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Basin topography and depositional styles controlled by collisional tectonics in the Alps-Apennines junction (Tertiary Piedmont Basin, NW Italy)

Andrea Di Giulio[1], Mattia Marini[2], Fabrizio Felletti[2], Marco Patacci[4], Massimo Rossi[3], Chiara Amadori[1], Niccolò Menegoni[1], Simone Reguzzi[5], Silvia Tamburelli[1]

[1] Dipartimento di Scienze della Terra e dell'Ambiente – Università di Pavia – Italy.
[2] Dipartimento di Scienze della Terra 'Ardito Desio' – Università di Milano – Italy.
[3] Guest Lecturer, Department of Environment and Earth Sciences, University of Milan-Bicocca.
[4] School of Earth and Environment – University of Leeds – UK.
[5] Eni S.p.a. Upstream & Technical Services – San Donato Milanese (Milan) – Italy.

Corresponding author e-mail: silvia.tamburelli01@universitadipavia.it

Cover page Figure: Panoramic view of the north-verging fold affecting the Priabonian turbidites of the Ranzano Formation near the village of Fontanelle.

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INDEX

INFORMATION

EXCURSION NOTES

ITINERARY

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ABSTRACT

The field trip illustrates the changes in the late Eocene-Miocene depositional systems filling the Tertiary Piedmont Basin in response to major palaeogeographic reorganizations linked to the evolution of the Alpine-Apennine tectonic junction. During days 1st-2nd-3rd the field trip aims to show some key outcrops of the southwestern part of the basin, where Tertiary sedimentary units unconformably cover the basement of the Ligurian Alps. During days 4th-5th the most significant outcrops of the upper Eocene-Lower Miocene sequence are shown covering the Ligurian Units of Northern Apennines in the Alps-Apennines tectonic knot. Several depositional systems are here examined, including alluvial, marginal marine, shelf, intra-slope, and basin-plain turbidites. Outcrop observations are integrated with photogrammetric models and seismic images from the time-equivalent buried systems within the study area. Topics covered in the guide include: 1) relationships between morphostructural elements and origin of sequence boundaries driven by relative sea level falls vs. hinged-margin drowning unconformities driven by hinged accommodation on oversteepened shelf margins; 2) morphologies of deep-water erosion; 3) controls of the basin morphology on the development of turbidite facies and architecture; 4) turbidite petrography and its implication on origin and source of mud-grade sediments; 5) implications for characterisation of analogue hydrocarbon plays and reservoirs.

Keywords: Tertiary Piedmont Basin, Alps-Apennines junction, clastic sediments, drowning unconformities, syn-sedimentary tectonics, shelfal system, turbidite system.

PROGRAM SUMMARY

Table 1 - Location of stops (described with geographic coordinates and altitude) of the field trip, organised per day.

Day	Stop number	Latitude	Longitude	Altitude a.s.l. (m)
1	1.1	44.59963053 N	8.407089778 E	241
	1.2	44.57907766 N	8.334191369 E	197
	1.3	44.56117143 N	8.347098237 E	230
2	2.1	44.50389391 N	8.434276928 E	344
	2.2	44.49636458 N	8.402554743 E	435
	2.3	44.51306082 N	8.351987864 E	356
	2.4	44.5476435 N	8.339477662 E	244
	2.5	44.53661862 N	8.350392528 E	349
	2.6	44.47116905 N	8.295235516 E	339
3	3.1	44.38256719 N	7.91851294 E	435
	3.2	44.4296652 N	7.923122864 E	306
	3.3	44.61332623 N	8.05557716 E	488

Day	Stop number	Latitude	Longitude	Altitude a.s.l. (m)
4	4.1	44.72646751 N	9.030416847 E	396
	4.2	44.77780556 N	9.031833333 E	343
	4.3	44.76983771 N	9.073133428 E	378
	4.4	44.77226398 N	9.100446019 E	495
	4.5	44.77219065 N	9.1285606 E	606
	4.6	44.7794047 N	9.137402551 E	484
	4.7	44.79827379 N	9.179400195 E	493
	4.8	44.79491939 N	9.230466737 E	502
5	5.1	44.80587337 N	9.183669315 E	493
	5.2	44.80388654 N	9.170071186 E	644
	5.3	44.81101849 N	9.182705838 E	502

SAFETY

It is advised to use appropriate clothes for outdoor walks on moderately steep slopes (such as hiking boots) and to be equipped to deal with a rapid worsening of weather conditions (warm and waterproof clothes, umbrella, etc.). High protection solar cream, sunglasses, hats and sweaters can be useful.
Always carry plenty of water and a first aid kit. If you have particular forms of allergy (e.g., insects, pollen, dust, food, etc.), always carry what you need in case of emergency.
Pay attention to animals that can prove to be harmful such as dogs, wild boars, insects, vipers. For the latter, the greatest risk is for the upper and lower limbs: never put your hands in the vegetation or in crevices where you cannot see. In the event of a viper bite or other incidents, you must consult a doctor and/or contact emergency numbers as fast as possible. Ticks can transmit Lyme disease (borreliosis).
Do not abandon waste of any kind. Smoking in the field is inadvisable, be careful not to cause fire.
Do not stop below rocky exposure from which blocks and stones can fall. Even a small rock fall can be extremely dangerous. Always carry and use a protective helmet when it is necessary to walk alongside vertical and potentially dangerous rocky outcrops.

Emergency telephone numbers in Italy

112 (all services); 113 (police); 115 (fire brigade);
118 (ambulance).

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HOSPITALS

Hospital "S.S. Annunziata"

Via Repetti, 2, 27057 Varzi Pavia, Italy
Medical Emergency
General Enquires: (0039) 0383 5471

Hospital "S. Antonio"

Via Badano Gerolamo, 23. Sv Sassello
Tel: (0039) 019 724127 / (0039) 019 723728

Hospital of Ceva

Pronto Soccorso:
Via San Bernardino, 4 - 12073 - Ceva
Tel: (0039) 0174 723902 / (0039) 0174 723904

Hospital "Regina Montis Regalis" of Mondovì

Pronto Soccorso
Via S. Rocchetto, 99
Tel: (0039) 0174677241

ACCOMODATIONS

There are several hotels, B&B, and camping in the area of the field trip. According to the field trip schedule, it is suggested to book accommodation in different areas in order to easily reach the daily stops.

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EXCURSION NOTES

Geological Setting

After the mid-Eocene continental collision between the Adria continental block and the European Plate (Doglioni, 1994), the Alps retrobelt hosted a thick clastic succession deposited during the flip of subduction polarity from the Alps to the Apennines (Argnani, 2012). The Tertiary Piedmont Basin (TPB; Fig. 1) originated in the retrobelt of the west- to southwest-verging Western Alps and Ligurian Alps. In the late Eocene-Oligocene, it was controlled by the Alpine tectonics causing uplift and erosion of the Ligurian Alps metamorphic core and subsidence of the northern margin of the belt and its retroforeland. Although in most of the basin this large scale process was associated to the development of a complex and wide transpressional-transtensional belt causing a mosaic of morphostructural highs and lows, the stratigraphic record (characterised by a long term subsidence-related deepening-upward organization during the whole Oligocene and associated to step-wise transgressive pulses leading to the submergence of large portions of the

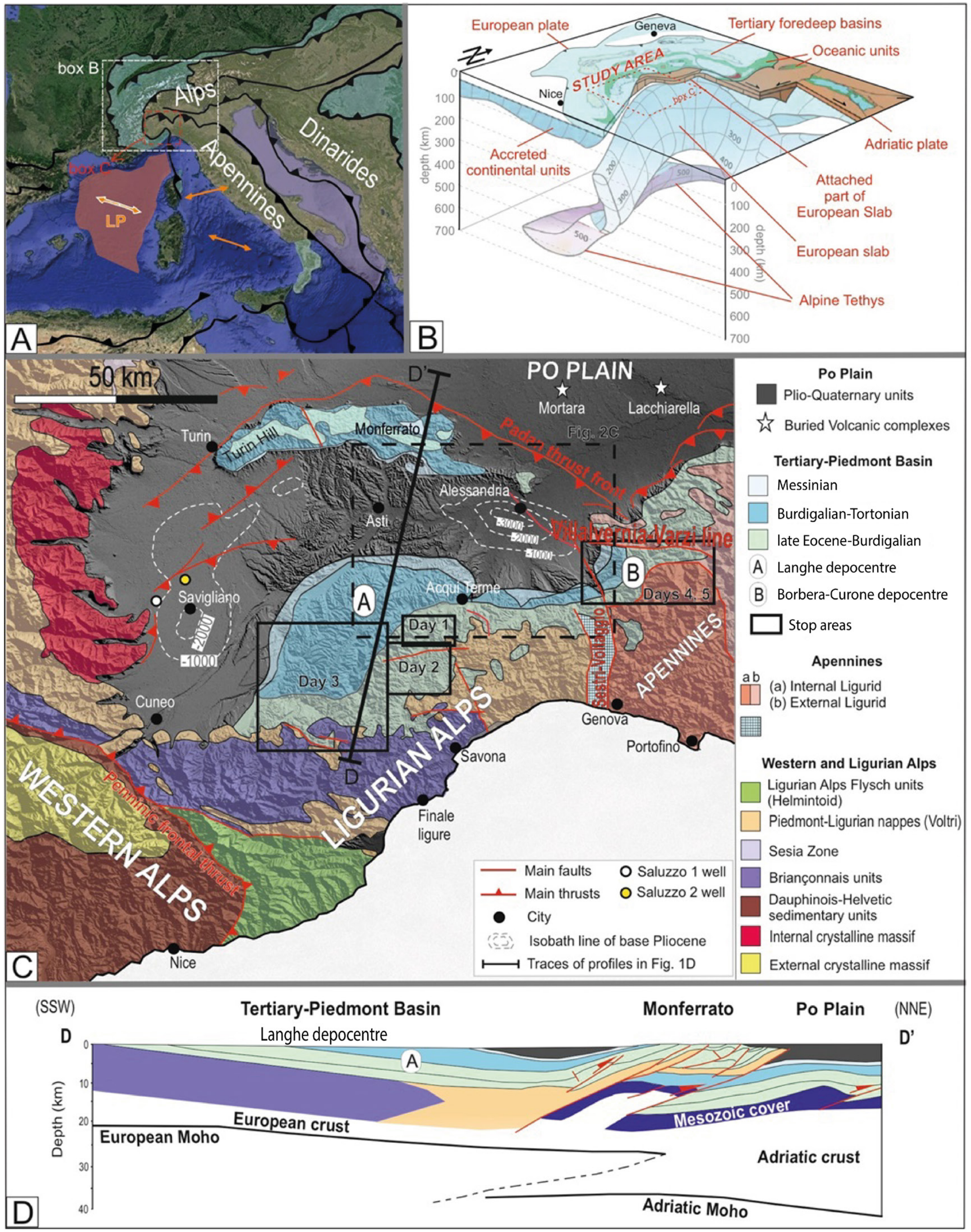

Fig. 1 - Geodynamic framework of the field-trip region (modified from Amadori et al., 2023). A) Geological and geodynamic setting of the Central Mediterranean area; B) 3D Lithospheric-scale reconstruction of the northwest Italy and the study area (modified after Handy et al., 2021); C) synthetic geological map of the Western and Ligurian Alps, Northern Apennines and Piedmont Tertiary Basin covering their junction (modified after Mosca et al., 2010 and Maino et al., 2013) with boxes reporting the area where different days of the field trip are developed. Sv = Sestri-Voltaggio line; gtz= Grognardo Thrust Zone; VV= Villavernia-Varzi tectonic line; Dashed grey lines are isobath (metres below sea level) of base Pliocene from Pieri & Groppi (1981) showing the Savigliano and Alessandria depocenters. D) Lithospheric-scale tectonic cross section D-D' modified after Bertotti et al. (2006).

Alpine axial zone) indicates that regional subsidence largely prevailed, perhaps suggesting an "orogenic collapse" *sensu* Selverstone (2005) (see that paper for a discussion). From latest Oligocene to Early Miocene, the Apenninic deformation started to interfere with Alpine ones. At this time, the lateral substitution of the Alpine east-dipping subduction with the Apenninic west-dipping subduction started to take place in almost all the basin, with the only exception of the western margin where the structures of the Alpine retrobelt were still active (Rossi & Craig, 2016). From the end of the Early Miocene to the Late Miocene, the velocity of the Apenninic slab rollback increased (Carminati et al., 2012), enhancing the opening of the Liguro-Provençal back-arc basin and the counter-clockwise rotation of Corsica and Sardinia (Maffione et al., 2008). This mechanism produced a regional subsidence, followed by uplift of the southern basin margin (i.e., the part of the basin immediately resting on the Ligurian Alps and Northern Apennines). Since latest Miocene, the Apennines completely overrode the Alpine retrobelt, so the northwest-verging Apenninic fronts accreted over the older southeast-verging Alpine margin (Mosca et al., 2010).

In summary, the area where the TPB developed is a very complex tectonic knot linking two collisional belts; the background aim of this field trip is to analyse how in the surface syn-tectonic deposition reacted to and therefore records major palaeogeographic reorganizations occurred in the Langhe area and in the Borbera-Curone area (Fig. 1, A and B respectively) in response to the lithospheric-scale tectonic evolution of the region (for a comprehensive overview of the domains in which the TPB and the western Po Plain areas are traditionally divided, the reader is referred to Ghibaudo et al., 2014 and references therein).

STRATIGRAPHIC FRAMEWORK

Large-scale stratigraphic units and their relations to the Alpine and Apenninic deformation

The evolution of the TPB can be disentangled only through the integration of outcrop and subsurface data involving different disciplines such as sedimentology, biostratigraphy, petrography, seismic stratigraphy and structural geology (see Rossi & Craig, 2016 and references therein). This is mainly due to the occurrence of separate outcrops and to major tectonic reorganisations that deeply modified the basin configuration meanwhile the Apennines' structures were displacing the Alps retroforeland (Carminati & Doglioni, 2012). For these reasons, during the last decade the cooperation between academia and oil company research centres produced significant advances in the understanding of such a complex basin covering the Alps-Apennines junction.

The stratigraphic succession observed in the field trip, spanning from Priabonian to Tortonian, can be subdivided into six large-scale unconformity-bounded stratigraphic units (Units I, II, III, IV, V and VI) recognised in both outcrop and subsurface by seismic profiles (Fig. 2). The bounding surfaces are generally tectonic-driven unconformities, non-conformities or paraconformities caused by basin reorganisations, expressed by structural hinges at the edges of the Alpine retrobelt or in relation to Apenninic deformation and enhanced close to seismically recognisable major morphostructural elements.

The Alpine margin collapse caused the seaward downwarping of shelf margins originating hinged-margin drowning unconformities (HDU *sensu* Rossi et al., 2018) affecting either siliciclastic shelves or carbonate ramps. Type I HDUs (Fig. 2) (characterised by seaward tilt with opposing accommodation and reciprocal stratigraphy) can be recognised in both outcrops and seismic profiles in the lower Oligocene succession. Since late Oligocene, Type II HDUs (characterised by seaward-tilt with backward-moving hinge and general accommodation increase) prevailed, due to an increase in rate of seaward tilt leading to a backward-moving of the hinge.

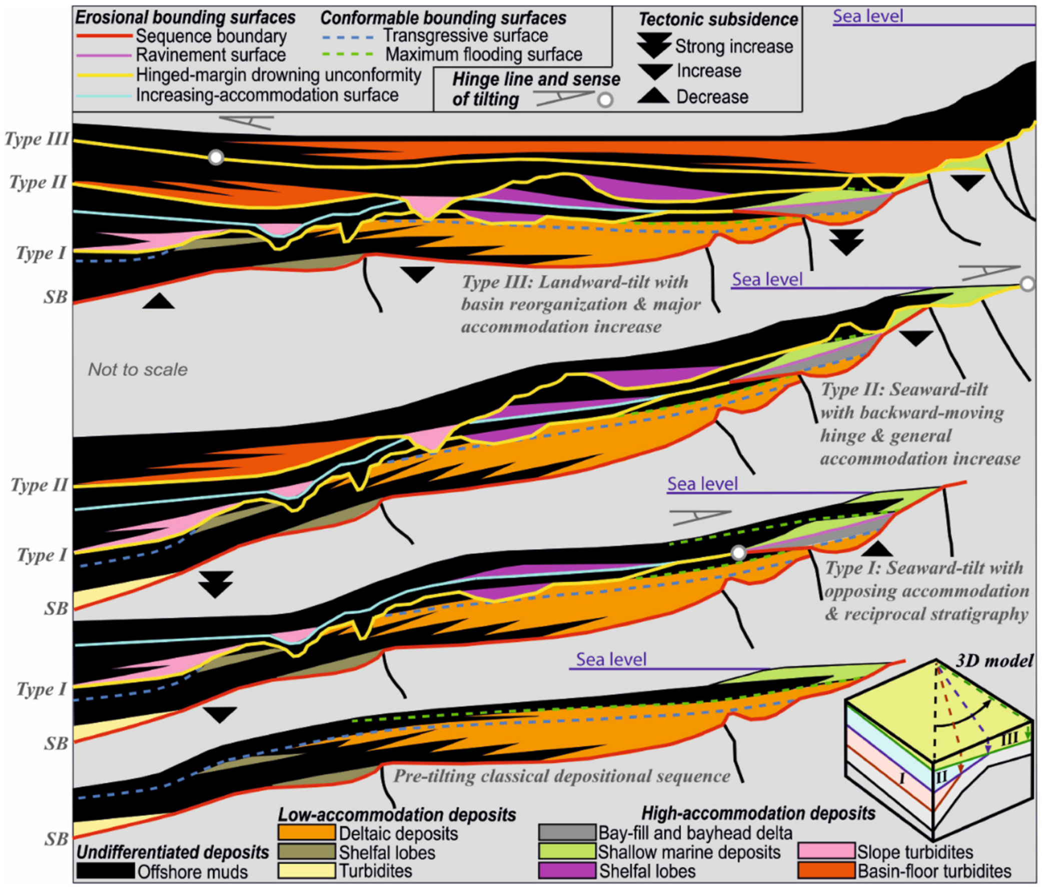

Fig. 2 - Types of hinged-margin drowning unconformities on tilted clastic shelves (from Rossi et al., 2018).

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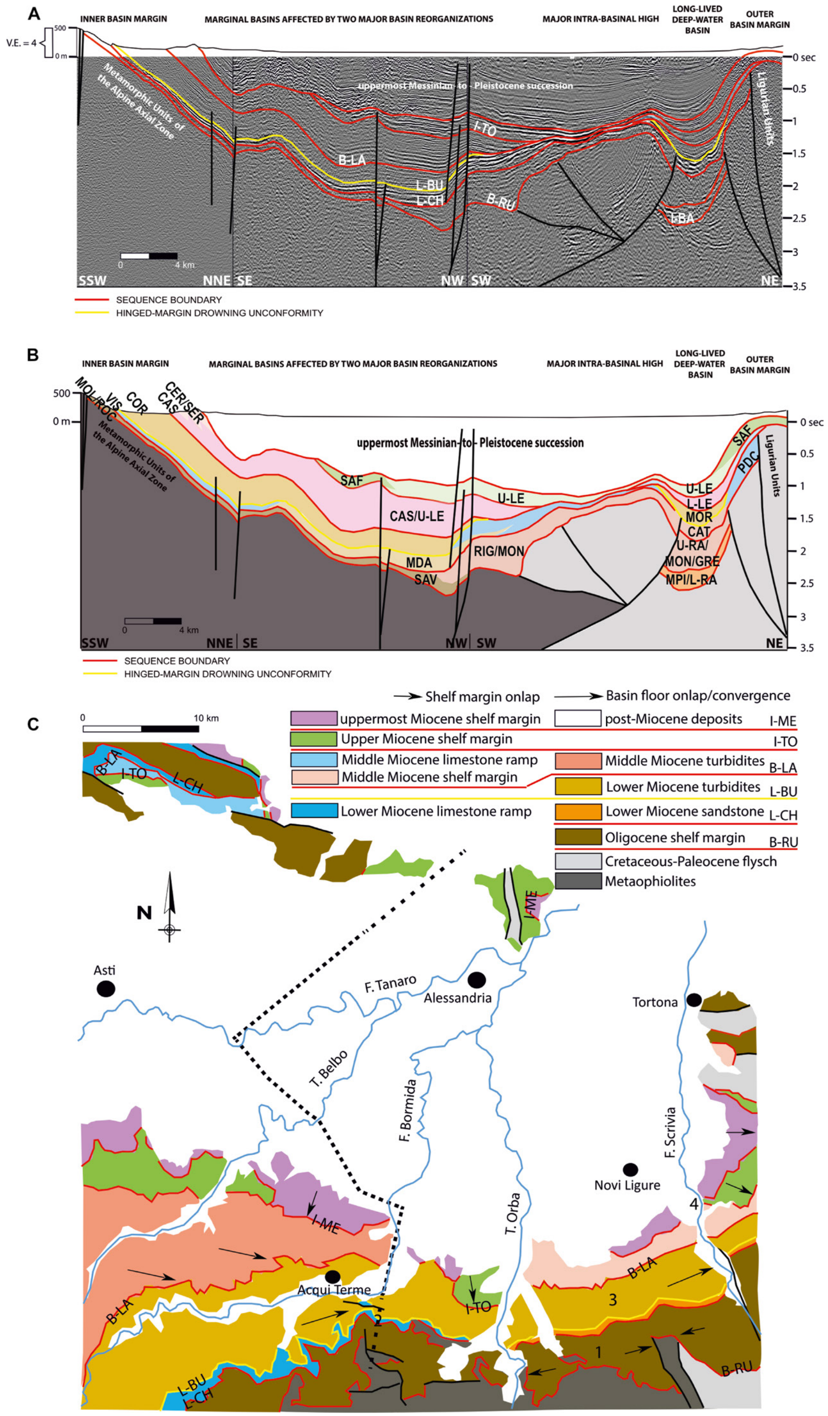

In the late Burdigalian, these unconformities were followed by type III HDUs (characterised by landward-tilt with basin reorganisation and major accommodation increase), when the Apennines structures involved the Alpine structures as the flip of subduction polarity moved Northward. This caused a high magnitude landward tilting and significant lateral changes in accommodation. More classical progressive unconformities, associated with seaward tilting and long-term relative sea level fall caused by the uplift of the Apennines, started to develop since the Langhian (Rossi, 2017).

Such structural and stratigraphic features, as well as the tectono-sedimentary evolution of the field trip area, are highlighted in the seismic profile shown in Figure 3, tied to outcrop and well data, and reported step by step in figures 2 and 4.

