Alpine Workshop 2024

16th EGU Emile Argand Conference on Alpine Geological Studies
Alpine Workshop

Siena, Italy • 16-17-18 September 2024

Field Trip A Pre-Congress

The ``Ligurian Knot'': from the Piedmont Tertiary Basin, through the Alpine and Apennine tectonic units to the Ligurian ophiolites

Field Trip Guide

Giancarlo Molli, Laura Crispini, Anna d'Atri, Laura Federico, Luca Barale, Paolo Conti, Fabrizio Piana

European Geosciences Union

Organized by

Università di Siena 1240 · Università di Pisa · Freie Universität Berlin · Fondazione Masaccio · EGU European Geosciences Union

Supported by

Istituto Nazionale di Geofisica e Vulcanologia · ISPRA Geological Survey of Italy · National Network for the Environmental Protection · Società Geologica Italiana · Gruppo Italiano di Geologia Strutturale · Parco Nazionale Arcipelago Toscano · MB 4D · AlpArray · Copernicus Meetings The Professional Congress Organizer

Contents

Foreword

The aim of this excursion is to give an introduction view of the geology of the junction area between the Alps and Apennines. What is the boundary between the two orogens? How did the Alps and the Apennines evolved and/or interacted during time?

These two questions represent the core of a still ongoing debate started at the beginning of last century. This guide-book includes a short outline of how its Authors have faced the problem in the last decades, pointing out the still unsolved and/or newly open problems.

This Guide-book also includes an almost complete reference list of papers (from historical time to now) dealing with the subject.

For people interesting in run the field trip by themselves the following guide-books could be also of interest:

- Vanossi et al 1990 Alpi Liguri, Guide Geologiche Regionali, vol. 2, Società Geologica Italiana, BE-MA Editrice, Milano, 293 pp.
- Abbate E. (1992) - Guida alla Traversata dell'Appennino Settentrionale. Società Geologica Italiana - 76a Riunione Estiva - Firenze 16-20 Settembre 1992. Società Geologica Italiana - Università di Firenze, Firenze, 262 pp.
- Bortolotti V. (1992) - Appennino Tosco-Emiliano, Guide Geologiche Regionali, vol. 4. Società Geologica Italiana, BEMA Editrice, Milano, 329 pp.
- Zanzucchi G. 1994 Appenino Ligure-Emiliano, Guide Geologiche Regionali, vol. 6. Società Geologica Italiana, BEMA Editrice, Milano, 381 pp.
- Tribuzio, R., Molli, G., Riccardi, M.P., Messiga, B. 1997. Third Day. Polyphase metamorphism in ophiolitic gabbros from Bonassola (Internal Liguride Units, Northern Apennines): a record of Western Tethys oceanization. Ofioliti, 22(1), 163-174.
- Molli G. (2002) - Field Trip Eastern Liguria/Alpi Apuane. Gordon Research Conference on Rock Deformation. Il Ciocco, Barga, Italy.
- Tribuzio R., Sanfilippo A., Garzetti F., Renna, M.R., Molli, G., Borghini, G., 2009 Rampone, E. Pre-conference field-trip to the Ligurian ophiolites Liguria (Italy), Alpine Ophiolites and Modern Analogues Continental rifting to oceanic lithosphere: insights from the Alpine ophiolites and modern oceans Parma (Italy), September 28-29, 2009 Field trip Guide book, 25 pp.
- Marroni et al . (2004), Field Trip Guide Book - P38. I n: L. Guerrieri, I . Rischia & L. Serva (Eds.), 32 ○ International Geological Congress, Florence 20-28 August 2004, Memorie Descrittive della Carta Geologica d'Italia, vol. 63, pp. 1-40. Servizio Geologico, d'Italia, Roma.
- Conti P., Conticelli S., Cornamusini G. & Marroni M. (2022) - Toscana, Guide Geologiche Regionali, vol. 15. Società Geologica Italiana, Roma, 375 pp.
- Piana, F., Barale, L., Borghi, A., Carosi, R., d'Atri, A., Fioraso, G., Mosca, P., Vaggelli, G., (2023) - Piemonte, Guide Geologiche Regionali, vol. 16. Società Geologica Italiana, Roma, 399 pp.
- Di Giulio A., Marini, M., Felletti, F., Patacci, M., Massimo Rossi, M., Amadori, C., Menegoni, N., Reguzzi, Silvia Tamburelli, S.(2024) Basin toography and depositional styles controlled by collisional tectonics in the Alps-Apennines junction (Tertiary Piedmont Basin, NW Italy). Geol. F. Trips Maps, Vol.16 No.1.2 (2024), 58 pp., 42 figs., 2 tabs. (https://doi.org/10.3301/GFT.2024.02).

The excursion is divided in three days:

a) the first day is dedicated to the introduction of the Tertiary Piemonte Basin;
b) the second day will focus on the Sesri Voltaggio Zone: the tradional area indicated as the Alps/Apennines boundary;
c) the third day deals with the geology of the ophiolitc units of the inner Northern Apennines in eastern Liguria a classical site for the study of ophiolites.

Most of the sites we will visit represent actual or potential geosites, therefore please don't use the hammer where you can avoid it. Please leave the exposures as we had inherited it. Nature and future students will be grateful to you!

We wish you an interesting excursion.

Giancarlo Molli
Laura Crispini
Anna d'Atri
Laura Federico
Luca Barale
Paolo Conti
Fabrizio Piana

September 2024

Part I

Geological overview

1

The Western Alps-Northern Apennine junction area: a regional review

1.1 Introduction

The Alps and the Apennines are two mountain ranges that belong to the central-western Mediterranean region (Fig. 1, Fig. 2). For a long time, differences and transition between the two ranges, which at least partially both face to the Po Plain, have been discussed considering them as independent geological domains. On the contrary they represent part of a continuous orogenic system derived from a complex space-time interaction between the two major European and Adria plates, and intervening oceanic domains and minor microcontinents and or extensional allochthons. Past and present-day geological features of the Alps/Apennines junction area show structures and basin sedimentation history associated with complex interfering processes developed during successive stages of growth of the orogens related with subduction frames which changed and reversed during time.

The relationships between the Western Alps and the Northern Apennines represent a classical and still debated issue in the geology of the Central Mediterranean (Argand, 1924; Staub, 1928; Elter *et alii*, 1966; Laubscher, 1971; Haccard *et alii*, 1972; Elter & Pertusati, 1973; Debelmas, 1986; Capponi & Crispini, 2008; Vignaroli *et alii*, 2008; Handy *et alii*, 2010; Molli *et alii*, 2010; Malusà *et alii*, 2015; Schmid *et alii*, 2017; Piana *et alii*, 2017b; Van Hinsbergen *et alii*, 2020; Martinod *et alii*, 2024; Brunsmann *et alii*, 2024) which finds in the NW parts of the Italian peninsula the topical ground for the discussion. The present knowledge of the subject derives from more than one century of research (see historical reviews in Gelati & Pasquarè 1970; Castellarin 2001; Molli *et alii* 2010) whose main steps are hereafter reported.

In the 19th century the problem was principally faced from a lithologic point of view highlighting the presence of mainly metamorphic rocks as characteristic of the Alps, in contrast to widespread exposures of sedimentary rock-types in the Apennines.

With the recognition (Argand, 1924) of nappe architecture for the Alps, Staub (1928) pointed out the identity of structural zones in the two orogens (Pennidic of the Alps correlated with the metamorphic units exposed in the tectonic window of the inner Apennines (e.g. the Alpi Apuane). Whereas, structural elements as the orogen-scale vergences were quoted as the key for distinction between the two chains (Stille, 1924). At this time it was pointed out that the western vergences as characteristic of the Alps, whereas the opposite i.e. eastern vergences can be observed in the Apennines.

In all these early interpretations, the Sestri/Voltaggio line (east of Genoa) was recognized as a key structural element defining the boundary between the Alps and the Apennines.

The role of the Sestri/Voltaggio line has been later discussed/undermined taking into account the basin sediments unconformably sealing the internal structures of the zone itself, as well as the surrounding (west and east) metamorphic and unmetamorphic units (Elter & Pertusati, 1973; Sturani, 1973; Laubscher, 1988).

The opposite-dipping subduction frame of the Alps and Apennines and their complex geometric and kinematic interactions

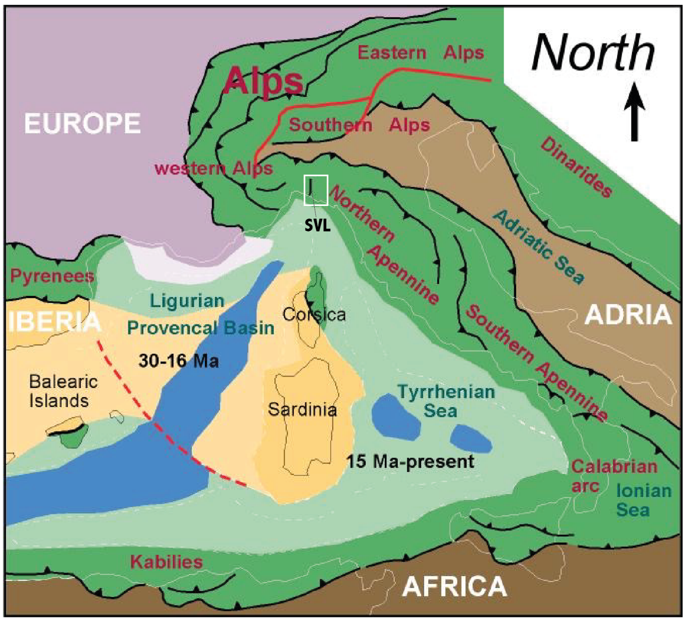


Fig. 1 – Tectonic setting of Central Western Mediterranean and surrounding orogens and basins. SVL, Sestri-Voltaggio line, traditional surface boundary between Alps and Apennines. The white rectangle figured the Field trip's area.

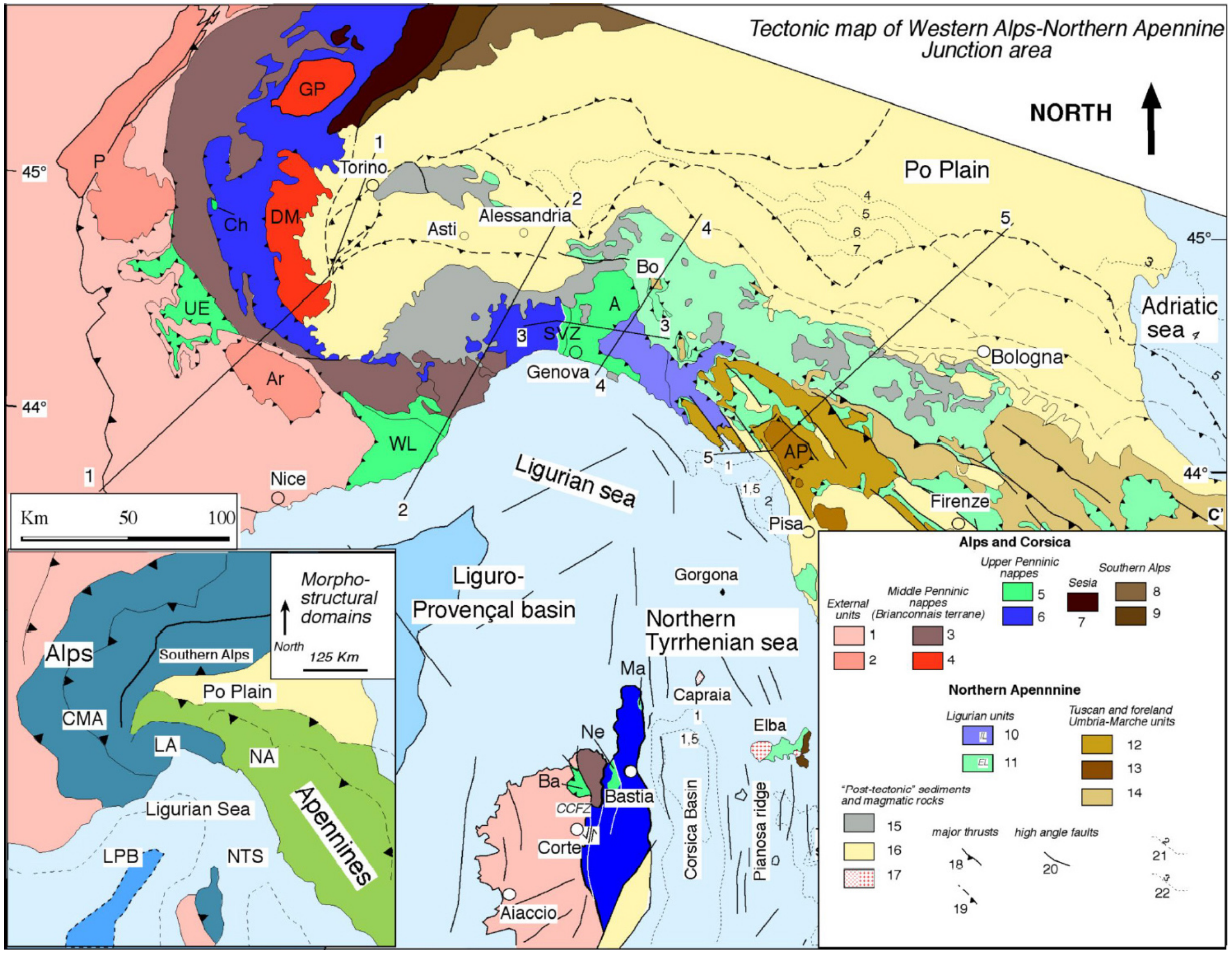


Fig. 2 – Tectonic map of the Western Alps - Northern Apennine junction area. CMA Cottian-Maritime Alps; LA Ligurian Alps, NA Northern Apennine; LPB Liguro-Provençal basin (dark blue oceanic crust); NTS Northern Tyrrhenian sea. In the map the main tectonic and lithostratigraphic units of the system are shown. For the Western Alps: (1,2) Europe-derived external Alpine units and external part of Corsica. 1) Alpine foreland units; (2) External massifs (Ar, Argentera and P, Pelvoux); (3) Middle Penninic Briançonnais nappes in the Alps and the Tenda unit in Corsica (4) Middle Penninic Internal Massif (DM, Dora Maira and GP, Gran Paradiso); (5) Upper Penninic Helminthoid Flysch: UE, Ubaye-Embrunais, Western Liguria Helminthoid Flysch (WL) and the Antola unit (A). With the same color are also represented the ophiolitic non-metamorphic unit of Chenaillet (Ch) and Sestri Voltaggio Zone (SVZ) and in Corsica Balagne (Ba), Nebbio (Ne) and Macinaggio (Ma) units; (6) Schistes Lustrés composite nappe system; (7) Sesia and related units ("lower Austroalpine nappes"); (8) Adria lower crust of the Southern Alps (Ivrea); (9) Adria upper crust basement and cover of the Southern Alps; Northern Apennine: (10) Internal Ligurian units, IL; (11) External Ligurian units (EL) and SubLigurian (Canetolo) units; (12, 13, 14) Adria-derived Tuscan and external foreland Umbria-Marche units; (12) Tuscan nappe; (13) Tuscan metamorphic units; (14) Cervarola and Umbria-Marche foreland units; (15) Post-tectonic cover of Tertiary Piemontese basin and Epiligurian units; (16) Neogene and Quaternary sediments of Po Plain and inner Tuscany (17) Magmatic rocks of Southern Tuscany, volcanic and intrusive bodies; major thrusts at surface (18) and in subsurface (19); (20) high angle normal and trascurrent faults; (21) sediment thickness in seconds TWTt for the Tyrrhenian Sea; (22) Pliocene isobaths (in Km) in the Po Plain and Adriatic sea. After Molli *et alii* (2010).

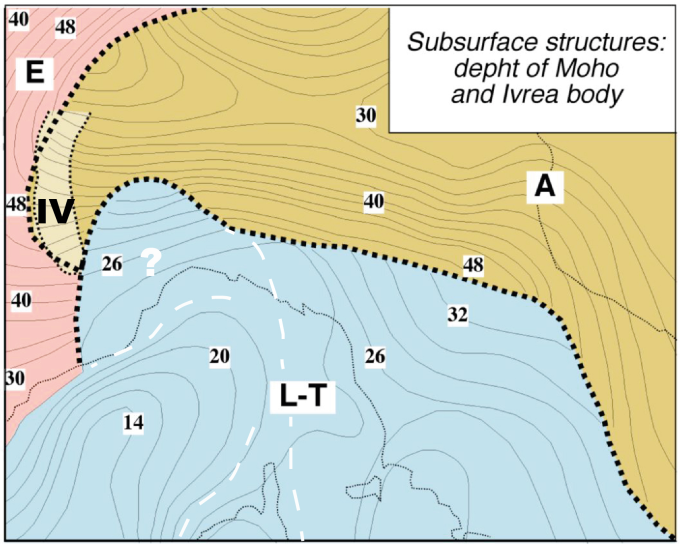


Fig. 3 – Map of crust - mantle configuration of the Western Alps/ Apenninea junction area.Contour intervals of 2 km. Dashed lines indicate the limits between the European (E), Adriatic (A) and Ligurian-Tyrrhenian (L-T) Moho. The Ivrea geophysical body (IV) is also reported. Modified after Molli *et alii* (2010), with references therein. More recente interpretations and references in Menichelli *et alii* (2023). White dashed lines, represent the interpreted outline of crustal relicts part of the former "Mediterranean Alps" affected by Corsica-Sardinia block rotation.

at the surface, represent the main topics of the recent debate (Principi & Treves, 1984; Capponi & Crispini, 2008; Molli, 2008; Vignaroli *et alii*, 2008; Capponi *et alii*, 2009b; Handy *et alii*, 2010; Malusà *et alii*, 2015; Le Breton *et alii*, 2017; Piana *et alii*, 2017b; Schmid *et alii*, 2017; Van Hinsbergen *et alii*, 2020; Martinod *et alii*, 2024).

The field trip aims at describing some key-characters of the Alps-Apennines junction area ("Ligurian Knot" after Laubscher *et alii* 1992) to give first order constraints on the relationship between the two mountain belts in space and time.

1.2 Geological setting and deep structures

Presently the Alps and the Apennines represent two independent orogens characterized by opposite tectonic vergence W/NW the former and E/NE the latter, roughly oriented perpendicular to their arcuate trends (Fig. 1).

Crustal seismic structures and 3D tomographic images draw a south/south- eastward-dipping European crust with a high velocity body related to European-plate subduction below the Alps, and an opposite rather continuous westward dipping structure below the Apennines (Király *et alii*, 2016; Eva *et alii*, 2020; Handy *et alii*, 2021, and references therein, Fig. 3).

In contrast with the simple crustal and mantle structure, at the surface the Alps/Apennines junction is more difficult to define considering:

- at least in part coeval age of tectonic events and deformation structures for the Alps and Apennines;
- the presence of tectonic units with similar lithostratigraphic features and comparable structural evolution;
- superficial continuities of tectonic units from the Western Alps to the Northern Apennines;
- presence of common sedimentary basins sealing or developing during the structural evolution of the two mountain belts.

