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# Sedimentology and hydrodynamics of mixed (siliciclastic-bioclastic) shallow-marine deposits of Acerenza (Pliocene, Southern Apennines, Italy)

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ABSTRACT

During the Pliocene, along the Apennines front of Southern Italy (Acerenza area), a sector of the wedge-top basin hosted shallow-marine siliciclastic-carbonate (-bioclastic) sedimentation. Sediments consist of mixed arenites and rudites forming an up to 30 m thick unit. Based on the recognition of textural features, sedimentary structures, and degree of segregation between siliciclastic and bioclastic particles, facies analysis revealed 10 facies grouped into 5 associations. They suggest the occurrence of either wave or current dominated environments, showing different degrees of heterolithic segregation between siliciclastic and bioclastic particles. The depositional system was characterised by a gentle sloping profile irregularly undulated by syndepositional gentle folds. Waves dominated the shallowest areas of the mixed system and the terrigenous fraction derived mainly from wave erosion of substrate (arenaceous) rocks. These areas were located at the top of anticlines at depths corresponding to that of an upper shoreface sector of a classic coastal profile. The bioclastic fraction derived from the fragmentation of an in situ *heterozoan* skeletal-carbonate factory. Almost constant waves activity prevented segregation of the siliciclastic and bioclastic fractions in the lower shoreface zones. In relatively deeper environment of the mixed system (offshore transition), persistent unidirectional currents dominated, with development of tide-influenced 2D and 3D dunes. Repeated oscillations of the water column in the sheltered coastal areas produced modulation of current velocity favouring segregation of the heterolithic fractions along the dune foresets. Finally, in the deepest sector of the system (offshore), pervasive bioturbation dominated causing unsegregation of the siliciclastic and bioclastic fractions.

Key words: *Mixed siliciclastic-bioclastic segregated deposits, shallow-marine depositional processes, tidal-modulated currents, Pliocene, Southern Apennines.*

## INTRODUCTION

Mixed siliciclastic-bioclastic deposits comprise both terrigenous and carbonate grains (see Mount, 1985, for a first-order textural/compositional classification). Terrigenous grains derive from river discharge to the basin or from submarine erosion of previous substrate rocks; bioclasts are skeletal fragments derived from a coeval carbonate factory. Until the 1980's the attention of most sedimentologists was focused on the relatively "pure" sediments, paying less attention on the spectrum of "mixed" sediments that lie between the siliciclastic and carbonate end members. This approach was supported by a common misconception that significant carbonate production cannot occur in areas of terrigenous input. However, mixed siliciclastic-carbonate systems may develop in marine areas with resulting deposition of mixed sediments. The past two decades have witnessed a remarkable flourishing of research efforts devoted to the characterization of mixed sediments. Moreover, also the petroleum industry world is attracted to unravel new insights about internal properties (e.g. porosity, permeability rock-fluid relationship) of mixed systems and to reconstruct predictive 3D models for siliciclastic-carbonate reservoirs (McNeill *et alii*, 2004).

Many studies on ancient and modern environments indicate that mixed siliciclastic-carbonate deposits are quite common and characterised by high facies variability (e.g. Budd & Harris, 1990; Lomando & Harris, 1991; Gillespie & Nelson, 1997; Dorsey & Kidwell, 1999; Wilson & Lokier, 2002; Coffey & Read, 2004; Wilson & Vecsei, 2005; Wright *et alii*, 2005; Hender & Dix, 2008; Chiarella *et alii*, 2009; Nalin *et alii*, 2010; Chiarella, 2011; Longhitano *et alii*, in press). Studies on mixed deposits are devoted to unravel original depositional environments in ancient shallow marine areas. Shallow-water environments are composite and dynamic settings that are influenced by a large number of interconnected and interacting processes, including sea-level changes, tectonics, climate, sediment supply and hydrodynamics. Each of these processes varies through space and time with different amplitudes and frequencies (Heward, 1981; Posamentier & Allen, 1993; Schlager, 2003; Smith, 1994; Bailey, 1998). Moreover, in these settings, carbonate production is influenced also by other factors, such as water luminosity and temperature, nutrient supply, salinity, kind of substrate and competitive displacement (Pomar, 2001; Mutti & Hallok, 2003; Pomar & Hallok, 2008). In particular, recent researches on mixed shallow-marine examples documented: (*i*) the environmental factors influencing the carbonate factory, (*ii*) the siliciclastic-carbonate distribution in space and time, and (*iii*) the interplay of sedimentary processes on the segregation of the two heterolithic fractions (for an upgraded bibliography see: Chiarella, 2011; Longhitano, 2011; Longhitano *et alii*, in press).

The present study describes a siliciclastic-bioclastic unit comprised in the Pliocene marine succession cropping out near the Acerenza village along the front of the Lucanian Apennine (Southern Italy) (fig. 1). The spatial distribution of facies assemblages, detected through a

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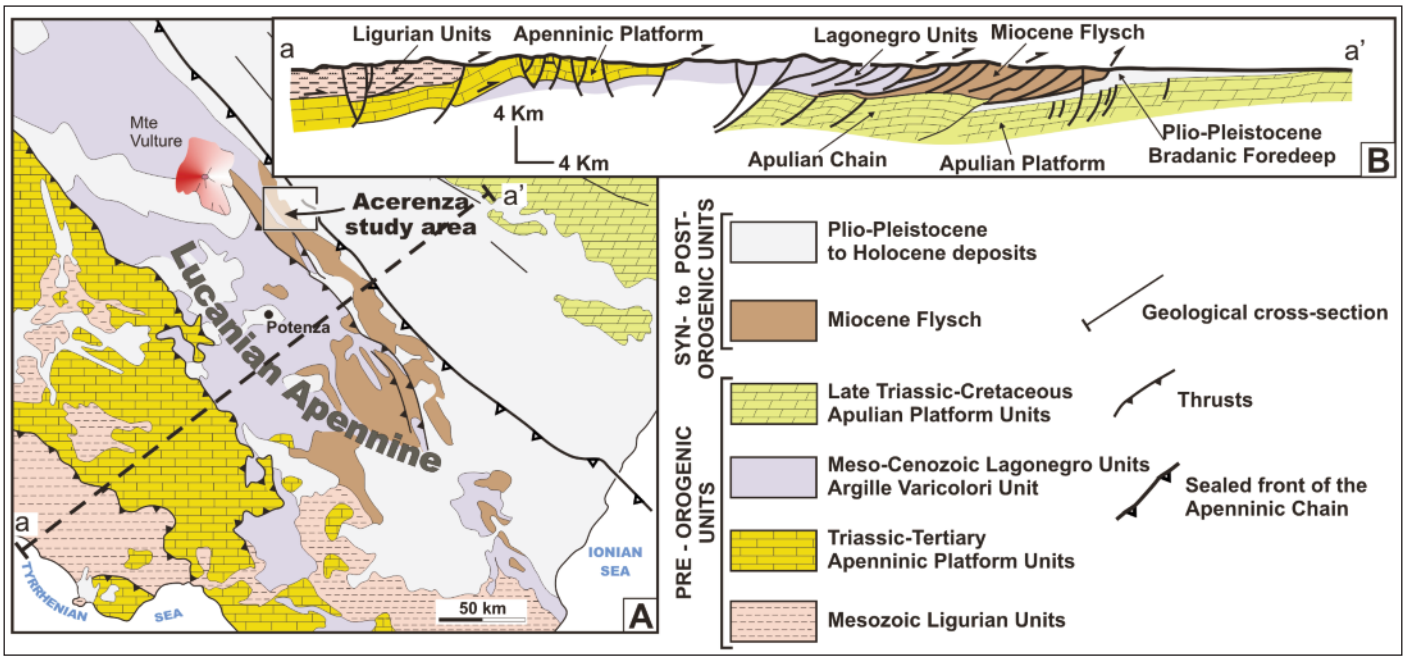



*Fig. 1 - A*) Simplified geological map of Southern Apennine with the indication of the study area; *B*) Geological cross-section showing the main tectonic units of the Lucanian Apennine (modified from PROSSER *et al.*, 1996).

facies analysis mainly aimed to the interpretation of hydrodynamic processes, allow us to propose a depositional model for the studied deposits. Since density and shape of bioclastic and siliciclastic material are remarkably different (PRAGER *et alii*, 1996), mixed sediments respond differently to sediment dispersal hydrodynamic processes. Therefore, a different internal segregation or organization of siliciclastic and bioclastic particles in the same deposit can be regarded as the result of energy fluctuations of a number of hydrodynamic processes affecting shallow-marine settings (CHIARELLA, 2011; LONGHITANO, 2011).

Concerning the time-scale used in this work, although the International Commission on Stratigraphy recently ratified to place the Pliocene-Pleistocene boundary at the base of the Gelasian stage/age (2.58 Ma) (GIBBARD *et alii*, 2010), the former definition of the Pliocene-Pleistocene boundary, that was placed at the base of the Calabrian stage/age (1.8 Ma) (*i.e.* GRADSTEIN *et alii*, 2004) has been followed in order to avoid confusion with the quoted literature about local and regional studies referred to the same deposits.

