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

Domenico Chiarella[1], Sergio G. Longhitano[2], and Marcello Tropeano[3]

[1]*Department of Earth Sciences, Royal Holloway, University of London, Egham TW20 0EX, UK*

[2]*Department of Sciences, University of Basilicata, 85100 Potenza, Italy*

[3]*Dipartimento di Scienze della Terra e Geoambientali, University of Bari, 70125 Bari, Italy*

ABSTRACT

Traditional sequence stratigraphic models provide limited understanding of internal complexity and variability when applied to mixed siliciclastic-carbonate strata accumulated in tectonically active settings. Coeval Lower Pleistocene (Gelasian) shallow-marine, mixed siliciclastic-carbonate depositional wedges accumulated within an active piggy-back 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 piggy-back 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 siliclicastics 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 (siliciclatic-carbonate ratio). We highlight the limitations of using sequence architectures and systems tracts for base-level changes and basin reconstructions in tectonically active settings. It is of great importance not only to correctly interpret the stacking pattern, but also to increase our understanding of the type of sediment (siliciclastic versus carbonate) and sedimentation rate, sedimentation loci, and subsurface prediction.

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 syn-tectonic stacking patterns developed within piggy-back basins, particularly those characterized by a mixed siliciclastic-carbonate stratal succession. The existing case studies show mainly two-dimensional (2D) dip-oriented models (e.g., Ćosović et al., 2017), confirming that 2D 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, tectonic, drainage area, oceanography), we have 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, nutrient, temperature). With a carbonate intrabasinal sediment source, mixed siliciclastic-carbonate systems can infill the accommodation space in many different ways that are often extrabasinal supply and space interdependent, similar to some carbonate-dominated systems. Accordingly, sediment budget depends on synsedimentary extrabasinal and intrabasinal factors, with the siliciclastic fraction following the source-to-sink concepts, and the carbonate one 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 syn-orogenic coastal wedges accumulated in one of the most external piggy-back 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 a compositional mixing (*sensu* Chiarella et al., 2017). Nevertheless, the studied coastal wedges show significantly different stacking patterns and siliciclastic-carbonate ratio, which we suggest are a response to local tectonic activities and related paleoceanographic circulations.

SYN-OROGENIC COASTAL WEDGES

The present study is focused on the Acerenza Bay mixed siliciclastic-carbonate deposits accumulated in one of the most external piggy-back 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) located just a few kilometers (~2 km) apart from each other have been documented (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 (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) controlling the development of the sequences (Fig. 2). The four wedges are therefore contemporaneous. The morphology produced by the thrust activity controlled the paleogeography of the wedge-top depozone and the characteristic ridge-and-swale topography in turn controlling the position of depocenters (Fig. 1). The paleogeography was a confined embayment where clastic wedges develop (Longhitano et al., 2012). Accordingly, the Acerenza Bay was bathymetrically diversified by the 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), 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 km apart, whose present-day geographic distribution and internal organization 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 et al., 2012). The siliciclastic fraction consists of mono-crystalline 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* ≥ 1) organized into 2D 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 2D 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 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* << 1) organized into plane-parallel and swaley cross-strata wedging-out landwards and gently dipping seawards. 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 ky).

Coastal Wedges and Shoreline Trajectory

The Acerenza (ACR) wedge (Fig. 2A) dips toward southwest and develops along one of the frontal thrust faults responsible for the eastward migration of the Southern Apennines. To the southwest, the development of the system is controlled by the presence of a growing backthrust-related anticline (Fig. 1). The basal unconformity (HDU) has considerable relief of the erosional surface and is marked by a transgressive lag (FA1, Chiarella et al. 2012). Volumetrically, FA4 is the most important deposit and it shows about equal amounts of siliciclastic and carbonate grains. 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 northeast and develops 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 5 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 southwest and develops on the western flank of the syndepositional anticline, south-eastwards 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 5 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 down-stepping geometry of the three T-R sequences (Fig. 3D). The Alvo Stream (AVS) wedge (Fig. 2D) dips toward southwest and develops 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 sub-horizontal with no evidence of significant erosion. This wedge shows a dominance of the 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 piggy-back basins is related to thrusting as well as backthrusts development, and normal faults, where the carbonate and clastic sediment accumulation may co-exist (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 a 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 carbonate factory in that specific area probably related to the fine grain size of the mobile sea bottom. The LGR and MdP wedges develop on the east and west flank of a backthrust-related anticline respectively (Fig. 1). The progradational stacking pattern of the LGR wedge indicates a relative sea-level rise accompanied by a high sediment supply ($A/S \leq 1$). In contrast, the down-stepping progradation of the MdP wedge points to a relative fall in base level ($A/S << 1$). The dominance of carbonate fraction in the deposits of FA4 and 5 found in the LGR and MdP wedges indicates an area of high carbonate production (*s/c* << 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 that 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 syn-orogenic piggy-back basins of the southern Apennines, a linkage between tectonic and depositional processes resulted in four coeval sedimentary wedges in different sedimentation *loci* whose component stratigraphic sequences form different stacking patterns over length scales of 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 show progradation and down-stepping 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 hinged-margin drowning unconformity. 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, the sequence stratigraphic analysis of mixed siliciclastic-carbonate sedimentary systems developed along active fold- and thrust-belt requires careful understanding of the tectonic evolution of the basin, s/c ratio, and geographical distribution of the two siliciclastic and fractions.