As matter of fact, the junction area between the Alps and the Apennines is represented by a wide area which includes three major geomorphological and structural domains (Fig. 4), each one largely composites from a geological point of view (Molli *et alii*, 2010).

They correspond to:

- a northern region that comprises former exhumed sectors of the orogenic belt partially subsided during Oligocene-Miocene (Tertiary Piemonte basin) and during the Neogene to form Apennine foredeep resting on the Adria Mesozoic-Paleogene successions and covered by thick alluvial sediments of the Po plain.
- a "S-shaped" mountain range formed by the Maritime, Ligurian Alps and the north-westernmost sector of the Apennines;
- a southern undersea region, the Ligurian Sea, geologically belonging to the Liguro-Provençal basin and to the Northern Tyrrhenian. This domain hidden the original connections between Western Alps, Alpine Corsica and easternmost prolongation of Pyrenees.

1.2.1 The northern domain: The Tertiary Piemonte Basin

The northern domain includes the western termination of the Po Plain (Fig. 4) a c. 500 Km long east-west trending Neogene basin, bordered to the north by the south-vergent fold and thrust belt, retro-foreland of the Alps (Southern Alps), and to the south by the north/north-east vergent structures of the Apennines (Roure *et alii*, 1990; Mosca *et alii*, 2010; Turrini *et alii*, 2014; Livani *et alii*, 2023).

The area of interest, can be subdivided from the geomorphological point of view in four main provinces (Fig. 4): the hilly systems of the Torino Hill-Monferrato to the north and of the Langhe to the south, with their interposed Savigliano and Alessandria plains, in turn separated by the Asti hills.

The domain is characterized in surface and subsurface by exposures of Upper Eocene to Miocene-Pliocene successions of the so called Tertiary Piemonte Basin (TPB).

In its southernmost part (Langhe) the TPB sequence consist of continental to transitional deposits of Late Eocene-Early Oligocene (Lorenz, 1969; Ghibaudo *et alii*, 2019, and references therein) followed by shelf to slope marly successions and turbidites which were deposited during Late Oligocene and Early Miocene (Ghibaudo *et alii*, 2019). A shelf environment of the Early Burdigalian is locally documented in the Alto Monferrato area (d'Atri, 1990b; Piana *et alii*, 1997)

By contrast, the northern TPB exposed in the Torino Hill-Monferrato shows more condensed successions with the lowermost portions consisting of basinal mudstones (Monte Piano Marls), followed in the Oligocene-Miocene shallow water clastic and carbonates facies (Clari *et alii*, 1995; Dela Pierre *et alii*, 2002b). Coarse-grained facies characterize the western outcrops (Torino Hill area, Bonsignore *et alii* 1969; Sturani 1973).

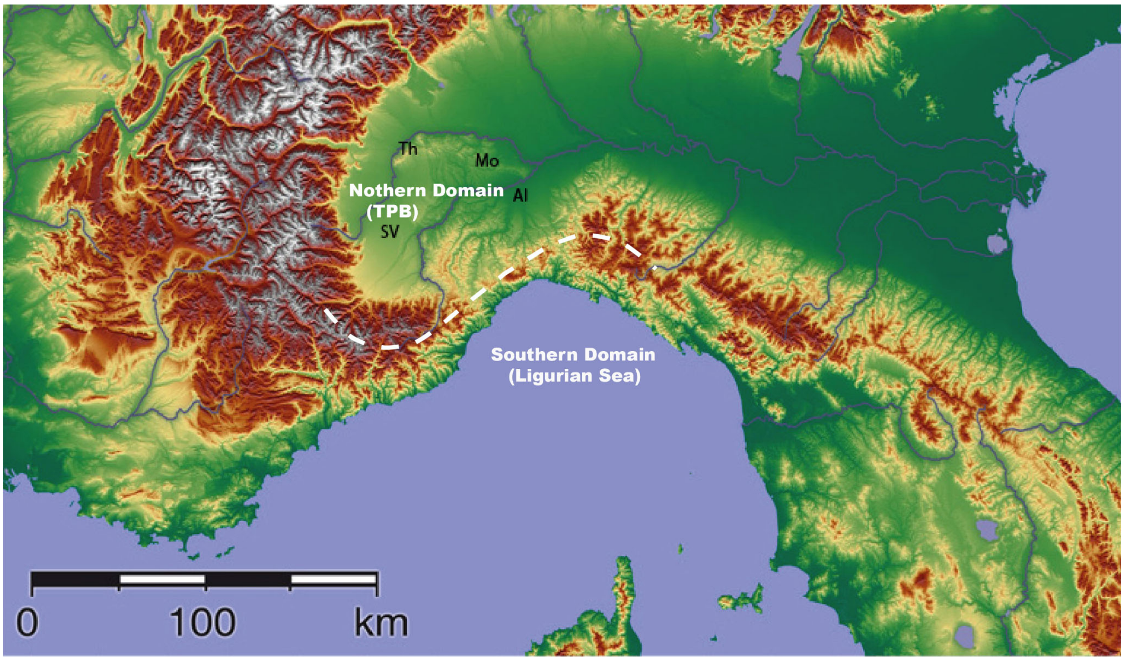


Fig. 4 – Geomorphological-structural domains of the Alps-Apennines junction area.

The southern and northern TPB sequences have in common their uppermost portions generally represented by homogenous marly sediments of Tortonian age, and by discontinuous evaporites and lagoon clays recording the Messinian salinity crisis, often in form of chaotic and/or resedimented assemblages (Irace *et alii*, 2005; Dela Pierre *et alii*, 2002a). In present outcrop exposures, lowermost Pliocene deposits are typically represented by marine clays followed upward by Pliocene sand-rich marginal marine and Pleistocene to Holocene continental successions (Ghibaudo *et alii*, 2019, and references therein).

Whereas the northern TPB sequences of Torino Hill-Monferrato rest on an Helminthoid Flysch in physical continuity with the similar unit of the Northern Apennines (External Ligurian Helminthoid Flysch units see below), the successions exposed in the Langhe basin unconformably rest on the exhumed metamorphic nappe-stack of the LA, the Sestri Voltaggio zone and to the west the Helminthoid Flysch of the Antola Nappe.

1.2.2 The "S-shaped" mountain range: between Alps and Apennine

The "S-shaped" mountain range includes the Maritime Alps (southern part of Western Alps), the Ligurian Alps and the northern sector of the Apennines (Fig. 4). It is continuous from the Argentera-Provence, across the Western and Eastern Liguria to the northern Tuscany.

The Maritime and Ligurian Alps (M-LA)

The Maritime and the Ligurian Alps are made up by tectonic units derived from the major paleogeographic domains of the western Tethys (Fig. 5). From W to E: the European continental margin, the Briançonnais/Sub-Briançonnais domains (distal part of European plate or independent terrane, Lemoine *et alii* 2000; Stampfli *et alii* 1998; Schmid *et alii* 1996; Schmid & Kissling 2000) and finally the Ligurian oceanic realm.

The external units comprise a foreland thrust system, forming the Digne and Castellane-Nice arcs, with Eocene-Oligocene foreland deposits floored by thick Mesozoic carbonates of the Dauphinois-Provençal domain (Sinclair, 1997; Ford *et alii*, 2002; d'Atri *et alii*, 2016). The sediments lay on a Variscan basement and post-Variscan cover exposed in the Argentera Massif (Bigot-Cormier *et alii*, 2006; Brunsmann *et alii*, 2024).

The Frontal Briançonnais Fault, observable south of Cuneo in the Maritime Alps, juxtaposed Sub-Briançonnais-Briançonnais units on top of cover units of the Argentera Massif.

The Briançonnais units are divided in two groups External and Internal units and are composed of a Pre-Namurian basement (exposed only in the Internal units) volcanic and continental clastic deposits (Permian to early Triassic in age), followed by a detached Meso-Cenozoic cover sequence (Cortesogno *et alii*, 1993; Seno *et alii*, 2005; Decarlis *et alii*, 2013).

The external Briançonnais units display a very low to low grade Alpine metamorphic overprint (anchizone up to greenschist facies) whereas the Internal Briançonnais units reach peak conditions up to P≈1.3 GPa and T>400 °C (Chiesa *et alii*, 1975; Cabella *et alii*, 1994; Seno *et alii*, 2005).

The innermost units of the Ligurian Alps are represented by the HP-LT ophiolitic units of the Voltri Massif and by three tectonometamorphic units of ophiolitic and continental origin (i.e. Cravasco-Voltaggio-Montenotte, Gazzo-Isoverde and Figogna units) historically referred to as the Sestri-Voltaggio Zone (Cortesogno & Haccard, 1984).

The Voltri Massif consists of two main tectonometamorphic units (Voltri Unit and Palmaro-Caffarella Unit, Capponi & Crispini 2008) composed of high pressure metamorphic ophiolites. The ophiolites consist of serpentinites with metagabbros and metabasites, metasediments and mantle peridotites, with peak eclogite (450-500 °C and 1.3-2.0 GPa for the Voltri Unit; Messiga & Scambelluri, 1991; Liou *et alii*, 1998; Federico *et alii*,

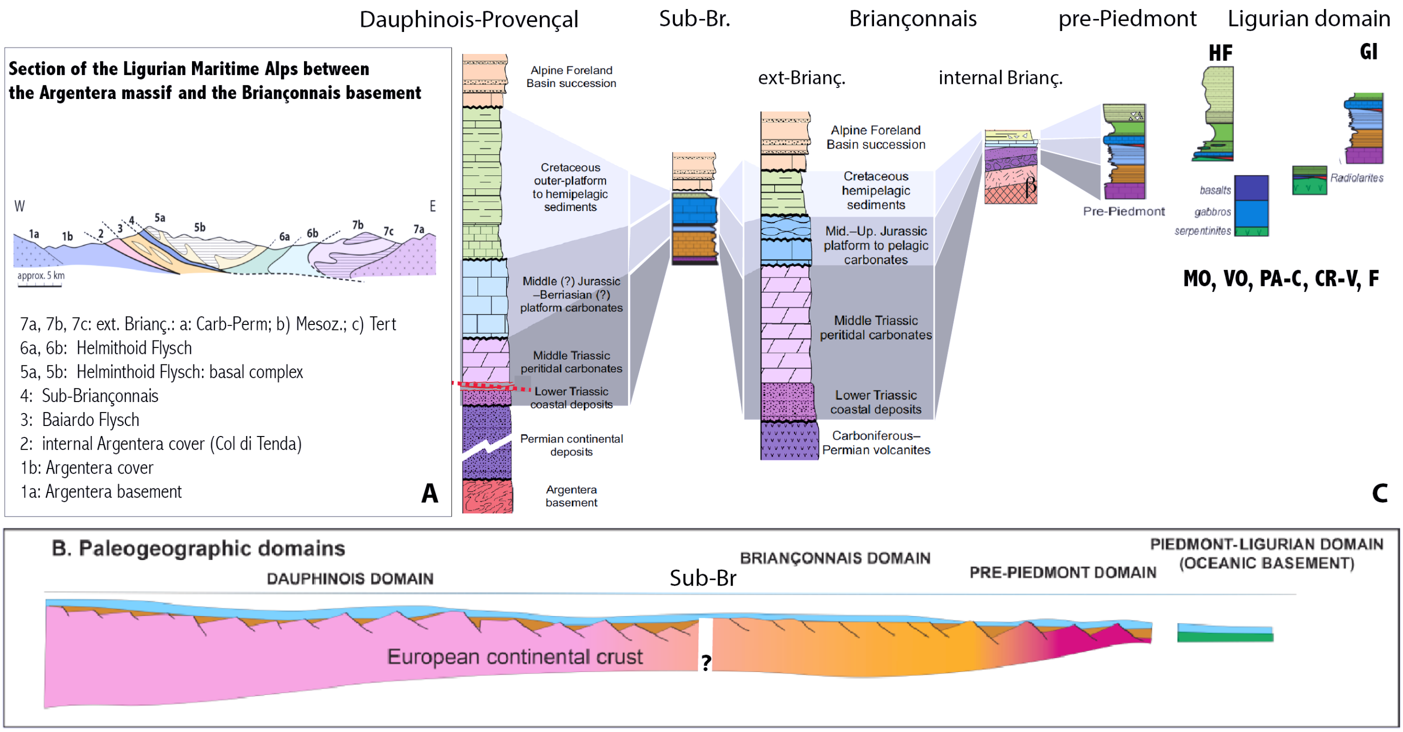


Fig. 5 – (a) Section of the Ligurian Maritime Alps between the Argentera Massif and the Briançonnais units, after Debelmas (1974) modified in Lagabrielle (2023). (b) Paleogeographic domain of the European margin to Ligurian ocean. (c) Sedimentary series from different domains of the continental margin and adjacent Ligurian ocean (b,c), modified after Lagabrielle (2023) using data from d'Atri *et alii*, 2016; Michard *et alii*, 2022. HF–Helmintoid Flysch, MO–Montenotte, VO–Voltri, PA-C–Palmaro-Caffarella, CRV–Cravasco-Voltaggio, GI–Gazzo-Isoverde, F–Figogna Unit.

2005) or blueschist (c.a. 350-400 °C and 1.2 GPa for the Palmaro-Caffarella Unit; Desmons *et alii*, 1999) alpine metamorphism, strongly overprinted by greenschist facies fabrics (Capponi & Crispini, 2002).

The Gazzo-Isoverde Unit (GIU) and the Cravasco-Voltaggio-Montenotte Unit (CVMU) are separated from the Voltri Massif by the Sestri-Voltaggio Line (Cortesogno & Haccard, 1984) that at present is a steeply dipping NS oriented km-scale fault. The main phase deformations predated the Oligocene, since the main structures are sealed by the Oligocene-Miocene formations of the Tertiary Piemontese Basin, even if later reactivations can be observed locally (see below). To the east the units of the Sestri-Voltaggio zone are in contact with very low-grade flysch units (Ronco, Mignanego and Montanesi Units, Capponi & Crispini, 2008) and the unmetamorphosed Antola flysch unit (see below).

The Cravasco-Voltaggio-Montenotte Unit and the Figogna Unit are metaophiolitic units and are re-equilibrated respectively in low-T blueschist facies (T= 300-350° C and P_{min}= 0.8-1.0 GPa for the Cravasco-Voltaggio-Montenotte Unit; Cabella *et alii*, 1994; Desmons *et alii*, 1999) and pumpellyite-actinolite facies conditions (T= 300-350° C and P= 0.7, Desmons *et alii*, 1999). The Gazzo-Isoverde Unit comprises carbonate rocks and shales of Triassic to early Jurassic age, which attained the same blueschist facies metamorphic conditions of the Cravasco-Voltaggio-Montenotte Unit. The Figogna Unit shows a polyphase structural evolution but developed at lower metamorphic conditions.

The timing of the high pressure metamorphic events in the internal units of the Ligurian Alps are constrained between ca. 50 Ma (eclogite facies) and 40 Ma (blueschist facies) in metaophiolitc rocks (Federico *et alii*, 2005, 2007, Fig. 6). Greenschist-facies retrogression during exhumation is locally dated at ca. 33 Ma (Federico *et alii*, 2005). For the SVZ adequate absolute time constraints for the Alpine deformational events are still lacking.

The Northern Apennines (NA)

The Northern Apennines are characterized by stacked units (Fig. 7) belonging to a former accretionary wedge (Ligurian and sub-Ligurian Units) formed during the Cretaceous-Tertiary closure stages of the Ligurian Tethys ocean, overlying the continental derived thrust-sheets and cover nappes of the Adria continental margin of Tuscan and Umbria-Marche Domains (e.g. Elter 1975; Bernoulli 2001; Carmignani, Kligfield, 1990; Butler et al. 2006; Molli 2008; Malavieille et al. 2016; Schmid et al. 2017).

The emplacement of Ligurian prism on top of Sub-Ligurian and Adria-continental margin occurred since Oligocene defines the inception of Apennines-related deformation history.

The uppermost units of the nappe stack are represented by the Ligurian units, the main focus of this Field Trip.

The Ligurian units are subdivided on the basis of stratigraphic and structural features into two main groups (Elter, 1975) well defined in the Ligurian-Emilian Apennine: the Internal Ligurian Units (IL) and the External Ligurian units (EL).

The first are characterized by the presence of ophiolites and an Upper Jurassic to Lower Cretaceous sedimentary cover (cherts, Calpionella limestone and Palombini shales) associated with Upper Cretaceous-Paleocene turbiditic sequences (Molli, 2008, and references therein). The Internal Ligurian units are considered as remnants of the Liguro-Piemontese ocean or Ligurian Tethys.

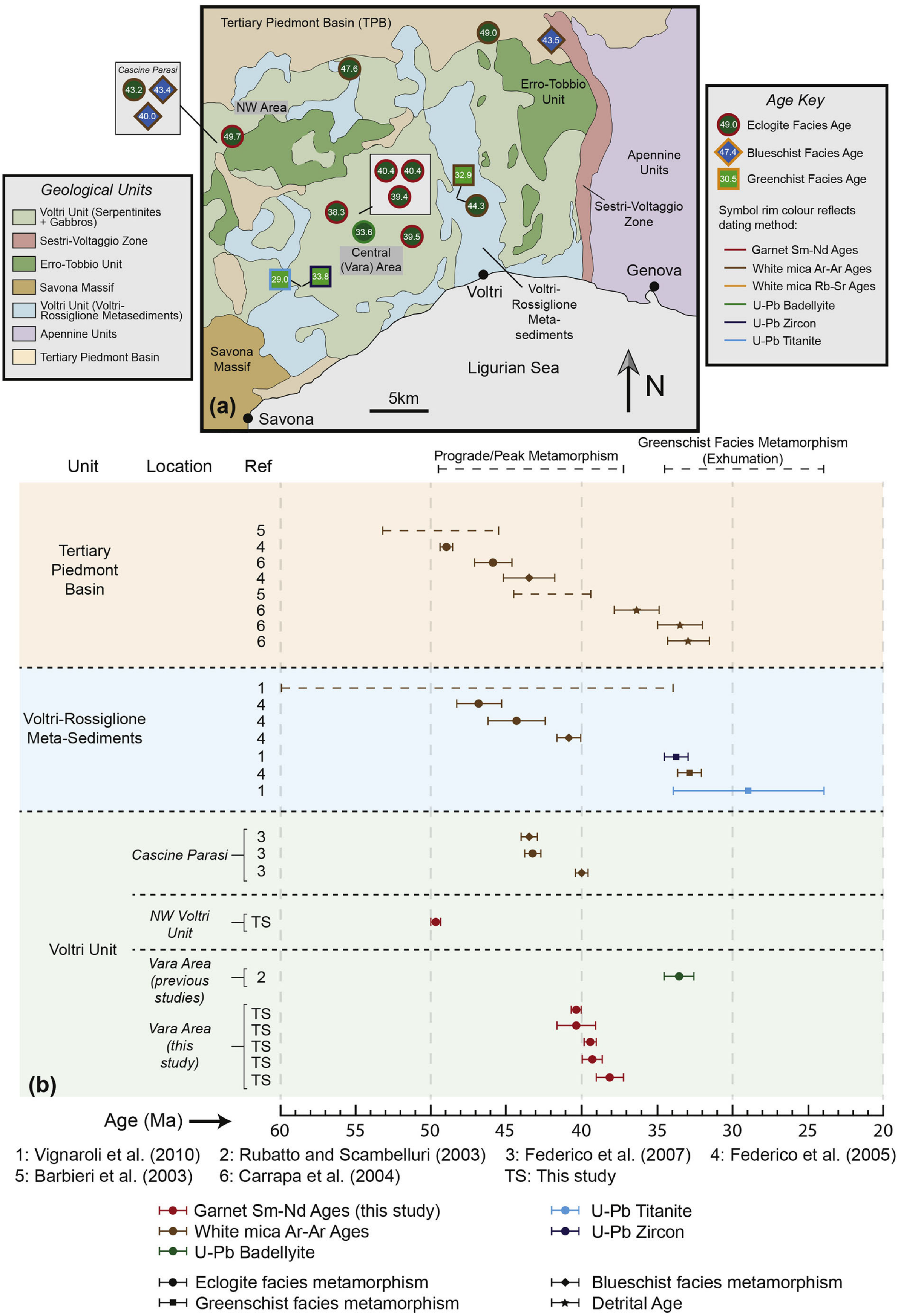


Fig. 6 – Compilation of age data from the Voltri Ophiolite and Tertiary Piedmont Basin, after Starr *et alii* (2020). (a) Data compilation shown in map form, indicating the age and the location of the dated sample. The interpretation of the metamorphic facies that is recorded by each age (i.e. recording mineral growth during eclogite, blueschist or greenschist facies conditions) is indicated by the shape and internal colour of the symbols (see key on right). The method used to obtain each age is indicated by the colour of the symbol rim (see key on right). (b) Age plot showing a full compilation of age data, split by unit (TPB, Voltri-Rossiglione meta-sediments, Voltri unit split by area).