From a morphostructural viewpoint, it is possible to identify from South-West to North-East (Mosca et al., 2010; Rossi et al., 2009) the following sectors: 1) an inner basin margin close to the Alpine axial zone originated after the uplift of the Alps, showing a progressive Southwestward coastal encroachment recording the orogenic collapse; 2) marginal basins, lying over the Alpine axial zone predominantly metamorphic substratum, and characterised by a large-scale transgressive-regressive organization driven by two major basin inversions; 3) an area with intra-basinal highs associated with polyphasic transpressional-transtensional deformation, representing the buried continuation of the inner

Fig. 3 - Stratigraphy of the late Eocene-Miocene succession of TPB framed into the major morphostructural elements that controlled the basin fill architectures from the west-central to the northeastern sectors of the basin. Derived by the integration of outcrop and seismic data (adapted from Rossi, 2017). (A) Major unconformities traced in seismics: I-BA) intra-Bartonian unconformity; B-RU) base-Rupelian unconformity; L-CH) latest Chattian unconformity; L-BU) late Burdigalian unconformity; B-LA) base-Langhian unconformity; I-TO) intra-Tortonian unconformity; I-ME) intra-Messinian unconformity. (B) Main lithostratigraphic units - MPI) Mt. Piano Marl; L-RA) lower Ranzano Fm.; U-RA) upper Ranzano Fm.; SAV) Savignone conglomerate.; MOL) Molare fm.; ROC) Rocchetta fm.; RIG) Rigoroso fm.; MON) Monastero fm.; GRE) Gremiasco fm.; CAT) Castagnola fm.; MDA) Montechiaro d'Acqui fm.; VIS) Visone Fm.; PDC) Pietra da Cantoni fm.; COR) Cortemilia fm.; CAS) Cassinasco fm.; CES) Cessole fm.; SER) Serravalle fm.; L-LE) lower Lequio fm.; U-LE) upper Lequio fm.; SAF) S. Agata Fossili marls. (C) Simplified geologic map and trace of the seismic multipanel (dashed/dotted line) shown in boxes (a) and (b); the dotted part indicates the extent of the seismic profile shown in Fig. 3.

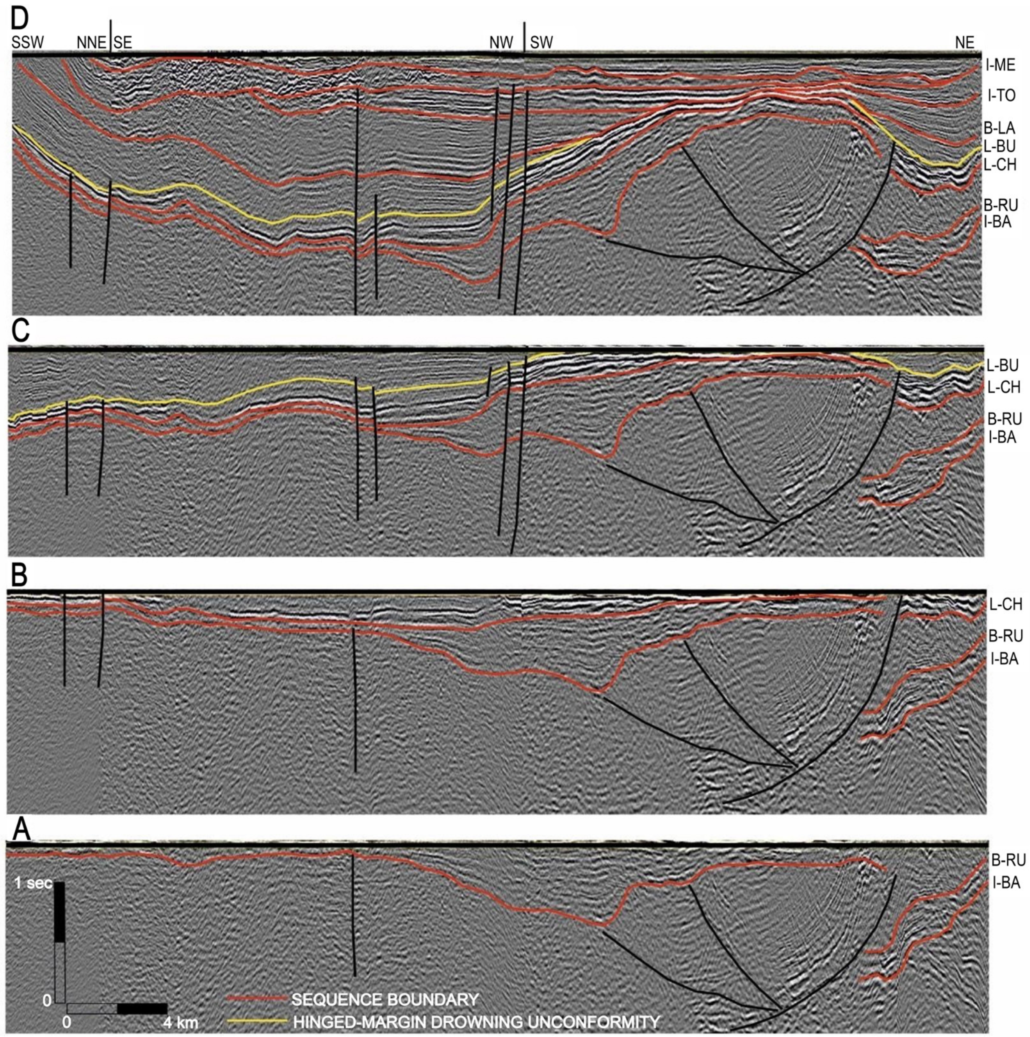

Fig. 4 - Step-wise reconstruction of tectono-sedimentary evolution of TPB by flattening. Panel D is central portion of the seismic multipanel in Fig. 3 (modified from Rossi, 2017).

Western Alps retroforeland margin , which juxtaposed the Alpine basement and the Cretaceous-Paleogene Ligurian flysch units; 4) a long-lived deep-water basin lying over the Ligurian units of the Apennines; 5) an outer basin margin Northward, bounded by a high angle transpressive fault system along which the Ligurian substratum was involved in the Apenninic deformation since the latest Oligocene.

Figure 4 shows part of the same seismic profile in Figure 3, where the tectono-sedimentary evolution of the TPB can be more easily appreciated through successive flattening, where for each significant time step the change in distribution of syn-depositional highs and lows highlights the reshaping that affected the overall basin configuration. This figure shows how the basin reorganisations controlled the stratigraphy, and in particular the major accommodation trends.

Relationships between physical stratigraphy and lithostratigraphy

Figures 3 and 4 illustrate the main changes occurring in the West-central sector and the Northeastern sector of the basin, observed during the field trip. The stratigraphy records: i) the sub-basin depocentres through time, illustrating the sequence of deformational events and the major basin reorganisations; ii) the effects on the areal distribution of depositional systems and large-scale shallowing- or deepening-upward trends (interpreted from lateral and vertical changes in seismic patterns); iii) the relationships between physical stratigraphy (derived from seismic data interpretation) and lithostratigraphy (derived from geologic mapping).

The large-scale seismo-stratigraphic units are briefly described and linked to the correlative lithostratigraphic units. This enables us to organise the field trip itinerary into the large-scale physical-stratigraphic units (as allostratigraphic units recording the tectono-sedimentary evolution of the basin) and local stratigraphy (smaller scale units and diachronous lithostratigraphic units recording depositional systems deposited in different sub-basins).

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Unit I (late Eocene) followed the mid-Eocene continental collision and is characterised by a predominantly deep-water mud-rich succession (*Marne di Monte Piano* - Mt. Piano Marl), locally including arkosic turbidites (lower Ranzano Fm.) overlain by shelfal lithic sandstones (Di Giulio et al., 1989, 1991; Martelli et al., 1998). These deposits change Westward into fluvio-lacustrine deposits (*brecce della Costa di Cravara* – Costa di Cravara breccia - and Pianfolco Fm.), non-conformably overlying the metamorphic basement of the Alpine axial zone (Mosca et al., 2010).

Unit II (Oligocene) overlies deposits of Unit I or, landward, the Alpine metamorphic basement (Mosca et al., 2010). Unit II records an increase of accommodation space due to the Alpine orogenic collapse, causing retrogradation of fan deltas adjacent to the Alpine axial zone and over the Ligurian units deformed after the collision. The lower Molare, Cardona and *conglomerati di Savignone* (Savignone conglomerate) fms. are overlain by – and change seaward into – shelf deposits (Rossi and Craig, 2016) punctuated by the seaward tilting of hinged shelf margins and intra-slope deposits (Mutti et al., 1995, 2002; Ghibaudo et al., 2014), creating type I and type II HDUs. This sedimentary succession mainly consists of mud-rich (Gremiasco and Rocchetta-Monesiglio fms.) and sand-rich (upper Ranzano, Monastero, Variano and lower Monesiglio fms.) lithostratigraphic units (Di Giulio, 1991; Cibin et al., 2003).

Unit III developed from latest Chattian to early Burdigalian, while Apenninic frontal splays started forming. At this time, the TPB became a large thrust-top basin of the Apennines, predominantly hosting turbidite systems (upper Rocchetta-Monesiglio and Castagnola fms.). The incipient growth of an antiformal stack involving Adria plate caused North- to Northwest verging Apenninic structures, broadly opposite to the vergence of the previous Alpine retrobelt. In the central part of TPB, some of these structural highs were rimmed by foramol-rhodalgal carbonate ramps (Visone and Pietra da Cantoni fms., Piana et al., 1997) passing seaward into basinal mudstones and resedimented carbonates (Montechiaro d'Acqui Fm., Ghibaudo et al., 2014). At the same time, fan deltas and braid deltas (upper Molare Fm.) developed adjacent to the Alps (Gelati & Gnaccolini, 1996), reaching a maximum regression during early Burdigalian. Generally, the basin configuration from Priabonian to early Burdigalian shows increasing accommodation toward the less elevated morphostructural belt to the northeast, punctuated by subaqueous unconformities.

Unit IV (late Burdigalian) records a significant increase in subsidence to the Southwest, leading to a basin inversion (Rossi & Craig, 2016). An abrupt deepening is observed and a new depocentre was created, hosting a 100 km-long, 1 km-thick mud-rich turbidite system, recording the maximum accommodation of the basin with high sedimentation rate, ranging approximately between 50 and 100 cm/kyr (Cortemilia and Costa Areasa fms.). Basin plain turbidites onlap over the tilted ramp, forming a type III HDU shaping an asymmetric basin created while the Apennines were overriding the Alps (Rossi et al., 2018).

Unit V (Middle-Late Miocene) records another major basin inversion caused by the growth of the antiformal stack (Rossi et al., 2017), and is characterised by the progradation of braid-delta systems (Serravalle and Mt. Vallassa fms.) above shelfal deposits (Murazzano and Cessole fms.) punctuated by a late Serravallian forced regression (Rossi et al., 2009). This is coeval with the deposition of sand-rich turbidites in the basin axis (Cassinasco and lower Lequio fms.; Gelati & Gnaccolini, 2003) and is followed by a marine transgression (expressed by the

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deposition of the S. Agata Fossili marls) in the Tortonian. The southern basin margin was uplifted, and progressive unconformities developed, due to Northward tilting of slope and basin floor sediments, associated with local development of mass-transport deposits (Rossi et al., 2009). The tilting and slope margin outbuilding due to the low accommodation that had developed upslope of the tectonic hinge, as well as the high sediment supply made the turbiditic depocenter narrower and oversupplied.

Unit VI was deposited during late Tortonian, when the Apennines completed their overriding of the Alps (Rossi, 2017), and frontal splays developed at the western basin margin show a Northwestward vergence that is opposite to the one of the older Alpine retrobelt. This unit is bounded by regressive surfaces of marine erosion and valley incision and is characterised by the deposition of shelfal (Diano d'Alba fm.) and turbiditic (upper Lequio fm.) sandstone units, associated with local development of mass-transport deposits. This succession is topped by Messinian primary evaporites (Dela Pierre et al., 2011) and is largely truncated by the intra-Messinian unconformity, which, in most places, is overlain by a mass-transport complex (Rossi, 2017), Valle Versa Chaotic Complex in the CARG maps (Dela Pierre et al., 2003).

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DAY 1 - DROWNING UNCONFORMITIES ON HINGED CLASTIC SHELVES OF THE OLIGOCENE SUCCESSION IN THE ALTO MONFERRATO REGION

Introduction

The aim of the 1st day of field trip is to observe and discuss some key outcrops in the Alto Monferrato region, framed into the overall deepening-upward Oligocene succession (Fig. 5). In addition, thanks to Unmanned Aerial Vehicles (UAV) photogrammetric surveys, the three-dimensional architecture of seismic-scale outcrops can be better appreciated. This helps to highlight the characteristics of submarine unconformities affecting shallow-marine to shelfal systems during multiple phases of structural tilting. Such hinged shelf margins were characterised by the drowning and partial erosion of the underlying fan delta systems.

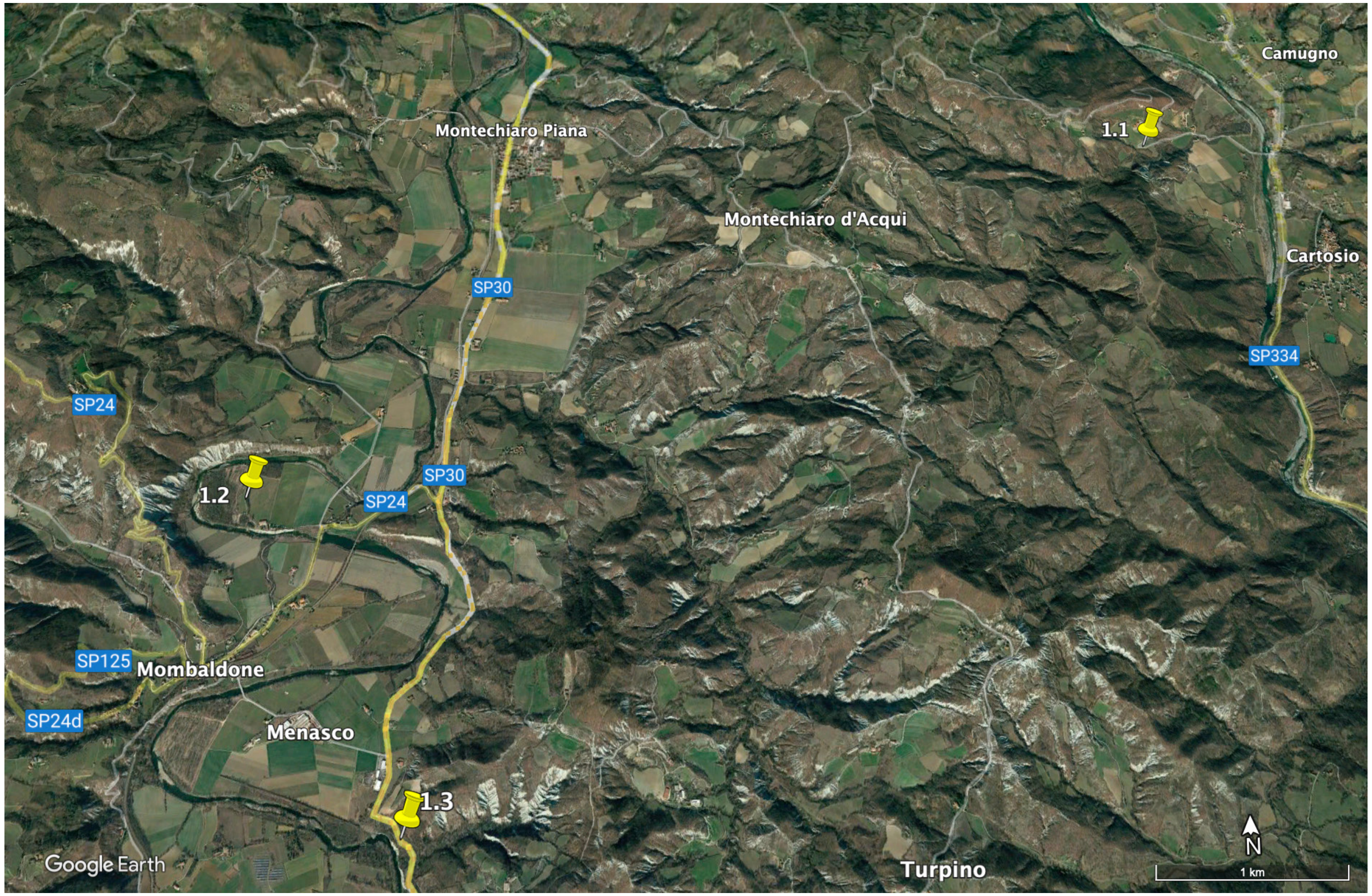

Fig. 5 - Day 1 itinerary with stops.

Stratigraphic architecture of the hinged clastic shelf margin of the Alps retroforeland affected by submarine drowning unconformities

The submarine unconformities occurring in the Oligocene deepening-upward succession testify the stepwise drowning of the hinged shelf margin of the Alps retrobelt due to the Alpine orogenic collapse, associated also to the rotation of structural hinges generated by basin reorganization, which causes differently oriented fault systems. Such features can be described as hinged-margin drowning unconformities

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(HDUs) developed on tilted clastic shelves with a scalloped morphology (Rossi et al., 2018), contrasting with the more regular shape of prograding shelf margins (Fig. 2).

There are three types of HDUs, depending on hinge position and sense of tilt (Fig. 2). Type I HDU can be recognised in both outcrops and seismic profiles in the lower Oligocene succession (Fig. 6). For the late Oligocene, Type II HDU prevailed as characterised by an increase in

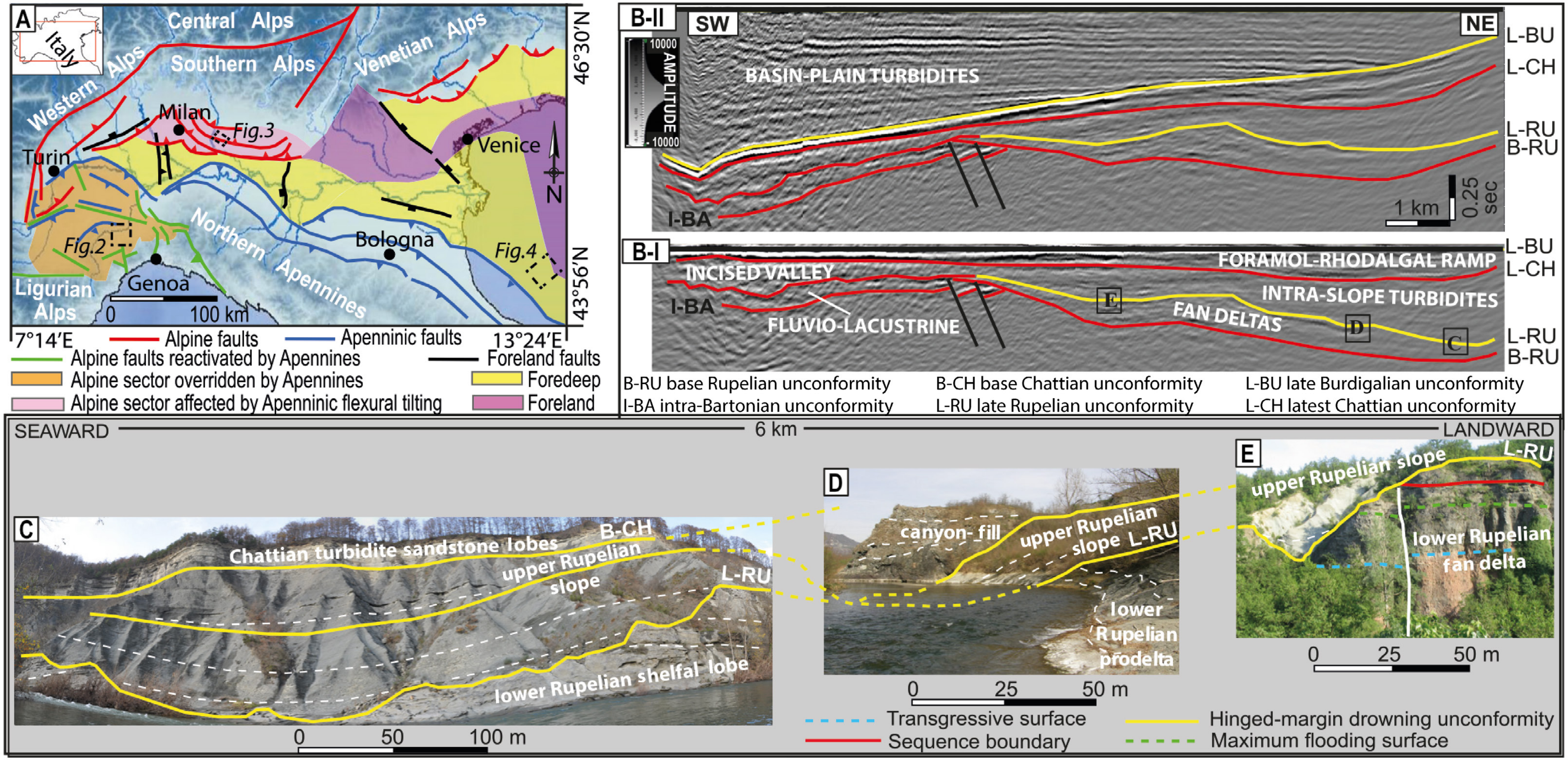

Fig. 6 - Outcrop and seismic expression of the hinged-margin drowning unconformities observed in the field trip area (modified from Rossi et al., 2018). A) geologic setting of the Alps retrobelt; B) Seismic profile crossing the dashed inset in A; C-D-E) from left to right, the three outcrops of Stops 1.2 (Fig. 8), 1.3 (Fig. 9) and 1.1 (Fig. 7), respectively (all of them located as well in the dashed inset in A).

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rate of seaward tilting, causing a backward-moving hinge. This is eventually followed by type III HDU, occurred when the Apennine structures overrode the Alps retrobelt, leading to a high-magnitude landward tilting and lateral changes in accommodation.

Such unconformities are expressed as subaqueous erosional surfaces, passing into paraconformities which should not be misinterpreted as conformable maximum flooding surfaces. As opposed to a marine flooding surface, an HDU is associated with angular stratigraphic relationships generated by tilting and with erosional and non-depositional lacunae of regional extent, ranging from a few hundred thousand years to a few million years. Paraconformable boundaries may show convergence and condensation, thus different from condensed sections caused by downlap surfaces associated to a maximum flooding (Rossi et al., 2018). Stacking patterns and palaeo-bathymetry suggest that subsidence rates exceeded sedimentation rates, leading to further deepening-upward.

HDUs are betrayed by a record of deep-water incision networks extending up to tens of kilometres, including canyons (as shown in stop 1.1), retrogressive slump scars (as shown in stop 1.2) and gullies (as shown in stop 1.3). The slope destabilization on tilted shelf margins, testified by sedimentation rates that may exceed 1 m/kyr in the depocenters (Rossi et al., 2015), led to a rearrangement of depositional processes, sediment fairways, style of erosion, and mode of sediment delivery to deep-water.

There are implications depending on whether erosion occurred through wave ravinement and shoreface retreat, or was due to failure on steepened, above-grade, slopes. The healing phase wedge downslope of the shallow water zone is mud-prone, but in tilted shelves shallow-water facies are remobilised by large-scale erosion and the seaward delivery of coarse-grained sediment to form intrashelf, intraslope, or basin floor turbidites (Rossi et al., 2018).

Such submarine erosion may leave remnants of drowned shelves, unconformably overlain by deeper-water facies. The erosion of deltas led to coarse-grained and relatively mud-free surge-type turbidity currents that delivered basinward of the hinge line. These turbidites are high accommodation–high supply systems driven by shelf and slope instability during regional transgressions caused by increasing but laterally changing accommodation. The retrogressive nature of slump scars, readjusting the slope equilibrium profile through the removal of progressively smaller volumes of sediment, produces a thinning-upward, retrogradational turbidite system eventually backfilling the erosional network.

