocene to Pleistocene, some parts of the back-arc zone were affected by extensional tectonic phase, WNW–ESE oriented, superimposed on strike-slip deformations, which resulted in the development of narrow transversal basins, such as the Catanzaro, Siderno and Messina straits, linking the Ionian Sea to the Tyrrhenian Sea with sublittoral sedimentation (Colella and D'Alessandro, 1988; Argnani and Trincardi, 1993; van Dijk et al., 2000; Chiarella et al., 2012a, 2012b; Longhitano, 2011; Longhitano et al., 2012; Longhitano et al., 2014; Chiarella, 2016) (Fig. 1B). Along these straits, tidal currents were amplified (Mercier et al., 1987; Di Stefano and Longhitano, 2009; Longhitano et al., 2012), generating the accumulation of siliciclastic tidalites characterized by large-scale (>1 m thick) cross-stratifications and a wide range of facies heterogeneities (Longhitano et al., 2014). During the lower Pleistocene, the Catanzaro Strait was tectonically active experiencing a change from left-lateral to right-lateral kinematics as the result of the rotation of field strength (Brutto et al., 2015).

3. Sedimentary facies associations

The Lower Pleistocene (Calabrian) Catanzaro strait-fill succession (up to 100 m thick) in the Catanzaro Basin records accumulation of tidal deposits composed by siliciclastic sediments derived from a metamorphic basement in the Sila and Serre Massifs (Fig. 2A) and bioclastic sediments derived from an *in situ* carbonate factory (Chiarella, 2011; Longhitano et al., 2014). The lower Pleistocene cross-stratified deposits occur above mudstone and marls (Fig. 2B) considered time-correlative with the Trubi Formation, and representing the stratigraphic record of the transgressive event at ~5.3 Ma ago that re-established open-marine conditions in the Mediterranean area after the Messinian salinity crisis (Krijgsman et al., 1999; Bache et al., 2012). The cross-stratified deposits, in turn, are overlain by highly bioturbated fine-grained sandstone, siltstone and claystone with abundant articulated bivalves and ichnofauna (Chiarella, 2011) (Fig. 2B).

The cross-stratified deposits contain a broad suite of tidally generated sedimentary structures (Chiarella, 2011; Longhitano, 2011; Longhitano et al., 2014). Cross-strata consist of a series of stacked bidirectional large-scale tidal dunes (40–60 cm thick) of mixed siliciclastic–bioclastic composition that accumulated in a narrow elongated basin (Chiarella, 2011; Longhitano et al., 2014). According to the internal organization, the cross-stratified interval can be divided into two laterally and vertically stacked stratal units (Fig. 2B), the Vena di Maida and the Pianopoli units (Chiarella et al., 2012a; Longhitano et al., 2014). The Vena di Maida Unit (up to 20 m thick) is composed of mixed siliciclastic–bioclastic deposits organized into vertically stacked 3D cross-strata. The ~40 m of Pianopoli Unit (Fig. 2C) consists mainly of siliciclastic sandstones, and is weakly fossiliferous. The Pianopoli Unit deposits occur as aggrading vertically stacked bidirectional 2D cross-strata. A tidal origin for these deposits has been extensively documented by several papers, and it is indicated by bimodal palaeocurrent pattern (*i.e.* herringbone cross-stratification), reactivation surfaces and tidal rhythmites composed by mixed siliciclastic–bioclastic couplets (Chiarella, 2011; Longhitano, 2011; Chiarella et al., 2012a; Longhitano et al., 2012; Longhitano, 2013; Longhitano et al., 2014).

Cross-stratified units pass laterally and vertically to the topmost Basile Unit. This unit consists of *ca* 20 m thick thinly bedded to indistinctly stratified, highly bioturbated and intensely homogenized fine sandstones, siltstones and claystones (Longhitano et al., 2014).

Although most of the cross-stratified beds observed in the Catanzaro strait-fill deposits are generally tectonically undeformed, different SSDS can be observed (Table 1, Chiarella, 2011).

3.1. Vena di Maida Unit

The Vena di Maida Unit contains two facies associations (i) *3Dcs* and (ii) *Gsb* (Longhitano et al., 2014) (Fig. 3). (i) Facies association *three-dimensional cross-strata* (*3Dcs*) consists of coarse to very-coarse siliciclastic sand admixed to sand-size bioclastic fragments (facies *3Dd*). Beds (up to 5 m thick) are composed of trough cross-strata (3D dunes), characterized by basal concave-up surfaces filled by foreset laminae (Fig. 3A). Foresets show cyclical alternation of 10–20 cm thick thinning/fining-upwards and thickening/coarsening-upwards bed intervals characterized by heterolithic, moderately segregated siliciclastic/bioclastic lamina-scale couplets (Fig. 3B; Longhitano, 2011; Chiarella and Longhitano, 2012). (ii) Facies association *gravel/shell beds* (*Gsb*) consists of clast-supported, rounded to well-rounded polymictic gravel (facies *Gb*), forming 20–60 cm thick tabular to lenticular layers. Facies association *Gsb* also contains 10–30 cm thick shell beds (facies *Sb*) having sharp basal contacts and containing polyspecific, densely packed skeletal fragments (*e.g.* molluscs, bryozoans, brachiopods and echinoid) (Fig. 3C). Outcrop-scale simple and complex recumbent folds are presented locally within the foreset lamina.