## GEOLOGICAL SETTING

The Southern Apennine is the segment of the circum-Mediterranean orogenic system between the Central Apennine to the north and the Calabrian Arc to the south. The Southern Apennine represents an accretionary wedge formed by a northeast verging fold- and thrust-belt, built on the western border of the Apulian plate from the late Oligocene to Pleistocene times (CASERO *et alii*, 1988; BOCCALETTI *et alii*, 1990; CARBONE & LENTINI, 1990; ROURE *et alii*, 1991; GUEGUEN *et alii*, 1997; PESCATORE *et alii*, 1999; PATACCA & SCANDONE, 2007). This wedge is composed of tectonically deformed stratigraphic units (*sensu* D'ARGENIO *et alii*, 1973), originally belonging to contiguous palaeogeographic domains, which were progressively incorporated in the chain. From internal to external domains, according to their original position, they are represented by (fig. 1): (*i*) ophiolite-bearing units scraped off from the Ligurian-Piedmont ocean (Ligurian Units); (*ii*) carbonate platform units of Late Triassic-Cenozoic age (Apenninic Platform Units); (*iii*) basinal units (Lagonegro and Argille Varicolori Units) of Mesozoic-Cenozoic age; and (*iv*) carbonate platform units (Apulian Platform Units) of Late Triassic-Cenozoic age (MOSTARDINI & MERLINI, 1986; PESCATORE *et alii*, 1999) (fig. 1). The deformed units of the first three domains formed wide allochthonous sheets onto the Apulia Platform. Then, from the early Pliocene onwards, the Apulia Platform was thrust in a duplex structure known in the literature as "Apulian chain" (CELLO *et alii*, 1989; LENTINI *et alii*, 1990; ROURE *et alii*, 1991; CATALANO *et alii*, 1993; PATACCA & SCANDONE, 2001). The generation of Pliocene to Pleistocene syntectonic thrust-top basins in the Southern Apennine is due to this duplexing process; specifically, it transferred part of the deformation of the active floor thrust-system to the overlying allochthonous sheets, causing the development of out-of-sequence thrusting in the roof structure and folding of the wedge-top area (ROURE *et alii*, 1991; PATACCA & SCANDONE, 2001).

In the studied area (fig. 2A), the front of the Lucanian Apennine consists of two 500 to 1,200 m thick, vertically-stacked tectonic units, made up of Cretaceous to Tortonian successions: the Daunia and the San Chirico (or Tufillo-Serra Palazzo) tectonic units (DAZZARO *et alii*, 1988; PATACCA *et alii*, 1992; PIERI *et alii*, 2004; PATACCA & SCANDONE, 2007). These two units belong to the allochthonous sheets, lie onto tectonically buried and successively deformed Apulian Platform Units, and are unconformably overlain by syntectonic Pliocene wedge-top deposits (PATACCA & SCANDONE, 2001; PALLADINO, 2006, 2011; LABRIOLA *et alii*, 2007, 2008). The mixed (siliciclastic-

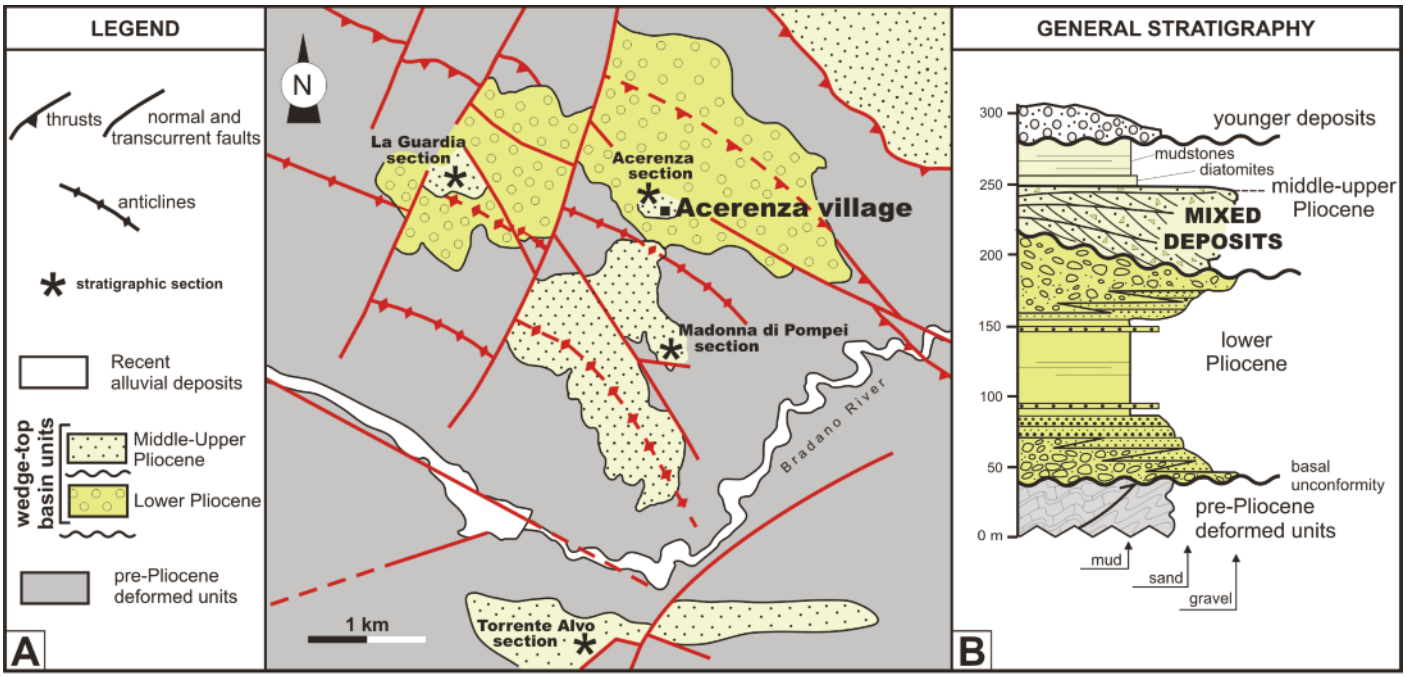



*Fig. 2 - A*) Geological map of the Acerenza area showing the location of the measured logs (asterisks); *B*) General stratigraphy of the Pliocene sedimentary succession measured in the area.

bioclastic) interval of these Pliocene deposits, named Acerenza succession, represents the focus of this study.

## THE PLIOCENE ACERENZA SUCCESSION

The Acerenza succession is time-correlatable with part of the Pliocene Ariano Unit (*sensu* D'Argenio *et alii*, 1973; Cocco *et alii*, 1974; Ippolito *et alii*, 1975; Bonardi *et alii*, 1988) that is the most recent and the most external wedge-top unit that accumulated onto the moving allochthonous sheets of the Southern Apennine chain (Patacca & Scandone, 2001). The Ariano Unit is characterised by two sedimentary cycles of early and middle-late Pliocene age, separated by an angular unconformity (fig. 2B) (D'Argenio *et alii*, 1973; Maggiore & Walsh, 1975; Labriola *et alii*, 2008). These deposits were recently analysed in the framework of the new geological map of Italy (CARG Project) and previous stratigraphic and age interpretation were confirmed (ISPRA, 2006).

The Acerenza mixed deposits belong to the middle-upper Pliocene cycle of the Ariano Unit and derive from an "in situ mixing" (*sensu* Mount, 1984) of siliciclastic arenaceous grains with carbonate skeletal grains (Chiarella, 2011). These deposits represent the lowermost part of the cycle and form a siliciclastic-bioclastic succession up to 30 m thick. This mixed unit is overlain abruptly by a 1-2.5 m thick diatomitic layer of regional extent (Patacca & Scandone, 2001) in turn covered by open marine mudstones (Lotito, 2002; Labriola, 2004; Onofrio, 2004; Palladino, 2006, 2011; Chiarella & Longhitano, 2008, 2009). Mixed deposits unconformably lie above either older Pliocene wedge-top deposits or pre-Pliocene tectono-stratigraphic units (fig. 2A). Well-rounded mono-crystalline quartz grains mainly represent the siliciclastic fraction of these mixed deposits; other minor components include fine-grained rock fragments represented, in order of abundance, by low/medium-grade metamorphic rock fragments and sedimentary rock fragments (e.g. siltstone). The bioclastic fraction is almost completely made up of a calcite-dominated assemblage of bryozoans and molluscs with minor contributions of benthic and planktonic foraminifers, serpulids, echinoids, brachiopods, barnacles and rare red algae (a *heterozoan* assemblage *sensu* James, 1997) (Chiarella, 2011).

## METHODS

The dataset discussed and interpreted in this study has been obtained by a field-based work. Over 130 m of stratigraphic sections have been logged in detail in four sites (Acerenza, La Guardia, Madonna di Pompei, Torrente Alvo) (figs. 2 and 3). The adopted descriptive sedimentological terminologies are from Harms *et alii* (1975), Potter & Pettijohn (1977) and Collinson & Thompson (1982). Facies have been defined by bed thickness and geometry, sedimentary structures, texture, and trace fossil content. Each facies has been coded by using a short descriptive name and a letter-code label deriving from recurrent sedimentary structures; facies have been grouped into facies associations.

In addition to classical facies analysis techniques, the distinction of facies associations has been supported by observations on: (*i*) the relative percentage of the amount of siliciclastic *versus* bioclastic fragments, which has been appreciated by using a *s/b* (silici/bio) *quantitative ratio*, and (*ii*) the estimation of the degree of the heterolithic segregation between the siliciclastic and bioclastic fractions, which has been appreciated by using a *s/b* (silici/bio) *segregation ratio*. In accordance with Chiarella (2011), the estimation of the *s/b* segregation ratio has