HDUs, unpredicted by conventional models, are commonly displayed in the stratigraphy of actively deforming areas, caused by high-magnitude changes in accommodation rates and sediment flux, linked to morphostructural reorganizations. The application of unhinged sequence stratigraphic models to tectonically active margins lead to an underestimation of the magnitude of events and to overlook or misinterpret the unconformities generated under increasing accommodation. Where such discontinuities are subtle or paraconformable, or tilting is masked by further deformation, they may be confused with maximum flooding surfaces, and their potential for delivering coarse-grained material into deep waters is overlooked.

Stop 1.1 - Submarine unconformity affecting the Rupelian hinged shelf margin near Cartosio (Unit II – lower Molare and Rocchetta fms.)

Coordinates: Lat. 44.59963053 N, Long. 8.407089778 E

Lower Rupelian fan-delta conglomerate and sandstone of the lower Molare Fm. are observed, organised in an overall deepening-upward succession (Fig. 7). From base to top, this depositional system consists of: 1) reddish alluvial conglomerate; 2) grey-greenish fan delta front conglomerate; 3) alternating delta front sandstone and conglomerate. The lower conglomeratic units record the debris flow-dominated proximal part of the system, whereas the upper, and more organised, part of the system represents deposition in the distal delta front.

This fan delta system is deeply incised by a submarine valley, oriented northwest-southeast and filled by mudstone of the Rocchetta fm., onlapping and converging toward the flanks. Laterally, retrogressive slump scars occurred. The erosional remnants of lower Rupelian conglomerate and sandstone, preserved between the loci of maximum erosion, remain as prominent features (Rossi & Craig, 2016).

Differential compaction, reshaping and repeated erosional episodes produced internal discontinuities, which are locally floored by pebbly mudstone (Gnaccolini et al., 1990). The erosional network acted as transport routes for gravel eroded from landward or lateral locations.

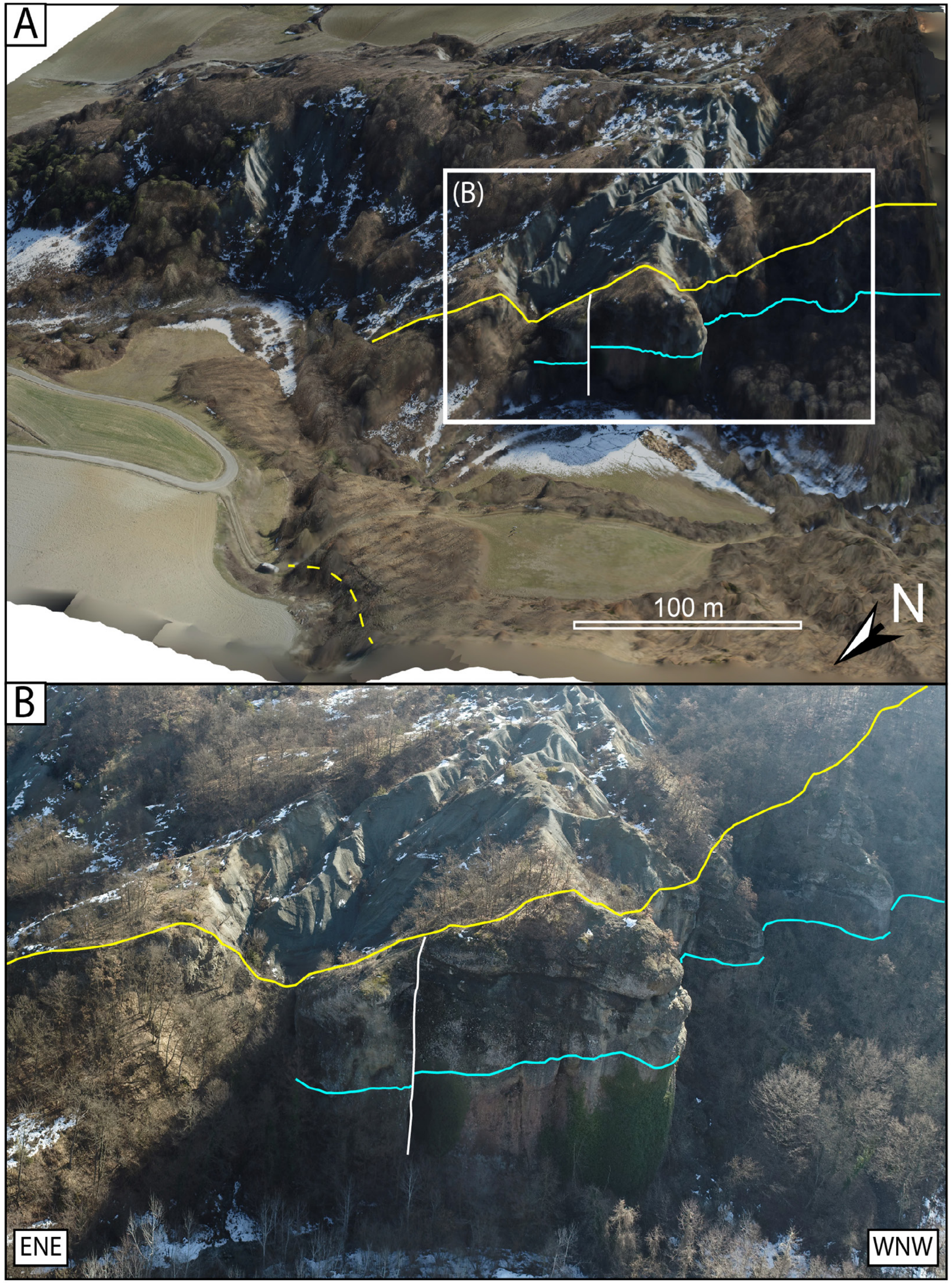

Fig. 7 - Drone oblique aerial views of the area observed at Stop 1.1 near Cartosio (blue line: major transgressive surface inside the lower Rupelian Molare fm.; yellow line: hinged-margin drowning unconformity of late Rupelian age; white line: fault). A) overview on the incision network; B) detailed view of the late Rupelian submarine erosional surface and its initial infilling in the area of maximum incision.

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Stop 1.2 - Submarine unconformities affecting the Oligocene hinged shelf margin along the Mombaldone meander bend, Bormida River (Unit II - Rocchetta fm.)

Coordinates: Lat. 44.5790776 N, Long. 8.334191369 E

A few kilometres to the West of Stop 1.1 (Fig. 5), in a more distal location, the late Rupelian hinged-margin drowning unconformity shows retrogressive slump scars cutting lower Rupelian shelfal lobes (Fig. 8). The axis of the depression is NNW oriented, and the slump scars are overlain by prodelta to slope mudstone (Rossi et al., 2009; Ghibaudo et al., 2014). Differential compaction and minor reshaping are highlighted by internal discontinuities which are onlapped by a few sandstone–mudstone beds. These confirm that the erosional process was retrogressive, and the erosional depression was periodically receiving sand eroded from landward or lateral locations.

Southwestward marine onlap of the Chattian Ovrano turbidite system (Gnaccolini et al.,

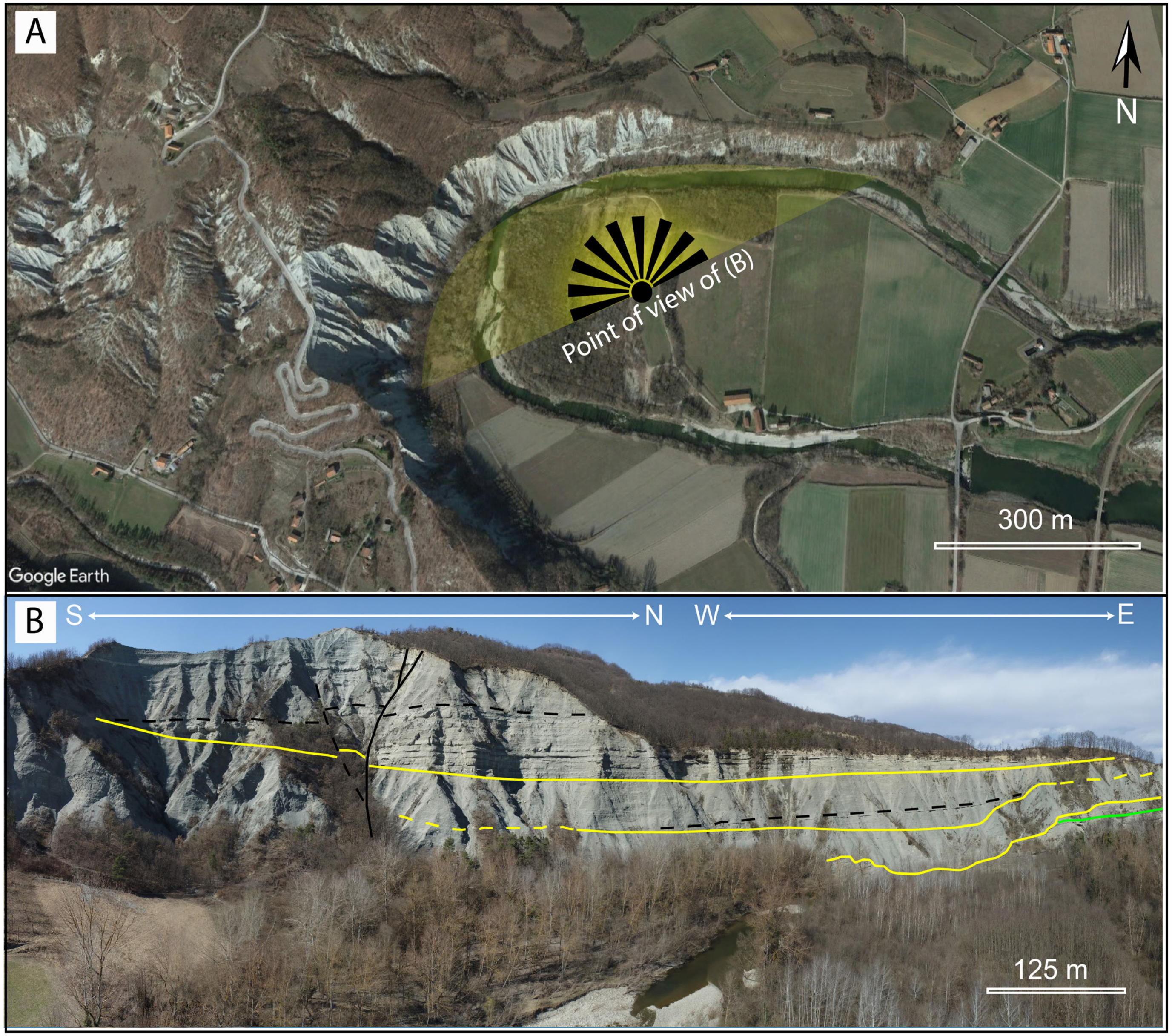

Fig. 8 - Drone oblique aerial photo on the area at Stop 1.2 (Molino di Mombaldone). A) Satellite image with indication of the point of view of the photo shown in B; B) Stratigraphic interpretation of the cliff exposed along the meander bend of the Bormida river (green line: maximum flooding surface; yellow lines: hinged-margin drowning unconformities; black dashed lines: top of intra-slope turbiditic bodies; black solid lines: faults).

1990) can also be observed at this stop, pinching-out against gently tilted mudstone. It is interpreted as the lateral onlap and fringing of lobe deposits over a NNW-SSE oriented syn-sedimentary high, related to the late Oligocene deformation phase. It suggests that the hinge line was not only moving backward but was also affected by a rotation, likely caused by the growth of a new morphostructural trend (Rossi & Craig, 2016).

Stop 1.3 - Submarine unconformities affecting the Rupelian hinged shelf margin along the Bormida River near Menasco (Unit II - Rocchetta fm.)

Coordinates: Lat. 44.56117143 N, Long. 8.347098237 E

At this location (Fig. 9), the topmost surface of the lower Rupelian prodelta can be walked out along the riverbank. This omission surface is characterised by a pervasive bioturbation by suspension feeders, including both *Cruziana* and *Zoophycos* ichnofacies, possibly merging on the same condensed surface during a rapid deepening. It is abruptly overlain by offshore mudstone intercalated by distal hyperpycnites.

This unit appears terraced due to a truncation produced by a steep submarine erosional surface draped by hemipelagic slope mudstone (Rossi et al., 2009). This mudstone was in turn faulted, tilted and truncated by another erosional surface, shaping a southeast-northwest oriented submarine canyon filled by very-coarse-grained monogenic breccia. This breccia was entirely derived from the ophiolitic basement outcropping a few km to the South, along a major WSW-ENE oriented syn-depositional high (Gnaccolini et al., 1990). The overall deepening-upward and the multiple, stepwise nature of late Rupelian HDUs suggest progressive collapse and downwarping of this shelf margin.

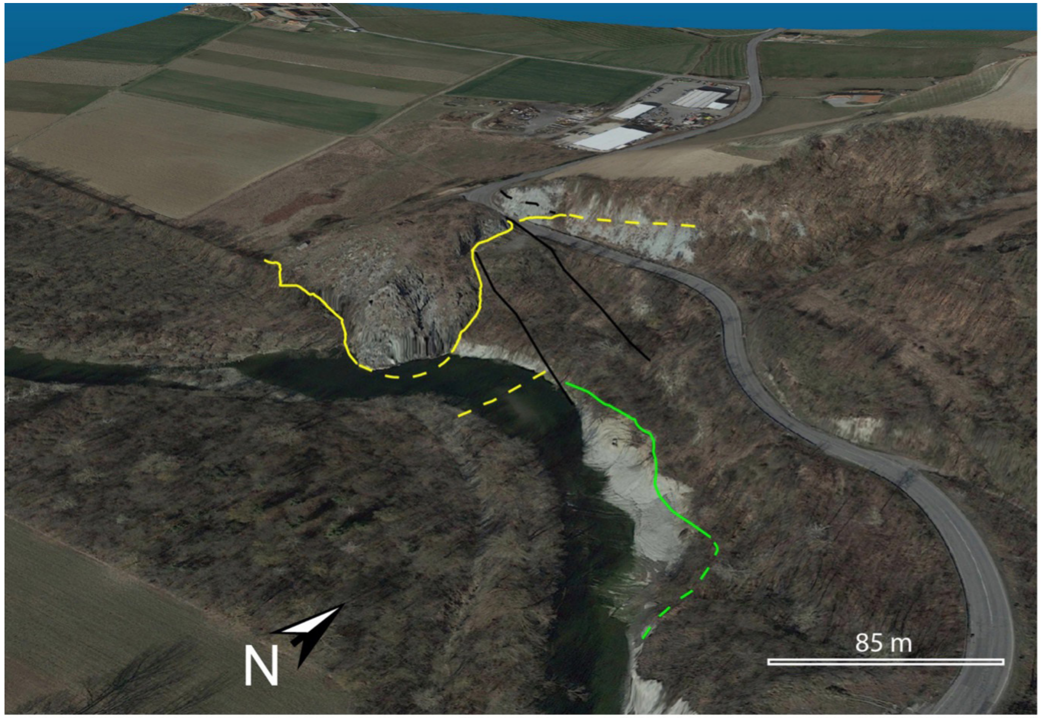

Fig. 9 - Drone oblique aerial view of the aera observed at Stop 1.2 near Menasco (green line: maximum flooding surface; yellow lines: hinged-margin drowning unconformities; black lines: faults.

DAY 2 - STRATIGRAPHIC RECORD OF MORPHOSTRUCTURAL RESHAPING IN THE OLIGOCENE SUCCESSION ACROSS THE LIGURIA-PIEDMONT BORDER

Introduction

The aim of the 2nd day of field trip is to observe and discuss the stratigraphy and palaeogeography of the central part of the TPB (Fig. 10). The Oligocene accommodation succession is examined in areas characterised by different morphostructural settings. Initially, the main control was exerted by the irregular coastline shaped by the Alpine orogenic collapse. Subsequently, the effects of morphostructural reshaping deeply modified the configuration of syndepositional highs and lows, thus affecting the nature of depositional systems and their dispersal patterns.

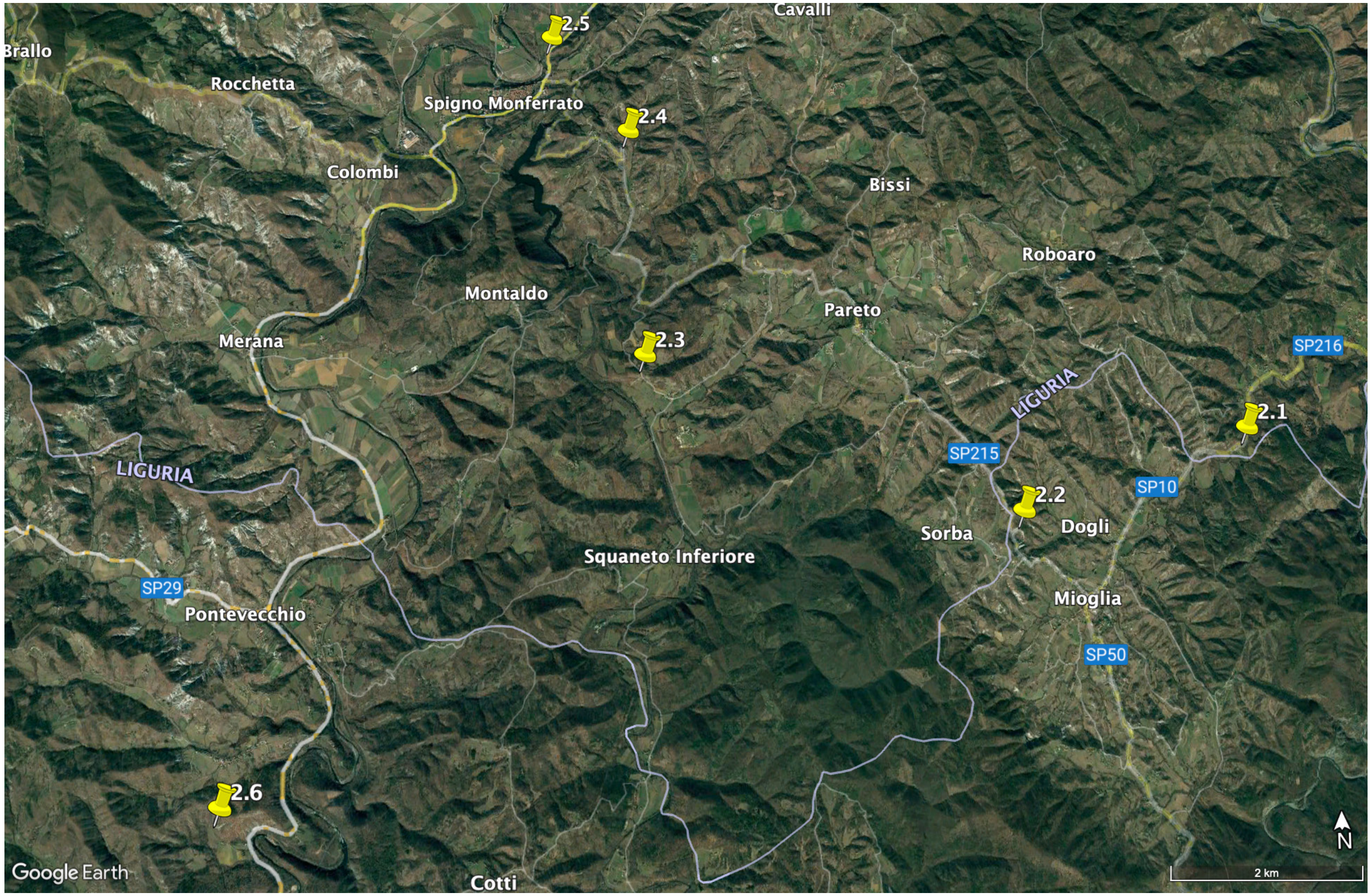

Fig. 10 - Day 2 itinerary with stops.

Stratigraphic architecture and palaeogeography of the Oligocene succession in the central TPB

The stacking patterns of the lower Oligocene succession, that can be examined in different outcrops, enable us to assess the interplay between various orders of cyclicity within the longer-term deepening-upward succession. This is illustrated in Figure 11, showing the correlation between stops 2.1 and 2.4 and highlighting the high-resolution sequence stratigraphy and internal architecture of the lower Rupelian sequence set. The palaeogeography of the area was continuously modified by basin reshaping.

