Geological Field Trips and Maps

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The sedimentary response of mixed lithoclastic-bioclastic Lower-Pleistocene shallow-marine systems to tides and waves in the south Apennine foredeep (Basilicata, southern Italy)

Tidalites Field Trips Special Volume - Tidalites, Matera, Field Trip T3

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The sedimentary response of mixed lithoclastic-bioclastic Lower-Pleistocene shallow-marine systems to tides and waves in the south Apennine foredeep (Basilicata, southern Italy)

Tidalites Field Trips Special Volume - Tidalites, Matera, Field Trip T3

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Cover page Figure: *Cover page Figure: Ripple-scale, tidal cross-stratification in mixed siliciclastic/bioclastic deposits (Lower Pleistocene) exposed near the village of Acerenza, Basilicata, southern Italy. This outcrop is the one that inspired the concept of heterolithic segregation in mixed sand-size sediments (see Longhitano, 2011; Chiarella and Longhitano, 2012).*

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Abstract

This two-day-long field trip is associated with the 10th International Congress of Tidal Sedimentology (Tidalites), Matera, Italy. The "foreland-basin system" of southern Italy preserves mixed lithoclastic-bioclastic deposits mostly accumulated in shallow-marine environments, reproducing types of mixing and degrees of segregation (*sensu* Chiarella and Longhitano, 2012; Chiarella et al., 2017) that are thought to be indicative of a variety of geological processes, including surficial waves and tides, acting at different time scales.

During the Late Pliocene and Early Pleistocene, small open piggyback basins reproduced marginal-marine settings with various hydrodynamic conditions in the wedge-top depozone. Siliciclastic-bioclastic sediments accumulated under the influence of geomorphological elements, such as coastal sheltering, promontories, presence of tectonic highs and local inlets, hosting shoreface to offshore-transition zones, whose cross-stratified facies indicate how sensitive shallow-water mixed systems are to recording surficial waves and weak tidal currents.

Along the outer-foredeep depozone, carbonate-bioclastic coastal wedges back-stepped over the gently sloping rocky flanks of a structural high, leading to the retrogradational stacking of seismic-scale prograding bodies. Their size and cross-sectional outcrop views apparently resemble those typical of large tidal sand waves developed in wide tide-dominated oceans. In contrast, internal facies features reveal the dominance of surficial waves and gravity-driven avalanches along clinoform depositional slopes, and a very negligible to no tidal influence.

Key words

Mixed lithoclastic-bioclastic sediments; wave and tidal influences; cross-stratification; particle segregation; palaeogeography.

Program summary

Departing from Matera, the itinerary of the field trip first moves northwestwards, along the exposed front of the southern Apennine Chain of Basilicata (Lucanian Apennine, *Auct.*). During the Late Pliocene and Early Pleistocene, the wedge-top depozone at the front of the orogen was segmented into small, piggyback basins, shallowly submerged, and intermittently connected with the adjacent foreland basin (Bradanic Trough, *Auct.*). This setting led to the establishment of embayments isolated by promontories, receiving the influx of surficial

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waves and marine tides. The latter was possibly subject to local phenomena of amplification due to coastal funneling, influencing sedimentation of mixed, siliciclastic-bioclastic deposits in a general shoreface to offshore setting (Chiarella et al., 2019a). Slightly deformed remnants of these successions are nowadays variously exposed in a series of stratigraphic sections, two of which are observable near the villages of Acerenza and Tricarico (Fig. 1). Facies reveal cross-stratification styles and internal structures distinctive of wave- and tide-influenced shallow-water processes in mixed sediments (Longhitano, 2011). The siliciclastic fraction originated from the erosion of structural highs, either exposed or representing the abraded shallow seafloor formed by Cenozoic units thrusted at the front of the Apennine accretionary wedge. The bioclastic fraction is derived from coeval cool-water carbonate factories, representing allochems of a heterozoan assemblage (*sensu* James, 1997).

The second day of the field trip is focused around the city of Matera (Fig. 1), inside the "Murgia Materana" Regional Park, included in the UNESCO World Heritage List since 1993, together with the famous and fascinating rupestrian old town of "Sassi" (Tropeano et al., 2018; Chiarella et al, 2019b). In the area, a peculiar typology of mixed litho-bioclastic carbonate-dominated sediment formed a shallow-marine Lower-Pleistocene unit around a submerging island during a major phase of subsidence-induced, relative sea-level rise. On the southwestern flank of the palaeo-island, prograding coastal bodies backstepped during this long-term transgression. Large-scale cross-stratification, imitating internal architecture common to large tidal sand waves typical of modern macrotidal settings, is one of the seismic-scale elements detectable from the outcrops. However, their internal facies features indicate coastal bodies, laterally extensive and parallel with the palaeo-shoreline, showing seaward progradation and originated by repeated processes of avalanches of sediment swept out from the shoreface zone onto a depositional slope by storm waves and wind-driven currents (Pomar and Tropeano, 2001). These depositional architectures observed along the southwestern flank of the palaeo-island are thus compared with another section showing a different stacking pattern developed along the steeper opposite side. Here, fan-shaped bodies coalesced to form an apron developed when a flat area of the island was flooded and bioclasts were shed from the carbonate factory (Mateu-Vincent et al., 2008).

Safety and logistic information

Outcrops are generally easily accessible and often located very close to the areas where the vehicles will be parked. However, a series of panoramic viewpoints are located close to the edge of high cliffs for which particular

Fig. 1 – (a) Location of the T3 field trip area with respect to the venue of Tidalites, in southern Italy. (b) General itinerary of the T3 field trip. The westernmost stops are those of the 1st day, whereas the easternmost stops around Matera are those of the 2nd day.

caution is recommended. Facilities to ensure accessibility for participants with physical disabilities are also contemplated (*cf.* Chiarella and Vurro, 2020). One only Stop (T3.2.2) requires walking for a certain distance (ca. 600 m) and the use of sturdy boots and comfortable clothing is necessary. We provide high-visibility jackets and protective helmets for all the stops. Outcrops are close to towns where there are small shops and pharmacies. Participants are continuously supplied with food packs and water bottles. Southern Italy is usually sunny and relatively dry all the year, but rains or rain showers can occasionally occur. Sunscreen protection and rain jackets are thus needed. We also suggest the use of binoculars during outcrop panoramic observation to appreciate details from distant cliffs.

Emergency contact numbers
112 – Police
113 – Police
118 – Ambulance
115 - Fire Department

Hospitals

Ospedale Madonna delle Grazie – Contrada Cattedra Ambulante, MT Tel: +39 0835 253111

Accommodations

Since the distance of the various outcrop localities does not exceed 75 km, the field trip starts from and ends to Matera every day. Participants are thus invited to arrange autonomously their accommodation there. Matera provides a variety of B&B and hotels, which become more expensive as they are closer to the Sassi central area.

Excursion notes

The itinerary of the present field trip takes place in the Basilicata region of southern Italy and is mainly focused on the observation of Lower Pleistocene mixed sediments and their internal sedimentary features recording wave- and tide-influenced processes in shallow-marine environments.

Mixed sediments observed in the various outcrops are a mixture of intrabasinal and extrabasinal grains mainly falling in the grain size interval of sand and gravel. The intrabasinal component is typically represented by bioclasts derived from carbonate skeletons or their fragments, while the extrabasinal component is of terrigenous origin, mostly generated from river discharge to the basin or from submarine erosion of bare substrate rocks (Mount 1984; Chiarella et al., 2017).

Lower Pleistocene mixed deposits of southern Italy were in the past simply described as "calcarenites" ("panchina" was the local term), based on the abundance of carbonate particles and their stronger cementation with respect to other arenites/rudites cropping out in the area. These deposits were only recently reconsidered in the light of their mixed composition, as their lithoclastic fraction often exceeds the bioclastic one and provides information on the source areas and the mechanisms of sediment supply (e.g., Chiarella and Longhitano, 2012). Moreover, quantitative observations on the degree of segregation between lithoclastic and bioclastic particles (*i.e.*, their cross-sectional random or systematic distribution within individual strata), have been indicated as a possible proxy for primary processes of sediment distribution and accumulation. The degree of segregation may potentially suggest the typology of the process of selection operated by hydrodynamic factors dominating shallow-marine sectors, such as surficial waves, tides, currents, or a combination of them (*e.g.*, Longhitano, 2011; Chiarella and Longhitano, 2012). Mixed deposits provide a suite of different types of mixing between the two components, from bed (core-plug) to stratigraphic (seismic) scales, producing a high vertical and lateral lithological variability and heterogeneities (Chiarella et al., 2017; 2019a) (Fig. 2a). The combination of the two components may occur as: (i) punctuated mixing, which results in a lithofacies-scale (strata mixing); (ii) facies mixing, generating both a bed scale compositional mixing and/or a stratigraphic-scale mixing; (iii) *in situ* mixing, resulting in a bed-scale (compositional mixing) (Fig. 2b).

The present field trip aims at observing examples of these varieties of mixed facies in different tectonic settings of southern Italy and to discuss the interplay of wave *vs*. tidal processes influencing the distribution of mixed sediments during the Plio-Quaternary.

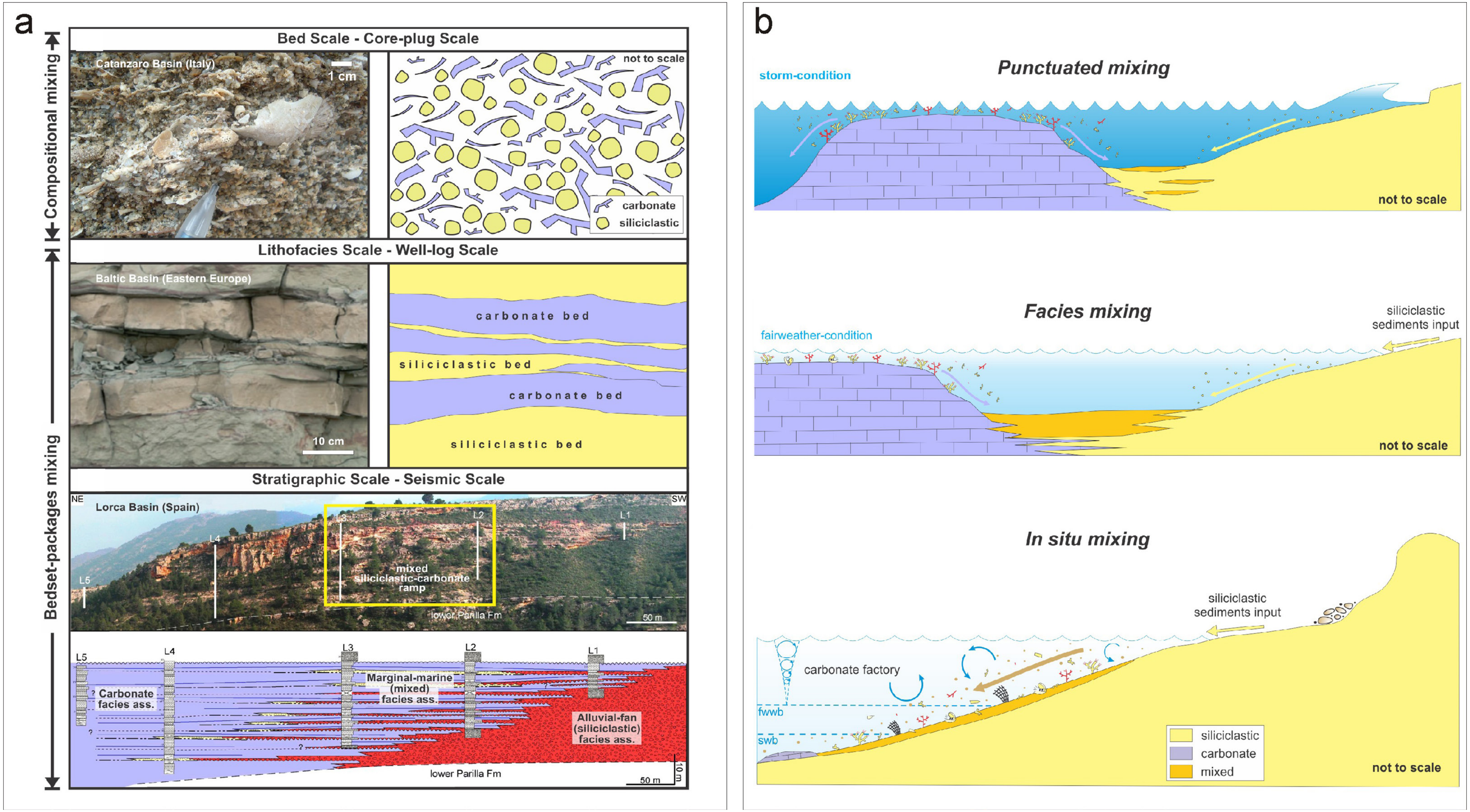


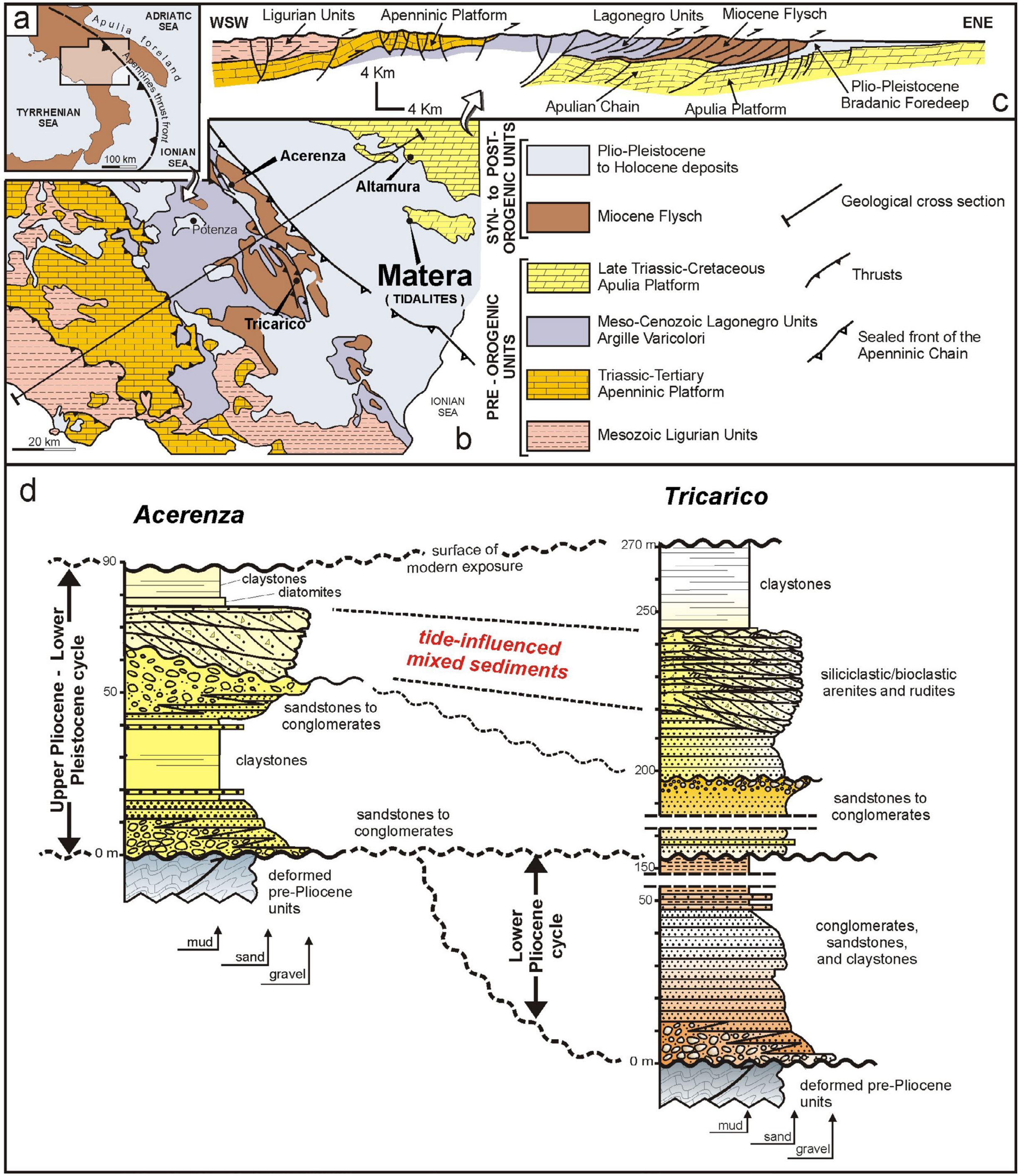
Fig. 2 – (a) Scales of compositional (bed and core-plug scale) and bedset (lithofacies to stratigraphic scale) mixing. (b) Main types of mixing (punctuated, facies, and *in situ*) deriving from specific depositional settings (both panels are after Chiarella et al., 2017).

General geological setting of the southern Italy foreland-basin system

The Apennine belt forms a *ca*. 800 km-long, northwest–southeast–trending, arc-shaped orogen (Fig. 3a) produced by subduction of Mesozoic Tethys oceanic arms and shortening and thrust-sheet deformation of adjacent palaeo-domains of the Adria Plate caused by the convergence between Africa and Europa plates. The Basilicata region comprises a segment of this belt where the three main geodynamic provinces of a chain system are exposed due to tectonic uplift: i) the orogenic belt (*i.e*., the south Apennine Chain), ii) the foredeep (*i.e*., the Bradanic Trough), and iii) the foreland (*i.e*., the Apulia Foreland) (Fig. 3b, c). They preserve thick sedimentary successions of different ages, recording a variety of palaeogeographic depositional settings involved in tectonic deformations (Fig. 3c). Among these settings, the Plio-Pleistocene "foreland-basin system" (*sensu* DeCelles and Giles, 1996) preserves mixed lithoclastic-bioclastic deposits on both sides of the basin (on the wedge-top and on the foreland edge of the basin), which are the focus of this excursion.

