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FACIES AND ARCHITECTURE OF A SAND-RICH TURBIDITE SYSTEM IN AN EVOLVING COLLISIONAL-TRENCH BASIN: A CASE HISTORY FROM THE UPPER CRETACEOUS-PALAEOCENE GOTTERO SYSTEM (NW APENNINES)

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Abstract. This study documents the main depositional elements of a dynamically-controlled sand-rich deep-water turbidite system (Upper Cretaceous–Palaeocene Gottero system, north-west Italy). The large exposures and the wide range of facies and deep-water sub-environments recognised, ranging from proximal channels, unconfined proximal and distal lobes and confined basin plain deposits make this an instructive case study to investigate the spatial-temporal relationships between fan features (channels and lobes) and confined to ponded basin-plain deposits developed in a trench-fill basin. The study focus on stratigraphic and palaeo-environmental reconstruction of the Gottero system in the western sector of the basin. Bed types, facies associations and depositional sub-environments are described in main outcrop locations and used to feed a comprehensive bed-scale database. A coherent stratigraphic framework of the system is proposed for the first time, linking its stratigraphic evolution with the collisional-trench context of the Ligurian units during the Upper Cretaceous-Palaeocene. It includes a first stage in which the Gottero was a prograding extensive basin-floor fan developed in a relatively unconfined setting (Gottero 1 and 2), and a second stage in which the system deepens and got progressively confined and segmented in multiple distal depocentres, dominated by sheet-like high magnitude events, meanwhile the proximal area forms a series of fan elements which display an overall retrograding trend (Gottero 3). The basin fill terminates with the deposition of the Giaiette mass-transport complex interepreted to represent the final collapse of the growing Ligurian accrectionary wedge.

Introduction

Evolving basin morphology has a huge impact on the development of deep-water turbidite systems influencing the stratal patterns and the sub-environment distribution (Barnes & Normark 1985; Shanmugam & Moiola 1988; Mutti & Normark 1987; Remacha et al. 2005; Milli et al. 2007; Talling et al. 2015; Tinterri & Tagliaferri 2015; Felletti & Bersezio 2010a,b; Malgesini et al. 2015; Marini et al. 2015, 2016a,b). In addition, the tectonic setting is an important factor to determine the character of the flow types reaching the deep-water depositional systems influencing the grain-sizes available in the source area and the mechanisms of remobilizations, having an impact on the flow efficiency and the longitudinal/lateral distribution of depositional facies (Mutti 1992; Mutti et al. 1985; 1988; Tinterri & Tagliaferri 2015).

The Upper Cretaceous-Palaeocene Gottero Sandstone located in the Ligurian units in NW of Italy offers an opportunity to study one of these dynamically-controlled sand-rich deep-water turbidite systems, allowing reconstruction of the main architectural elements, from slope to

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basin-floor sector and relate their development to the syn-tectonic evolution of the system. The spectacular exposures and the wide range of deep-water sub-environments recognised, ranging from proximal channels, unconfined proximal and distal lobes and confined basin plain deposits make this an instructive case study to investigate the spatial-temporal relationships between fan features (channels and lobes) and confined to ponded basin-plain deposits developed in a trench system. In this sense, it is one of the few flysch sequences in the Apennine chain preserving both proximal and distal sectors and it is therefore a particularly interesting place to observe downslope facies variations spanning much of the system. The system has not been extensively studied in the past from a sedimentological standpoint (relevant studies have been published by Casnedi 1982; Nilsen & Abbate 1984; Marini 1991, 1992, 1993, 1994; Pandolfi 1997). However new attention has been recently given to the system due to the common presence of hybrid event beds (*sensu* Haughton et al. 2009; Talling, 2013), and therefore specific sedimentological studies at outcrop and system scale have been undertaken (Fonnesu et al. 2015, 2016, 2018).

The present paper has the purpose to give a larger and more general overview of the system by: 1) describing and interpreting in the stratigraphic and paleogeographic context the main outcrop locations and stratigraphic sections of the Gottero Sandstone in the western basin sector; 2) highlighting the main facies associations and depositional sub-environments present in the Gottero system; 3) setting-up for the first time a coherent stratigraphic framework of the system and 4) linking its stratigraphic evolution during closure of the Ligurian ocean basin during the Upper Cretaceous-Palaeocene. The data are presented in a full and as much as possible objective way, in order to guide the reader to the observation of the real outcrops that have been described in detail for the first time. The descriptions are also supported by a bed-scale database.

The present work wants also to highlight the value of the detailed facies analysis in the reconstruction of regional settings following the same approach of Mutti et al. (1985, 1988), Tinterri et al. (2011), Tinterri & Tagliaferri (2015), as integration of petrographical, structural and biostratigraphic analyses (e.g. Marroni et al. 2017).

Geological and stratigraphic setting

The Gottero system in NW of Italy is a siliciclastic deep-water system of Maastrichtian to early Palaeocene age (Passerini & Pirini 1964; Marroni & Perilli 1990). It developed on top of the Jurassic-Cretaceous Ligurian ophiolitic crust and the overlying Cretaceous sedimentary cover (Marroni & Pandolfi 2007; Marroni et al. 2010), and was subsequently deformed and thurst north-eastward as an allochthonous sheet during the Eocene and Oligocene (Marroni et al. 2004, 2017). Today the Gottero outcrops extend discontinuously for about 70 km along the Eastern Ligurian coast from Genova to Carrara and for about 45 km inland along the Ligurian and Emilian Apennines (Fig. 1). The Gottero system developed in a complex Late Cretaceous paleogeography setting on the floor of the Ligurian Ocean during the east-west convergence between the Europe and Adria plates (see Marroni & Pandolfi 2007; Marroni et al. 2010; Critelli, 2018). In this context, calcareous turbidites were fed from the Alps from the north and accumulated to form the Helminthoid flysch sequences (i.e. a thick and regionally widespread deep-water carbonate turbidite, deposited during the initial stage of Alpine collision), while a series of arenaceous turbidite successions were sourced from the Corsica-Sardinian block lying to the southwest (Abbate & Sagri 1982). Sediment from the two areas mixed each other in the external basin sector (external Ligurian units), while calcareous beds are rare in the internal sector (internal Ligurian units) where the Gottero system belongs. The Gottero sandstones are quartzofeldspathic sandstones containing fragments of metamorphic, volcanic and sedimentary rocks derived from the European-Corsica massif (Sagri & Marri 1980; Marroni & Pandolfi 2007) where large igneous crystalline masses were exposed.

Stratigraphic and geodynamic evolution of the ligurian margin

The internal Ligurian units succession cropping out in the Gottero area starts with Jurassic ophiolites composed of mantle lherzolites and gabbros, covered by a volcano-sedimentary complex including breccias, pillow basalts and cherts (Decandia & Elter 1969; Abbate et al. 1980; Marroni & Miccheri 1993). The sequence is interpreted to be a product of rifting and passive extension of the

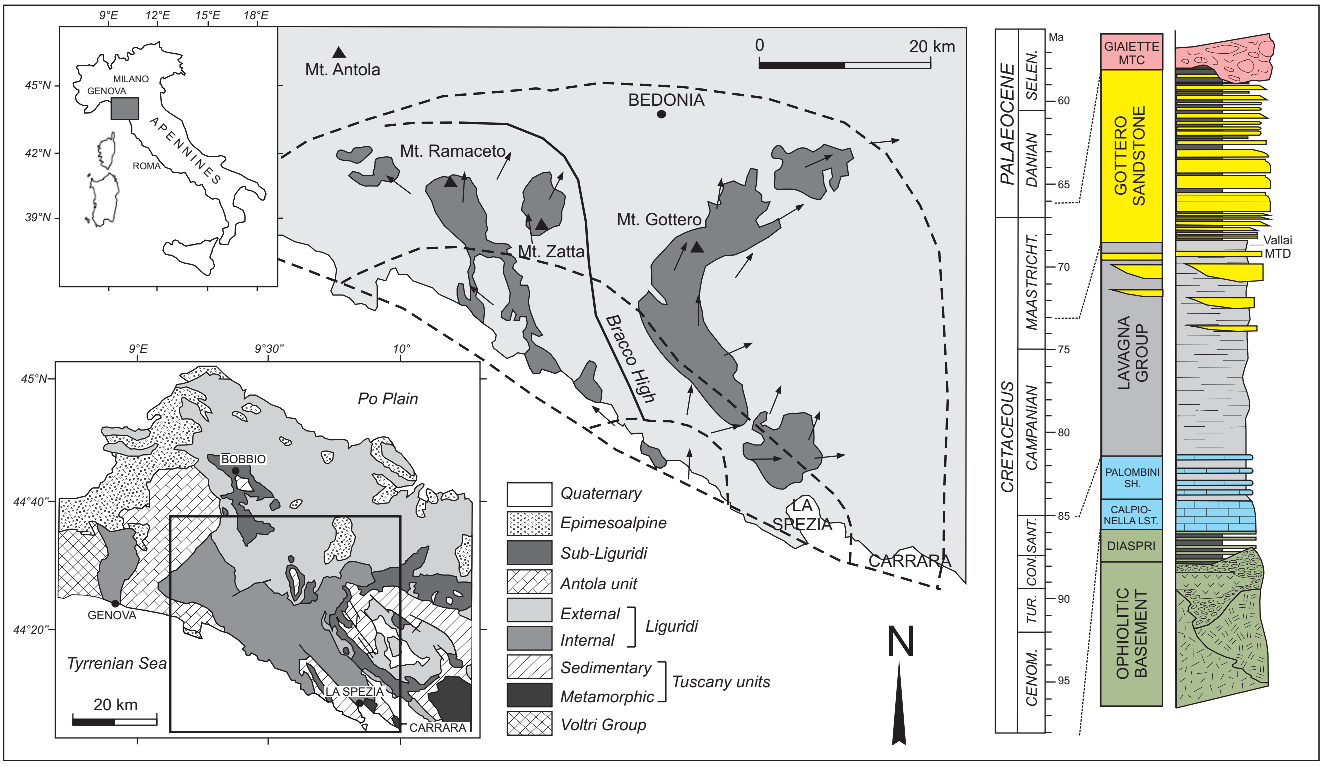


Fig. 1 - Location map of the Gottero system (modified from Nilsen & Abbate 1984) and sketch map showing the tectonic units of the Northern Apennines (modified from Marroni & Pandolfi 2007). The arrows in the location map indicate the main palaeocurrent pattern deduced by Nilsen & Abbate (1984).

lithosphere (Marroni & Pandolfi 2007) leading to the development of a slow-spreading ridge (Barrett & Spooner 1977; Treves & Harper 1994; Principi et al. 2004). The two conjugate margins were likely strongly asymmetric with the Corsican margin controlled by high-angle normal faults whereas the Adria margin had a wider ocean-continent transition (Marroni et al. 2002; Marroni & Pandolfi 2007). The original oceanic lithosphere was capped by pelagic deposits represented by the Radiolarite Formation (Diaspri cherts of Callovian-Tithonian age), Calpionella Limestone (Berrasian-Valanginian) and Palombini Shales (Valanginian-Santonian). Starting from the Campanian, clastic input from the European-Corsica margin began to increase leading to the formation of the thick, mostly siliciclastic turbidite sequences (Marroni et al. 2002; Marroni & Pandolfi 2007) of the Lavagna Group. Those are mostly fine-grained and laminated basin-plain turbidites in which carbonate megaturbidites are occasionally interbedded (Monte Verzi Marls Formation). In the upper part of the Lavagna Group they are interbedded with four thicker sandstone bodies interpreted as channel/lobe deposits (Casnedi 1982; Marini 1991, 1994). Hereafter these deposits interbedded with fine-grained slates of the Lavagna Group will be called "Lower Gottero" (following Marini 1991, 1994). The uppermost part of the *internal Ligurian units* succession is occupied by the Gottero system interpreted as a deep-water turbidite system, fed from the European-Corsica margin and developed in a trench-slope basin (Nilsen & Abbate 1984). The Gottero Sandstone is unconformably overlain by Early Paleocene Giaiette shales (alternatively named Giariette shales or Bocco shales): a chaotic unit containing abundant exotic material, ophiolite-bearing material and large slabs of Gottero Sandstone interpreted as lower-slope trench deposits related to the frontal tectonic erosion of the Alpine accretionary prism (Marroni & Pandolfi 2001). The entire succession has a pre-Oligocene (di Biase et al. 1997) polyphase deformation history including underthrusting, underplating and exhumation in the Alpine accretionary prism (Marroni et al. 2004; Meneghini et al. 2007).

A geodynamic reconstruction of the Ligurian margin has been proposed by Marroni et al. (2010, 2017). According to these authors, the previously described sequence is interpreted to reflect the trenchward motion of an area of the Ligure-

Piemontese sea floor towards the Adria plate and the growth of an Alpine accretionary prism. During pre-Santonian time the Ligure-Piemontese Sea was dominated by pelagic sedimentation that draped the inherited topography created by Jurassic rifting (Marroni et al. 1998; Marroni & Pandolfi 2007). From the Santonian-Campanian, subduction of the Ligure-Piemontese crust started to take place. The orientation of the Benioff zone is still matter of debate: older models from Sholle 1971; Abbate et al 1980; Sagri & Marri (1980); Abbate & Sagri (1982); Treves (1984) and Principi & Treves (1984) suggested a western-dipping subduction below Europe. More recently, Marroni & Pandolfi (1996) and Marroni et al. (2004, 2010), proposed an east-dipping intra-oceanic subduction zone, producing an Alpine accretionary prism subdividing the *Internal* (towards the west) from the *external* (towards the east) *Ligurian units*. The former basin was progressively shortened and consumed during the convergence and subduction; the latter was less deformed and remained as a supra-subduction complex located between the accretionary prism to the west and the Adria margin to the east (Marroni et al. 2010). Probably the prism at first developed in the northern sectors and progressively towards the south, with the Gottero unit as the last portion of the Ligure-Piemontese basin involved in the underthrusting (Marroni et al. 2004, 2010).

For the present work only the western, and best exposed part of the Gottero system is threated in detail, leaving considerations about the relationships between the two basin sectors in the discussion part.

Methodology and Facies analysis

The work includes the collection of about 5200 m of sedimentary logs, 4307 m of which were measured bed-by-bed at 1:50 scale and a resolution of 1 cm, the remaining *ca* 800 m of logs was drawn by using photomosaics of inaccessible cliff sections. Bed thickness measurement was performed mainly with a Jacob's staff (e.g. a 1.5 metre high rod provided with a clinometer and a flat disc on top). The analysis is conducted at bed scale but also incorporates textural and structural characteristics of the component facies and information on their arrangement within the event beds (*sensu* Kneller & McCaffrey 2003). Seven bed type groups have been distinguished (Fonnesu et al. 2018). These includes (Fig. 2): mass transport deposits (MTDs), debrites (DEBs), gravelly high-density turbidites (GHDTs), high-density turbidites (HDTs), low-density turbidites (LDTs), mudstone-clast-rich beds (MRBs), hybrid event beds (HEBs) and limestone beds (Ls). Bed types are named according to the dominant association of sub-facies due to flow transformation recorded at the observation point (Kneller & McCaffrey 2003). For example, a bed including a basal mudstone-clast conglomerate overlain by a structureless coarse sandstone and a laminated fine sandstone is classified as GHDT despite the other bed divisions are deposited by more dilute evolved parts of the flow characterising the same event. Association of bed type groups defines six different facies associations: Inner fan channels (FA-A1) and sandy channel-lobe transition (FA-A2); mid fan lobes (FA-B); outer fan lobes (FA-C); weakly amalgamated sheets (FA-D); isolated sheets (FA-E1) - mud-prone sheets (FA-E2); thin bedded intervals - basin plain (FA-F1) - slope deposits (FA-F2) - supra-MTD deposits (FA-F3) (Plate 1).

The data are afterwards included in an Excel spreadsheet (Gottero_spreadsheet.xlsx) including a series of quantitative and qualitative data for each of the logged beds. The database includes: locality, log, unit, sub-unit, bed ID, bed thickness, mud cap thickness (if present), bed type, facies associations, type and direction of paleocurrent indicators.

The correlation between measured logs can be often traced physically by walking-out beds or with the use of aerial/satellite photographs inside the same location. In absence of lateral outcrop continuity and biostratigraphic control, the regional correlations are achieved by comparison of common stratigraphic patterns and compatible facies association tied with general paleoflow direction.

Stratigraphic sections

The Gottero Sandstone has been explored in the area located on the western side of the Bracco massif (see map of Fig. 3). The Gottero outcrops occur in two belts separated by the Levanto - Ottone tectonic lineament (Elter & Pertusati 1973) that marks the boundary between the Gottero unit in the west (mostly represented by deep-water turbidites) and the Bracco unit (composed of the ophiolite and volcanic complex basement and in which the deep-water succession is thinned or completely absent).

In this area the Gottero succession has undergone significant deformation during the Apennine Orogeny. The hinge of an important regional syncline (the inclined to recumbent *Cichero syncline* with the Giaiette unit in its core and the Gottero Sandstone on its limbs) trends SE-NW and extends from Moneglia to Mt. Ramaceto. An anticline (or a series of meso-scale folds) crops out in the Sturla Valley (see Mezzanego Fig. 3) exposing the older Lavagna Group formations (Marroni 1991). The same large scale anticline can probably be traced to Moneglia separating the two Gottero outcrops of Punta Baffe - Madonnina from Deiva Marina beach. Towards the east, an open syncline with the Giaiette unit at its core exposes the Gottero Sandstone on either side of Mt. Zatta.

A detailed facies analysis was conducted in order to subdivide the more extensive sedimentary succession of the upper Gottero system into sub-

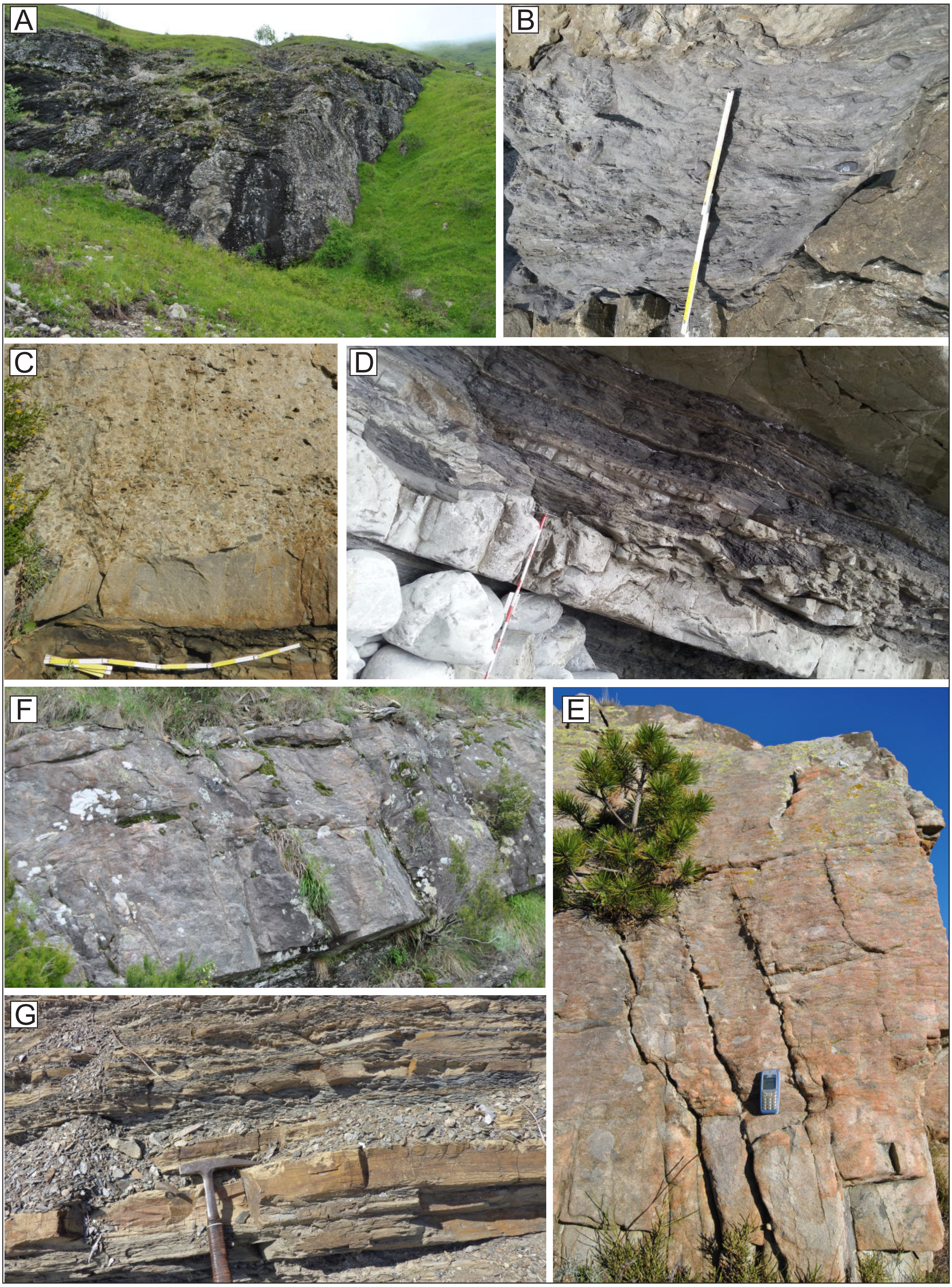


Fig. 2 - Main bed types distinguished in the Gottero system. A) Mud-rich Vallai MTD from the Mt. Ramaceto section. B) Debrite (DEB) from Riva Trigoso section. C) Clast-supported conglomerate lag (GHDT) at the base of Monterosso channel fill. D) Hybrid event bed (HEB) from Riva Trigoso section. E) Mudstone clasts rich bed (MRB) exposed in the A section of Mt. Ramaceto. F) Highly dewatered and dish-structured coarse sandstone in Mt. Zatta section (HDT). G) Thin-bedded rippled and laminated sandstones interbedded with mudstones in basal Monterosso section (LDT).