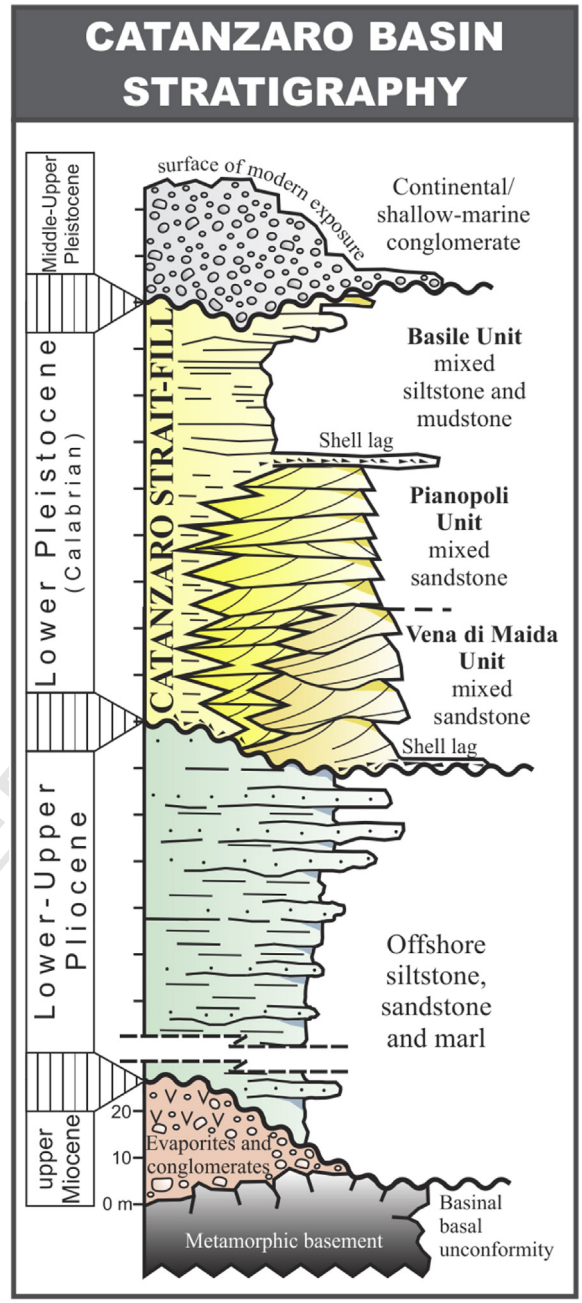

Fig. 2. General stratigraphy of the Catanzaro Basin succession.

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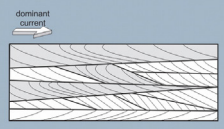
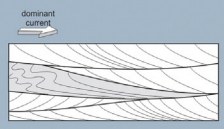
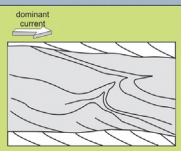
Table 1
Main groups and types of soft-sediment deformations structures (SSDS) recognized in the Early Pleistocene Catanzaro-Strait fill succession.

Group of SSDS	Type of SSDS		Key face	Facies Ass. of SSDS occurrence
Plastic deformations	Simple folds	Overturned		2Dcs Two-dimensional dunes
	Complex folds	Buckled		
Fluid-escape structures				3Dcs Three-dimensional dunes
Load and flame structures	Simple load casts			
	Detached pseudonodules			2Dcs Two-dimensional dunes

The lowermost part of the Vena di Maida Unit (FA *Gsb*) is interpreted as the sedimentary record of a major transgressive episode that marked the return of marine conditions after a long-lasting phase subaerial exposure in the Catanzaro Basin (Longhitano et al., 2014). In particular, deposits pertaining to the FA *GSb* represent a coarse-grained pavement (facies *Gb*) located in the narrowest sector of the strait, which is successively associated with shell material (facies *Sb*) that accumulated during the ensuing transgression. Cross-strata of FA *3Dcs* are interpreted as the result of the migration of large 3D tidal dunes (*sensu* Harms et al., 1982; Ashley, 1990) deposited under the influence of dominantly unidirectional currents as the marine transgression progressed. The tidal origin of these cross-strata is supported by the presence of tidally generated sedimentary structures (*e.g.* bundle cross-lamination, reactivation surfaces and herringbone cross-stratification). Dunes migrate in a subtidal environment, beneath the wave base level, where sustained currents (high bed shear stress) act as main sediments transport (Chiarella, 2011; Chiarella et al., 2012a; Longhitano et al., 2012; Longhitano et al., 2014).

3.2. Pianopoli Unit

The Pianopoli Unit includes two facies associations (i) *2Dcs* and (ii) *Tsb* (Longhitano et al., 2014) (Fig. 4A). (i) Facies association *2Dcs* consists of a rhythmic alternation of coarse-grained simple (facies *Scs*) and compound (facies *Ccs*) cross-strata sets. Facies *Scs* (Simple cross-strata) contains up to 5 m thick planar cross-strata sets with angular to tangential toeset geometry (Longhitano et al., 2014; Chiarella, 2016) (Fig. 4B). Facies *Ccs* (Compound cross-strata) forms 2 to 6 m thick compound cross-strata complexes. Laminae bundles forming couplets of segregated thicker siliciclastic and thinner bioclastic intervals define cross sets (Fig. 4C). In the axial zone of the palaeostrait, Fa *2Dcs* shows alternating clusters of thinner and thicker cross-laminated strata sets. Cross-strata forming the thicker beds show the occurrence of deformed foresets (complex folds) in the upper part of the set. (ii) Facies association *Tsb* marks the top of the Pianopoli Unit and consists of *ca* 25 cm thick tabular to lenticular strata that are made up of densely packed articulated shell deposits.

The Pianopoli Unit record the migration of 2D tidal dunes (*sensu* Harms et al., 1982; Ashley, 1990) under the influx of mainly unidirectional currents. If compared with the underlying 3D dunes of the Vena di Maida Unit, these cross-strata formed under lower energy flow conditions (low bed shear stress) (Longhitano et al., 2014). The lack of wave-induced structures suggests sedimentation below the main wave base. Rhythmic alternations of segregated siliciclastic (thicker and coarser) and bioclastic (thinner and finer) foresets are considered to record diurnal to monthly tidal cycles in mixed sediments (Longhitano, 2011). Shell concentrations of FA *Tsb* show absence of encrusted and bored epibionts indicating a short time exposure of the shells on the sea floor during post-mortem reworking. The dominance of articulated shells generally suggests relative low-energy conditions, probably in connection with a short, relatively high-energy period during which the fauna was smothered (Fürsich and Pandey, 2003).

3.3. Basile Unit

The sandy–silty deposits that constitutes the Basile Unit is up to 20 m thick (Fig. 5). This unit is characterized by highly bioturbated, centimetre thick cross-laminated tabular strata composed of very fine-grained mixed siliciclastic/bioclastic siltstones (FA *Hbm*). In the upper part, this unit consists of claystones and subordinate siltstones organized into thinly bedded horizons, having scarce or absent sedimentary structures, probably due to the very high degree of bioturbation.

The Basile Unit records the late phase of the marine transgression progressively transforming the Catanzaro Strait in a less tidally influenced basin. The presence of massive claystones, whose features indicate shelf sedimentation, records the end of any tidally induced circulation probably due to the enlargement of the strait after the end of transgression (Longhitano et al., 2014).