The wedge-top depozone

The deformed units of this sector of the Apennine Chain (namely, "the Allochthon"; *cf*. Carissimo et al., 1962; Mostardini et al., 1966; Boenzi et al., 1971) include Mesozoic to Oligocene pre-orogenic successions overlain by Miocene foredeep deposits (Vitale and Ciarcia, 2013), (Fig. 3b, c). On the submerged accretionary wedge of the southern Apennines (*i.e.,* the wedge-top depozone), shallow-marine depositional systems developed on deformed sedimentary units during the Pliocene-Early Pleistocene (D'Argenio et al., 1973; 1975; Patacca and Scandone, 2001; 2004; 2007).
The succession focused on this field trip is represented by remnants of the original sedimentary infill of "piggyback" and/or "thrust-top" basins (*sensu* Ori and Friend, 1984), "satellite basins" (*sensu* Ricci Lucchi, 1986), or "wedge-top" basins (*sensu* Mutti et al., 2003) (Fig. 3b, c). During the Plio-Pleistocene, thrusts propagation mostly proceeded by long sheets ("the Allochthon") that overthrusts the Apulia Foreland-ramp and its foredeep cover (Mostardini and Merlini, 1986; Patacca and Scandone, 1989). At first, the wedge-top depozone developed on the moving "Allochthon". Later, deep-seated thrusts propagated into the foreland ramp only after its underthrusting, involving the inner segment of the flexed Apulia Platform. This tectonic event, responsible for the genesis of an additional but deeper thrust system known as the "Apulian Chain" (Fig 3c; Cello et al., 1989; Lentini et al., 1990; Roure et al., 1991; Catalano et al., 1993), transferred part of the deformation to the overlying Allochthon, causing further folding of the wedge-top depozone and the development of "apparent" out-



of-sequence thrusting (Roure et al., 1991; Patacca and Scandone, 2001; 2004) (Fig. 4a, b). The Plio-Pleistocene deposits originally filling the wedge-top depozone discontinuously crop out along the outer belt of the orogen. At the exposed front of the chain, a main angular unconformity divides the succession into two stratigraphic cycles (Fig. 3d; Centamore et al., 1971; Maggiore and Walsh, 1975; Sabato and Marino, 1994; Labriola et al., 2008; Pieri et al., 2017; Pescatore et al., 2012). The underlying cycle consists of *ca.* 150 m-thick, Upper Pliocene alluvial to deltaic conglomerates, evolving upwards to shoreface sands and offshore silts and clays. The overlying cycle is made up of *ca*. 120 m-thick, Upper Pliocene-Lower

Fig. 3 – (a) Southern Apennine orogenic belt and location of the map in (b). (b) Simplified sketch map of the southern Apennines with the main locations visited during the T3 field trip. (c) Geological cross-section showing the main tectonostratigraphic elements of the southern Apennines (b and c are redrawn after Piedilato and Prosser, 2005). (d) Stratigraphic logs reconstructed for the Acerenza and Tricarico areas showing the main lithological features of the two Lower Pliocene and Upper Pliocene-Lower Pleistocene cycles and the stratigraphic position of the mixed deposits (modified, after Longhitano et al., 2010; Chiarella and Longhitano, 2012).

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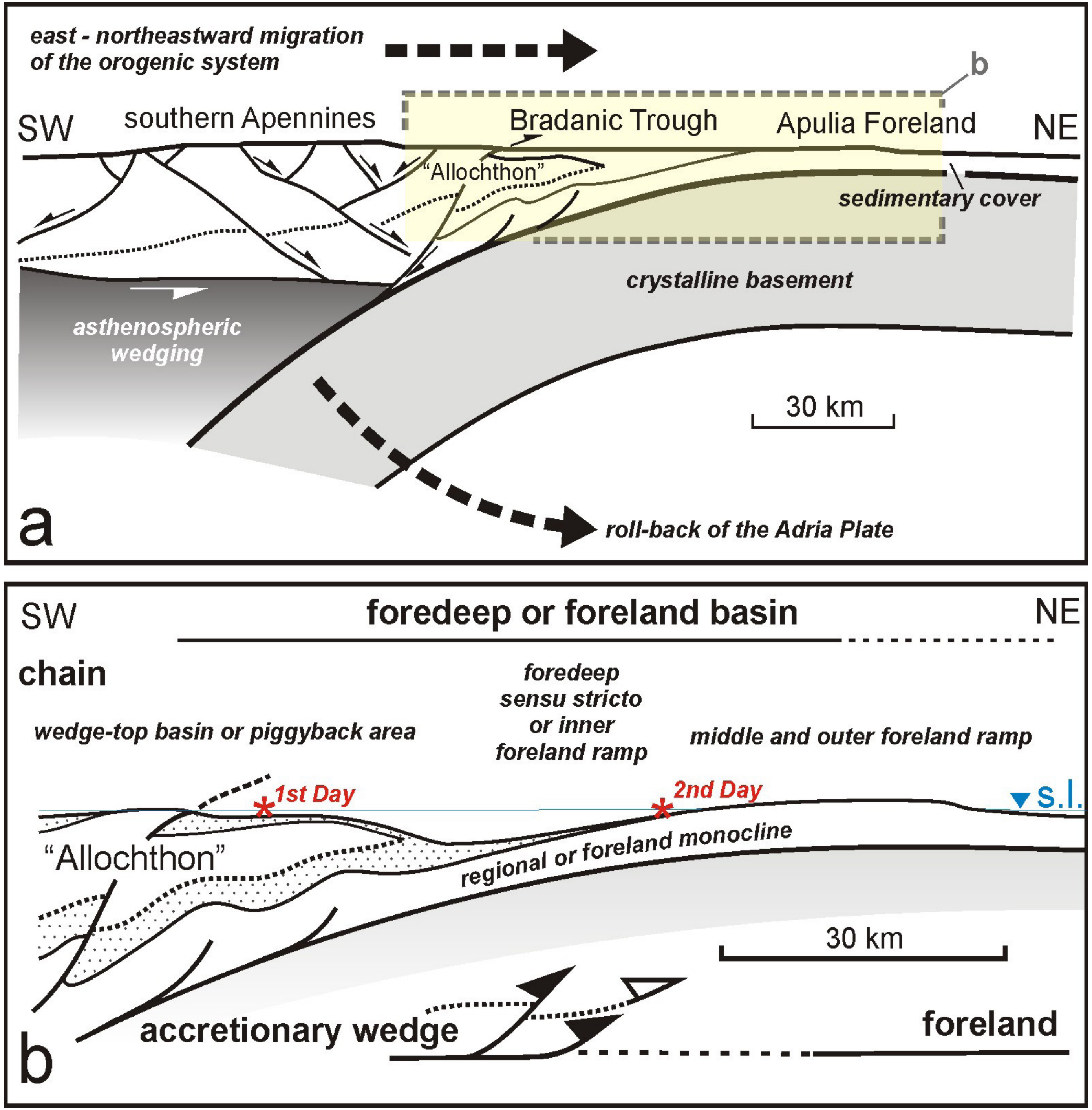

Pleistocene deltaic conglomerates, and sandstones, erosionally overlain by mixed arenites, passing into diatomites and offshore clays (Longhitano, 2008; Bonardi et al., 2009). Siliciclastic-bioclastic deposits representing the intermediate part of the Upper Pliocene-Lower Pleistocene cycle are discontinuously exposed along the front of the orogen. Two of the best sections are today visible near Acerenza and Tricarico villages, which are the focus of the first day of the field trip.

The mixed deposits cropping out near the villages of Acerenza and Tricarico (Fig. 3b) have been

Fig. 4 – (a) Structural-geodynamic sketch-section of the southern Apennine orogenic system; "Allochthon" propagation follows basin subsidence, while thrusts in the Apulia Foreland grow after underthrusting. (b) Detail from the sketch in (a) showing the three main segments of the foreland basin. The first day of the field trip focuses on the wedge-top area, whereas the second day focuses on the foreland SW edge of the foredeep (modified, after Tropeano et al., 2002a).

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recently documented based on a detailed field-based facies analysis (Longhitano et al., 2010; 2011; 2012; Chiarella and Longhitano, 2012; Chiarella et al., 2012a; 2019a). Outcrops form up to 30 m-thick successions (Fig. 3d) that diffusely exhibit an aggradational to progradational stacking pattern and a variety of cross-stratification of different scales (Chiarella, 2011; Chiarella et al., 2019a). These deposits pass upwards into shelf claystones containing a 1–2 m-thick diatomitic keybed of regional extent (Patacca and Scandone, 2001; Longhitano, 2008) (Fig. 3d). The succession is top truncated by a surface of modern exposure (Fig. 3d) or is overlain by recent alluvial deposits.

The foreland edge (Matera Horst in the Apulia Foreland)

The Apulia Foreland (*sensu* D'Argenio et al., 1973; 1975) (Figs 3a, 4a, and 5a) is a relict part of the Apulia Platform, one of the wider peri-Adriatic carbonate platforms developed until the end of Cretaceous, after the Early Jurassic rifting affecting the Adria Plate (Bernoulli, 2001). It plays the role of foreland for two oppositely facing and converging active mountain chains: the southern Apennines and the Dinarides, respectively located W-SW and E-NE of the Apulia Foreland (Biju-Duval et al., 1978; Ricchetti et al., 1988; Fantoni and Franciosi, 2010; Cicala et al., 2021). Three regional-scale major structural highs mainly consisting of Cretaceous limestones form nowadays the Apulia Foreland. From NW to SE they are: the Gargano, the Murge, and the Salento areas (Fig. 5b). In particular, the Murge consists of an articulated system of horsts and grabens recording the remnants of an archipelago drowned during the Late Pliocene and Early Pleistocene, when a long-term subsidence-induced relative sea-level rise affected the Apulia Foreland due to the eastward migration of the Apennine orogen (Tropeano et al., 2002a; 2002b) (Fig. 6). The Matera High (the "Murgia Materana") is one of the horsts of the Murge (Fig. 6a), This roughly striking NW-SE high, was almost totally submerged during the maximum of the relative sea-level rise (Fig. 6b), being subsequently exposed and incised by rivers (Tropeano et al., 2018; Sabato et al., 2019) due to a still active tectonic uplift that started at least at the beginning of the Middle Pleistocene (Ciaranfi et al., 1988; Doglioni et al., 1994; 1996) (Fig. 6c).

The deposits of the "Calcarenite di Gravina" Fm surround the structural highs and regionally record the phase of long-term transgression (Iannone and Pieri, 1979) (Fig. 5b, c). The "Calcarenite di Gravina" Fm comprises coarse-grained shallow-marine carbonate soft rocks (*sensu* Andriani and Walsh, 2010) forming a succession up to 70-100 m-thick unconformably lying onto abraded Cretaceous limestones (Fig. 5c, d). The same formation is diachronously sealed by hemipelagic clays of the "argille subappennine" Fm (Tropeano and Sabato, 2000; Tropeano et al., 2002a; 2002b) through a drowning unconformity (*sensu* Schlager, 1989). In places (*i.e.*, the

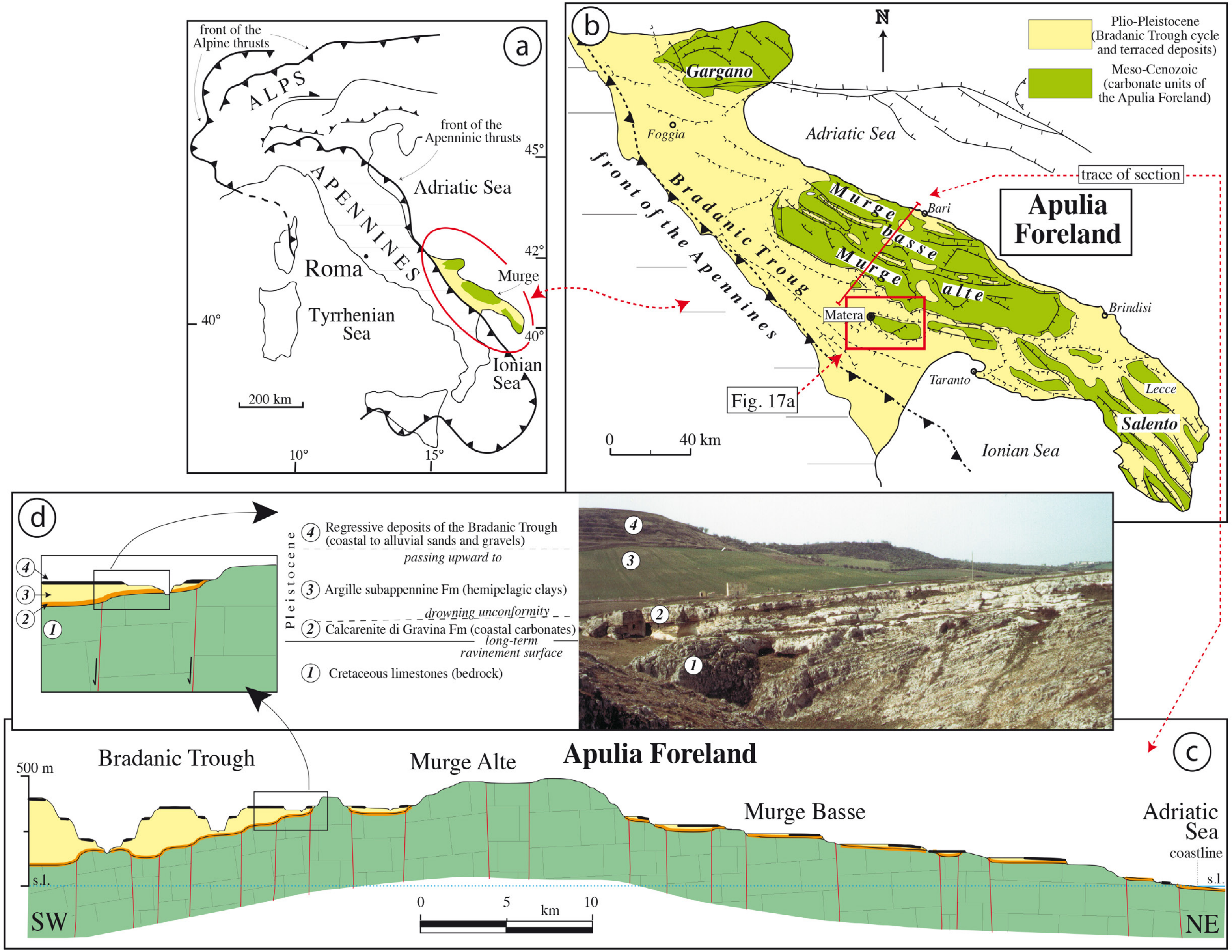

Fig. 5 – (a) Schematic structural map of Italy. In the red inset the location of the Apulia Foreland. (b) Geological sketch-map of the Apulia Foreland in southern Italy. (c) Geological cross-section showing the main stratigraphic relationships between the Cretaceous substrate and the Plio-Quaternary units, including the Calcarenite di Gravina Fm, focus of the second day of the T3 field trip. (d) Outcrop photograph showing the basal stratigraphic discontinuity of mixed deposits over the Cretaceous limestones (modified, after Tropeano and Sabato, 2000).

Matera area), the “Calcarenite di Gravina” Fm exhibits a mixed composition, deriving from a combination of carbonate lithoclasts and bioclasts. Lithoclasts are represented by rounded coarse-grained fragments (ranging from granules to pebbles in size) of Cretaceous limestones (extraclasts, *sensu* Folk, 1962). Bioclasts belong

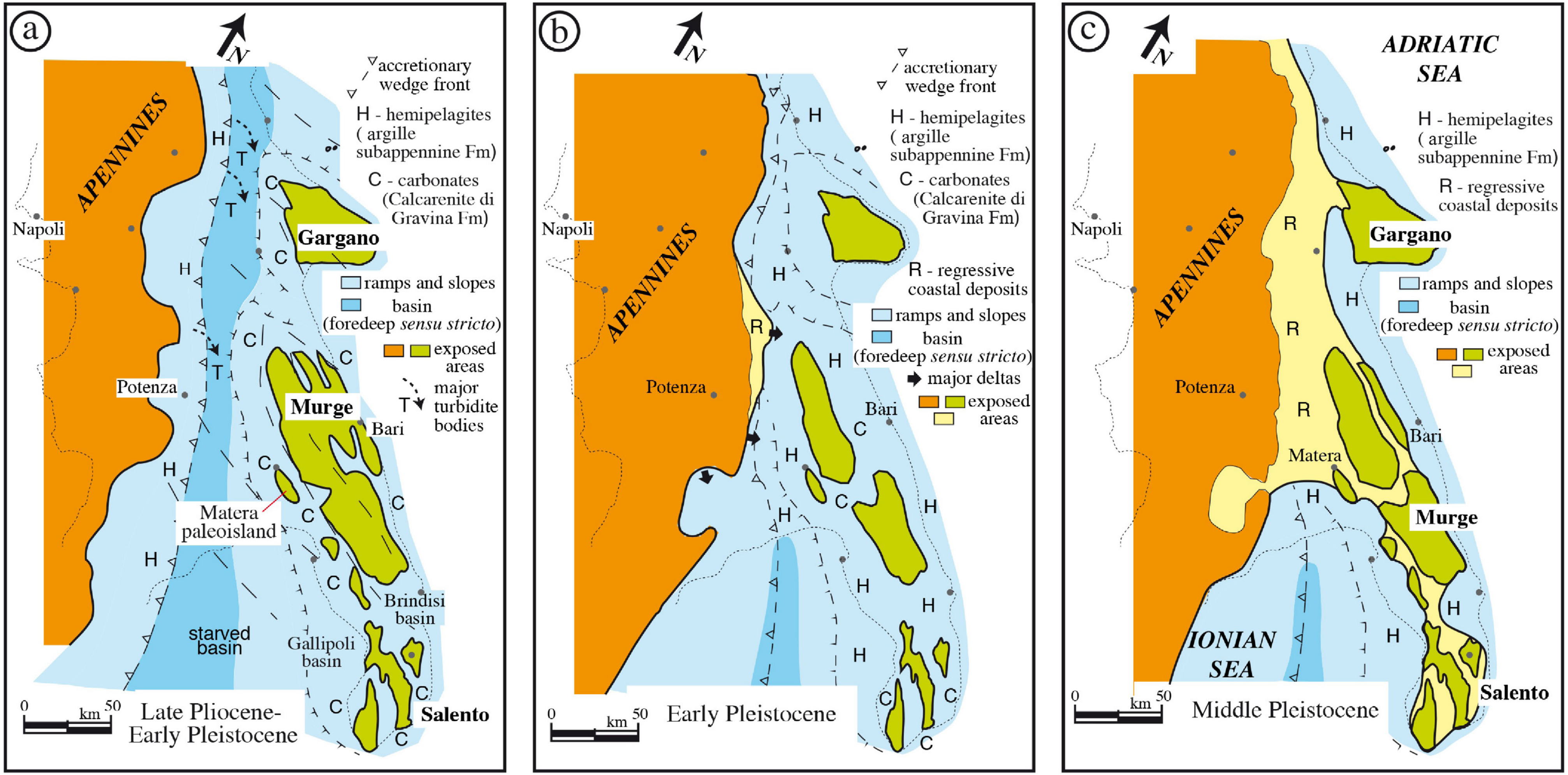

Fig. 6 – Palaeogeographic reconstructions of the Apennine Foredeep during (a) Late Pliocene-Early Pleistocene, (b) Early Pleistocene, and (c) Middle Pleistocene (modified, after Tropeano et al., 2002a).

to benthic and rare planktonic foraminifera associated with whole or fragmented skeletal grains of bivalves, echinoids, red algae, serpulids, barnacles, brachiopods, gastropods, and bryozoans. This carbonate assemblage indicates a temperate-water carbonate factory developed in open shelves or ramps (Tropeano and Sabato, 2000). This type of mixing (extraclastic-bioclastic) points out the main difference if compared with the particle components of the mixed deposits observed near Acerenza and Tricarico.