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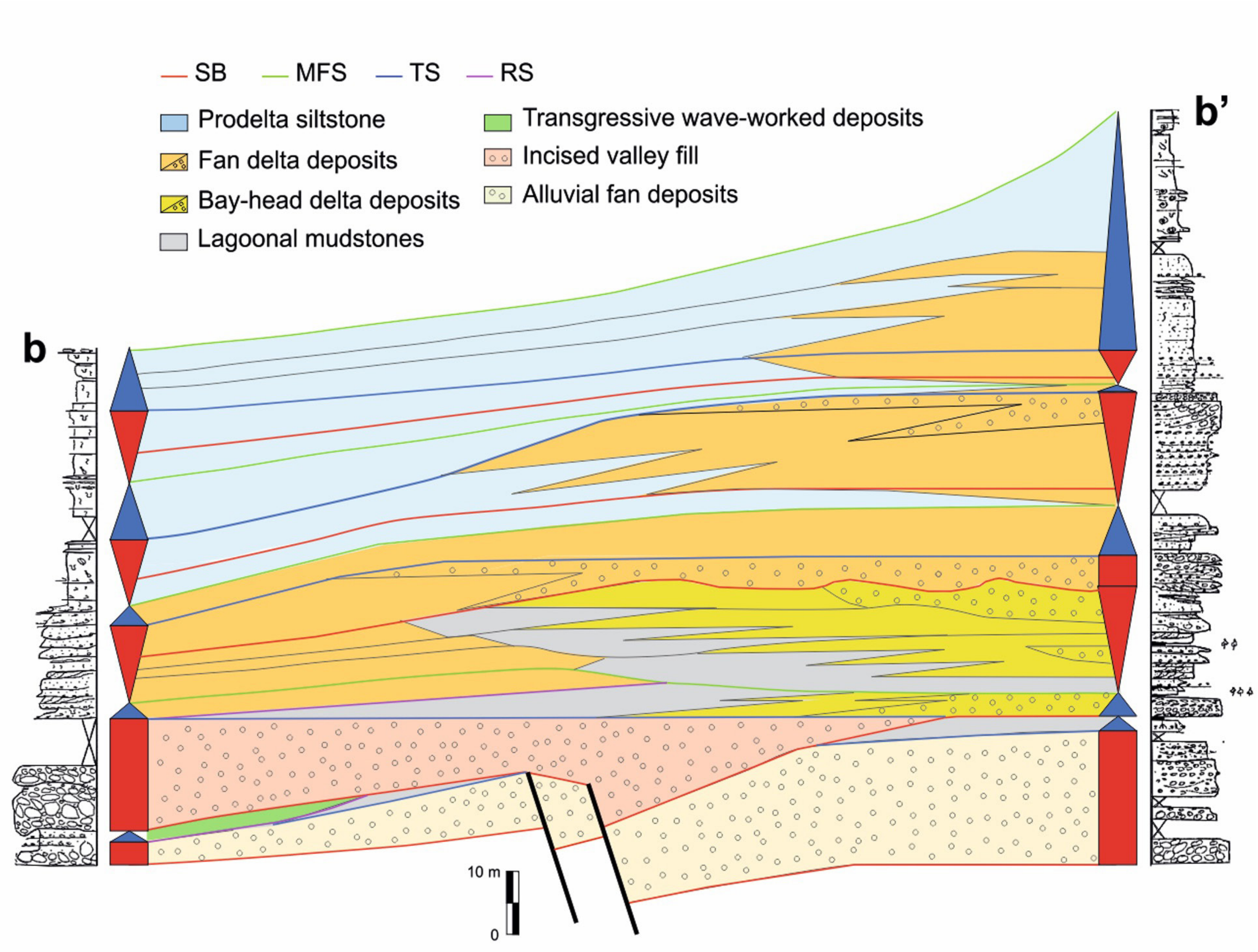
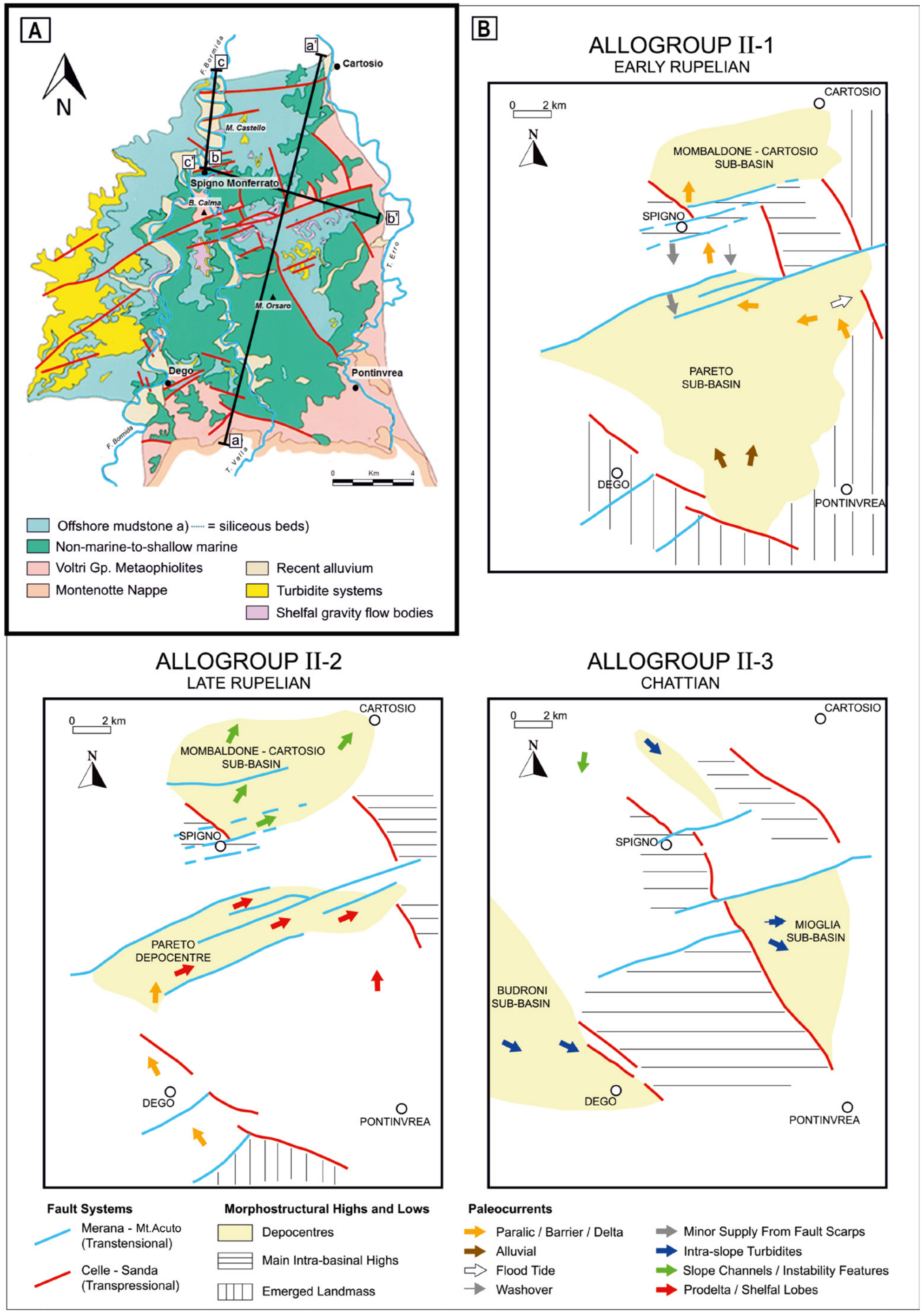


Fig. 11 - Correlation panel of the lower Rupelian sequence set in the area observed during the second day (from Rossi & Craig, 2016). Location shown in Fig. 18a (Stop 2.4 at the WNW side of the panel is on the left; Stop 2.1 at the ESE side of the panel is on the right).

The palaeogeographic sketch maps shown in Figure 12, referring to the early Rupelian, late Rupelian and Chattian time intervals, facilitate understanding the significance of basin reorganizations.

During the early Rupelian, WSW-directed palaeocurrents recorded a local effect driven by an irregular shoreline produced by the structural elements that define a WSW–ENE oriented bay (recorded by the succession exposed in stop 2.1). The bay was separated from the open sea to the north (around the area examined in stop 2.5) by a high-angle fault system bounding a syn-depositional depression plunging Westwards (Rossi & Craig, 2016).

Further deepening was then related to the reconfiguration of the basin, which resulted in the late Rupelian unconformity, locally associated with an along-axis inversion of the depression owing to the scissor nature of the border fault. The drowning event and the increasing accommodation rate were associated with a greater fault throw. Shelfal gravity flows fed from deltas (giving origin to the rocks observed in stop 2.3) shifted to the south in relation to the transgression associated with the drowning. They were confined by the reactivated syn-depositional high, whereas in the depression the gravity flows show Eastward palaeocurrents as a consequence of the above described along-axis inversion (Rossi & Craig, 2016).



The base-Chattian unconformity is overlain by an intra-slope turbidite system (observed in stop 2.2), likely controlled by the growth of a local structure consisting of a NNW-SSE oriented flexure front associated with a blind thrust (Bernini & Zecca, 1990). The fault-bend fold involved the pre-Chattian sequences and created a sub-basin filled by deep-water sediments onlapping on both margins. The palaeocurrents of this system indicate a source area related to the growth of the flexure front (Mutti et al., 1995). In stop 2.6 it can be then observed the edge of another intra-slope system, mostly filling as well a NNW-SSE oriented structural depressions.

Stop 2.1 - The Rupelian accommodation succession and high-resolution sequence stratigraphy of the lower Rupelian sequence set near the village of Mioglia (Unit II - lower Molare and Rocchetta fms.)

Coordinates: Lat. 44.50389391 N, Long. 8.434276928 E

In this area (Fig. 10), the lower Rupelian sequence set records a morphostructurally-controlled embayment (Rossi et al., 2009). The overall transgressive organization occasionally presents minor regressions. The sequence starts with alluvial fan conglomerate, overlain by lagoonal mudstone. A higher frequency sequence boundary coincides with a ravinement surface overlain by a retrogradational, gravel-rich bay-head delta dominated by fluvial floods but showing some tidal influence (Fig. 13). This system grades into a central bay muddy interval with lignite beds recording a condensed section,

Fig. 12 - Oligocene palaeogeographic sketch maps of the area observed during the first and second day (from Rossi & Craig, 2016). (A) Geological map of the Oligocene succession between the Bormida and Erro Valleys. (B) Morphostructural reshaping and syn-depositional faults active during the sedimentation of Allogroups II-1 (Early Rupelian) and II-2.

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Fig. 13 - Transgressive bay-head delta overlain by a lignite-rich condensed section deposited in the central bay, cropping out along SP10 between Miogliola and Mioglia. Explanation of colours: Red surface: sequence boundary (coinciding here with a transgressive surface); Green surface: maximum flooding surface (Stop 2.1).

overlain by a regressive bay-head delta composed of conglomerate and sandstone alternated with mudstone rich in organic debris.

Conglomerate beds were emplaced by catastrophic fluvial floods (Mutti et al., 1995), whereas sandstone beds were affected by tidal modification creating sigmoidal cross-bedding, recording ebb flows from East-northeast and subordinate flood flows with opposing palaeocurrents. This tidal amplification was likely due to confinement along a narrow palaeovalley mainly controlled by the WSW-ENE oriented Merana-Monteacuto fault system.

The maximum regression is recorded by erosional-based fan-delta plain, disorganised, and very coarse-grained conglomerate, capped by another transgressive interval with sigmoidal cross bedding, showing Southwestward palaeocurrents. Subsequently, the progradation of a clinostratified gravel-rich Gilbert-type delta with wave-worked topset can be observed, testifying an accommodation increase sufficient to heal the morphological relief that gave origin to the protected embayment. This established an open marine setting in the area, as well as a more regular shoreline.

Fig. 14 - Thickening-upward stacking pattern of the Mioglia system along road SP50 (Stop 2.2)

Stop 2.2 - Chattian intra-slope turbidites near Mioglia (Unit II - Rocchetta fm.)

Coordinates Lat. 44.49636458 N, Long. 8.40255474 E

A Chattian intra-slope turbidite system is observed. It is a small and poorly efficient sand-rich system (Mutti, 1992; Mutti et al., 1995) fed from the west at the intersection between the previously established Merana-Monteacuto transtensional fault system and a new NNW-SSE oriented transpressional fault system. The configuration of syn-depositional depressions was reshaped and controlled by the radial dispersal pattern of the turbidite sandstone lobes.

The overall stacking pattern shows a thickening-upward (Fig. 14) due to the superposition of thick-bedded sandstone lobe deposits over thinner-bedded lobe fringe sandstone-mudstone alternations. In the upper part of the system, scour and fill locally occur, interpreted as a channel-lobe transition facies. A forestepping organization is inferred from these relationships.

Stop 2.3 - Upper Rupelian intra-shelf coarse-grained body confined by a syn-depositional high near the village of Valla (Unit II - Rocchetta fm.)

Coordinates: Lat. 44.51306082 N, Long. 8.351987864 E

The upper Rupelian Valla system (Mutti, 1992; Mutti et al., 2002) is a coarse grained shelfal body, consisting of gravity flow deposits showing palaeocurrents from WSW to ENE. The Valla system records the infill of a syn-depositional depression, bounded landward by the Northward downwarping of the lower Rupelian shelf margin (Rossi et al., 2009), and seaward by the reactivation of the Merana-Monteacuto fault system, that can be traced for at least 20 km in the field.

The Westward marine onlap can be clearly observed in the field (Fig. 15). This termination is due to the axial plunge of the intra-shelf depression and possibly to the occurrence of different *en-echelon* segments of the fault system, likely affecting sediment routing and by-passing areas. The palaeocurrents indicate palaeoflows parallel to the structural confinement. A rapid shoaling-out can be observed both laterally and downcurrent in the lower part of the body.

Fig. 15 - The Westward marine onlap of the Valla system (Stop 2.3).

Stop 2.4 - The lower Rupelian accommodation succession along road SP215 (Unit II - lower Molare and Rocchetta fms.)

Coordinates: Lat. 44.53661862 N, Long. 8.350392528 E

The lower Rupelian succession starts with alluvial fan conglomerate intercalated by a high-frequency marine incursion consisting of prominent isolated boulders collapsed from a palaeo-fault scarp, washed by major storms, and draped by mottled backshore facies.

At the top of the conglomerate, a high-rank marine transgression is overlain by flood-generated and laterally continuous coarse-grained sandstone characterised by graded beds with escape burrows and strongly bioturbated top. This predominantly parallel-bedded system is interpreted as delta front dominated by catastrophic fluvial floods, although some of these beds show evidence of sigmoidal reshaping with palaeocurrents toward North-northwest (Fig. 16).

Fig. 16 - Thick- and parallel-bedded coarse-grained sandstone cropping out along road SP215, interpreted as delta front catastrophic river flood deposits in the interval between two marine flooding surfaces (Stop 2.4).

This fan delta system is abruptly capped by a starved bioturbated horizon, interpreted as a firm ground colonised by thick-shelled oysters (relict shoreface deposits), indicating a condensed section corresponding to a maximum flooding event (Rossi et al., 2009).

Above this surface, the deposits of the lower Molare Fm. are abruptly overlain by shelfal siltstone of the Rocchetta fm., rich in macrofossils and leaves.

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Stop 2.5 - The Rupelian intra-basinal high near the village of Spigno Monferrato (Unit II – lower Molare and Rocchetta fms.)

Coordinates: Lat. 44.5476435 N, Long. 8.339477662 E

The lower boundary is a non-conformable contact with the Alpine metaophiolitic basement (Fig. 17), while the upper boundary shows angular stratigraphic relationships with the fine-grained and deeper-water deposits of the Rocchetta fm. At the base, disorganised and very coarse-grained breccia and conglomerate show a Southward onlap toward the structural high. The first marine ingression is recorded by transgressive sandstones; towards the top of the conglomeratic unit, boulders and cobbles appear more rounded and draped by shoreface sandstone during the following transgression.

Northward, in the downthrown side of a fault, several erosional surfaces with cross-cut geometry are infilled mainly by gravity flow deposits. This is interpreted as the collapse of the delta front due to the steep gradient and differential subsidence/compaction at the fault-bounded transition from the intra-basinal high and the open marine setting to the North. Toward the top of the succession, a firm ground colonised by thick-shelled bivalves marks a major maximum flooding surface.

The lower Rupelian sequence is truncated by the late Rupelian submarine unconformity, overlain by the Rocchetta fm., that here is made by shelfal mudstones interbedded with distal hyperpycnites.

Fig. 17 - The lower Rupelian sequence set near the village of Spigno Monferrato, non-conformably overlying the metamorphic basement. Onlap relationships toward the South highlight the presence of a major syn-sedimentary high (Stop 2.5).

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Stop 2.6 - Oligocene polyphasic syn-sedimentary tectonics near Bric Forest along the left side of Bormida Valley (Unit II – lower Molare and Rocchetta fms.)

Coordinates: Lat. 44.47116905 N, Long. 8.295235516 E

The evolution of a polyphasic syn-sedimentary high is examined. Initially, it was a site of erosion and non-deposition while thick lowermost Rupelian alluvial fan conglomerate was infilling an adjacent syn-sedimentary depression, broadly East-West oriented (Ghibaudo et al., 2014) partly bounded by a high-angle transtensional fault. Subsequently, a sand-prone shallow marine succession covered the structural high. Pebble and cobble lags sometimes occur, delivered basinward and then washed by marine processes, locally encrusted by thick-shelled bivalves and corals. Major transgressions are recorded by condensed sections characterised by sediment starvation highlighted by thin pervasively-bioturbated intervals.

This Rupelian sequence set (Molare Fm.) was then tilted toward the Southwest and onlapped Northeastward by the sand-rich uppermost part of a Chattian intra-slope turbidite system. The oldest, gravel-rich portion of this system was confined in a syn-sedimentary depression shaped by a Northwest-Southeast oriented late Oligocene transpressional fault system (Fig. 18).

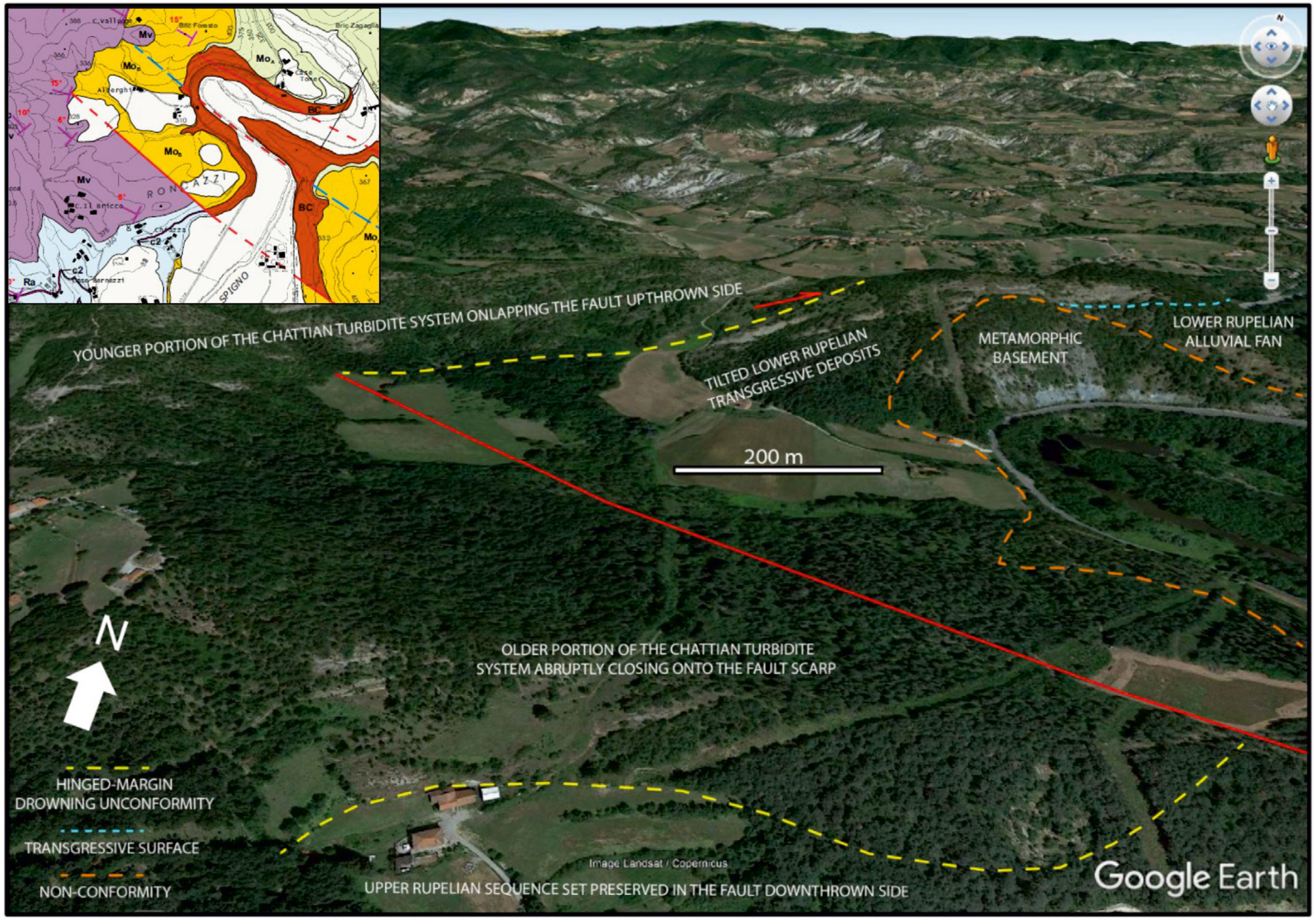

Fig. 18 - Vertically exaggerated oblique view from south-southeast showing the tectono-stratigraphic relationships between Chattian intra-slope turbidites and lower Rupelian shallow marine deposits near Bric Forest. In the inset, geologic map of the stop area (from Ghibaudo et al., 2014): Red: Metaophiolitic basement; Light green: Molare fm. conglomeratic unit; Yellow: Molare fm. sandstone unit; Light blue: Rocchetta fm. mudstones; Purple: Mogliavacca coarse-grained body (Chattian intra-slope turbidites); White: Recent alluvium.

DAY 3 - LOWER-MIDDLE MIOCENE TRANSGRESSIVE-REGRESSIVE CYCLE PUNCTUATED BY TECTONIC UNCONFORMITIES IN THE MONREGALESE AND LANGHE REGIONS

Introduction

The aim of the 3rd day of field trip is to observe and discuss the stratigraphic architecture of the Southwestern margin of the TPB. Here, the Lower-Middle Miocene succession is examined, initially looking at shallow marine systems fed by the Ligurian Alps, and later observing the effects caused on stratigraphy meanwhile the Apenninic deformation was interfering with the Alpine ones. Such an interplay generated a long-term transgressive-regressive cyclicity, punctuated by major tectonic unconformities resulting from alternating phases of tectonic uplift and shelf margin drowning (Fig. 19).

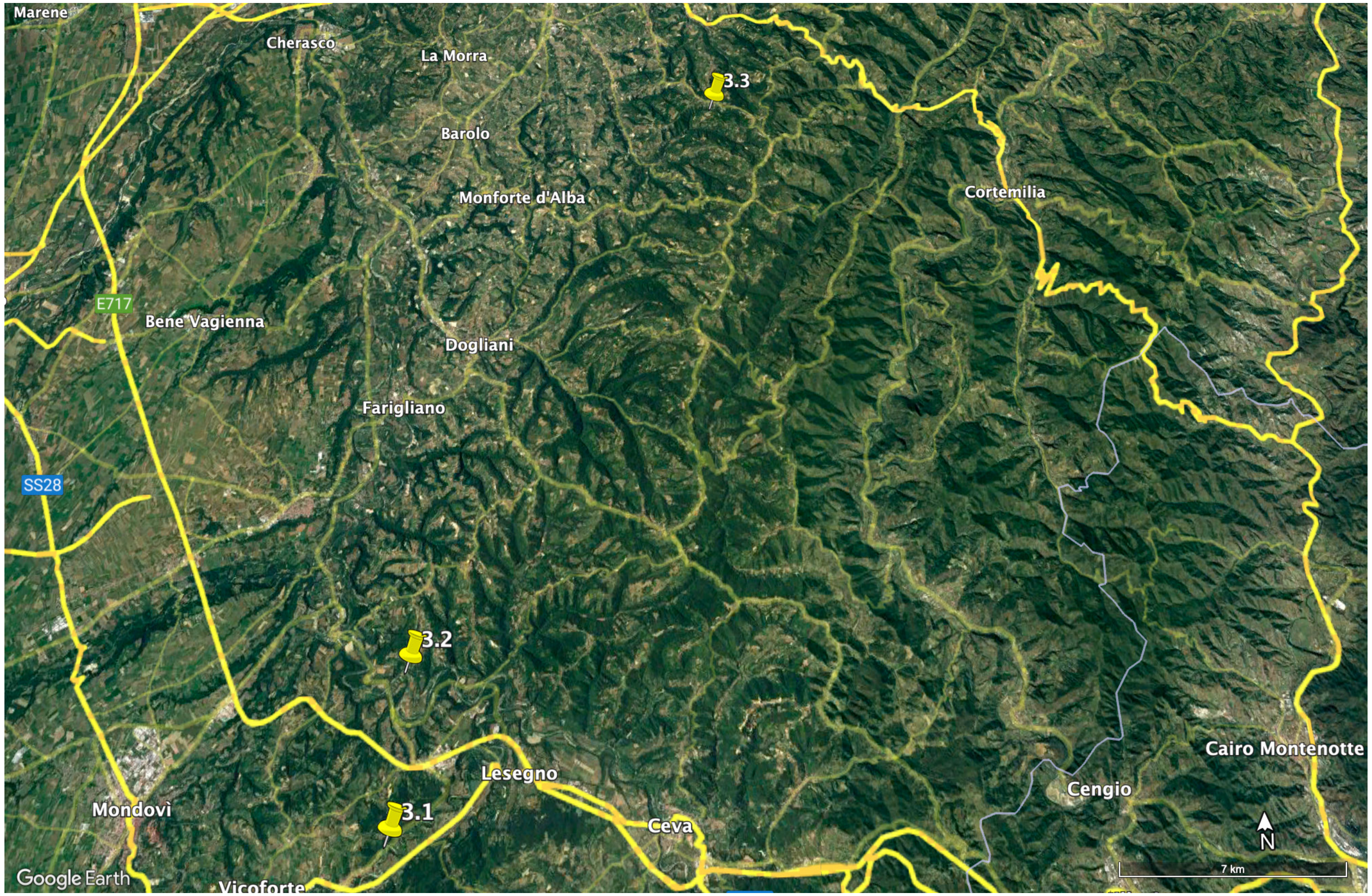

Fig. 19 - Day 3 itinerary with relative stops.