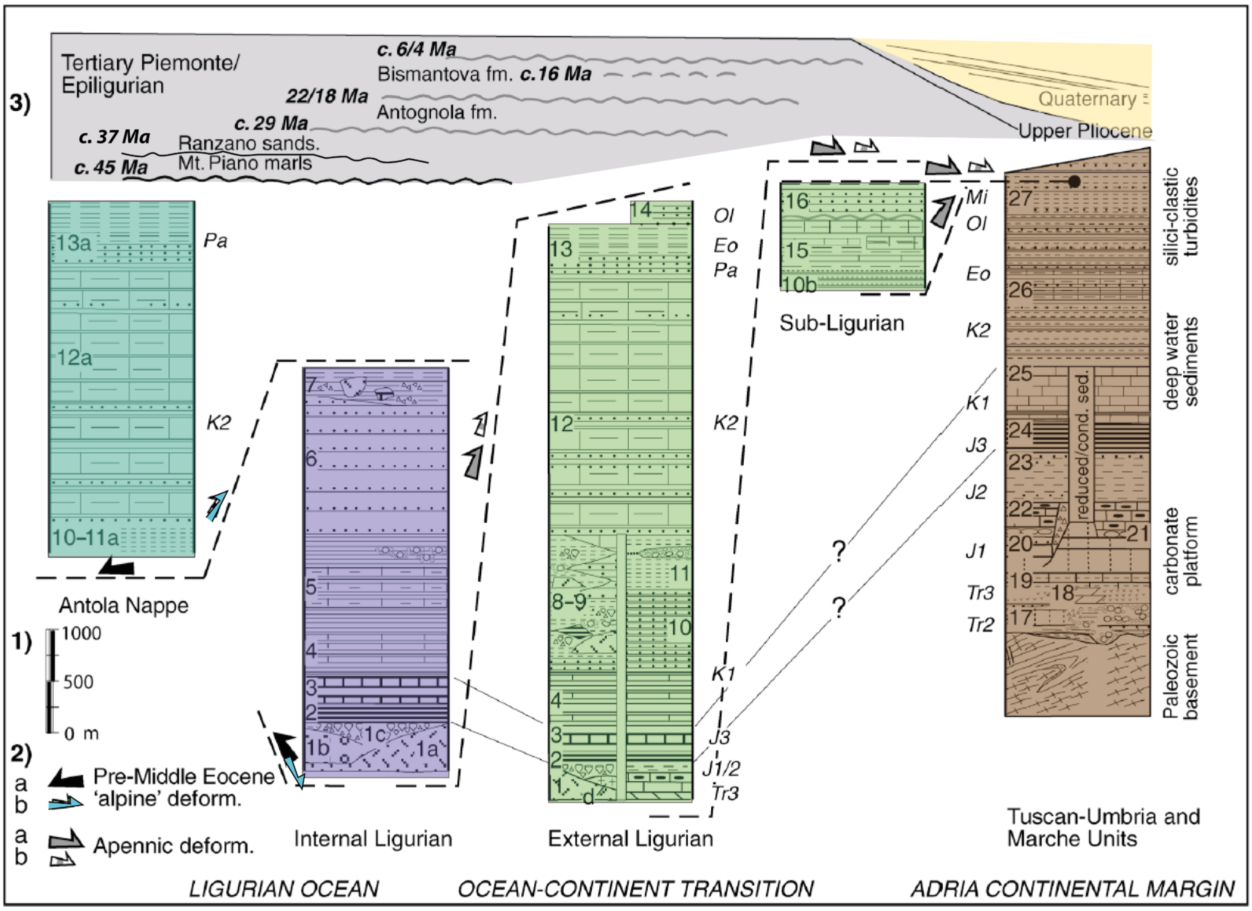


Fig. 7 – Schematic sedimentary sequences of the main tectonic systems of the Northern Apennine and related paleotectonic setting. (1) ophiolitic basement: (1a) mantle serpentinites, (1b) gabbros, (1c) basalts, (1d) continental granites (in the External Ligurian units); (2) Cherts; (3) Calpionella limestones; (4) Palombini shales; (5) Val Lavagna schists; (6) Gottero sandstones; (7) Bocco/Colli Tavarone schists; (8-9) Casanova melange and sandstones; (10) Ostia/Scabiazza sandstones; (11) Varicoloured shales with Salti del Diavolo Conglomerates, (11a), Montoggio shales; (12) Helminthoid Flysch, (12a) Antola Flysch; (13) Viano/Signano shales, (13a) Pagliaro shales; (14) Val Sporzana fm.; (15) Canetolo fm. (limestone and shale), Groppo del Vescovo and Vico Flysch; (16) Aveto/ Petrignacola/Bratica sandstones and Coli/Marra marls; (17) continental "Verrucano" and marine transgressive deposits on Hercynian and post-Hercynian units; (18) evaporites and dolomites; (19) Rhaetavicula contorta limestone and marls; (20) Massiccio limestone; (21) Rosso Ammonitico; (22) cherty limestone; (23) Posidonia marls; (24) Cherts; (25) Maiolica; (26) Scaglia Toscana, Scisti a Fucoidi, Scaglia Umbra and Bisciaro; (27) siliciclastic turbidites (Macigno, PseudoMacigno, Cervarola, Marnoso-Arenacea, Laga). After Molli (2008).

The External Ligurian Units are, on the other hand, distinguishable for the presence of the typical Cretaceous-Paleocene calcareous dominant sequences (the Helminthoid Flysch) associated with complexes or pre-flysch formations called "basal complexes".

According to their stratigraphic differences,within the EL two main subgroups of units can be recognized (Molli, 1996; Marroni *et alii*, 1998, and references therein): (i) those associated with ophiolites and with ophiolite derived debris, and others (ii) without ophiolites and associated with fragments of Mesozoic sedimentary sequences and conglomerates with Adria affinity Sturani (1973); Zanzucchi (1988); Molli (1996).

Because of their age (Elter *et alii*, 1966; Wildi, 1985; Zanzucchi, 1988; Daniele & Plesi, 2000) and composition, these coarse grained conglomerates (Salti del Diavolo Conglomerates) have been compared since the early 1970s with those of Prealpes Romandes (Mocausa conglomerates of the Simme Flysch) implying a common source-area and therefore a common paleotectonic setting on the distal side of the Adria continental margin (Elter, 1997; Stampfli *et alii*, 1998; Lemoine *et alii*, 2000, and references therein).

As a whole, the External Ligurian units can be regarded as relics of the former ocean-continent transition area and of the distal Adria continental margin in the Apennines transect (Molli, 1996; Marroni *et alii*, 1998).

The IL units were affected by polyphase deformation with peak metamorphic P-T conditions of very-low to sub-greenschist facies (prehnite-pumpellyite in metabasic rocks). Recently, however, Meneghini *et alii* (2023) and Sanità *et alii* (2024) suggested at least locally HP/LT peak (T=230-300 °C; P=0.6-0.9 GPa). On the other hand the EL units were deformed at more shallow structural levels (diagenesis-anchizone transition in pelites).

Among the Ligurian units, the Antola Nappe deserves a special mention. From the lithostratigraphic point of view, the unit can be correlated with the External Ligurian units Helminthoid Flysch (Abbate & Sagri, 1984; Cerrina Feroni *et alii*, 2002;

Levi *et alii*, 2006), even though it occupies a structural position at the top of the IL units, in contrast to the other EL units which are structurally below.

Moreover, it is classically correlated with the Helminthoid Flysch of the Ligurian and Maritime Alps and therefore played a special, still non well understood, role during the pre-Oligocene evolution of the Alps/Apennine orogenic system (Elter & Pertusati, 1973; Elter, 1997; Corsi *et alii*, 2001; Levi *et alii*, 2006).

On top of EL units and Antola nappe the deposits of the Epiligurian Succession may be considered as the distal-lateral portion of the time-equivalent TPB. They consist mainly of terrigenous clastics even if they include facies ranging from pelagic and hemipelagic deposits to siliciclastic turbidites and to shelf sandstones and calcarenites. The Epiligurian Succession is characterized by ages ranging from Middle Eocene to Late Miocene-Pliocene and overlies the at least in part already deformed Ligurian Units.

From a stratigraphic point of view, the Epiligurian Succession consists of unconformity-bounded units whose limits (major unconformities) are strongly controlled by sub-marine tectonics which often generated slumpings and olistostromes (sedimentary melanges).

Five major unconformities define the main lithostratigraphic units (Monte Piano, Ranzano; Antognola, Bismantova, Termina, Gessoso-solfifera and Argille Azzurre formations).

The oldest two unconformities (Monte Piano and Ranzano) may be used to define:

- the end of "Alpine"-related deformations, subduction and exhumation up to the surface of the Ligurian Alps nappe stack, Sestri Voltaggio zone and overlying Ligurian and Antola units;
- the beginning of deformation events related to the Apenninic-related geodynamics.

The younger unconformity within the Epiligurian basins may be related to surface response of Apennines wedge growth and NNE-verging migration of the orogen which progressively incorporated the foredeep units of the Adria continental margin.

The southern domain: the Liguro-Provençal and Northern Tyrrhenian basins

The southern domain includes an undersea region geologically belonging to two different geological provinces: the Liguro-Provençal basin and the northern part of the Tyrrhenian basin (Fig. 2, Fig. 7).

Both basins are interpreted as Late Oligocene to Miocene backarcs developed in relationships with Apulian westward subduction and eastward slab retreat (Laubscher, 1988; Patacca & Scandone, 1989; Doglioni *et alii*, 1999; Vignaroli *et alii*, 2008). These basins are therefore parts of the Apennines geodynamic system, and developed during its successive stages of evolution (Gueguen *et alii*, 1998; Faccenna *et alii*, 1997; Jolivet *et alii*, 1998; Le Breton *et alii*, 2021).

The rifting stages in the Liguro-Provençal basin are dated to Oligocene to Early Miocene (Aquitanian-early Burdigalian) and were associated with calcalkaline magmatism on land (Lustrino & Wilson, 2007). The following oceanic spreading (drifting stage) occurred in the Burdigalian (19-16 Ma) with formation of an atypical oceanic crust (Gueguen *et alii*, 1998; Fanucci & Morelli, 2003; Rollet *et alii*, 2002; Jolivet *et alii*, 2020)characterized by discontinuous tholeitic volcanic edifices settled within the exhumed mantle, related with slow-to very slow tectonically controlled oceanic spreading (Chamot-Rooke *et alii*, 1999; Séranne, 1999; Rollet *et alii*, 2002; Jolivet *et alii*, 2020).

The drifting stage and oceanic accretion were associated with the anticlockwise Corsica-Sardinia block-rotation of 30° (Speranza *et alii*, 2002; Maffione *et alii*, 2008) or 45-50° (Gattacceca *et alii*, 2007). The rotation occurred after Aquitanian and was essentially completed at about 15 Ma according to (Gattacceca *et alii*, 2007). A third of the total amount of rotation occurred at a rate of c.15°Ma between 20.5 and 18 Ma. Relevant to be noted that paleomagnetic data of Bormioli & Lanza (1995), Carrapa *et alii* (2003) and Maffione *et alii* (2008) in lower Oligocene-Middle Miocene sediments of TPB documented counterclockwise rotation (up to c. 50°) (with respect to Africa) during the same Aquitanian-Serravalian time, thus supporting the idea that the TPB basin and Corsica-Sardinia block jointly rotated as a whole.

A still debated issue with relevant implication for kinematic reconstructions, hinge on whether Sardinia-Corsica was attached to the Provence in southern France or was part of Iberia (Stampfli *et alii*, 2002; Rosenbaum *et alii*, 2002; Handy *et alii*, 2010; Advokaat *et alii*, 2014; van Hinsbergen *et alii*, 2014; Le Breton *et alii*, 2021; Siravo & Speranza, 2024). The assumption that Corsica-Sardinia block was attached to southern France imply a post early Eocene and pre-Oligocene c.45° ccw rotation relative to Eurasia with relevant implication for Alps-Apennines junction area history (Schmid *et alii*, 2017; Van Hinsbergen *et alii*, 2020; Le Breton *et alii*, 2021; Mantovani *et alii*, 2023).

1.3 Final remarks

The present-day morpho-structural domains of the Western Alps/Northern Apennine junction area result from a kinematically complex interaction between interfering orogenic systems related to the opposite-dipping east-southeast "Alpine" and west-northwest "Apennine" subductions. Within the junction area reworked and reactivated structures of a formerly continuous Late Cretaceous/mid-Eocene intraoceanic and continental subduction-related "Alpine" system are preserved. They presently are exposed in the Ligurian Alps and became part of the the younger "apenninic" system after being incorporated since Aquitanian during the Corsica-Sardina block rotation.

The shallow and deep configuration and related structural zones of the Western Alps/Northern Apennines junction area are therefore the result of different orogenic processes such as the collisional indentation of Europe and Adria plates (40-35 Ma); the development of structures related with the opposite dipping "Alpine and "Apennines" subductions after a subduction reversal (35-33 Ma) and the kinematic development of the northern segment of the Apennines in a frame of Adria slab retreat to which the opening of the backarc Liguro-Provençal basin (33-23 Ma) and Corsica-Sardinia and joined Ligurian Alps-TPB block rotation (23-15 Ma) occurred.

Part II

Field Trip

Day 1 : Eastern Tertiary Piemonte Basin

Edit by: Luca Barale[1], Anna d'Atri[2], Fabrizio Piana[1]

Contributions of: Edoardo Barbero[1], Carlo Bertok[2], Gianluca Frasca[1], Andrea Irace[1], Igor Marcelli[1], Pietro Mosca[1], Luca Ossella[1], Massimo Rossi[1]

Geological overview

This first part of the Field Trip will focus on the syn-orogenic basin system developed since the late Eocene - early Oligocene at the junction between the two orogens. The sedimentary successions of these basins recorded the main stages of the Western Alps (neoAlpine events) and Apennines tectonic evolution, whose evidence, mostly represented by regional-scale unconformities, can be correlated within each basin and, partially, across them.

The field trip runs through the Tertiary Piemonte Basin (TPB), whose successions were deposited in the southern part of the Alpine retroforeland realm since the Late Eocene up to the Messinian (Fig. 8). Although the TPB differentiated in partially independent sub-basins, it recorded well, as a unique syn-orogenic basin system for the Alps and Apennines orogens, the entire geodynamic history of the Adria-Europe collision in NW Italy. The TPB went from being an Alpine retroforeland basin to being a thrust-top Apennines basin system, as the Western Mediterranean geodynamics experienced the change in the continental subduction polarity and the onset of the Ligurian-Balearic oceanic spreading.

An overview of the TPB stratigraphy and tectono-sedimentary evolution will be provided by visiting some representative outcrops and landscapes. An interpretive synthesis will be given as grounded on calibration of surface geological features, traced at regional scale on continuous geologic maps, with some seismic sections that cross the whole TPB succession for more than one hundred km. The data integration process provides constraints for critical discussion on the evolution of the Alps-Apennines interference zone.

[1]Istituto di Geoscienze e Georisorse - CNR, Torino, Italy
[2]University of Torino, Italy

The Tertiary Piemonte Basin (TPB)

South of the Po River, the successions of the TPB crop out in different geologic domains (Torino Hill, Monferrato, Monregalese, Langhe, Alto Monferrato, and Borbera-Grue) and are recognizable in the subsurface (to the depth of 4-6 kilometres). These successions mask both the tectonic boundaries between the metamorphic units of the Alpine axial sector, the Ligurian units (i.e.: the non-metamorphic sedimentary units belonging to the eastern margin of the Liguria-Piemonte domain) and the paleo-Adriatic margin units (Cassano *et alii*, 1986; Falletti *et alii*, 1995; Mutti *et alii*, 1995; Piana & Polino, 1995; Biella *et alii*, 1997; Piana, 2000; Mosca, 2006; Molli *et alii*, 2010; Piana *et alii*, 2017a; Rossi, 2017; Ghibaudo *et alii*, 2019; Ghielmi *et alii*, 2019)

Although strongly differentiated by synorogenic tectonics, these successions were deposited in a single, long-lived (late Eocene-Miocene) and poly-historic (sensu Kingston *et alii*, 1983) sedimentary basin, affected by coeval tectonic and depositional events in all its parts, which are marked by unconformities physically traceable at a regional scale, each bounding major, regional scale synthems, whose ages and distribution are reported in Fig. 9 and Fig. 10.

The TPB underwent a complex evolution, marked by a high tectonic mobility reflecting the geodynamic reorganization of the central Mediterranean area during Oligocene and Miocene times (Mutti *et alii*, 2002; Ghibaudo *et alii*, 2019). This is documented by its stratigraphic architecture, which records multistage migrations of the source areas and depocenters with time, originating a complex distribution of terrigenous depositional systems (Mutti *et alii*, 2002), developed as a response to local or regional uplift and subsidence events. These events occurred in a different way and at different extent in the several subdomains into which TPB can be subdivided, leading to the deposition of a complex setting of laterally changing lithostratigraphic units, which have been classified in the last decades with different names and partially different criteria.