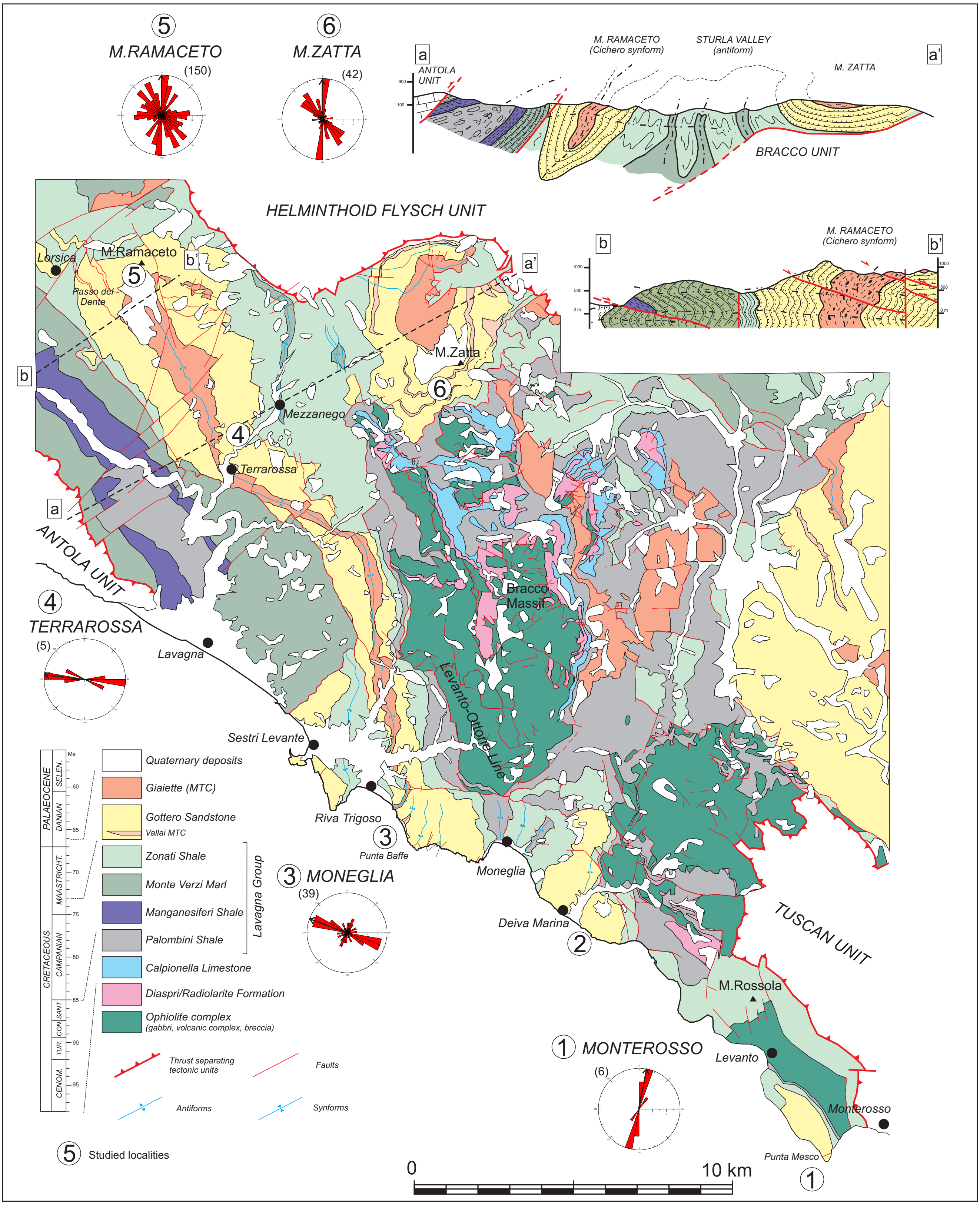


Fig. 3 - Geological map and cross-section of western Gottero and surrounding units (modified from Foglio 232 Sestri Levante, Foglio 215 Bedonia, Foglio 214 Bargaglia, cartografia italiana 1:50.000; sections modified from Marroni 1991; Marroni et al. 2004). The map shows the location of measured sections and the palaeocurrent roses obtained during this study; the numbers in brackets indicate the number of palaeoflow measurements at each station.

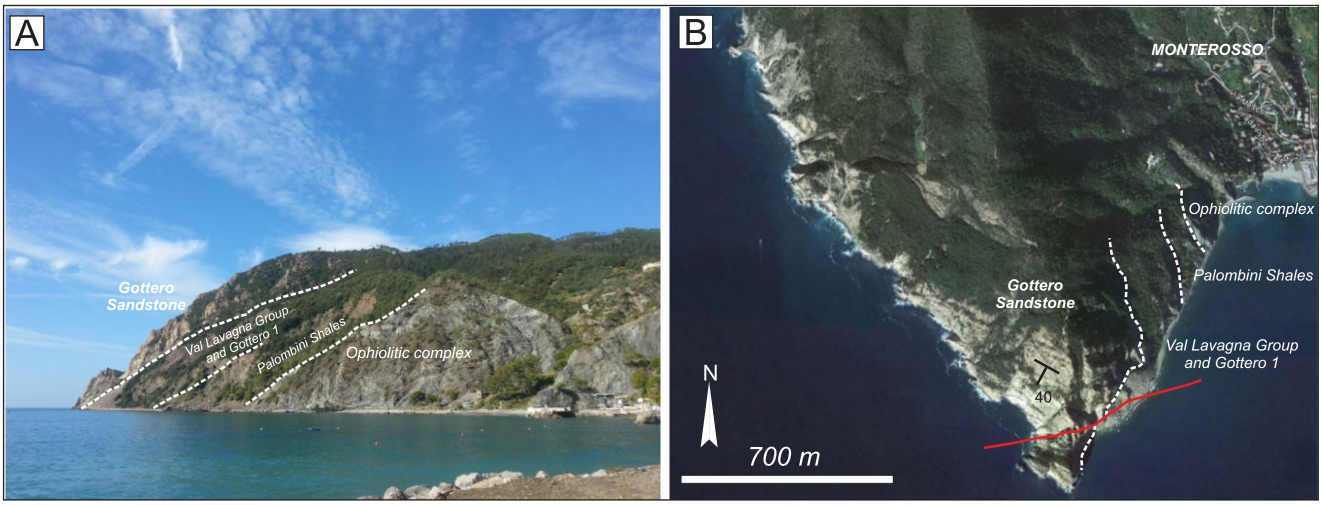


Fig. 4 - Monterosso exposures. A) Panoramic view from Monterosso town towards Punta Mesco. B) Satellite map (Google Earth) upon which are labelled the main geological boundaries and structural features. In red is indicated the trace of a normal fault observable from the cliff exposure.

units. Based on their spatial grouping and depositional architecture, the sedimentary facies have been recognized to form three main assemblages (lithostratigraphic units) of genetically related facies. These facies associations are described and interpreted in the present section. The unit boundaries are based on important changes in the sedimentological character of the deposits and a consistent vertical trend along the outcrop belt (Plate 1). The units are designated:

Gottero 1: a unit including mostly thin-bedded sandstones and mudstones.

Gottero 2: unit marked by a rapid basinal shift of the system indicated by the abrupt superposition of amalgamated thick-bedded sandstone packages separated by muddier units on the thin-bedded Gottero 1 unit.

Gottero 3: a thick and complex unit marked by a progressive backstepping pattern, and displaying a different facies character from proximal to distal sections.

The upper Gottero succession which represent the main focus of this work, is bounded by two chaotic units named the Vallai MTD and Giaiette MTC respectively. Data were collected from six locations (Fig. 3; Monterosso, Deiva Marina, Moneglia, Terrarossa, Mt. Ramaceto, Mt. Zatta), five of which are aligned along a SE-NW transect roughly parallel to the general palaeoflow direction (Plate 1 - see supplementary files).

Monterosso

The Gottero Sandstone crops out at the Punta Mesco cliff (Figs 3, 4 and 5) between Monterosso and Levanto villages (Latitude: 44°8'12.08"N; Longitude: 9°38'15.93"E). The Gottero succession is exposed on top of a succession made of gabbros and serpentinites of the Bracco ophiolitic complex (Fig. 3) and highly deformed Palombini shales. The top of the succession is not exposed; the section is oriented roughly parallel to the main palaeoflow direction which is aligned towards the NNE.

Log description and facies interpretation. The stratigraphically lower part of the studied succession (**Gottero 1** stratigraphic unit) is made of a thick sequence (about 250 m) of predominantly thin-bedded and parallel-to-ripple laminated sandstones (each 5 to 10 cm thick) interbedded with mudstones (Fig. 6 A-B) and rare limestone beds. Metre-thick slumped intervals are locally interstratified displaying folding with prevalent vergence towards the East (Fig. 6 B). A basal larger chaotic unit (about 30 m thick including a 1.7 m of mudstone cap) is developed at the base of the thin-bedded succession and this inludes pieces of deformed turbidite sandstone but lacks in exotic material.

The overlying succession (**Gottero 2**) has an erosive contact with the underneath strata. The first sandbody has a remarkable lenticular and basally concave shape being thicker towards the NW (23 m thick) and thinning and 'fraying' towards the SE (about 8 m thick), resembling a channel-fill (Fig. 5 A-C). Beds are internally poorly continuous and amalgamation and erosive surfaces are common. The axis is marked at the base by a distinct clast-supported conglomeratic lag and then filled by pebbly-sandstones and mudstone clast conglomerates interbedded with massive to cross-laminated coarse-grained sandstone beds. Mudstone clast conglomerates have a lenticular shape with a lateral continuity not exceeding a few tens of metres and are composed of mudstone clasts up to 50 cm in diameter surrounded by coarse and very coarse sandstone with scattered granules and pebbles. Such deposits are internally poorly graded and clasts are not layered or imbricated. They can be interpreted as having been deposited by hyperconcentrated, mostly-frictional flows (Facies F2 of Mutti 1992; Mulder & Alexander 2001) able to deeply erode the substrate upslope and rip-up mudstone blocks, rapidly decelerating and freezing.

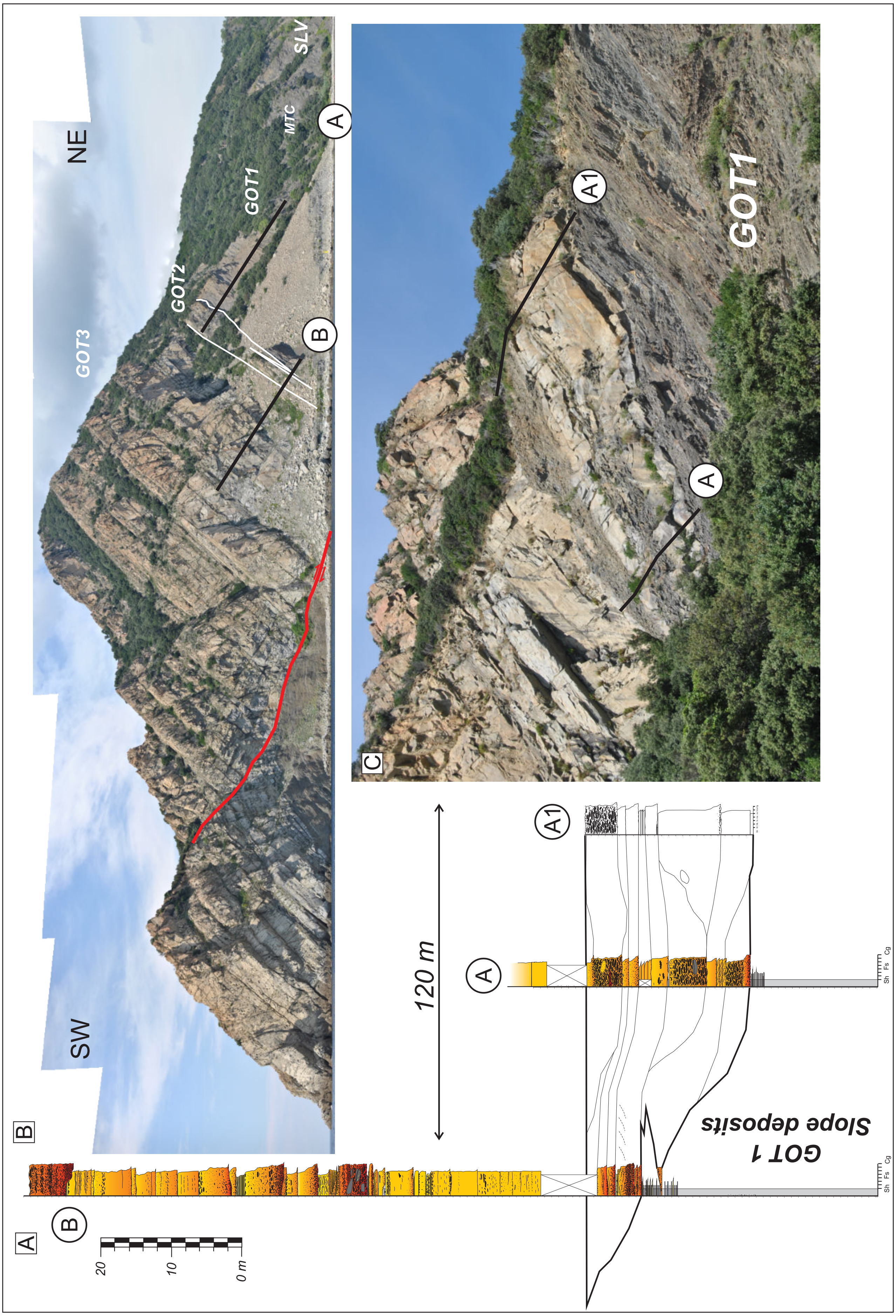
Laterally the sandbody thins into a channel margin/wing in which the axial facies are replaced by coarse-grained beds with flat bases and undulated tops on which are developed 3-dimensional dunes (Fig. 6 C). Stoss-side laminae are marked by alignments of granules and pebbles. Bed bases can have conglomeratic traction carpets. These deposits are interpreted as bypass features (see Facies F6 and F7 facies of Mutti 1992) created by high-concentration flows which overspilt the thalweg margins and dropped their coarser sediment load adjacent to the channel to form channel wings. The wider stratigraphic context of this section is uncertain but it is inferred to represent the proximal expression of the **Gottero 2** unit on the basis that it directly overlies a Gottero 1 style succession.

A second sandbody (Fig. 5) displays a progressive thickening-upward trend of the first sandy beds above the thin-bedded interval; it is composed of stacked massive to graded sandstones (Fig. 6 D) and conglomerates organised in at least nine thickening upward cycles (15 to 70 m thick). Individual beds are mostly continuous when traced laterally despite common amalgamations, uneven and erosive bases (local erosional relief up to 1.5 m) and important bed thickness changes. Sandstones are unstructured or occasionally display metres to decimetre-scale cross-laminations, traction carpets and convolute lamination at the top. Sandstones are fine to very coarse-grained commonly containing granules, pebbles and mudstone clasts (often armoured), up to metre-size, and concentrated at the bed base. Mudstones interbeds are rare (<1%), thin and laterally discontinuous due to overlying bed erosion. Individual sandstone event beds are 1.6 m thick on average, however some thicker graded beds up to 7 metres thick occur and these show well-developed grain-size grading (see Fig. 7A). The example shown in Fig. 7 is interpreted as a single event despite being composed of a series of distinct facies as it shows a very clear vertical fining upward trend. It is characterised at the base by a mudstone breccia including mudstone blocks, sometimes containing thin-beds, surrounded by granules to pebble-size sandy conglomerate. The facies shape is lenticular, pinching out laterally in few tens of metres to reappear again laterally. It is overlying by coarse-grained sandstone with collisional traction carpets (*sensu* Postma et al. 2014) of pebbles and granules (F4 facies of Mutti 1992 and S2 of Lowe 1982) followed by large scale cross-bedding (about 2 m high) oriented in counter-flow direction and highlighted by trains of granules and pebbles on top of the oblique laminae. The bed is completed by a fine-sand interval rich in convolute laminae and water-escape features before being erosionally cut down by the overlying bed.

The described composite facies sequence is interpreted as produced by events evolving from supercritical flow conditions (Cartigny et al. 2014; Postma et al. 2014), undergoing a hydraulic jump and finally depositing their subcritical tail.

Significance and paleo-environment. The Monterosso succession records the initiation of the Gottero turbidite system in its more proximal preserved section. The basal facies association is related to deposition by low-concentration and presumably low-volume turbidity currents. The interval is interpreted as a **fine-grained slope** (FA-F1) presumably dipping towards the east as reflected by the synsed-

Fig. 5 - Monterosso correlation panel and panorama. A) Measured sedimentological log and correlation panel within the Monterosso sandbodies. The thickness of Gottero 1 slope deposits is only partially represented. Coloured logs were measured directly in the field; white logs can only be estimated from photographs. B) Panorama of Monterosso exposure in Punta Mesco, location of the measured logs, basal channel boundaries, and trace of a normal fault segmenting the outcrop. C) Close-up of the Monterosso basal channel axis and erosive base cutting into the underlying Gottero 1 deposits.