Stratigraphic architecture of the Lower-Middle Miocene succession deposited in the South-western basin margin while the Apenninic deformation was overriding the Alps retrobelt

Since the latest Chattian, the shelf margin was confined between the Western Alps and the Alto Monferrato intra-basinal high that was growing more to the east. This was caused by a deep-seated antiformal stack related to the first significant onset of the Northern Apennines deformation (Rossi & Craig, 2016). To the Southwest, fan deltas of the upper Molare Fm. developed adjacent to the Western and Ligurian Alps

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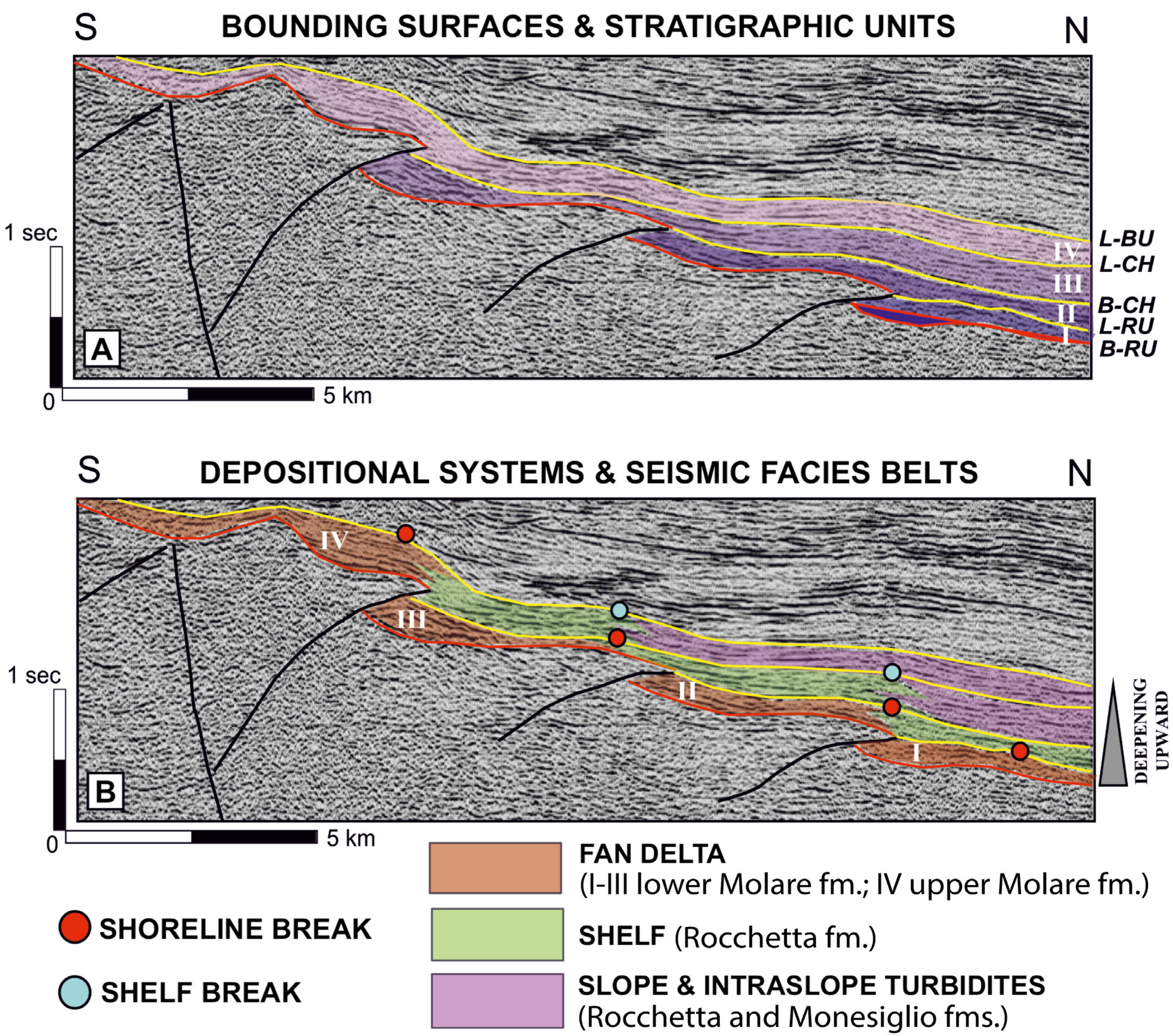

Fig. 20 - Oligocene-Early Miocene seismic-stratigraphic framework of the Ligurian Alps retrobelt shelf margin (modified from Rossi, 2017). Note subsidence polarity reversal across tectonic hinges in Units II and III, when sequence boundaries changed seaward into hinged-margin drowning unconformities; on the other hand, Unit IV records the deposition of basin floor turbidites due to the Northwestward propagation of the Apenninic subsidence.

retrobelt margin (Fig. 20), locally associated with the development of incised valley fills like the one observed in stop 3.1; to the East and Northeast, intrabasinal highs rimmed by foramol-rhodalgal ramps developed in the Alto Monferrato region (Figs. 2 and 3).

Since late Burdigalian, increasing tectonic subsidence, caused by Apenninic deformation, that was overriding the Alps retrobelt, is recorded by an abrupt deepening and by the deposition of a basinwide, 1 km-thick high efficiency basin-floor turbidite system. This consists of lobe deposits (like the ones observed at the bottom part of stop 3.2) passing Northeastward into basin plain deposits filling an elongated basin created by the reshaping of the previous basin configuration. The tectonic subsidence was rapidly compensated by the increase in sediment supply (Rossi et al., 2018).

Since Langhian, the propagation of the deep-seated antiformal stack and associated frontal splays caused progressive uplift of the basin margins, locally generating a basin inversion (Figs. 2 and 3). An overall progradation (visible in the topmost part of the exposure examined in stop 3.2) occurred along the South-western and South-eastern basin margins, reaching a maximum regression in the latest Serravallian (Fig. 21).

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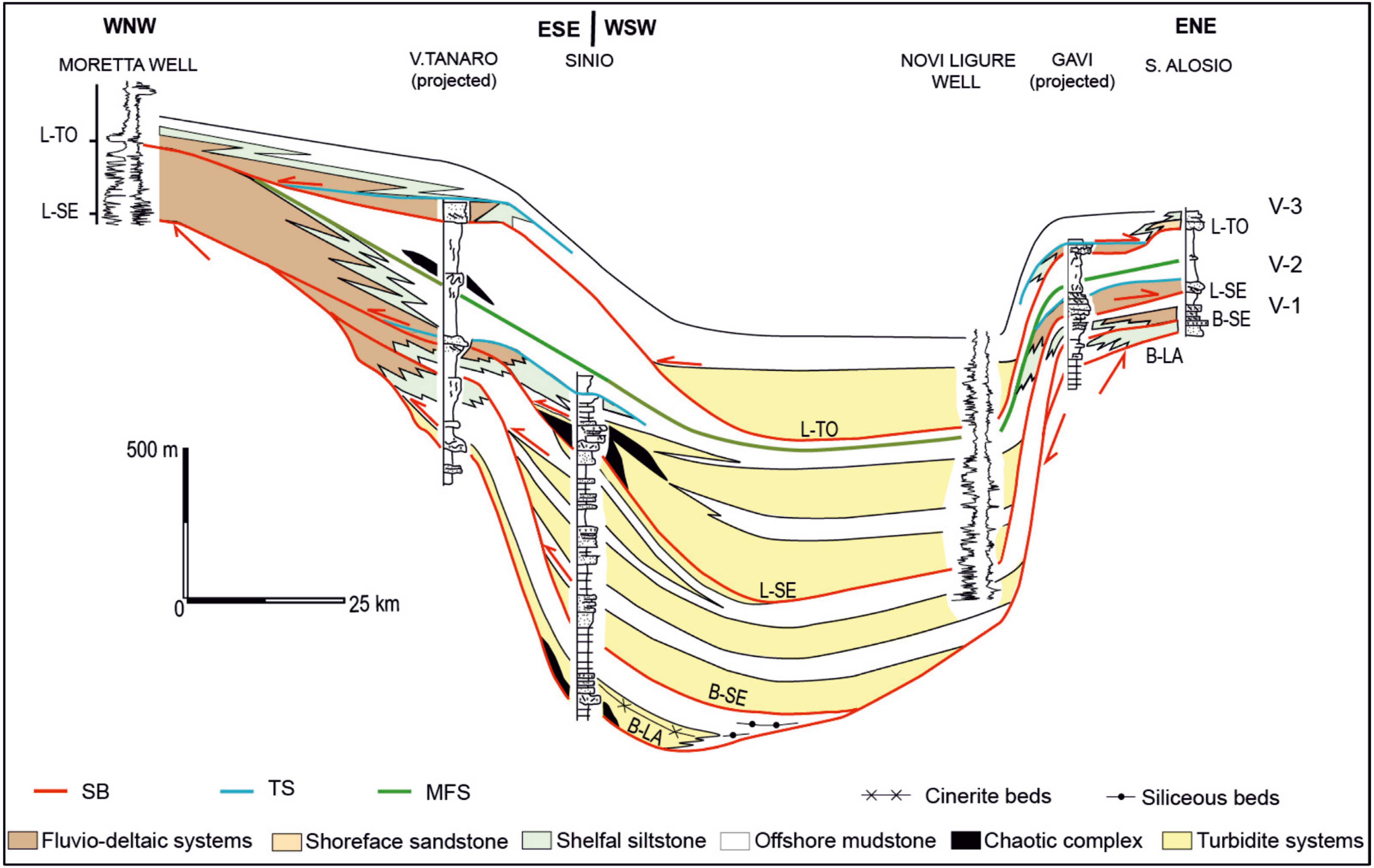

Fig. 21 - Correlation panel of the Middle-Upper Miocene succession (from Rossi & Craig, 2016).

This process was triggered by steepening of the shelf margins, which caused the uplift and denudation of the landward areas (Rossi, 2017) and the local accumulation of mass transport deposits like the one observed in stop 3.3. The deltas crossing the shelf and the basin-floor turbidites can be considered intermediate between accommodation- and supply-dominated end members. A narrowing of the turbidite depocentre can be observed, due to the combination of the basinward tectonic tilting and the deposition of successive offlapping shelf margins.

Stop 3.1 - The Aquitanian-lower Burdigalian fill of an incised valley adjacent to the Ligurian Alps retrobelt near the village of S. Michele di Mondovì (Unit III – upper Molare Fm.)

Coordinates: Lat. 44.38256719 N, Long. 7.91851294 E)

The succession observed at this stop (Fig. 19) starts with Chattian (Unit II) gravel-rich fan delta deposit capped by a sand-rich transgressive unit made of parallel-bedded delta front sandstone beds with bioturbated top, unconformably overlain by Lower Miocene deposits (Unit III). The Chattian succession is indeed incised by an erosional surface (Fig. 22, see also Gelati & Gnaccolini, 1996 for further details) filled by fluvial underflows periodically reworked by wave action recorded by hummocky- and swaley-cross stratification. This is interpreted as late lowstand deposit, with early lowstand deposit expected to occur seaward.

The late lowstand deposit is abruptly overlain by finer grained and thinner-bedded sandstone, still onlapping the valley flanks and grading upward into light grey prodelta siltstone. As a whole, the incised valley fill is referred to the S. Paolo fm. (Casnedi & Mosna, 1970). These transgressive deposits are capped by darker grey mudstone, whose base is interpreted to mark the maximum flooding surface, and then overlain by a shallowing-upward highstand delta front succession (Rossi & Craig, 2016).

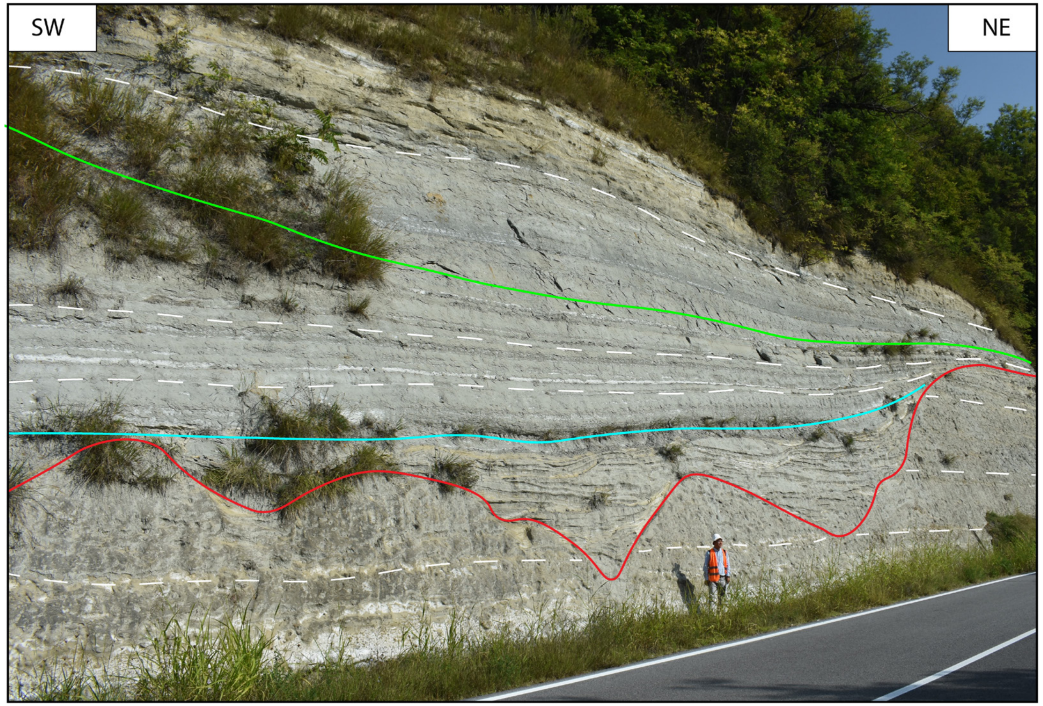

Fig. 22 - Incised valley fill at the base of the uppermost Chattian-lower Burdigalian sequence along road SP60, approximately 1 km to the northeast of San Michele di Mondovì along the left side of the Corsaglia River. Explanation of colours: Red surface: sequence boundary; Blue surface: transgressive surface; Green surface: maximum flooding surface (Stop 3.1).

Stop 3.2 - The upper Burdigalian basin-floor turbidites overlain by the Langhian shelf margin along the right bank of the Tanaro River near the village of Ciglié (Units IV and V – Cortemilia, Murazzano and Cassinasco fms.)

Coordinates: Lat. 44.4296652 N, Long. 7.923122864 E

An upper Burdigalian turbidite sandstone lobe (Unit IV, Cortemilia fm.) onlaps toward the west over the Early Miocene shelf margin (as seen in the previous stop, Fig. 19) and crops out at the base of the succession exposed along a meander bend of the Tanaro River (Fig. 23). It represents the maximum transgression at the basin scale, likely caused by Apenninic driven subsidence.

The upper Burdigalian lobes are overlain by a downlap surface over which slope mudstone (Murazzano fm.) progrades onshelf margin. This slope is onlapped by a Langhian, gravel-rich channel-lobe turbidite system (Unit V, Cassinasco fm.). These deposits show conglomeratic remnants (*cf*. facies CGR *sensu* Mutti, 1992) overlain by fine-grained sandstone suggesting the by-pass of the missing grain size population (e.g., medium-coarse sand) toward the depocentre, where thick-bedded sandstone lobes were deposited. These gravel-rich sediments are overlain by a shallowing-upward succession, where slope mudstone is capped by shelfal, highly bioturbated siltstone and very fine-grained sandstone, reflecting the Northeastward progradation of the Langhian shelf margin (Rossi et al., 2009).

Fig. 23 - Panoramic view of the upper Burdigalian-Langhian shelf margin along the Tanaro River near the village of Ciglié. The late Burdigalian and Langhian unconformities are reported as solid lines. The late Burdigalian unconformity crops out in the left lower corner of the image, while the Langhian unconformity appears in the lower-middle part of the relief at the base of a more resistant coarse-grained body. Toe-of-slope downlap surfaces are shown, whereas the dotted line represents, in a poorly exposed sector due to abundant vegetation cover, a hypothetical expression of slope clinoforms. The dashed line just below the top of the hill to the top right corner of the image marks the base of shelfal deposits overlying slope mudstone (Stop 3.2).

Stop 3.3 - The upper Serravallian mass-transport complex along the Fosso dei Quiri Valley between the villages of Montelupo Albese and Albaretto della Torre (Unit V - Murazzano and Cassinasco fms.)

Coordinates: Lat. 44.61332623 N, Long. 8.05557716 E

The shelf margin reached its maximum Northeastward regression during the latest Serravallian, associated with a progressive unconformity caused by the stepwise basinward tilting of the whole shelf margin. For this reason, the mass transport complex (Murazzano fm., Fig. 24) contains decametric olistoliths and slumps derived from the collapse of previous shelf edge deltas. It shows offlapping of successive debris

Fig. 24 - Upper Serravallian mass-transport complex in the Fossa dei Quiri valley between the villages of Montelupo Albese and Albaretto della Torre (Stop 3.3).

flow-dominated tongues recording an increasing oversteepening, periodically blanketed by turbiditic bedsets (Rossi, 2017).

The main facies are slump and cohesive debris flow deposits preserving internal shear planes with cobbles and boulders floating at the top (Gelati et al., 1993). The relatively more organised turbiditic bedsets, and the background mudstone, were continuously enclosed by the basinward propagation of the instability, creating rough topography. The blanketing turbidites show evidence of bypass betrayed by conglomeratic remnant facies reshaped by currents, whose tail deposited fine-grained sandstone over the conglomerate remnant. Such flows transported basinward the missing grain size populations, which are found in the sandstone lobes deposited in the proximal part of the time equivalent basin floor turbidite systems. The system was eventually capped by a parallel bedded sandstone lobe of the Cassinasco fm., recording the end of the oversteepening and probably a backstepping phase.

DAY 4 - THE EASTERN TPB AND THE SEDIMENTARY SEAL ON THE ALPS-APENNINES TECTONIC JUNCTION

Table 2 - Synoptic scheme of the lithostratigraphic nomenclature used in reference maps and papers in the easternmost part of the TPB which is the area covered during Days 4-5.

	Boni et al. (1974) **Foglio 71 – Voghera Carta Geologica d'Italia - 1:100,000**	Cavanna et al. (1989) **1:25,000**	Martelli et al. (1998) **&** Cibin et al. (2003)	Servizio Geologico d'Italia (2014) **Foglio 178 Voghera CARG 1:50,000**	Servizio Geologico d'Italia (in press). **Foglio 196 Cabella CARG 1:50,000**
LOWER MIOCENE	ERODED	ERODED	ERODED	ERODED	ERODED
	"Cessole Marl"	Castagnola fm. Mt. Brugi mb.	Castagnola fm. Mt. Brugi mb.	"Mt. Brugi Marl"	
	Castagnola fm.	Castagnola fm. Arenaceous mb.	Castagnola fm. Arenaceous mb.	Castagnola fm. Torrente Dorbida mb.	
		Castagnola fm. Costa Grande mb.	Castagnola fm. Costa Grande mb.	Castagnola fm. Costa Grande mb.	Castagnola fm. Costa Grande mb.
OLIGOCENE	"Rigoroso Marl"	"upper Rigoroso Marl"	"upper Rigoroso Marl"	Gremiasco fm. Nivione mb.	Gremiasco fm. Nivione mb.
		"Nivione sandstone"	"Nivione sandstone" Variano mb.		
		"lower Rigoroso Marl" CdV	lower Rigoroso Marl CdV		CdV
				Hiatus	*Hiatus*
	Monastero fm. / "Ranzano Sandstone"	"Ranzano Sandstone"	Ranzano Fm. S. Sebastiano Curone Mb.	Monastero Fm.	Monastero fm.
	"Savignone Conglomerate" /	"Rio Trebbio sandstone" / *Hiatus*	Ranzano Fm. Val Pessola Mb.	"Savignone Conglomerate"	"Savignone Conglomerate"
UPPER EOCENE		Hiatus	*Hiatus*		Rio Trebbio fm.
	"Vigoponzo Marl"	"Ranzano Sandstone"	Ranzano Fm. Pizzo D'oca Mb.	Dernice fm.	Dernice fm.
		"Bosmenso marl"	*Hiatus*	"Vigoponzo Marl"	"Vigoponzo Marl"
	Hiatus			*Hiatus*	
PALEOCENE-UPPER CRETACEOUS	"Antola Unit"				

Introduction

The aim of Day 4 of field trip (Fig. 25) is to observe and discuss some key outcrops of the Eocene-Miocene sedimentary fill in the Eastern TPB, which provide an invaluable record of the complex interplay between tectonics and sedimentation at the structural knot linking Alps and Apennine orogenic belts (Fig. 26). In order to guide the reader through the multiple stratigraphic nomenclatures used by various authors over the decades, we show in Table 2 a synthetic chronostratigraphic scheme where all nomenclatures are listed and compared. This scheme will also allow to correctly interpret and correlate previous and in-progress works on the eastern TPB sedimentary sequence. Differently from what observed in Days 1-2-3, with evidence of sedimentation onto the subsiding Ligurian Alps retrobelt, stops of Day 4 highlight how sediment routing and accumulation in the eastern TPB was severely controlled by the Oligocene-Miocene compressive stress field related to both the Apennines structuration and the transpressive activity along the crustal-scale Villalvernia-Varzi line.