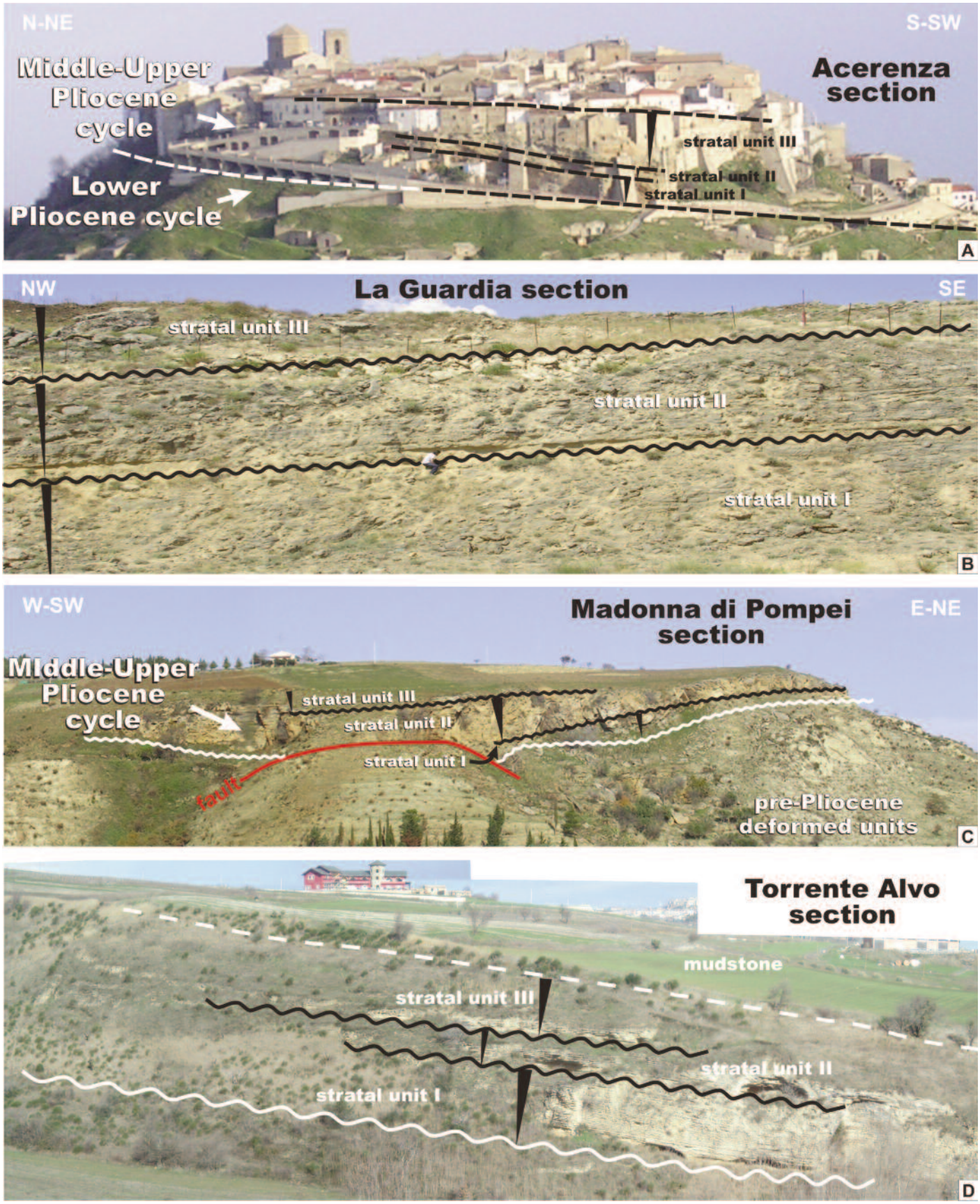



*Fig. 3* - Outcrop views of (*A*) Acerenza; (*B*) La Guardia; (*C*) Madonna di Pompei and (*D*) Torrente Alvo sections. In all the sections, three main stratal units (I, II and III) can be recognized.

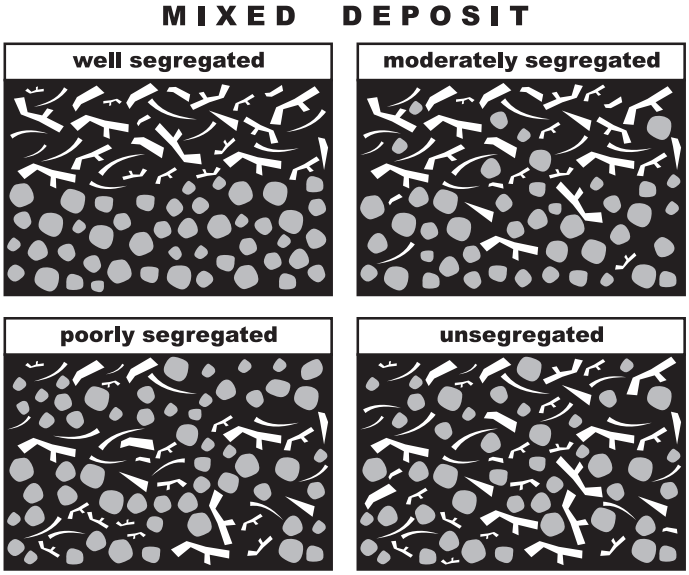



*Fig. 4* - Visual comparator used to appreciate the heterolithic sorting in mixed sediments. The chart includes four main degrees of segregation of the bioclastic (light) and the siliciclastic (dark) fraction. For simplicity, the packing and the grain size sorting of the particles are here assumed as constants in all four frames (CHIARELLA & LONGHITANO, *in review*).

been based on four main classes of heterolithic sorting, where the segregation has been evaluated by using a visual comparator; it allowed to distinguish well-, moderately-, poorly- and/or un-segregated siliciclastic and bioclastic grains (fig. 4). Bioturbation intensity was described by using bioturbation index values (BI) proposed by BANN *et alii* (2008).

In order to assign to each facies and facies association an inferred position along a hydrodynamic depositional profile, this study focused on the physical processes responsible for the distribution of mixed sediments. Therefore, the presence of a carbonate fraction was stressed only in order to recognise physical processes active in the environments, since the carbonate fraction is here considered to represent only clastic particles that physically (by density, shape, and size) differ from siliciclastic particles. Accordingly, environmental interpretations related to the presence of a carbonate factory and its biological peculiarities need to add different analytical approaches that are not addressed herein and they are expected from future studies.

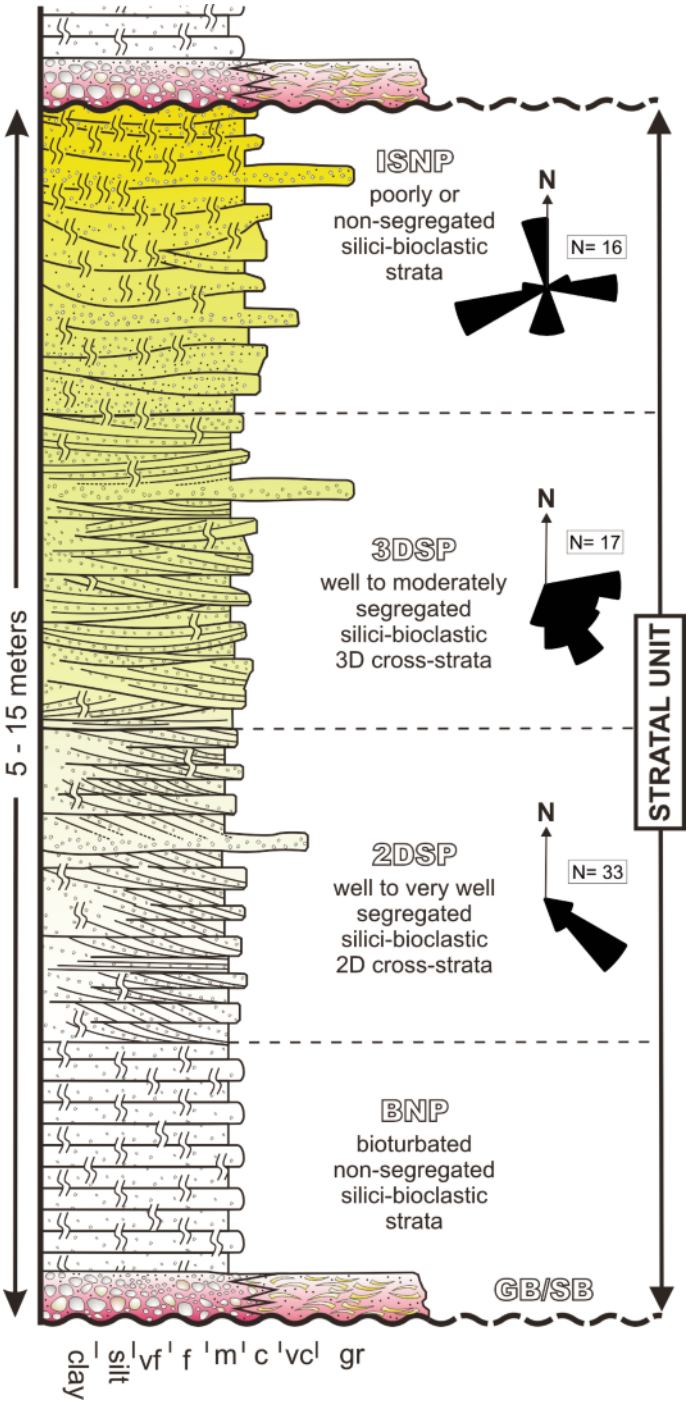



*Fig. 5* - Stratigraphic column summarizing the vertical succession of facies associations documented for each stratal unit. Palaeocurrent data derive from measurements acquired at the La Guardia Section.

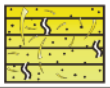
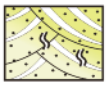
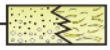
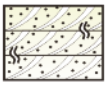
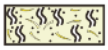
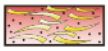
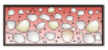
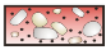
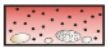
## THE ACERENZA MIXED SUCCESSION

Sedimentary facies of the Acerenza mixed succession were analyzed in detail along 20 logs spatially distributed; across the study area 10 sedimentary facies grouped into five major facies associations (hereafter f.a.) have been recognised and differentiated. In accordance with both lateral and vertical facies relationships observed along wide natural sections, an idealised facies-association succession (fig. 5 – idealised stratal unit) was reconstructed. This idealised stratal unit consists of a basal deposit made up of reddish conglomerates, shell fragments, and/or grey to reddish terrigenous-dominated siltstones, passing upwards to mixed arenites or rudites composed of an abundant yellowish bioclastic fraction admixed to a siliciclastic fraction. In each locality, the mixed succession comprises three stacked bodies (numbered from I to III from the lowest/oldest one) (see fig. 3), corresponding to three stratal units that may lack some facies. Individual stratal units are 5 to 15 m thick, bounded by erosional surfaces, and show a similar succession of facies.

According to the idealised stratal unit (fig. 5), facies associations are discussed in their stratigraphic order (tab. 1).