A
B
C
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NE
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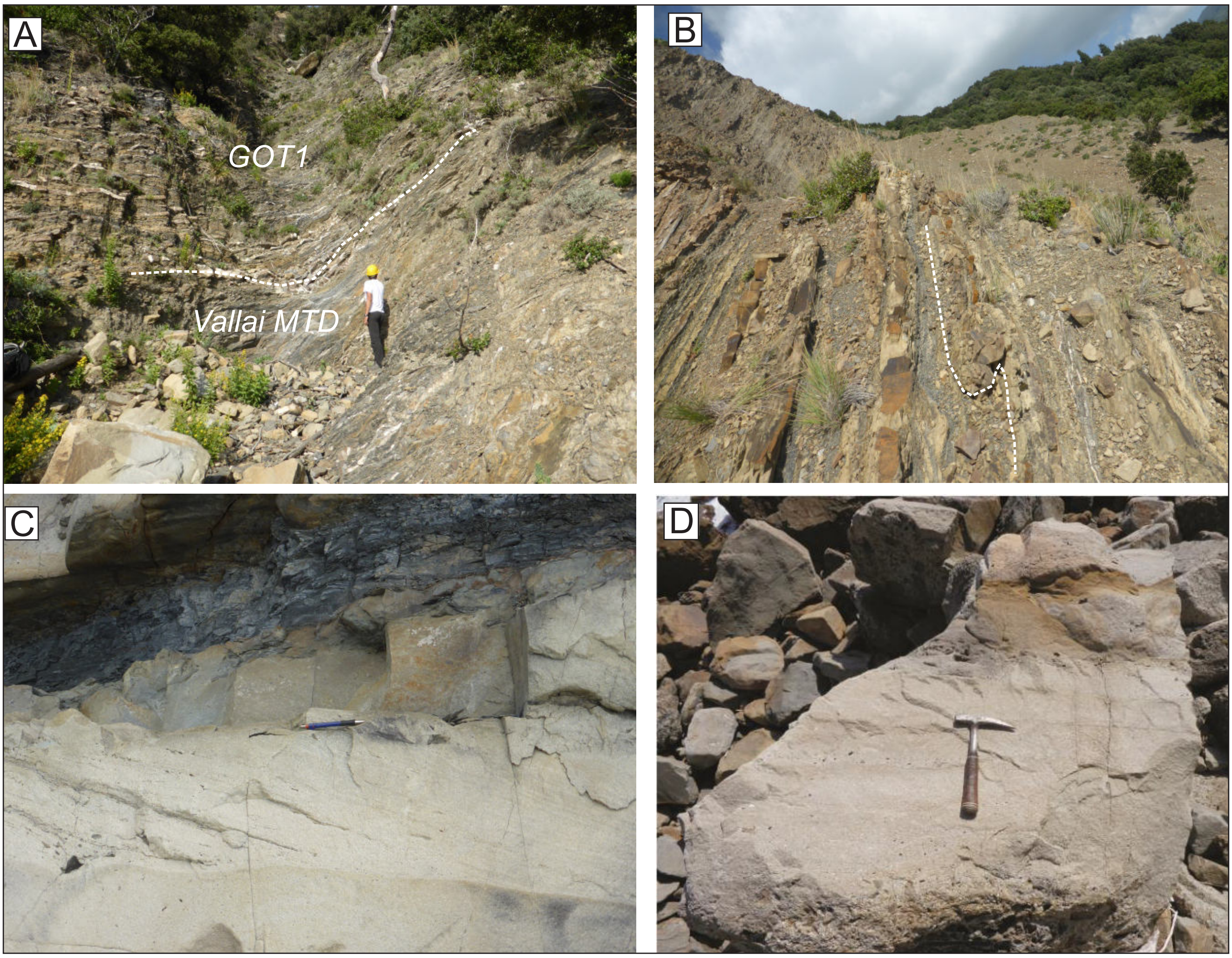


Fig. 6 - Gottero 1 and Vallai MTC deposits at Monterosso. A) Exposure of basal chaotic deposit interpreted as the Vallai MTD. B) Thin-bedded succession disturbed by synsedimentary slumps. C) Bed with megaripple cross-bedded top with bedform migration down slope to the east (facies F6 of Mutti 1992); pencil for scale. D) Well developed granules to fine sandstone graded bed in the fallen debris at the base of the exposure (hammer for scale).

imentary fold vergence in the slumps. The contrasting orientation of the slump folds with the overall palaeocurrent indicators (oriented mainly towards the north) suggests that it may represent a lateral slope confining the proximal part of the fan.

The lower Gottero 2 sandbody is interpreted as a coarse-grained **base-of-slope channel** (FA-A1) erosively cutting through the underlying slope deposits. No levee deposits are observed; instead the channel tends to thin laterally producing distinctive asymmetric edges in flow-transverse cross sections, generally with step-like, coarse-grained and wing-like edges.

The channel feature was created and backfilled by a series of very coarse-grained and pebbly-carrying flows as testified by the channel lag and the mudstone clast conglomerates preserved in the axis. The deposition of the cross-bedded and tractive-dominated pebbly sandstones in the channel wings could be contemporaneous to the onset of the pebbly mudstones in the axis and therefore may be interpreted as self-formed coarse-grained levees produced by inertia-driven highly-concentrated flows, in a fashion similar to what happens in sub-areal debris flows (e.g. Iverson 1997; Kane et al. 2009). Alternatively, the two facies have to be considered genetically unrelated and produced by set of flows with different rheology (inertia-driven vs. tractive flows; Mutti 1992).

The uppermost and thicker part of the succession is here interpreted as a very sandy **channel-lobe-transition** (FA-A2) *sensu* Cazzola et al. 1981; Mutti et al. 1985; Mutti & Normark 1987; 1991; Wynn et al. 2002. The interpretation can be

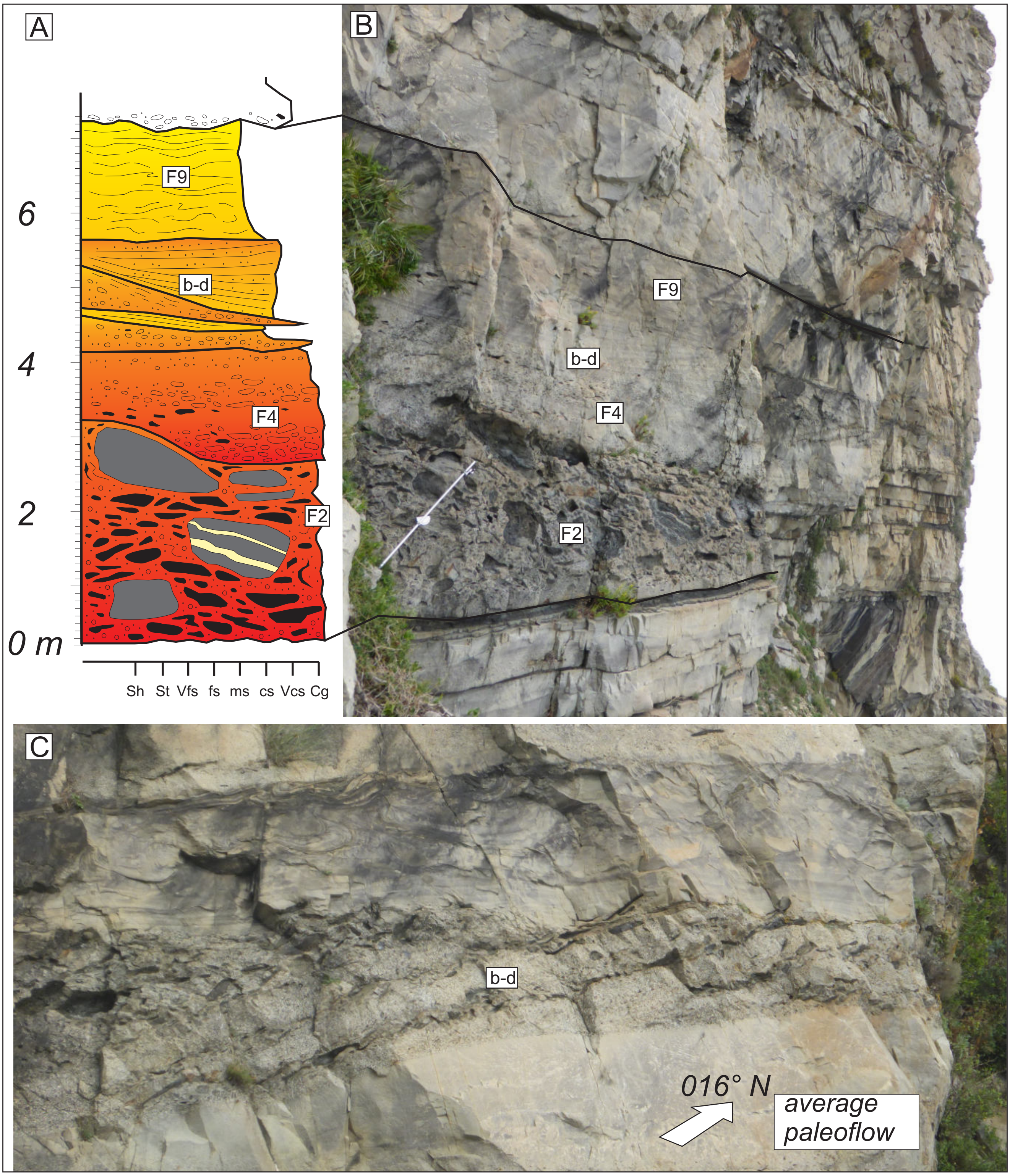


Fig. 7 - Composite graded event bed in upper Monterosso sandbody. A) Bed log and B) overview of the exposure; the bed include: F2 – lenticular mudstone-clast breccia; F4 – very coarse-grained sandstone and granules with traction carpets; b-d – back-current oriented dunes; F9 – fine grained, laminated and convoluted bed top. 2 m long laser Jacob's staff for scale. C) Close-up of back-set foresets highlighted by trains of mudstone clasts and granules. The arrow indicates the direction of the average paleoflow direction measured from sole marks with respect to the outcrop.

justified by: 1) the higher lateral continuity of the beds making up the upper sandbody in comparison to the lenticular shape of the clearly channelized lower one; 2) the presence of facies (backsets due

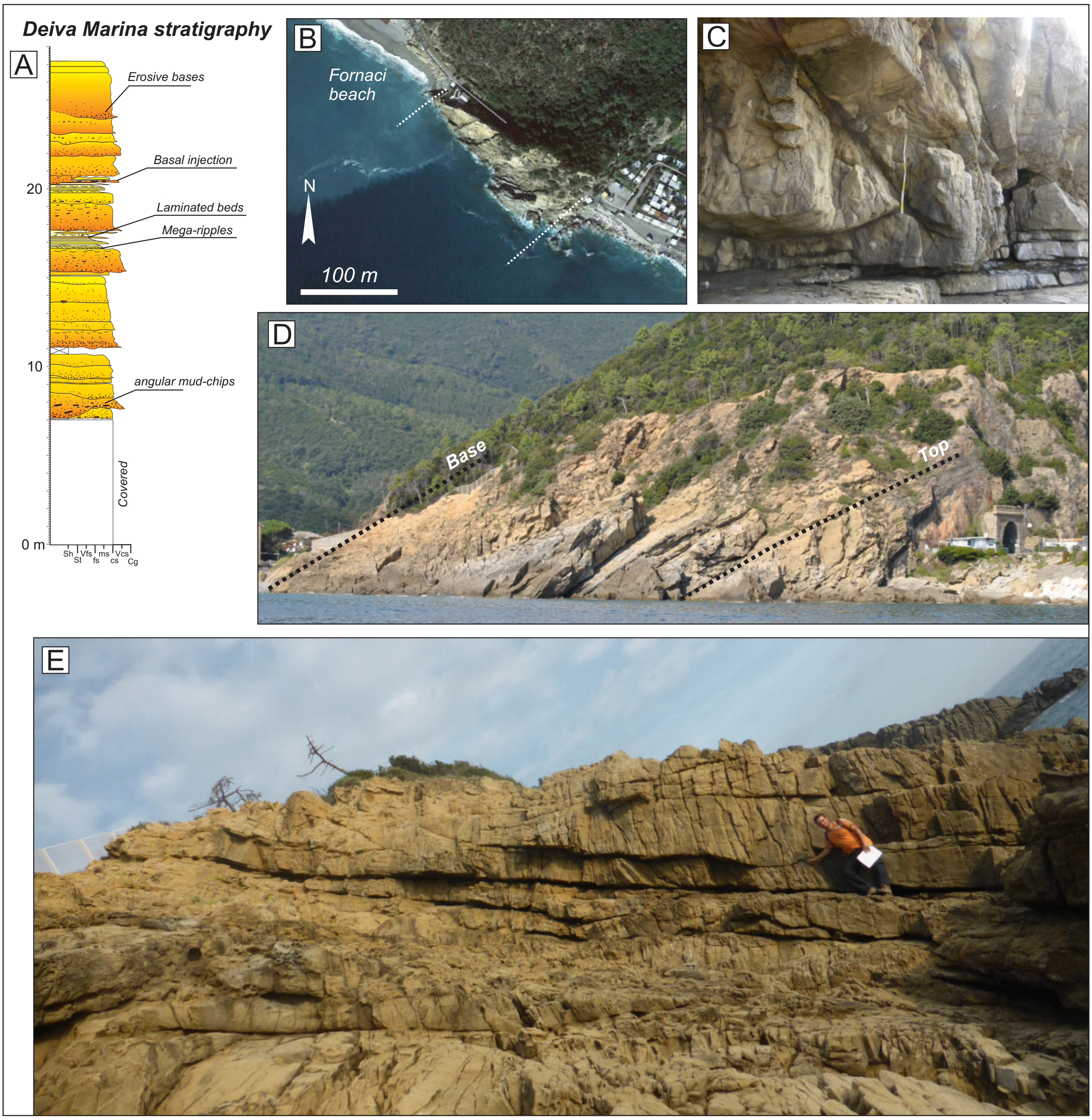
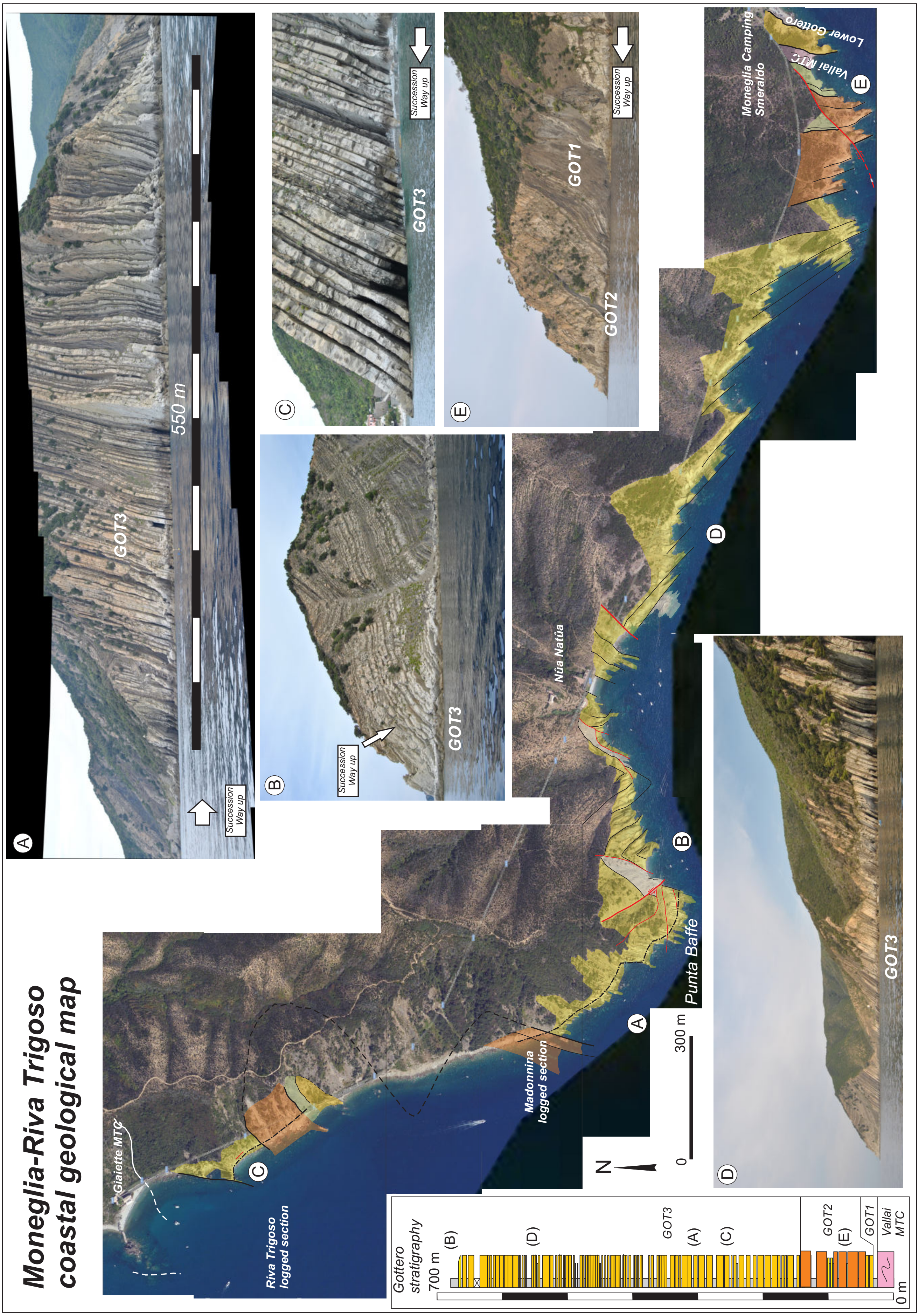


Fig. 8 - Deiva Marina outcrops and log. A) Stratigraphic log and main facies features. B) Geographic position of Deiva Marina exposure from Google maps. C) Convex-downward scour at the base of an amalgamated sandstone package. D) Deiva Marina exposure seen from the sea. E) Rotated field photograph showing cut-and-fill feature at the base of an amalgamated sandstone bed.

to supercritical bedforms) displaying the role of hydraulic jumps and 3) the association with facies displaying traction carpets and megaripples characteristic of bypass and unstable flow conditions (Mutti 1992; Mutti et al. 2003; Pandolfi 1996).

Although bypass is recognised as an important feature, many turbidites still display a strong normal grain-size grading and important thicknesses of single events (Fig. 7). This suggests the flows reaching the Gottero system were probably sus-

Fig. 9 - Moneglia-Riva Trigoso coastal geological orthophoto map (from Google maps) and simplified stratigraphic log of the Gottero succession. Colours distinguish the stratigraphic units highlighted in the log. Letters refer to position of the various photographs on the map. A) Coastal cliff exposure of Gottero 3 succession in Punta Baffe. B) Upper and inverted Gottero 3 succession near Nûa Natûa Resturant (Latitude: 44°14'26.41"N; Longitude: 9°27'10.17"E). C) Upper part of the Gottero 3 succession in the Riva Trigoso section. D) Extensive cliff exposure of Gottero 3 near Salto nel Blu location. E) Lower Gottero – Gottero 1 – Gottero 2 transition near Moneglia camp site (Latitude: 44°14'21.40"N; Longitude: 9°28'41.80"E).



Moneglia-Riva Trigoso
coastal geological map
Giaiette MTC
Riva Trigoso
logged section
Madonnina
logged section
Punta Baffe
Nüa Natüa
Moneglia Camping
Smeraldo
Vallai MTC
Lower Gottero
300 m
0
N
A
B
C
D
E
GOT3
550 m
Succession
Way up
GOT1
GOT2
Gottero
stratigraphy
700 m
0 m
(B)
(D)
(A)
(C)
(E)
Vallai
MTC

tained and able to evolve gradually allowing different sedimentary structures to form and even locally preserving supercritical bedforms. Furthermore, evidence for longitudinal fractionation implies that there was a sufficient distance from the flow source to allow the fractionation to occur. Importantly fine-grained material (silt and mud) is almost absent in the Gottero 3 unit at this location meaning it was either completely bypassed though this part of the system or was not preserved due to continual substrate erosion.

Deiva Marina

The Gottero Sandstone crops out in two hills surrounding Deiva Marina village but the best exposures are located along the Ligurian coast where we focussed on the section just to the east of the village at Fornaci beach (Fig. 8 B; Latitude: 44°12'42.52"N; Longitude: 9°31'16.65"E). The beds here are upright and dip about 36° towards SE as they are on the eastern limb of a north-trending anticline (Fig. 8). No stratigraphic relationships can be observed with the overlying and underlying formations at this locality but the Lavagna Group is mapped along both limbs of the anticline (see map of Fig. 3).

Log description and facies interpretation. The measured section is 27 m thick and composed of a series of highly amalgamated fine to very coarse grained sandstones with rare granules and pebbles, with coarse and very coarse grain-sizes dominant (Fig. 8). Beds are mostly unstructured and poorly graded, or coarse-tail graded (facies F5 of Mutti 1992): exceptions are the few fine-grained sandstone intervals displaying plane-parallel or convoluted lamination. These are separated by an abrupt surface associated with a grain-size break from the underlying massive sandstones or by a facies displaying poorly-defined, medium sandstone with megaripples (facies F6 of Mutti 1992). Dish and sheet dewatering features are present in most of structureless beds. Mudstone clasts are present but not as common as in other localities and are generally small (few centimetres), angular and concentrated along erosive bed bases. Cut-and-fill erosive features are frequent at the base of sandy packages (Fig. 8) but with erosional relief not exceeding a few centimetres. The bases of coarser beds are also locally affected by bed-parallel injections when they overlie finer-grained intervals.