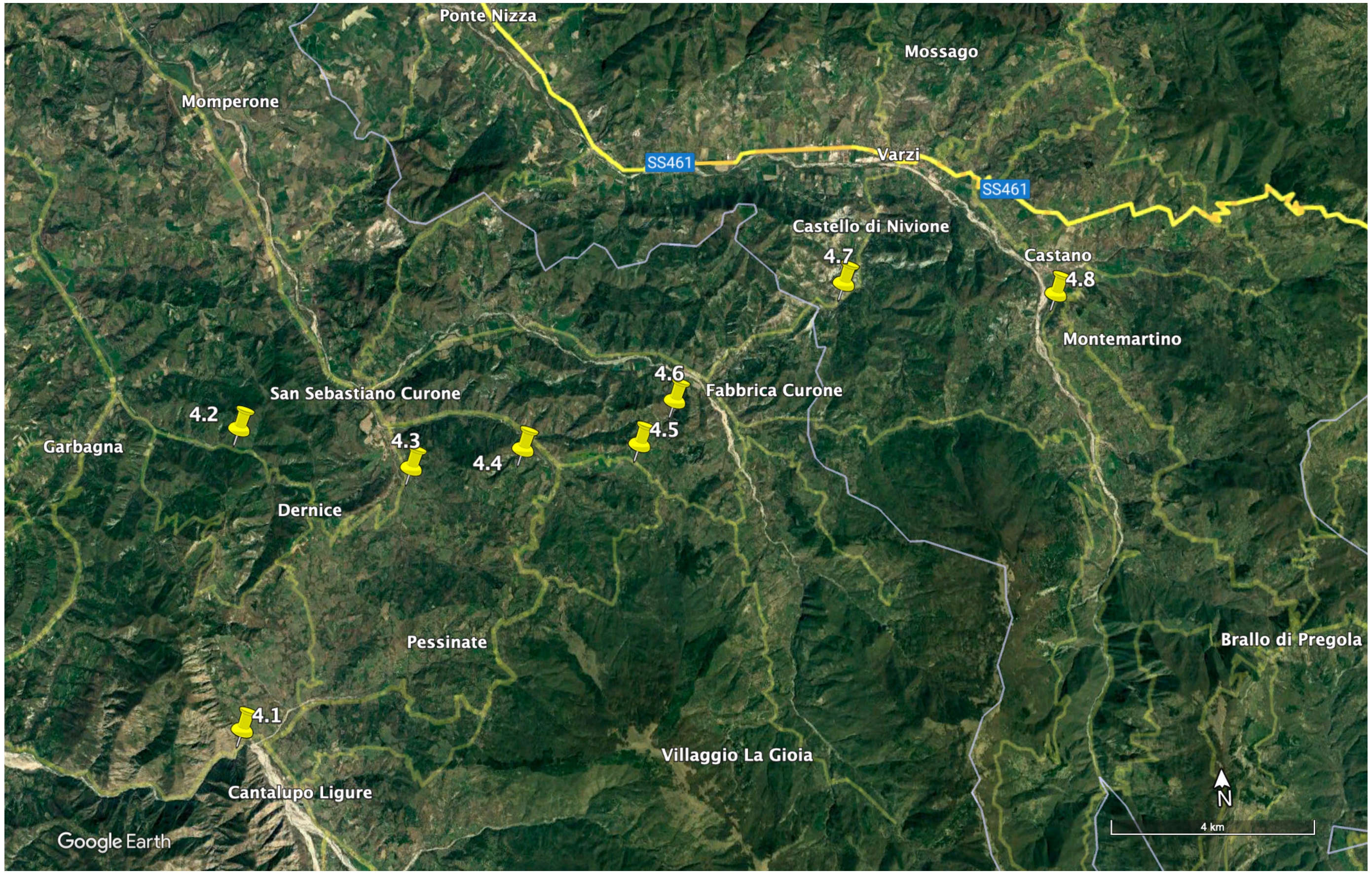

Fig. 25 - Day 4 itinerary with stops.

Stops 4.1 and 4.2 illustrate some of the sedimentary and compositional key features in a conglomeratic fan-delta of early Rupelian age, and partly coeval to relatively younger (early- to late Rupelian) delta-fed hyperpycnal deposits, respectively. The contrasting sedimentary facies and petrographic composition of these deposits highlight the stratigraphic changes from a proximal setting, provided with considerable amount of coarse sediments from the uplifting Apennines, to a more distal slope to basinal setting, representing the final sink of finer sediments sourced from the Ligurian Alps.

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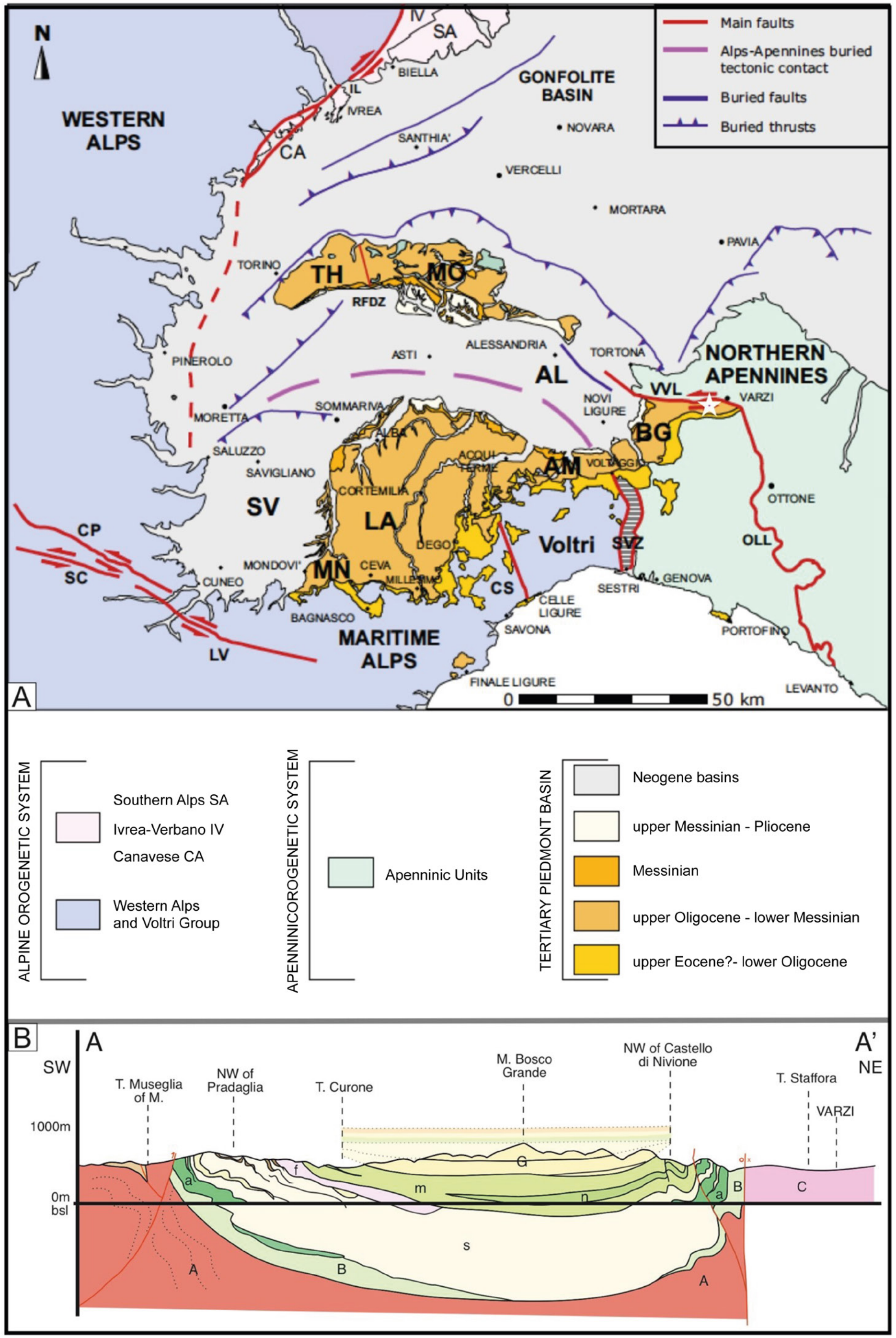

Fig. 26 - A) Synthetic geological map with regional structural framework of the Alps–Apennines Junction (NW Italy) and location of the Tertiary Piedmont Basin. Red lines show the Alpine related tectonic lineaments whereas in blue are the Apennine ones. CA: Canavese; IV: Ivrea-Verbano zone; SA: Southern Alps; IL: Insubric Line; SC: Stura Couloir Line (Giglia et al., 1996); CP: Cicatrice del Preit Line (Lefevre, 1983); LV: Limone-Viozene deformation zone (Piana et al., 2009; d'Atri et al., 2016); RFDZ: Rio Freddo Deformation Zone; OLL: Ottone–Levanto Line; SVZ: Sestri–Voltaggio deformation Zone; VVL, Villavernia–Varzi Line; CS, Celle–Sanda Line; TH: Torino Hill; MO: Monferrato area; MN: Monregalese area; SV: Savigliano; LA: Langhe; AM: Alto Monferrato; AL: Alessandria; BC: Borbera-Curone. Modified from Ghibaudo et al. (2014). B) Geological cross-section illustrating the stratigraphy of the eastern TPB in the Castagnola syncline (modified, after Di Giulio & Galbiati, 1995). A=Antola Unit; B=Bosmenso Marls; a, s, f = amalgamated sandstones, conglomerates, thin-bedded 'turbidites' and mass transport deposits of the Monastero Fm ; m, n=marlstone and main turbidite sandbodies of the Gremiasco fm.; G= ponded turbidites of the Castagnola fm. (Costagrande member).

Stops 4.3 and 4.4 show seismic-scale outcrop expressions of the interplay of sedimentation and early Oligocene contractional tectonics and provide insights into age of the deformation and related stratigraphic changes of depositional systems.

Finally, the variety of deep-marine sedimentary facies exposed in stops 4.5 to 4.8 allows tracking the transition from a slope, which configuration was influenced by uplift of the Apennines to the South, to a dynamic basin floor controlled by the transpressive activity of the Villalvernia-Varzi line, which bounded the basin to the North.

Stop 4.1 - Savignone conglomerate (Oligocene) in the Borbera Valley, near the village of Pertuso

Coordinates: Lat. 44.72646751 N, Long. 9.030416847 E

The Savignone conglomerate forms a large lenticular rock body resting unconformably on different deep-water flysch deposits of the Ligurian units in the Northern Apennines (Fig. 27). Ligurian units include the Monte Antola formation (Campanian-Paleocene) and the Pagliaro formation

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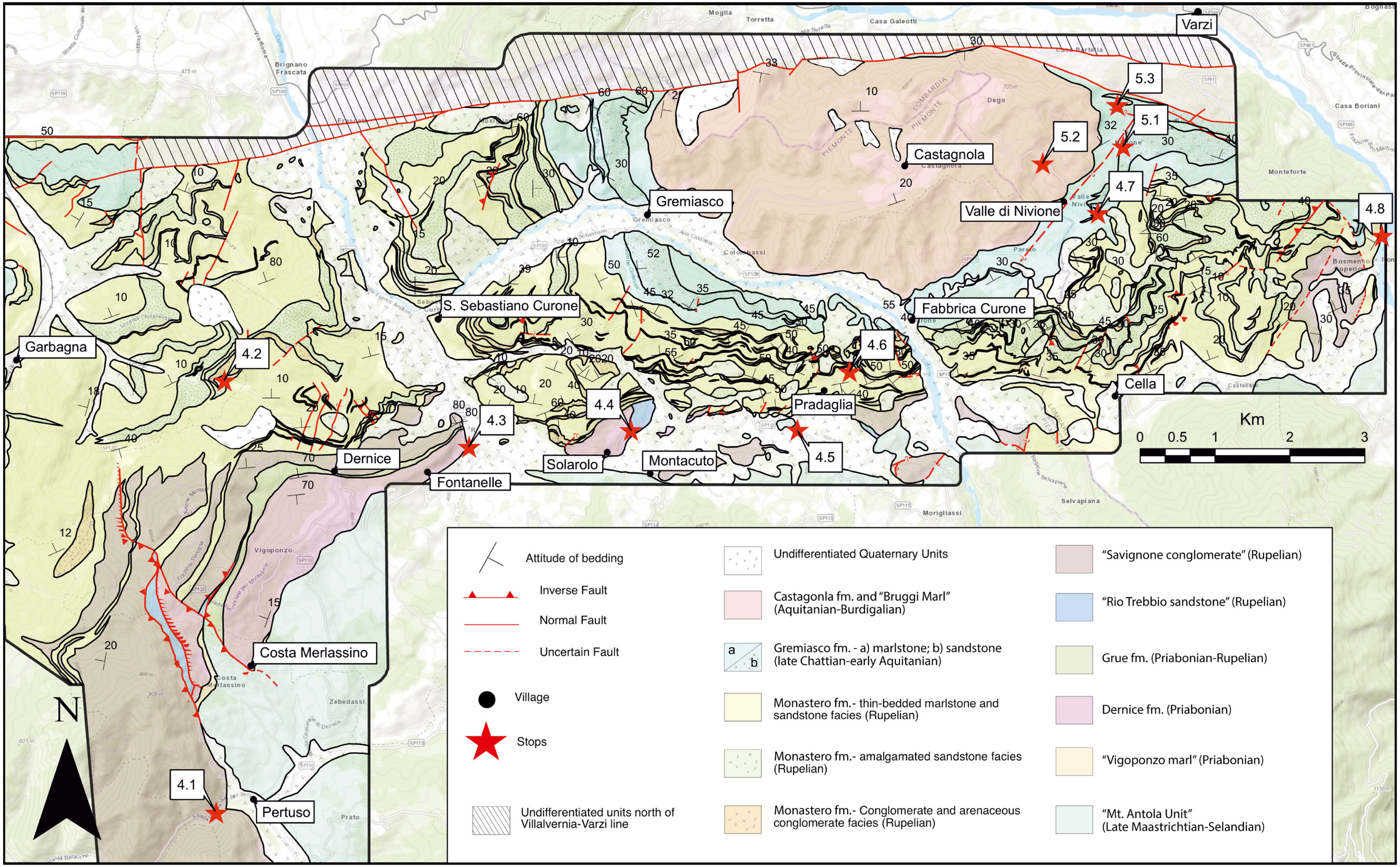
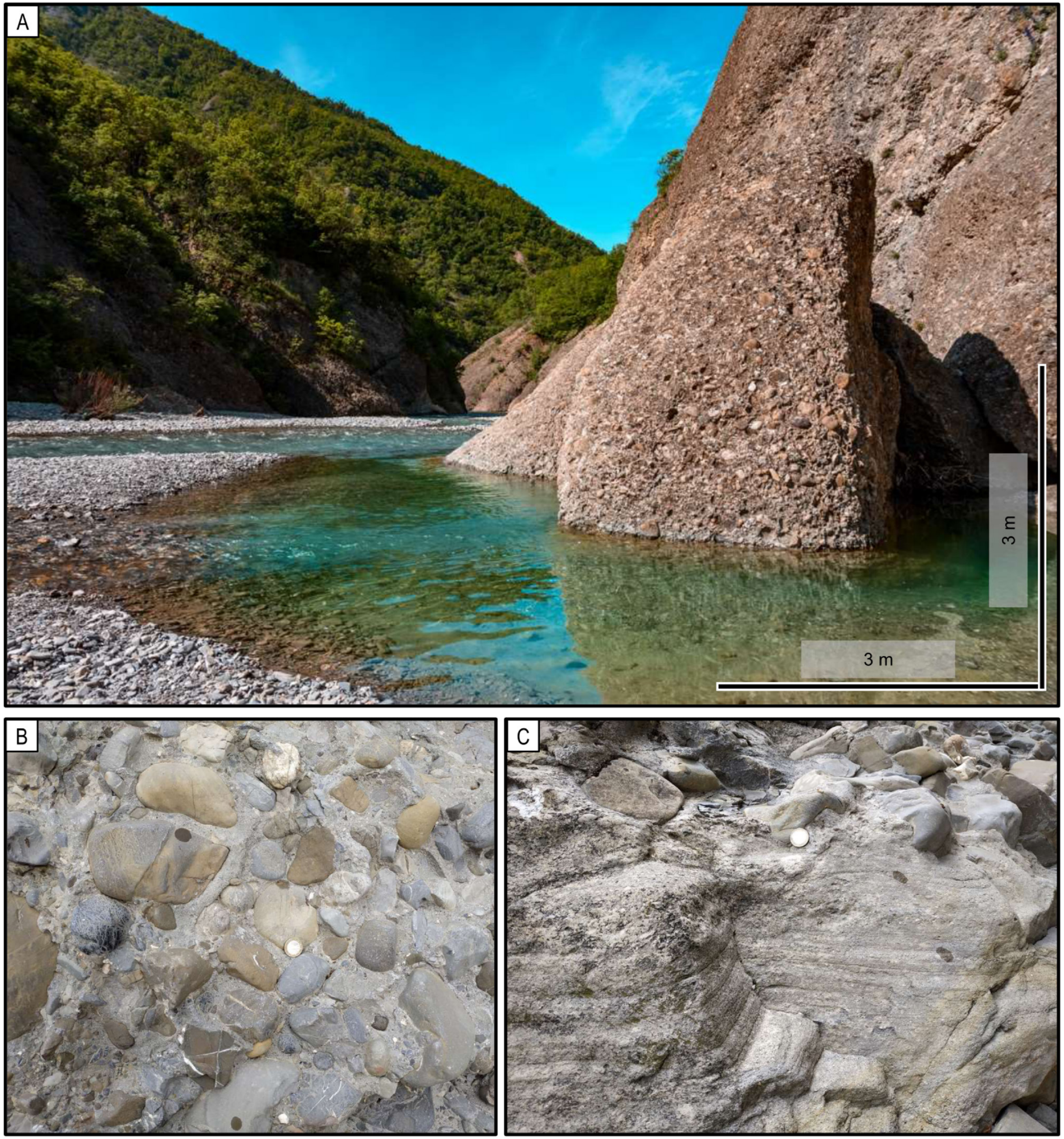


Fig. 27 - Simplified geological map obtained by merging and modifying the maps after Cavanna et al. (1989), Servizio Geologico d'Italia (2014, in press) and Uchman et al. (2017); the map illustrates the location of stops of day 4 and 5 (red stars in the figure). The used stratigraphic nomenclature is the one proposed by CARG sheets n. 178 and 196 (Servizio Geologico d'Italia., 2014, in press); for a synoptic scheme of regional lithostratigraphic nomenclature refer to Table 2.



(Paleocene). The Savignone conglomerate is interpreted as a fan delta (Gelati & Gnaccolini, 1978; Mutti et al., 1995) deposited from the South and Southwest (Gelati & Gnaccolini, 1978, 1982), with a minor contribution from the North. Estimation of its maximum thickness varies among authors, from 1300 m (Gnaccolini, 1974) to 2500 m (Gelati & Gnaccolini, 1978; Di Biase & Pandolfi, 1999). The main body of the Savignone conglomerate is formed by the Val Borbera unit (Fig. 28), which shows clasts composed mostly of limestone and marlstone (Fig. 28B) deriving from the underlying Monte Antola formation with minor contributions of sandstone (Fig. 28C), ophiolites, radiolarites or other rocks (Gnaccolini, 1974). In the upper part of the Savignone conglomerate (Persi member; up to 200 m thick), ophiolitic material and metamorphic carbonate clasts dominate. The conglomerate is mostly clast-supported with limited exposures of matrix-supported conglomerate. The sorting of coarse-grained fractions varies from place to

Fig. 28 - Stop 4.1 at the Borbera river near Pertuso village. (A) The main body of the Savignone Conglomerate Formation: the Val Borbera Unit. (B) Example of Savignone Conglomerates: clasts are composed mostly of limestones and marlstones deriving from the succession of the underlying Monte Antola fm. The conglomerates are mostly clast supported. Only locally, matrix supported parts are present. The sorting of coarse-grained fractions varies from place to place (coin for scale); (C) Fine-grained arenite interbedded with conglomerate, showing sharp boundaries. They are generally normally graded with horizontal lamination or low-angle cross-lamination (coin for scale).

place. Locally, sandstone lenses are present within the conglomerate. They are characterised by generally medium- to fine-grained arenite forming medium to very thin beds, intercalated into prevailing siltstone with widespread fine lamination and locally bioturbation, bioclasts and abundant plant remains. The arenitic strata show sharp boundaries and are generally structureless or normally graded; horizontal lamination or low-angle cross-lamination are also present (Fig. 28B). They can contain benthic foraminifers and some macrofossils, including molluscs and corals. According to Gelati & Gnaccolini (1978), this lithofacies association was deposited in the frontal zone of a fan-delta system (i.e., prodelta zone). The conglomerate beds can be regarded as the result of the freezing and *en-masse* deposition of hyperconcentrated flows (*sensu* Mutti, 1992) originated by fluvial floods and developed during the main activity phases of the system. On the contrary, the fine-grained beds are the result of deposition by low density turbidity currents generated by minor volume floods that record a low efficiency phase of the fan-delta system.

Stop 4.2 - Between Garbagna and Dernice – Delta-fed turbidites – the Monastero fm. (Oligocene)

Coordinates: Lat. 44.77780556 N, Long. 9.031833333 E

The Rupelian Monastero fm. (San Sebastiano Curone mb. of the Ranzano Fm. in Martelli et al., 1998; S3 according to the sequence frame after Di Giulio, 1991; see also stops 4.4 and 4.6) represents the sedimentary fill of a partly confined basin, which crops out over ca. 15 km. To the West, it terminates against the Val Scrivia Fault (Ghibaudo et al., 1985) and thickens rapidly Eastward from ca. 200 m (Scrivia Valley) to 1100 m (San Guadenzio section, Borbera Valley; Gelati, 1977; this stop location), before thinning again toward its eastern termination against the Villalvernia-Varzi line (Staffora Valley). To the south, the unit is substituted by the fan-delta deposits of the Savignone conglomerate, whereas to the east it disconformably overlies the late Eocene-earliest Oligocene units of the eastern TPB or directly the Ligurian units of the Apennines. Upwards, the Monastero fm. passes to slope and basinal hemipelagic marlstones (Gremiasco fm., cf. “Marne di Rigoroso” Auct.; Gnaccolini, 1974; Gelati, 1977; Gelati & Gnaccolini, 1982).

Early sedimentological studies describe the Monastero fm. as comprised primarily of thin-bedded turbidites with mud to sand ratios <1, intercalated with volumetrically subordinate channelised

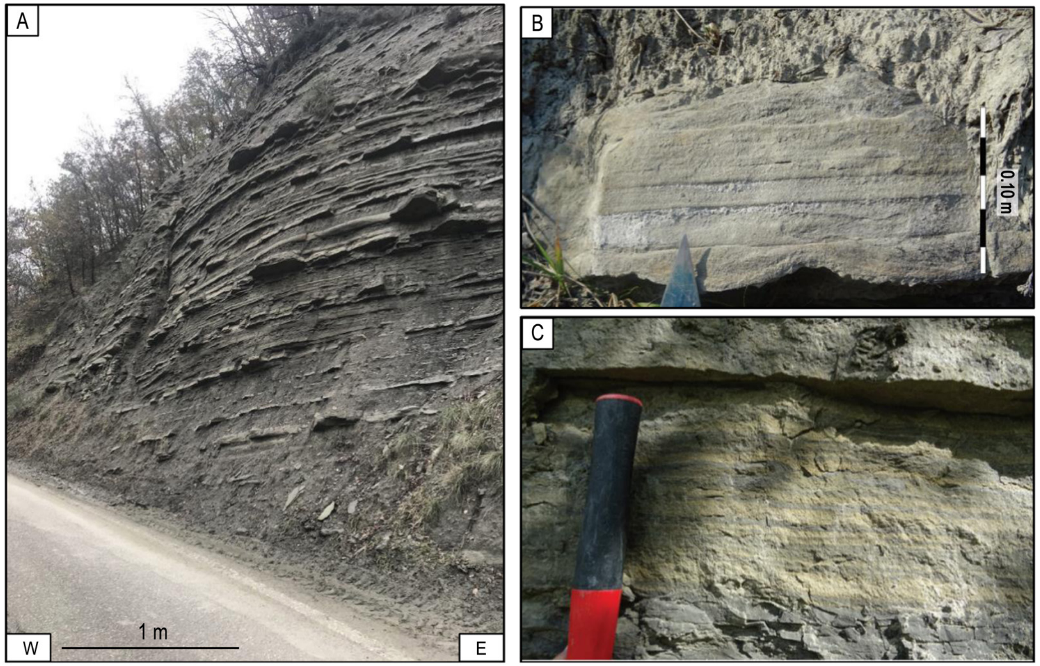


Fig. 29 - A) Representative section (Stop 4.2A) of the dominant sedimentary facies of the Monastero fm., which is represented by a thin-bedded alternation of sandstones and mudstones deposited by a range of sediment gravity flows including flood generated hyperpycnal flows; B) Sandstone bed with multiple grading and repeated sequences of sedimentary structures and C) alternation of very thin sandstone and mudstone beds with gradational contacts suggesting deposition from pulsating hyperpycnal flows.

