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# Different stacking patterns along an active fold-and-thrust belt—Acerenza Bay, Southern Apennines (Italy)

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## ABSTRACT

**Traditional sequence stratigraphic models provide limited understanding of the internal complexity and variability of mixed siliciclastic-carbonate strata accumulated in tectonically active settings. Coeval Lower Pleistocene (Gelasian) shallow-marine, mixed siliciclastic-carbonate depositional wedges accumulated within an active piggyback basin along the southern Italy fold-and-thrust belt are characterized by similar internal architecture of sequences but different stacking patterns. In particular, four coastal wedges (up to 30 m thick each), just a few kilometers (~2 km) apart from each other, show aggradational versus progradational stacking patterns related to their location within a deforming piggyback basin. In all the studied sections, mixed siliciclastic-carbonate strata form isolated sedimentary wedges organized into three vertically stacked transgressive-regressive sequences bounded by sharp flooding surfaces. Aggradational versus progradational internal architecture results from (1) local syndepositional compressive and/or extensional tectonics controlling differential uplift and subsidence, and (2) sediment supply characterized by a combination of intrabasinal and extrabasinal siliciclastics and carbonates. Aggradation occurs in areas showing a balance between both accommodation and sediment supply, and siliciclastic and carbonate fractions. Progradation is typical of supply-dominated areas located close to the active anticline, and dominated by the carbonate fraction. The present work documents the local variability of stratal stacking patterns and sediment supply (siliciclastic-carbonate ratio). We highlight the limitations of using sequence architectures and systems tracts for base-level change and basin reconstructions in tectonically active settings. It is important not only to correctly interpret the stacking pattern, but also to increase our understanding of the type of sediment (siliciclastic vs. carbonate) and sedimentation rate, sedimentation loci, and subsurface predictions.**

## INTRODUCTION

Stratal stacking patterns are widely used to analyze the sedimentary response to changes in base level (*A*) and sediment supply (*S*). The effects of variability of sequence stacking and rate of sediment supply along active rift margins have been perceived for a long time and re-emphasized in recent works (Martinsen and Helland-Hansen, 1995; Gawthorpe et al., 2017). There is, however, a lack of data concerning the evolution of syntectonic stacking patterns developed within piggyback basins, particularly those characterized by a mixed siliciclastic-carbonate stratal succession. The existing case studies show mainly two-dimensional (2-D) dip-oriented models (e.g., Ćosović et al., 2017), confirming that 2-D thinking is still the preferred sequence stratigraphic approach (Burgess, 2016), and they do not take into account intrabasinal coeval sediment supply from wave abrasion and *in situ* bioclastic production.

Mixed siliciclastic-carbonate sequences are typical of foreland basins (e.g., Puigdefàbregas et al., 1986). Mixed systems are peculiar because they represent a unicum, where, in addition to the conventional controlling factors operating in siliciclastic-dominated systems (e.g., climate, tectonics, drainage area, oceanography), there is a significant sediment contribution from an intrabasinal *in situ* carbonate factory (sensu Mount, 1984; Chiarella et al., 2017) controlled by biological factors (e.g., salinity, nutrients, temperature). With a carbonate intrabasinal sediment source, mixed siliciclastic-carbonate systems can infill the accommodation space in many different ways that are often interdependent on extrabasinal supply and space, similar to some carbonate-dominated systems. Accordingly, the sediment budget depends on synsedimentary extrabasinal and intrabasinal factors, with the siliciclastic fraction following source-to-sink concepts, and the carbonate fraction following a process where the source is in the sink (Pomar and Haq, 2016).

In our study, we present an integrated sedimentological and sequence stratigraphic analysis of four coeval Lower Pleistocene synorogenic coastal wedges accumulated in one of the most external piggyback basins (i.e., Acerenza–Oppido Lucano–Tolve Basin) developed onto the moving allochthonous sheets of the Southern Apennines chain (Italy). Coastal wedges are distributed within an area of ~40 km$^2$ and characterized by shallow-marine deposits showing compositional mixing (sensu Chiarella et al., 2017). Nevertheless, the studied coastal wedges show significantly different stacking patterns and siliciclastic-carbonate ratios, which we suggest are responses to local tectonic activities and related paleoceanographic circulation.