4. Soft-sediment deformation structures

Three different groups of SSDS have been recognized in the sandy cross-stratified deposits of the Catanzaro Strait (Table 1).

Plastic deformations;

- Fluid-escape structures;
- Load and flame structures.

4.1. Plastic deformations

Two kinds of deformed cross-lamination have been recognized and distinguished on the basis of the main morphological elements (see Allen, 1982). Both involve high-porosity sandy deposits with a low degree of cementation.

4.1.1. Simple recumbent folds

4.1.1.1. Description. Simple recumbent folds consist of a deformed cross-lamination in which cross-strata of the FA *2Dcs* are completely overturned (Fig. 6). The deformation is restricted to individual sets, and does not continue into the underlying or overlying strata. Deformation is generally regular showing some specific features that are common to all the SSDSs of this kind in the analysed stratigraphical sections: (i) the lower part of the set has a normal angle of foreset dip, but higher up the foreset gradually, or locally abruptly, steepens and

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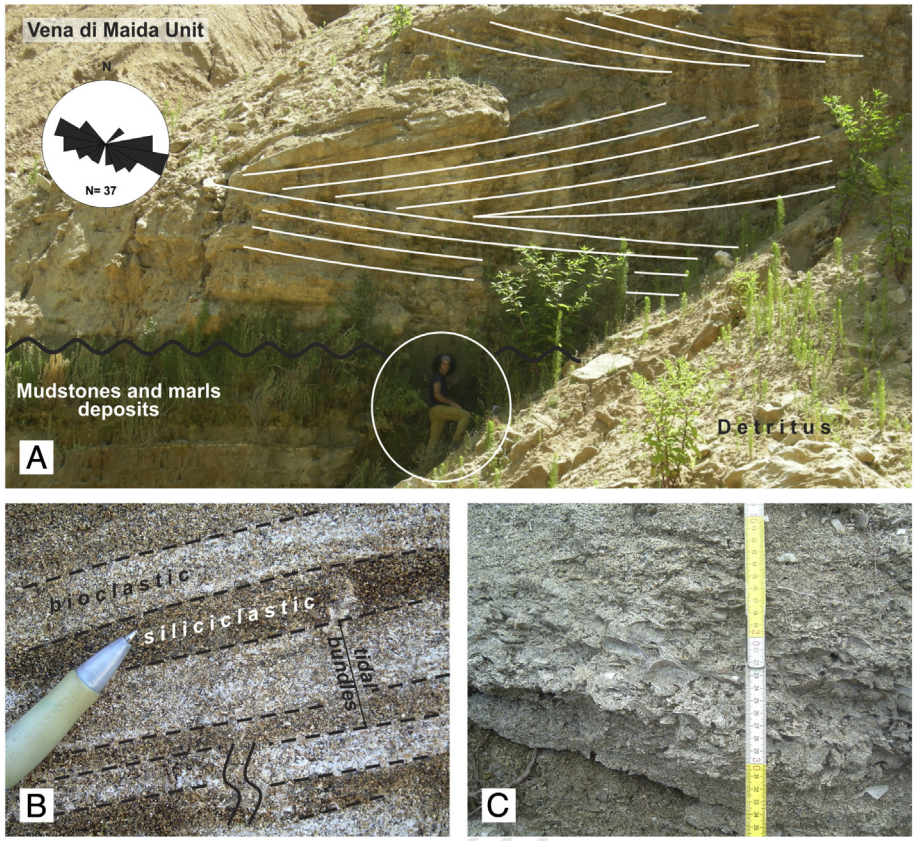

Fig. 3. A) Outcrop view of the FA *3Dcs* (3D dunes) in the lower part of the Vena di Maida Unit (palaeocurrents are towards the observer, perpendicular to the section). B) Close-up view from the FA *3Dcs*, showing tidal bundles of rhythmically alternated bioclastic and siliciclastic cross-laminae. C) Close-up view of shell bed pertaining to the FA *Gsb*.

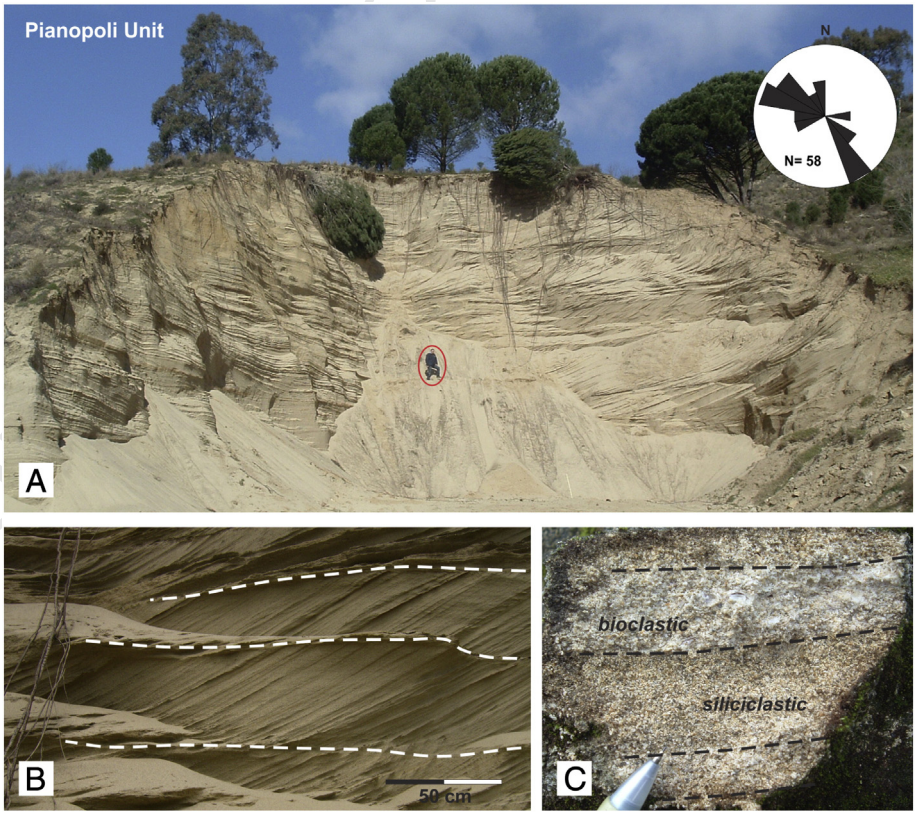

Fig. 4. A) Outcrop view of the FA *2Dcs* (2D dunes) of the Pianopoli Unit. B) Simple cross-strata (facies *Scs*) with tabular base and internal bundles of foreset laminae (palaeocurrent towards the left). C) Close-up view of tidal bundles of segregated siliciclastic/bioclastic lamina-sets.