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conglomerate and sandstone, turbidite sandstone lobes (e.g., "*Lobi di San Gaudenzio*"; Gelati, 1977) and mass-transport deposits (Gelati, 1977; Ghibaudo et al., 1985; Cavanna et al., 1989).

At this stop, a representative section of the thin-bedded component of the Monastero fm. can be observed, which is chiefly represented by co-genetic sandstone-mudstone couplets with repeated normal grading and sedimentary structures suggestive of pulsating flow conditions (*sensu* Mulder et al., 2001, 2003).

Correlations and relative facies proportions indicate that this thin-bedded facies association is hardly the distal and/or lateral equivalent to coarser-grained and thicker-bedded lobe and channel fill deposits. Rather, the sedimentary repetitions typifying these deposits suggest deposition by long-lived pulsating flows of hyperpycnal origin generated after plunging of turbid river plumes (Mulder et al., 2003). Thus, the Monastero fm. can be interpreted as a mixed hyperpycnal-turbidite system accumulated on a clastic ramp confined to the north by the Villalvernia-Varzi Line.

Stop 4.3 - Fontanelle fold, lowermost Dernice fm.

Coordinates: Lat. 44.76983771 N, Long. 9.073133428 E

The upper Eocene turbidite of the Dernice fm. (Pizzo d'Oca mb. of Ranzano Fm. according to Martelli et al., 1998), that represents the base of the TPB depositional sequence in this area, experienced ductile deformation. In Figure 30, it can be appreciated the North-verging fold (hundreds of metres in size) affecting the lowermost part of the formation. Deformation style and northern vergence can be observed allowing a comparison with tectonics affecting units observed in the previous days, which introduces the theme of the following Stop 4.4 (early Oligocene TPB deformation).

Fig. 30 - Panoramic view of the north-verging fold affecting the Priabonian turbidites of the Ranzano Formation near the village of Fontanelle (Stop 4.3).

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Stop 4.4 - Rio Trebbio section (NE from Solarolo village), Priabonian-early Rupelian eastern TPB units and early Oligocene TPB deformation

Coordinates: Lat. 44.77226398 N, Long. 9.100446019 E

Along the Rio Trebbio section (Di Giulio & Galbiati, 1995; Martelli et al., 1998) the complex geometrical relationships among Dernice-Rio Trebbio-Monastero fms. at the base of the eastern TPB can be observed in the landscape (Fig. 31). Specifically, light grey/whitish turbidites of Dernice fm. (Priabonian Pizzo d'Oca mb. of Ranzano Fm. in Martelli et al., 1998; S1 sequence in Di Giulio, 1991) and the overlying shallow marine lower Rupelian Rio Trebbio sandstone (S2 sequence in Di Giulio, 1991) dipping toward Northeast are stratigraphically cut by coarse-grained upper Rupelian turbidites of Monastero fm. (San Sebastiano Curone mb. of Ranzano Fm. in Martelli et al., 1998; S3 sequence in Di Giulio, 1991) dipping toward North-Northwest. The contact surface represents a regional unconformity (which here is clearly angular) recording an intense deformation phase dated to the early Rupelian, with tilting and folding (like the Fontanelle fold observed in the previous Stop 4.3) of the Priabonian-base Rupelian part of the succession.
In addition, along the Rio Trebbio River, it is possible to observe facies and composition of the 3 units forming here the base of the TPB depositional succession, i.e. the Dernice-RioTrebbio-Monastero fms. (Pizzo d'Oca, Rio Trebbio and San Sebastiano Curone mbs. of the Ranzano Fm. according to Martelli et al., 1998). These features provide evidence for a base Oligocene shallow marine episode interbedded in relatively deep-water

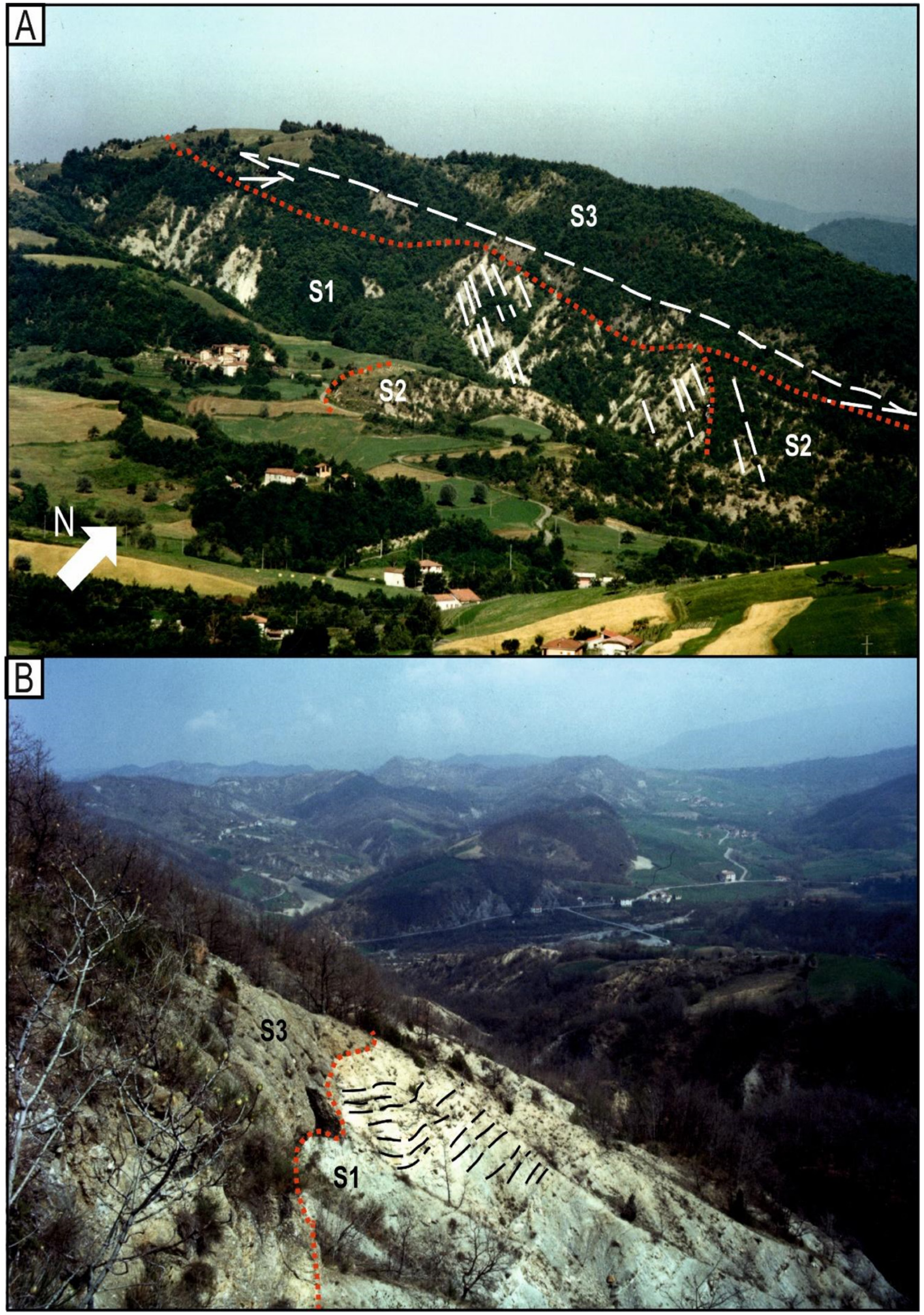

Fig. 31 - A) Panoramic view of the Rio Trebbio section and the angular unconformity (red dotted line) dividing the Priabonian-lower Rupelian units (Dernice-Rio Trebbio formations – S1 and S2) by the late Rupelian unit (Monastero Formation – S3). The white dashed lines follow the bedding; B) Close-up of the angular unconformity between the Priabonian turbidite (S1) and the upper Rupelian turbidites (S3) (Stop 4.4).

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turbidite units, and the complete change of composition of terrigenous materials recording an overall reorganisation of the source-to-sink system during the Rupelian. This gives the opportunity to discuss the interplay between tectonics and eustasy in the tectonic knot between Ligurian Alps and Northern Apennines.

Stop 4.5 - (44.77219065 N, 9.1285606 E) – Overview on seismic-scale bed geometry of the Castagnola fm. (Aquitanian)

At this stop, placed along the road going from Magroforte village to Pradaglia village, the panoramic view (Fig. 32) illustrates the overall sheet-like architecture of the lower member of the Castagnola fm. (Costa Grande mb., Aquitanian; Marini et al., 2020), which is made of basin-wide and km-scale turbidite beds with highly tabular geometry interpreted to reflect ponding by basin topography (Marini et al., 2016a, b). The depositional facies of these beds will be observed in detail in the last day of the field trip.

Fig. 32 - Overview of the km-scale tabular geometry of thick turbidite beds forming the Aquitanian interval of the Castagnola fm. (Costa Grande mb.); Pradaglia village is visible in the foreground (Stop 4.5).

Stop 4.6 - Facies and geometries of the upper Rupelian deposits of the Monastero fm. (Pradaglia section)

Coordinates: Lat. 44.7794047 N, Long. 9.137402551 E

Along the southern margin of the eastern TPB, the Monastero fm. (San Sebastiano Curone mb. of the Ranzano Fm. according to Martelli et. al., 1998; see also Stops 4.2 and 4.4) is formed by a turbidite complex with lenticular coarse-grained (from sandstone to conglomerate grade) channelised bodies within a fine-grained thin-bedded depositional background (Fig. 33A). This stop aims to present the depositional facies of this uppermost part of the lower Oligocene unit and their depositional setting and provenance in relation to older and younger deposits. These channelised bodies are interbedded with thin-bedded turbidites, which are often characterised by syn-depositional deformation resulting in 100s m-thick chaotic bodies interpreted as the product of submarine slides. All these features contrast with the geometry of the overlying part of the succession and suggest that they represent deposits of an unstable slope subject to tectonic Northward tilting under the effects of the Northern Apennines contraction and uplift.

Specifically, in this stop it can be observed the very rapid lateral change of facies from channel-filling conglomerate beds to channel levee thin-bedded facies (Fig. 33B); this indicates that at least a part of the background thin-bedded fine-grained deposits are the depositional levees of the coarse-grained channelised bodies.

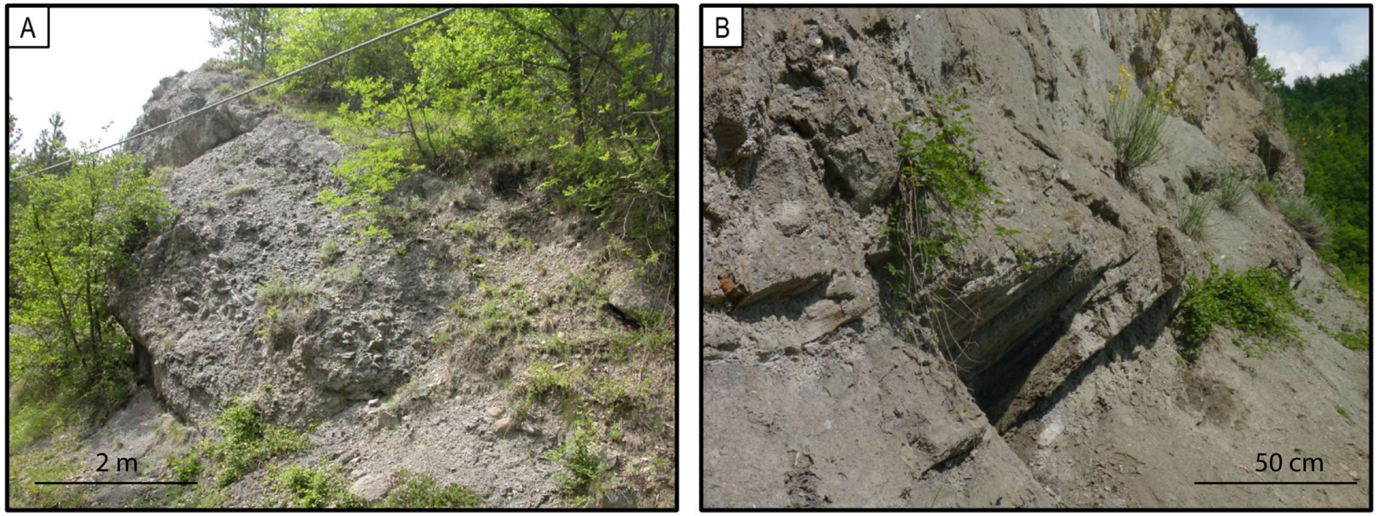


Fig. 33 - A) Coarse-grained lenticular turbidite bodies interbedded with thin-bedded turbidite forming the typical depositional facies of the upper Rupelian Monastero Formation along the southern margin of the eastern TPB basin; B) Detail of the abrupt lateral facies change from amalgamated conglomerate beds to thin-bedded fine-grained turbidite beds that together with erosion along channel axis explain the outcrop-scale lenticular shape of the coarse-grained bodies in this part of the succession (Stop 4.6).

Stop 4.7 - Cappella della Valle mb., Gremiasco fm. (late Chattian, Valle di Nivione)

Coordinates: Lat. 44.79827379 N, Long. 9.179400195 E

The Cappella della Valle mb. (CdV) is the lowest sandstone body within the sandy-marly Gremiasco fm. ("*Marne di Rigoroso"* fm. in Boni et al., 1974; Cavanna et al., 1989; Cibin et al., 2003). CdV consists of sandstone filling an erosional channel up to 80 m-high and up to 200 m wide exposed in three disconnected outcrops located at the same stratigraphic position (i.e., below the Nivione sandstones) along a fairly straight E-W path. Based on similar size, component facies, petrography and palaeoflow directions well visible at the base of these outcrops, Di Giulio & Galbiati (1993) suggested these three outcrops to expose the same submarine channel, extended over at least ca. 8 km along current (Fig. 34).

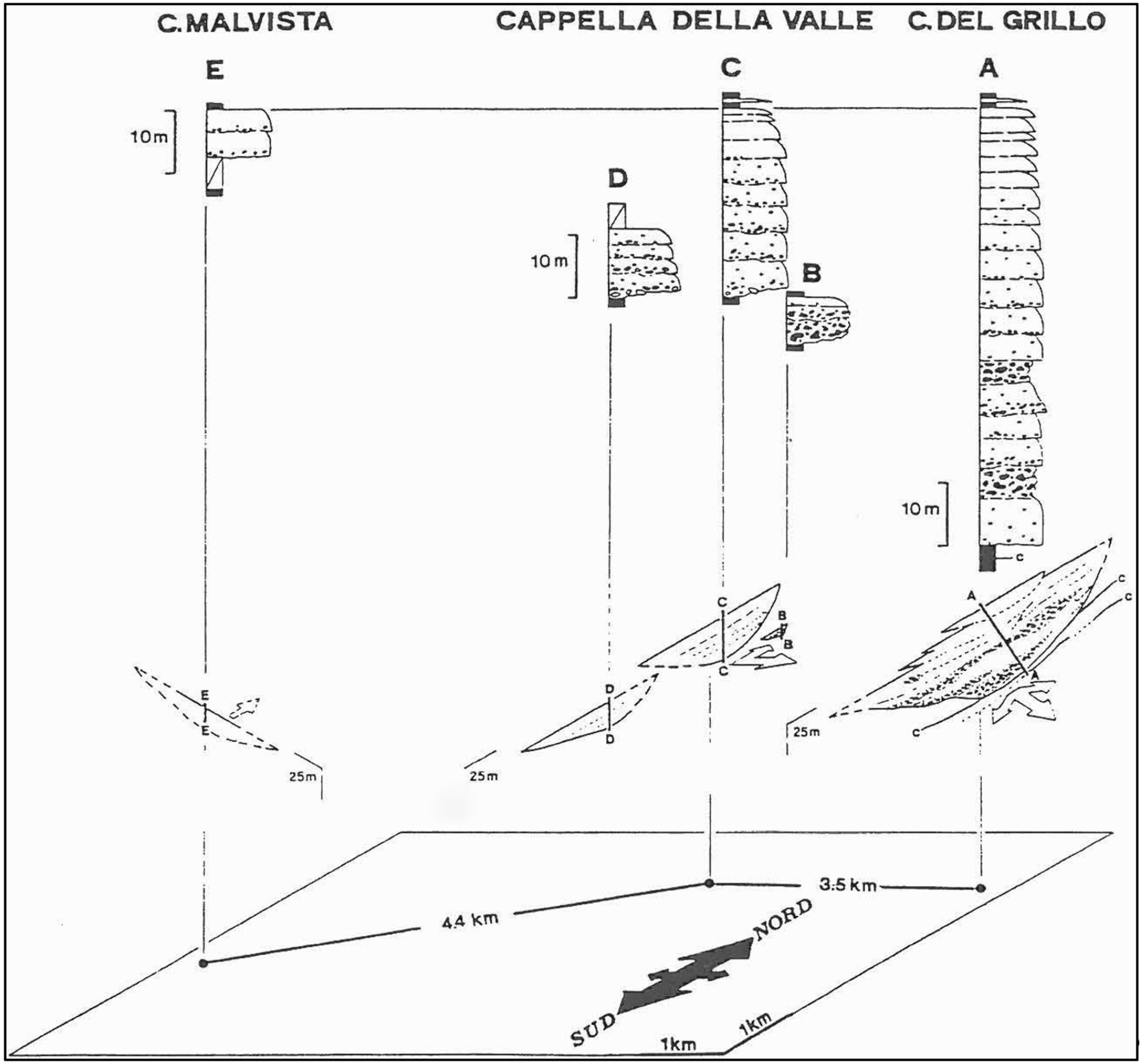
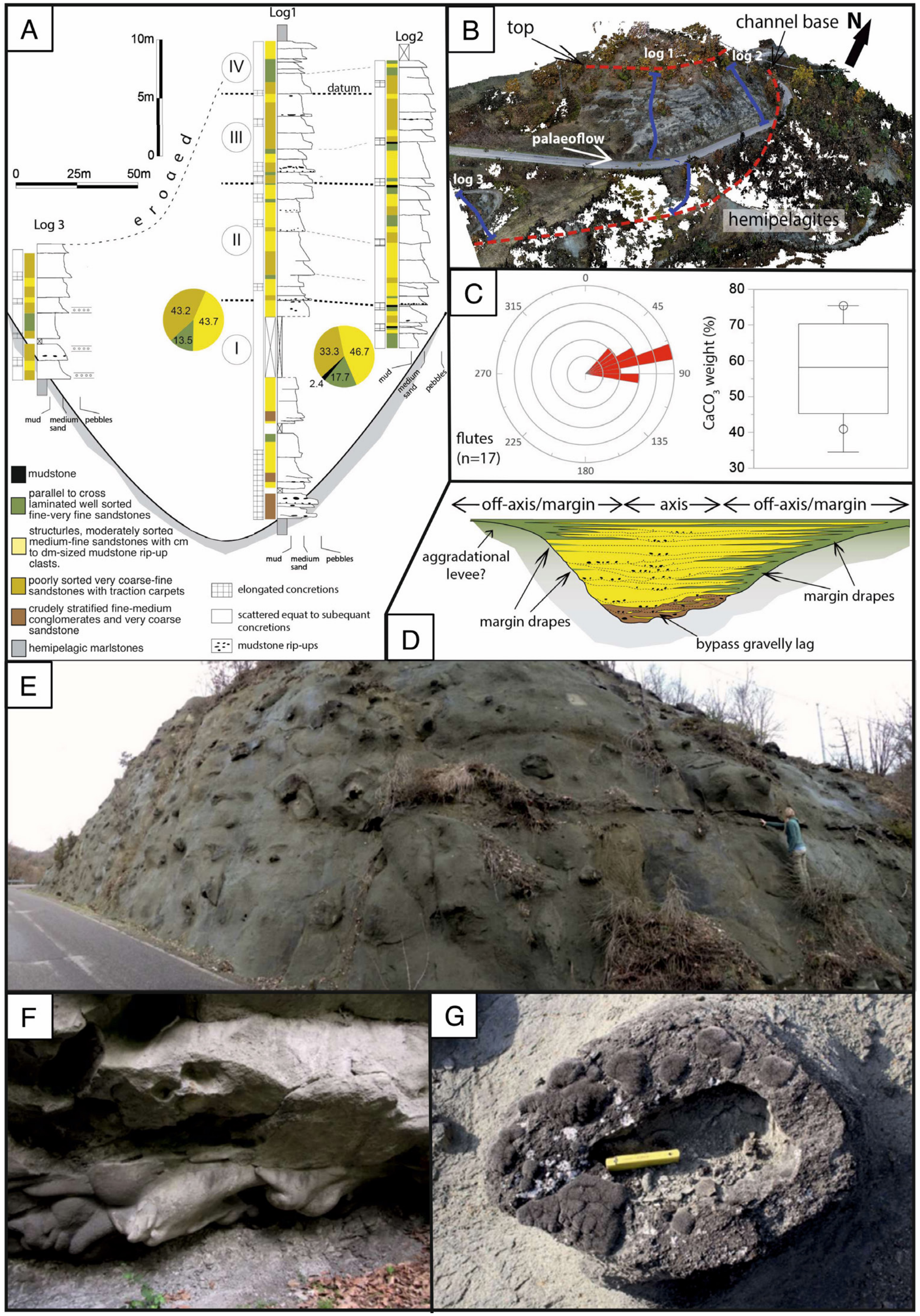


Fig. 34 - Sedimentological logs and correlation panel of the sand-bodies of Ca' Malvista, Cappella della Valle and Ca' del Grillo, here interpreted as three cross sections of the same submarine channel (from Di Giulio & Galbiati, 1993; Stop 4.7).

At the visited locality (Cappella della Valle; Fig. 34C), CdV is c. 40 m thick and c. 200 m wide (Fig. 35A), though the cover and the roadway split it into two separate outcrops. The CdV base is ornamented with large dm-sized flute casts (Fig. 35F) with palaeocurrent toward East (Felletti, 2002; Fig. 35C), which is consistent with the correlation pattern described above (Fig. 34). The facies of CdV consists dominantly in medium-fine normally graded sandstone with a range of faint to well-developed laminations and sparse mud clasts, some of which of several cm in size, and rare fine-grained rippled tops which become more abundant up-section and in off-channel locations (Fig. 35A). Event beds are typically amalgamated, with basal scours filled up with poorly sorted basal lags of coarse sand, granules and very small mud clasts. Moving from South-West to North-East (i.e., from channel axis to off-axis) it can be seen the gradual passage from some amalgamation surfaces to preserved mudstone caps (Fig. 35E).