## SYNOROGENIC COASTAL WEDGES

The present study is focused on the Acerenza Bay mixed siliciclastic-carbonate deposits, which accumulated in one of the most external piggyback basin of the Southern Apennines (Fig. 1; Chiarella and Longhitano, 2012; Chiarella et al., 2012). Here, four coastal wedges (i.e., Acerenza, La Guardia, Madonna di Pompei, and Alvo Stream) have been documented, located just a few kilometers (~2 km) apart from each other (Fig. 2). Conventional field methods of sedimentological analysis were used (e.g., detailed logging and line drawing). In all studied sections, the mixed deposits consist of three sequences (each 2–15 m thick) bounded by sharp transgressive surfaces and developed on top of a hinged-margin drowning unconformity

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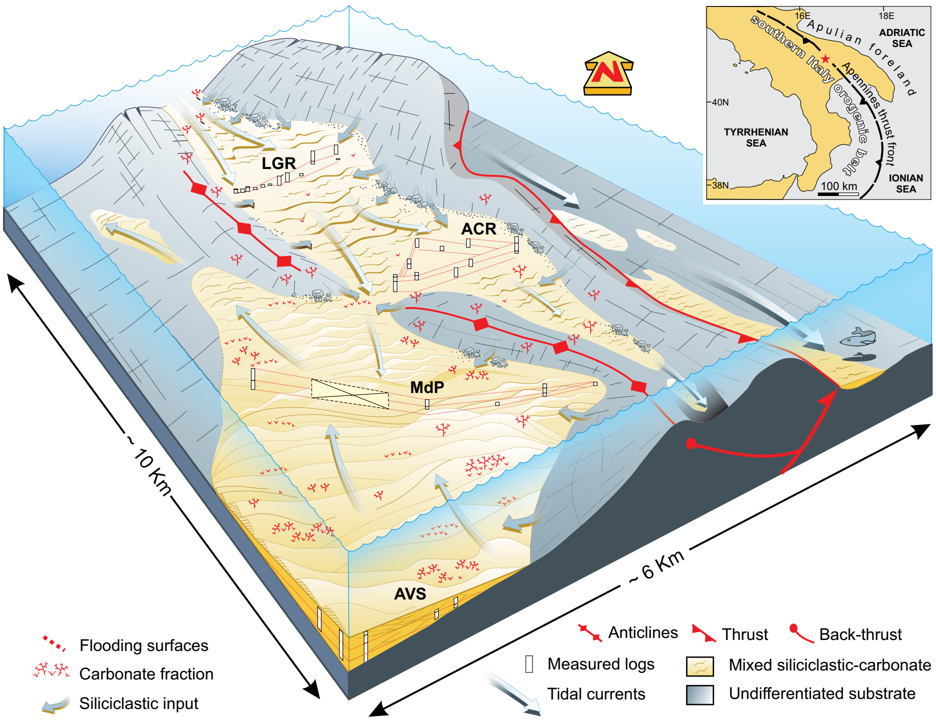
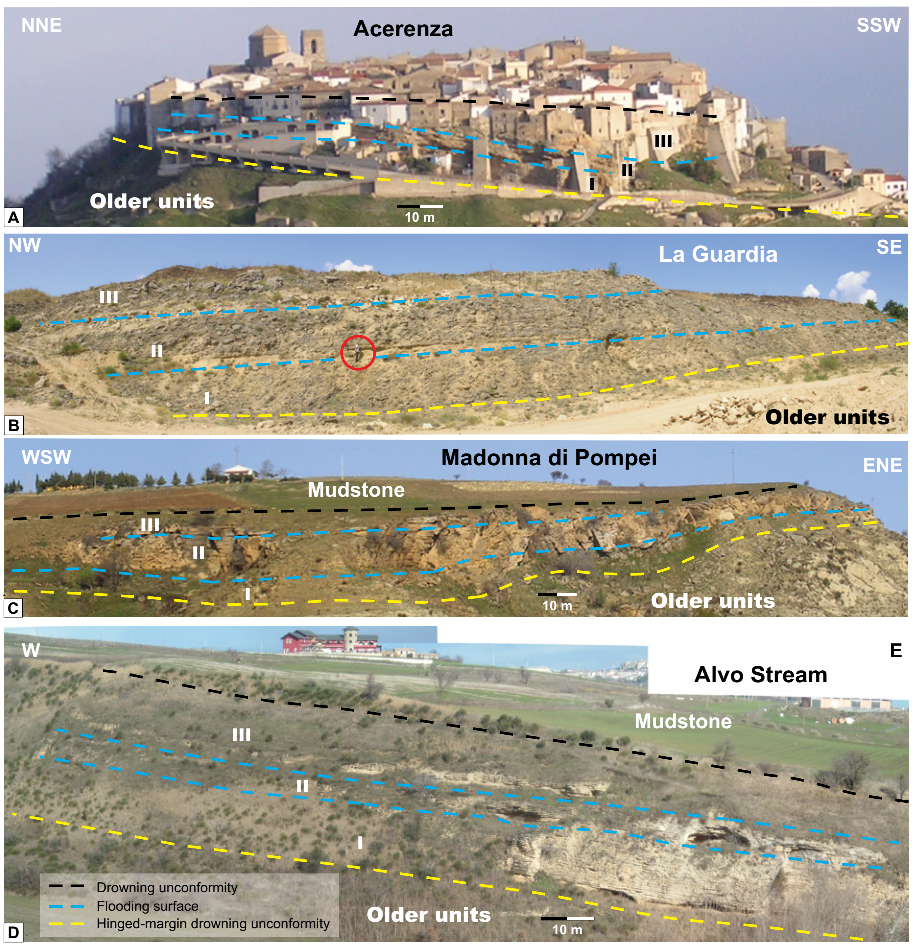