Day 1

The itinerary of the first day moves from Matera with the destination Acerenza. Participants travel towards W-NW following the roads SS655, SS96bis, and SP122, for a total distance of 75 km and *ca.* 1 h of driving time. One of the typical features of the Apennines and, in particular, of Basilicata, is that many small villages are sited on top of little circular hills, as it offered defence advantages during Medieval times. Acerenza and Tricarico are examples of this kind of urban style.

Acerenza (*ca.* 2,400 habitants) lies on top of a small hill with a maximum elevation of *ca*. 800 m (Fig. 7). It is a quite well-known place thanks to the presence of a Romanesque-Gothic Cathedral in the centre of the ancient town encircled with fortified walls. Acerenza was conquered by the Romans in 318 B.C. Later, it was taken by the Ostrogoths and then by the Longobards, who fortified the town. In 1041, after it was fought over by the Principality of Salerno and the Byzantine Empire, Acerenza was conquered again by the Normans. The town has been the seat of an archbishop since at least 499 but became legendary for having conserved the tomb of Count Dracula's daughter and, according to the legend, the Holy Grail for a while.

After having stopped at a parking area, participants follow a circular itinerary (Fig. 7) around the southern flank of the Acerenza hill. At the base of the fortified walls (Stop T3.1.1) and along a road, the bottom of the mixed succession comprised within the Upper Pliocene-Lower Pleistocene stratigraphic cycle is observable, together with its internal organisation into three, vertically stacked aggradational units, consisting of coarsening and shallowing-upward cross-bedded strata (Fig. 8). The road rises stratigraphically, allowing the observation of a variety of sedimentary features and introducing participants to the concept of mixing and textural segregation between siliciclastic and bioclastic particles observable in a variety of cross-bedded facies (Stop T3.1.2). Attendees walk up to the top of the Acerenza walls and inside the borough, reaching a panoramic terrace viewing over the Bradanic Trough to NE (Stop T3.1.3). Here, a summary of the facies variety observed during the stops is presented, together with the elements useful to reconstruct a palaeogeographic scenario proposed for the observed succession. After a light lunch in one of the taverns of the centre, the itinerary of the field trip moves S-SE towards Tricarico, reaching the SS277 for *ca.* 45 km drivable in *ca.* 50 min.

Tricarico (*ca.* 5,300 habitants) either occupies the top of another hill up to *ca*. 680 m high. It was an Arabic stronghold between the 9th and the late 10th century. The terrace gardens of Arabic origin are still in use today and remnants of small towers (Towers of *Ràbata* and *Saracena*) are still well preserved. In 968 Tricarico was conquered by the Byzantine Empire, and then, in 1048, it became a Norman fortified town.

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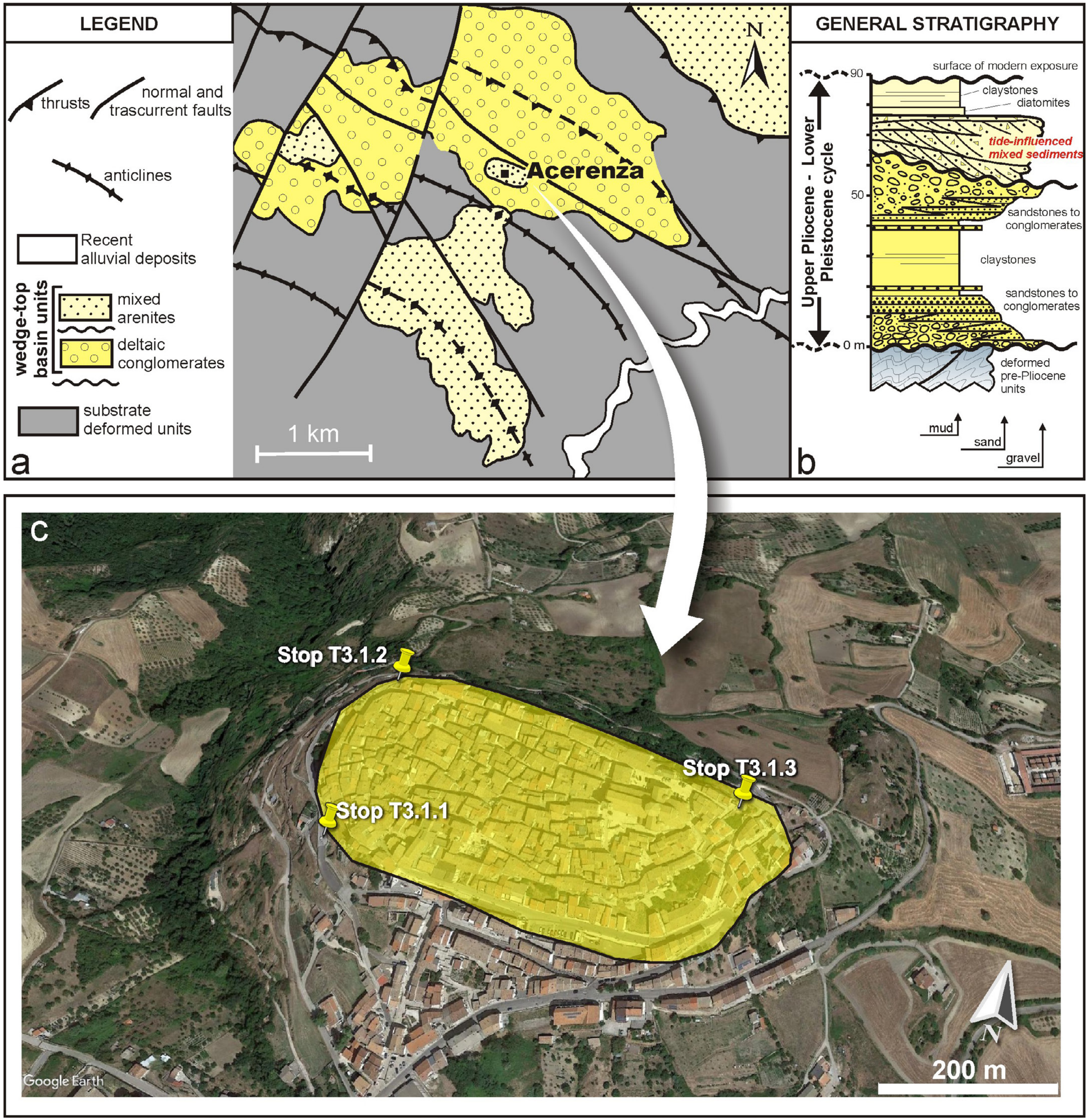

Fig. 7 – (a) Geological sketch map of the Acerenza area, showing the aerial distribution of the Lower Pleistocene mixed deposits. (b) General stratigraphy including the mixed deposits focuses on the first day of the T3 field trip (modified, after Chiarella and Longhitano, 2012). (c) Aerial photograph of Acerenza with indicated the mixed deposits (yellow) and the location of the stops.

After having parked in one of the main squares (*i.e.*, *Piazza Monsignor Raffaello delle Nocche*), besides the Cathedral of Santa Maria Assunta, where Louis I of Anjou was crowned king of Naples in 1383, participants walk through the ancient part of the borough, until the northern periphery (Fig. 13). From there, a panoramic view of the Torre Saracena section can be seen (Stop T3.1.4; Fig. 14). A series of vertically stacked cross-stratified units up to 5 m thick form an aggrading mixed succession with the direction of migration towards S-SW, inferred to represent a flood-tidal delta entering a wide Lower Pleistocene embayment (Longhitano et al., 2010). Cross-stratification styles and larger reactivation surfaces suggest some tidal influence, generated by hydrodynamic amplification through a structural inlet formed by an undulation of the axis of an anticline. The viewpoint provides the possibility to observe other geological elements useful for envisaging the depositional setting during the accumulation of cross strata. The subsequent outcrop exposed along a road cut located northwards and strike-oriented with respect to the previous section (Stop T3.1.5; Fig. 16), provides close-up details of the mixed, siliciclastic-bioclastic cross strata, including a variety of tidal indicators. At the end of the day, the itinerary returns to Matera.

Stop T3.1.1. General introduction to the geology of the southern Italy foreland-basin system and the field trip subject

Coordinates: **40°47'47.35"N - 15°56'19.14"E**

Topic: Main structural framework of southern Italy and of the thrust-top basin of Acerenza.

This stop, located at the base of the ancient walls of the city of Acerenza, opens the field trip and introduces participants to some of the most important phases of the Cenozoic evolution of the southern Apennines and its last stages of the accretionary building during the Pliocene and Quaternary. The stratigraphic framework is presented with the general features of the sole younger Upper Pliocene-Lower Pleistocene cycle cropping out in this sector (Fig. 7a, b). The base of the ancient walls (Figs 7c and 9a) roughly corresponds with an angular unconformity separating the mixed deposits from the underlying deltaic conglomerates and sandstones (Fig. 7b) and show outcrops where the basal facies of the lowermost of the three stratal units composing the mixed interval can be observed (Chiarella et al., 2012a, 2012b). Stratal units are coarsening-upward 5-to-20 m-thick intervals (Fig. 8), arranged into aggrading,

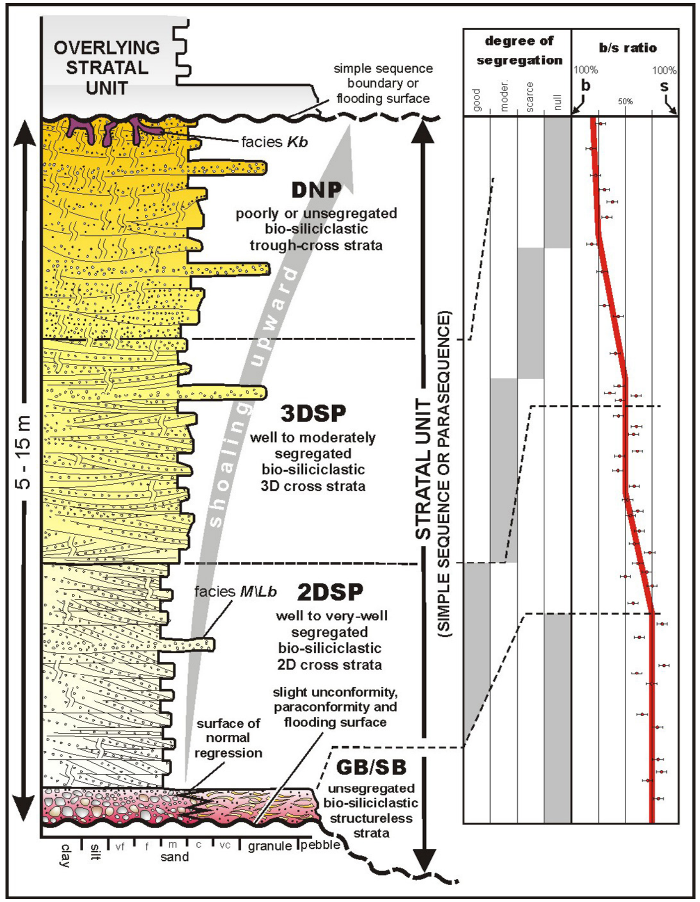

Fig. 8 – Reconstructed sedimentological log of one of the three units composing the mixed succession of Acerenza (modified, after Chiarella and Longhitano, 2012). Facies associations reflect a shoaling upward trend defined by the internal degree of segregation between siliciclastic and bioclastic particles (Letter symbols: GB/SB = gravel beds and shell beds; 2DSP = 2-dimensional dunes of segregated particles; 3DSP = 3-dimensional dunes of segregated particles; DNP = dunes of non-segregated particles).

prograding, or back-stepping trend, based on the interaction between local tectonics and accommodation, and separated by surfaces of marine flooding or angular unconformities that become surfaces of conformity basinward (Chiarella, 2011; Chiarella et al., 2019a). Each unit consists of four main facies associations (Fig. 8), indicating a progressive shoaling from offshore to shoreface and beach face environments (Fig. 9b, c), each of them identified based on a different degree of segregation between siliciclastic and bioclastic particles (Chiarella and Longhitano, 2012).

Stop T3.1.2. Degrees of segregation within cross-stratified siliciclastic and bioclastic deposits of Acerenza

Coordinates: **40°47’52.17”N – 15°56’20.58”E**

Topic: Segregation of mixed particles and hydrodynamic processes.

This stop (Fig.10a) was the one that inspired the idea of compositional segregation between siliciclastic and bioclastic particles in mixed deposits as a possible response of different hydrodynamic factors acting in a shallow-marine setting (Longhitano, 2011). Segregation is indeed particularly pronounced here and evidenced by marked chromatic differences within the laminae foreset (Fig. 10a, b). Sediments consist of siliciclastic and bioclastic coarse to medium well-rounded sand, organised into 0.1 to 0.8 m thick beds. The siliciclastic fraction consists of quartz-dominated sand, while the bioclastic fraction is composed of fragmented remains of a bryomol-type association. These sediments form up to 1 m thick cross sets, showing planar cross-stratification (Fig.10c). The regular shape indicates the migration of subaqueous dunes with straight or slightly sinuous crest lines, most likely oriented perpendicular to the mean flow lines. Foreset lamination shows repeated bundles of laminae forming couplets of well-segregated thinner bioclastic and thicker siliciclastic intervals of laminae (Fig. 10b). In turn, siliciclastic/bioclastic couplets form cycles including 14–15 tidal bundles (Fig. 10c), where each bundle is considered as a pair of strata, one siliciclastic and one bioclastic (Longhitano, 2011). Discontinuity surfaces are also present within the foresets, as well as at the tops of single cross strata. In this latter case, these surfaces are draped by intervals of bioclastic hash, 0.03–0.07 m thick. Most of the cross strata show unidirectional, SSW-trending direction of migration, whereas a minor percentage of foresets has a reversal trend. The Bioturbation Index (B.I.) ranges between 1 and 2, indicating a sparse to uncommon bioturbation. The bioclastic *versus* siliciclastic ratio (*b/s* of Chiarella and Longhitano, 2012) varies between 1 and 0.5 (Fig. 8). Segregation occurs at different scales: (i) in isolated bioclastic hash layers, at the tops of single cross strata;

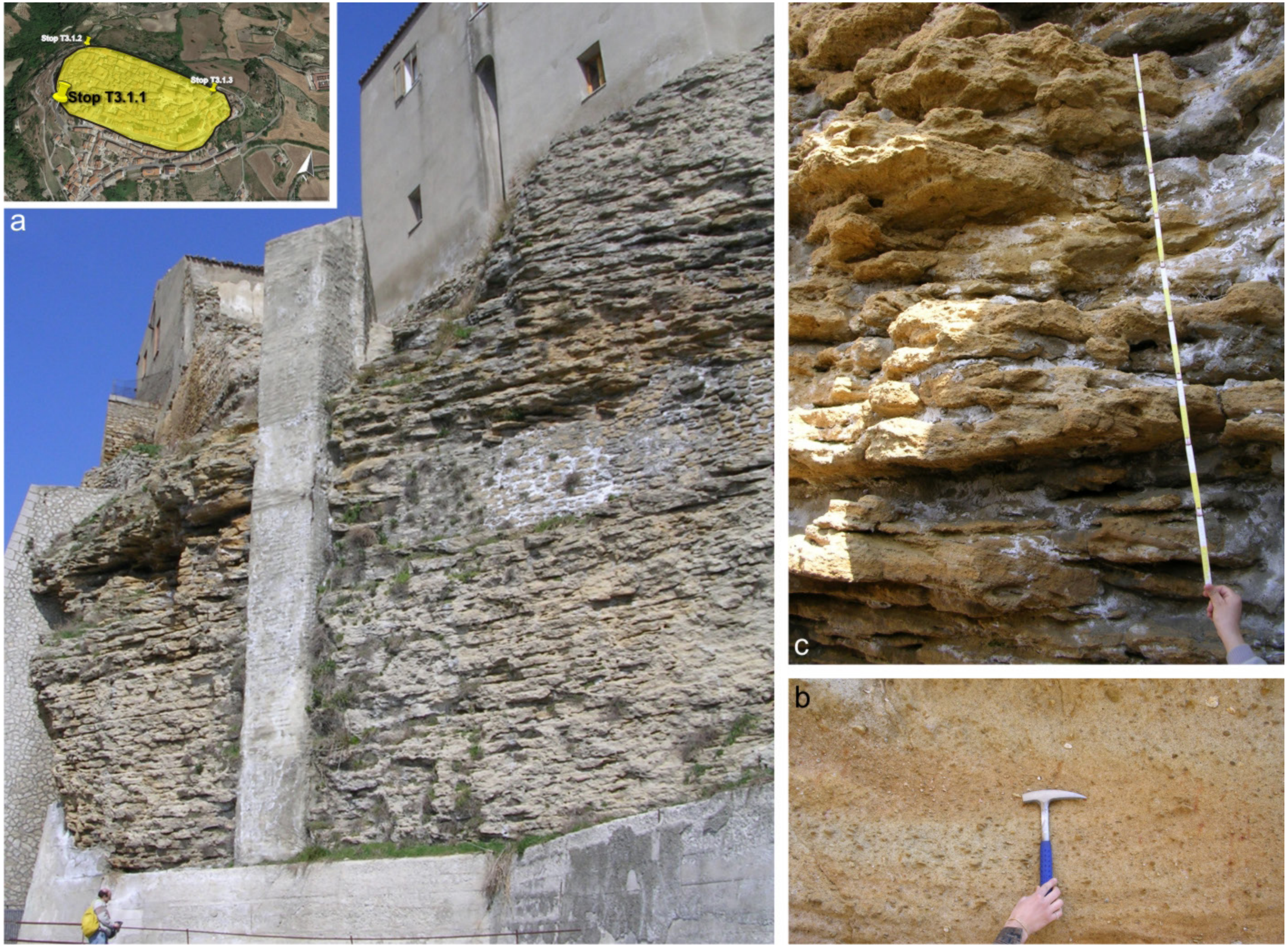

Fig. 9 – Outcrop photographs of the Stop T3.1.1 (inset). (a) Mixed deposits at the base of the ancient city walls. Their vertical stacking of sedimentary facies indicates a progressive shoaling from offshore to shoreface and beachface environments. (b) Condensed interval observable at the base of the succession. (c) Detail from the photograph in (a).