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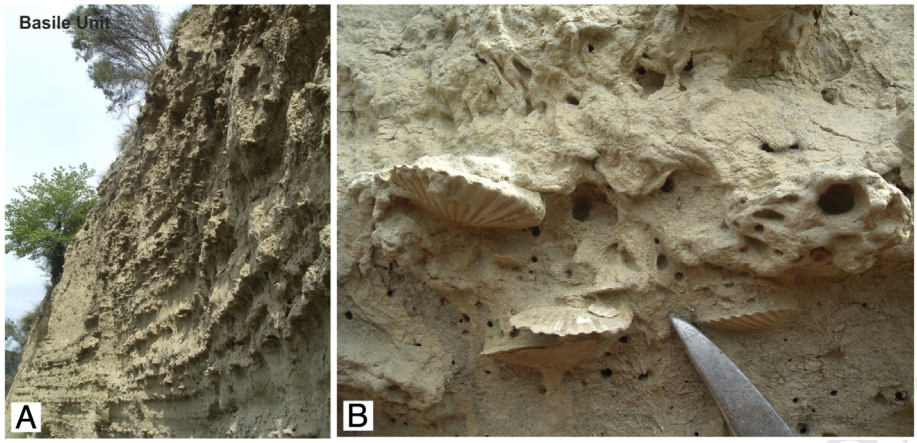

Fig. 5. A) Outcrop and B) close-up view of deeply bioturbated beds of the Basile Unit (FA *Hbm*).

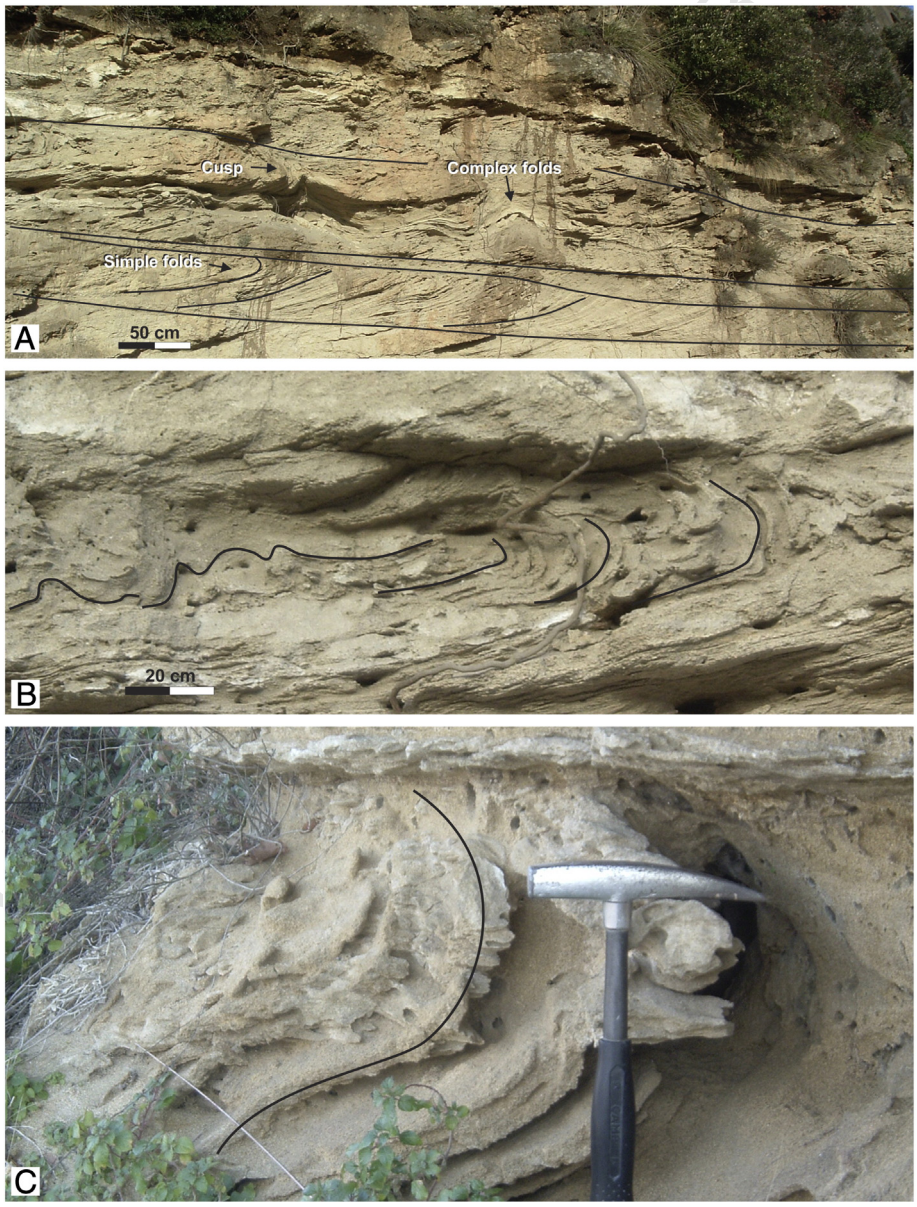

Fig. 6. A) Simple and complex deformed cross-strata in the FA *3Dcs* (Vena di Maida Unit). B) Overturned cross-strata within a single set. C) Close-up view of overturned foresets.

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overturns to form a recumbent fold; (ii) the fold axes are sub-horizontal and generally perpendicular to the dip azimuth of the undeformed foresets and likewise the folds have mainly rounded hinge zones; (iii) deformation is always towards the dip direction of undeformed cross-beds within the same set (Fig. 6A); (iv) in sections perpendicular to the fold axes, the axial surfaces are gently concave upwards, intersecting the upper bounding surfaces of the sets. Thus, the folded cross-laminae occur within a restricted part of each set, and the intensity of deformation decreases in upstream and downstream directions so that the deformed strata pass in both up- and down-palaeocurrent directions into undeformed cross-strata. An essential feature of the disturbance is that cross-strata are overturned into more complex folding without accompanying fracture. Throughout each folding, the laminae remain parallel to one another (Fig. 6B and C), and in most instances, the basal portions remain completely unaffected.