ACKNOWLEDGMENTS

The research was conducted in the framework of the “Clastic Sedimentology Investigation” research group (Royal Holloway, University of London).

REFERENCES CITED

Abreu, V.S., and Anderson, J.B., 1998, Glacial eustasy during the Cenozoic: Sequence stratigraphic implications: The American Association of Petroleum Geologists Bulletin, v. 82, p. 1385–1400.

Burgess, P.M., 2016, The future of the sequence stratigraphy paradigm: Dealing with a variable third dimension: Geology, v. 44, p. 335–336, https://doi.org/10.1130/focus042016.1.

Chiarella, D., and Longhitano, S.G., 2012, Distinguishing depositional environments in shallow-water mixed bio-siliciclastic deposits on the base of the degree of heterolithic segregation (Gelasian, Southern Italy): Journal of Sedimentary Research, v. 82, p. 969–990, https://doi.org/10.2110/jsr.2012.78.

Chiarella, D., Longhitano, S.G., and Tropeano, M., 2017, Types of mixing and heterogeneities in mixed siliciclastic-carbonate sediments: Marine and Petroleum Geology, v. 88, p. 617–627, https://doi.org/10.1016/j.marpetgeo.2017.09.010.

Chiarella, D., Longhitano, S.G., Tropeano, M., and Sabato, L., 2012, Sedimentology and hydrodynamics of mixed (siliciclastic–bioclastic) shallow-marine deposits of Acerenza (Pliocene, Southern Apennines, Italy): Societa': Geologica Italiana: Bollettino, v. 131, p. 136–151, https://doi.org/10.3301/IJG.2011.36.

Ćosović, V., Mrinjek, E., Nemec, W., Španiček, J., and Terzić, K., 2017, Development of transient carbonate ramps in an evolving foreland basin: Basin Research, v. 30, p. 746–765, https://doi.org/10.1111/bre.12274.

Gawthorpe, R.L., Andrews, J.E., Collier, R.E.L., Ford, M., Henstra, G.A.H., Kranis, H., Leeder, M.R., Muravchik, M., and Skourtsos, E., 2017, Building up or out?: Disparate sequence architectures along an active rift margin—Corinth rift, Greece: Geology, v. 45, p. 1111–1114, https://doi.org/10.1130/G39660.1.

Helland-Hansen, W., and Hampson, G.J., 2009, Trajectory analysis: concepts and applications: Basin Research, v. 21, p. 454–483, https://doi.org/10.1111/j.1365-2117.2009.00425.x.

James, N.P., 1997, Cool-water carbonate depositional realm, *in* James, N.P. and Clarke, J.A.D., eds., Cool-Water Carbonates: Society for Sedimentary Geology Special Publications, v. 56, p. 1–20, https://doi.org/10.2110/pec.97.56.0001.

Longhitano, S.G., Chiarella, D.D.I., Stefano, A., Messina, C., Sabato, L., and Tropeano, M., 2012, Tidal signatures in Neogene to Quaternary mixed deposits of southern Italy bays and straits: Sedimentary Geology, v. 279, p. 74–96, https://doi.org/10.1016/j.sedgeo.2011.04.019.

Martinsen, O.J., and Helland-Hansen, W., 1995, Strike variability of clastic depositional systems—Does it matter for sequence-stratigraphic analysis?: Geology, v. 23,

p. 439–442, https://doi.org/10.1130/0091-7613(1995)023<0439:SVOCDS>2.3.CO;2.

Mount, J.F., 1984, Mixing of siliciclastic and carbonate sediments in shallow shelf environments: Geology, v. 12, p. 432–435, https://doi.org/10.1130/0091-7613(1984)12<432:MOSACS>2.0.CO;2.