The event beds are deposited by highly concentrated turbidity currents (Lowe 1982; Mutti 1992; Mulder & Alexander 2001; Tinterri et al. 2003; Baas et al. 2004). Apparently structureless or poorly graded coarse-grained sandstones can be produced by flow with rapid suspension fallout (Mutti 1992; Baas et al 2004) or by steady or quasi-steady sustained flows (Kneller & Branney 1995). The lack of preservation of crude laminations and traction carpets as well as the abundance of dewatering features and basal injections indicating water expulsion presumably due to rapid sediment settling argues in favour of the first hypothesis (rapid suspension fallout). The laminated and convoluted fine-grained top preserved in few of the event beds was probably deposited by the turbulent wake (Mutti 1992).

Significance and paleo-environment. The predominant facies association is made of highly amalgamated massive sandstones and can be interpreted as a **proximal mid-fan lobe** (FA-B) environment (Mutti & Ricci Lucchi 1972; Nilsen & Abbate 1984; Mutti & Normark 1987, 1991). The lack of lateral and vertical stratigraphic relationships means that it is difficult to place this section in context. Comparison with the stratigraphic position of similar facies elsewhere (see later) suggest it probably lies close to the base of the **Gottero 2** unit.

Moneglia and Riva Trigoso

The Gottero Sandstone crops out relatively continuously for about 10 km in a WNW-ESE oriented transect along the Ligurian coast between Moneglia, Riva Trigoso and Sestri Levante villages. The outcrops are generally well exposed but mostly located along inaccessible coastal cliffs that can only be observed by boat (Fig. 9). Two accessible exposures are located on the gravel beaches between Riva Trigoso and Moneglia just after the second tunnel on the Strada Statale 370 (SS370) connecting the two towns (*Riva Trigoso section* - Latitude: 44°14'54.04"N; Longitude: 9°26'10.64"E. *Madonnina section* - Latitude: 44°14'30.22"N; Longitude: 9°26'23.29"E) (Fig. 10).

The Gottero succession in this area is involved in a series of north-trending overturned folds (Fig. 9D) and associated thrust faults that affect the lateral continuity and correlation between the different sections. A continuous stratigraphic section in mostly vertical-dipping beds extends between the Moneglia Smeraldo camp (Latitude:

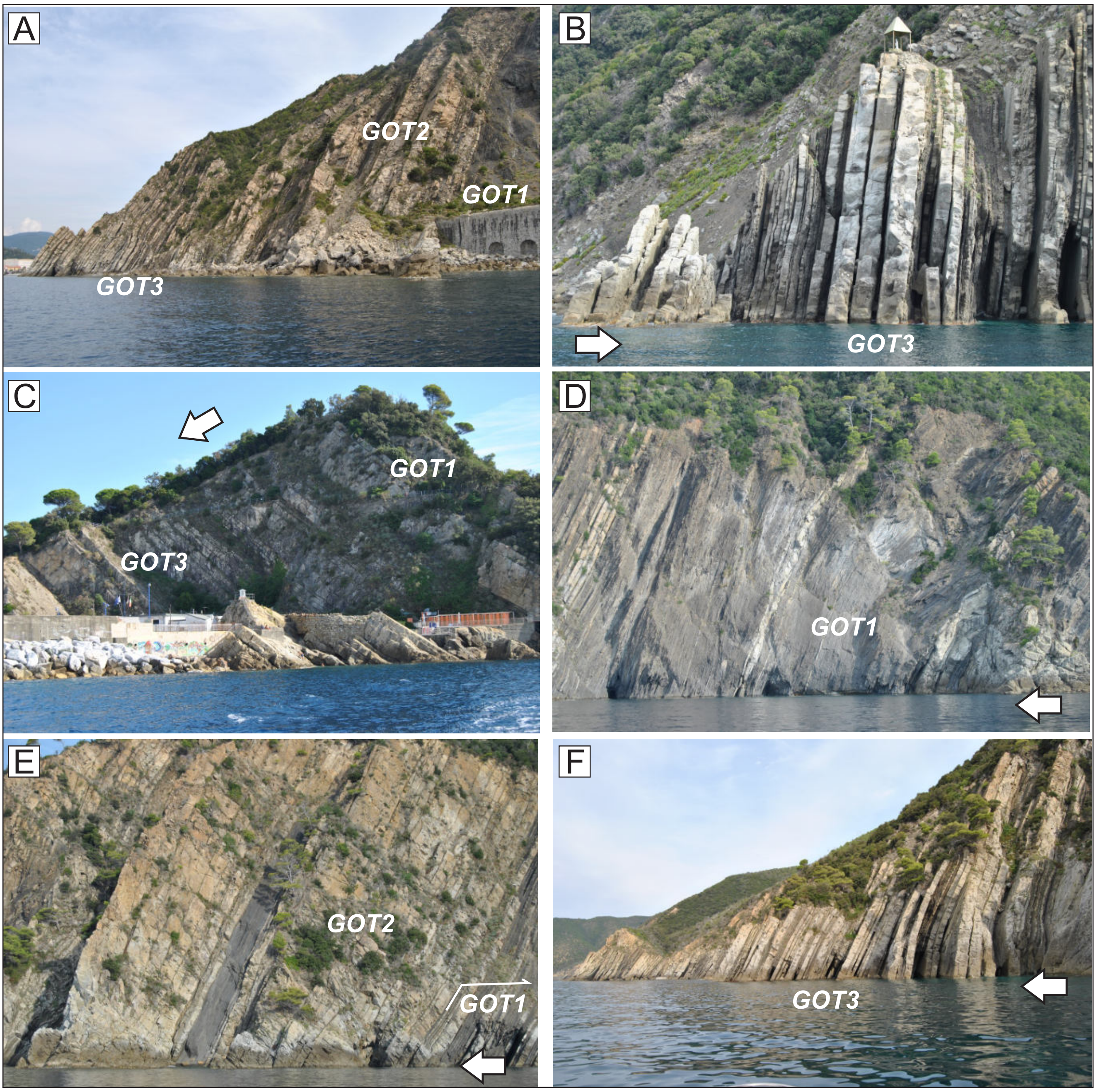


Fig. 10 - Sections and stratigraphic units in the Moneglia and Sestri Levante coastal outcrops. A) Exposure of Riva Trigoso measured section captured from the boat and a contrasting stacking pattern between the thick bedded Gottero 2 and thin-bedded Gottero 3 lobes. B) Partial view of the Madonnina section from a boat illustrating the stacking pattern of the Gottero 3 lobes. C) View of Sestri Levante section. D) Mud-prone and thin-bedded succession characterising the Gottero 1 succession as seen in coastal cliffs at Moneglia. E) Amalgamated sandstone packages characterising the Gottero 2 succession at its transition with underlying Gottero 1 thin beds in the Moneglia coastal cliffs. F) View of Gottero 3 sandstone lobes on an inaccessible part of the Moneglia coastal cliffs.

44°14'21.40"N; Longitude: 9°28'41.80"E) site and the end of the third tunnel along the SS370 road, exposing progressively younger strata towards NW. From the tunnel towards the NW (between Nûa Natûa Resturant - Latitude: 44°14'26.41"N; Longitude: 9°27'10.17"E - and Punta Baffe), a series of overturned asymmetric folds and associated thrusts deform the succession into vertical to overturned beds with progressively older strata encountered between Punta Baffe towards Madonnina beach (*Madonnina section*) repeating the same Gottero succession as seen to the south. Further north, a poorly exposed interval hides a deformation zone including a series of anticline-syncline fold pairs with axes plunging towards the NW in which the succession is repeated again and generally youngs towards north (*Riva Trigoso section*). The overlying Giaiette mass transport complex crops out just after this deformed zone but the contact with the upper Gottero Sandstone is not exposed.

Log description and facies interpretation. The logged sections at Riva Trigoso and Moneglia Madonnina are mostly the Gottero 2 and the lower part of Gottero 3 succession. A further 450 metres section of Gottero 3 stratigraphy has been documented on basis of panoramic photographs of the Punta Baffe succession taken from a boat.

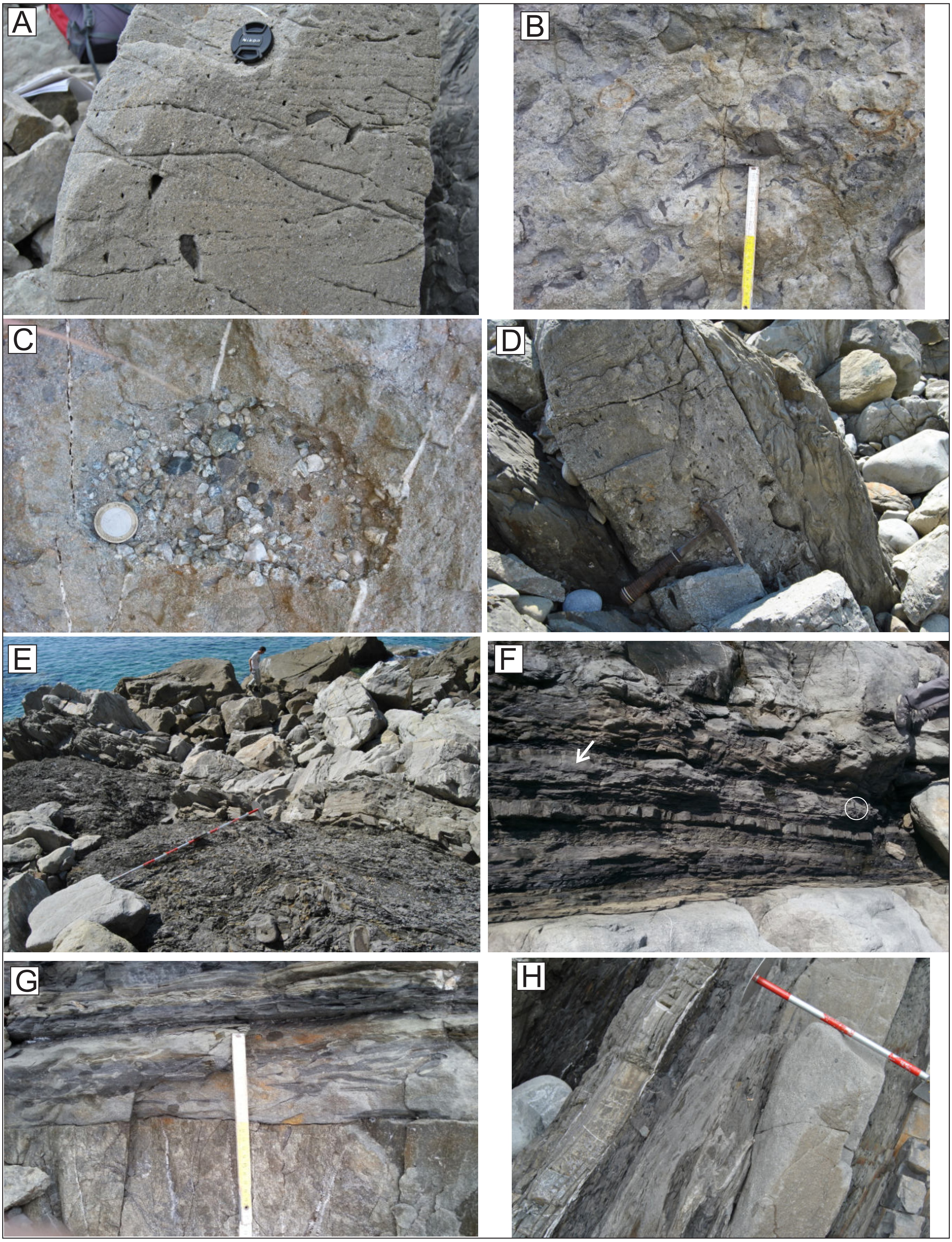
The succession above the **Gottero 1** thin-bedded interval starts with a thickening and coarsening upward trend recorded in all the sections and visible as well in Moneglia camp site coastal cliff exposures (Fig. 9E). The **Gottero 2** succession includes fine to coarse grained mudstone-clast rich beds interbedded with thin intervals including mudstones, laminated thin-bedded turbidites and thin hybrid event beds. Sandstones are generally ungraded and poorly sorted: High-density turbidites (HDTs) dominate the succession and they often preserve a tractive granule layer (facies F4 of Mutti 1992) at the bed base beneath a structureless coarse and very coarse-grained sandstone (facies F5 of Mutti 1992) with scattered cm-size mud chips or larger mudstone clasts throughout the bed (Fig. 11A). These are sometimes armoured with quartz-granules and accumulated in layers close to the very top of the bed (Fig. 11B-C). No fine-grained laminated part of these beds is preserved. The presence of armoured mudstone clasts suggests erosion of a sticky muddy substrate upslope. These clasts were transported and hydraulically fractionated in the rear and upper part of a basal dense flow (Mutti & Nilsen 1981; Postma et al. 1988) and then deposited in the very top of the bed. The bed tops were probably bypass surfaces for finer grain-sizes which are not preserved at this location and presumably were transported further down slope.

Towards the top of the interval (in the *Riva Trigoso section*) a series of conglomeratic lenses (facies F3 of Mutti 1992) overlain directly by horizontally laminated and rippled fine-grained sandstones are recognised (Fig. 11D). Those are interpreted as small lags releasing by bypassing frictional flows in shallow distributive channels. Furthermore, the interval includes a mud-rich debris flow deposit partially reworking the top of an underlying amalgamated sandstone package but also including pieces of conglomerates and laminated turbidites (Fig. 11E). The sandstone packages are separated by 1-2 metres thick intervals containing thin-bedded low-density turbidites and thin (about 25-35 cm thick) and well-mixed clast-poor hybrid event beds (Fig. 11F). Hybrid event beds are absent inside the sandier packages except within the very first, thinner and finer grained package.

The overlying unit (assigned to **Gottero 3**) includes a repetitive stack of coarse-grained mostly massive sandstones often rich in mudstone clasts (either dispersed or concentrated towards the bed top, in this case only rarely armoured; Fig. 11G), mid-sized to thin hybrid event beds (Fig. 11H), and interbedded thin-bedded laminated and/or rippled turbidites. Occasionally sand-alone debrites are encountered. The bed stacks form 5-10 m thick packages displaying thickening upwards or symmetric trends (Fig. 9A). Those comprise hybrid event beds usually concentrated at the base of the cycles. Many beds are amalgamated or preserve relatively little mud in between; however, beds and sandstone packages tend to be vertically separated by progressively thicker mudstone interlayers moving up through the section (Fig. 9F). At the outcrop-scale, two of the mudstone are particularly prominent in terms of thickness and lateral continuity and may be the deep-water expression of condensed sections.

Significance and paleo-environment. The basal thin-bedded succession ascribed to Gottero 1 can be interpreted as a **basin plain** (FA-F1) succession in which only low-density and high-efficiency flows reached the basin floor. In contrast to the equivalent

Fig. 11 - Facies inventory in the Moneglia exposure. A) Poorly sorted coarse-grained bed with scattered mudstone clasts (5 cm diameter camera lens cap for scale). B) Mudstone clasts enriched at the top of a bed (20 cm ruler for scale). C) Imprint of armoured mudstone clasts containing mostly quartz and lithic granules (1€ coin for scale). D) Lenticular clast-supported conglomerate capped by fine-grained and rippled sandstone (geological hummer for scale). E) 5 m thick mud-rich debrite capped by fine-grained laminated sandstone (1.5 m Jacob's staff for scale). F) Inter-lobe thin-bedded package containing an 18 cm thick hybrid event bed (indicated by white arrow); the scale is a circled pencil. G) Sandstone beds containing sub-angular mudstone clasts concentrated towards its top. H) Hybrid event beds with clean sandy base and uppermost argillaceous sandstone containing scatter mudstone clasts (Jacob's staff for scale, colour bands represent 10 cm).


A
B
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interval in the Monterosso section (see above) the absence of slump deposits suggests a position remote from the slope and a stable and flat sea floor. Nevertheless, the transition to very different coarse-grained Gottero 2 deposits is quite sharp (over about 12 m), but characterised by a clear thicknening upward trend and presence of interbedded hybrid event beds in outer fan lobe deposits (FA-C), testifying a very rapid basinward shift of the Gottero system during this phase.

The overlying Gottero 2 succession is interpreted as dominated by **proximal mid-fan lobe association** (FA-B). Small conglomeratic lags, sharp bed tops and cut and fill features testify the occurrence of important bypass typical of the proximal parts of lobe fans (Mutti & Normark 1987).

The thick Gottero 3 succession is made up of thinner and less internally amalgamated sandy packages that are interpreted as **outer fan lobes** (FA-C; Mutti & Ricci Lucchi 1972; Mutti & Normark 1987). They are thought to represent a different fan sub-environment rather than lateral (off-axis) expression of the previously described mid-fan lobes because very coarse grained/conglomeratic beds and highly amalgamated units are absent over the entire Gottero 3 succession. Thinner-bedded units (where most of the hybrid event beds are encountered) are interpreted as lobe fringe deposits. The complex changes in the vertical bed thickness stacking are interpreted as an effect of local lobe progradation (Mutti & Ghibaudo 1972; Mutti & Ricci Lucchi 1972), compensational stacking (Mutti & Sonnino 1981) or autocyclic lateral lobe axis switching (Macdonald et al. 2011; Prélat & Hodgson 2013).

The very upper part of the Gottero 3 succession is dominated by more isolated event beds (FA-D) and may represent a later phase in which the fan retreated and only outsized event beds developed in a more confined basin plain setting.

Terrarossa

The Gottero Sandstone crops out in an abandoned quarry near the town of Terrarossa (Fig. 3; Latitude: 44°22'28.75"N; Longitude: 9°21'29.34"E). The average palaeoflow orientation measured is towards 281°N.

Log description and facies interpretation. The 137 m thick succession displays two main facies associations (Fig. 12). The lower 35 m includes two internally highly-amalgamated sandstone packages separated by a 3.5 m thick muddier interval. The sandstone packages are composed of granule to medium-grained, poorly graded and sorted sandstone beds sometimes displaying lenticular shapes (in coarser-grained beds). Exceptions include a mudstone clast-rich hybrid event bed located on the top of the first sandstone package, and a mudstone conglomerate, interpreted as a debris flow deposit, situated at the base of the second sandstone package. The second part of the section presents series of sandstone packages with only local bed amalgamation in contrast to the underlying beds, and separated by mudstone and thin-bedded intervals. Beds remain generally poorly sorted, ungraded and coarse-grained with the exception of a few better graded beds rich in horizontal parallel laminations and including a thick mudstone cap (max 2 m). Mud chips are common, but are small (cm-size), scattered and angular in shape. Only a single thin hybrid event bed is found.

Significance and palaeo-environment. Facies associations suggest they could represent the topmost part of the **Gottero 2** unit (the amalgamated sandstone packages) and the base of **Gottero 3**. The Gottero 2 unit is interpreted here to represent relatively proximal **mid-fan sandstone lobes** (FA-B) displaying a similar character to those distinguished in the Moneglia and Deiva Marina outcrops but with a slightly finer grain-size and a lack of armoured clasts consistent with a position further down dip. The uppermost (basal Gottero 3) deposits are interpreted as **outer fan lobe deposits** (FA-C) due to the lower degree of amalgamation and the generally finer grain-size.

Mt. Ramaceto

The Gottero Sandstone and the units immediately below and above it crop out extensively in a key exposure along the foothills of Mount Ramaceto (Fig. 3; Latitude: 44°25'58.68"N; Longitude: 9°18'25.44"E).