4.1.1.2. Interpretation. Overturned cross-strata corresponds to the Type I of deformed cross-laminae of Allen and Banks (1972) interpreted as due to the action of current drag on liquefied sand bed. The passage of undeformed foresets into intensely deformed ones within the same cross set, and the absence of scour between cross-strata, indicate that the disturbance took place immediately after and not during deposition (Jones, 1962). Thus, structures are truly penecontemporaneous. Therefore, the failure of cross-strata by folding suggests that disturbance took place when the sediments still contained water. Moreover, the regularity of the deformation, the orientation of the deformation axes perpendicular to the current direction, and the regular passage within a set from deformed to undeformed cross beds in both up- and downcurrent directions suggest a common origin for deposition and deformation. In addition, the fold-style of overturned cross-strata suggests that the deforming force was wholly unidirectional in its action. According to Mckee et al. (1962) and Brenchley and Newall (1977), shearing drag on liquefied sand may produce recumbent folds. In addition, Owen (1996) experimentally demonstrates that overturned cross-laminae can be generated by tangential shear acting on a liquefied bed, and that sufficient shear can be provided by a current. The depth to which liquefaction develops controls the thickness of the deformed zone, and the degree of overturning is a function of the magnitude of the shear stress (*i.e.* the current strength) and the duration of the liquefied state.

4.1.2. Complex folds

4.1.2.1. Description. Complex fold structures are buckled foresets (*sensu* Allen, 1982) characterized by the presence of numerous smaller folds, differing in shape, size and position of the axial plane (Figs. 7 and 8). The primary lamination is visible within the folded interval. Complex

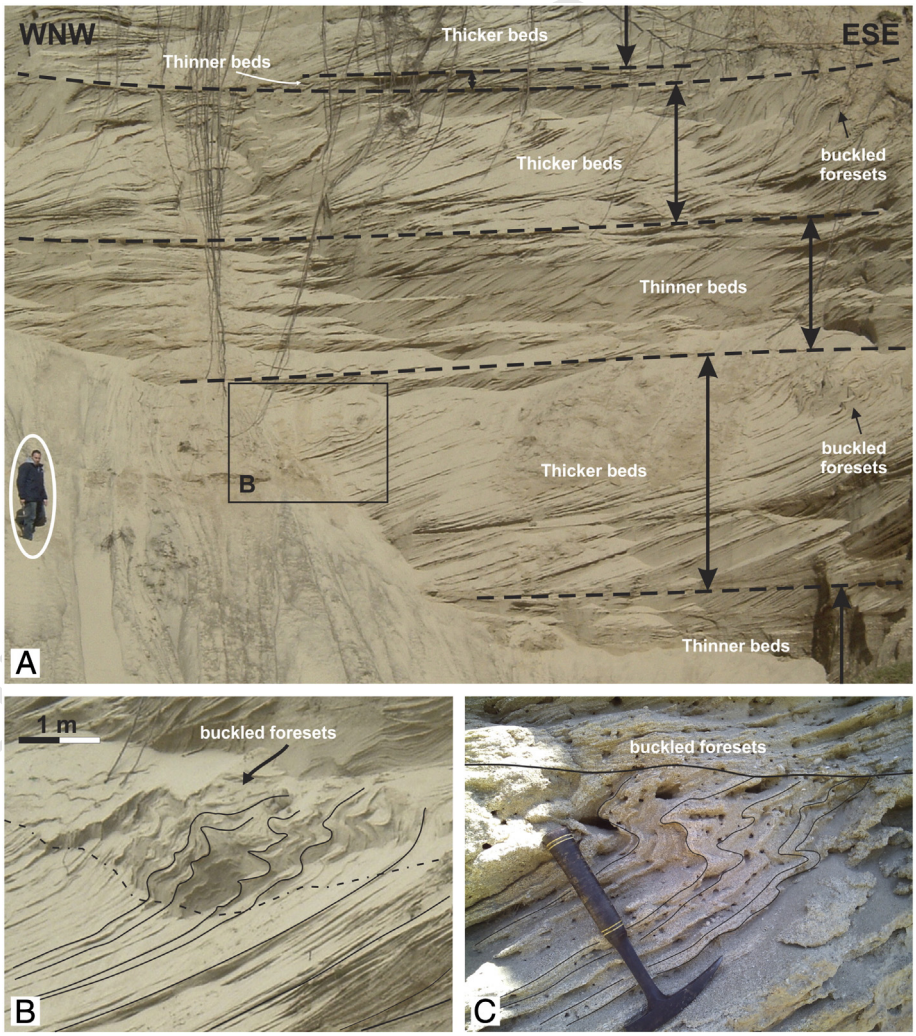

Fig. 7. A) Cluster packages of thinner and thicker beds recognizable in the FA *2Dcs* of the Pianopoli Unit. B) Complex buckled folds localized in the upper part of the foresets. C) Close-up view of buckled foresets.

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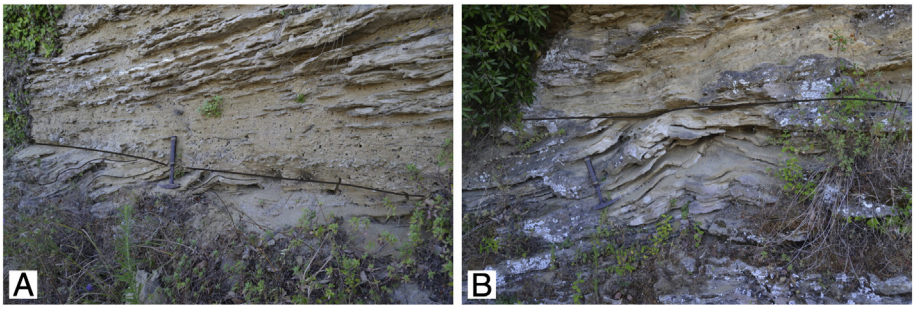

Fig. 8. A) Large scale and B) close-up view of the geometry of complex buckled foresets in sections perpendicular to the main palaeocurrent of FA *3Dcs* (in a perpendicular cross-section, 3D dunes show concave-up basal surface, filled by trough cross-laminae).

folds occur within the thicker (up to 5 m thick) cross-laminated strata (Fig. 7A). Buckled foresets mainly involves the FA *2Dcs*, and deformation occurs in the upper part of the interval, with example of both disharmonic and locally harmonic geometries (Fig. 7B and C). Downwards, the amount of deformation progressively decreases, folds being simpler in geometry and smaller in dimension. The deformed cross-sets are slightly truncated by the overlying undeformed cross-set. Buckled foresets occur also in the FA *3Dcs* (Fig. 8A and B) where laminae are gently deformed showing a wavy shape along the whole foreset.