The main post-Eocene tectonic stages in the TPB stratigraphic record

During the middle Eocene-Messinian time interval, the syn-orogenic basins of the Alps-Apennines interference zone formed

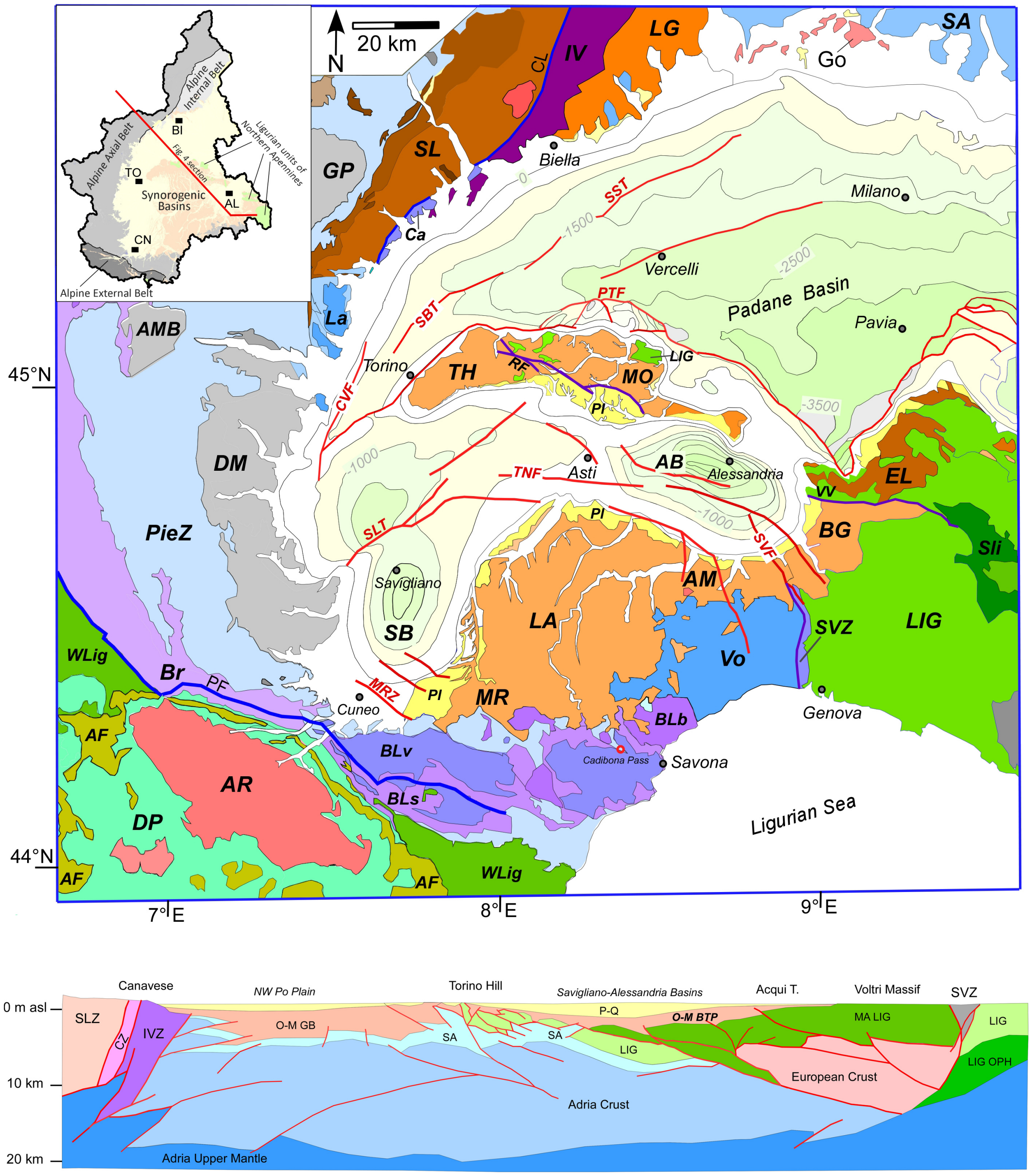


Fig. 8 – (a) Tectonic sketch-map of the Alps-Apennines junction zone. Legend: CL: Canavese Line; IV: Ivrea-Verbano Zone; LG: Granite of the South Alpine "Lake District"; Go: outcropping Gonfolite s.l. successions; SA: Southern Alps; GP: Gran Paradiso polymetamorphic Massif; SL: Sesia-Lanzo Unit (AustroAlpine Domain); Ca: Canavese Zone; La: Lanzo Ultramafic Massif; AMB: Ambin polymetamorphic Massif; PieZ: Piemonte Zone; DM: Dora Maira polymetamorphic Complex; WLig: Western Ligurian Units; Br: Briançonnais Domain; BLv, BLs, BLb: metavolcanics (v), sedimentary and metasedimentary successions (s), polymetamorphic basement (b) of the Ligurian-Briançonnais Domain; Vo: Voltri metaophiolite Massif; SVZ: Sestri-Voltaggio Zone; LIG: undifferentiated Ligurian units; Sli: Sub-Ligurian Units; AF: Eocene-Oligocene successions of the Alpine Foreland Basin; DP: Dauphinois-Provençal Domain; AR: Argentera Massif; PF: Pennidic Front (Internal Briançonnais Front); CL: Canavese Line; SB, AB: Savigliano and Alessandria Basin; MR, LA, AM, BG, TH and MO: Monregalese, Langhe, Alto Monferrato, Borbera-Grue, Torino Hill and Monferrato TPB sub-domains; EL: Epi-Ligurian units; Pl: Pliocene deposits. Red lines: main subsurface fault systems: CVF: Cavour transpressive fault; SBT: San Benigno thrust; SST: Salussola thrust; VFT: Vercelli-Trecate fault; PTF: Padane (Apennines) Thrust Front; SLT: Savigliano-Moretta thrust system; TNF: Tanaro Fault system (sensu Ghielmi *et alii*, 2019). Blue lines: surface fault systems: SVF: Scrivia Fault; VV: Villalvernia-Varzi Fault; RF: Rio Freddo Deformation Zone and Villadeati fault system. The grey lines bounding the yellow-green contoured areas refer to the depth in metres of the subsurface base of the Pliocene successions (after Bigi *et alii*, 1990. The inset map of Piemonte region in the upper left corner reports the trace of the regional cross-section and the three main structural subdivisions of the Western Alps: Legend: BI: Biella, TO: Torino, AL: Alessandria, CN: Cuneo. (b) Regional-scale, geological cross-section. Legend: CZ, Canavese Zone; IVZ, Ivrea-Verbano Zone; LIG, non metamorphic Ligurian units; O-M BTP, Oligocene-Miocene succession of Tertiary Piemonte Basin; O-M GB, Oligocene-Miocene succession of the Gonfolite Basin; LIG OPH, Ligurian ophiolites and metaophiolites (MA LIG); P-Q, Pliocene-Quaternary succession; SA, Mesozoic sedimentary successions of the SouthAlpine domain and subsurface Adria crust; SLZ, Sesia-Lanzo Zone; SVZ, Sestri-Voltaggio Zone. Mainly after Cassano *et alii* (1986); Biella *et alii* (1988, 1997); Falletti *et alii* (1995); Roure *et alii* (1996); Schmid *et alii* (2004, 2017); Mosca *et alii* (2010).

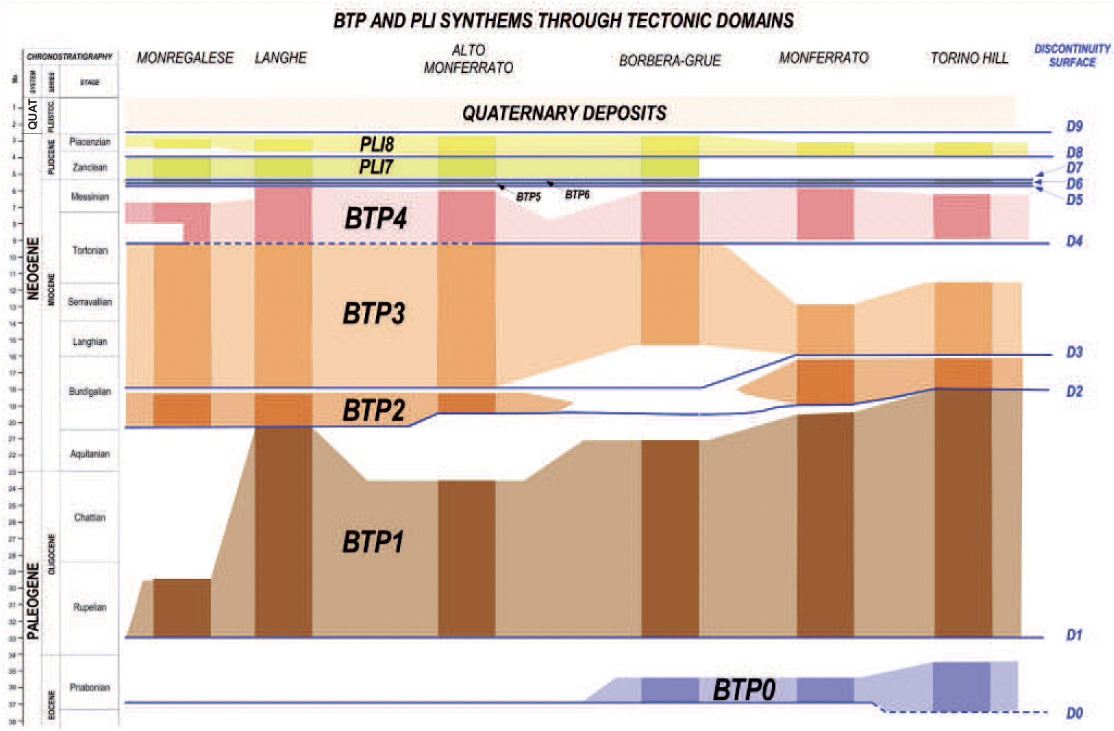


Fig. 9 – Chronostratigraphic framework of the TPB and Pliocene synthems and relevant unconformities. After Piana *et alii* (2017a).

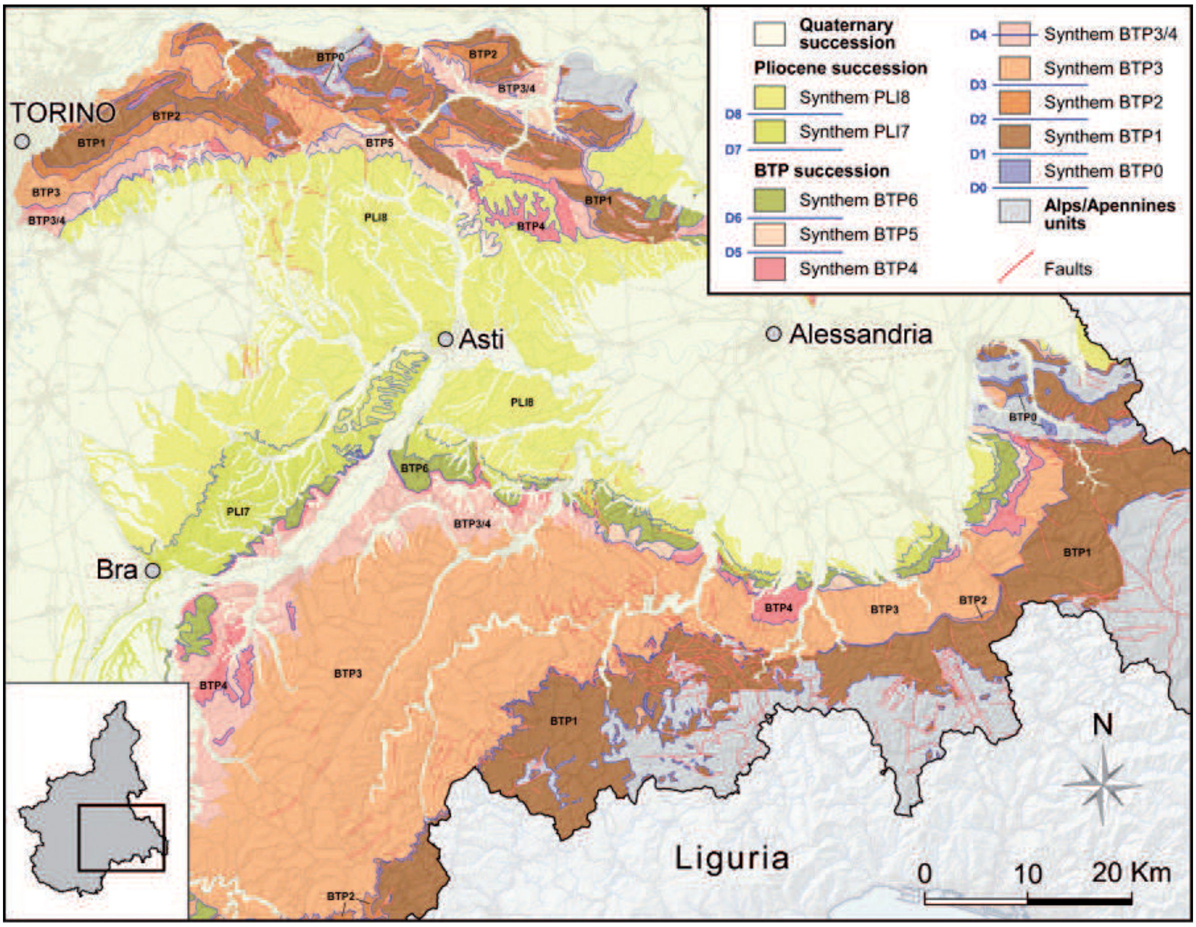


Fig. 10 – Distribution of the synthems into which the Pliocene and Tertiary Piemonte Basin (TPB) sedimentary successions have been subdivided. After Piana *et alii* (2017a).

through three main tectono-sedimentary stages each one consisting of some steps and several Geologic Events that are recognizable at regional scale.

Stage 1 (Alpine stage)

A first major stage ("Alpine stage", middle Eocene - Aquitanian) was coeval with the collisional evolution of the Alpine belt, whose control on the sedimentation was recorded with major effects in the Alpine Foreland Basin and, with a lesser extent, also in the retro-foreland domains. In this stage the TPB can be considered as an epiMesoAlpine basin system (sensu Mutti *et alii*, 1995).

Stage 1a - Continuum of the Alpine collisional tectonics and beginning of local transtensional regime (lower part of Rupelian)

The continuum of the collisional contractional tectonics ("Ligurian phase), coeval with the westward movement of the Adriatic indenter, induced at shallow crustal levels a complex partitioning of transpressional and transtensional regime, synchronous with the main exhumation phase of the HP metamorphic units of the SW Alps, as largely described in literature (Hoogerduijn Strating, 1991; Rubatto & Scambelluri, 2003; Carrapa *et alii*, 2003; Federico *et alii*, 2004, 2005; Vignaroli *et alii*, 2008, 2009, 2010; Mosca *et alii*, 2010; Rossi *et alii*, 2009; Argnani, 2012; Beucher *et alii*, 2012; Ghibaudo *et alii*, 2014).

The Rupelian tectonic phase, mostly transpressional in the overall southern part of the Western Alps (e.g., Dumont *et alii*, 2012), can be related in TPB to a local transtensional regime developed in the inner side of the uplifting Alpine belt.

High angle, synsedimentary faults dissected the units of the TPB substratum in a series of fault blocks (Mutti *et alii*, 2002). A marked regional uplift occurred, followed by an intense regional denudation, which resulted, during the Rupelian, in widespread coarse-grained sedimentation (either continental or marine) over the exhumed basement (Bertotti *et alii*, 2006; Vignaroli *et alii*, 2010).

A marked transgressive event (Lorenz, 1969; Haccard *et alii*, 1972) occurred in the internal part of the Alpine belt. This occurred in an overall geomorphological context marked by fast uplifting areas and adjoining throughs, with subsidence rates highly variable through space and time.

In the TPB the stage 1a induced the sedimentation of *Sub-synthem TPB 1a*, bounded at the base by the Unconformity D1 (lower part of Rupelian), which, in the southern part of the TPB, consists of a nonconformity surface between the bedrock (either metamorphic or non-metamorphic) and the overlying sedimentary successions. In the northern part of the TPB, it consists of an angular unconformity between the Priabonian marly successions of Synthem TPB 0 and the shallow water coarse-grained deposits of the base of Synthem TPB 1. This begins with continental to shallow water Rupelian conglomerates and arenites (Molare Fm., Lorenz, 1969; Cardona Fm., Clari *et alii*, 1987; Savignone Fm., Bellinzona & Boni, 1971, that grade to sandy and muddy sediments, i.e, the lower part of Rigoroso-Rocchetta Fm. (Gelati, 1968) in Langhe and Alto Monferrato, and the Monastero Fm. (Bellinzona & Boni, 1971) in Borbera-Grue sub-domain.

Stage 1b - Transtensional regime and related subsidence (late Rupelian - Aquitanian)

This tectonic phase is related with the bending of the Adriatic continental margin, which created the space for the sedimentation in the early stages of the Apennine foredeep evolution.

The westward subduction of the Adria crust ("Apennines subduction") induced the inflection of the Adriatic margin and caused a general extension in the internal part of the Alpine belt (Jolivet & Faccenna, 2000; Jolivet *et alii*, 2009; Jourdan *et alii*, 2013). This led to the formation of fault-bounded basins which occurred in a context of regional extensional and left-lateral strike-slip faulting (Ghibaudo *et alii*, 2019). In this way, the Ligurian Alps belt experienced more than 4 km of subsidence from 30 to 26 Ma (Bertotti *et alii*, 2006), whilst in late Oligocene the erosion (Jourdan *et alii*, 2013) and subsidence rates slowed down to average values.

Step 1b led to a first interaction between the Apennines tectonic fronts, which were progressively migrating toward North and NE, and the Alpine internal boundary faults that were driving the uplifting and back thrusting of the Western Alps.

In the TPB the *Sub-synthem BTP1b* was deposited, which is bounded at the base by local discontinuous unconformities, detectable in seismic sections but not easy to be traced at regional scale. This sub-synthem consists of late Rupelian to Aquitanian hemipelagic slope marls (Antognola Fm, Rigoroso Fm., Rocchetta Fm.) with interbedded arenaceous to conglomeratic resedimented bodies, e.g., Garbagna and Variano member (Rigoroso Fm.) in the Borbera-Grue sub-domain (Ghibaudo *et alii*, 2019).

Sub-synthem BTP1b ends with Aquitanian-lower Burdigalian siliceous slope deposits rich in siliceous plankton (e.g., Marne a Pteropodi inferiori, siliceous member of Montechiaro d'Acqui Fm.; (Gelati *et alii*, 2010; Clari *et alii*, 1987; d'Atri *et alii*, 2015) due to a paleoceanographic event extended to the whole Mediterranean area.

Stage 2 (Apennine stage)

A second major stage ("Apennine stage", Burdigalian-Messinian), starting with the opening of the Balearic basin, i.e., when the southern prolongation of the Alpine belt (the "mesoMediterranean plate" sensu Carminati & Doglioni, 2005) was dismembered by the back-arc extension induced by the onset of the Adriatic (Apennines) subduction (Réhault *et alii*, 1984; Jolivet & Faccenna, 2000; Rollet *et alii*, 2002). This stage continued through the Miocene, as the north-eastward propagation of the Apennines tectonic fronts proceeded. In this way the TPB became a basin system whose sub-domains evolved as thrust-to-top basins on the roof of the Apennine frontal thrust.

Stage 2a - Compressional tectonics at the Burdigalian basin reorganisation

The change in the direction of motion of the Adriatic Indenter (AI) with respect to Europe from NW-ward to WNW-ward at about 20 My (Edel *et alii*, 2001; Schmid & Kissling, 2000; Handy *et alii*, 2010) resulted in conditions of oblique convergence and increased collisional tectonics, whose effects were recorded in a large part of the Mediterranean area in the lower Burdigalian.