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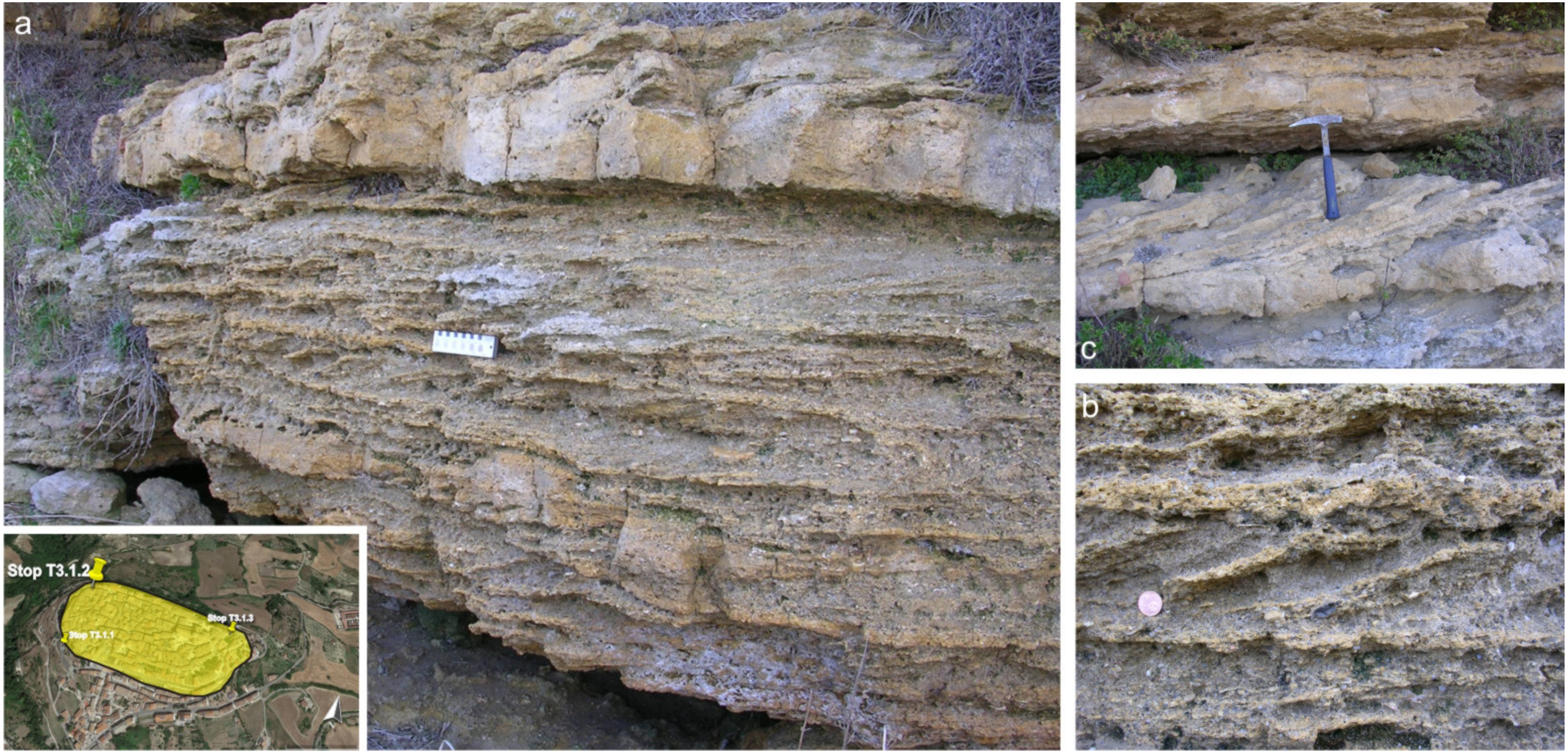

Fig. 10 – Outcrops visible at the Stop T3.1.2 (inset). (a) Mixed deposits consist of aggradational tabular-based, ripple-scale cross strata, including angular foreset dominantly pointing towards NE. (b) Foreset with tangential geometry includes bioclastic- and siliciclastic-rich lamina-sets, indicating a high degree of segregation. (c) Upwards, the succession includes dune-scale cross strata with tangential foreset.

(ii) within single cross strata, as 0.05 to 0.07 m thick siliciclastic-rich foreset alternating with 0.02 to 0.05 m thick bioclastic-rich foreset, arranged into harmonic cycles of bundles of thinning to thickening laminae; or (iii) at lamina scale, observable in thin section, as randomly alternated bio-siliciclastic laminae.

These deposits accumulated due to subaqueous tractional currents flowing under conditions of low bed shear stress (Fig. 11a) (Allen, 1968; Costello and Southard, 1981; Ashley, 1990; Southard and Boguchwal, 1990; Southard, 1992). The unvarying directionality of cross strata indicates flows with unimodal direction (Fig. 11a), except for local reverse flows. The absence of wave-induced structures suggests that sediment accumulation occurred below the fairweather wave base (*f.w.w.b.* in Fig. 11a, b). The distinct segregation between siliciclastic and bioclastic foreset laminae suggests that the hydrodynamic processes of sediment accumulation were characterised by periodically and cyclically modulated variations of the current energy (Fig. 11b to d). Based on grain distribution, specific density, and shape, the siliciclastic heavier fraction was presumably transported as bedload during periods of the higher energy of the flow (except during rare storms), whilst the bioclastic lighter fraction was transported as suspended load (Fig. 11b to d). Bioclasts were included in the deposit by avalanche or fallout, only during periods of lower flow energy (Longhitano et al., 2010; Longhitano, 2011). Accordingly: (i) the isolated intervals observed at the tops of cross-bedded deposits represent temporary decreases or arrests of flow power that deposited a drape of bioclastic material. Within these intervals, the siliciclastic fraction is not completely absent but it is interspersed in a bioclastic-rich matrix (*b/s* >>1). (ii) The rhythmic alternation of thicker siliciclastic and thinner bioclastic foreset, repeated with sequences of laminae thickness that show tidal periodicities of diurnal (ebb/flood) to monthly (neap/spring) duration (Longhitano, 2011), indicates that the current velocity was subject to a tidal modulation (Fig. 11a to d). This process can be attributed to the influence exerted by the microtidal changes of the water-column thickness on unidirectional marine currents, which likely occurred in peripheral parts of a semi-confined basin (Longhitano, 2011). (iii) The segregation at the lamina scale can be due to the sorting effect that occurs during the avalanche of clastic grains along a lee face of a dune (Allen, 1980). Heterolithic segregation of siliciclastic and bioclastic particles at this scale would reflect a process of separation occurring because of intra-clast friction during a gravity-driven avalanche, due to their different shape. This effect results in millimetre-scale segregated horizons (Fig. 11d). Anyhow, the presence of distinct segregation of bio-siliciclastic particles at different scales suggests that sedimentation occurred in a moderate-energy subaqueous environment, sufficiently distant from the zones where waves, and consequent mixing of heterolithic particles, dominated (Fig. 11c, d).

homoclinal subaqueous profile in mixed sediments

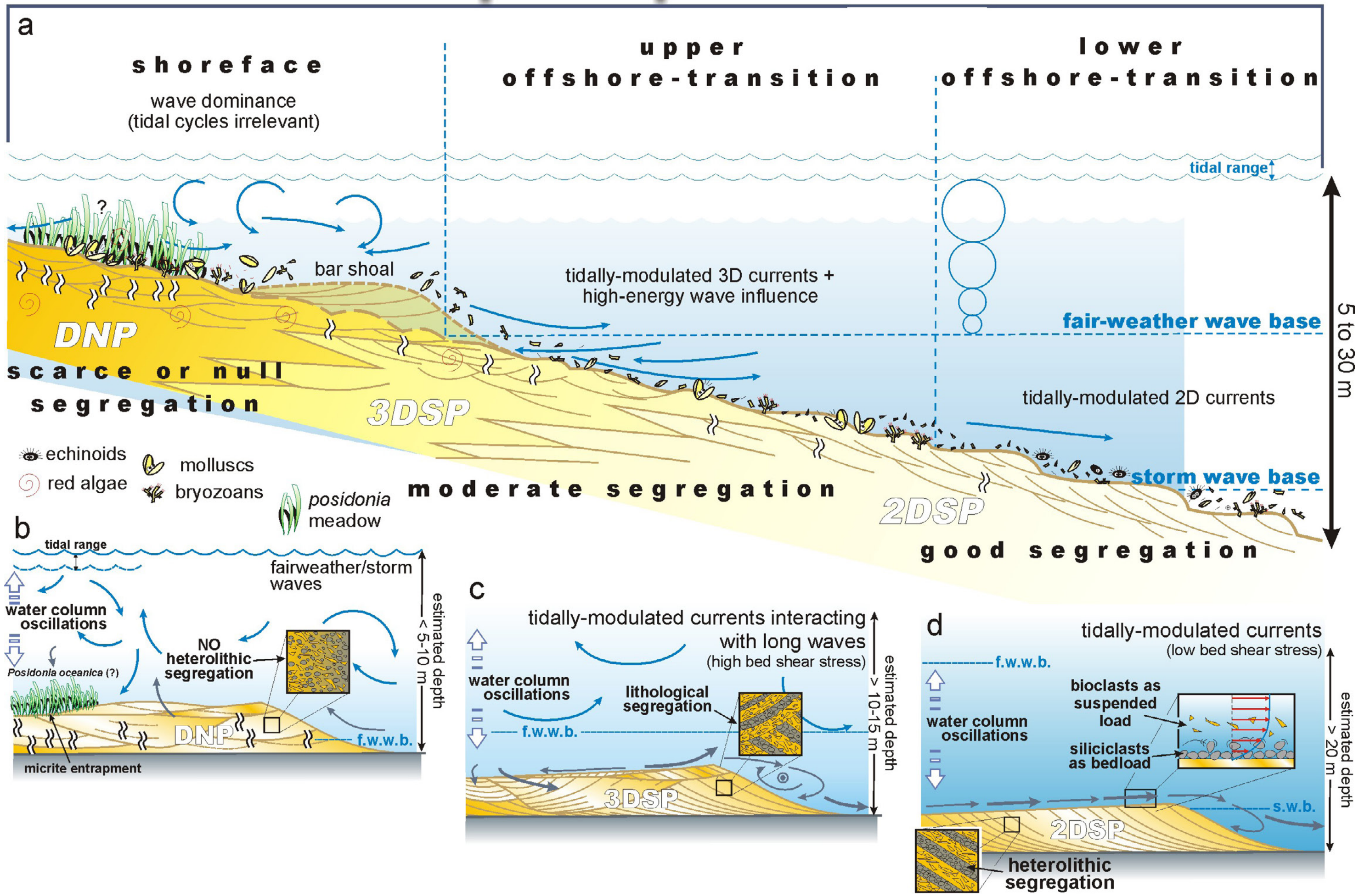

Fig. 11 – (a) Conceptual model illustrating the 2D distribution of the environments inferred from the Acerenza mixed deposits. Mixed sediment distribution and accumulation occurred along with a homoclinal subaqueous profile under persistent currents and waves. The relative increase in the abundance of the bioclastic fraction in the shallower environments corresponds with the presence of an *in situ* or near *situ* carbonate factory. (b) In the shoreface zone, surficial waves did not induce segregation in the mixed deposits of facies association (f.a.) DNP (dunes of non-segregated particles). The occurrence of fine micrite could be associated with the presence of *Posidonia oceanica* meadows. (c) 3D dunes of f.a. 3DSP accumulated in a deeper zone subjected to the influence of sporadic shoaling waves, where a moderate heterolithic segregation of mixed deposits occurred. (d) Unidirectional currents forming planar cross sets of f.a. 2DSP (2D dunes of segregated particles), developed the deepest zone of the profile (f.w.w.b. = fairweather wave base; s.w.b. = storm wave base) (modified, after Chiarella and Longhitano, 2012).

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Stop T3.1.3. The Acerenza palaeo-bay and its mixed sediment infill

Coordinates: **40°47'50.35"N – 15°56'34.52"E**

Topic: Summary and conclusive interpretation of the mixing sedimentation.

This stop provides an overview of the exposed front of the Apennines, the Bradanic Trough, and the Apulia Foreland (Fig. 12a). From here, the depositional scenario for the Acerenza mixed deposits can be envisaged (Fig. 12b, c). The Acerenza area preserves remain of mixed deposits referable to the sedimentary infill of an ancient embayment, entered by waves and tides, here amplified due to phenomena of geomorphic resonance (*i.e.*, the tidal wavelength roughly corresponds with the radius of the bay, generating a local water-mass reverberation) (Fig. 12b). The interaction between tectonic activity and resulting palaeogeographic and palaeobathymetric configuration controlled the distribution of the carbonate factory and resulting geographic and stratigraphic variations registered in the bioclastic/siliciclastic ratio (Fig. 12c; Chiarella et al., 2019a). Progradation of mixed deposits in the Acerenza Bay occurred through the basinward advancement of depositional environments distributed along with a gently inclined subaqueous profile and subjected to different conditions of hydrodynamic energy (Fig. 11a). The interplay between shoaling waves, bottom currents, and short-term periodic tides produced specific ranges of heterolithic segregation in mixed sediments, that were used here as distinctive palaeo-environmental proxies (Chiarella and Longhitano, 2012).

Scarce or nearly absent heterolithic segregation is typical of the uppermost facies interval of the succession, which records a wave-dominated shoreface zone (Fig. 11b). Here, the abundance of the bioclastic fraction suggests the occurrence of an *in situ* carbonate factory made up of heterozoan species that usually live in the light and nutrient-rich clear waters. The hydraulic conditions for low flow circulation became less unstable in the upper offshore-transition zone (Fig. 11c), where currents generated 3D dunes alternating with trough cross strata due to a decreased depth and the vicinity to the main wave base level. In this environment, quantitative assessment of particle distribution (Chiarella and Longhitano, 2012) indicates moderate bio-siliciclastic segregation within the dunes, whereas lower to absent segregation within shallower strata suggests high-energy events, such as shoaling long waves and post-storm oscillatory flows. The deeper environment prograding over the transgressive horizons recorded a lower offshore-transition zone (Fig. 11d), where currents acting under low flow conditions generated 2D dunes. The corresponding cross-stratification contains markedly segregated cosets of bioclasts and siliciclastic grains forming bundles indicating tidal cycles of semidiurnal to monthly periodicity. The tidal influence generated the rhythmic accumulation of