4.1.2.2. Interpretation. Buckled foresets correspond to the Type II of deformed cross-laminae described by Allen and Banks (1972). The mechanism of deformation is the same as the Type I (liquefaction and horizontal shearing) but the buckled geometries are interpreted in

Fig. 9. A) Fluid-escape structures in a deeply deformed cross set of FA *3Dcs*. B) Close-up view of an upward directed internal rupture fluid-escape structures characterized by the hinge zone of dome-shaped laminae curved in the same direction of the main palaeocurrent direction.

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terms of initial foreset shape, being localized only in the sigmoidal foresets (Allen, 1985). Segregation between the siliciclastic and the bioclastic laminae within the cross-bed (Longhitano et al., 2014) can represent additional driving force causing complex folds (buckled forests) inducing heterogeneities within single laminae couplet.

4.2. Fluid-escape structures

4.2.1. Description

Fluid-escape structures show upwards directed water-escape morphology forming isolated dome-shaped structures and can be described as internal ruptured fluid-escape structures (*sensu* Owen, 1995) with a relief up to ~50 cm (Fig. 9). Lamination is generally preserved and is highlighted by more cemented bioclastic laminae. Isolated homogenized sandstones occur just below main dome-shaped laminae. Fluid-escape structures occur along the entire foreset development in the beds of FA *3Dcs* and they involve foreset laminae (Fig. 6A). No interpenetrative fluid-escape structures are found. Fluid-escape structures show an unusual vertical development where the hinge zone of dome-shaped laminae is curved in the same direction of the main palaeocurrent direction. Finally, fluid-escape structures appear always in association with other SSDSs (Fig. 6A).

4.2.2. Interpretation

Internal fluid-escape structures are interpreted here as the result of fluidization of large portions of the bedset producing a dome-shaped displacement in it. The presence of permeability barriers or upwards permeability decrease (as in graded beds) does not allow a simple dissipation of the excess pore fluid pressure by simple filtration: upwards directed flows can induce the complete or partial fluidization in the involved cross-set. Under these conditions, the excess pore water in the liquefied bed may escape upwards in a nonuniform manner arching the stratification upwards around the axes of maximum flow. This could be locally amplified by the rhythmic repetition of heterolithic mixed siliciclastic–bioclastic couples (Chiarella, 2011; Longhitano et al., 2012; Longhitano et al., 2014). This deformation mechanism has been experimentally observed by Owen (1996) in silicon carbide marker layers used to highlight deformation in cross-stratified deposits. However, since lamination is, locally, still recognizable, fluidization state has been short-lived (Owen, 1995). The anomalous orientation of the fluid-escape structures can be interpreted as the result of minimum path trajectories in the foreset. In fact, along the entire profile of the foreset, the water–sediment interface is located in the same direction as the main current direction. For this reason, water-escape morphologies are not vertical, but are influenced by the internal bounding surfaces (*e.g.* cross-stratification) inclined in the direction of the migration of the foresets. Finally, water escape processes involve foreset laminae and that implies that they originate during the migration of the sand dunes (Fig. 6A).

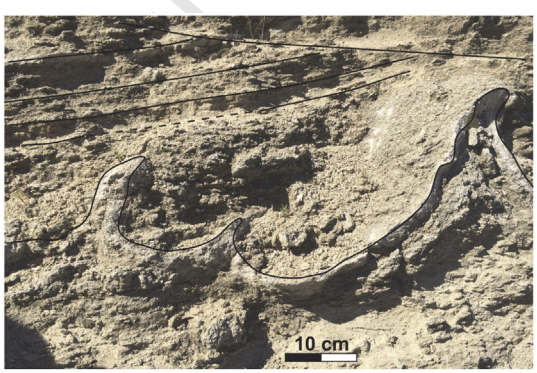

Fig. 10. Simple load cast structure showing a concave profile slightly penetrating into the underlying bed.

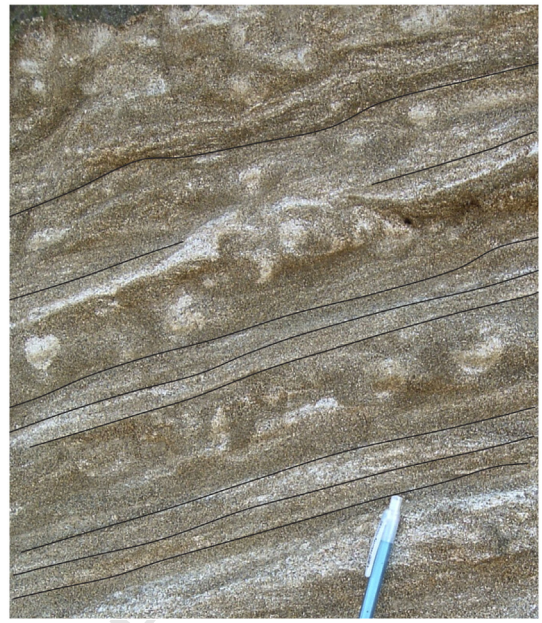

Fig. 11. Detached pseudonodules of FA *2Dcs* characterized by the occurrence of fine-grained bioclastic sediments floating in medium- to coarse-grained siliciclastic sand.

4.3. Load and flame structures

4.3.1. Simple load cast

4.3.1.1. Description. Simple load casts (cm to dm in scale) occur in different lithologies of FA *3Dcs*, and they seem to be localized at the interface between poorly sorted coarse-grained sand on fine-grained sand and coarse-grained silt (Fig. 10). Deformations show a concave profile and slightly penetrate into the underlying bed. Laminations are always preserved and gently deformed. Between adjacent load-casts, narrow flame structures occur.