This area preserves the only complete section of the Gottero Sandstone in which both lower and upper boundaries are preserved with the Vallai and Giaiette MTCs, respectively. The Gottero Sandstone is here about 1075 m thick. The extensive outcrop and quality of the exposure (Fig. 13) allowed

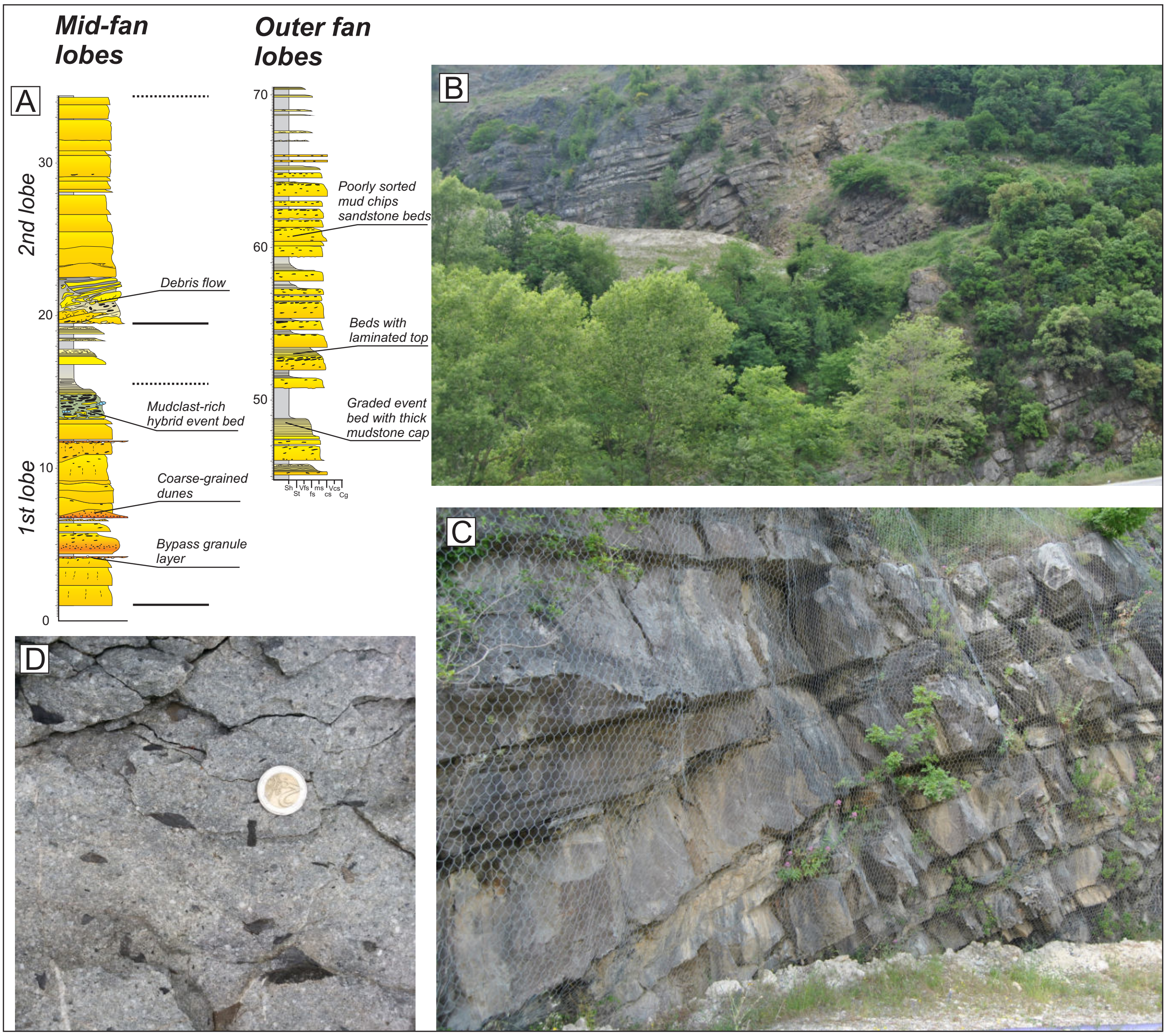


Fig. 12. Schematic logs and facies in the Terrarossa section. A) Schematic logs representing the basal and the upper part of Terrarossa section. B) Exposure quality. C) Sandstone packages at the base of Gottero 3 succession. D) Poorly sorted sandstone with scattered angular mud chips characterising proximal mid-fan lobe deposits.

the measurement of nine partially overlapping stratigraphic logs resulting in a total of about 3000 metres of logged section. These logs were used to produce a composite stratigraphic log of the entire unit.

The area is affected by important polyphase tectonic deformation (Marroni et al. 2004). The main structural feature is a large-scale syncline (*Cichero syncline*) with Giaiette shales at its core and the fold hinge oriented in a SE-NW direction along the Cicana valley (Casnedi 1982; Marroni 1991; Marroni et al. 2004) (Fig. 3). The structure is further deformed by secondary NE-verging meso-folds with sub-horizontal axis planes (Marroni et al. 2004). The effect of these two deformation phases is that most of the stratigraphy cropping out in the Mt. Ramaceto area is overturned, being exposed on the inverted limb of the syncline. Only the southern section (*Passo del Dente;* A section in Plate 2) preserves right-way up bedding. The structural setting is further complicated in the area by the occurrence of a series of N-S/NE-SW trending strike-slip faults displacements on which have resulted in the vertical rotation of individual fault blocks (Marroni et al. 2004).

The tectonic deformation does not affect the correlatability of individual beds which can be traced laterally for more than 4 km. However, it has

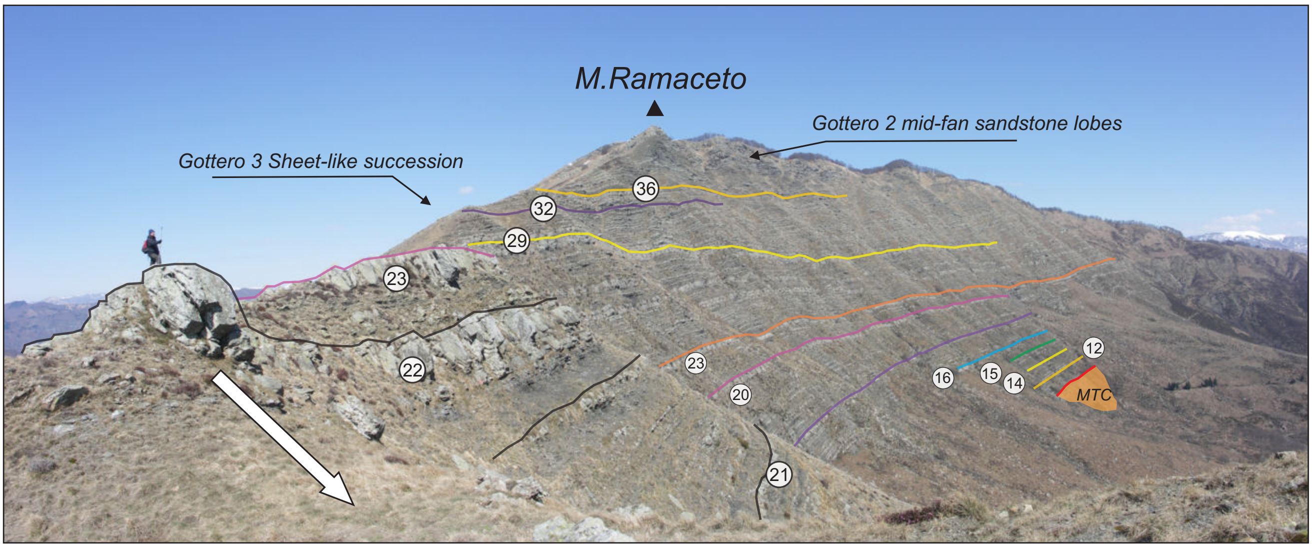


Fig.13 - Exposure of the upper stratigraphic part of Gottero Sandstone in the Mt. Ramaceto area. Note the succession is tectonically inverted. Numbers refer to key horizons highlighted in Plate 2. Orange colour represents the outcrop of the stratigraphically overlying Giaiette mass transport complex unit (MTC).

produced additional variability in the orientation of palaeoflow indicators as it is unclear how to correctly restore the beds to horizontal (map in Plate 2). In particular, the central block (including the sections “Rovi”, “Mezzo” and “A.C.L.I”.) shows consistent E-W oriented palaeocurrents that are at variance with the S-N or SE-NW regional trend. This deviation is interpreted to have been caused by the movement along two strike-faults which rotated the central block by about 90 degrees. Restoration of the bedding to correct the palaeoflow has been done by simply rotation about strike in the absence of any means to constrain the vertical rotations. The more reliable palaeoflow orientations (aligned mostly towards the north) come from the southern “Passo del Dente” section.

Log description and facies interpretation. The base of the measured succession is represented by a c.30 m-thick mud-rich chaotic unit defined by Marini (1993) as the Vallai Shales (Fig. 14A). The unit includes deformed turbiditic sandstones (not dissimilar to the Gottero Sandstones) embedded in a muddy matrix. Exotic material is not observed.

Above the Vallai, a 143 m thick mud-rich unit (Net/Gross: 40%; Tab. 1) is present, here **Gottero 1**. The succession is in the lower 118 metres as dominated by thin-bedded turbidites and upper 25 m thick interval in which thicker high-density turbidites and hybrid (HEBs) bed progressively appear. The basal interval is mostly composed of densely packed, laminated and rippled, thin-bedded low-density turbidites (LDTs; Fig. 14B) with thicknesses ranging from 1 to 110 cm (Fig. 15-1). This monotonous stacking pattern is interrupted by the presence of three thicker and coarser-grained

	Total thickn. (m)	*Total sandst. (m)*	*Total mudst. (m)*	*Net/Gross (%)*	*N° of beds*	*HDTs*	*MRBs*	*HEBs*	*LDTs*	*Ls*
GOT 3c	236	121	115	51%	254	12	3	20	211	8
GOT 3b	293	176	117	60%	332	21	13	54	233	11
GOT 3a	218	139	79	64%	194	13	14	40	125	2
GOT 2-3	69	28	41	40%	126	2	0	13	104	7
GOT 2	110	86	24	78%	85	45	10	14	15	0
GOT 1*	73	29	44	40%	309	4	2	5	294	4

Tab. 1 - Quantitative characteristics and bed type counts for the various upper Gottero units in the Mt. Ramaceto section. HDTs: high-density turbidites; MRBs: high density turbidites with mudstone clasts; HEBs: hybrid event beds; LDTs: low-density turbidites; Ls: limestone beds. (N/G: net-to-gross). * = only the upper 73 m of Gottero 1.

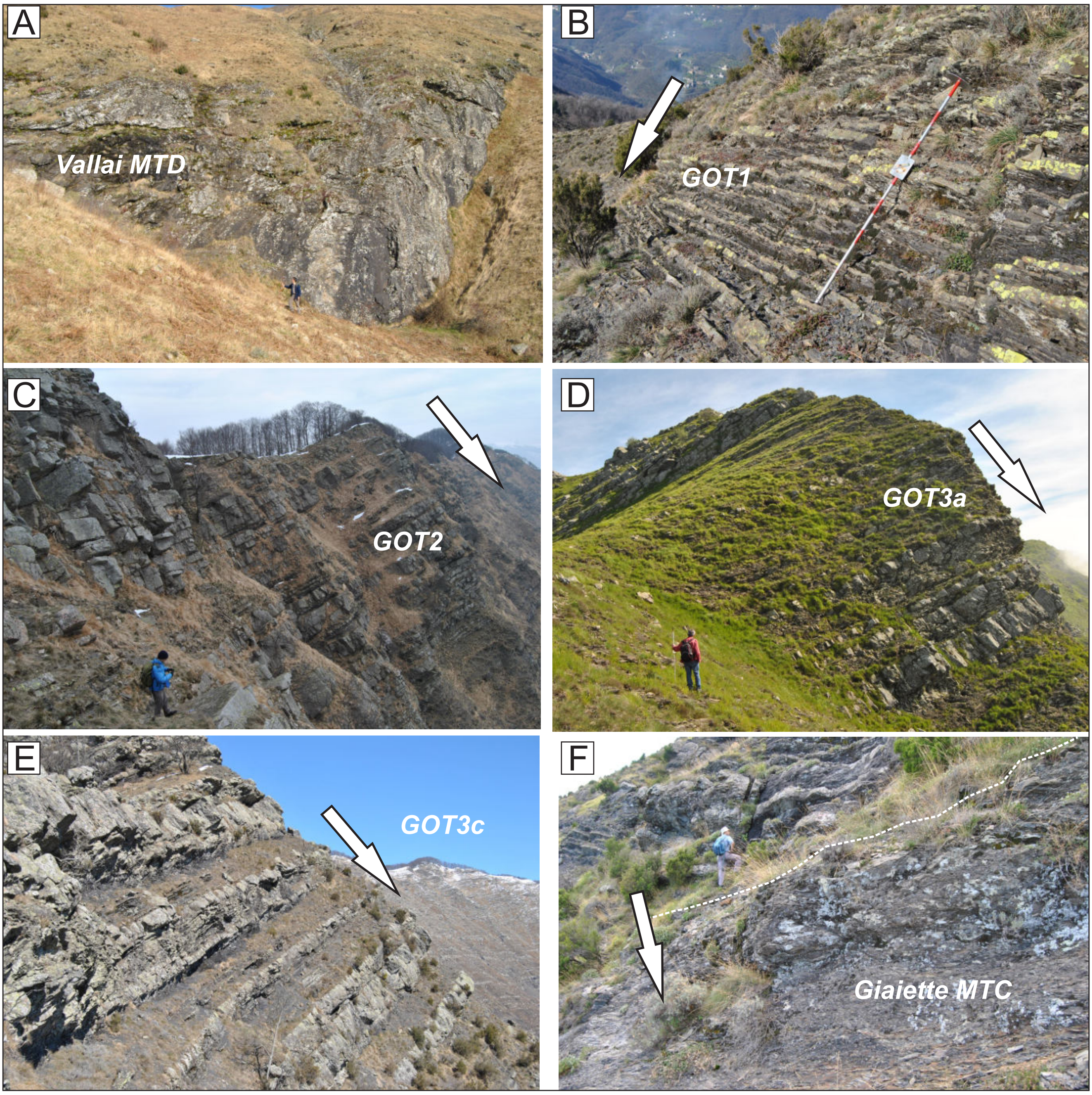


Fig. 14 - Stratigraphic features in the Mt. Ramaceto succession. A) Vallai basal MTD. B) Fine-grained thin-bedded sandstones in the Gottero 1 succession. C) Sandstone lobes of Gottero 2 at the very top of Mt. Ramaceto peak. D) Weakly amalgamated packages in the lower Gottero 3 succession (GOT3a). E) Isolated and thick tabular event beds separated by mudstone and thin-bedded interval in the upper part of Gottero 3 succession (GOT3c). F) Erosive contact between the uppermost part of Gottero Sandstone and the Giaiette MTC deposit near Cichero village. The white arrows indicate the way-up of the succession.

sandstone beds constituting a 5.5 m thick package situated 32 m above the base of the Upper Gottero unit. The upper part of the Gottero 1 unit is characterised by progressively thicker beds associated with thicker mudstone caps (Fig. 15-2).

The following stratigraphic unit (**Gottero 2**) crops out at the top of Mt. Ramaceto (Fig. 13) and includes eight sandstone packages separated by metre-thick mudstone intervals, with a total thickness of about 110 m (Fig. 14C). The net-to-gross ratio is high, approaching 78% (Tab. 1). Each of the packages is constituted by amalgamated very coarse-grained to medium grained sandstone beds (Fig. 15-3). Massive and heavily dewatered sandstones are common, although a few beds display small pebbles to granules arranged in crude laminations (facies F4 and F7 of Mutti 1992) demonstrating that bypass was an important active process. Mudstone clasts are occasionally concentrated at the top of some of the beds. Hybrid event beds are present especially at the base of the unit and are characterised by variable thickness and texture. Sandy packages are separated by relatively thin muddy intervals (metre-thick) mostly devoid of thin-bedded turbidites but sometimes including thin hybrid event beds.

A rapid thickening upward trend is observed at the base of the Gottero 2 (Fig. 15-2); the unit also terminates abruptly with a thinning-upward cycle marking the passage to an overlying mudstone-rich interval. Despite being considered part of the Gottero 2 unit (see below), overlying fine-grained interval represents a distinct stratigraphic interval here defined as **Gottero 2-3**. It is characterised by a drastic drop in the net-to-gross (40%; Tab. 1), and event bed grain-size (medium to very fine sandstones), associated with deposition of thin-bedded laminated graded turbidites and occasional micritic limestone beds (Fig. 15-4). Thicker events (1-1.5 m thick) are represented by a few interbedded hybrid event beds.

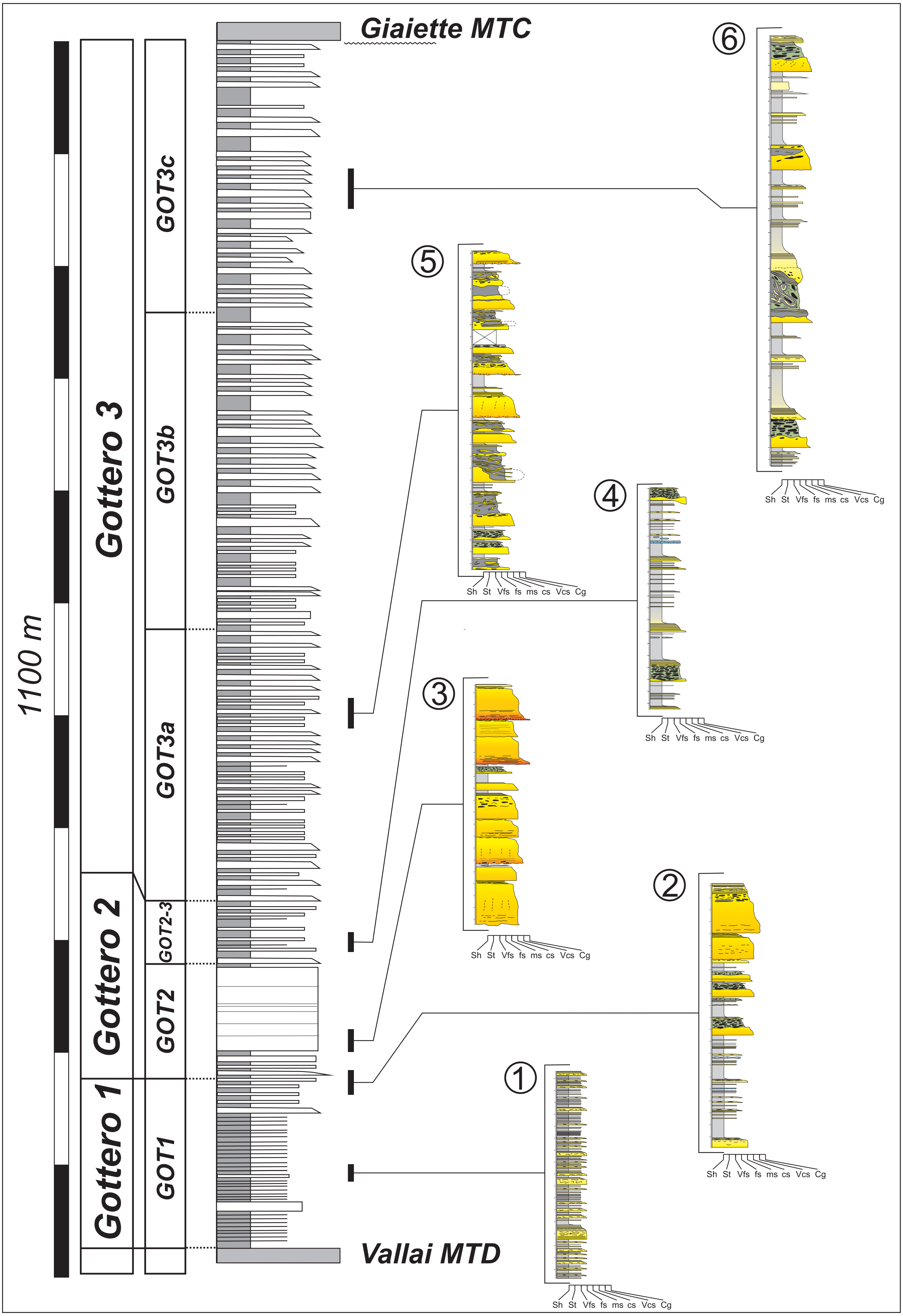
The remaining part of the Mt. Ramaceto succession is attributed to the **Gottero 3** unit (Fig. 15). The stacking pattern is dominated by tabular and laterally extensive event beds, many of which are represented by hybrid event beds (making up 35% in thickness of the unit). The beds are characterised by thick mudstone caps which are interbedded with packages of thin-bedded turbidites and limestone-marly beds. In order to characterise and better constrain the vertical evolutionary trend of Gottero 3, three sub-units (**GOT3a, 3b and 3c**) are distinguished. Their boundaries are placed at two distinctive thick dark mudstone intervals that include diagenetic "Septarie nodules" (see Andri & Zavatteri 1990; Marini 1994; Fonnesu et al. 2016). Their occurrence could indicate periods of relative starvation of the system thus forming laterally extensive markers that potentially correlate with the similar mud-rich intervals occurring in a comparable stratigraphic position in the Moneglia section.