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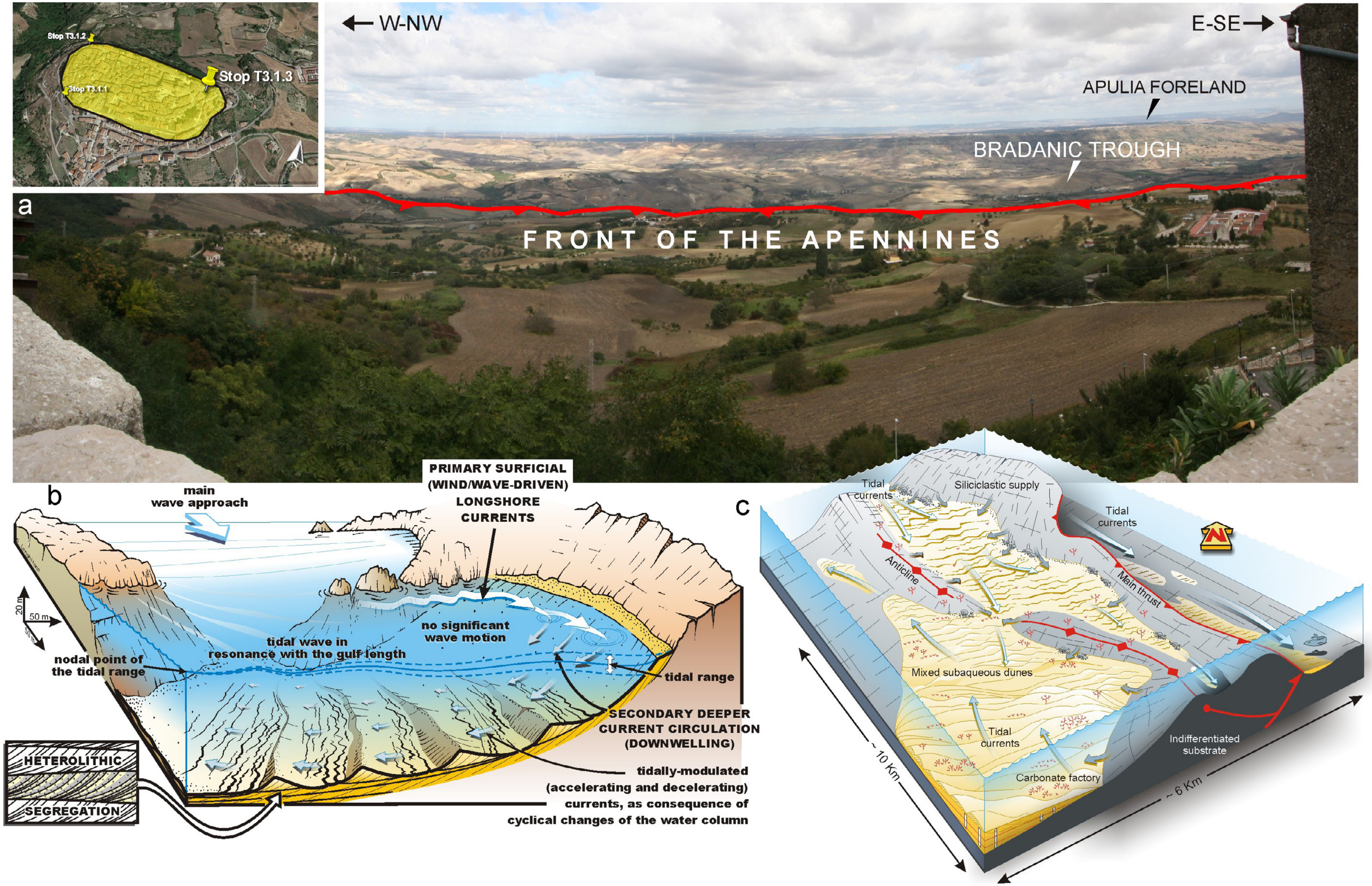
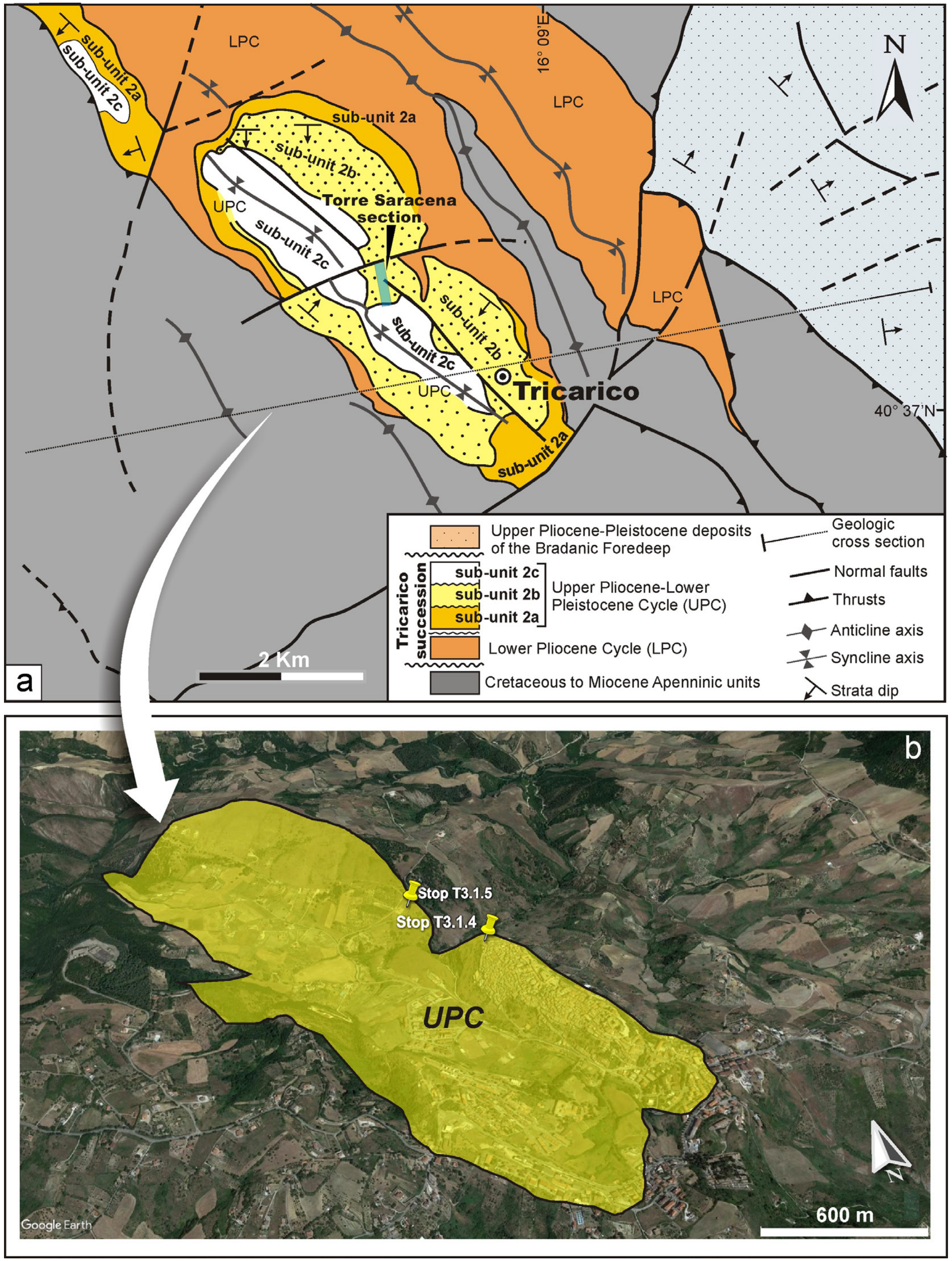


Fig. 12 – (a) Panoramic view over the front of the Apennines and the Bradanic Trough, with the Apulia Foreland in the very background visible at the last Stop T3.1.3 (inset). (b) Depositional models proposed to explain the tidal influence in enclosed shallow-marine settings and the unidirectionality of bedforms (modified, after Longhitano, 2011). (c) Palaeogeographic reconstruction of the Acerenza area during the Early Pleistocene (modified, after Chiarella et al., 2019).



segregated cosets within the 2D dunes, because of a selection of the sediment particles based on their specific density and shape (Fig. 11d).

Stop T3.1.4. The Torre Saracena section and the Tricarico flood-tidal delta

Coordinates: **40°37'33.71"N – 16° 8'31.72"E**

Topic: Panoramic observation of large-scale cross-stratification in mixed arenites.

After lunch, the itinerary moves southeastwards to Tricarico (Fig. 1). Here, both the Lower Pliocene and the Upper Pliocene-Lower Pleistocene cycles are exposed (Fig. 3d). The younger cycle is composed of at least three stratigraphic intervals or sub-units. (i) The lower sub-unit consists of arenites (sub-unit 2a in Fig. 13a), with thin interlayered calcarenite beds, rich in molluscs, bryozoans, and vegetal remains, passing into conglomerates for a total thickness of up to 50 m. These deposits are erosionally overlain by an intermediate sub-unit (2b in Fig. 13a), which is made up of about 30 m-thick sandstones passing into about 30 m-thick mixed deposits; this latter is the focus of this stop. The uppermost sub-unit (2c

Fig. 13 – (a) Geological sketch map of the Tricarico area showing the location of the Torre Saracena section (Stop T3.1.4) (modified, after Longhitano et al., 2010). (b) Aerial photograph with the mixed deposits indicated in yellow and the location of the two stops.

in Fig. 13a) consists of a succession of ca. 30 m-thick claystones, bounded at the top by a surface of modern exposure (Sabato, 1984; Sabato and Marino, 1994; Pieri et al., 2004; Longhitano et al., 2010).

Stop T3.1.4 is located in the northern periphery of the village (Fig. 13b) where an artificial terrace looks to the north on a natural section, along the flank of an incised canyon (*Torre Saracena section*). This S-N-oriented stratigraphic window (Fig. 14a) reveals the intermediate mixed, siliciclastic-bioclastic interval (sub-unit 2b; Sabato and Marino, 1994). The viewpoint allows the detection of 11 tabular sand bodies, vertically

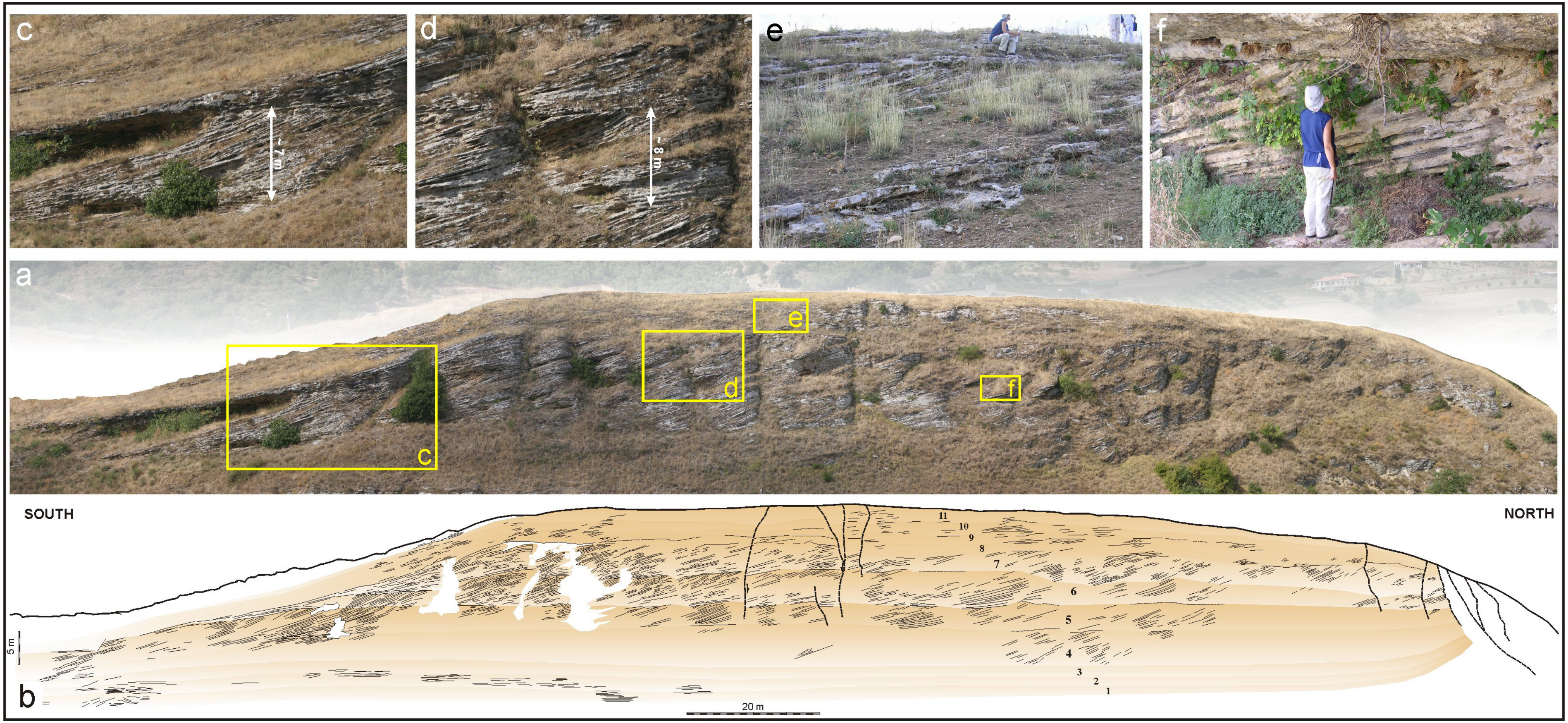


Fig. 14 – (a) Outcrop view of the Torre Saracena section and (b) line-drawing. (c to f) Details of the internal architecture of the mixed cross strata (modified, after Longhitano et al., 2010).

superimposed to form a more than 30 m-thick aggradational succession (Fig. 14b). The thickness of each body ranges from 2 m to 6 m, organised in thinner and thicker stratasets. Common to all strata is the presence of internal foresets, dipping southwards and showing angular, tangential, and sigmoidal geometries (Fig. 14c to f). Surfaces bounding each tabular sand body are regular discontinuities showing weak erosion of the underlying cross strata and gently dipping (1-2°) towards the same direction of foreset migration (southwards). Internally, additional lower-rank discontinuities can be seen, interrupting regular foreset series.
Large-scale cross-stratification is interpreted to represent the result of the migration of subaqueous tidal dunes, dominantly moving southwards in this area (*i.e.*, against the orogen massif and opposite with respect to the direction of orogenic transport; Fig. 15a, b). Palaeocurrents measured in this section and others indicate an overall radial distribution, which is a common feature of dunes migrating along tidal deltas. Bi-directionality has rarely been recognised in localised places and reflects rare ebb currents. Tidal dunes may have developed in an environment deeper than the main wave base depth, based on a general lack of wave-induced structures in the dune-bedded deposits. Based on these major observations, these deposits have been interpreted as the record of a flood (landward prograding) tidal delta (Fig. 15b).

Stop T3.1.5. Facies detail and internal architectural hierarchies of the Tricarico mixed deposits

Coordinates: **40°37’45.75”N – 16° 8’18.74”E**

Topic: Close-up views of textural features of mixed sediments and their geometrical elements.

This stop is located in a road trench forming a wide bend (Fig. 16a), allowing detailed observation of the textural features of mixed sediments, and offering a three-dimensional exposure of some of the major architectural elements, including foreset geometry, main discontinuities, and foreset shape.
Mixed deposits are represented by medium to coarse siliciclastic sands and coarse sand- to granule-sized bioclasts, consisting of red algae, bivalves, bryozoans, echinoids, and *Balanus* fragments, associated with benthic foraminifera (Sabato and Marino, 1994). The cross-stratified succession visible from this stop exhibits descending hierarchical orders of internal structures. (i) *First-Order Cross-Stratification Sets* are bounded by the largest discontinuity surfaces considered as first-order surfaces (s_1). Cross-strata sets range from less than 1 m to more than 6 m in thickness and 300-400 m in length (Fig. 16b) and with sharp (often erosional) and/or gradational, horizontal bases and tops (s_1 surfaces in Fig. 16b, c). Often “formset” (*i.e.*: foreset passing upwards to topset) can be seen. These represent preserved dunes discernible thanks to off-lap breakpoints (Fig. 14d).

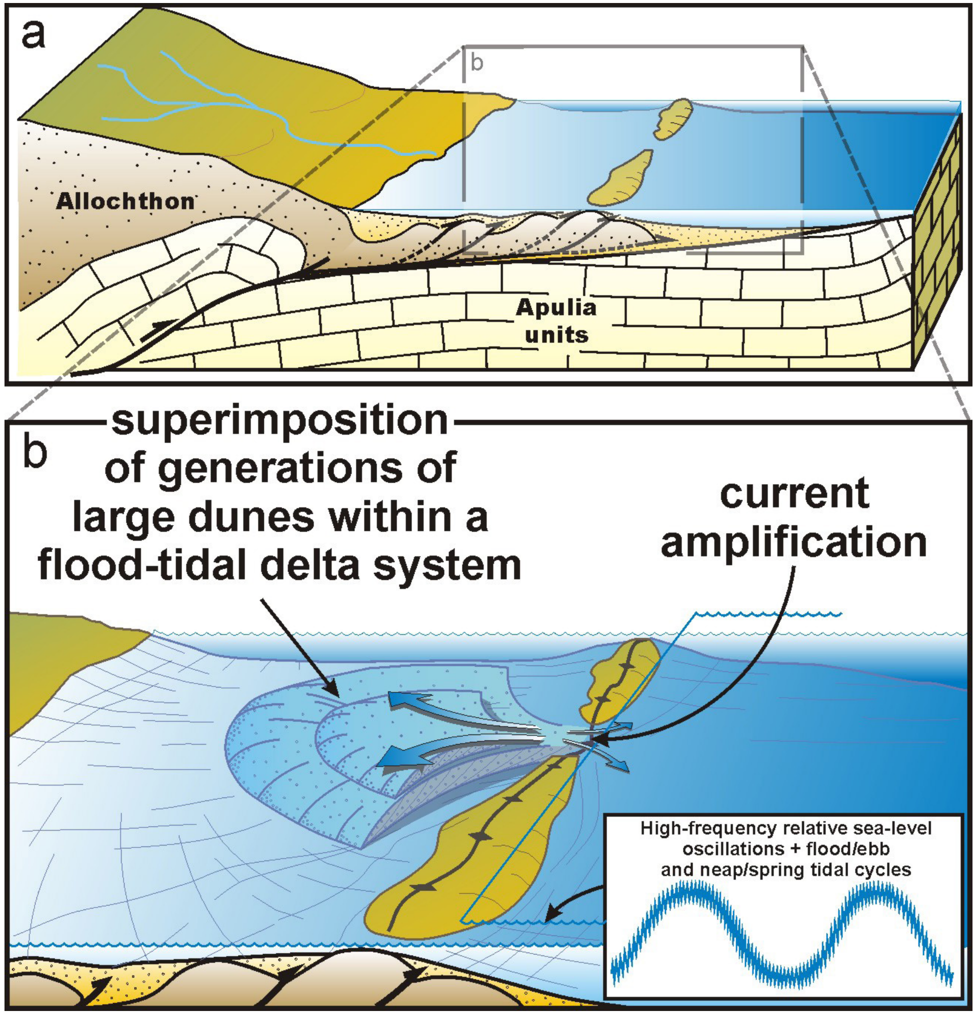


Fig. 15 – (a) Depositional scenario reconstructed for the Tricarico area at the front of the Apennine orogen. Emergent thrust culminations isolated a portion of the internal foreland basin creating conditions for structural inlets and tidal amplification. (b) Flood tidal currents flowing landwards generated the development of a flood-tidal delta subjected to high-frequency sea-level changes controlling the variable thickness of the cross strata observable at the Stop T3.1.4 (after Longhitano et al., 2010).

Second-Order Cross-Stratification Sets represent smaller-scale cross strata, comprised within each single first-order accretionary unit. They range from 0.1 to 0.4 m and are bounded by second-order discontinuities (s_2 in Fig. 16b, c), which are either reactivation surfaces caused by erosion or pause planes caused by non-deposition (Allen et al., 1994). Palaeocurrents show prevalent unidirectional, SSW-migrating directions. Locally, sets of bi-directional cross strata (herringbone) occur (Fig. 16b). *Third-Order Cross-Lamination Sets* are inclined laminae, the thickness of which is greater than 1 cm. They are bounded by tabular to broadly curved strata planes (s_3), with an elevated concentration of detrital quartz grains. Bundles of alternating cycles of coarser- and finer-grained strata, forming thicker and thinner laminae (Visser, 1980; Allen, 1981) occur along with a single accretionary unit (Fig. 16b, c). Locally, opposite current ripples develop along tabular surfaces of truncation or fill small scours that are incised into the master lamination. *Fourth-Order Cross-Lamination Sets* represent lamina-sets bounded by conformable surfaces and by reactivation surfaces or pause planes (s_4) (Fig. 16b). Diffused burrowing occurs at this scale. Laminae are identified by the rhythmic alternation of siliciclastic and bioclasts grains, composed of cyclical lamina rhythmites (Longhitano, 2011) of thicker/finer (siliciclastic) and thinner/coarser (bioclastic) foreset laminae. The thickness of the siliciclastic and bioclastic laminae ranges from 0.5 cm to 1-2 cm, respectively (Fig. 16d).
The first-order hierarchical level, represented by alternating packages of thicker and thinner unidirectional

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Fig. 16 – (a) Outcrop view of the Stop T3.1.5. (b to d) Details visible along the road trench (modified, after Longhitano et al., 2010).