4.3.1.2. Interpretation. Simple load cast are interpreted as the result of a deformation occurring at the interface between layers with different bulk density (an unstable density gradient system) when the sediment becomes liquidized (Owen, 2003). The final morphology of load-structures depends on various parameters: the duration of the liquidized state, the actual bulk density gradient during deformation, and the kinematic viscosity of the involved sediments. If the deformation of the interface between the two terms is more pronounced, simple load cast structures evolve to become detached pseudonodules (see below).

4.3.2. Detached pseudonodules

4.3.2.1. Description. Detached pseudonodules are 3–5 cm in size and associated with fine-grained bioclastic sand floating in medium- to coarse-grained siliciclastic sand of FA *2Dcs* (Fig. 11). Deformation involve laminae set intervals that are separated by undisturbed foreset laminae.

4.3.2.2. Interpretation. Detached pseudonodules structures are related to unstable density contrasts when sediment becomes liquidized. In particular, the loading of the bioclastic-rich (denser) layer enchased between the siliciclastic-rich layers produce detached pseudonodules if the rising diapirs pierced the denser sediment (Owen, 2003). In some case, this structure can be associated with other load-structures.

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5. Discussion

The detailed description and interpretation of deformed cross-lamination (and associated soft-sediment deformation structures) together with knowledge coming from the facies analysis (Chiarella, 2011; Longhitano et al., 2014) allow tracing the following evolutionary stages:

- Fluid-escape structures occur as result of fluidization along the entire profile of foresets and involve foreset laminae; they locally occur during the migration of foreset laminae;
- Deformed cross-lamination involves 2D and 3D dunes (FAs *2Dcs* and *3Dcs*). They form after liquefaction of the upper portion of the foresets and involve two or more foresets. Deformed cross-lamination occurs only in thicker foresets beds and is virtually absent in the thinner foresets beds (see Fig. 7);
- Load-structures involve plane-beds or low-angle foresets and form after liquefaction in unstable density gradient systems.

These conclusions are strictly based on field evidences, but the trigger mechanism for the liquefaction and fluidization processes has been not established yet. As mentioned in Section 1, literature data support different possible origins for the occurrence of soft-sediment deformation in cross-laminated sands (Wells et al., 1993). The possibility to disentangle between soft-sediment deformation events triggered by autogenic and allogenic processes is controversial (Owen and Moretti, 2011). This challenge arises because the structures related to liquefaction and fluidization processes may show similar morphologies even if they are formed by different trigger agents (Owen et al., 2011).

Since deformation involves specific facies and undeformed beds show the same susceptibility to seismic liquefaction as the deformed ones, a possible allogenic origin for the described liquefaction and fluidization processes is not likely. Furthermore, external trigger agents such as seismic shocks are not able to induce liquefaction during the migration of foreset laminae or involving the upper part of foreset lamina, since this mechanism is not reliable in terms of time of recurrence. However the synsedimentary character of the observed SSDSs allows us to exclude the occurrences of collapses (slides and slumps) induced by tectonic tilting or earthquakes (Mastrogiacomo et al., 2012). Other collapses can be related to the karstic processes in the substrate (see examples of submarine synsedimentary collapses in Moretti et al., 2011) but we do not observe the typical localized and mainly circular morphologies that denote this kind of SSDSs.

On the contrary, all data show that the trigger responsible for the described liquefaction and fluidization effects should be strictly associated with the sedimentary environment (autogenic triggers) since they involve specific facies and intervals. The specific literature on deformed cross-laminae shows that the possible autogenic trigger mechanisms related to different sedimentary environments are (i) storm waves or interval waves, (ii) current drag, (iii) changes in the groundwater level, and (iv) overloading. Q10

Dalrymple (1979) mentioned the occurrence of small-scale deformed cross-laminations in intertidal modern sands as result of the impact of breaking waves. The influence of both transient and cyclic effect of storm waves (Molina et al., 1998; Alfaro et al., 2002) can easily be discarded because the tidally dominated cross-stratified bodies in the Catanzaro strait developed at deeper water depths (Longhitano et al., 2014). In particular, the cyclic effect of the storm waves may be able to induce liquefaction at maximum water depths of 12–15-m in every storm conditions (Henkel, 1970). Furthermore, no typical erosional (wave-induced scours) or sedimentary features (tempestites and other wave-induced bedforms like hummocky cross-stratification) have been observed. Action of internal waves able to modify tidal bedforms cannot be ruled out. However, SSDSs associated to this particular trigger mechanism are not reported (Pomar et al., 2012). Based on our interpretation, the action of the shear stress exerted directly by the current on the water–sediment interface (Stewart, 1961; Daily et al., 1980) is not able to induce liquefaction in the underlying sediments. The shear stress induces only traction and/or erosion in the stoss side of the dunes and, furthermore, it cannot be responsible for the occurrence of water-escape structures in the lee side. Finally, the action of the sudden changes of the groundwater level is a powerful trigger agent for liquefaction of cross-stratified sandy bodies in aeolian and fluvial settings (Williams, 1970) but is not a reliable mechanism in a tidally dominated environment.

Therefore, the only reliable trigger mechanism for the observed effects of liquefaction and fluidization seems to be represented by the action of overloading processes. Various authors mention this process as possible trigger agent of deformation in cross-laminated sands but with different modalities and effects (see Wells et al., 1993 and references therein). Some authors interpret the overloading evidences as related with slump and slide occurrence (Doe and Dott, 1980; Jones and Rust, 1983). In the examples investigated in the present paper, this possibility is not likely because this process produces easily-recognizable re-sedimentation bodies at the base of the lee side and scar surfaces in the stoss side of the dunes that are totally absent in the study outcrops. The change of flow regime, as the transition from dune to plane bed, is also cited as possible trigger mechanism (Røe and Hermansen, 2006). This process consists in a frontal collapse of dunes producing localized portions of massive sands and the establishment of re-activation surfaces over these liquefaction intervals. These distinctive features have