Patacca, E., and Scandone, P., 2004, The Plio-Pleistocene thrust belt - foredeep system in the southern Apennines and Sicily (Italy), *in* Crescenti, U., et al., eds., Geology of Italy: Special Volume of the Italian Geological Society for the IGC 32, Florence 2004, p. 93–129.

Pomar, L., and Haq, B.H., 2016, Decoding depositional sequences in carbonate systems: Concepts vs experience: Global and Planetary Change, v. 146, p. 190–225, https://doi.org/10.1016/j.gloplacha.2016.10.001.

Puigdefàbregas, C., Munoz, J.A., and Marzo, M., 1986, Thrust belt development in the Eastern Pyrenees and related depositional sequences in the southern foreland basin, *in* Allen, P.A., and Homewood, P., eds., Foreland Basins: Special Publication of the International Association of Sedimentologists, v. 8, p. 229–246, https://doi.org/10.1002/9781444303810.ch12.

Rossi, M., Minervini, M., and Ghielmi, M., 2018, Drowning unconformities on hinged clastic shelves: Geology, v. 46, p. 439–442, https://doi.org/10.1130/G40123.1.

FIGURE CAPTIONS

Figure 1. Early Pleistocene structural and paleogeographic reconstruction of the Acerenza Bay (southern Italy). Position and depositional development of the studied wedges is indicated. The siliciclastic fraction was derived mainly from submarine erosion of the

substrate. The bioclastic fraction was derived from the fragmentation of an *in situ* heterozoan carbonate factory. Wedges: ACR—Acerenza; LGR—La Guardia; MdP—Madonna di Pompei; AVS—Alvo Stream.