The character and architecture of the Gottero 3 deposits change through the succession. 1) The net-to-gross decreases towards the top reducing from 64% of GOT3a, to 60% of GOT3b and to 51% of GOT3c (Tab. 1). 2) Weakly amalgamated sandbodies (Fig. 14D; Fig.15-5) are occasionally present in GOT3a, they are still present in GOT3b albeit with a reduced thickness, while they do not occur in GOT3c. 3) The ratio between bed thickness and their associated mudstone cap thickness increases upward as the succession progressively becomes dominated by thicker and more isolated beds associated with thicker mudstone caps and thin-bedded turbidites intervals (Fig. 14E; Fig. 15-6). 4) Younger sandstone beds display generally thicker laminated upper divisions, alternations of structureless and laminated sandstone and silty homogenous caps. Pandolfi (1997) recognised beds with ophiolite-derived petrography in the upper part of Gottero succession (probably Gottero 3b and 3c) in the Mt. Ramaceto section.

The upper Gottero succession is capped by an erosional truncation with the overlying chaotic Giaiette unit (Giaiette MTC) (Fig. 14F). The erosive surface cuts down more than 250 m into the Gottero succession over less than 2.5 km laterally (Plate 2). The Giaiette unit is made up of deformed sandstones and mudstones derived from the Gottero succession together with exotic blocks of serpentinite, basalt, radiolarite and Calpionella Limestone derived from the internal Ligurian units succession (Marroni and Pandolfi 2001). Below the erosive contact it is usually possible to recognise a 20-25 m thick deformed interval of the Gottero beds where a layered stratigraphy is still recognisable and exotic material is absent.

Significance and palaeo-environment. The basal **Gottero 1** succession in the Mt. Ramaceto section is interpreted as a **basin plain** succession (FA-F1) dominated by deposition from low-density turbidity currents. The uppermost part of Gottero 1 succession start to shows the first effects of progradation of the Gottero fan with the occurrence of hybrid event bed deposits and then an upward transition into sheet to distal lobe fan fringe deposits (FA-E2; FA-C) (Marini 1994). Hybrid event beds are the thicker event beds in the interval and could constitute deposition from outsize events bypassing the

Fig. 15 - Mt. Ramaceto stratigraphic log, stratigraphic subdivisions and main facies associations. 1) thin-bedded succession; 2) thickening and coarsening upward trend; 3) Amalgamated sandstone packages and inter-bedded mudstones; 4) thin-beds and thin hybrid event beds; 5) weakly amalgamated hybrid-prone packages; 6) isolated sheet turbidites and hybrid event beds with thick mudstone caps and interbedded with thin-bedded packages.


Giaiette MTC
Vallai MTD
1100 m
Gottero 1
Gottero 2
Gottero 3
GOT1
GOT2
GOT2-3
GOT3a
GOT3b
GOT3c
①
②
③
④
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Sh St Vfs fs ms cs Vcs Cg

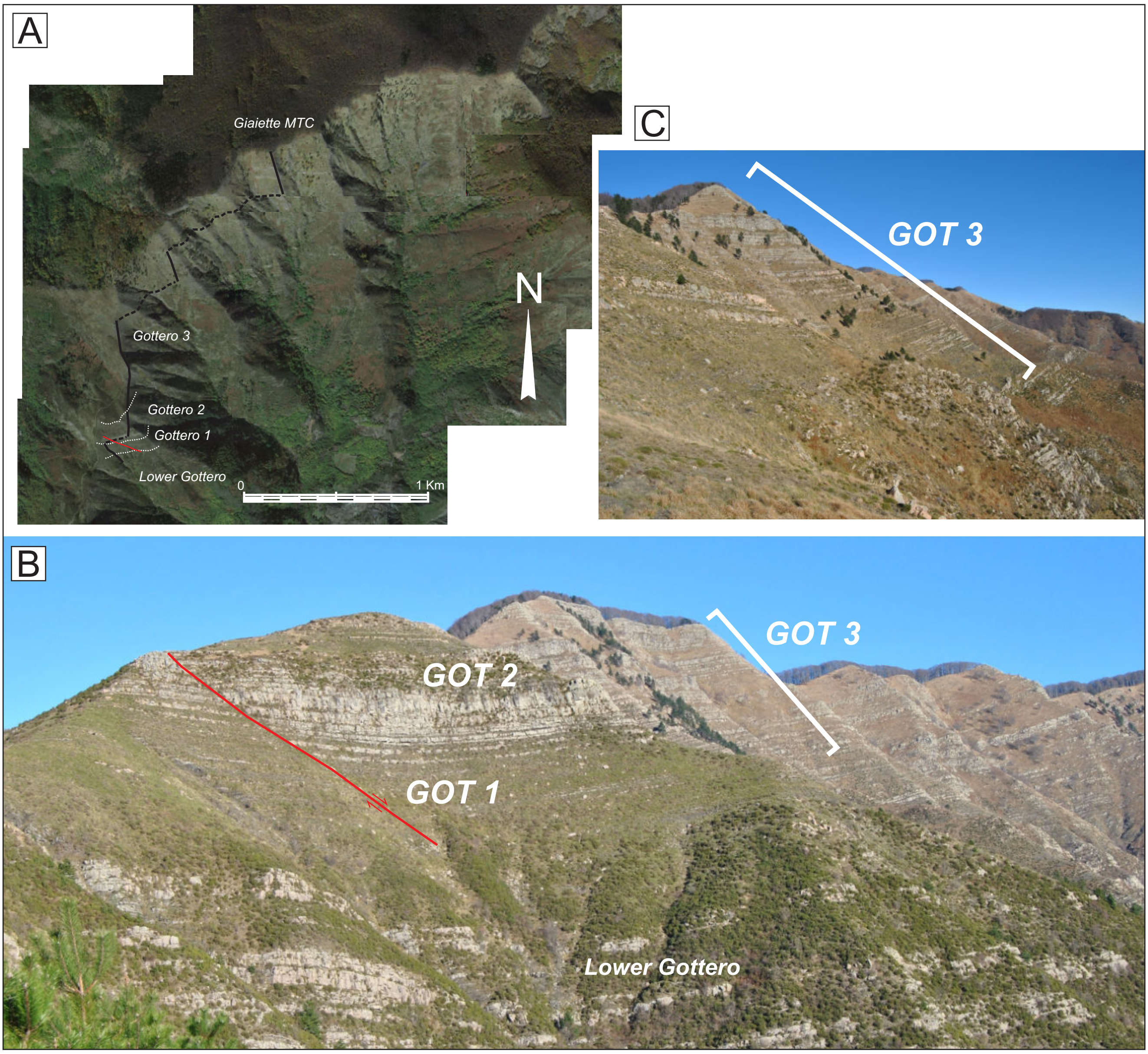

Fig. 16 - Mt. Zatta outcrop section location and exposures. A) Orthophoto and trace of the measured section. B) Exposure of the lower part of the Gottero succession in Mt. Zatta. A normal fault displacing the Gottero 1 and 2 beds is indicated. C) Exposure of the Gottero 3 succession.

fan fringe (FA-D).

The **Gottero 2** unit is interpreted as represented stacked **mid-fan to outer fan sandstone lobe deposits** (FA-B and rarely FA-C)**.** The event beds show more distal characteristics (finer grain-size, better grading, tractive sedimentary structures) compared to equivalent Gottero 2 deposits in other sections and they lack microconglomerates and erosional features common elsewhere. The muddy intervals separating the lobes are interpreted as interlobe deposits.

The mud-rich interval referred as **Gottero 2-3** is interpreted as a fan fringe deposits with development of mud-prone sheets (FA-E2), possibly marking a phase of system retrogradation and distal starvation in Mt. Ramaceto area.

The thick **Gottero 3** succession shows progressive variation in its sedimentological character. The succession is dominated by laterally extensive event beds (at least 4 km but likely more) which because of their tabularity suggest deposition on a flat sector of the basin floor (FA-E1). The presence of event beds with thick mudstone caps (in particular toward the top of the succession) indicates that most of the mud transported by the dilute part of the flows was trapped in the receiving basin by topography. The presence of repetition of structureless laminated sandstones, wavy lamination and expanded fine-grained laminated division observed in many beds towards the top of Mt. Ramaceto succession, are considered indication of flow reflection or deflection against basin boundaries (Pickering & Hiscott 1985; Haughton 1994, 2001; Kneller & McCaffrey 1999; Felletti 2002; Muzzi Magalhaes & Tinterri 2010). Similar structures are not identified in the lower part of the beds suggesting that the flow reflection only affected the dilute and out-running part of the currents. Occasional more closely stacked bed intervals found in the lower part of Gottero 3 interval, rich in hybrid event beds and with lower internal correlatability of individual beds at km-scale (Plate 2 - see supplementary files), constitute confined weakly amalgamated sheets (FA-D).

The overall trend can be interpreted as a progressive increase in the confinement of the Mt. Ramaceto depocentre, until fully ponded conditions were reached in the final part of the succession.

Mt. Zatta

The measured section is located on the southern side of the Mt. Zatta (Fig. 3; Latitude: 44°23'9.00''N; Longitude: 9°26'32.97''E) where the Gottero succession crops out extensively for about 2.3 km striking towards the NE (Fig. 16). Palaeoflow orientations do not show systematic divergences and have a limited range of variability between NW and N.

The 732 m thick sedimentological log covers the interval between a basal chaotic event (interpreted as Vallai MTD) extending to the top of the Gottero succession. The boundary with the Giaiette MTC is not exposed because of vegetation cover, but following Marini (1995), it is thought to be very close to the point where the measured section ends.

Log description and facies interpretation. The succession starts with a mud-rich chaotic unit around 30 m thick. Its characteristics are similar to the ones reported for the Vallai MTD in the Monterosso and Mt. Ramaceto sections, including deformed sandstone rafts and an absence of extrabasinal material.

Above the Vallai MTD, a mostly fine-grained unit 42 m thick was deposited (**Gottero 1**). A clear onlap relationship with the underlying Vallai MTD can be observed (Fig. 17A). The Gottero 1 unit can be split in a lower part (30 m thick) dominated by thin-beds and an upper part (16 m thick) in which thicker event and hybrid event beds start to appear. The lower interval includes beds with common wavy laminations, small hummocky-cross-laminations, alternations of structureless and structured divisions and bi-convex ripples (see Tinterri 2011), which are absent in other localities.

The succession becomes progressively dominated by coarser sandstone beds arranged in amalgamated packages alternating with shaly intervals forming a 65 m thick unit attributed to **Gottero 2.** Grain size varies from very coarse sand and scattered small granules to medium sand; beds are mostly structureless or highly dewatered, are poorly graded and have mudstone clasts concentrated in bed tops. A few hybrid event beds are present at the base of each package.

The overlying **Gottero 3** succession is about 730 m thick and can be subdivided in six parts:

An 88m thick interval in which amalgamated sandstone packages (15-20 m thick) are interbedded with intervals (about 10 m thick) dominated by thin-bedded turbidites.

A 130 m thick interval in which the same type of amalgamated sandstone packages are interbedded with thick hybrid event beds.

A 47 m thick mud-prone chaotic deposit with erosive base and undulated top (Fig. 17B) interpreted as a mass transport deposit (MTD). The event was able to rip-up part of the underlying sandstones forming thrust-like compressive features at its base and containing sandstone blocks in its central part. The upper part of the MTD is more mud-prone and enriched in exotic carbonate boulders. The top of the MTD is marked by a 1.1 m thick graded and laminated interval and a 3.3 m thick mudstone cap.

There is then a mud-rich interval up to 15 m thick that infills the topographic lows along the top of the MTD. It is made up mostly of thin-beds, but also includes thicker beds (0.3 – 1.6 m) showing the reflected flow facies similar to that previously described in the lower part of Gottero 1.

A 158 m thick interval with thick and laterally extensive event beds sometimes preserving thick mudstone caps alternated with weakly amalgamated sandstone packages and abundant hybrid event beds.

The top 183 m are dominated by sandstone amalgamated packages interbedded with mud-prone intervals enriched in hybrid event beds.

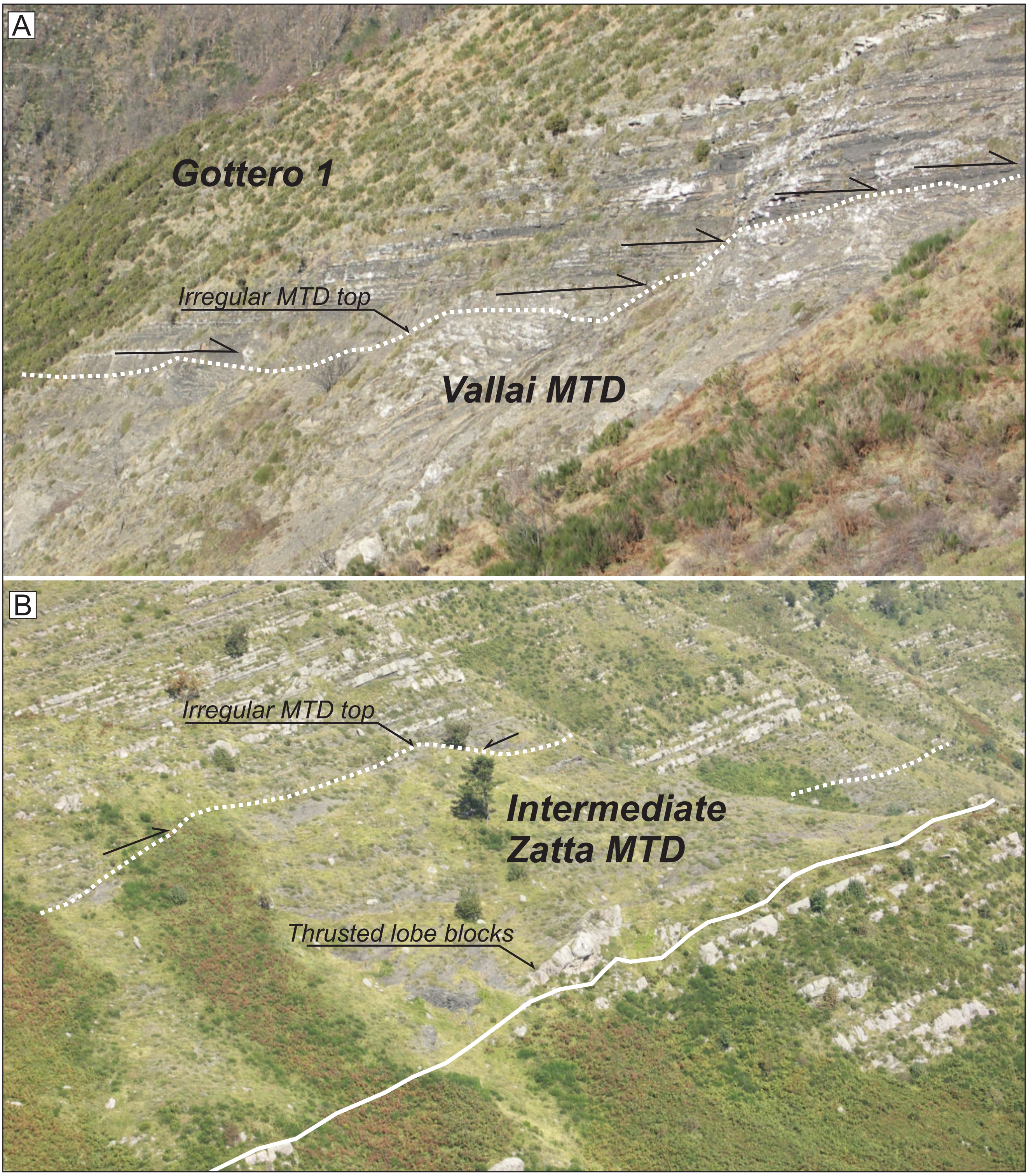

Fig. 17 - Chaotic events in the Mt. Zatta succession. A) Basal Vallai MTD and onlap relationship with the uppermost mud-prone Gottero 1 succession. B) Intermediate Zatta MTD featuring an irregular top upon which fine-grained deposits onlap and a basal surface with deformed and thrusted sandstones derived from the underlying lobe deposits.

Significance and paleo-environment. The basal **Gottero 1** succession is interpreted similarly to other localities as a basin plain succession (FA-F3). The reduced thickness in comparison to Mt. Ramaceto and the described facies association including flow-reflection facies and the onlap relationships with the underlying Vallai chaotic unit, suggest that deposition was influenced by topographic irregularities on top of the Vallai MTD (Kneller et al. 1991; Haughton 2001; Armitage et al. 2009; Bersezio et al. 2009; Felletti & Bersezio 2010a; Tinterri & Tagliaferri 2015; Tinterri et al. 2016). The thickening upward trend of the basal **Gottero 1** succession is interpreted as progradation of **fan fringe facies** (FA-E2) on top of distal basin plain deposits.

The **Gottero 2** succession is interpreted as a stack of **mid-fan to outer fan sandstone lobes** (FA-B and FA-C). Lobe deposition occurred after a rapid transition from thinner and finer grained lobe deposits interpreted as **outer fan lobes** (FA-C) marking the rapid progradation of the fan.

The **Gottero 3** succession is dominated by sandstone packages interpreted as **lobe units** (outer or mid-fan; FA-B and C) interbedded with mud-prone intervals or isolated event beds (FA-D and FA-E1). Vertical and lateral changes in the stacking pattern could be related to either lobe lateral switching or individual lobe progradation. The overall Gottero 3 unit trend shows an increase in the average grain size and degree of amalgamation towards the top of the succession, interpreted as the effect of system progradation ("progradational suite" of Mutti 1985; Marini 1995). This trend is in strong contrast with the Gottero 3 make-up in other locations suggesting that Mt. Zatta locality could represent a different sub-basin at this time. The succession is interrupted by a chaotic event that does not show equivalents in other locations. The presence of transported limestone blocks, external to the Gottero succession, suggests that this MTD could reflect uplift of the external basin boundary and reworking of previous formations (e.g. Calpionella Limestone).

System-scale stratigraphy and facies distribution

The Gottero system has been described in the past as an unconfined fan system with a radial dispersal pattern (Nilsen & Abbate 1984). Nevertheless, the analysis of the measured logs shows that this setting could be more dynamic and complex than previously interpreted. Five main stratigraphic units are distinguished which record the wider tectonic and sedimentary evolution of the system (Fig. 18).

Lower Gottero and Vallai MTD

The lower Gottero unit has not been studied in detail in this work because of the lack of good quality exposures. Previous workers (Casnedi 1982; Marini 1991, 1992, 1995) recognised a series of sandstone bodies interfingering with the fine-grained deposits of the Lavagna Group. The number of sandbodies and the overall thickness of the unit tend to increase from SE to NW. Sandbodies at this level are absent in the Monterosso locality, a single sandbody about 30-40 m thick in the Moneglia section, and up to four sandy-units with an overall thickness of 300-350 metres near Sestri Levante (Marini 1991) and the western Val Lavagna (Casnedi 1982). The sandy units are interpreted as lobe and channelized bodies as part of an earlier prograding fan system (Casnedi 1982).