The tectonic indentation of the European and Apulia continental margin caused the switch from transtensional to contractional and transpressional regime in the TPB, inducing inversion of a great number of tectonic structures (Piana & Polino, 1994, 1995; Falletti *et alii*, 1995; Piana *et alii*, 1997; Piana, 2000; Festa *et alii*, 2005; Piana *et alii*, 2006; Rossi *et alii*, 2009; Maino *et alii*, 2013; Ghibaudo *et alii*, 2019). This process was coeval with the transpressional tectonics recorded in Sardinia and southwestern Corsica (Carmignani *et alii*, 2004, and references therein).

This important tectonic stage was accompanied by significant change in sediment composition within the TPB, as the formerly active lower Oligocene sources, mostly located in the southern areas (Ligurian Alps), gradually moved to the West (Carrapa, 2002). A marked regional uplift occurred, with subsequent high denudation rates of the West-Alpine axial sector. This resulted in the eastward migration of fan-delta systems, prograding from the western margin of the TPB (the "Saluzzo-Monregalese belt" of Rossi *et alii*, 2009; Carrapa *et alii*, 2016).

In this period (Early Miocene) the TPB underwent a rotation of ca. 50° counterclockwise with respect to Africa (Maffione *et alii*, 2008). The counter-clockwise rotation of the Corsica-Sardinia microplate is known to have been accompanied by oceanic spreading and generation of the central oceanic portion of the Ligure-Provençal basin as a back-arc basin in the wake of the south-eastward roll-back of the Apennines-Maghrebides subduction (Rehault *et alii*, 1984; Vigliotti & Langenheim, 1995; Doglioni *et alii*, 1997; Gueguen *et alii*, 1998; Speranza *et alii*, 2002; Faccenna *et alii*, 2001; Rollet *et alii*, 2002; Gattacceca *et alii*, 2007; Cherchi *et alii*, 2008; Carminati *et alii*, 2012).

Gattacceca *et alii* (2007) established that approximately 30° of rotation occurred between 20.5 and 18 Ma, that is mostly during the Burdigalian. Volcaniclastic layers found in the Pietra da Cantoni in northern TPB (Monferrato) also date to 18.7 Ma (d'Atri et al., 2001) recording a coeval volcanic activity.

In response to these major tectonic events, a number of regional scale unconformities developed throughout the Alps-Apennines syn-orogenic basins.

In the TPB, the D2 major regional unconformity formed in response to the above-described events. It is an angular unconformity which cuts into the Marne a Pteropodi inferiori/siliceous member of the Montechiaro d'Acqui Fm. and Antognola / Rigoroso formations (Monferrato, Alto Monferrato) and corresponds to a Chattian (or Aquitanian) - lower Burdigalian hiatus. In the deep-water settings (Langhe, Torino Hill), it laterally grades to a correlative conformity, dated to the early Burdigalian (d'Atri et al., 2015). The D2 discontinuity surface formed during the Burdigalian event and led to a major reshaping of the basin (Clari *et alii*, 1995; Falletti *et alii*, 1995; d'Atri *et alii*, 1997).

The succession deposited during the stage 2a (*Synthem BTP 2*) consists mainly of Burdigalian carbonate ramp deposits passing upward into deeper-water calcareous marls through glauconite-rich outer ramp condensed sediments (e.g. Visone Fm., in Alto Monferrato, Pietra da Cantoni in Monferrato; d'Atri, 1990a,b; d'Atri *et alii*, 1997; Piana *et alii*, 1997; d'Atri *et alii*, 2015). In the Monregalese mixed siliciclastic-carbonate ramp deposits (San Paolo Fm., Casnedi & Mosna, 1970) rest unconformably on Oligocene deposits or directly on the metamorphic substrate. Locally (i.e., in Torino Hill and western Monferrato) Burdigalian-lower Langhian mainly sandy resedimented deposits are present (Moransengo Fm, Termofourà Fm, Clari *et alii*, 1995; Dela Pierre *et alii*, 2003; Festa *et alii*, 2009). Carbonates and glauconite-rich resedimented arenites, derived by the erosion of the carbonate ramp deposits, form distinct layers at the base of the synthem in the Langhe sub-basin (Amorosi *et alii*, 1997; Gelati *et alii*, 1998), and in Monferrato (S. Michele Member, Dela Pierre *et alii*, 2003).

Stage 2b - The late Burdigalian TPB inversion and the Langhian-early Tortonian northward shifting of the basin depocenter

Following the early Burdigalian phase of uplift, a major late Burdigalian basin inversion occurred in TPB, leading to a dramatic increase of subsidence rate and accommodation space creation followed by another contractional event which induced, in Langhian and early Serravallian, the underthrusting of the Ligurian and Adria margin units and the uplifting of TPB margins (Gnaccolini, 1968; Ghibaudo *et alii*, 1985; Gnaccolini & Rossi, 1994; Piana & Polino, 1994; Clari *et alii*, 1995; Mutti *et alii*, 1995; Dela Pierre *et alii*, 2002a; Rossi & Craig, 2016; Ghibaudo *et alii*, 2019).

This event gave origin to a regional scale discontinuity D3 (late Burdigalian) that is clearly detectable at a seismic scale (Mosca et al., 2009). In Monferrato and Torino Hill, it is an angular unconformity separating the prevalent carbonate deposits of Synthem TPB2, below, from the mixed deposits of *Synthem TPB3a* (Areniti di Tonengo, Dela Pierre *et alii*, 2003; Baldissero Fm., Festa *et alii*, 2009 above. In the southern TPB, the D3 becomes a correlative conformity at the base of turbidite successions of the Serole, Cortemilia and Costa Aresa formations (Ghibaudo *et alii*, 1985; d'Atri *et alii*, 2015; Ghibaudo *et alii*, 2019). The accommodation space increased in the SSW portion of the basin, which became the major depocenter. Consequently, late Burdigalian to early Serravallian depocenters formed in the western TPB, accommodating more than 2800 m of westerly-derived turbidites (e.g., Cortemilia Fm, Mutti *et alii*, 2002. During this stage, a progressive exhumation of tectonic units of the Alpine poly-metamorphic basement units has continued, inducing general uplifting of the orogenic belt, which in turn was bounding the basin to the SW. This was recorded in TPB as a marked change in the sediment provenances and a consequent change in the sandstone composition, namely a sharp decrease of serpentinite clasts in Cortemilia Formation (gelati). The regional subsidence continued during Langhian with the deposition of marly sediments (e.g., Marna di Paroldo) and siliceous, condensed deposits (e.g., Bistagno Formation, d'Atri *et alii*, 2015; 2nd siliceous horizon) in the southern TPB.

During Stage 2b the continuing Apennines contractional tectonics led to the underthrusting, at depth, of Ligurian successions resting on the Adria margin below Alpine metamorphic units. This resulted in the formation of a regional scale antiformal stack (Falletti *et alii*, 1995), also described as "Alto Monferrato High" in Rossi *et alii* (2009) and Mosca *et alii* (2010) or as "Langhe deep structure" (Ghielmi *et alii*, 2019) (see below, seismic transect 7). This caused a new partial basin inversion and the onset of the progressive northward shifting of the TPB main depocenters (Rossi & Craig, 2016; d'Atri *et alii*, 2015), the uplift of the SW and SE-to-E basin margins and the continuing growth of the Monferrato structural high with relevant major uplift of the northern TPB margin.

These events induced the local occurrence of angular unconformities during the Langhian (Rossi & Craig, 2016; Ghibaudo *et alii*, 2019) and the northwestward progradations of slope and shelf sediments (*Synthem TPB 3*b) (Marne di Cessole, Siltiti di Gavi, Serravalle Fm) in Alto Monferrato and Borbera-Grue, making a basinward lateral transition to slope and turbidite deposits in Langhe (Cessole Fm., Cassinasco Fm. and Lequio Fm.). In the northern TPB Serravallian outer platform to slope sediments (Marne di Mincengo, Dela Pierre *et alii*, 2003; Festa *et alii*, 2009 were deposited. Step 2b ends with a widespread hiatus (i.e., D4 unconformity) to the north and east, and deposition of lower Tortonian outer shelf sediments (lower member of the Marne di S. Agata Fossili; see also Ghibaudo *et alii*, 1985, 2014) to the south, in Alto Monferrato and Borbera- Grue. The latter interfinger, to the west, with turbidites of the Lequio Fm. at the top of Synthem BTP 3b.

Stage 3 - Padane stage

A third Stage (Padane Stage) followed up to the Present, whose early evolutionary steps are reported here below even though not related to the Field Trip stops.

Once that the TPB was quite filled, i.e., during the Messinian evaporitic stage, the persisting collision of the Europe and Adria lithosphere (Handy *et alii*, 2021) induced a deep physiographic reorganisation during the late Messinian. A rapid exhumation and surface uplift of the Western Alps and Northern Apennines occurred during the Plio-Pleistocene transition, maybe due to, or enhanced by, the detachment of the European slab (Fox et al., 2015) and consequent subhorizontal tearing (Lippitsch *et alii*, 2003; Kissling *et alii*, 2006). Finally, unloading effects due to glacial erosion and melting (Champagnac *et alii*, 2004) enhanced the uplifting ratios. These events paved the way to a third stage, the Padane Stage, during which the reorganisation of the synorogenic basins occurred. The post-Miocene Padane tectonics led to a further northward thrusting of the TPB, with minor tilting and limited faulting of the basin at the rear of the Monferrato-Torino Hill frontal thrust system.

The Padane stage reshaping modified only partially the previous TPB physiography, so that the lateral relationships between the Oligocene-Miocene successions of the different subdomains can be still recognized in the field and in the subsurface.

Structural setting of the TPB subdomains

Torino Hill and Monferrato subdomains

In the northwestern edge the TPB succession presently crops out in the NE-SW directed anticline of the Torino Hill, which is bounded on its eastern side by the transpressive Rio Freddo Deformation Zone (RFDZ, Piana & Polino, 1994, 1995 that separates it from the Monferrato domain. The RFDZ was active from the early Oligocene until at least the Tortonian (Piana, 2000) and controlled, together with the Villadeati transpressive fault system (Dela Pierre *et alii*, 2003), the sedimentary evolution of the Monferrato domain. Both Torino Hill and Monferrato are displaced at depth by the Apennine (Padane) thrust front (Cassano *et alii*, 1986), active until the early Pleistocene, that overrode them onto the Neogene and Paleogene successions resting, in their turn, onto the Adria Mesozoic successions, presently placed below the Po plain. For this reason, Torino Hill and Monferrato are often considered as a single tectonic system at the northwestern edge of the Northern Apennines, although they show a different structural setting and pre-Pliocene kinematic evolution. The tectonic-sedimentary evolution of Monferrato was controlled by NW-SE steep fault zones rooted at depth that acted as transpressive faults during the Late Eocene-very early Oligocene, as transtensional faults during the late Rupelian and Chattian and again as mostly contractional faults during the Early Burdigalian, Tortonian and intra-Messinian tectonic stages, prior to the final emplacement due to the Apennine thrust front (Piana & Polino, 1995; Clari *et alii*, 1995; Festa *et alii*, 2005). The present setting of Torino Hill is due to the activity of NE-SW transpressive faults, rooted in the Alpine metamorphic basement roughly parallel to the inner boundary of the NW Alps (Ghielmi *et alii*, 2019; Mosca *et alii*, 2010), which induced the growing of the Torino Hill anticline since the late Tortonian, together with marked Plio-Pleistocene uplifting (Forno *et alii*, 2018). This structural setting ends towards East against the RFDZ, characterized by a complex indentation of the above-described NE-SW contractional faults and the NW-SE transpressive faults of Monferrato (Piana, 2000), rooted in the Ligurian units of the TPB substratum, which separates the Torino Hill from Monferrato.

Monregalese subdomain

The southwestern part the TPB is represented by the Monregalese (MR) succession resting directly on the basement rocks of the Ligurian Alps and displaced at depth by north-vergent transpressive faults propagating from the bedrock (Rossi *et alii*, 2009; Piana *et alii*, 2021).

Langhe subdomain

The Monregalese succession, which lacks a large part of the Oligocene interval, grades to the North into the Langhe domain (LA), which shows the more thick and complete succession of the TPB, since it has been deposited in the more subsiding and deep part of the basin for most of the Oligocene-Miocene time span (Rossi *et alii*, 2009). The northwestern margin of the Langhe basin is represented, in the subsurface, by the Saluzzo basin margin, which can be considered a transition zone to the Torino Hill domain.

Alto Monferrato subdomain

The eastern and northeastern margins of the Langhe basin are represented by the Alto Monferrato domain (AM), whose succession rests on the Ligurian Alps meta-ophiolites and is less thick and complete with respect to the Langhe one (Fig. 11, Fig. 12). The eastern margin of the Langhe basin was differentiated from the adjoining "Alto Monferrato high" (sensu Rossi *et alii*, 2009) by the multistage Miocene activity of a major contractional structure rooted in the Adria basement at the depth of more than 4 km (Langhe Deep Structure, sensu Ghielmi *et alii*, 2019).

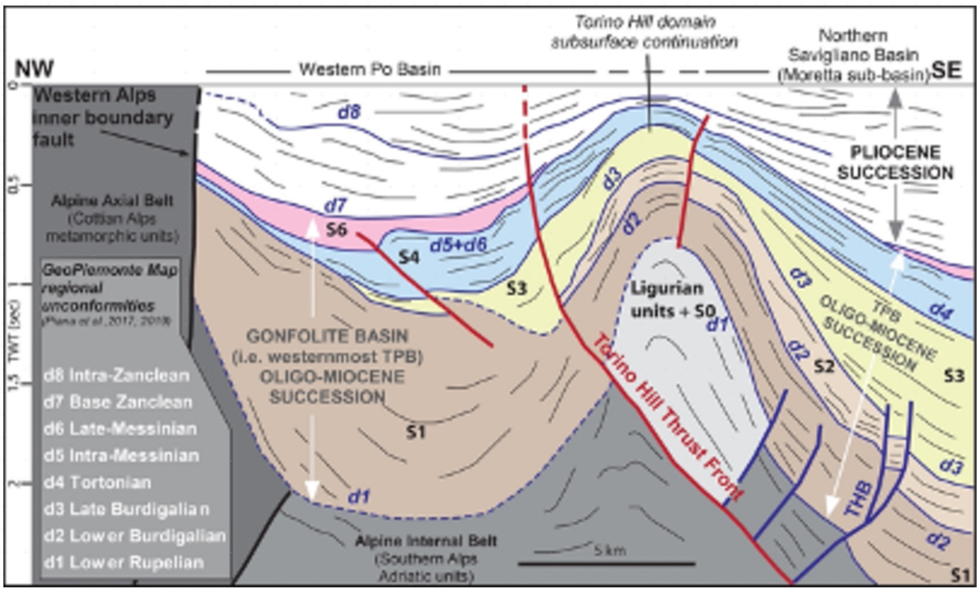


Fig. 11 – Line Drawing of seismic section across the Torino Hill TPB domain (modified after Comerci *et alii*, 2021).

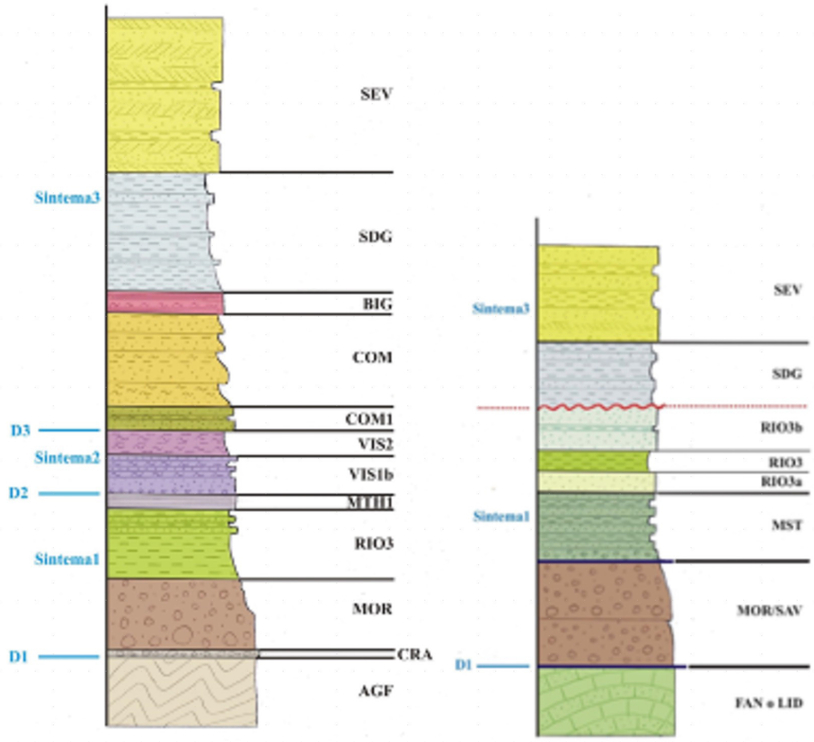


Fig. 12 – Simplified stratigraphic logs of the successions of the Alto Monferrato (left) and Borbera-Grue (right) TPB subdomains. AGF–Undifferentiated internal Ligurian Units (Cretaceous) FAN= Antola Formation and LID–Bruggi-Selvapiana Formation (Upper Cretaceous), CRA–Brecce della Costa di Cravara (upper Eocene - base Rupelian?): continental deposits, MOR–Molare Formation (Rupelian): continental to marine shallow water and fan delta deposits, SAV–Savignone Formation (Rupelian): continental to fan delta deposits, MST–Monastero Formation (Rupelian): deposits related to hyperpycnal flows with local turbidite layers, RIO–Rigoroso Formation (upper Rupelian-Aquitanian): marly deep water deposits with intercalated arenaceous lenticular resedimented bodies (RIO3a Garbagna lithozone; RIO 3b Variano lithozone).

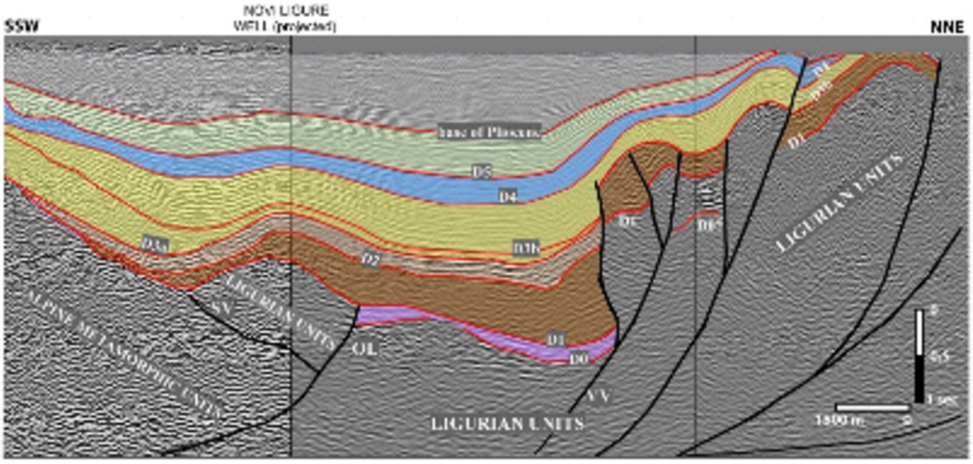


Fig. 13 – Line drawing across the Borbera-Grue TPB domain. Modified after Rossi & Craig, 2016. Black lines: interpreted faults of the Monferrato thrust front (north-easternmost sector) and Villalvernia-Varzi fault system (VV).