TABLE 1

Characteristics of facies associations recognized in the studied succession. Depositional environments inferred for each association were interpreted based on sedimentary structures and the degree of segregation between heterolithic (silici-bioclastic) particles.

| | | Facies Ass. | Facies | Description | Interpretation | trend | Key Face |
|---|---|---|---|---|---|---|---|
| DEGREE OF SEGREGATION | scarce | *ISNP* | *Scb* | **Swaley cross-stratified beds -** Very coarse sand and granule-sized mixed bioclastic and siliciclastic grains arranged into 5 to 30 cm thick layers wedging-out landward and dipping gently seaward. | shoreface deposits | shallowing |  |
| | | | *Pplb* | **Plane-parallel laminated beds -** Coarse to very coarse mixed sands organized into 5 to 10 cm thick well-cemented beds showing a plane-parallel lamination. | | |  |
| | moderate | *3DSP* | *Tcb* | **Trough cross-stratified beds -** Siliciclastic-bioclastic coarse sand organized into up to 80 cm thick cross-stratified beds recording progradation of 3D dunes. | upper offshore-transition deposits | |  |
| | | | *M/Lb* | **Massive beds -** Siliciclastic and bioclastic coarse to medium sands, forming 5 to 13 cm thick, normal graded or laminated beds. | | |  |
| | good | *2DSP* | *Pcb* | **Planar cross-stratified beds -** Siliciclastic-bioclastic medium to coarse sands organized into 8 to 100 cm thick cross-stratified beds recording progradation of 2D dunes. Foresets have tabular bases and tangential strata geometry. Bundle cross-stratification occurs. | lower offshore-transition deposits | |  |
| | null | *BNP* | *Bb* | **Bioturbated beds -** Intensely bioturbated mixture of coarse to fine siliciclasts and bioclastic sands, organized into 5 to 25 cm thick beds. | offshore deposits | |  |
| | null | *GB/SB* | *Sb* | **Shell beds -** Densely packed (5 to 15 cm thick) shell beds of reoriented and disarticulated specimens. | transgressive deposits | |  |
| | | | *cGb* | **Clast-supported gravel beds -** Clast- (locally matrix-) supported gravels and subordinate sands, massive and moderately sorted, rich in rests of broken shells in 30 to 70 cm thick beds. | | |  |
| | | | *mGb* | **Matrix-supported gravel beds -** Matrix-supported gravelly beds 20 to 60 cm thick. Clasts are sub-rounded to sub-angular with size ranging from 2 cm to 50 cm (2 to 5 cm on average). | | |  |
| | | | *Mb* | **Massive beds -** Very fine to coarse siliciclastic and bioclastic sands admixed to skeletal remains, glaucony and mud clasts. Beds of this facies are locally paved by cobble-thick lags; cobbles are typically well rounded, spherical to discoidal in shape. | | |  |

FACIES ASSOCIATION *GB/SB* (GRAVEL-/SHELL-BEDS)

**Description -** Facies association *GB/SB* (f.a. *GB/SB*) occurs always at the base of each stratal unit (fig. 5). It unconformably overlies either older Pliocene wedge-top deposits or pre-Pliocene Apennine units. The basal contact of f.a. *GB/SB* is readily recognizable in outcrop since it is represented by a marked erosional surface (fig. 3), whereas its top is typified by a sharp, non-erosional surface. Deposits of f.a. *GB/SB* show a lenticular shape and a lateral variability of facies; thickness ranges from 20 to 70 cm. This f.a. comprises four sedimentary facies: *mGb*, *cGb*, *Mb* and *Sb* (tab. 1).

Facies *mGb* (*matrix-supported Gravel bed*): occurs in the lowermost position of stratal units and represents the only facies of the f.a *GB/SB* that locally overlies the pre-Pliocene deformed bedrock. Facies *mGb* consists of matrix- to locally clast-supported pebbles, cobbles and boulders with scattered granules organised into 20 to 60 cm thick massive beds (fig. 6A). Clasts largely derive from marls and sandstones, and have sub-rounded to sub-angular shapes with size ranging from 2 to 50 cm (2 to 5 cm on average); less abundant clasts derive from older polymictic conglomerates. The matrix consists of an unsegregated mixture of bioclastic and siliciclastic sand. The bioclasts mainly consist of skeletal remains of molluscs and echinoids.

*Facies cGb (clast-supported Gravel bed)* mainly occurs in the La Guardia and Acerenza sections (fig. 2A) and is characterised by clast-supported pebbles mixed with indeterminate skeletal fragments (fig. 6B) organised to form 30 to 70 cm thick massive beds. Clasts are rounded to well-rounded and range in size from 2 to 5 cm.

*Facies Mb (Massive bed)* crops out in all studied sections and is composed of very-fine to coarse siliciclastic sands admixed to abundant skeletal remains, glaucony and mud clasts. Randomly, this facies also contains fish teeth. This facies forms up to 100 cm thick layers with erosive bases, and locally consists of laterally-persistent pavements of well-rounded spherical- and disc-shaped cobbles and rare boulders (fig. 6C), occasionally characterised by lithophaga boring traces. Clasts include limestones, marls and sandstones with minor plutonic rocks; disc-shaped clasts are generally oriented with their long axes parallel to the bed surface. The upper portion of beds shows a colour change; stereo-microscope observations suggest that this is due to a diffuse state of alteration recognizable on feldspate minerals (P. BENEDUCE personal communication, 2010).

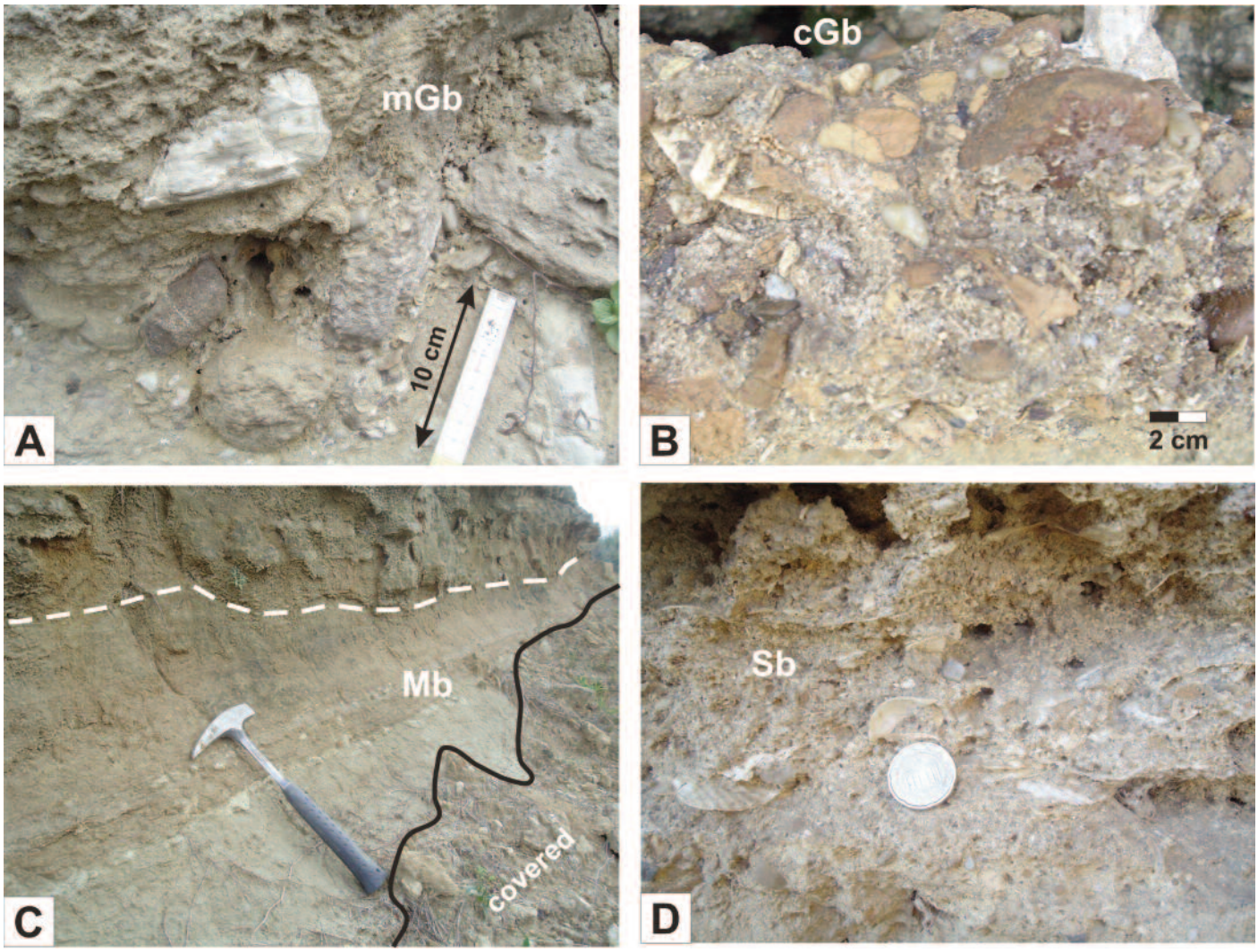



*Fig. 6* - Facies association *GB/SB*: *A*) Particular of facies *mGb; B*) Close-up view of facies *cGb* characterized by clast-supported texture; *C*) Very-fine to coarse sand of facies *Mb* in the lowermost stratigraphic position at the La Guardia section (hammer is 35 cm long); *D*) Skeletal concentration (shell bed) of facies *Sb* (coin is 2 cm in diameter).

*Facies Sb (Shell beds)* is characterised by 5 to 15 cm thick, densely packed skeletal assemblage that consists of bivalves, bryozoans, echinoids and gastropods remains. Skeletal remains exhibit various stages of preservation, ranging from undamaged to completely broken. Usually, specimens are reoriented and disarticulated (fig. 6D) although locally articulated organisms are found. Coarse bioclastic fragments represent the beds framework, with both fine and very-coarse arenitic particles filling the interstices. Through a progressive decrease in the shell-packing density, this facies grades upward into less fossiliferous sediments (f.a. "2DSP or 3DSP).