The Lower Gottero Sandstone is directly overlain by a fine-grained chaotic deposit defined by Marini (1991, 1992, 1994, 1995, 1996) as the Vallai unit or Vallai shales. This unit is recognised at the Mt. Ramaceto, Mt. Zatta, Moneglia and Monterosso localities (Fig. 19). It varies from about 20 m thick at Monterosso to 30-40 m thick on Mt. Ramaceto. The Vallai unit is composed of deformed and incompletely mixed black shales, siltstone, marlstones, micritic limestones and sandstone layers. The unit has a monomictic character and does not include any extrabasinal material (i.e. beyond reworked Gottero Sandstone or Lavagna Group lithologies). Despite being previously interpreted as a hemipelagic unit (Marini 1991, 1992, 1994, 1995, 1996), the evidence for extensive disruption suggests it is a mass transport deposit (MTD). A post-depositional tectonic origin for the disruption, as suggested by Marini (1994), is excluded because of the undeformed character of the bounding successions which preserve undisrupted bedding. The available outcrops do not allow a distinction to be made between a single or multiple mass transport events, but the onset of a laminated turbiditic interval directly on top of the unit, and the presence of an associated mud cap, suggest that it could be a single mass failure that generated an associated turbidity current. The intrabasinal composition suggests the failure did not tap deeper stratigraphic levels and it was therefore probably triggered by oversteepening and/or oversupply of the slope/margin. The base is only slightly erosive on the underlying substrate. The internal structure includes a combination of highly disrupted "block-in-matrix" texture (Ogata et al. 2012; Festa et al. 2012) and soft-sediment slump-like deformation, indicating an intermediate to long mass flow run-out (Ogata et al. 2012). Due

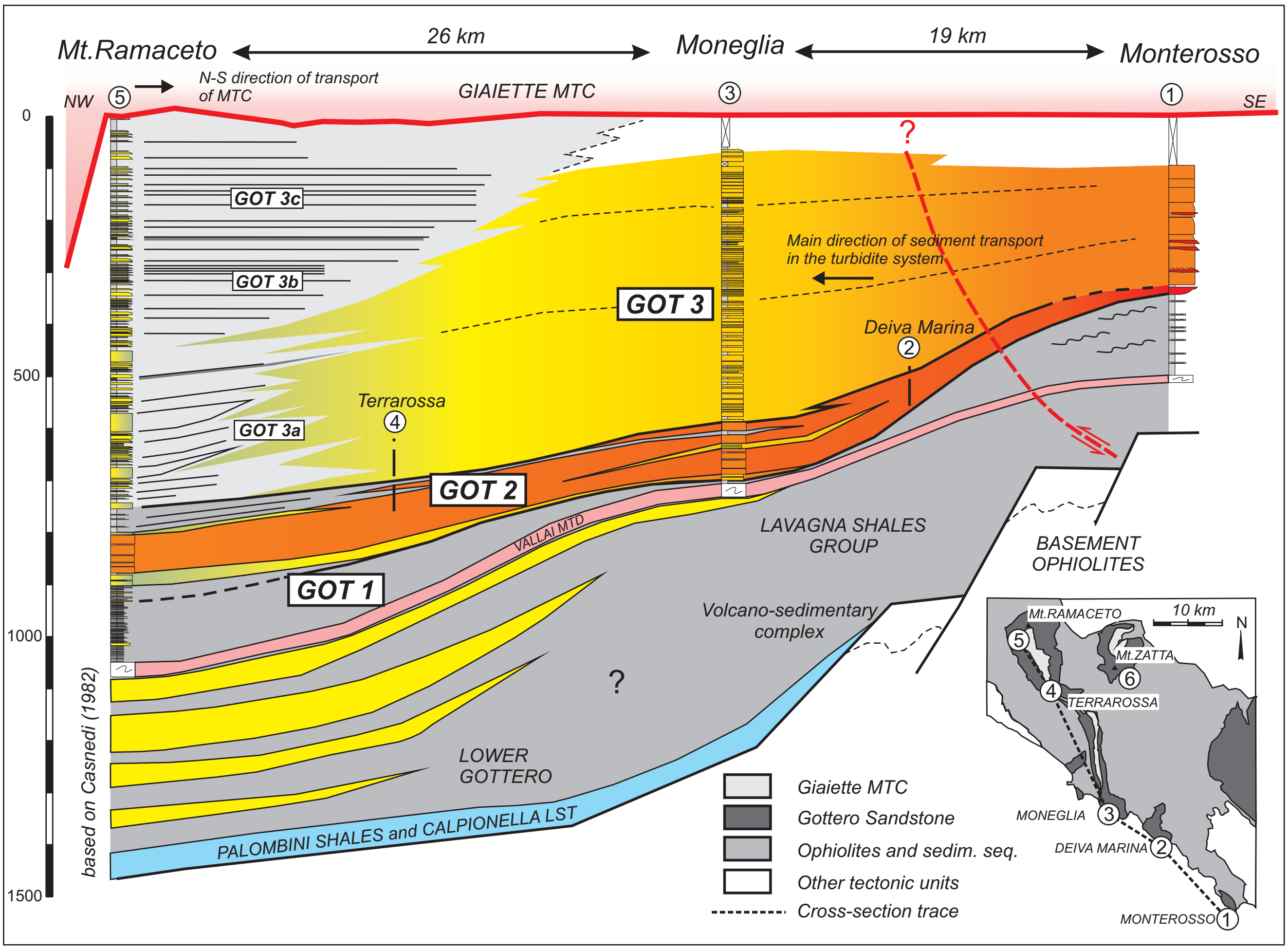

Fig. 18 - NW-SE aligned summary cross-section of the Gottero system (modified after Fonnesu et al., 2018) approximately parallel to the sediment transport direction (SE to NW). Colour shading according to the major grain-size and lithofacies (red colours: conglomerate and coarse grained sandstones, green: hybrid event beds, grey: mostly siltstone and mudstones or fine-grained sandstones, pink: mass transport complexes, light gray: confined turbidites and hybrid event beds). The area interpreted as confined basin plain is coloured in light grey. Poorly exposed sections are left blank. Note that the distances between sections have not been palinspastically restored and could potentially be longer than indicated.

to its character and composition and its relative stratigraphic position in the context of the Gottero system, an origin from the destabilisation of the Sardinian-Corsica margin is considered likely, therefore it shares the same provenance to the rest of gravity flow deposits of the Gottero.

Gottero 1

The Vallai MTD is overlain by thin-bedded fine-grained deposits, here defined as Gottero 1 (Figs 18-20). They form a laterally-extensive unit the thickness of which varies from a few hundred metres at Monterosso, 40-50 metres at Moneglia and Mt. Zatta, and 140 m on Mt. Ramaceto. The unit is generally constituted by thin-bedded and fine-grained turbidite sandstones associated with a predominant mudstone facies, but its facies character can change greatly: in the proximal Monterosso section the Gottero 1 contains several slumped beds as well as thin-bedded turbidites, and is interpreted as slope deposits. In Mt. Zatta the Gottero 1 interval is enriched in thicker beds with sedimentary structures indicating flow reflections and combined flow conditions (see Kneller et al. 1991; Haughton 2001; Tinterri 2011; Patacci et al. 2015; Felletti 2002). This character is interpreted to relate to flow reflections against irregular topography produced at the top of the underlying Vallai mass transport deposit. Examples of the same kind of stratigraphic relationship are provided by Kneller et al. (2016) from a range of modern and ancient deep-water systems. In the Mt. Ramaceto area, the succession is dominated by a thick stack of thin-bedded laminated turbidites, resembling a basin plain succession, but it is occa-

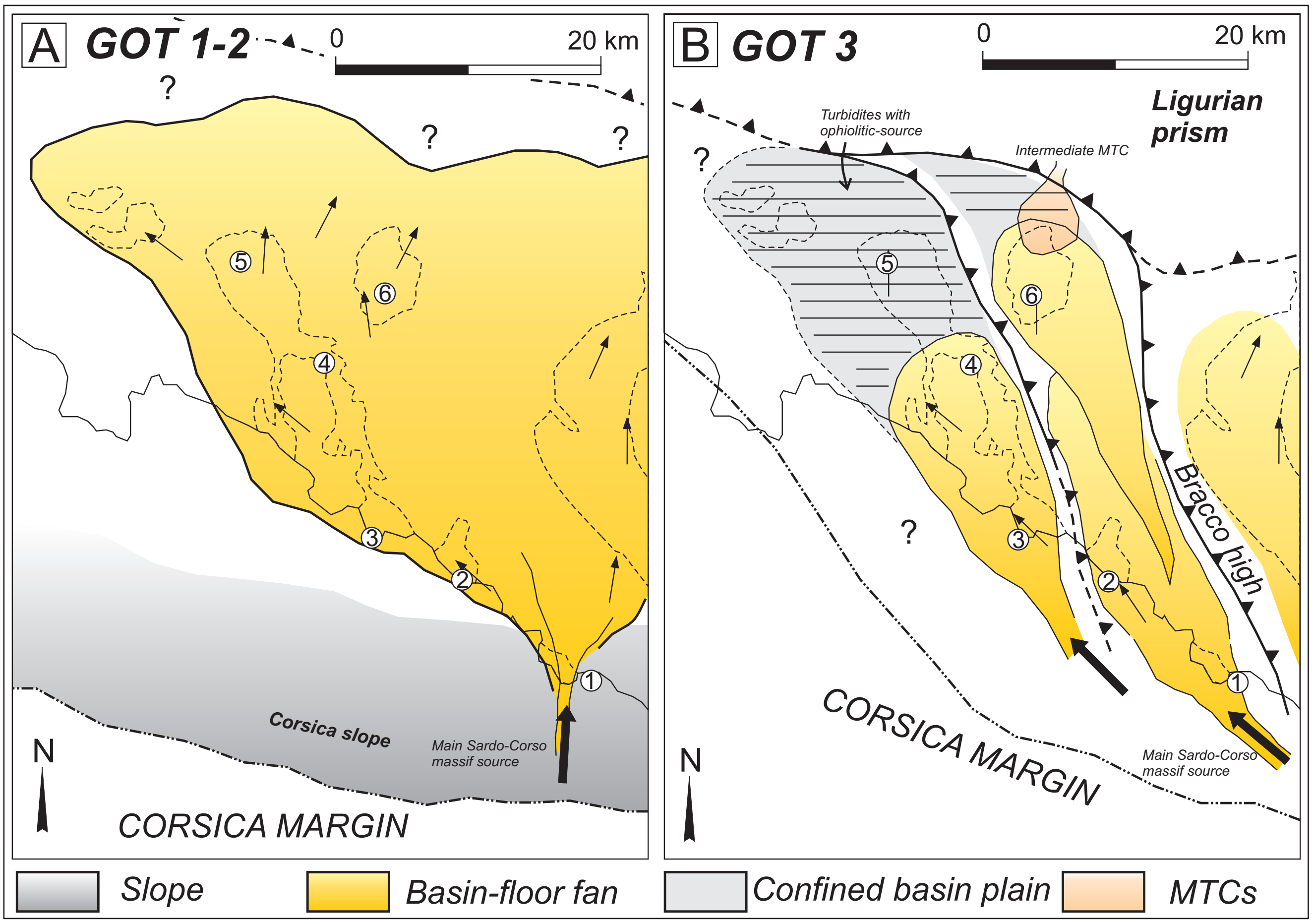

Fig. 19 - Palaeogeographic maps showing the evolution of the Gottero system. A) Gottero 1-2: the system is dominated by an unconfined basin floor fan. B) Gottero 3: the evolution of Ligurian margin creates tectonic segmentation of the basin and formation of a proximal fan system and a distal confined basin floor. The thin dashed lines represent the shape of actual outcrops (from Nilsen and Abbate, 1984). Large arrows represent sediment sources, smaller arrows are general palaeoflows. The maps have not been restored for original configuration with respect to the north due to plate rotation. 1) Monterosso; 2) Deiva Marina; 3) Moneglia; 4) Terrarossa; 5) Mt. Ramaceto; 6) Mt. Zatta.

sionally punctuated by a few coarser-grained events interpreted as distal lobes. The unit can be interpreted as a fine-grained prograding wedge similar to the ones recognised by Mutti et al. (1988) in the South-Central Pyrenees basin in which slope deposits thin out in a basinward direction passing downdip to widespread thin-bedded units separating the sandstone-rich basin floor fan deposits.

Gottero 2

Gottero 2 is a regionally extensive sand-rich unit (N/G of 85%) made up of up to eight sandstone packages forming tabular sandstone bodies (interpreted as lobes) separated by relatively continuous mud-prone deposits with a total thickness varying from 20 m to 105 m (Fig. 18; Fig. 19). The transition from the underlying Gottero 1 unit has a different character in the various localities. At Monterosso, the fine-grained Gottero 1 deposits are erosively cut by a channel thalweg interpreted to represent the base of the Gottero 2 unit. In other sections the passage is more transitional and expressed by a thickening- and coarsening-upward trend (Fig. 20). The transition occurs over only 12 m in the Moneglia section; however, it is considerably expanded in the Mt. Zatta (about 30 m) and Mt. Ramaceto sections (about 55 m).

The sandbodies constituting the bulk of the Gottero 2 tend to be relatively coarse grained and become less amalgamated when traced basinward (Mt. Ramaceto), and coarser and more densely nested in proximal sections (Moneglia, Deiva Marina, Sestri Levante). No correlations can be traced with enough confidence throughout the very up-dip section at Monterosso, but it could be argued that the earliest of channel-bodies described here represents

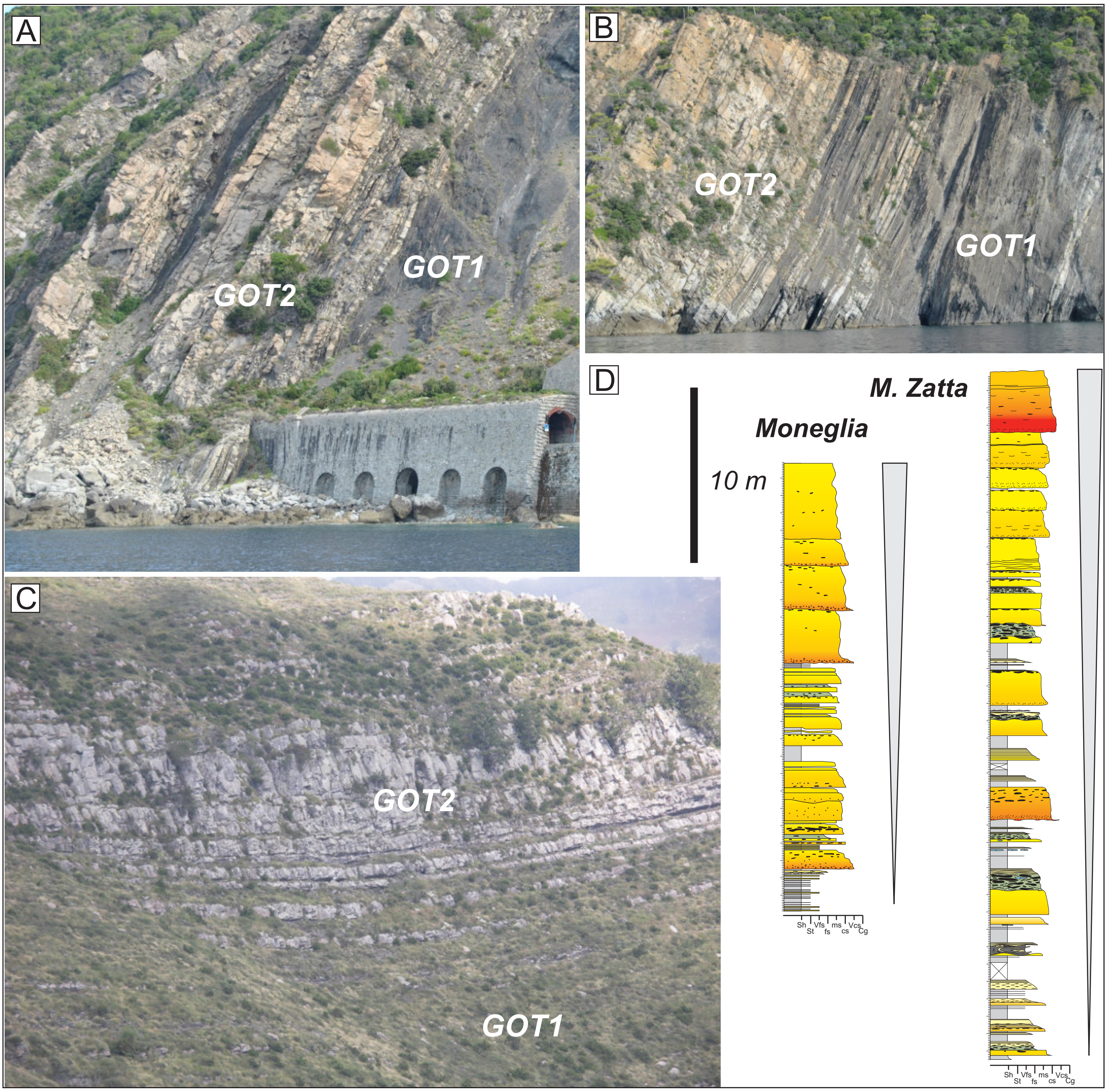

Fig. 20 - Outcrop and log exposure of the Gottero 1/Gottero 2 transition characterised by a thickening and coarsening upward trend in different locations. A) Riva Trigoso section (Moneglia). B) Moneglia coastal cliff. C) Monte Zatta. D) Logs (at the same scale) representing the condensed and expanded transitions exposed in the Moneglia and Mt. Zatta successions respectively.

the apex of the system close to the base of slope at this time. The lack of conspicuous facies and thickness changes in the unit (i.e. lack of fan fringes facies) suggests that it extended well beyond the available outcrops. Therefore, the Gottero 2 unit can be interpreted as an extensive **basin floor fan** fed by sediment routed from the Corsica margin (Fig. 19A). Similar units have been interpreted in the South-Central Pyrenees in the Banastón Group, where laterally extensive lobe units can be traced for ~60 km down-dip (Remacha et al. 2005).

The Gottero 2 unit is capped in the Mt. Ramaceto by a 52 m thick mud-prone interval (Gottero 2-3) which is not clearly recognised in the other sections. At Terrarossa and Mt. Zatta, three extra sandstone bodies are found at this stratigraphic level. In contrast to the lowermost Gottero 2 packages, they show a lower degree of bed amalgamation and are split by mud-prone intervals. The upper Gottero 2 section could hence constitute a later phase of system retrogradation during which fan fringe facies were developed in the distal sectors. This trend could indicate the relative starving of the system (or transgression), or an increasing in subsidence which characterise the following stage of basin filling in its distal depocentres (Mt. Ramaceto and Mt. Zatta).

Gottero 3

Gottero 3 represents the thickest unit distinguished (Fig. 18). It shows a very different character across the various outcrop localities, being dominated by lobe deposits in the Moneglia locality and mostly by extensive isolated sheets in the more distal Mt. Ramaceto area. The position of the base of Gottero 3 in the proximal Monterosso outcrop is uncertain but it could coincide with the facies association change from the lower channelized body and the uppermost more tabular unit interpreted as a sandy channel-lobe transition. The medial part of the system (Moneglia, Terrarossa) is dominated by outer fan lobes indicating a relative backstepping trend in comparison to the previous Gottero 2 phase. This stratigraphic evolution therefore suggests that starting from the top of Gottero 2 basin floor fan, the system progressively retreated but still developed as a relatively **unconfined turbidite fan** in the proximal and medial domains (Fig. 19B). On the contrary, the distal part of Gottero 3 succession is interpreted to be deposited in a **confined basin plain** (Fig. 19B). Although basin plains are commonly considered mud-prone, those developed in confined and tectonically-active settings are generally sandier (Pickering & Hiscott 2015) and include thick mud (-stone) caps where flows are ponded (Mutti & Johns 1978; Remacha et al. 2005; Mutti et al. 2009; Marini et al. 2015, 2016a,b). Despite the very different character between the proximal and distal areas of the Gottero outcrops at this level, the presence of two completely separate systems with different sources appears unlikely due to: 1) consistent palaeoflow directions; 2) similar petrographic signature (Parea 1964; Pandolfi 1997); 3) clear correlation of the basal Gottero 1 and Gottero 2 units across the proximal and distal domains.