Borbera-Grue subdomain ("Eastern TPB")

To the East and NE of the present Scrivia valley, i.e., externally to the northern boundary of the exhumed Alpine metamorphic units (Axial Alpine Front in Mosca *et alii*, 2010, the TPB is represented by the Borbera-Grue domain (BG), whose succession rests on Ligurian non-metamorphic units, which locally overthrust the Oligocene part of the TPB succession itself (Fig. 13, Fig. 12). The Borbera-Grue domain is bounded to the North by the Villalvernia-Varzi fault system (Boni, 1961, 1962, 1969; Di Giulio & Galbiati, 1995; Festa *et alii*, 2015), a major transpressive structure that controlled the sedimentary evolution of the eastern TPB during several stages from the early Oligocene to the Late Miocene.

In the Monferrato, Borbera-Grue and Alto Monferrato subbasins the steps of the regional tectonic evolution at the Alps-Apennines junction are better recorded that in the other subdomains, due to the abundance of shelf successions marked by regional-scale unconformities (Piana *et alii*, 2017a; Ghibaudo *et alii*, 2019) originated by the activity of contractional faults (e.g, Rio Freddo Deformation Zone, Piana & Polino, 1995; Piana, 2000; Val Gorrini thrust and Grognardo thrust Zone, Piana *et alii*, 1997, 2006.

Field Trip Route

Tortona - Albarasca - Borghetto Borbera - Sottovalle - Carrosio - Bosio - Voltaggio (Fig. 14).

Stop 1.1

Locality: Albarasca.
44.754670,8.950913
Topic: Langhian unconformity (D3b), the late Burdigalian TPB inversion and the Langhian-early Tortonian northward shifting of the basin depocenter.

Following the early Burdigalian phase of uplift, a major late Burdigalian basin inversion occurred in TPB, leading to a dramatic increase of subsidence rate and accommodation space creation followed by another contractional event which induced, in Langhian and early Serravallian, the underthrusting of the Ligurian and Adria margin units and the uplifting of TPB margins (Gnaccolini, 1968; Ghibaudo *et alii*, 1985; Gnaccolini & Rossi, 1994; Piana & Polino, 1994; Clari *et alii*, 1995; Mutti *et alii*, 1995; Ghibaudo *et alii*, 2019).

In the eastern TPB, this event induced the local occurrence of angular unconformities during the Langhian (Rossi & Craig, 2016; Rossi, 2017; Ghibaudo *et alii*, 2019) and the northwestward progradations of slope and shelf sediments (Synthem TPB 3b) (Marne di Cessole, Siltiti di Gavi, Serravalle Fm) in Alto Monferrato and Borbera-Grue subdomains, making a basinward lateral transition to slope and turbidite deposits in Langhe (Cessole Fm., Cassinasco Fm. and Lequio Fm.). Synthem 3 bends with a widespread hiatus (i.e., D4 unconformity) and deposition of lower Tortonian outer shelf sediments (lower member of the Marne di S. Agata Fossili; see also Ghibaudo *et alii*, 1985, 2014.

This Stop is dedicated to the observation of the D3b unconformity, bounding at the base the Synthem TPB 3b. D3b cuts the Miocene and Oligocene successions down to the Rigoroso Formation (Variano lithozone) of the underlying Synthem 1b. In front of Albarasca village, Langhian outer shelf sediments (Siltiti di Gavi) unconformably rest onto Oligocene (Rupelian) sandstones of the Variano lithozone. A lag deposit, made up of fragments of sandstones, marls and siliceous marls, locally occurs along the D3b basal erosional surface (Fig. 15).

Stop 1.2

Locality: Val Borbera.
44.720780,8.916722
Topic: The Middle Miocene succession: Siltiti di Gavi - Serravalle Formation.

In this Stop (Fig. 16) we can see the Middle Miocene succession of Borbera-Grue subdomain with the gradual transition from the Siltiti di Gavi to the Serravalle Formation.

The Siltiti di Gavi (middle-upper Langhian) consist of bioturbated marly siltites deposited in an outer shelf environment. In the upper part decimetre to meter thick layers of bioclastic sandstones rich in molluscs and red algae are intercalated.

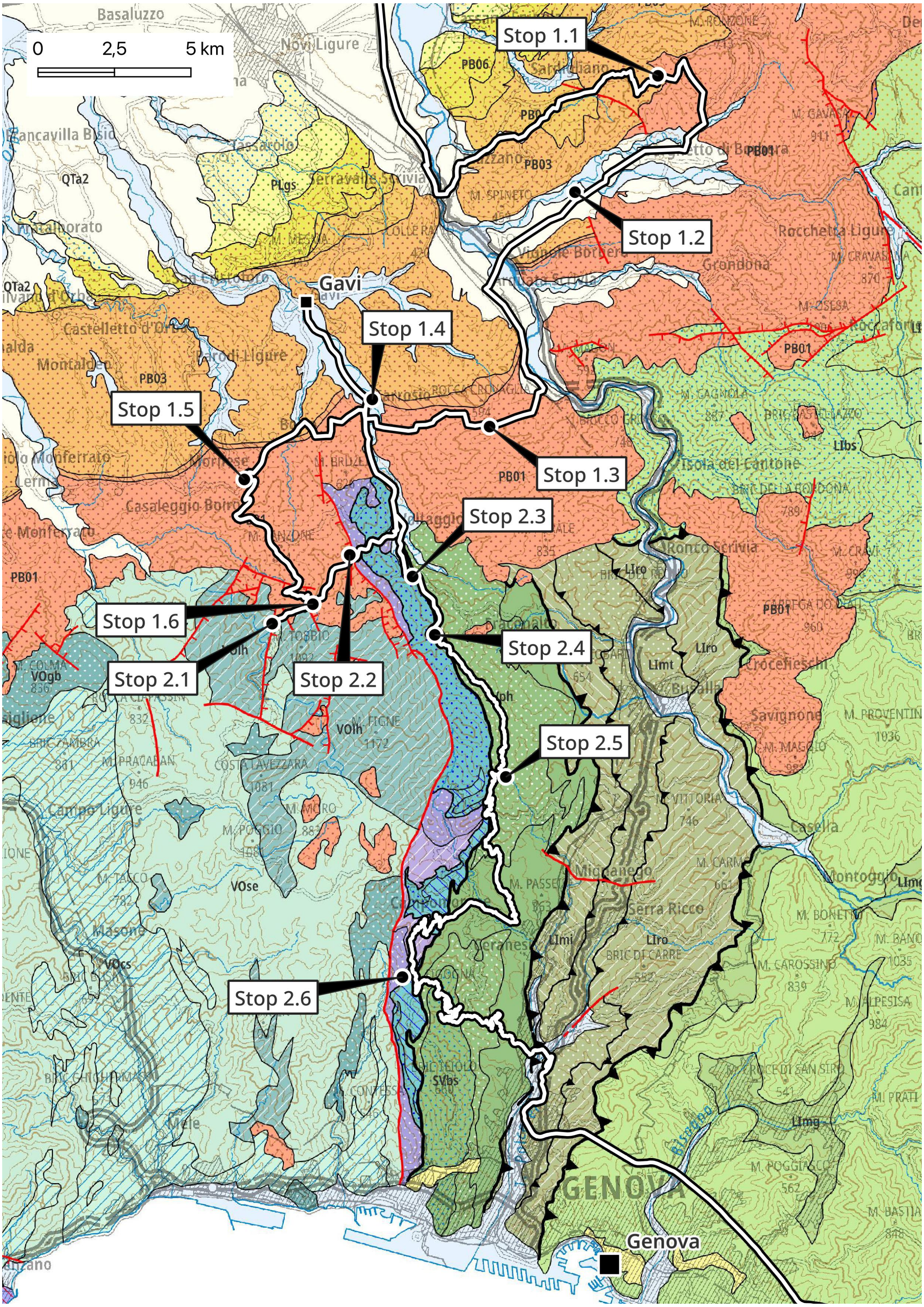


Fig. 14 – Geological map of the southern Piemonte-Liguria area, with Itinerary and Stops of Day 1 and Day 2.

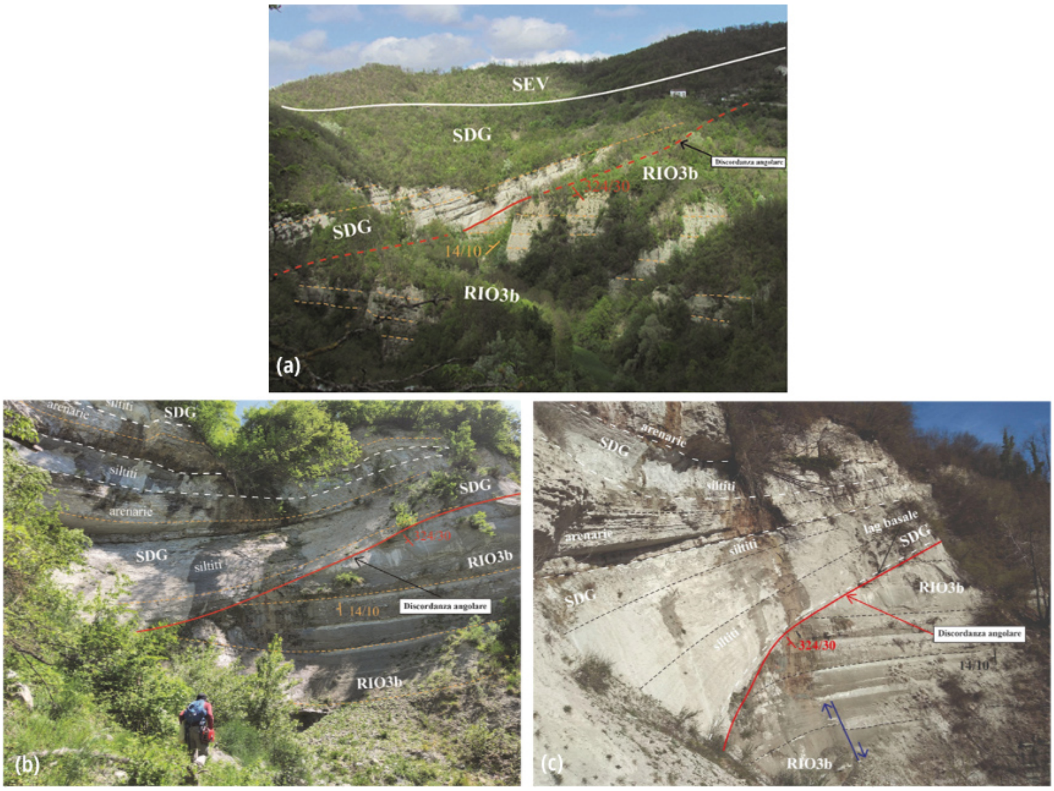


Fig. 15 – (a) Angular unconformity at the base of Siltiti da Gavi (SDG) cutting into the Variano lithozone of the Monastero Formation (RIO3b). SEV: Serravalle Fm. Locality; Piscine di Sorli. (b), (c) Detail of the angular unconformity (red line) followed by a basal lag with clasts of the underlying Early Miocene - Late Oligocene successions. Locality: Piscine di Sorli.)

The Serravalle Formation in the Borbera-Grue sub domain is characterized by an alternation of gray siltstones and sandstones passing to bioturbated bioclastic sandstones, organized in groups of layers of plurimetric to decametric thickness and characterized by the presence of large-scale cross-lamination (sandwaves). The transition between the two formations is gradual, without evidence of discontinuity.

Lunch at Borghetto Borbera.

Stop 1.3

Locality: Sottovalle.
44.652395,8.881689
Topic: TPB as an inverted Early Miocene basin, now involved in the Apennine belt; compressional tectonics and the Burdigalian basin reorganization.

During the very late Oligocene and the Early Miocene, the tectonic indentation of the European and Apulia continental margin caused the switch from transtensional to contractional and transpressional regime in the TPB, inducing inversion of a great number of tectonic structures (Piana & Polino, 1995; Falletti *et alii*, 1995; Piana *et alii*, 1997; Piana, 2000; Festa *et alii*, 2005; Piana *et alii*, 2006; Rossi *et alii*, 2009; Maino *et alii*, 2013; Ghibaudo *et alii*, 2019). This process was coeval with the transpressional tectonics recorded in Sardinia and southwestern Corsica (Carmignani *et alii*, 2004).

In response to these major tectonic events, a number of regional scale unconformities developed throughout the Alps-Apennines syn-orogenic basins.

In the TPB, the D2 major regional unconformity formed in response to the above-described events. It is an angular unconformity which cuts into the siliceous member of the Montechiaro d'Acqui Fm. and Marne di Rigoroso Fm. (Alto Monferrato) and corresponds to a Chattian (or Aquitanian) - lower Burdigalian hiatus. In the deep-water settings (Langhe), it laterally grades to a correlative conformity, dated to the early Burdigalian (d'Atri et al., 2015). The D2 discontinuity surface formed during the Burdigalian event and led to a major reshaping of the basin (d'Atri *et alii*, 1997).

The succession deposited during step 2a (Synthem BTP 2) consists mainly of Burdigalian carbonate ramp deposits passing upward into deeper-water calcareous marls through glauconite-rich outer ramp condensed sediments (e.g. Visone Fm., in Alto Monferrato, d'Atri, 1990a,b; d'Atri *et alii*, 1997; Piana *et alii*, 1997; d'Atri *et alii*, 2015).

In the Alto Monferrato sub domain, the D2 corresponds to an angular unconformity (enhanced by a significant chronostratigraphic hiatus) at the base of Burdigalian shelf deposits of the Visone Fm., which rests on Chattian slope marls of the Rigoroso Fm and/or Aquitanian siliceous marls of the Montechiaro d'Acqui Fm. In the Lemme-Scrivia valley sector the shelf deposits of the Visone Formation are replaced by resedimented bioclastic sandstones of the Rocca Crovaglia Lithozone, a lenticular unit corresponding to a submarine incised valley fill. The basal part of the filling is made up of paraconglomerates with a pelitic-sandy matrix and clasts ranging from centimetres to several metres in size consisting of basement rocks, marly clasts, folded silicified marl blocks, clasts perforated by lithophagus

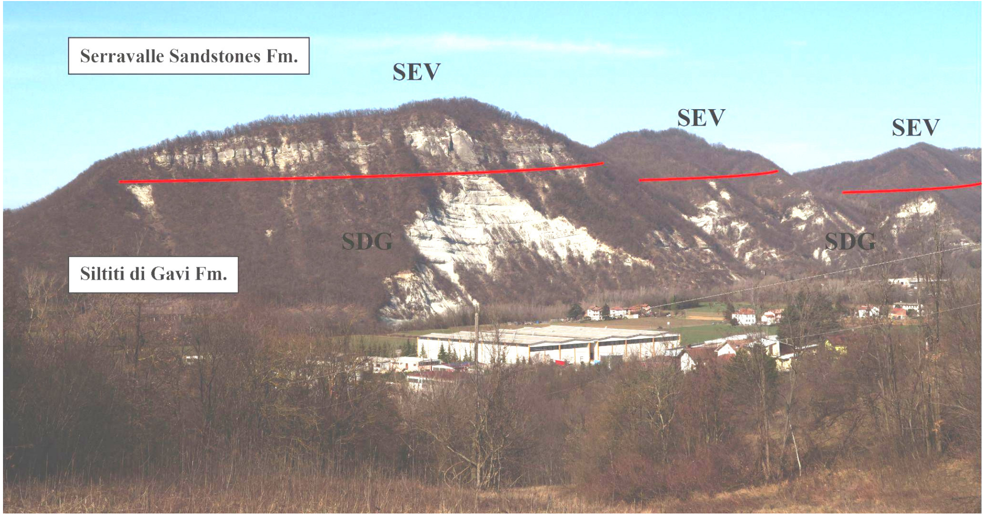


Fig. 16 – Northern (right) side of the Borbera valley between Vignole and Borghetto Borbera. In the southern slope of Monte Spineto, in front of Variano village, the transition from the outer shelf Siltiti di Gavi (SDG, Langhian) and the inner shelf sandstones of the Serravalle Fm. (Serravallian) is exposed. Stop 1.2 is located at the base of the cliff, just in front of it, on the left side of the stream.

organisms and bioclasts of a littoral/circalittoral environment (macroforaminifera, ostreids, pectinids, red algae, bryozoans). The succession continues with layers of medium to coarse grain-size bioclastic turbidite sandstones in thick and very thick layers, which become thinner, with finer grain size and with pelitic interlayers towards the top.

This Stop is dedicated to the view of Rocca Crovaglia Lithozone of the Visone Fm., which unconformably rests on the siliceous member of the Montechiaro d'Acqui Fm. or on the the Marne di Rigoroso fm., well exposed in the lower part of the Rocca Crovaglia southern slope (Fig. 17, Fig. 18, Fig. 19). Here in the Rupelian part of the Marne di Rigoroso Fm. decimetre to meter thick layers of cinerites (zeolitites) linked to a trachytic magmatism are present (d'Atri & Tateo, 1994).

Stop 1.4

Locality: Carrosio.
44.660303,8.833732
Topic: D2 unconformity.

This Stop allows a more detailed and proximal observation of D2 unconformity (Fig. 20).

Relations with evidence of the early Burdigalian contractional tectonics found in other domains of TPB will be discussed here.

Stop 1.5

Locality: Bosio.
44.636947,8.781046
Topic: Early Oligocene transgression: the Molare Fm., from continental to shallow marine sedimentation.

The Alpine collisional tectonics induced the exhumation of the Alpine metamorphic units, the deepening of the foreland basins with the deposition of turbidite systems and, in the retroforeland, the onset of the epi-MesoAlpine basin (sensu Mutti *et alii*, 1995).

In the more proximal part of the basin, near the uplifting areas of the Ligurian Alps, continental sediments (e.g. Brecce della Costa di Cravara) are locally preserved. These sediments would be later unconformably covered by other continental to shallow marine sediments (i.e. Molare Fm.), after the onset of the early Oligocene transgression (TPB Synthem 1a).

The early Rupelian tectonic phase, mostly transpressional in the overall southern part of the Western Alps (Dumont *et alii*, 2012), can be related in TPB to a local transtensional regime developed in the inner side of the uplifting Alpine belt.