**Interpretation -** F.a. *GB/SB* overlies the basal erosional surface of each stratal unit. The sedimentary properties of facies *mGb* and *cGb* suggest that they are lag deposits generated by erosion and reworking of older sediments/rocks during ravinement processes (*i.e.* CATTANEO & STEEL, 2003, and references therein). The most common scenario for the formation of this kind of lag deposit is a transgressive setting (HWANG & HELLER, 2002; CATTANEO & STEEL, 2003). In this context, cobbles and boulders of facies *Mb* can be explained as collapses of large blocks induced by wave action along sea cliffs during a transgression (*i.e.* POMAR & TROPEANO, 2001). A transgressive setting is also suggested by the condensed horizon of facies *Sb*, which corresponds to well-defined shell beds.

Moreover, the presence of bored and encrusted clasts suggests low rates of net sedimentation (KIDWELL, 1989; NALIN & MASSARI, 2009). According to AMOROSI (1995), sediment starvation determines conditions most favourable for authigenesis and precipitation of glaucony, typically associated with abundant fossils (facies *Sb*) and hardgrounds in the condensed section. In absence of river inputs to the basin, these deposits can be considered as the *in situ* clastic product of localised erosion, due to the main ravinement episodes (ARNOTT, 1995). In short, f.a. *GB/SB* recorded rapid sea-level rises, promoting sediment starvation and winnowing of underlaying deposits (e.g. LOUTIT *et alii*, 1988; ABBOTT & CARTER, 1994; ABBOTT, 1997; CASTLE, 2000). The limited thickness of the f.a. *GB/SB* is consistent with other examples of basal transgressive deposits (e.g. KIDWELL, 1989; ARNOTT, 1995; CARACUEL *et alii*, 2004; NALIN & MASSARI, 2009).

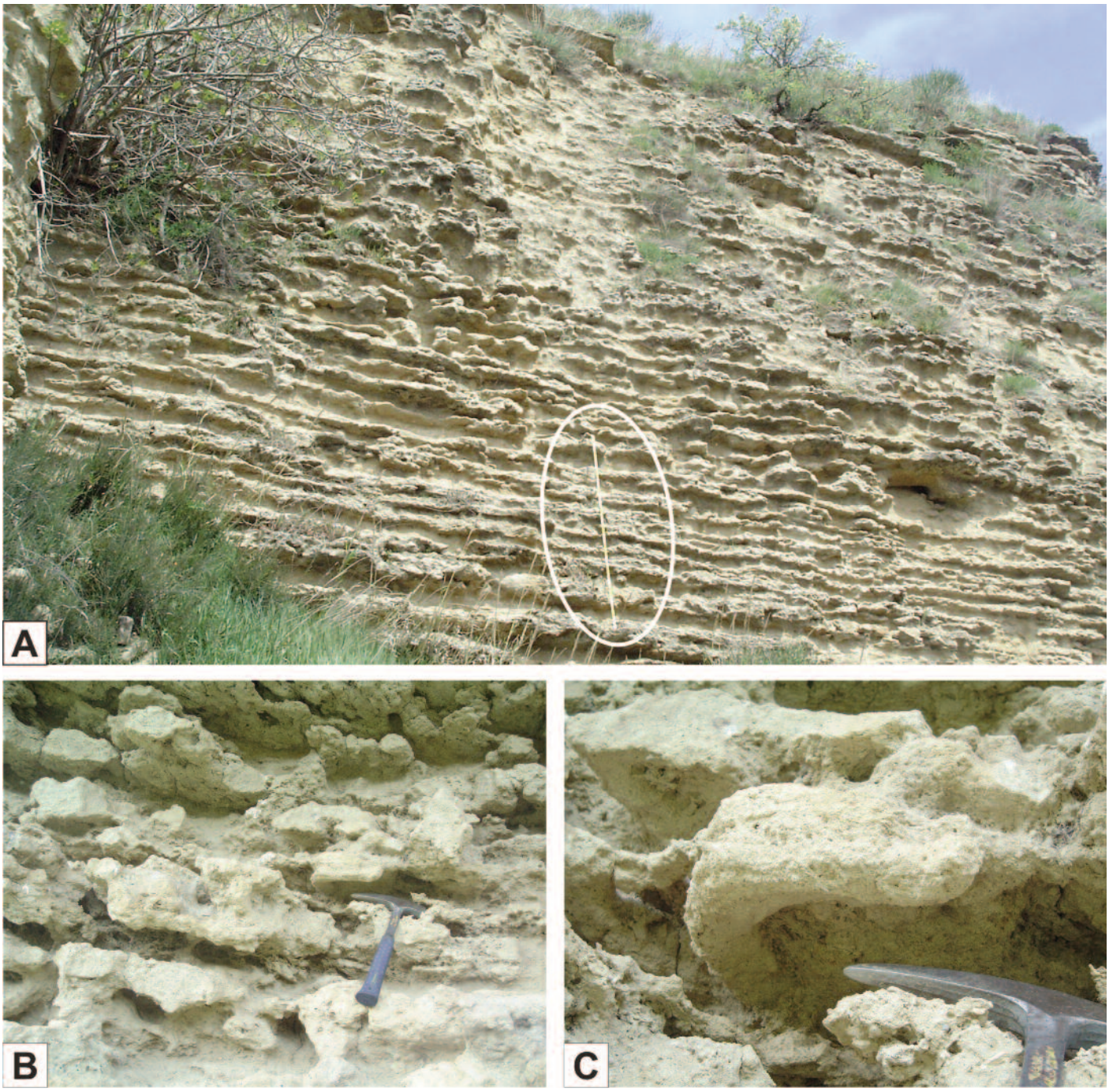



*Fig. 7 - A*) Facies association *BNP* showing pervasive bioturbation (staff is 2 m long); *B*) Close-up view of the previous outcrop; *C*) *Thalassinoides* trace fossils of facies association *BNP*.

### Facies association *BNP* (Bioturbated beds with unsegregated particles)

**Description -** F.a. *BNP* (fig. 5) has been recognised only in the Madonna di Pompei and Torrente Alvo sections (fig. 2A) above deposits of f.a. *GB/SB*. F.a. *BNP* consists of unsegregated to poorly-segregated siliciclastic and bioclastic deposits, whose grain size ranges from medium to very coarse sand (tab. 1). Primary sedimentary structures are very difficult to distinguish within f.a. *BNP* because of the very intense and widespread bioturbation (B.I. =5-6). The *s/b* quantitative ratio, which indicates the relative amount of siliciclastic *versus* bioclastic materials, is ~1. The most recurrent characteristics observable in this deposit can be summarised in the facies *Bb*.

*Facies Bb (Bioturbated beds)* consists of a mixture of coarse to fine siliciclastic sand and coarse bioclastic fragments, organised into 5 to 25 cm thick beds that are alternatively well cemented and poorly cemented according to regular patterns (fig. 7A). Beds display a tabular to broadly lenticular geometry with sharp bases. Internally, beds range from massive to crudely normally graded, with local mollusc-rich bioclastic concentration. Despite the indistinct character of many individual burrows, a

number of ichnogenera has been recognised; observed structures comprise large forms of *Thalassinoides*, *Conichnus*, *Piscichnus*, *Skolithos* and large (decimetre-scale) J-shaped burrows (figs. 7B and 7C).

**Interpretation -** The large size and the abundance of the ichnofossils observed in this facies association strongly suggest unstressed environmental conditions. The occurrence of small burrow-filling biogenic concentrations of coarse bioclastic fragments suggests an intense remobilization of sediments carried out from feeding organisms. The identified ichnofauna represents a reasonable diversity of downwellings of filter and/or suspension-feeding organisms (e.g. *Conichnus* and *Skolithos*). Trace-fossils assemblage in the deposits of this facies association can be attributed to the *Cruziana* ichnofacies (Pemberton *et alii*, 1992). The diffuse presence of sands suggests that relative high-energy processes should have been active in this environment in order to move sandy grains toward this setting and to move away finer sediments. On the other hand, amalgamation of sands due to bioturbation suggests that during wide spans of time the same setting was hydrodynamically unperturbed. This kind of setting could be compared to the zone of transition between the proximal and the distal environment of the shelf systems described by Swift *et alii* (1991), where the return period of storms was enough long to led the bioturbation to be a prevalent feature respect to episodic traction processes, whose sedimentary structures were deleted by later biogenic activity. This interpretation is in agreement with the described ichnofacies, that is typical of sectors located below the mean storm wave base. Therefore, this facies association represents offshore environments rarely interested by storms (Reading, 1996; MacEachern & Bann, 2008).

### Facies association *2DSP* (2D dunes with segregated particles)

**Description -** F.a. *2DSP* develops above the f.a. *GB/SB* through sharp contacts in the Acerenza and La Guardia sections, and above the deposits of the f.a. *BNP* in the Madonna di Pompei and Torrente Alvo sections. F.a. *2DSP*, which has an average thickness of ~3 m and occurs in all the studied sections, consists of a mixture of medium to very coarse and granule-sized siliciclasts and bioclasts that are very well segregated. The *s/b* quantitative ratio for this facies association is >1. F.a. *2DSP* is composed of two facies: *Pcb*, and *M/Lb* (tab. 1).

*Facies Pcb (Planar cross-stratified beds)* consists of a moderately to well-rounded siliciclastic sand admixed to a bioclastic sand and granule, forming 8 to 100 cm thick cross-stratified beds (fig. 8A). Sediments are organised into 2D dunes and consist of repeated couplets (bundles) of well-segregated siliciclastic/thicker and bioclastic/thinner laminae (figs. 8B, 8C and 8D). Rhythmic alternation of bundles along foresets exhibits regular variations in thickness forming cycles whose main pronounced periodicity includes ~28 and 15 bundles. Foresets are mainly unidirectional and show non-deformed angular and tangential basal contact with slight concave frontal profile, even if rare deformed foresets locally occur. Cross-strata are stacked into cosets bounded by planar, locally erosional, surfaces. Bounding discontinuity surfaces are generally horizontal and are present on the base and on the top of single cross-strata (fig. 8C). A few centimetres thick layers of bioclastic fragments drape these surfaces (fig. 8A).