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cross strata, records the physical response to the influence of high-frequency sea-level oscillations that cyclically increased and decreased the water column across a narrow structural inlet (Longhitano et al., 2010). These water-depth changes produced repeated conditions of differential preservation of the dunes due to the variation in the bed shear stress of tidally driven currents (Longhitano and Nemec, 2005). Simple and compound second-order sets represent dunes with variable sinuosity. Sets of herringbone laminae indicate the preservation of tidal ebb flows in the rock record. Third-order lamination represents ripple-scale units formed by segregation of siliciclastic- and bioclastic-dominated foreset laminae. Such a feature becomes the prevailing attribute of the fourth order set lamination and is interpreted as the result of traction or grain fall processes occurring on the lee sides of larger dunes under the influence of diurnal or semidiurnal tidal cycles (Longhitano et al., 2010).
Cross stratification observable in the Torre Saracena section is largely unidirectional and formed as a result of traction currents within a generally SSW-NNE-oriented structurally controlled inlet. Although this basin developed under a micro-tidal oceanographic setting, tide-driven currents may have supplied a significant amount of energy to the system, producing powerful set-up flows, which forced dune migration. This current set-up may have been reinforced by the presence of a strait or inlet across a thrust-core anticline, which may have created the conditions for tidal current amplification. Accordingly, a flood-tidal delta developed landwards in a quasi-confined small micro-tidal Apennine basin (Fig. 15a, b).

Day 2

The focus of the second day of this field trip is the investigation of the depositional characteristics of the Lower Pleistocene "Calcarenite di Gravina" Fm cropping out around Matera.
One of the principal goals in the Matera area is the analysis of coarse-grained clinobedded coastal bodies, forming accretional units lapping onto the southwestern flank of a palaeo-island (the Matera Horst *i.e.*, "Murge di Matera"), and that stack in a back-stepping configuration (Stops T3.2.1 and T3.2.2). This depositional style is thus compared with different depositional architectures developed on the opposite, northeastern flank of the same palaeo-island. Here, shallow-marine fan-shaped/apron-like lithosomes developed fed by longshore drifts (Stop T3.2.3) (Fig. 17c). All these stops represent spectacular outcrop analogues for the interpretation of high-resolution seismic sections bearing comparable subsurface stratigraphic architectures and geometries. Moreover, the outcropping rocks are a remarkable example of a peculiar type of mixed, litho-bioclastic carbonate-dominated deposits, accumulated around a drowning small island in a temperate marine setting. As well as for the "compositional" mixing of sediments exclusively due to carbonate particles, these rocks represent also a rare example exhibiting all the three varieties of mixing scales (*cf*. Chiarella et al., 2017): punctuated, facies-, and *in situ*- mixing (Fig. 2b).

Stop T3.2.1. Introduction to the geology of Matera

Coordinates: **40°39'21.38"N - 16°37'1.74"E**

Topic: Panoramic view from the Cappuccini-Casalnuovo area over a vertical side of the Matera canyon showing the onlap of Lower Pleistocene strata on the Cretaceous limestones (bedrock) of the flank of the palaeo-island.

During the Early Pleistocene, the Matera palaeo-island was separated from the main Murge archipelago to the north by the 6-7 km-wide Viglione Graben (Fig. 17a) and from the Apennine chain-front to the southwest by a *ca.* 50 km-wide seaway (the Bradanic Trough), connecting the open Mediterranean (Ionian Sea) with the central Adriatic Sea (Fig. 5a). Nowadays, the Matera palaeo-island corresponds to the "Murge di Matera", *i.e.*, the few tens of km^2 wide and up to 500 m high culmination of the original drowning horst, which stands out from clays of the "argille subappennine" Fm partly filling both the Viglione Graben and the Bradanic Trough (Fig. 17a, b). The modern deep canyon of the "Gravina di Matera" incises the horst and widely exposes both the Cretaceous bedrock of the palaeo-island and the Lower Pleistocene covers (Fig. 17a, b).

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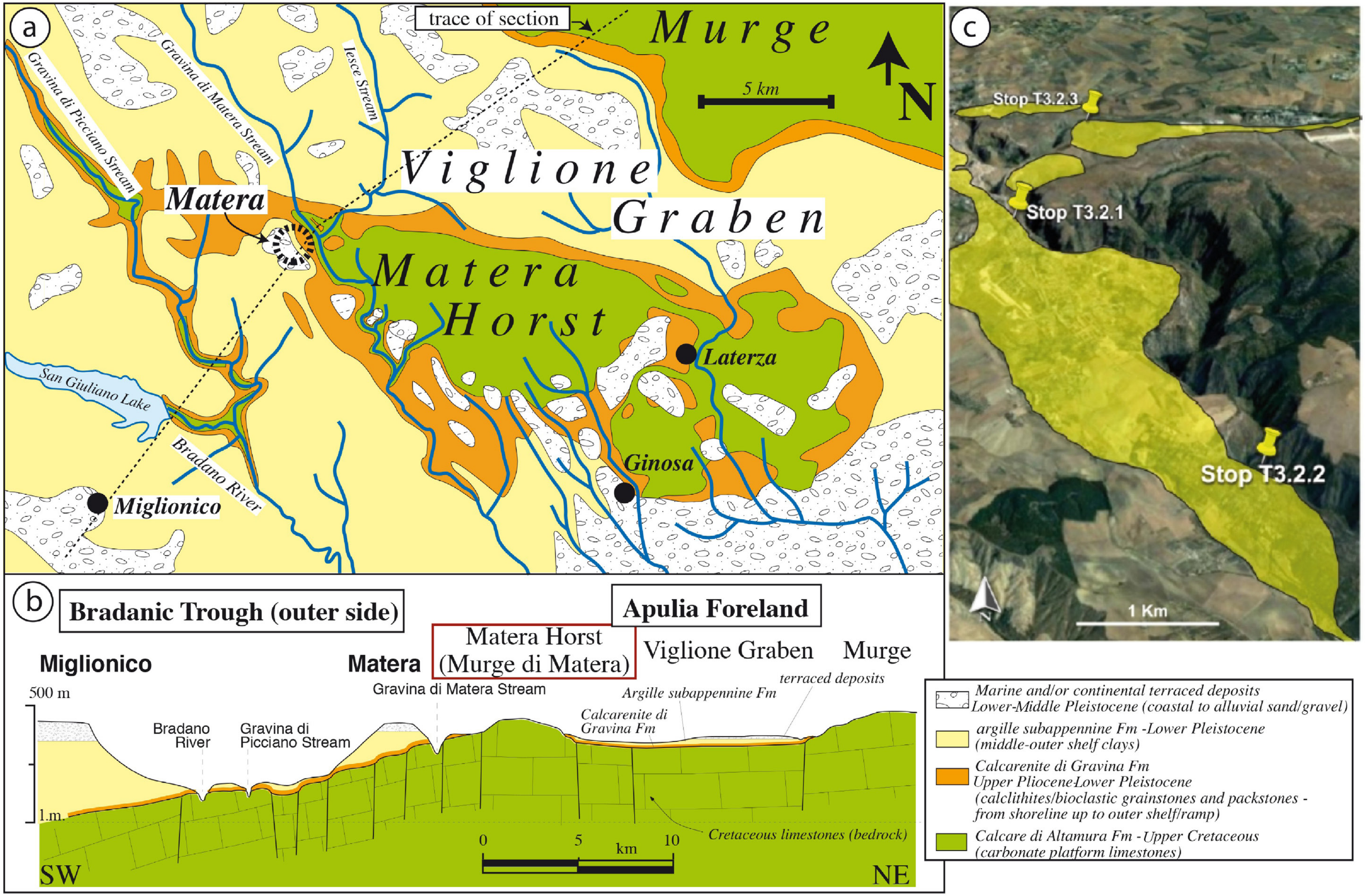

Fig. 17 – (a) Geological sketch map of the area around Matera with the location of the stops of the second day. (b) Geological cross-section reconstructed across the area [see the trace in (a)]. (c) Aerial photograph showing the location of the three stops and the distribution of the mixed deposits (in yellow).

Stop T3.2.1 (Fig. 17c) provides a panoramic overview from the left side of the "Gravina di Matera" canyon, very close to the parking area. From this viewpoint, some of the best-exposed sections of the "Calcarenite di Gravina" Fm can be appreciated. The spectacular coastal onlap on the southwestern flank of the palaeo-island is visible near the town, in front of the Sassi area (Fig. 18a). Here, the "Calcarenite di Gravina" is mainly lithoclastic in origin and shows dominant sub-horizontal to gently inclined plain-parallel discontinuity surfaces (diastems), whose lateral terminations mark the onlap contact onto the basal unconformity. Internally, some bed-sets exhibit large-scale clinoform architectures.
Along the canyon, the exposed Cretaceous carbonate succession has been recently attributed to either inner-platform or intraplatform-basin facies (Festa et al., 2018).

Stop T3.2.2. The Lamaquacchiola section

Coordinates: **40°37'28.39"N – 16°38'34.73"E**

Topics: Prograding coastal bodies, back-stepping on the gently sloping south-western flank of the Matera High.

After a walk of about 15-20 minutes, we reach the location of Stop T3.2.2 (Fig. 17c), where a panoramic view over the cliff of Lamaquacchiola can be observed (Fig. 19a). The cliff provides a spectacular dip-oriented cross-section of the southwestern flank of the Matera palaeo-island, from where the coastal bodies of the Lower Pleistocene "Calcarenite di Gravina" Fm prograded. Although the exposed clinoforms represent the most noticeable geometry of this section (Fig. 19b), we first focus on sub-horizontal first-order surfaces dividing the entire successions into several prograding units (Fig. 19c). First-order surfaces lead to the identification of the gently sloping (up to 5°) basal discontinuity which, affected by intense marine bioerosion, represents a long-term ravinement surface created on the flank of the island during the Early Pleistocene (Tropeano and Sabato, 2000).
The same panoramic stop also provides a strike-oriented view, useful to appreciate the prismatic geometry of the prograding bodies and their along-strike elongation. This indicates that these bodies developed parallel to the paleo-coastline along the flank of the palaeo-island forming laterally extensive seaward-prograding lithosomes. Although thickness and internal high-angle clinobeds (up to 35°) resemble depositional architectures common to large tidal bars (Fig. 19b), the 3D attitude of these prisms (Fig. 19a, b) is associated with close-up facies observations, suggests a different genesis. Actually, lithofacies are part of coarse-grained, gravel-dominated nearshore to offshore systems, conglomeratic at their proximal inner edge (rocky coast) and progressively

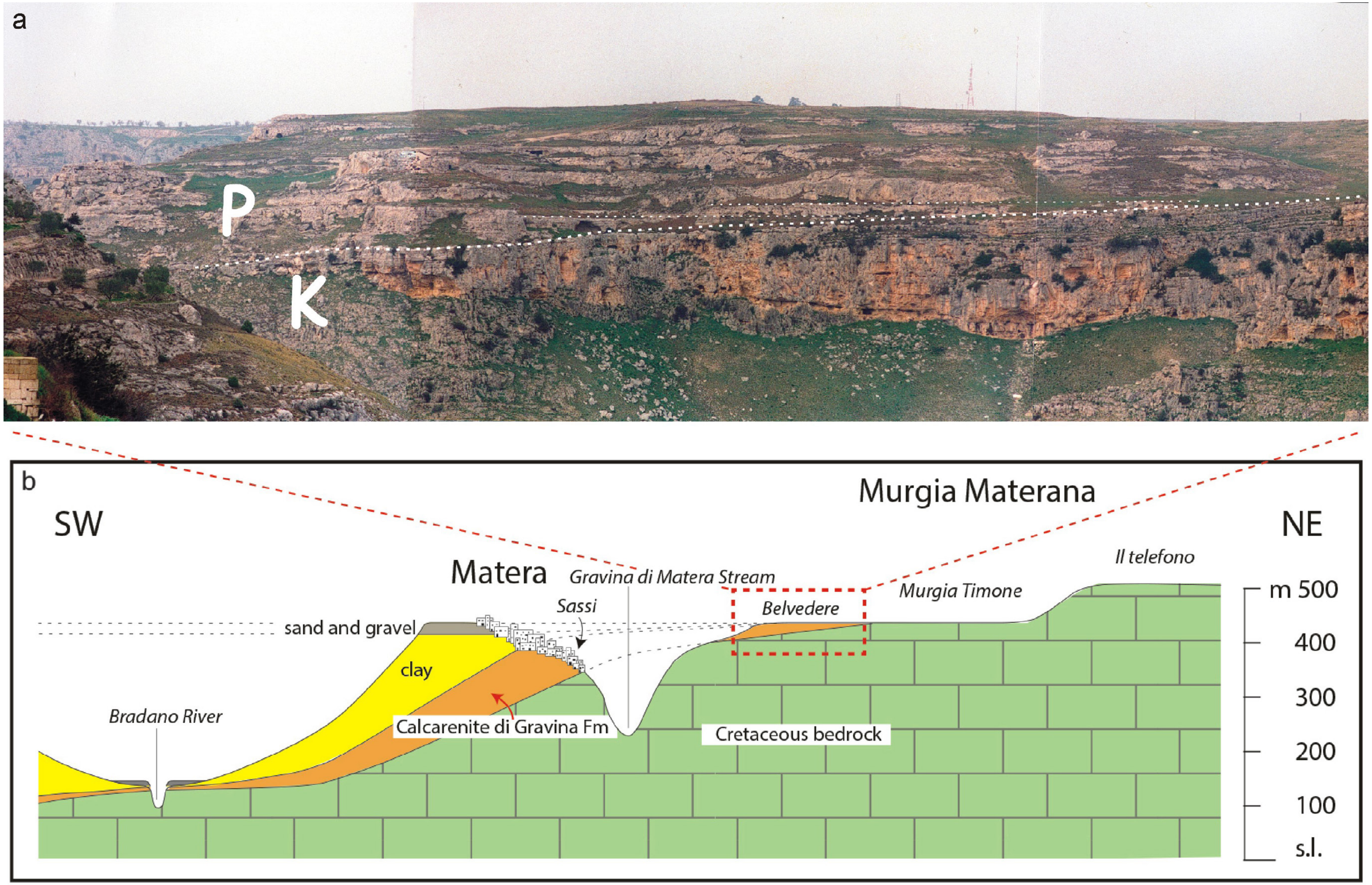

Fig. 18 – (a) The spectacular coastal onlap of the Lower Pleistocene "Calcarenite di Gravina" Fm (P) onto the Cretaceous limestones (K) exposed in the southwestern flank of the palaeo-island along the left side of the Gravina di Matera canyon and visible at the Stop T3.2.1. (b) Geological cross-section across the Gravina di Matera River, showing the stratigraphic relationships between the "Calcarenite di Gravina" Fm and the underlying and overlying units (modified, after Beneduce et al., 2004). The red inset indicates the location of the outcrop shown in (a).

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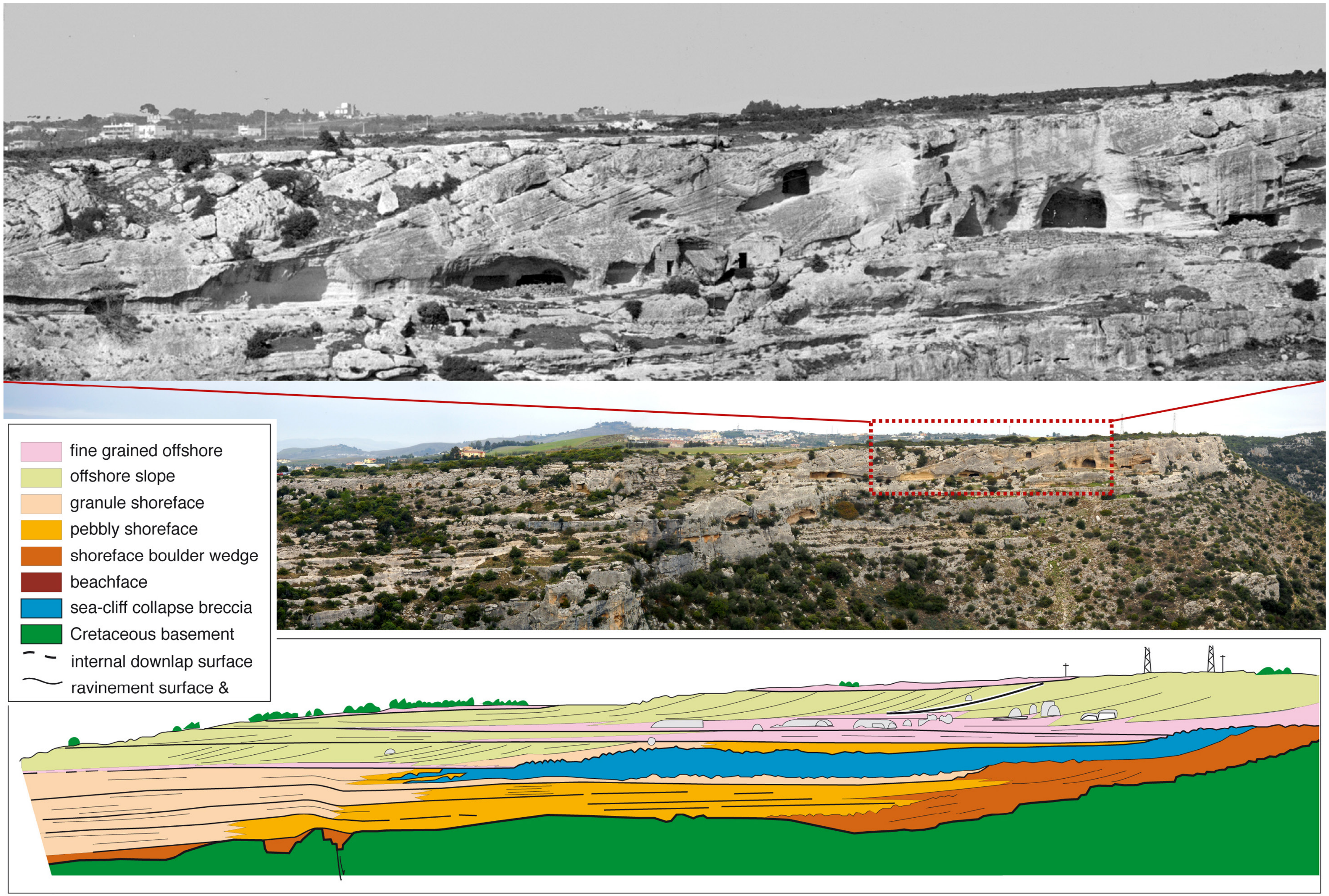

Fig. 19 – (a) The Lamaquacchiola section visible from Stop T3. 2.2. (b) Close-up view of the transition slope deposits. (c) Line drawing of the section in (a) and facies description (modified, from Pomar and Tropeano, 2001).