It is noteworthy the presence of calcite concretions with sub-spherical to oblate shape which protrude from the outcrop face and that in a few instances bear mud clasts at their core (Fig. 35G). Carbonate content, along with the foraminiferal assemblage



observable on this section, indicates that these mud clasts were eroded from the channel marly substrate. Calcite cement characteristics, grain to grain contacts and carbon and oxygen stable isotopes (Milliken et al., 1998; Marini et al., 2019) indicate that the concretions formed during burial diagenesis and that the marlstone surrounding CdV and forming the rip-ups in the sandstone represent the dominant source of carbonate ions for calcite precipitation. Recently, the spatial distribution of these concretions has been assessed with the aid of UAV photogrammetry, showing that highly elongated concretions up to several metres long are associated to fine grained tops and comparatively more abundant in channel margin locations and in the uppermost part of the channel-fill (Marini et al., 2019). These concretions are likely to baffle fluid flow in analogue hydrocarbon reservoirs, making their prediction important for reservoir modelling.

Stop 4.8 - Ca’ del Grillo sandstone-body (Cappella della Valle mb., Gremiasco fm., upper Chattian), Bosmenso, Val Staffora.

Coordinates: Lat. 44.79491939 N, Long. 9.230466737 E

The upper half of the hill in the foreground (Fig. 36) provides another cross-section of the lower Gremiasco fm. stratigraphy (Cappella della Valle mb., late Chattian). The geology is complicated by the presence

Fig. 35 - A) Correlation of sedimentary logs from the Cappella della Valle outcrop (Stop 4.7). Pie charts indicate facies percentages in the correlative interval of logs 1–2. B) View of a photogrammetric model of the Cappella della Valle outcrop with base and top of the channel and location of the sedimentary logs. C) Rose plot (left) of palaeoflow from flute casts at the CdV base and box-plot (right) of calcimetry of marlstone rip-ups and hemipelagic marlstones above and below CdV. D) Depositional model for CdV (modified after McHargue et al., 2011). E) The Cappella della Valle sandstone-body outcropping along the SP166. F) Large flute casts at the base of the Cappella della Valle channel. Elongated mudstone clasts in cross section can also be observed. Pen is 15 cm long. G) Calcite cemented concretion with a large marlstone clast in its core (modified after Marini et al., 2019).

Fig. 36 - Overview of the Gremiasco fm. (upper half of the cliff), including the Cà del Grillo channel-fill sandstone belonging to the Cappella della Valle mb. (Stop 4.8). View is from the SP48, NE of Bosmenso Superiore village, on the right flank of the Staffora Valley, but the outcrop is on the opposite flank (western flank) of the valley. See Fig. 37A-B for a line drawing of the channel and a detail of its southern margin.

of a thrust fault outcropping along the crest (see Fig. 37A-B). The Gremiasco fm. marlstone is incised by a ~70 m thick lenticular sandstone body. Palaeocurrents from large flute casts are roughly from West toward East (out of the cliff), allowing a view orthogonal to palaeoflow direction (Di Giulio & Galbiati, 1993). Although the southern margin of the sandstone body is deformed (and steepened) by a thrust fault, its overall geometry – including its onlap relationships to the margin – can be still observed (Fig. 37A-B).

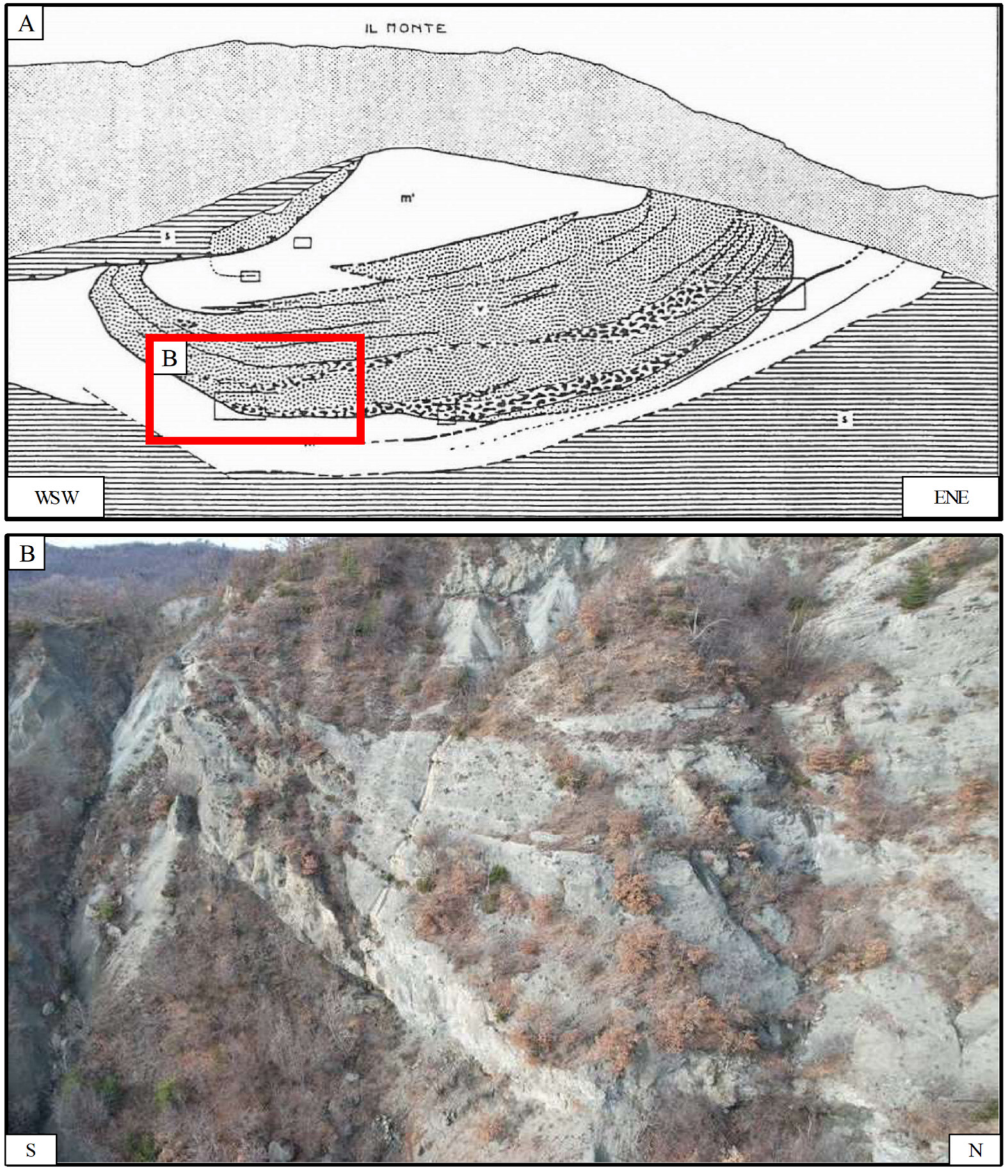


Fig. 37 - A) Schematic drawing of the Ca' del Grillo sand-body (from Di Giulio & Galbiati, 1993; Stop 4.8). The sandstones (v) represent the fill of an erosive surface within the Gremiasco fm. marls (m'). The maculated intervals are characterised by mudstone clast breccias. The strata appear deformed for a combination of syn-sedimentary sliding within the marls and tectonic overprint. The red square indicates the field of view of the photo of part B; B) Detail of the Ca' del Grillo sand-body southern margin.

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DAY 5 - THE CASTAGNOLA FORMATION: FACIES AND GEOMETRY OF A TURBIDITE SYSTEM ACCUMULATED INTO A TECTONICALLY CONFINED BASIN

Introduction

The aim of Day 5 is to expand the discussion on sedimentation and tectonics in the eastern TPB introduced in Day 4. Particularly, in Day 5 we will be looking into more detail at the Castagnola fm., the sedimentary fill of a relatively small turbidite basin (Castagnola Basin) confined to the north by the positive flower-structure associated to the Villalvernia-Varzi line (Fig. 38).

Stop 5.1 illustrates the scale and nature of strain affecting the Gremiasco fm. as the slope bounding the Castagnola Basin to the north was involved in the deformation of Villalvernia-Varzi line and oversteepened.
In Stop 5.2 we will look at the lower and relatively more confined part of the Castagnola turbidite system, to discuss how flow containment and local interaction with basinal slopes can result in formation of peculiar sedimentary facies. Finally, Stop 5.3 illustrates the geometry of the onlap termination of the Castagnola fm. onto the northern bounding slope, highlighting the different geometry of thin vs. relatively thicker beds and its significance.

Fig. 38 – Day 5 itinerary and stops.

https://doi.org/10.3301/GFT.2024.02

Stop 5.1 - Viewpoint near Chiesa di Nivione (Castagnola fm. overview)

Coordinates: Lat. 44.80587337 N, Long. 9.183669315 E

During the Oligocene, syn-sedimentary tectonics affected deep-water sedimentation, configuring the shape of this basin sector, inducing the development of several unconformities and controlling the shape and architecture of the turbidite units. This tectonic activity is related to left–lateral transpressive motion along the Villalvernia – Varzi fault, which acted in two major steps. A Rupelian phase conditioned the deposition of the Ranzano Fm. turbidite systems; the subsequent Chattian phase folded and faulted this succession during sedimentation of the Gremiasco fm. ("*Marne di Rigoroso*" fm. *Auct.*). Stop 5.3 (Fig. 38) will provide an opportunity to observe some of the deformation in the Gremiasco marlstone.

Fig. 39 - Aerial view of the NE margin (dashed line) of the Castagnola fm. host basin highlighting the onlap (arrows) of turbidites.

From this viewpoint, looking toward E-NE, it is possible to observe the sandstone beds of the lower part of the Castagnola turbidite system. They are characterised by a km-scale tabular geometry (that has been seen at distance in Stop 4.5), but here it can be observed their fast pinch-out towards the northern uplifting basin margin (Fig. 39 and Fig. 40). The onlap terminations of the sandstone bodies are associated to characteristic facies changes, affecting mostly the lower part of the basin fill (Felletti, 2002).

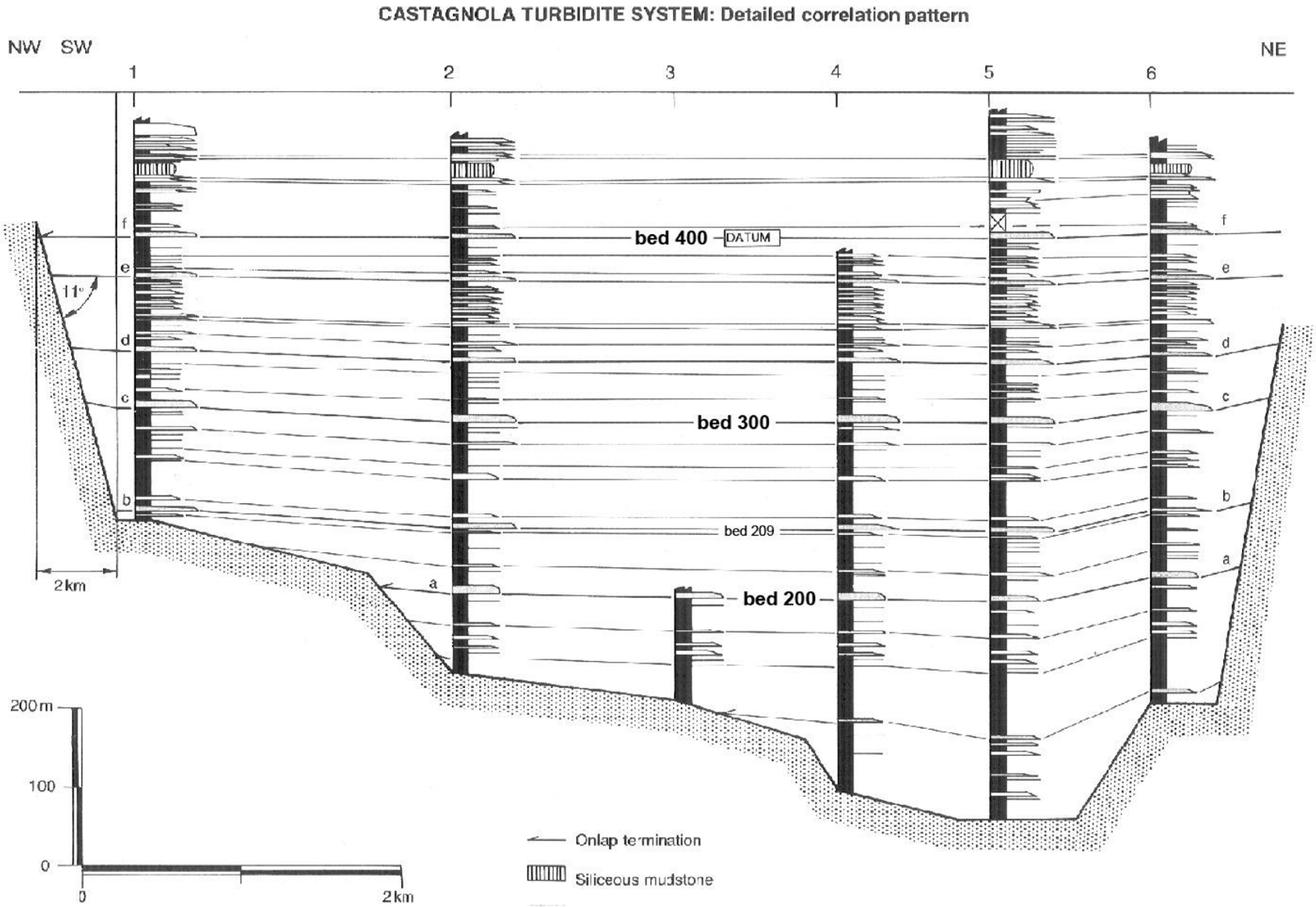

Fig. 40 - General stratigraphic cross-section of the Castagnola turbidite system (modified after Stocchi et al., 1992), illustrating high bed continuity and abrupt pinch-outs towards the northern basin margin.

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Stop 5.2 - Sedimentology of the Costa Grande mb. Along the road section toward Dego village

Coordinates: Lat. 44.80388654 N, Long. 9.170071186 E

The road section here provides a relatively fresh section (~250 m) through the interval of the Costa Grande mb. between megabeds 200 and 300 (see Southern et al., 2015). The observation can be focussed here on the interval above bed 208 (Log 4, Fig. 40). Deposits are approximately 1 km away from the northern basin margin and display a wide range of sedimentological characteristics so some time can be spent examining the facies and features present in event beds. Detailed bed-to-bed correlations across the basin also allow to assess the lateral setting of event beds across the system.

We will focus on the interval above bed 208 (Log 4, Fig. 40). The outcrop comprises two common medium and thick-bedded (0.5-5 m) gravity current event bed styles (Type B and C; Fig. 41): normally graded event beds of very fine- to medium-grained sandstone dominated by tractional structuration (e.g., current ripple lamination, planar lamination, undulated lamination and convoluted lamination) and occasional dewatering structures.

Normally to weakly-normally graded, lower fine- to medium-grained sandstone beds typically comprising a lower massive to weakly-structured sandstone overlain by a mud clast-charged interval in which mud clasts are supported in a sandy matrix. This is in turn overlain by a capping, often strongly normally graded, tractionally structured sandstone (e.g., current ripple, planar, undulated and convoluted lamination), which can display loading and syn-sedimentary growth into underlying mud clast-charged intervals. Mud clasts within the basal and capping facies are characterised by a lower frequency and/or average size compared to mudclast-charged facies; except where basal sandstones are strongly erosive resulting in localised enrichment of larger clasts.

Here, one of the key research questions concerns the origin of the mud clasts and their link with the development of the hybrid character (*sensu* Haughton et al., 2009). Mud clasts can be sourced at different positions along the flow pathway, and this has a direct effect on their role in the evolution of the flow and its rheological changes (Patacci et al., 2020). Many of the observed hybrid beds show a characteristic mud-clast vertical distribution within the bed. In the lower part of the bed (clean sand – H1) there is often a narrow horizon where large mudstone rafts are deposited (up to 1 m in length and some tens of cm in height). Sometimes 'frozen' entrainment of mudstone substrate at bed bases can also be observed (i.e., delamination *sensu* Fonnesu et al., 2016). The chaotic middle division (H3) is often filled with mud clasts and can laterally pass to mud clasts dispersed into a clean sandstone.

The normal grading and thick mudstone caps, lack of bioturbation in both mudstone caps and the underlying sandstones and the statistical analysis of the bed thicknesses suggest deposition by ponded turbidity currents (see Marini et al., 2016 a, b). Analysis of the vertical change of the mean direction of palaeocurrent indicators within the stratigraphy between key beds 200 and 300 shows a coherent rotation from a S-N to a W-E orientation for most logs; in map view, the point of rotation shifts Northwards over time (Southern et al., 2015). Such stratigraphic change and geographic shift are interpreted to reflect change in the position of the base of slope and point of onlap onto the confining northern

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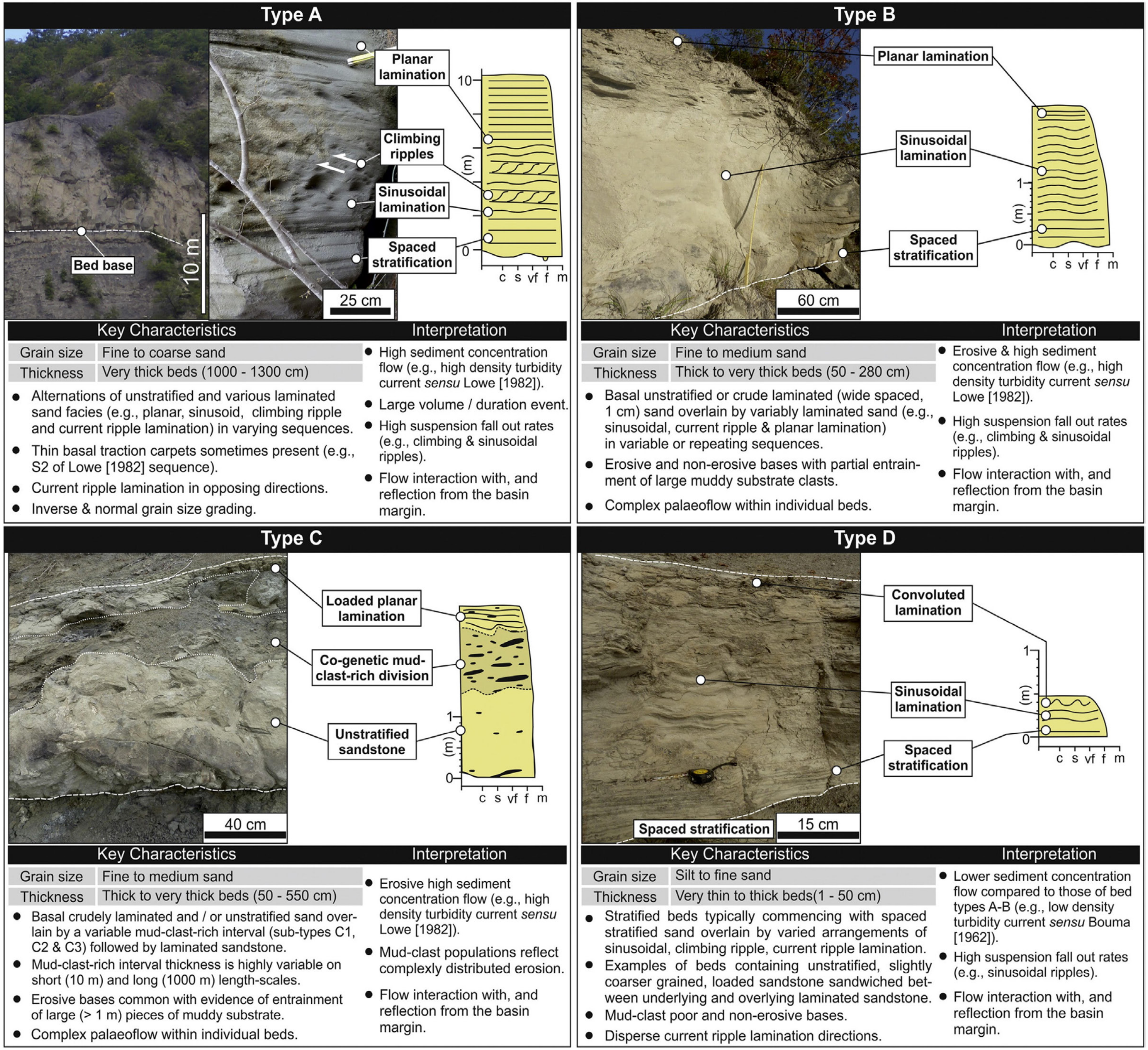

basin margin during basin floor aggradation (*sensu* McCaffrey & Kneller, 2001). Subsequently, the region of flow deflection shifts both stratigraphically upwards and spatially towards the confining slope whilst tracking the changing onlap point which migrated up the confining slope during basin floor aggradation.

Published data on sandstone petrography (Cibin et al., 2003) show that the beds in the ponded interval of the Castagnola fm. have sandstone compositions falling into discrete categories. Most are either ophiolite-rich lithic or arkosic in character; a much smaller proportion is of mixed lithic-arkosic composition. This compositional division suggests that initially the parent flows might have been sourced by completely different parent rocks exposed in two (possibly neighbouring) drainage areas (Patacci et al., 2020).

Fig. 41 - Bed types in the interval between key bed 200 and 300 (modified from Southern et al., 2015); Stop 5.2.

https://doi.org/10.3301/GFT.2024.02

Stop 5.3 - Castello di Nivione and Sentiero dei Partigiani (onlaps and tectonics)

Coordinates: Lat. 44.81101849 N, Long. 9.182705838 E

This short walk provides an overview of the northern bounding slope of the Castagnola Basin. The slope is represented by the hemipelagic marlstone of the Gremiasco fm. onlapped by a variety of very thin to very thick turbidite beds. It is possible to observe hemipelagic marlstone of the Gremiasco fm. with deformations related to the syn-sedimentary activity of the Villalvernia-Varzi Line (see Festa et al., 2015 for further details) and (above) a thin bedded interval overlain by a prominent key bed (megabed 200, Fig. 42), which pinches out further to the north as they onlap onto the slope.

Fig. 42 - Deformations in the marlstones of the Gremiasco fm. (below) witnessing the syn-sedimentary activity of the Villalvernia-Varzi Line and onlap of the Castagnola fm. (above).

Acknowledgments

This fieldtrip guide is a tribute to Guido Ghibaudo, colleague and friend, who passed away at the beginning of 2019. His death has deprived the Italian sedimentological community of a rigorous scientist and a great person. Guido's sedimentological work on the Tertiary Piedmont Basin will be the foundation of all future research on that basin. Apart from Guido, this guide is the result of years of work of several of us on different parts of the basin; this long-lasting job benefitted of collaborations and discussions with many colleagues and friends throughout the years; they are too many to be cited, but (in alphabetic order) Benito Galbiati, Romano Gelati, Mario Gnaccolini, and Emiliano Mutti merit a special mention. We want to thank Eni S.p.a. for the concession of the drone images used in the publication. Last but not least, we want to acknowledge the Editor and two anonymous reviewers that contributed to improve the final quality of the guide through their detailed revisions and constructive comments.

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