**Figure 1. Early Pleistocene structural and paleogeographic reconstruction of Acerenza Bay (southern Italy). Position and depositional development of studied wedges are indicated. Siliciclastic fraction was derived mainly from submarine erosion of substrate. Bioclastic fraction was derived from fragmentation of *in situ* heterozoan carbonate factory. Wedges: ACR—Acerenza; LGR—La Guardia; MdP—Madonna di Pompei; AVS—Alvo Stream.**




(HDU) (*sensu* Rossi et al., 2018) referred to ca. 2.5 Ma (Patacca and Scandone, 2004), locally characterized by a complex topography with an incision network (e.g., slump scars, gullies). Isotopic values (Sr) of brachiopod samples collected along the four wedges indicate an age of 2.5 ± 0.2 Ma for the mixed deposits. They are abruptly overlain by a 1–2-m-thick diatomitic layer of regional extent, conformably passing upward to marine mudstones referred in the study area to the Gelasian (MPL5b biozone and MNN18 biozone; Longhitano et al., 2012), an early Pleistocene stage characterized by 41 k.y. low-amplitude Milankovitch cycles (Abreu and Anderson, 1998) that controlled the development of the sequences (Fig. 2). The four wedges are therefore contemporaneous (see the GSA Data Repository[1]). The morphology produced by the thrust activity controlled the paleogeography of the wedge-top depozone and the characteristic ridge-and-swale topography, which in turn controlled the positions of depocenters (Fig. 1). The paleogeography was a confined embayment, where clastic wedges developed (Longhitano et al., 2012). Accordingly, the Acerenza Bay was a bathymetrically diversified environment with shallowly submerged ridges of a blind-thrust anticline on which a coeval *in situ* cool-water carbonate factory developed (heterozoan assemblage; sensu James, 1997). The embayment was characterized by persistent currents with a tidal modulation (Chiarella and Longhitano, 2012; see the Data Repository), because the bay's length and depth caused tidal resonance and consequent amplification of the tidal current velocities. In this environment, the combination of siliciclastic and carbonate sediment sources produced coastal wedges with different stacking patterns.