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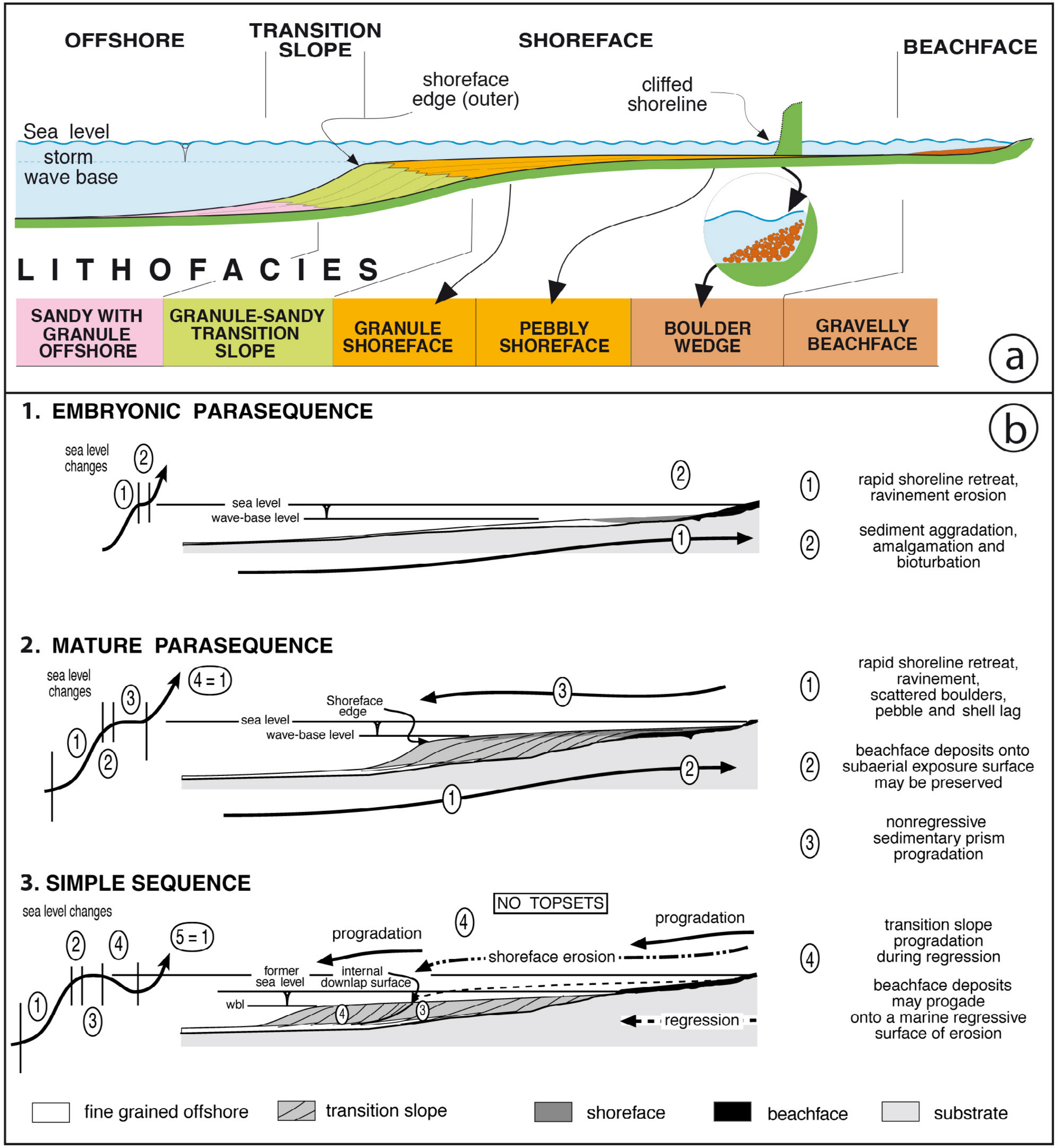
sandier basinward (offshore) (Pomar and Tropeano, 2001). Four main depositional zones can be recognised (Fig. 20a), placed adjacent along with an idealised depositional profile: i) the *beachface*, replaced by boulder wedges on cliffed coastlines, indicating the zone affected by breaking waves and wave-swash processes; ii) the *shoreface*, indicating the gently inclined zone dominated by wave traction and where sediments were swept seawards during strong wave activity; iii) the *transition slope*, indicating a steep zone located just seawards of the shoreface edge, where storm- and wind-driven tractive flows change into gravity-driven currents, forming seaward-inclined steep beds; iv) the *offshore*, indicating a low-energy and sediment-starved flat area where bioturbation was significant (Fig. 20a).

The depositional system

The depositional architectures exposed along the Lamaquacchiola section and the related component facies with their interpretations, represent an outcrop analogous model for coarse-grained coastal systems (Fig. 20a). The presence of a steep slope adjacent to an area swept by waves in carbonate coarse-grained systems was suggested by Likorisch and Butler (1996) for outcrop deposits observed onshore of Sicily whose age is almost coeval with the exposed rocks around Matera. Later, the same interpretation was proposed by Massari and Chiocci (2006) as typical for Plio-Pleistocene cool-water carbonate and mixed systems in the Mediterranean Sea and extended to several older carbonate systems by Pomar et al. (2015).

Fine-grained present-day shallow-marine bodies observed on seismic lines offshore of Spain and showing geometries resembling those observed at Lamaquacchiola were defined as "Infralittoral Prograding Wedge" (IPW) by Hernandez Molina et al. (2000). The same interpretation was proposed by Cattaneo et al. (2003) in the Adriatic Sea, where laterally extensive prograding muddy bodies were termed "subaqueous deltas".

With regard to the cross-sectional distinctive architecture of their idealized coastal system, Pomar and Tropeano (2001) pointed out that two breakpoints may be identified from the shoreline-to-shelf profile, corresponding with the shoreline and the shoreface edges. The possibility that more than one rollover point could be present along the same depositional profile running from the shoreline to deeper shelf settings, was firstly introduced and discussed by Carter et al. (1991). A composite coastal profile was modelled by Hellan-Hansen and Hampson (2009) and Hellan-Hansen et al. (2012) and highlighted as a potential generator of sequence stratigraphy flaws by Tropeano et al. (2002c). The latter suggested that a subaerial and a subaqueous delta may coexist forming compound clinoform sets, while Patruno and Helland-Hansen (2018) and Pellegrini et al. (2020) assumed the presence of up to five different genetically related clinoform sets along with an idealised profile from the coastal



plain to the oceanic abyssal plain.
Within this framework, the transition slope, one of the main topics discussed in this stop, represents the steepest zone of the coastal profile where the clinoform set develops seawards the shoreface. Tractive flows, sweeping the shoreface and triggered by storm waves and wind-induced currents, change at the outer shoreface edge from tractive to gravity-driven and produce a depositional slope as a result of sediment avalanche processes. In accordance with this genesis, the transition slope cannot be considered a bedform (a giant sand-wave) but it represents a segment of the equilibrium coastal-profile that migrates according to the evolution of the depositional system (Pomar and

Fig. 20 – (a) Depositional system and lithofacies observed at Stop T3.2.2 compared with the nomenclature used in Reading and Collinson (1996). (b) Three types of accretional units are characteristic in the "Calcarenite di Gravina" Fm, according to the bedding pattern, facies architecture, and its relationship with the highest frequency changes of sea level. (1) Embryonic parasequences; (2) Mature parasequences; (3) Simple sequences (after Pomar and Tropeano, 2001).

Tropeano, 2001). This field-data interpretation was harshly rejected ("they are tidal sand-waves!") when it was firstly presented in the Ph.D. dissertation of Tropeano (1994a; 1994b) but gains credibility after Pomar and Tropeano (1998; 2001). Processes and facies of the transition-slope (or IPW or subaqueous delta) are now widely accepted by the international community. Exhaustive reviews about the topic have been provided by Patruno et al. (2015a; 2015b; 2015c) who, based on a wide range of case histories, indicate the Lamaquacchiola section of Matera as one of the few documented field examples of ancient delta-scale compound clinoforms.

Sediment mixing and depositional environments

A further aspect of the discussion in the Lamaquacchiola depositional system is based on the mixed nature of the constituent facies. Sediment supply for these deposits was two-fold: carbonate lithoclasts derived from the erosion of exposed highlands and bioclasts produced along with the depositional profile (Tropeano et al., 2010). Mixing of both types of carbonate particles (lithoclasts and bioclasts), falling in the compositional mixing of Chiarella et al. (2017), derived from the *in situ* production of a heterozoan factory (*sensu* James, 1997) in a "terrigenous" fed setting. The coexistence of intrabasinal production with a terrigenous input was favoured by the absence of land-sourcing fine-grained particles since the exclusive presence of Cretaceous limestones on land could not provide either clay or carbonate lime to the system. It must be recalled that clay derives from either the alteration of siliceous rocks or the recycling of older clayey successions (both sources are not exposed on the palaeo-island), while alteration on limestone causes dissolution of rocks (karsts phenomena) rather than the creation of fine-grained particles. Moreover, the lack of significant alluvial/fluvial systems on the small palaeo-island and the abundance of erosion terraces bored by molluscs and sponges (shore platforms) on the intensely fractured limestone covered by coarse-grained facies indicates that lithoclasts were mainly produced by both the abrasion of the bedrock and the erosional retreat of the rocky coast in a wave-dominated system. According to Mateu-Vicens et al. (2008), the distribution along the depositional profile of the intrabasinal carbonate component can be explained following the same hydrodynamic environmental zonation proposed by Pomar and Tropeano (2001). Barnacles and isolated fragments of oyster and pectinid shells are present within the pebbly deposits of the beachface, while whole shells and fragments of echinoids, pectinid, and oysters are locally abundant in moderately to well-sorted pebble to granule deposits of the shoreface, deposits which frequently appear structureless. Thin-section observations, in particular the presence of some kinds of epiphytic foraminifera, suggest that the shoreface was populated by mixed algal-seagrass meadows (Mateu-Vicens et al., 2008). The structureless appearance of the shoreface facies is thus attributed to the

sediment amalgamation generated by the action of rhizomes or roots. Seawards, shoreface beds transit into steeply inclined, basinward-dipping beds (10 to 35°) of the transition-slope, forming 10-20 m-thick (locally up to 30 m) lithosomes, extending up to 1 km long down dip. These mainly granule-grained deposits show moderate to abundant echinoid bioturbation and commonly contain scaphopods, pectinids, bivalves, irregular echinoids, and complete brachiopods towards the distal part. Epiphytic foraminifera appears dominant in thin sections, while planktonic and deeper-water indicators are absent. The mixture of skeletal fragments and the well-preserved foraminiferal tests indicate that bioclasts were shed from shallow-water settings. However, infaunal sediment-feeder traces (echinoids) and whole shells of filter-feeding invertebrates (brachiopods and scaphopods) indicate quiescent periods (Mateu-Vicens et al., 2008). Cross-strata of the transition-slope prograde basinward, downlapping, and interfingering with sub-horizontal sand-grained and bioturbated deposits of the offshore in which locally abundant bioclasts occur. Here, common fossils include rhodoliths, branching and encrusting bryozoans, solitary corals, foraminifera, entire brachiopods, and irregular echinoids, suggesting that sedimentation occurred in the deeper part of the photic zone. The abundance of planktonic foraminifera (*i.e.*, *Globigerinoides*) may indicate a bathymetry increase but mostly a decrease in benthonic production/accumulation (Mateu-Vicens et al., 2008). The occurrence of very rare low-oxygen-related *taxa* (bolivinids and *Ammonia*), commonly associated with increased organic-matter levels, and the scarcity of suspension-feeders such as barnacles, infer low-to-moderate trophic resources, which agrees with the absence of a river feeding to the coast. Moreover, the absence of large benthonic foraminifera or hermatypic corals, related to warm climatic conditions, indicates that carbonate production took place in a temperate environment, similar to the present-day Mediterranean (Mateu-Vicens et al., 2008).
Although bioturbation is pervasive, faint cross-stratification observable in places indicates the presence of contour-parallel currents perpendicularly flowing along with the depositional profile. The inferred presence of these currents becomes meaningful to explain deposition on the opposite flank of the palaeoisland (Stop T3.2.3).

Sequence stratigraphy training with the Lamaquacchiola section
The Lamaquacchiola panoramic section represents a good training ground for sequence-stratigraphy exercises and stratigraphic-architecture interpretations (Tropeano, 2006; Tropeano et al., 2009). Between the end of the ‘80s and the beginning of the ‘90s, a series of works described basin-margin successions and provided models to apply sequence-stratigraphic concepts to sedimentary cycles induced by high-frequency relative sea-

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level changes ("simple sequences" and "parasequences" *sensu* Van Wagoner et al., 1990; Mitchum and Van Wagoner, 1991; Vail et al., 1991). Definitions of parasequences and simple sequences, which now represent key words in the modern sequence stratigraphic concepts, originated both from those works and models (for a historical overview see Emery and Myers, 1996; Posamentier and Allen, 1999; Coe, 2003; Catuneanu, 2006). These models became the working base for metre- to decametre-scale sequence-stratigraphic studies referring either to outcropping or subsurface successions. Many of these sequence stratigraphic concepts may be applied and verified in the Matera example, both to each building block (accretional units bounded by first-order sub-horizontal surfaces) and to their stacking.

Three types of building blocks bounded by the sub-horizontal first order surfaces can be recognised (Fig. 20b): (i) embryonic parasequences, (ii) mature parasequences, and (iii) simple sequences (Pomar and Tropeano, 2001). Parasequences (both embryonic and mature) formed during stillstands of sea level, whereas simple sequences formed during high-frequency cycles of the relative change of sea level. Embryonic parasequences (i) represent thin accretional units lacking transition-slope deposits. The base level for the depositional system was the wave base, which governed the position of the shoreface zone. During slow relative sea-level rises (eustatic still-stand + tectonic subsidence) also the base level rose, generating accommodation space both for the aggradation of the shoreface deposits and, according to the seafloor morphology, for the progradation of transition-slope deposits with the growth of sigmoidal bodies (mature parasequence - ii). The upper boundary of both types of parasequences is a flooding surface produced during the subsequent rise of the sea level (Fig. 20b). Evidence of erosion on these surfaces is interpreted to be due to a dynamic balance between deposition and shoreface erosion during sea-level stillstand (*i.e.*, the "shaved shelf" in James et al., 1994), landward modified by ravinement during transgression.

Simple sequences are characterised by a wedge to sigmoidal configuration (Figs 20b and 21). After the growth of a body with the same features as a mature parasequence (HST), if the relative sea-level fell (eustatic fall > subsidence) also base level went down, and the shoreface zone became eroded and bypassed zone of the system. Progressively, former shoreface deposits and the top of former clinobeds were eroded (sigmoids became wedges) while a steeper transition-slope prograded (FSST). An internal downlap surface (IDS) inside the foreset deposits indicates this base-level fall and represents the boundary between the HST and the FRST (Fig. 21). There is no stratigraphic evidence recording the end of the relative sea-level fall. It can be assumed when the transition slope decreases its steepness (LST) before being covered by offshore deposits (TST). Landwards, the base of these deposits corresponds with the flooding surface produced during the subsequent

rise of the sea level, similarly to the parasequence top (Fig. 21).
The retrogradational stacking pattern of simple sequences and parasequences shown along the Lamaquacchiola section is the depositional result of a tectonically induced transgression punctuated by high-frequency eustacy. It resembles the back-stepping configuration of a TST of a major (third-order?) depositional sequence (Fig. 21).

Stop T3.2.3. The "Palomba" and "Jesce" sections

Coordinates: **40°40'32.56"N – 16°37'38.33"E**

Topics: Shallow-marine fan-shaped bodies on the north steep-sloping flank of the Matera High.