Palaeocurrents inferred from foreset dips of the facies *Pcb* are unimodal towards southeast in the Acerenza and La Guardia sections and towards northwest in the Madonna di Pompei and Torrente Alvo sections, with few foresets showing opposite transport direction (fig. 8A). Beds are sparsely to fairly bioturbated showing a low trace fossils density (B.I. =1-2). Burrows are horizontal (*Planolites*), vertical or sub-vertical oriented (*Skolithos*). Horizontal trails show sinuous locomotion tracks.

*Facies M/Lb (Massive/Laminated beds)* is represented by 5 to 13 cm thick beds made up of medium to coarse mixed sand (fig. 9A). This facies typically overlies deposits of facies *Pcb* often draping them (freezing the original depositional profile of cross-beds) or covering them through a slight erosional surface that affects their topmost part. Sediments are generally massive, normally graded or laminated.

**Interpretation -** The pronounced heterolithic stratification and the occurrence of current-generated structures in the mixed arenitic beds of facies *Pcb* suggest that the sediment was supplied/mobilised by unidirectional flows. Planar cross-stratified arenites of facies *Pcb a*re interpreted to record the migration of 2D dunes, in response to unidirectional currents flowing towards southeast or northwest, that means almost parallel to the main structural trends of the region (i.e. folds axes). The azimuthal distribution of palaeocurrents is unimodal with a standard deviation ($\sigma$) of ~24°. This datum is in agreement with the basic description of 2D dunes that are structures with straight or slightly sinuous crestlines oriented perpendicular to the mean flow lines and deposited under persistent tractional currents flowing without significant dispersion in their direction (Ashley, 1990). The high-grade of compositional segregation occurring between siliciclastic and bioclastic particles suggests that the hydrodynamic processes of sediment accumulation were able to sort the heterolithic fragments. In agreement with Longhitano (2011), depending on their specific density ($\sigma$) and shape, the siliciclastic fraction ($\sigma$ = ~2.6 g/cm$^3$) would be accumulated during periods of relative higher energy of the flow, whilst the bioclastic fraction (whose lowest density is ~1.1 g/cm$^3$; according to Prager *et alii*, 1996) would be maintained in suspension. On the contrary, bioclasts would be included in the deposit during periods of relative lower energy of the flow. Very similarly, in classical flaser structures, sandstone and clay drapes along cross-strata sets suggest repeated fluctuations in flow velocity (e.g. Reineck & Wunderlich, 1968). Moreover, according to Longhitano (2011), the regular variations in thickness of bundles measured along foresets of facies *Pcb*, whose periodicity roughly comprises 28 and 15 bundles, indicate the record of diurnal and spring-neap tidal cycles respectively, in which bioclastic drapes were deposited during periods of decreasing flow-energy. The opposed palaeocurrent directions of some cross-strata also confirm a tidal influence of different amplitude (e.g. Nio & Yang, 1991).

The unidirectionality of 2D dunes of facies *Pcb* and the lack of wave structures (except for occasional storm records – facies *M/Lb*) indicate that sediment accumulation occurred in a sector located below the fair-weather wave base but influenced by nearly constant tractive currents. This sector may correspond to a lower offshore-

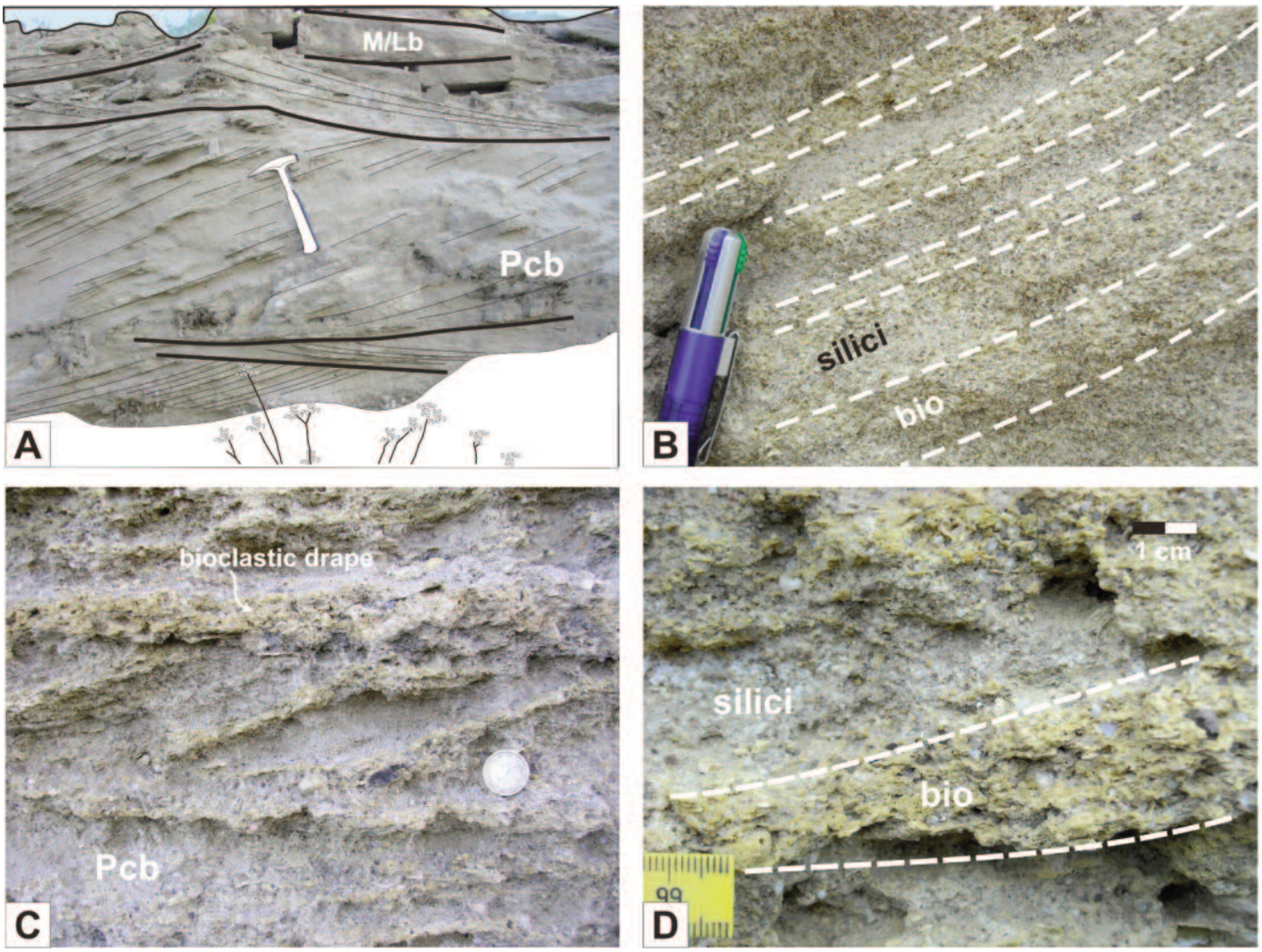



*Fig. 8* - Outcrop photos of facies association *2DSP*: *A*) Planar 2D dunes of facies *Pcb* showing bidirectional foresets; *B*) Close-up view of the previous photo showing tidal bundles of siliciclastic and bioclastic pairs of strata; *C*) 2D dunes of facies *Pcb* composed of thicker siliciclastic-rich and thinner bioclastic-rich strata; *D*) Close-up view of previous picture showing a marked silici-bioclastic segregation.

transition zone of a classical coastal profile (Dott & Bourgerois, 1982; Swift *et alii*, 1983; Walker & Plint, 1992; Reading & Collinson, 1996). This interpretation fits with data coming from the trace-fossils assemblages, that resemble those of the *Cruziana* ichnofacies of Pemberton *et alii* (1992) (see also: Reading, 1996; MacEachern & Bann, 2008).

### Facies association *3DSP* (3D dunes with segregated particles)

**Description -** F.a. *3DSP* develops above the previous deposits through either gradual or sharp contacts. This association is 5 to 8 m thick and has been recognised in all the three stratal units in the Acerenza, La Guardia and Madonna di Pompei sections (figs. 2A and 3). Sediments consist of a mixture of siliciclastic and bioclastic grains that are well to moderately segregated. The amount of the siliciclastic *versus* the bioclastic material (*s/b* quantitative ratio) is ~1. F.a. *3DSP* has been subdivided into facies *Tcb* and facies *M/Lb* previously described in the F.a. *2DSP* (tab. 1).

*Facies Tcb (Trough cross-stratified beds)* consists of a mixture of coarse to medium well-rounded siliciclastic sand admixed to bioclastic sand and granule. Sediments are organised into 3D dunes up to 80 cm thick (fig. 9A). The base of each strata is trough-shaped, forming elongated (elliptical) erosional scour filled with curved strata. Scours show either a symmetric or an asymmetric filling. Foresets show a tangential basal contact and a slight concave frontal profile (fig. 9A). Palaeocurrents of facies *Tcb* have two main trends: a trend towards southeast in the Acerenza and La Guardia sections and a trend toward northwest in the Madonna di Pompei section. The two heterolithic fractions show a well to moderate segregation ratio since cyclical bundles of siliciclastic and bioclastic laminae occur (fig. 9B). Trough cross-stratification are sparsely bioturbated with a low trace-fossils density (B.I. =1). Ichnogenera recognised correspond to *Planolites* and *Skolithos*.