The Acerenza Bay deposits are organized into four aggrading and prograding wedges a few kilometers apart, the present-day geographic distribution and internal organization of which reflect the complex paleophysiography of the basin. Each wedge, up to 30 m thick, consists of three 2–15-m-thick sequences (Fig. 3A) bounded by sharp surfaces. The sequence consists of well-sorted, medium- to coarse-grained mixed siliciclastic-carbonate arenites grouped into five main facies associations (FA; Chiarella

[1]GSA Data Repository item 2019054, supplemental data pertaining to facies, sample locations, biostratigraphy, isotopic analysis, and statistical analysis, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

**Figure 2. Outcrop views of Acerenza (A), La Guardia (B), Madonna di Pompei (C), and Alvo Stream (D) wedges, highlighting geometry of basal hinged-margin drowning unconformity (HDU, yellow) and stacking organization of sequences in both strike and dip views.**

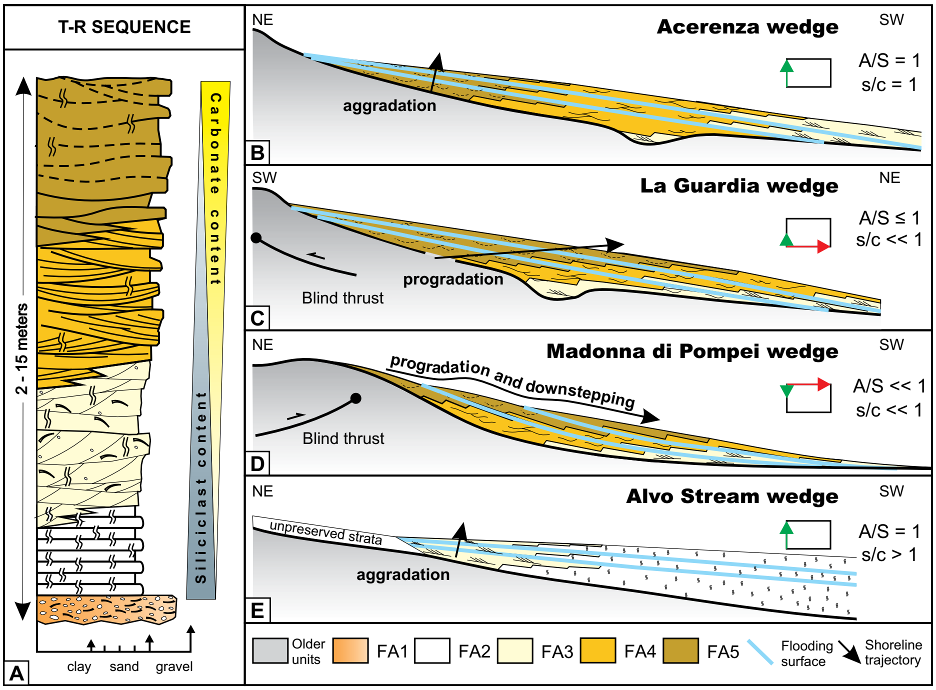



**Figure 3. A: Composite stratigraphic column showing internal organization of facies associations within a sequence. B–E: Cross sections of coastal wedges analyzed in present study (see Fig. 1 for location). Note accretionary (Acerenza and Alvo Stream wedges), ascending regressive (La Guardia wedge), and descending regressive (Madonna di Pompei wedge) stacking patterns. Red arrows indicate progradational component, and green arrows indicate aggradational component. *A/S* is accommodation (*A*) to sediment flux (*S*) ratio; *s/c* is the siliciclastic (s) to carbonate (c) content ratio. FA—facies association. Position of FA1 in wedges corresponds to flooding surfaces. Models are not to scale.**