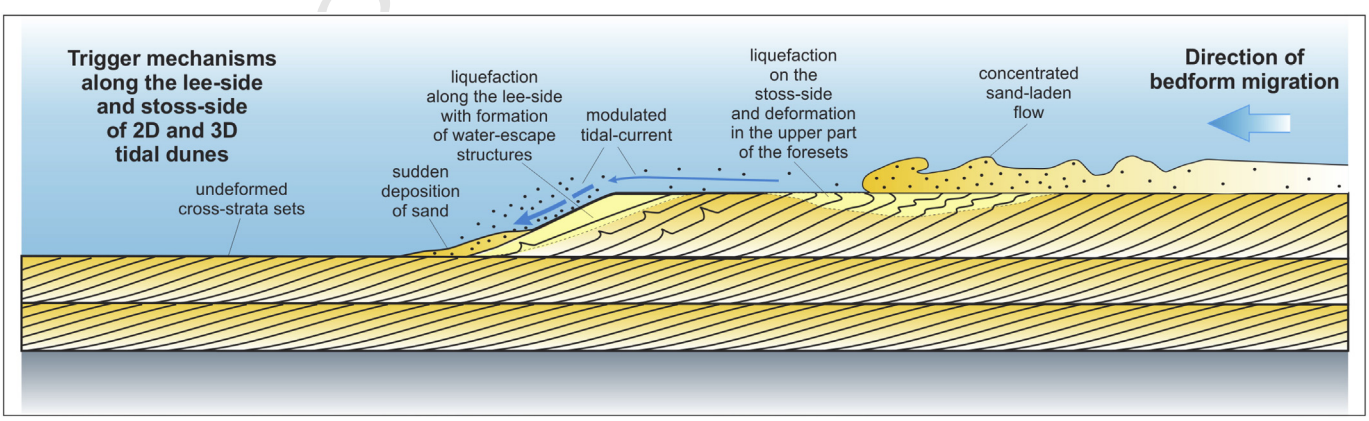

Fig. 12. A) Conceptual model showing the hypothetical deformed mechanisms to explain the recognized SSDS. Liquefaction and fluidification are induced by overloading related to two main syn-depositional mechanisms occurring in different times and place. (i) Overloading induced by sudden deposition along the lee side of the cross-strata producing fluidization along the entire foreset with the development of fluid-escape structures and load structures. (ii) Overloading related to concentrated sand-laden flows along the stoss side of cross-strata producing liquefaction and simple and/or complex deformations.

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not been recognized in the studied deposits. Deformation in the tidally dominated sandbodies of the Catanzaro Strait occur during foreset migration, without evidences of flow-regime transitions. Also the presence of scour surfaces and other irregularities at the water sediment interface as agents for changes in the flow regime and deformation in the underlying foresets in the same direction of the flow (as suggested by Rust, 1968) can be rejected since irregular scour surfaces filled by homogenized sands are totally absent.

The deformed mechanism proposed to explain the recognized SSDS suggests that liquefaction and fluidization are induced by overloading related to two main mechanisms that occur in different times and places during the sedimentation (Fig. 12).

i. The first one is related with the overloading induced by the sudden deposition of sand along the lee side of the dunes. This process explains the occurrence of localized fluidization paths (inclined fluid-escape structures) along the entire foreset development and the fact they are located only in the interior of a foresets laminae set. Furthermore, they occur only in the 3D dunes (FA *3Dcs*) where the instantaneous sedimentation rate is relatively higher than in the other facies. The same process can be responsible for the liquefaction occurring in the load-structures involving the superposition of poorly sorted coarse-grained sands that are suddenly deposited on sand or coarse-grained silt. Accordingly, fluid-escape structures and load-structures represent the result of fluidization and liquefaction in foresets and plane to low-angle cross-laminated beds respectively. The depth of liquefaction, compared with the thickness of the instantaneously deposited beds is consistent in both cases with the calculations and analogue models suggested by Moretti et al. (2001) for overloading processes.
ii. The second process involves only the stoss side of dunes and is induced by the overloading effect related with the occurrence of concentrated sand-laden flows. The process has been advocated in many papers (see a complete revision in Wells et al., 1993) as a trigger mechanism for liquefaction in cross-laminated sand and it seems consistent with our field evidences. In fact, when it is possible recognize their vertical occurrence (Fig. 7), it is clear that they involve only the higher portion of the foresets and only the beds in which the 2D dunes are thicker. This overloading process should be responsible for the liquefaction of the underlying stoss sands and the liquefacted interval reaches a thickness that is probably related with the actual density and dynamic viscosity of the sand-laden flow. After liquefaction induced by overloading (and perhaps even after a partial decrease in the shear strength), the involved sediments are susceptible to deform following the shear stress exerted by the overlying flows, and causing recumbent and more complex (buckled) deformed cross-lamination.

The relationship between the occurrence of recumbent/complex folds and other soft-sediment deformation structures in cross-laminated sand and the overloading processes has been established only in fluvial and glacial settings (Wells et al., 1993). Until now, in fact, their occurrence in tidally dominated deposits has been interpreted as seismically induced (Anderton, 1976), wave-induced (Dalrymple, 1979) or with both possible triggers (Johnson, 1977).

6. Conclusions

The Early Pleistocene Catanzaro-Strait fill succession is characterized by the occurrence of vertically stacked set of two- and three-dimensional (2D and 3D) cross-strata in a tidally dominated setting. Cross-stratified sandy deposits are very susceptible to liquefaction and fluidization processes being characterized by a typical unstable texture with a high porosity index. The numerous and well exposed stratigraphic sections of the Early Pleistocene Catanzaro-Strait fill allow us to recognize and describe in detail the occurrence of soft-sediment deformation structures related with liquidization processes, documenting their lateral and vertical distribution. Results coming from facies analysis show that the occurrence of different kinds of soft-sediment deformation structures (simple (recumbent) and complex (buckled) folds, inclined fluid-escape structures and load structures) can be interpreted as genetically related to the depositional environment (autogenic trigger). The present study documents examples of deformed cross-laminations occurring in a tidal succession that are interpreted in terms of overloading processes. Previous literature data mentioned only storm waves and seismic shocks as possible trigger mechanisms. However, even if these two possible trigger mechanisms could theoretically induce the SSDSs described in this study, they are not able to explain the complex relationships between facies, time and morphologies of deformations. On the contrary, we hypothesize to have recognized the action of two types of overloading agents: (i) the first type related with the overloading induced by sudden deposition of sediments along the migrating foreset. Accordingly, fluid-escape structures and load-structures represent the result of fluidization and liquefaction in foresets and plane to low-angle cross-laminated beds respectively and involving only the lee side of foreset laminae. (ii) The second type involves the stoss side of dunes with the occurrence of concentrated sand-laden flows. This overloading process should be responsible for the liquefaction of the underlying stoss side making the upper part of the dunes prone to deform in accordance with the overlying shear stress. This process induces simple- (recumbent) and complex- (buckled) folding of the cross-strata.

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