**Interpretation -** Cosets of trough cross-strata of facies *Tcb* are interpreted to record the migration of 3D dunes, that, according to Harms *et alii* (1975), form under currents characterised by high velocity and more

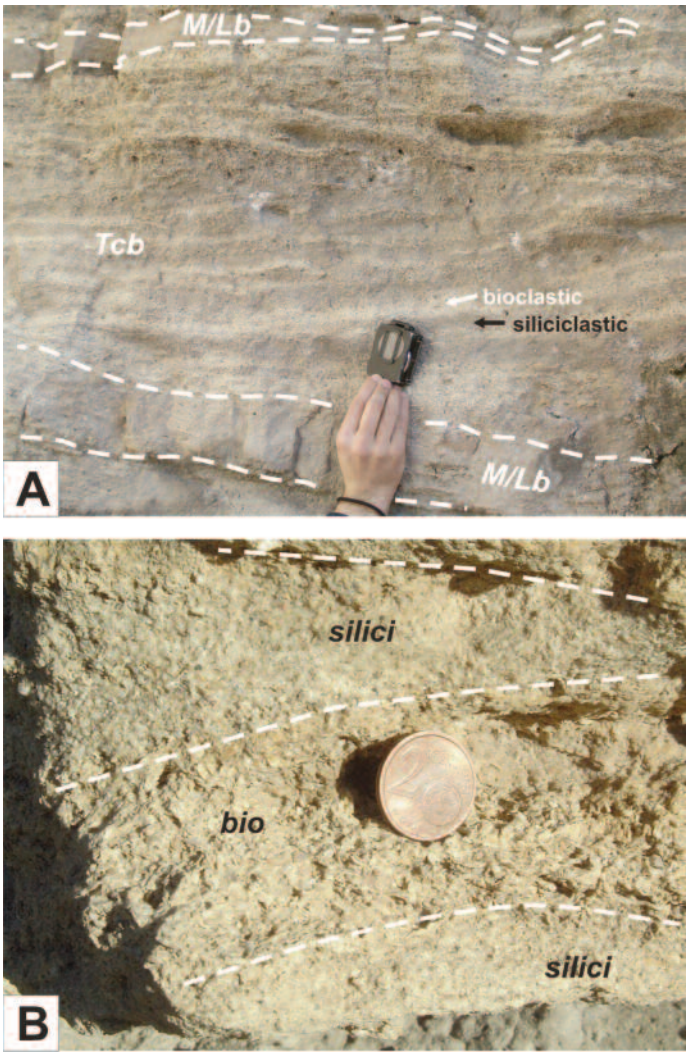



*Fig. 9 - A*) Facies *Tcb* organized into couplet of siliciclastic-rich (dark) and bioclastic-rich (light) strata; *B*) Close-up view of the previous picture showing a good to moderate silici-bioclastic segregation.

instable flows if compared to the same parameters inferred from 2D dunes. These circumstances may suggest an original shallower position of this facies association respect to the association *2DSP* along the original depositional profile. Well- to moderate-segregation observed in heterolithic dunes suggest that deposition occurred under the influence of tractional currents subjected to tidal cycles. According to the method proposed by De Celles *et alii* (1983) in order to estimate paleocurrent directions, two-dimensional bed exposures have been used for azimuth data determination from trough cross-stratification. In each studied section the local current run about parallel to the folds axes and most of the dispersion observed in the palaeocurrent dip azimuths can be related to the configuration of 3D dunes and not to changing current directions during deposition. Trough cross-stratification is randomly interrupted by the occurrence of the facies *M/Lb* that suggests the action of intermittent and very-high energy hydrodynamic-processes likely related to storm events.

The described set of features suggests that the f.a. *3DSP* developed in a shallow-marine sector that was current-dominated, tide-influenced, but not persistently interested by wave activity; broadly it could correspond to the upper offshore-transition zone of a classical coastal profile (e.g. Harms *et alii*, 1975; Dott & Bourgeois, 1982; Leckie & Walker, 1982; Walker & Plint, 1992; Reading & Collinson, 1996). This interpretation is in accordance with the observed trace fossil assemblages, that corresponds to the proximal *Cruziana* ichnofacies of Pemberton *et alii* (1992) and MacEachern & Bann (2008).

### Facies association *ISNP* (Indistinctly stratified-beds with unsegregated particles)

**Description** - F.a. *ISNP* represents the topmost stratigraphic interval of each stratal unit recognised in the Acerenza, La Guardia and Madonna di Pompei sections (figs. 2A and 3). These deposits show variable thicknesses that range from 1 to 7 m. In the stratal unit III the observed thickness is understimated due to the present-day topography. Sediments of this facies association consist of a mixture of unsegregated siliciclastic and bioclastic particles. The amount of siliciclastic *versus* bioclastic material (*s/b* quantitative ratio) varies between 0.3 and 0.5, indicating a prevalence of the bioclastic fraction. The siliciclastic fraction, occurring in a lower percentage if compared to the underlying deposits (f.a. *3DSP*), is highly dispersed into the bioclastic fraction without any preferential fabric, indicating a poorly or absent degree of segregation. F.a. *ISNP* has been subdivided into facies *Scb* and *Pplb*, which occur in the same bed and/or bedset. At the La Guardia section (fig. 3B), at the top of the stratal unit I, these facies are truncated at the top by erosive surfaces, and interested both by a remarkable cementation and by vertical to sub-horizontal cavities filled by reddish-brown silt with a low content of mixed sand (pipes?).

*Facies Scb (Swaley cross-stratified beds)* crops out in the Acerenza, La Guardia and Madonna di Pompei sections where it overlies facies *Tcb* through a pronounced erosive surface. Facies *Scb* consists of mixed very coarse sand-sized and granule-sized arranged into 5 to 30 cm thick layers wedging-out landward and gently dipping seaward. Beds of this facies are often amalgamated (fig. 10A). Cross-strata sets of facies *Scb* show swaley structures characterised by both low-angle (generally up to 10°) erosional surfaces, and internal stratification, approximately parallel to the basal surface; moreover, dip directions of both internal laminae and scoured surfaces are scattered, i.e. both them dip with equal frequency in all directions. Scours of swaleys are wider and more flat than troughs of the facies *Tcb*, with strata draping the lower scours surface or discordantly onlapping their margin (fig. 10B). Swaley cross-stratification shows a moderately to commonly bioturbation index (B.I. =3-4).

*Facies Pplb (Plane-parallel laminated beds)* consists of mixed coarse to very coarse sand and granule. Sediments are organised into 5 to 10 cm thick well-cemented beds showing a poorly recognizable plane-parallel lamination (fig. 10B). Facies *Pplb* are diffusely bioturbated (B.I. =3-4).

**Interpretation** - According to Harms *et alii* (1982), swaley cross-stratification is typical of very fine arenite beds, whereas Leckie & Walker (1982) and Datta *et alii* (1999) document swaley cross stratification also in coarser deposits. In the studied sections, facies *Scb* and facies *Pplb* exhibit coarse-grained facies that are arranged

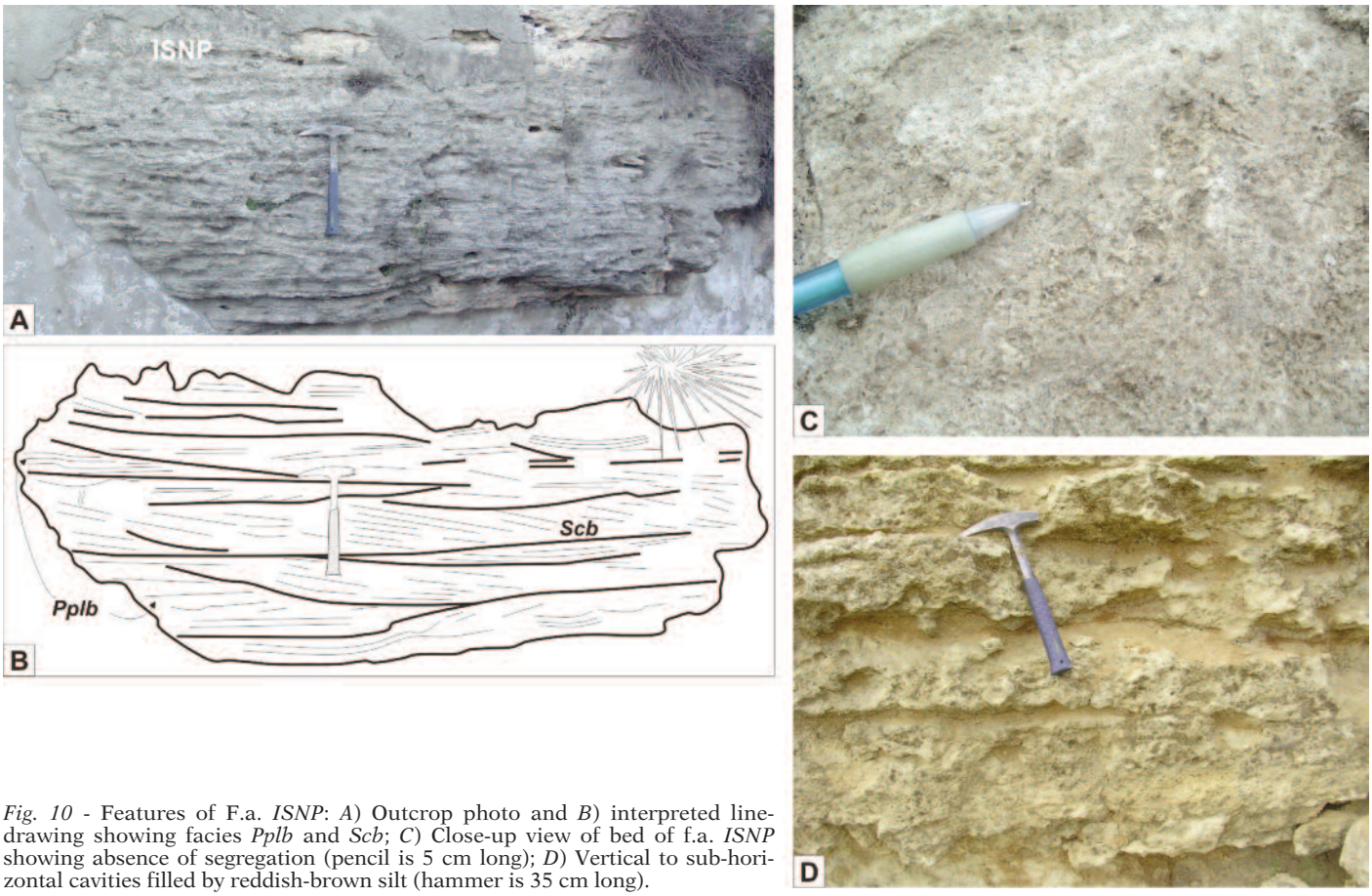



*Fig. 10* - Features of F.a. *ISNP*: *A*) Outcrop photo and *B*) interpreted line-drawing showing facies *Pplb* and *Scb*; *C*) Close-up view of bed of f.a. *ISNP* showing absence of segregation (pencil is 5 cm long); *D*) Vertical to sub-horizontal cavities filled by reddish-brown silt (hammer is 35 cm long).