et al., 2012). The siliciclastic fraction consists of monocrystalline quartz grains. The carbonate fraction is almost completely made up of bryozoans, molluscs, benthic and planktonic foraminifers, echinoids, brachiopods, barnacles, and red algae. The lowermost facies association (FA1) is recognized at the base of all sequences and represents the transgressive basal interval (i.e., transgressive lag) accumulated during a period of relative quick sea-level rise. Upward, FA2 consists of intensely bioturbated (*Cruziana* ichnofacies), medium- to coarse-grained mixed arenites having a siliciclastic-carbonate (*s/c*) quantitative ratio >1 (Chiarella and Longhitano, 2012). This facies association is interpreted as the transition zone between proximal and distal (i.e., offshore) environments, where the return period of high-energy processes was long enough to allow bioturbation to be a prevalent feature with respect to episodic traction processes. FA3 is composed of medium- to coarse-grained mixed arenites ($s/c \geq 1$) organized into 2-D planar cross-strata. Foresets display regular internal segregation of the siliciclastic and carbonate fractions, forming tidal rhythmites in bundles of thicker (siliciclastic-rich) and thinner (carbonate-rich) cosets. This facies association suggests the presence of persistent, and cyclically modulated tidal currents able to generate 2-D ripples and dunes in an offshore-transition environment below the fair-weather wave base.

FA4 consists of coarse-grained mixed arenites ($s/c = 1$) organized into three-dimensional (3-D) cross-strata. The occurrence of 3-D dunes implies high-energy flow conditions and elevated bed shear stress due to currents modulated by waves in a lower shoreface/offshore-transition environment. The topmost facies association FA5 consists of very coarse mixed arenites and granules ($s/c \ll 1$) organized into plane-parallel and swaley cross-strata wedging out landward and gently dipping seaward. This facies association is interpreted to reflect sedimentation under strong unidirectional currents as well as oscillatory flows of variable energy in an upper shoreface environment. Each sequence records a transgressive-regressive (T-R) sequence (Chiarella and Longhitano, 2012) driven by icehouse eustasy related to Milankovitch cycles (41 k.y.).

### Coastal Wedges and Shoreline Trajectory

The Acerenza (ACR) wedge (Fig. 2A) dips toward the southwest and developed along one of the frontal thrust faults responsible for the eastward migration of the Southern Apennines. To the southwest, the development of the system was controlled by the presence of a growing back thrust–related anticline (Fig. 1). The erosional surface of the basal unconformity (HDU) has considerable relief and is marked by a transgressive lag (FA1; Chiarella et al. 2012). Volumetrically, FA4 is the most substantial deposit, and it shows about equal amounts of siliciclastic and carbonate grains. The stacking pattern of the three T-R sequences forms an aggradational accretionary shoreline trajectory (sensu Helland-Hansen and Hampson, 2009; Fig. 3B). The La Guardia (LGR) wedge (Fig. 2B) dips toward the northeast and developed on the east flank of the syndepositional anticline (Fig. 1). As in the ACR wedge, the basal unconformity reflects inherited basin topography. The LGR deposits show a dominance of the carbonate fraction over the siliciclastic fraction, with FA4 and FA5 volumetrically more important. The facies associations in successive T-R sequences record an ascending regressive trajectory generating a progradational architecture for the LGR wedge (Fig. 3C). The Madonna di Pompei (MdP) wedge (Fig. 2C) dips toward the southwest and developed on the western flank of the syndepositional anticline, southeastward of the LGR wedge (Fig. 1). The basal unconformity is erosional, showing a complex topography with an incision network. Similar to the LGR wedge, the MdP wedge is slightly carbonate dominated, with FA4 and FA5 representing most of the sediment volume. The facies associations, through successive T-R sequences, record a descending regressive accretionary shoreline trajectory (sensu Helland-Hansen and Hampson, 2009), producing a progradational and downstepping geometry for the three T-R sequences (Fig. 3D). The Alvo Stream (AVS) wedge (Fig. 2D) dips toward the southwest and developed far from the frontal thrust fault in an area characterized by relatively minor tectonic activity along a gently inclined subaqueous ramp (Fig. 1). The basal unconformity is subhorizontal with no evidence of significant erosion. This wedge shows a dominance of FA2, indicating unfavorable conditions for the development of the *in situ* carbonate factory. The T-R sequences are vertically stacked, showing an accretionary shoreline trajectory indicative of an overall aggradational stacking pattern (Fig. 3E).