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

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

FIGURE 1

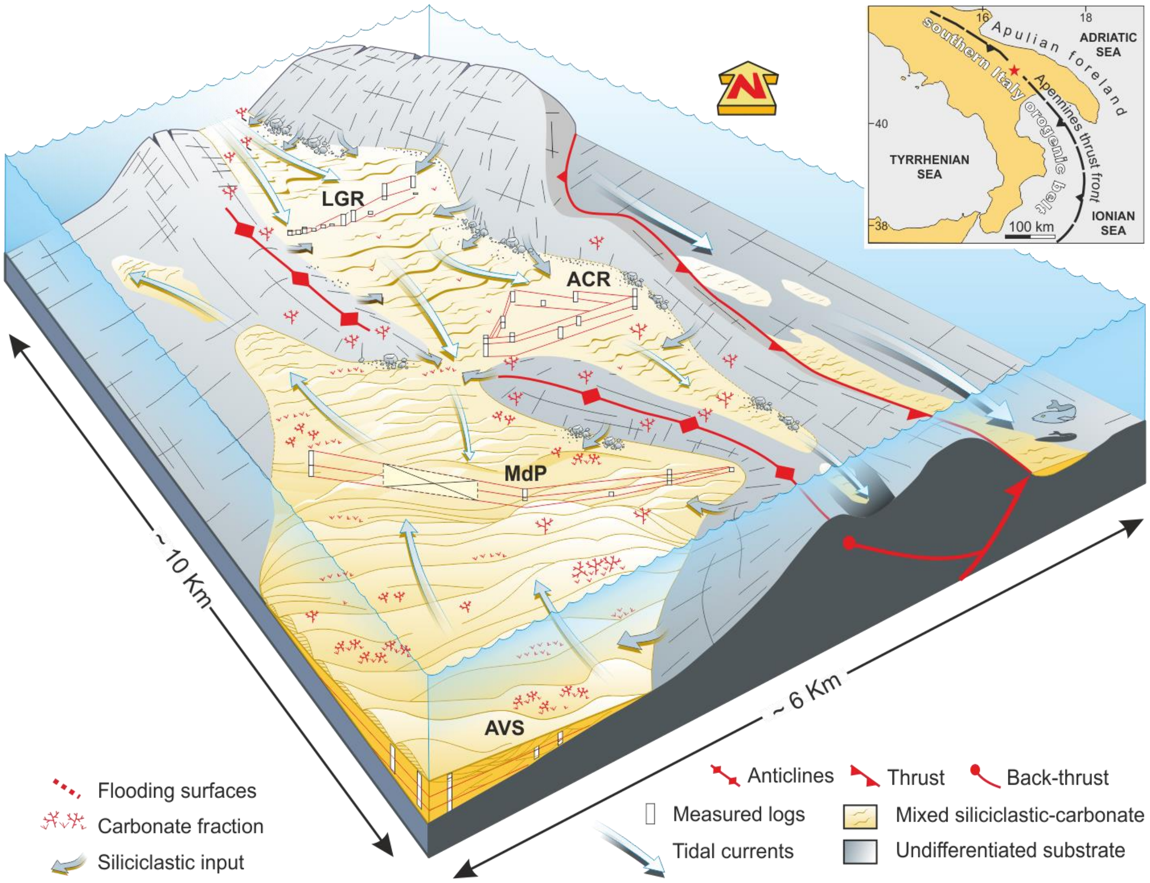

LGR
ACR
MdP
AVS
~ 10 Km
~ 6 Km
N
16
18
Apulian foreland
ADRIATIC SEA
Southern Italy
Apennines thrust front
orogenic belt
40
TYRRHENIAN SEA
38
100 km
IONIAN SEA
Flooding surfaces
Carbonate fraction
Siliciclastic input
Anticlines
Thrust
Back-thrust
Measured logs
Tidal currents
Mixed siliciclastic-carbonate
Undifferentiated substrate

FIGURE 2

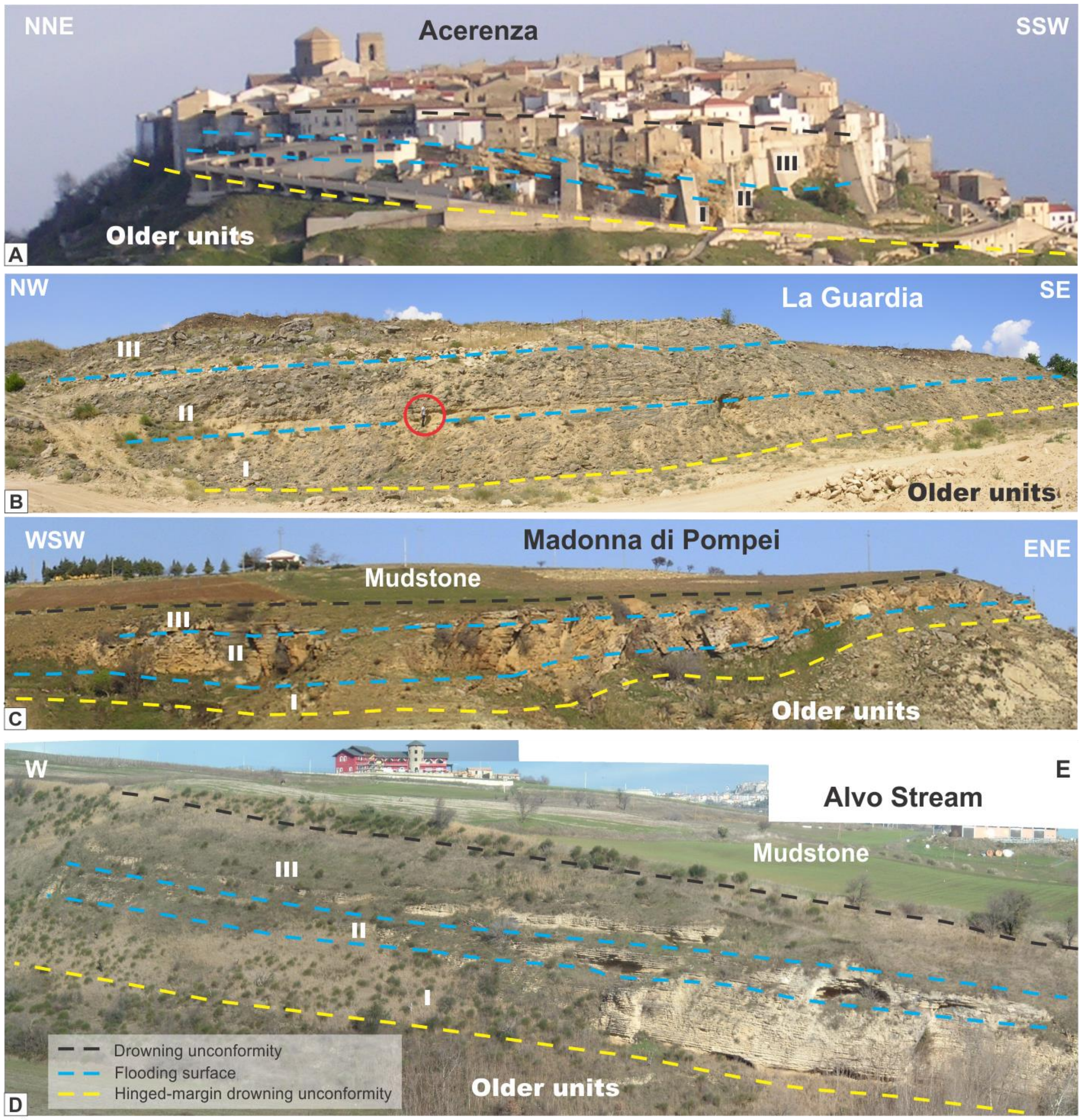
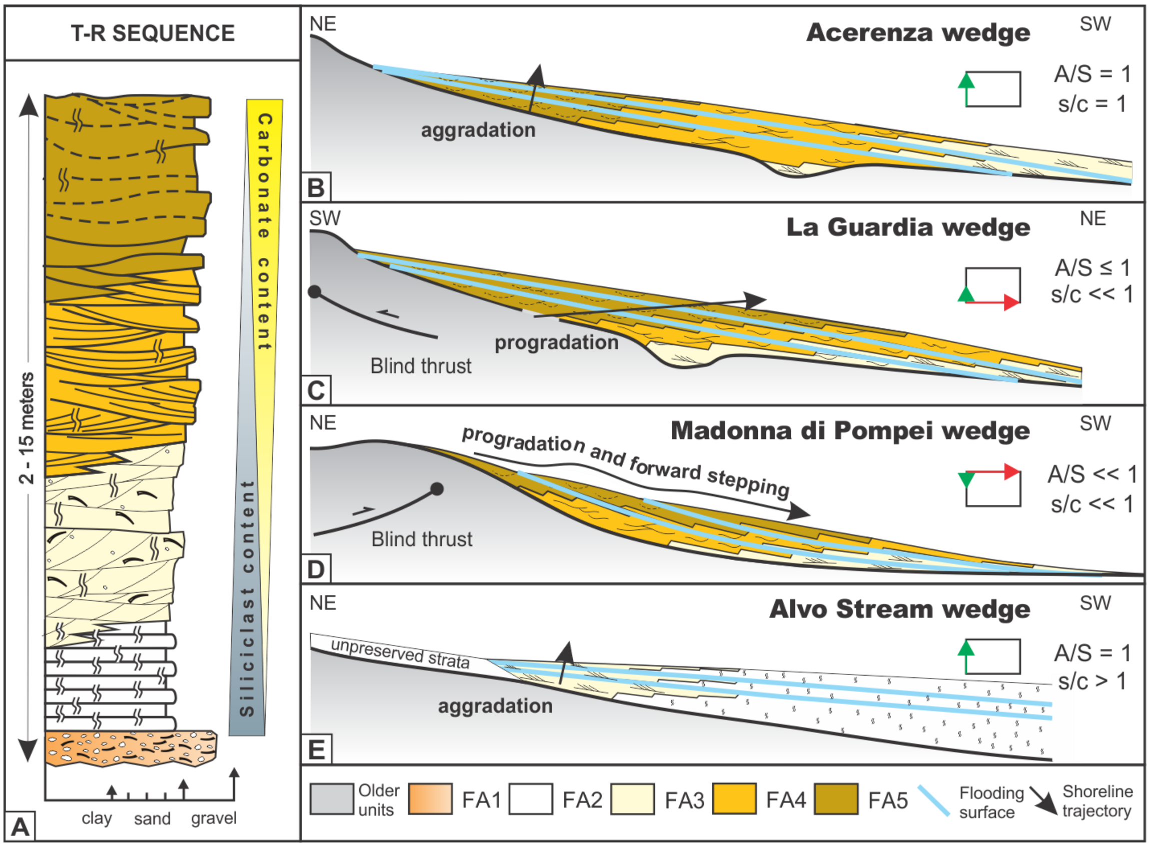

NNE
Acerenza
SSW
III
II
Older units
A
NW
La Guardia
SE
III
II
I
Older units
B
WSW
Madonna di Pompei
ENE
Mudstone
III
II
I
Older units
C
W
E
Alvo Stream
Mudstone
III
II
I
Drowning unconformity
Flooding surface
Hinged-margin drowning unconformity
Older units
D

FIGURE 3


T-R SEQUENCE
Carbonate content
Siliciclast content
2 - 15 meters
clay
sand
gravel
A
NE
Acerenza wedge
SW
A/S = 1
s/c = 1
aggradation
B
SW
La Guardia wedge
NE
A/S ≤ 1
s/c << 1
Blind thrust
progradation
C
NE
Madonna di Pompei wedge
SW
progradation and forward stepping
A/S << 1
s/c << 1
Blind thrust
D
NE
Alvo Stream wedge
SW
unpreserved strata
A/S = 1
s/c > 1
aggradation
E
Older units
FA1
FA2
FA3
FA4
FA5
Flooding surface
Shoreline trajectory