The stratigraphic relationship between the Mt. Zatta succession with the equivalent Gottero 3 succession exposed in the Mt. Ramaceto section (Fig. 18) remains unclear. The Mt. Zatta proximal amalgamated lobes are stratigraphically above outer fan and sheet deposits, in contrast to the sequence at Mt. Ramaceto, where the bed pattern suggests an increase in basin confinement with time. The presence of a 40 m thick chaotic event in the Mt. Zatta succession with no equivalents in the Mt. Ramaceto section further indicates that the two sections do not share a common depositional history. The two sections are geographically only 8 km apart, but the structural restoration of the tectonic folds suggests that they could originally have been around 16 km apart (Fig. 3; cross-section a-a'). Several hypotheses might explain the divergent stratigraphic character:

the overall muddier Mt. Ramaceto section may record a down-current counterpart of the Mt. Zatta succession;

the two sections may represent two systems separated by a topographic palaeo-high;

the two systems developed in separate depocentres filled at different times.

The first hypothesis considers that the two sections could represent lateral equivalents of the same basin and the differences in facies would have to be ascribed to rapid down-dip changes in the flow character leading to the formation of different architectural elements (lobes vs. sheets). This option cannot be easily reconciled with the presence of opposite trends recorded in the two sections (progradational at Zatta vs. progressively confined at Mt. Ramaceto) and therefore it appears unlikely.

In the second scenario the two successions were separated by a pre-existing topographic high (e.g. approximately aligned along the Sturla valley, see map of Fig. 3) as suggested by Marini (1991, 1995). The issue related to this interpretation is that the basal Gottero 1 and Gottero 2 successions have clear similarities and therefore seem to represent part of the same depositional system.

The third option implies that the two sections are developed in separate depocentres related to the formation of a series of tectonically-controlled trenches younging from east to west during Gottero 3 time (Fig. 19). In this case the Deiva Marina and the Monterosso outcrops where probably related to the same Gottero sub-basin as the Mt. Zatta, while the Moneglia, Sestri Levante, Terrarossa and Mt. Ramaceto successions could represent expression of a second trench fill. This model could also include the most eastward exposure of the Gottero Sandstone in Mt. Gottero-Mt. Molinatico, situated outside of the studied area (see Fig. 1), where an earlier trench could have developed.

Giaiette Shales (MTC)

According to Marroni & Pandolfi (2001), Giaiette deposits (Fig. 18) are interpreted as the result of the tectonic erosion that occurred at the front of the Alpine accretionary margin during the Early Palaeocene. The exotic material derived from the ophiolite sequence and its sedimentary cover could have been previously deposited and stacked at the base of an accretionary wedge and then remobilized by catastrophic collapse. Similar highly-erosive MTCs are commonly observed at the front of subduction-related active margins. These mass-transport events are able to produce erosional excavation of the sea floor up to 100s of metres deep. The reduction in thickness of the Giaiette unit in the southern locations (e.g., Moneglia) is consistent with this interpretation as the MTCs are commonly strongly tapered.

Basin filling style of the Gottero 3 succession

The very different stacking pattern and the variable nature of the bed types deposited in the proximal and distal part of the system highlight the complex nature of the Gottero basin filling. In particular, during the Gottero 3 time the sedimentation in the system develop with two different styles and stacking patterns: in the proximal areas (Deiva Marina, Moneglia, Terrarossa) the system is very sand-rich, amalgamations are common, beds are generally poorly graded, and poorly-sorted other than lacking of associated mudstone caps. In outer lobe/off-axis lobe succession, argillaceous-type hybrid event beds are present, which origin is interpreted to derive from clay-entrainment in the proximal base-of-slope sector by turbulent erosion (see Fonnesu et al. 2018). Bed stacks are organized into discrete lobe cycles separated by thin-bedded intervals and lenticular coarse-grained lags can be found. In general, it can be described as a poorly efficient sand-prone fan system. Otherwise, the succession cropping out in the Mt. Ramaceto depocentre is dominated by very thick and laterally extensive event beds showing well developed internal grain-size grading, thick associated mudstone caps that are interbedded with thin-bedded packages. The abundant hybrid event beds present are thick mudstone-clast rich or raft-bearing type and the origin of entrained material is mostly derived by delamination of the basin floor substrate (Fonnesu et al. 2018). The area during the Gottero 3 time, can be interpreted as a high-efficiency and laterally confined or ponded system. Overall, because these two group of facies and stacking pattern characteristics are never found interbedded in the same vertical succession (Walther law) is reasonable to infer that the proximal to distal transition observed cannot be simply explained as a down-dip flow evolution of the same events depositing along the entire basin profile. However, the two areas cannot also be interpreted as different sub-basins because: 1) are mapped in continuous from the Ligurian coast to the Apenninic inland (Fig. 3) have a coherent paleflow orientation, 3) have correlatable Gottero 1 and Gottero 2 succession, 4) and share the same petrographic signature (Pandolfi 1997).

In this type of configuration and in the absence of facies continuity between the proximal and distal areas, the Mt. Ramaceto depocentre could be fed by outsize flows able to reach the basin plain area bypassing the proximal fan (maybe just leaving few local lags or channels; Fig. 21). Smaller volume and less efficient flows otherwise formed the sandstone beds and hybrid event beds in the proximal area and probably occasionally reached the distal basin plain area where they deposited laterally extensive low-density turbidites forming the heterolithic thin-bedded packages (Fonnesu et al. 2018).

Alternatively, the distal depocentre could be fed by an intervening eroding channelized system that, at a certain time, would cut the proximal fan and deliver sediment directly to the confined basin plain area. This hypothesis implies that the Gottero 3 succession in the Moneglia and Mt. Ramaceto areas cannot be considered isochronous, but the sedimentation would happen before in the proximal sector followed by the channel formation and deposition in the distal area. Despite this second hypothesis have many examples in modern and ancient basins (see Fonnesu 2003), it is considered less probable in this case. It is due to: 1) no evidences of a channelized system in the upper stratigraphic part of proximal Gottero 3 unit has been found; 2) it would imply a consistent sedimentation gap or unconformity between the Gottero 2 and Gottero 3 succession in Mt. Ramaceto that has not detected; 3) would inva-

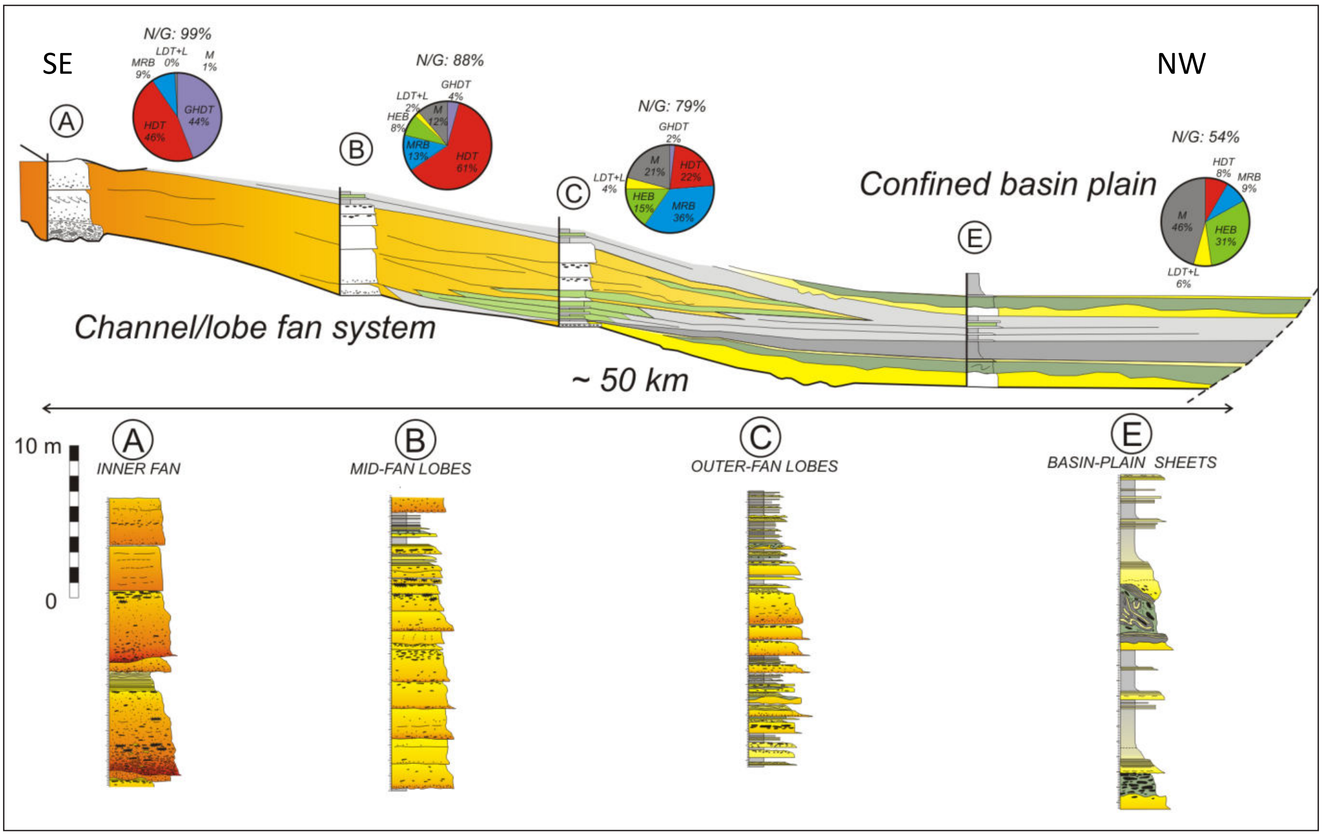

Fig. 21 - Diagram summarising facies association of the Gottero system with the relative palaeogeographic setting. N/G calculations and bed type proportions are also reported for each depositional sub-environment. GHDT: gravelly high-density turbidites; HDT: high-density turbidites; MRB. Mudstone clasts-rich beds; HEB: hybrid event beds; LDT+L: background thin beds and limestone layers; M: mudstone.

lid the supposed correlation between the mud-prone intervals (septarie), found in both Moneglia and Mt. Ramaceto location.

However, despite no long-range correlations and/or high-resolution biostratigraphic control on the succession are available, the first hypothesis is preferred.

Paleogeography in the Ligurian collisional setting background

The previous outcrop and regional scale observations can be tentatively tight in with the general background tectonic context of the Ligurian convergent margin setting.

The Gottero Sandstone represents a turbidite system developed in the later stages of the evolution of the Ligurian-Piedmont Sea, at a time and in an area of active convergence between Europe and Adria plates (Bortolotti et al. 1990; Cavazza et al. 2004; Carmignani et al. 2004; Critelli 2018). Sediments were sourced from the Corsica margin (Sagri & Marri 1980) which, according to the reconstruction by Marroni & Pandolfi (2007), formed a steep fault-controlled slope onto an originally passive margin setting.

The onset of the deposition of the Gottero system was initially built out into a relatively unconfined basin setting. The first fan phase was controlled by intermittent sediment supply and resulted in relatively extensive turbidite lobes (Lower Gottero) interbedded with fine-grained deposits. Following an important failure of the Corsica margin with the emplacement of the regionally extensive Vallai MTD, the Gottero system underwent a rapid growth with the progradation of Gottero 1 slope and Gottero 2 basin floor fan systems (Fig. 22-I). Fan initiation appears to have been very rapid, despite the transition happening more gradually in the most distal sections (Mt. Zatta and Mt. Ramaceto). At the end of this phase of fan growth, the system backstepped, forming a wedge of fine-grained sediments in more distal regions (Gottero

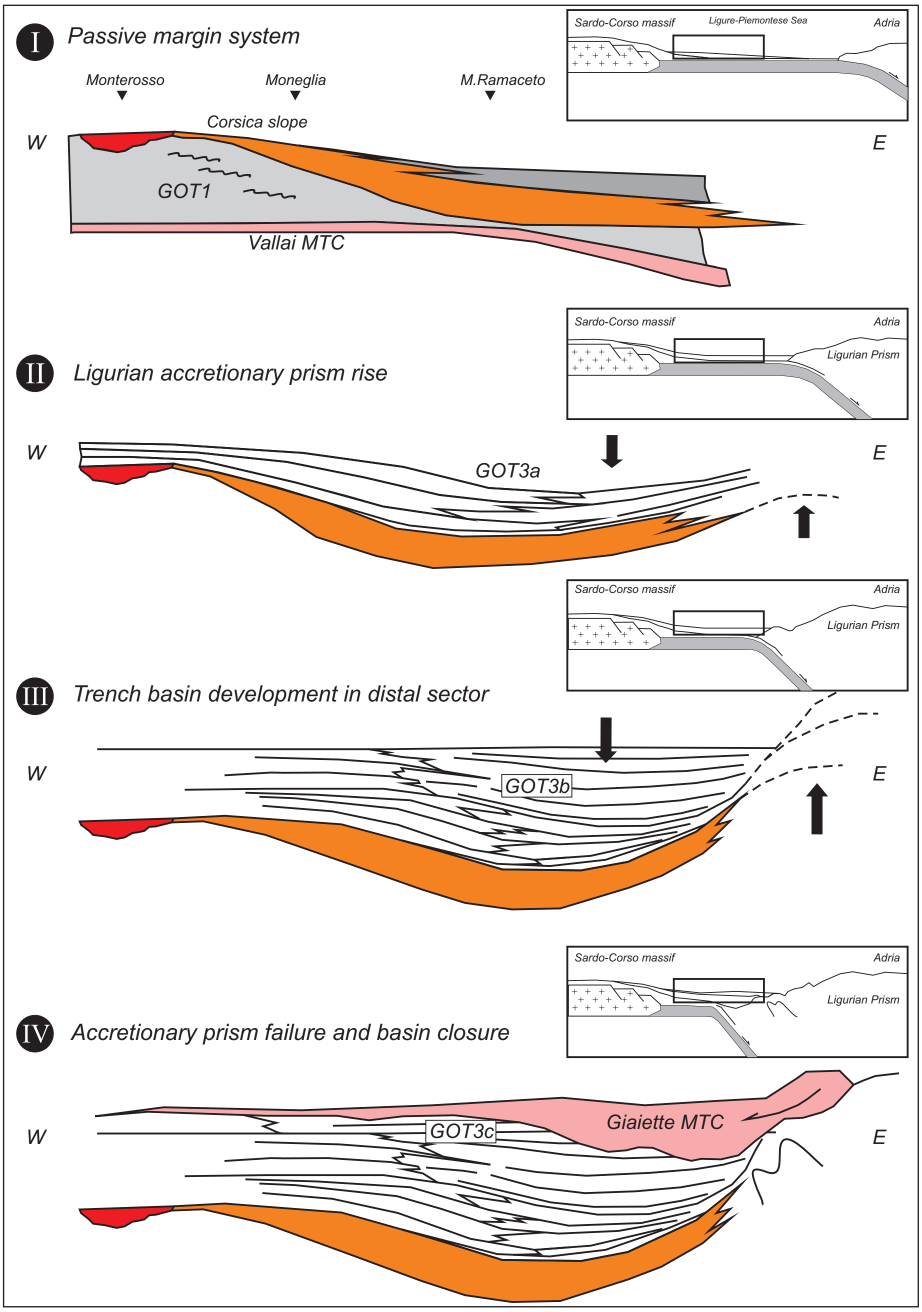

Fig. 22 - Schematic representation of the stratigraphic architecture of the Gottero system in response to the evolution of the Ligurian margin.

2-3) and stacks of receding lobes in more proximal areas. Such a backstepping phase could be related to a change in basin topography due to the arrival of the Ligurian basin closer to the area of subduction underneath the Ligurian accretionary prism.

At this point (Gottero 3) the system underwent a phase of basin reconfiguration marked by important facies changes across the fan and linked basin plain (Fig. 22-II; Fig. 22-III). The proximal area was still dominated by a relatively unconfined submarine fan, while in the distal sector two distinct depocentres were developed (Mt. Zatta and Mt. Ramaceto). The basin probably became confined at its frontal end due to the rise of tectonic structures (Bracco high; Elter & Raggi 1965), possibly related to the contemporaneous growth of the Alpine accretionary prism. The new basin configuration may have been related to subduction-related flexural subsidence and contemporaneous rise of the Ligurian prism which started to grow and advance, as previously deposited sediments located nearer the deformation front were off scrapped (Pandolfi 1997; Marroni et al. 2004). An increase in the subsidence towards the end of Gottero deposition could be responsible for the unusual stacking pattern recorded in Mt. Ramaceto succession with the evidence for increased basin confinement with time. Such a pattern is distinctive and differs from other successions originated in foredeep settings (Oligocene Macigno; Cornamusini 2004; Amendola et al. 2016; Langhian – Lower Messinian Marnoso Arenacea; Tinterri & Muzzi Magalhaes 2011; Messinian Laga basin; Milli et al. 2007; Marini et al. 2011, 2015; 2016b; Stalder et al., 2018; Pliocene Cellino Basin; Felletti et al. 2009; Carruba et al. 2004, 2007) or tectonically-controlled minibasins (Miocene Castagnola; Marini et al. 2016a; Southern et al. 2015; Oligocene Cengio; Bersezio et al. 2010; Felletti & Bersezio 2010a,b; Felletti 2016) which usually tend to get progressively filled and hence became less confined through time. The Gottero 3 succession could therefore be interpreted as a trench-fill succession which recorded the progressively narrowing of the trench during the convergence between the accretionary prism and the European plate. The coastal Gottero succession could have been deposited in an area further from the deformation front, which implies a less dramatic increase of the subsidence rate due to the pattern of flexural subsidence. Nevertheless, the presence of more vertically separated sandbodies in the uppermost part of the Moneglia section suggests that the increase of subsidence might have started to also affect the more proximal fan area toward the end of the Gottero history.

The advance of the front of an accretionary prism is also consistent with the hypothesis of the evolution of multiple trenches used to explain the problematic correlation between Mt. Zatta and Mt. Ramaceto successions. The prograding trend identified in the Mt. Zatta succession could be explained by the progressive filling of a Gottero sub-basin during an earlier phase of Ligurian prism accretion and more modest subsidence. The ponded conditions that developed in the Mt. Ramaceto sector might reflect an increase in subduction-related flexural subsidence that exceeded the sediment supply leading to the formation of a narrow undersupplied trench in which flows could pond.

Towards the end of Gottero 3 deposition, the first evidence of destabilisation of the northern basin margin could be inferred by the presence of sandstone beds with an ophiolite-derived provenance signature at Mt. Ramaceto (Pandolfi 1997) and the presence of an MTD with exotic limestone blocks at Mt. Zatta. The end of sedimentation in the Gottero Ligurian trench (Fig. 22-IV) is recorded by the collapse of the Ligurian accretionary prism and the formation of the Giaiette MTD.

Conclusions

This study contributes to the existing knowledge on turbidite systems, allowing reconstruction of the main architectural elements of a sand-rich fan, from slope to basin floor in a convergent margin setting. The Cretaceous-Palaeocene Gottero system represents one of the few deep-water fan in the Apennine chain preserving both proximal and distal sectors. The wide range of deep-water sub-environments provide new insight into how submarine sediment flows evolve as they spread across low gradient basin floor fan. The core findings of this research are as follows:

The Gottero system was deposited in a dynamic tectonic setting which drove overall system trends and accounts for the evolution of different sectors of the basin.

A set of deep-water facies associations and related sub-environments are recognised (Fonnesu et al., 2018), including slope deposits, inner-fan channels and channel-lobe transition deposits, mid-fan lobes, outer-fan lobes and confined basin plain sheets.

The evolution from an extensive basin floor fan to a system including a proximal fan and a distal confined basin plain, can be explained by flexural subsidence in front of a rising accretionary complex. Such a configuration challenges the interpretation of Nilsen and Abbate (1984) of the Gottero fan as an unconfined radial-shaped submarine fan.

The transition between the relatively unconfined basin floor fan (Gottero 2) and the interval during which the system assumes a more complex palaeogeography (Gottero 3) could be related to the start of the structural segmentation of the basin in response to the growth of the Alpine accretionary prism.

The different facies character and stacking pattern of the proximal and distal during Gottero 3 time, from amalgamated sand-prone unconfined channel-lobe system to sheeted confined/ponded sheet system, can be explained by the presence of outsize flows bypassing the proximal area and depositing in the distal depocentre. Smaller volume and less efficient flows otherwise formed the beds in the proximal area and only occasionally reached the distal basin plain area forming the thin-bedded packages.

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