## STACKING PATTERN VARIABILITY

The formation of piggyback basins is related to thrusting, back-thrust development, and normal faults, where carbonate and clastic sediment accumulation may coexist (e.g., Ćosović et al., 2017). Petrographic analyses show that all four coastal wedges were sourced from the same siliciclastic rocks and carbonate factory (Chiarella and Longhitano, 2012) during a regional flexural subsidence (Patacca and Scandone, 2004). Although the documented coastal wedges, being coeval and adjacent, developed under the same climatic conditions, which possibly controlled the base level and the type of the biota of the carbonate factory, the coastal systems nevertheless record significant different stacking patterns (Fig. 2).

The ACR and AVS wedges show an overall aggradational stacking geometry, suggesting a relative base-level rise ($A/S = 1$). In the ACR wedge, the dominance of FA4 with $s/c$ ratio = 1 suggests the coexistence of carbonate factory and terrigenous input, providing a similar sediment budget. In contrast, in the AVS wedge, the $s/c$ ratio > 1 recorded in the FA2 indicates unfavorable environmental conditions for the carbonate factory in that specific area, probably related to the fine grain size of the mobile sea bottom. The LGR and MdP wedges developed on the east and west flanks of a back thrust–related anticline, respectively (Fig. 1). The progradational stacking pattern of the LGR wedge indicates a relative sea-level rise accompanied by high sediment supply ($A/S \leq 1$). In contrast, the downstepping progradation of the MdP wedge points to a relative fall in base level ($A/S \ll 1$). The dominance of the carbonate fraction in the FA4 and FA5 deposits found in the LGR and MdP wedges indicates an area of high carbonate production ($s/c \ll 1$), which may have locally reduced the siliciclastic substrate available for currents or wave winnowing. Fauna colonization was favored by the paleogeographic conditions created by the growing thrust, which enhanced the circulation of nutrient-rich sustained currents. Tidal currents moved parallel to the main tectonic structures, which defined the paleoshoreline trends, and controlled the distribution of sediments and nutrients in the shoreface-offshore transitional setting (Fig. 1).

## CONCLUSIONS

In the synorogenic piggyback basins of the Southern Apennines, a linkage between tectonic and depositional processes resulted in four coeval sedimentary wedges in different sedimentation loci, the component stratigraphic sequences of which form different stacking patterns over length scales of a few kilometers. Each wedge consists of three vertically stacked T-R sequences that are organized into an aggradational or progradational stacking pattern. In particular, the ACR and AVS wedges are characterized by an aggradational stacking pattern, while the LGR and MdP wedges show progradation and downstepping progradation geometries, respectively. Our results show that stacking pattern and sedimentation loci are influenced by the position and synsedimentary activity of the main tectonic elements, as well as the development of the HDU. Moreover, the *in situ* carbonate fraction plays a determinant role controlling the total sediment budget available in the system and its specific areal distribution in relation to the local physical and ecological conditions. This strongly suggests that the classic source-to-sink concept of pure siliciclastic and carbonate systems does not work in mixed systems. Accordingly, sequence stratigraphic analysis of mixed siliciclastic-carbonate sedimentary systems developed along active fold-and-thrust belts requires careful understanding of the tectonic evolution of the basin, $s/c$ ratio, and geographical distribution of the two siliciclastic and carbonate fractions.

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