into close-spaced vertical transitions; a similar feature was observed by DE RAAF *et alii* (1977) in a lower-Carboniferous shallow-marine succession. In accordance with these Authors, swaleys indicate conditions of considerable wave activity. The presence of planar parallel lamination may suggest that these deposits may have been accumulated in response to strong either oscillatory- or combined unidirectional- and oscillatory-flows of variable energy (e.g. DUKE, 1985; SOUTHARD *et alii*, 1990; DUMAS *et alii* (2005). Moreover, contrary to the deeper environments where segregation is markedly present, in this shallower-water environment the continuous activity of waves prevented processes of heterolithic sorting producing a chaotic admixture of siliciclastic and bioclastic fragments. This environment indicates a lower shoreface zone of a coastal profile (REINECK & SINGH, 1975; REINSON, 1992; SEIDLER & STEEL, 2001). The occurrence of beds amalgamation supports the hypothesis of deposition in a proximal marine environment progressively shallower (e.g. DOTT & BOURGEOIS, 1982). The internal lamination is poorly recognizable due to the dominance of the bioclastic fraction that produces a lower compositional and granulometric contrast within each strata (fig. 10C).

In the La Guardia section, the topmost features of the f.a. *ISNP* (filled cavities and cementation) indicate a subaerial exposure of these sediments. Probably already case-hardened by an early cementation which usually affects intertidal, carbonate-rich beach deposits (DAVIES & KINSEY, 1973; KRUMBEIN, 1979), they were successively intensely karstified. The overlying transgressive deposits of the younger stratal unit II filled these karstic cavities, generating neptunian dikes DEMOULLIN (2003) (fig. 10D).

## THE MIXED DEPOSITIONAL SYSTEM OF ACERENZA

The studied mixed deposits comprise three superimposed stratal units. Within each stratal unit, the stacking pattern of the recognised facies associations suggests a shallowing-upward trend, as represented in the reconstructed idealised stratigraphic-sedimentologic succession (fig. 5). This depositional system developed under subaqueous (marine) conditions although rare subaerial exposures occurred (e.g. the cavities at the top of the stratal unit I at the La Guardia section). It evolved in a shallow wedge-top basin whose sea-bottom, in accordance with the geological reconstruction proposed by LABRIOLA *et alii* (2007, 2008), was characterised by gentle folds inducing the presence of some bathymetric highs. In spite of these morphological undulations, the studied facies associations can be located along a gentle sloping subacqueous profile and subdivided in several hydrodynamic zones or environments (fig. 11). The deepest part of the inferred profile included offshore environments; the middle part comprises offshore transition and lower shoreface environments. The shallowest part of the inferred profile was rarely exposed and it was represented by the waves-eroded folds-top. Likely, thrusts top was also the main source areas for the siliciclastic supply induced by wave erosion (fig. 11).

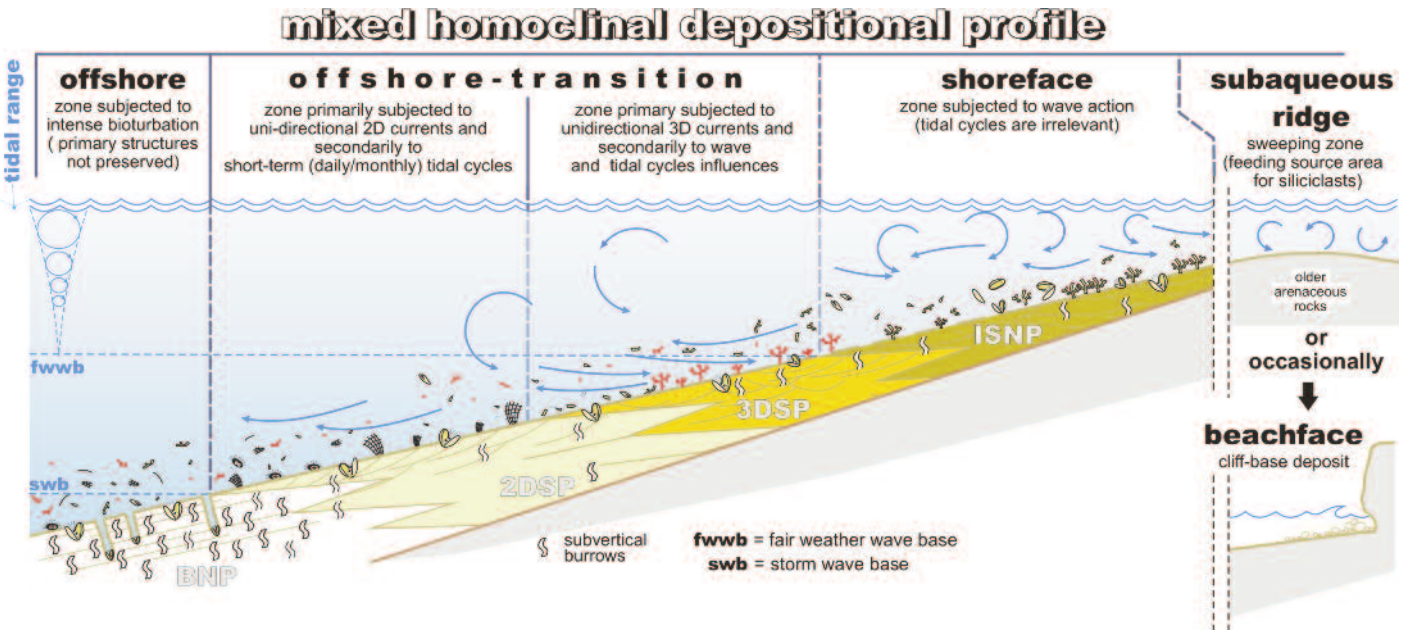



*Fig. 11* - Depositional profile including the environments characterized by different depths. Sediment distribution and accumulation occurred under persistent currents and waves, depending on the depth conditions of each hydrodynamic zone.

Therefore, three main depositional zones may be recognised in the mixed system of Acerenza. From the deepest to the shallowest, they are: (*i*) the offshore zone; (*ii*) the offshore-transition zone and (*iii*) the shoreface zone.

(*i*) The offshore zone is recorded by the f.a. *BNP*, that comprises unsegregated mixed sediments showing indistinct beds mostly bioturbated. The presence of sand-sized sediments suggests that sandy transport driven by wave and/or current should occasionally occur in this setting; since the same sandy facies are very rarely characterised by sedimentary structures produced by hydrodynamic processes, most probably these features were deleted by a much more constant bioturbation activity.

(*ii*) The offshore-transition zone is recorded by the f.a. *2DSP*, whose deposits are noticeably segregated because attributed to the influence of tidally-modulated unidirectional and persistent currents, with relatively low bed shear stress (~0·4 N $m^{-2}$). Accordingly, these features suggest that current flowed at relative higher velocity during low tide and at relative lower velocity during high tide, in consequence of the alternating decreasing and increasing of the hydraulic cross-section in this part of the depositional profile. The offshore-transition zone is recorded also by the f.a. *3DSP* whose depositional environment was subjected to tractional currents modulated by tidal cycles, but characterised by a greater bed shear stress (>1·0 N m-2), that caused the migration of 3D dunes with a moderate to good heterolithic segregation. Therefore, the occurrence of either 2D or 3D dune trains allow to distinguish a lower offshore-transition zone (f.a. 2DSP) from an upper offshore-transition zone (f.a. 3DSP).

Finally, (*iii*) the shoreface zone is recorded by the f.a. *ISNP*. This zone was most likely characterised by high-energy conditions induced by a constant wave action, with a consequent absence of segregation of heterolithic grains.

The shallower parts of the profile was a non depositional/erosional zone (fig. 11) whose bathymetric position corresponded to upper shoreface environments of a classical depositional coastal profile. When and were folds were subaereally exposed, shallower environments (beachface or sea cliff and rocky coast) could develop in the innermost part of the profile (fig. 11) The depositional/erosional zone coincided with the subaqueous folds tops swept by waves (see the example proposed by CARON *et alii*, 2004).

## CONCLUSIONS

Mixed siliciclastic-bioclastic shallow-marine systems developed during middle-late Pliocene times along frontal thrusts of the Apennines. In such a setting, depositional processes were regulated by the influence of different hydrodynamic factors, including: (*i*) waves in the shallowest environments (shoreface) of the mixed system and occasionally (storms) in relatively deeper ones; (*ii*) persistent currents, that dominated in environments deeper than the shoreface (offshore-transition); (*iii*) short-term tidal cycles that interplayed with currents in the offshore-transition zones. It should be underlined that tidal processes were not primarily responsible for the genesis of currents, whose energy was only "modulated" by the tidal cyclicity.

The deepest zones (offshore) were dominated by bioturbation, but the sand-grade sediments suggests high-energy events (storms).

In the offshore-transition zones, currents dominated and trains of 2D and 3D dunes developed. Basin features led tidal cyclicity to be recorded by siliciclastic/bioclastic bundles and by regular (rhythmic) alternation of strata thickness along dune foresets.

In the lower shoreface zones, waves dominated generating swaley and plane-parallel stratifications.

The shallowest zones of the mixed system were typically below the sea surface, since beach or continental deposits are rare. Swept (wave eroded) shoreface zones should have been developed onto the top of the main folds that characterised the sea-bottom of the wedge-top basin. This area likely supplied siliciclastics to the studied mixed depositional system.

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