The continuum of the collisional contractional tectonics ("Ligurian phase II" sensu Mutti *et alii*, 1995, coeval with the westward movement of the Adriatic indenter, induced at shallow crustal levels a complex partitioning of transpressional and transtensional regime, synchronous with the main exhumation phase of the HP metamorphic units of the SW Alps, as largely described in literature (Hoogerduijn Strating, 1991; Rubatto & Scambelluri, 2003; Carrapa *et alii*, 2003; Federico *et alii*, 2004, 2005; Vignaroli, 2006; Maino, 2009; Vignaroli *et alii*, 2008, 2009, 2010; Rossi *et alii*, 2009; Mosca *et alii*, 2010; Argnani, 2012; Beucher *et alii*, 2012; Ghibaudo *et alii*, 2014)

High-angle, synsedimentary faults, probably correlated to the rifting phase of the Balearic basin (Rehault *et alii*, 1984), dissected the units of the TPB substratum in a series of fault blocks (Mutti *et alii*, 2002). Anyway, in the northern edge of the Balearic-Ligurian rift, the stretching of the lithosphere was less pronounced, rapidly decreasing toward the North due to the hindering effect of the southern prolongation of the Ivrea high-density body (Maino *et alii*, 2013). The gradual decrease of the rifting, and then of the incipient subduction rate, was partitioned by E-W, transpressive faults in the Ligurian Alps (e.g. LIVZ of Piana *et alii*, 2006, see also Ghibaudo *et alii*, 2019).

Consequently, in this domain a wide extensional regime did not developed, but a marked regional uplift occurred (Jourdan *et alii*, 2013), followed by an intense regional denudation, which resulted, during the Rupelian, in widespread coarse-grained sedimentation (either continental or marine) over the exhumed basement (Bertotti *et alii*, 2006; Vignaroli *et alii*, 2010). A marked transgressive event (Lorenz, 1969; Haccard *et alii*, 1972) occurred in the internal part of the Alpine belt. This occurred in an

Fig. 17 – Panoramic view on the southern slope of Rocca Crovaglia from Sottovalle-Rigoroso road. D2 unconformity separates the Rocca Crovaglia lithozone (VIS1b) of the Visone Fm. from the siliceous member of the Montechiaro d'Acqui Fm (MTH1) or directly the marls of the Rigoroso Fm. (RIO3) well exposed in the lower part of the slope.

Fig. 18 – Masseria Praga. Chaotic deposits present at the base of Rocca Crovaglia lithozone. To the right a block consisting of folded silicified marl.

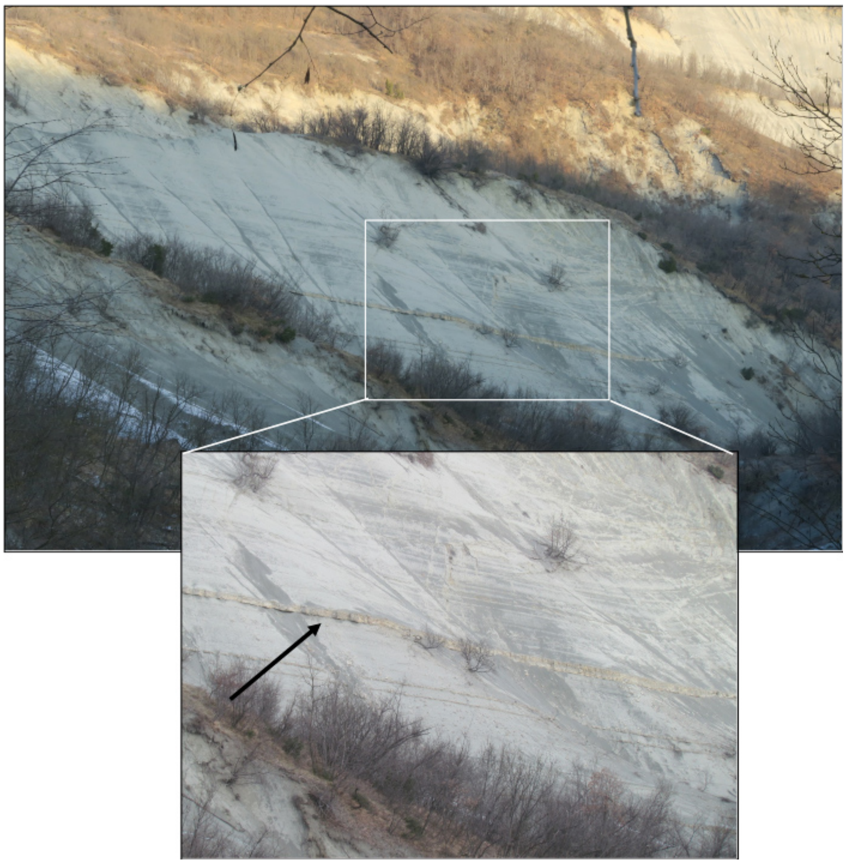


Fig. 19 – Cinerite layer (black arrow) in the Marne di Rigoroso Fm., consisting of silty marls with intercalated turbidite layers. Locality: Sottovalle.

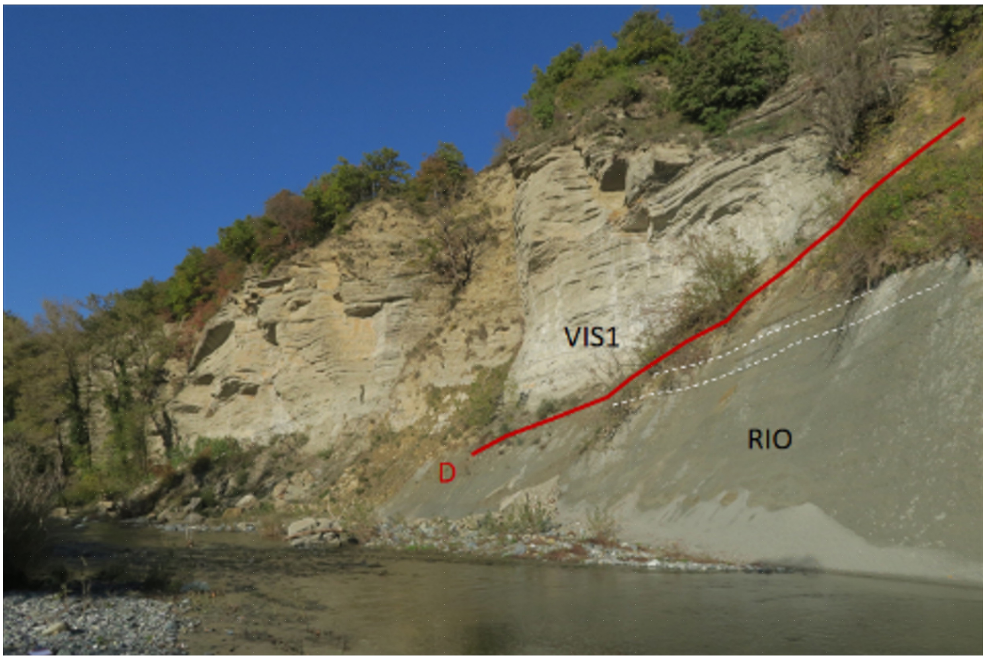


Fig. 20 – Lemme River near Carrosio. D2 unconformity (red line) separates the Rocca Crovaglia lithozone (VIS1b) from the marls of the upper member of the Marne di Rigoroso Fm. (RIO3).

overall geomorphological context marked by fast uplifting areas and adjoining throughs, which were characterized by subsidence rates highly variable through space and time.

In the TPB the Alpine tectonics induced the sedimentation of Synthem TPB 1, bounded at the base by the Unconformity D1 (lower part of Rupelian), which, in the southern part of the TPB, consists of a nonconformity surface between the bedrock (either metamorphic or non-metamorphic) and the overlying sedimentary successions. Synthem TPB1 begins with continental to shallow water Rupelian conglomerates and arenites (Molare Fm., Lorenz, 1969; Savignone Fm., Bellinzona & Boni, 1971) that grade to sandy and marly sediments, i.e, the lower part of Rigoroso Fm. (Gelati, 1968) in Alto Monferrato, and the Monastero Fm. (Bellinzona & Boni, 1971) in the Borbera-Grue sub-domain.

The stop consists of two sites where the Rupelian Molare Fm can be observed.

The first one (Stop 1.5a, Fig. 21) is dedicated to the bioclastic coastal and fan-delta deposits (conglomerates, sandstones and siltites) of the Molare Fm. (MOR3), which were deposited during the last steps of the Stage 1a, just before the Rupelian drowning of the platform and the subsequent deposition of the Marne di Rigoroso.

The second one (Stop 1.5b, Fig. 21d) concerns the underlying and slightly older continental (fluvial and/or slope fan) deposits (conglomerate, and breccia with sandstone matrix, MOR 2). Clasts are made of metaophiolite, calcschist, marble, limestone and dolostone. Sediments were deposited in narrow fault-bounded basins showing marked lateral facies changes (in composition and internal organization).

Stop 1.6

Locality: Eremiti pass.
44.600543,8.809135
Topic: The incipient continental sedimentation after the main Ligurian tectonic phase, Brecce della Costa di Cravara.

The Brecce della Costa di Cravara (late Eocene?-early Oligocene?) are a thick interval of continental breccias lying on the peridotite and serpentinite of the Voltri Massif in the sector between the Gorzente and Lemme valleys (Allasinaz *et alii*, 1971; Capponi & Crispini, 2008). These breccias are unconformably overlain by the Rupelian Molare Formation, as can be observed in the upper Morsone Valley (Lorenz, 1969; Lorenz & Rebora, 1982).

The Brecce della Costa di Cravara (Fig. 22) are heterometric breccias with angular to subrounded clasts, a few centimetres to several metres in size. The clast composition mirrors that of the ophiolite substrate: clasts are mainly composed of peridotite and serpentinite, and very minor metabasite. These breccias commonly lack any internal organization; only locally (Lago delle Ciocche) an ill-defined, metre-thick bedding can be observed. These breccias are characterized by a dark-green matrix, which becomes reddish when weathered, and can be interpreted as continental slope breccias

Fig. 21 – (a) Stop 1.5a. Fan-delta conglomerates and coastal bioclastic sandstones of the upper part of the Molare Formation (MOR 3 member). (b) Stop 1.5a. Detail of a microconglomerate bed with abundant, dark-green serpentinite clasts and bioclasts (pectinid bivalves). (c) Stop 1.5a. Bioturbated sediments of the MOR 3 member of the Molare Fm. Bedding surface of a sandstone layer preserving y-shaped crustacean burrows (*Thalassinoides*). (d) Stop 1.5b - Continental conglomerates and sandstones of the MOR2 member of the Molare Formation

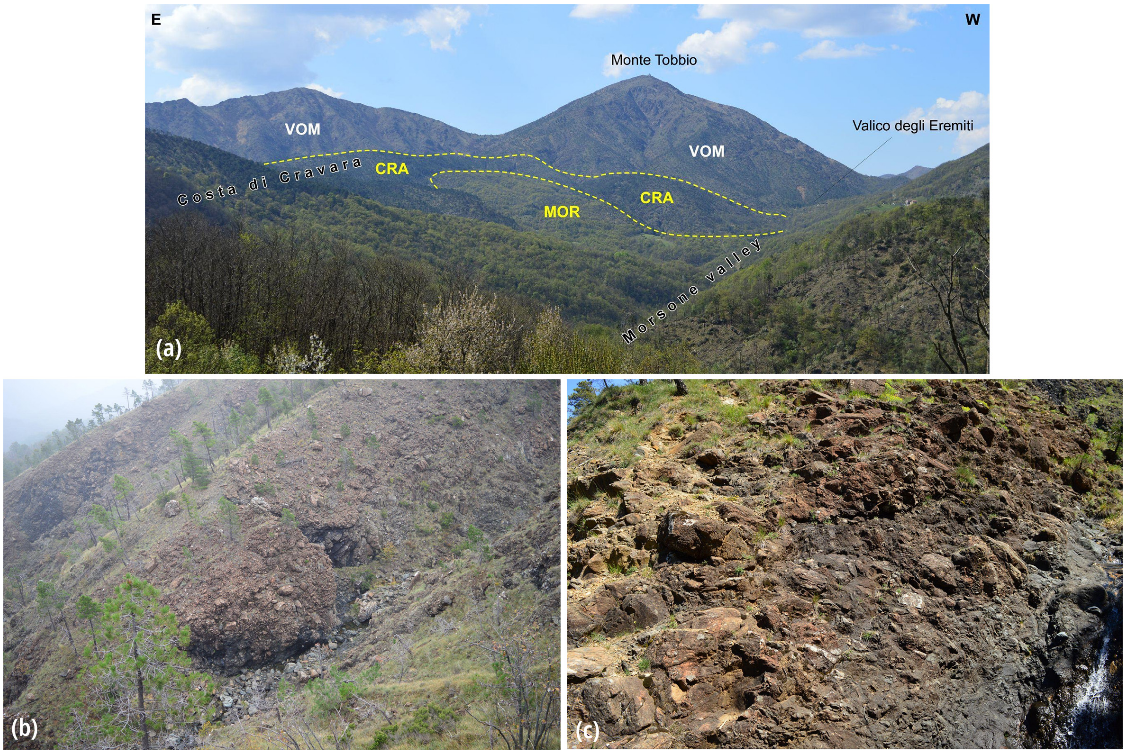


Fig. 22 – (a) Panoramic view of the Brecce della Costa di Cravara (CRA) cropping out in the upper Morsone valley, Voltaggio. This unit lays on the peridotite and serpentinite of the Voltri Massif (VOM) and is unconformably overlain by the Molare Formation (MOR). (b) Brecce della Costa di Cravara cropping out near the Valico degli Eremiti. Note the lack of internal organization and the abundant blocks more than a meter in diameter (the height of the pine trees is about 8-10 metres). (c) Detail of the Brecce della Costa di Cravara cropping out near the Valico degli Eremiti, here composed of decimeter-sized, angular to subrounded blocks of peridotite and serpentinite, with a dark-green to reddish matrix.)

Day 2 : Crossing the "Ligurian Knot": tectonic units between the Alps and the Apennine (Sestri-Voltaggio Zone)

Laura Crispini[1], **Laura Federico**[2], **Giancarlo Molli**[2]

Field Trip Route

Voltaggio, Passo della Bocchetta, Genova (Fig. 14).

Topics

During the second day of the excursion we will go through the innermost metamorphic units of the Ligurian Alps which are represented by the HP-LT units of the Voltri Massif (or Voltri Group, Chiesa *et alii*, 1975) and by three tectono- metamorphic units (Cravasco-Voltaggio-Montenotte Unit (CVMU), Gazzo-Isoverde Unit (GIU), Figogna Unit (FU) historically referred to and mapped as the Sestri-Voltaggio Zone (Cortesogno & Haccard, 1984). The Sestri Voltaggio Zone is a km-wide north-south oriented structural domain that includes tectono-metamorphic units of the Alpine belt and it is limited to the west by the HP-LT Voltri meta-ophiolite (through the Sestri-Voltaggio Line), to the North is overlain by the TPB sediments and to the east is in contact with very low grade Ligurian units (Fig. 23).

The Sestri-Voltaggio Zone (SVZ) was defined in the 60s referring to a complex of rocks, occurring from Sestri Ponente to Voltaggio in a 5-6 km-wide N-S strip (Görler & Ibbeken, 1964) and the great complexity of the area has been attracting the interest of generations of geologists . The SVZ western contact with the HP-LT Voltri Massif (usually referred to as the Sestri-Voltaggio Line) has been considered as the boundary between the Alps and the Apennines for a long time. Elter & Pertusati (1973) questioned its significance as a boundary between the two chains, pointing out that the Sestri - Voltaggio line cuts across structural directions and emphasizing that the structures with opposite vergence, of which it seems to represent a line of symmetry, are partly posterior to the age of the line itself. They see the Sestri - Voltaggio line as an early fracture, with the characteristics of a "transform" fault, that connects with the Voghera - Pavia line and the Giudicarie line.

Since the 80s other researchers have described the Sestri-Voltaggio Line as a contact between units with different metamorphic conditions, later tilted to the vertical by late-orogenic tectonics (Cortesogno & Haccard, 1984; Capponi, 1991)or as an extensional tectonic surface placing low pressure on high pressure metamorphic units (Hoogerduijn Strating, 1991). Crispini & Capponi (2001) and Crispini *et alii* (2009) highlighted the evolution of the role of the Sestri-Voltaggio Line, changing from a boundary between different tectono-metamorphic units to a dextral transcurrent system, in the different stages of the Alpine and late Alpine evolution.

Actually the Sestri Voltaggio Zone can be considered as a high strain zone or fault zone and it can be better referred to as Sestri-Voltaggio Fault Zone. In the present-day map view it marks the contact among units of different paleogeographic derivation and re-equilibrated at different P-T metamorphic conditions.

The cross-section of Fig. 23b shows the simplified structural architecture at shallow level of the area across the innermost units of the Ligurian Alps (Voltri Massif, Sestri-Voltaggio Zone and Flysch units). The cross-section is representative of the geometric stacking of the units, of the relationships among the units and their internal structural arrangement. The poorly exposed contacts among the tectonic units are generally steeply dipping to the east so that the HP-LT units are the lowermost units and the very low grade Flysch units the uppermost units of the tectonic pile; the Antola Unit is in the top structural position, with a low-dipping tectonic contact (Fig. 24). At the outcrop scale, the boundaries among the metamorphic units are folded shear zones commonly reactivated by strike-slip faults with the same longitudinal trend. Moreover the area close to the Sestri-Voltaggio Line can be considered as a high strain zone and is characterized by intense shearing and fracturing (Fig. 25).

[1]University of Genova, Italy
[2]University of Pisa, Italy

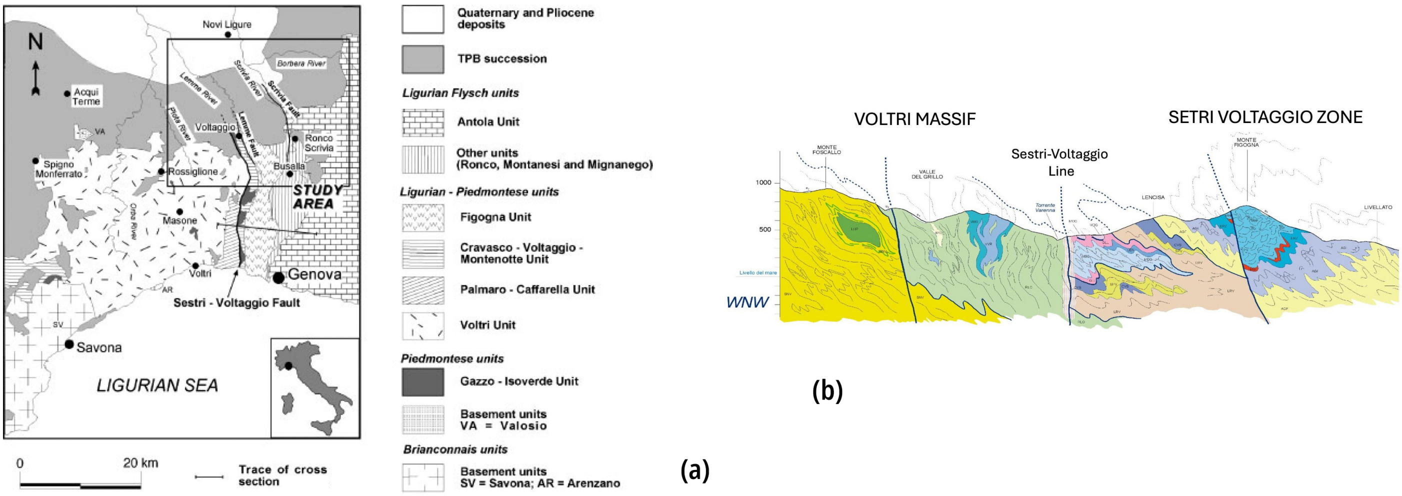


Fig. 23 – (a) Sketch map of the Alps-Apennines boundary, after CAPPONI *et alii* (2009a). (b) Geologic cross section (WNW-ESE) of the metamorphic basement across the Sestri Voltaggio Line, after CAPPONI & CRISPINI (2008).