Moving towards the northern margin of the Matera structural high, marine sedimentation along a steep rocky foreslope can be observed (Fig. 17c). Natural sections cutting perpendicularly the northern side of the Matera palaeoisland show shallow-marine, fan-shaped bodies, composed of coarse- to fine-grained skeletal packstones and grainstones, abutting against the original steep bedrock (a "slope onlap" *sensu* Nemec, 1990; a "foreslope onlap" *sensu* Playton et al., 2010) (Fig. 22). These deposits are also included in the "Calcarenite di Gravina" Fm , and have been described in detail by Mateu-Vicens et al. (2008). Tropeano et al. (2004; 2021) have also described almost coeval and similar bodies in the Salento Peninsula. Two sections provide either panoramic or close-up views from areas adjacent to the parking zones.
The deposition of the fan-shaped bodies on the northern side of the palaeoisland was controlled by the Cretaceous-basement physiography. Sediments started accumulating against the western corner of the island, where the Cretaceous was in a relatively lower topographic position (Fig. 23). As a sea-level rose, the production area, and consequently the off-platform shedding, migrated successively to the east and new fans amalgamated to produce an apron-like body lapping onto the Cretaceous substrate and expanding basinward (Fig. 23). Common megafossils in the skeletal grainstone-packstone are rhodoliths, large brachiopods, bryozoa, balanids, solitary corals, scaphopods, echinoids, pectinids, and bivalves. Among benthonic foraminifera, epiphytic *taxa* predominate and rhizome/sediment dwellers are abundant. Some of them are associated typically with seagrass-fleshy algae meadows. Test preservation of benthonic foraminifera varies from broken to almost intact, and the proportion of broken to unbroken slightly increases up-section. Among planktonic foraminifera, the dominance of globigerinids, along with the absence of deep planktonic *taxa* such as globorotaliids, permits the inference of slightly open-marine conditions. The content of planktonic *taxa* (globigerinids), along with a few deep benthonic *taxa*, fluctuates along these sections. Among the other skeletal components, red algae fragments are frequent

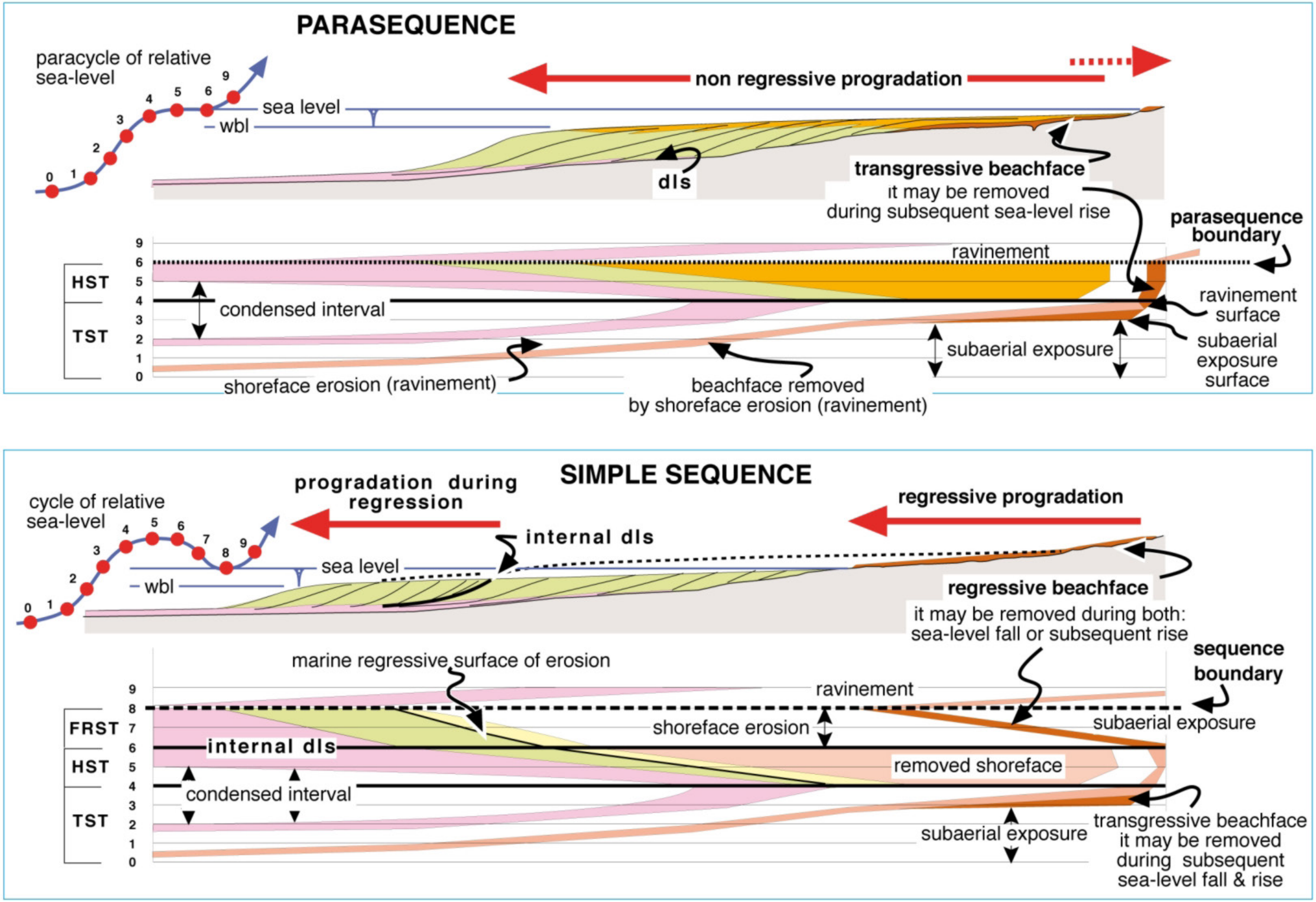


Fig. 21 – Time (Weeler) diagrams of a mature parasequence and a simple sequence (after Pomar and Tropeano, 2001).

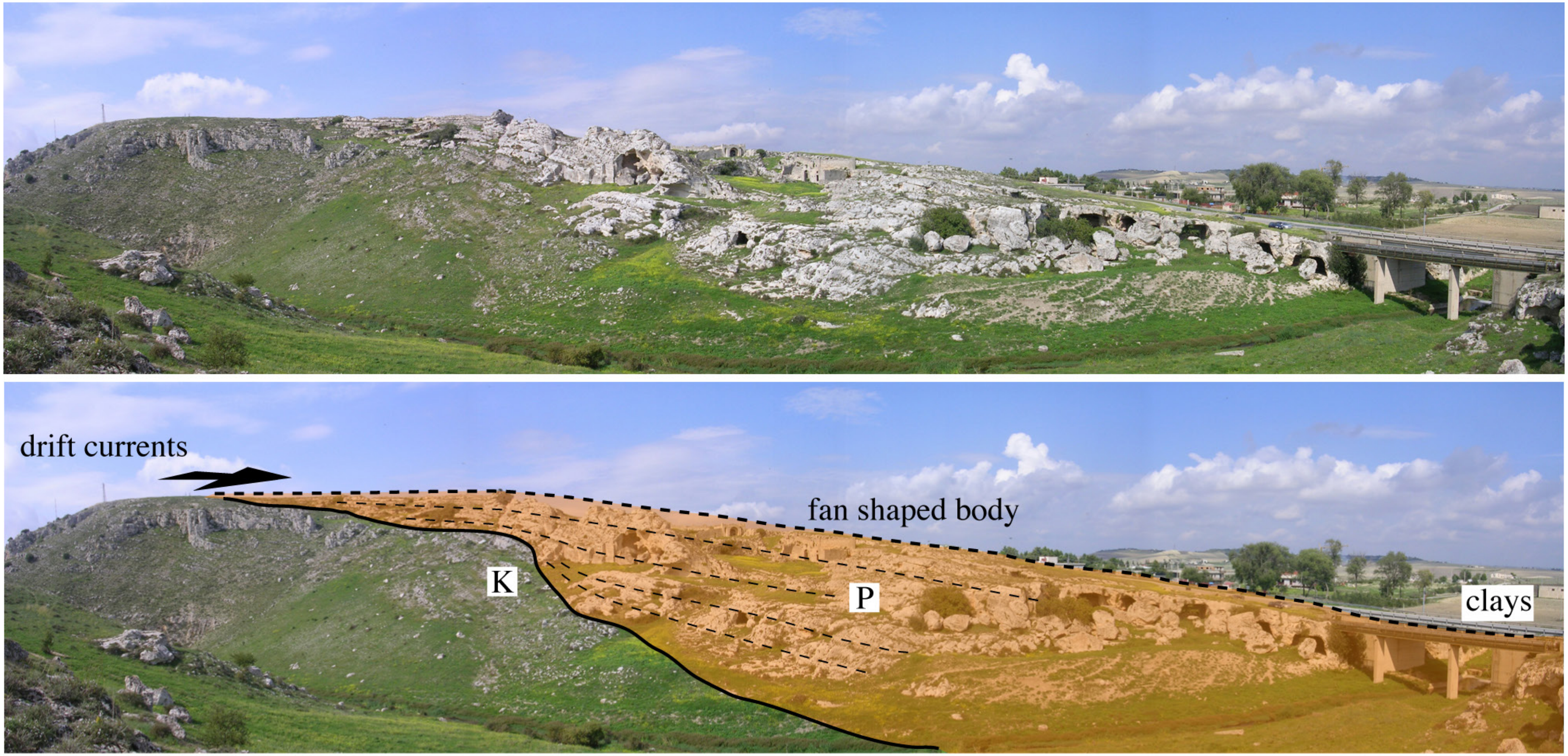
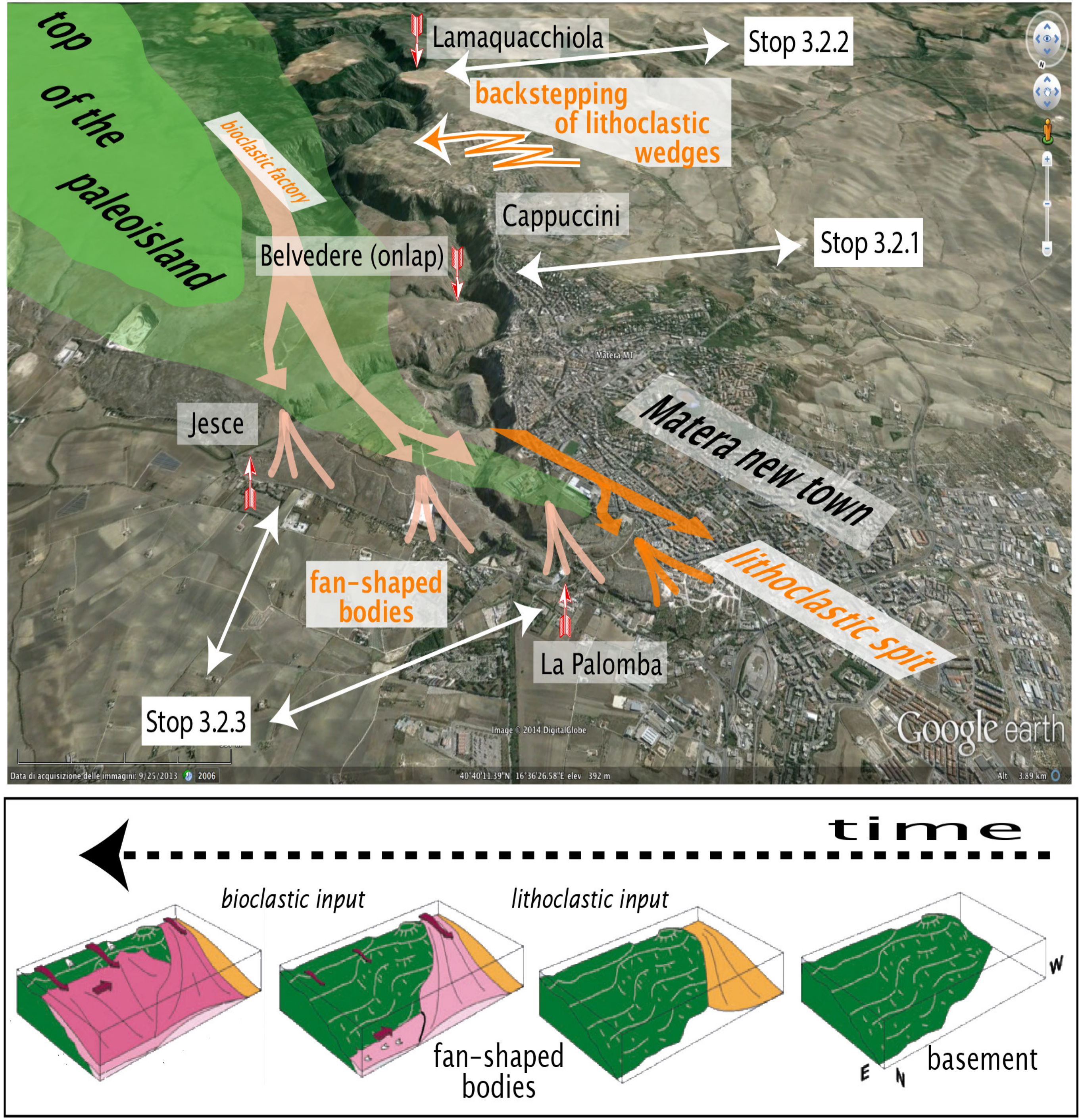


Fig. 22 –The Jesce section (Stop T3.2.3). K = Cretaceous (bedrock); P = Pleistocene (“Calcarenite di Gravina” Fm).

to abundant, in agreement with moderately deep conditions. Moreover, filter-feeder and suspension-feeder metazoans (barnacles, bryozoans, serpulids, and solitary corals) are rare or very rare, indicating low levels of suspended organic matter. Only echinoids, mostly detritus feeders, are abundant throughout measured sections.

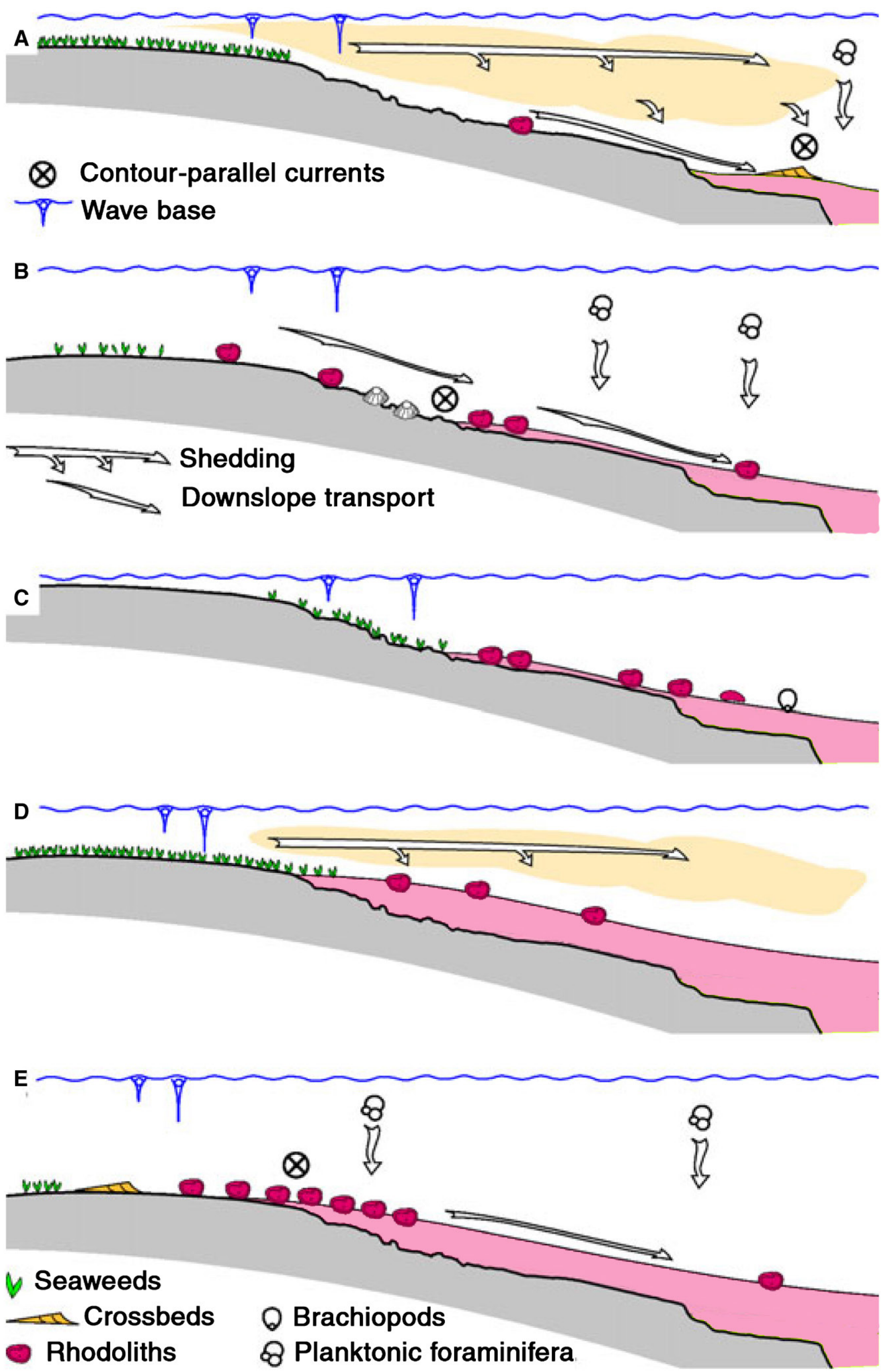
Differently from carbonates observed at the previous stops (Fig. 19a), the lithoclastic contribution from the



Cretaceous basement erosion is scarce in these deposits, indicating that an area of carbonate production existed to the south, *i.e.*, back to the apex of the fan-shaped bodies (Figs 23 and 24). This area was populated by meadows where epiphytic carbonate-producing biota thrived. Waves and storm-induced currents shed the skeletal sediments to the north. When currents reached the edge of the steep foreslope, their transport processes changed from tractive to gravitative, producing debris flows and sediment avalanche of *ex situ* bioclasts.

High-frequency sea-level cyclicity is also recorded in these fan-like deposits (Fig. 24): most of the

Fig. 23 – Summary scheme of the carbonate systems around the northwestern corner of the Matera palaeoisland, with the temporal succession of lithosomes, facing the Viglione Graben, based on their geometrical relationships observed in outcrop. In orange, the oldest fan is represented and consists of carbonate lithoclasts; in pink, the younger fans are represented and consist of both *ex situ* and *in situ* bioclasts.



volume of these calcarenites accumulated when sediment production on the extensive structural platform was dominated by seaweed epiphytic production (euphotic conditions) and these sediments were shed off the platform to form the apron. The plankton/benthos ratio (P/B) and changes in other skeletal components reflect some cyclicity. Increases in the P/B ratio thus indicate a decrease in the shedding of epiphytic *taxa* associated with the landward migration of the euphotic zone during pulses of sea-level rise. Moreover, the rhodolithic intervals with abundant planktonic foraminifera have to be related to pulses of deeper conditions. A bathymetry increase placed part of the structural high in the oligophotic zone, allowing the red algal pavements to develop. Under these conditions, rhodoliths were shed off the platform and accumulated downslope. The abundance of planktonic foraminifera in these intervals indicates a decrease in the epiphytic contribution associated with the landward migration of the seaweeds. Nevertheless, the rhodoliths documented in the uppermost part of the fans may represent *in situ* accumulation, as they occur associated with *in situ* branching red algae and small red algae bioherms. Some large-scale cross-lamination indicates the occurrence of western-directed bottom currents, flowing parallel to the contours of the palaeoisland (Fig. 23).
Recently, accretionary and prograding point-sourced (channel-related) carbonate-bodies have been defined as

Fig. 24 – High-frequency sea-level cyclicity influencing the component distribution within the fan-like deposits (after Mateu-Vicens et al., 2008).

"carbonate delta drift" (Lüdmann et al., 2018; Eberli et al., 2019; Reolid et al., 2019; Slootman et al., 2019). To a first approximation, the fan-shaped carbonate bodies of Matera can be considered examples of such carbonate deltas. However, this terminology contrasts with the primary meaning of the term 'delta', that, as reminded by the U.S. Geological Survey, is "the fan-shaped area at the mouth, or lower end, of a river, formed by eroded material that has been carried downstream and dropped in quantities that cannot be carried off by tides or currents"; as a consequence, the term delta should be avoided to describe carbonate shallow-marine fan-shaped bodies like those ones exposed on the northern flank of the Matera High (see discussion in Tropeano et al., 2021). Moreover, the classic term "carbonate apron" (*sensu* Mullins and Cook, 1986) can be properly applied to indicate the entire depositional coalescent fan-shaped bodies observed in this last stop of the field trip.

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