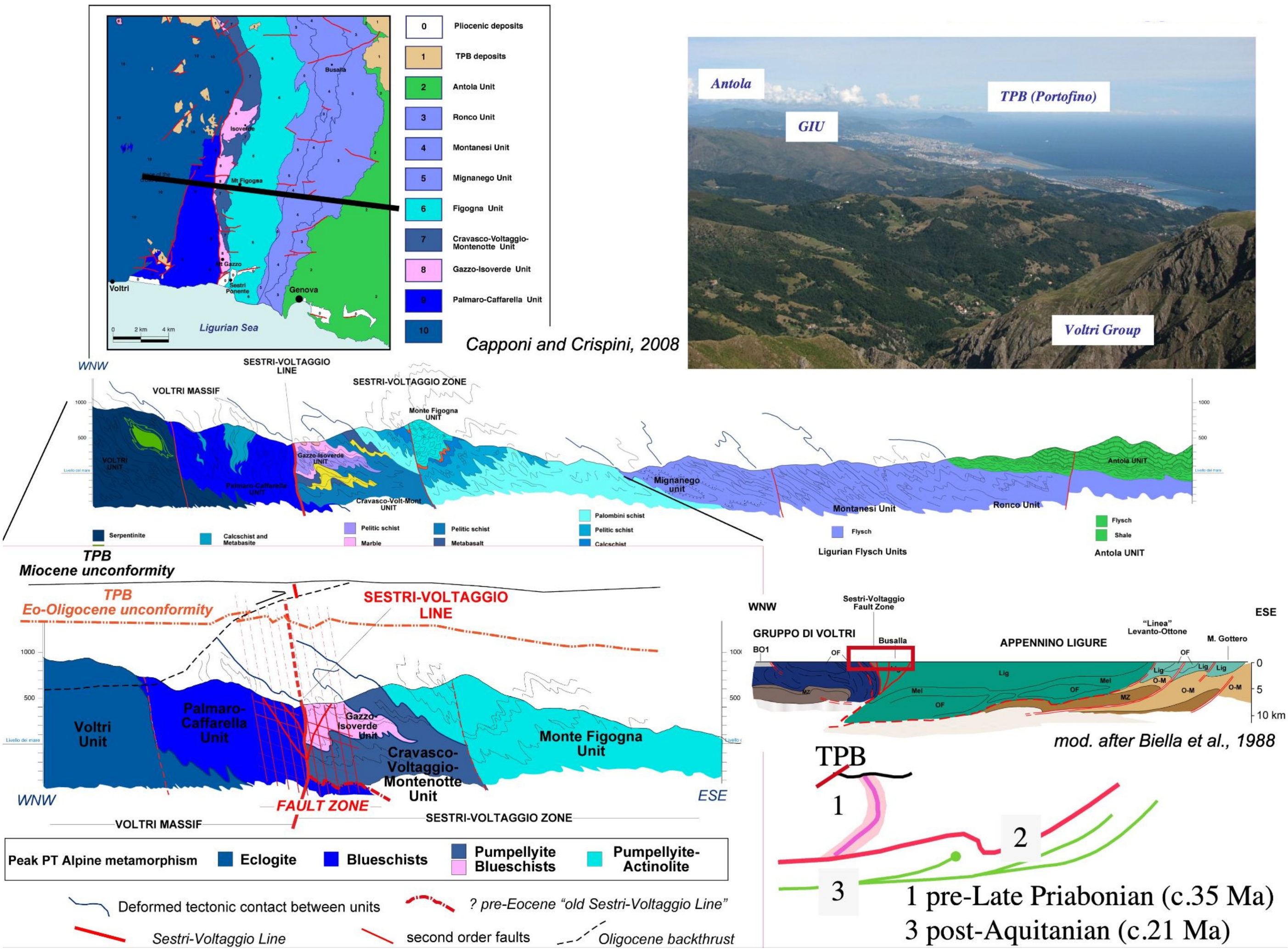


Fig. 24 – Schematic summary of the Sestri-Voltaggio Zone and its tectonic story (after MOLLI *et alii*, 2010). After the main orogenic syn-metamorphic Alpine phases, in the Ligurian Alps, a regional top to E-NE backthrusting phase that involves the Oligocene TPB successions and the metamorphic basement is described for the Ligurian Alps and testifies to a major tectonic activity lasting up to the Oligocene (D'ATRI *et alii*, 1997; CAPPONI *et alii*, 2001, 2009a). The principal tectonic activity of the Sestri-Voltaggio Fault Zone possibly lasted up to Late Oligocene-early Miocene as the related subsidiary structures involve the Aquitanian-Burdigalian TPB deposits. The SVZ and the backthrusts can be inserted in a same tectonic framework where SVZ acted as a dextral tear fault in the general migration of the Ligurian Alps towards NE-N.

Deformation	Tectonic event	Fabric	Metamorphism	Vergence
D_1/D_2	subduction	tight to isoclinal similar not cylindrical folds and related schistosity	blueschist facies low T	unconstrained
Sth_2	exhumation-uplift of the metamorphic units and nappe emplacement	reverse, ductile to brittle-ductile shear zones	limit greenschist/ pumpellyite - actinolite facies metamorphism	top to S-SW
D_3	nappe emplacement	open to close sub-cylindrical folds	albite + chlorite + epidote	top to NW
Sth_3	nappe emplacement	low-angle reverse and normal faults	albite + chlorite + epidote	top to NW
D_4	backthrusting	open folds thrust faults	zeolite facies	top to E-NE
D_1/D_2	subduction	tight to isoclinal similar not cylindrical folds and related schistosity	pumpellyite - actinolite facies	unconstrained
Sth_2	exhumation-uplift of the metamorphic units and nappe emplacement	reverse, ductile to brittle-ductile shear zones	albite + chlorite + epidote	top to S-SW
D_3	nappe emplacement	open to close sub-cylindrical folds	albite + chlorite + epidote	top to NW
Sth_3	nappe emplacement	low-angle reverse and normal faults	albite + chlorite + epidote	top to NW
D_4	backthrusting	open folds thrust faults	zeolite facies	top to E-NE

Fig. 25 – Schematic synthesis of the relationships between deformations and metamorphism for the SVZ units (modified from Capponi & Crispini, 2008).

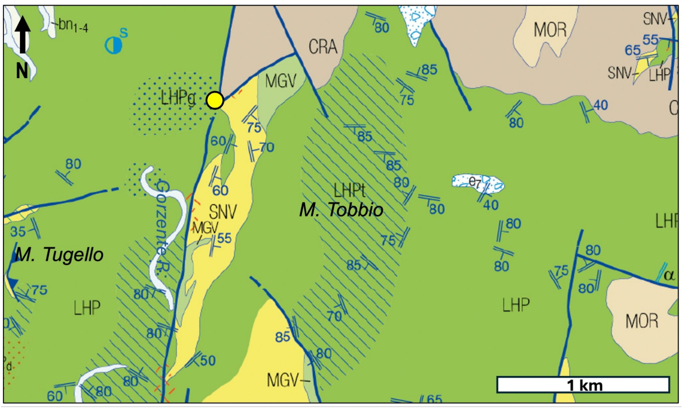


Fig. 26 – Location of Stop 2.1 (yellow dot), after Capponi & Crispini (2008). CRA–Eocene-Oligocene Sedimentary Breccia, MGV–Greenschist Metagabbro with eclogitic relics , SNV–HP-LT serpentinite , LHP–peridotite with HP-LT overprint.

Stop 2.1

Locality: Panorama view west of Eremiti Pass.
44.595003, 8.793280
Topic: The emerging HP-LT alpine basement: mantle peridotite with metamorphic overprint (Erro-Tobbio or Voltri Unit) next to continental sediments (Cravara Breccia).

The aim of this stop is to get a panoramic view of the scenario at the transition between the sedimentary cover of the TPB and the metamorphic substrate. We are located in the northern sector of the Voltri Massif close to the contact with the overlying sedimentary successions of the TPB and the adjacent units of the SVZ (Fig. 26).

In this outcrop the Voltri Massif is represented by outcrops of mantle peridotite (lithospheric spinel lherzolites, reactive spinel peridotites, plagioclase-rich peridotites with pyroxenite and dunite bodies, Fig. 27) and serpentinised peridotite with minor lenses and dykes of metagabbro, known in literature as "Erro-Tobbio peridotite"- ET (Chiesa *et alii*, 1975; Piccardo & Vissers, 2007) and ascribed to the Voltri tectono-metamorphic Unit for the Alpine metamorphic features (Capponi *et alii*, 2016).

In spite of the HP-LT Alpine overprint the Voltri-ET peridotite preserves metre- to-kilometer-scale volumes of preserved peridotite that retain mantle textures and mineral assemblages (spinel-to plagioclase paragenesis), thus allowing the study of their pre-Alpine mantle evolution (Piccardo & Vissers, 2007; Padovano *et alii*, 2015). The peridotite bodies are enclosed in HP-LT serpentinite; there is a gradual transition from partially-serpentinized peridotite tectonites to serpentinite mylonites with an antigorite + magnetite + titanian-clinohumite + chlorite + diopside foliation. In the north-eastern sector of the Voltri Massif (close to the SVZ) partly serpentinized peridotites are variably sheared along a steeply dipping N-S regional schistosity. Serpentinites enclose bodies of metagabbros and metasediments; these bodies are variable in size and record different peak conditions (from eclogite to blueschist facies) and different P-T paths (Fig. 28). Moreover, disrupted parts of the Palmaro-Caffarella Unit are sheared and boudinaged inside the Voltri Unit following the regional foliation. This tectonic setting has been interpreted as assembled in a subduction domain at the interface between the converging plates ("fossil" serpentinite-subduction channel) and possibly matching the characteristics of a tectonic mélange (Malatesta *et alii*, 2012).

Stop 2.2

Locality: Morsone River Valley, Voltaggio.
44.614866, 8.824549
Topic: Eo-Oligocene tectonics in TPB sediments and metamorphic basement.

We drive back towards the village of Voltaggio following the Morsone River and crossing road cuts of the sedimentary de-

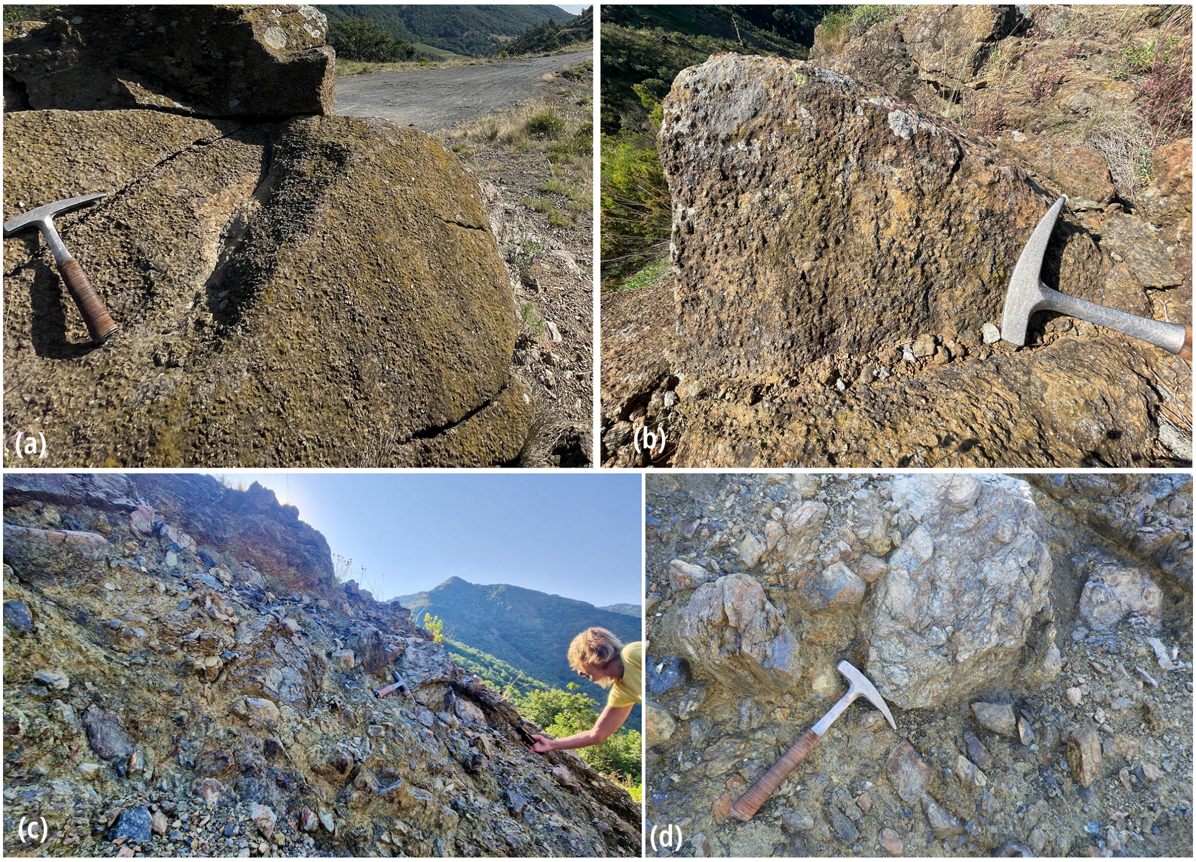


Fig. 27 – (a), (b) The Voltri (Erro-Tobbio) peridotite. Lherzolite showing granular to low strain tectonic fabric. The main deformation fabric in the outcrop is related to mantle shear zones. (c), (d) Continental Cravara Breccia (view to the SE, Mt Tobbio in the back), clasts are mainly composed of Voltri Massif serpentinite.)

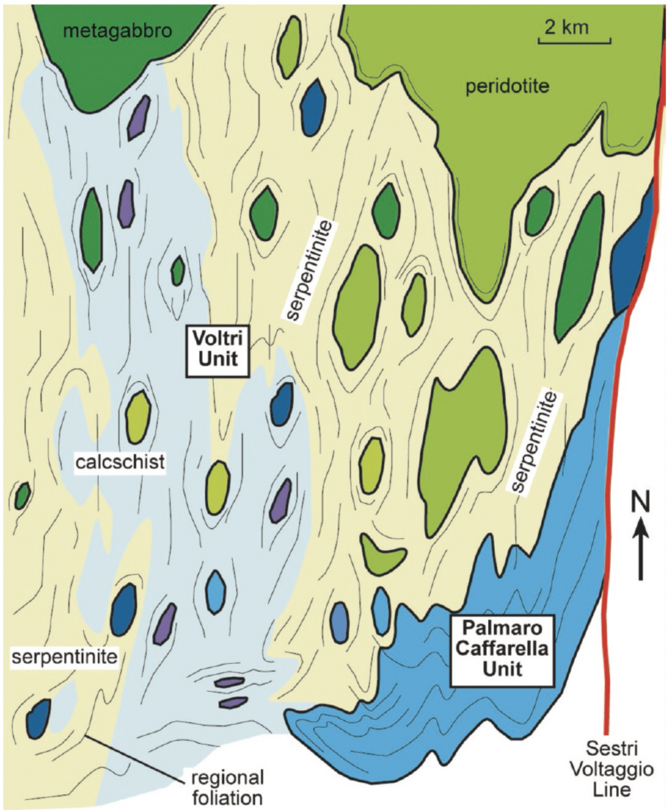


Fig. 28 – The eastern sector of the Voltri Massif, interpreted as a fossil subduction channel. A sheared matrix of serpentinite and calcschists encloses bodies of different lithologies, with different metamorphic evolution. Modified after Malatesta *et alii* (2012).

posits of the Piedmont Tertiary Basin (TPB).

In this stop (Fig. 14, Fig. 29), we can see various evidence of the brittle tectonics that follows the main folding and metamorphic Alpine events. The main structures are part of the NNW-SSE fault system that separates the HP-LT tectono-metamorphic units of the Voltri Massif from the Sestri-Voltaggio zone in its northern sector.

Descending towards the bed of the Rio Morsone on the S-SE facing wall, we have a panoramic view of the continental and marine-marginal deposits of the Oligocene Molare Formation (Fig. 30, Fig. 31). In this section, typical alluvial fan deposits outcrop, characterized by polygenic conglomerates with rounded coarse elements, sandstones with a carbonate matrix, and coarse sandstone levels with prevailing carbonate and serpentinite elements, poorly graded and angular. To the west, the strike of sediment bedding is approximately 160-170 with 25° dip to the W (typical attitude in the southern sector of the BTP), moving towards the east, bedding maintains the same strike but becomes steeply inclined up to 60° towards the W, following a N-S axial flexure (see Fig. 30). Descending the course of the Rio Morsone we can observe the steeply dipping bedding of the conglomerate and sandstone that to the east pass to a serpentinite breccia. This contact is characterised by a N-S steeply dipping fault zone.

If accessible, we go downriver where we can reach the Gazzo-Isoverde Unit dolomitic limestone of the SVZ and observe a ESE-WNW steep strike slip slickenside (approx 70/70 E) that cuts folds and foliations of the limestones, and marks the south contact with conglomerates and sandstones of the TPB. The serpentinite breccia is a mixing between continental sedimentary breccias and tectonic breccia. The metamorphic substrate to the west of the NS fault consists of foliated serpentinites structured in metric “lithons” overlain by serpentinites with a cataclastic to fault gouge texture. The breccias are monogenic at the base where they are formed by serpentinised lherzolites, towards the top they change to polygenic breccias with heterometric clasts of serpentinites and, less frequently metabasite, eclogite and limestone. The contact with the metamorphic substratum is of the transgressive type with secondary reactivations linked to overthrust of the breccia-serpentinite assemblage. The bedding of the breccias is clear only in the summit parts of the succession where it appears to be very inclined towards the W. The contact between the breccias and the conglomerates is transgressive.

This fault, together with the one observed in the Rio, is part of the NNW-SSE fault alignment that separates the Voltri Group and the Sestri-Voltaggio area in the northern sector. Also in this outcrop along the stream is another tectonic contact (of uncertain interpretation) with an approximately WNW- ESE trend that brought Eocene breccias and underlying serpentinites to the same level as the Oligocene deposits. The tectonic surfaces presented in this outcrop (already reported in Haccard & Lorenz, 1979) are interpreted as Oligocene syn-depositional structures and are characterised by the presence of zeolite mineralogical associations and rising sulphurous springs.

Stop 2.3

Locality: South of Voltaggio village, along the SP160 road.
44.608243, 8.849182
Topic: Metamorphic Oceanic units, blueschist sedimentary cover of the Cravasco-Voltaggio-Montenotte Unit.

This Stop (Fig. 14, Fig. 29) will be used to introduce the general architecture of the SVZ and the structures and composition of the metamorphic oceanic units.

We can see metamorphic sediments of the oceanic cover of the SVZ (considered the equivalent of the Calpionella Limestone of the Internal Ligurian units of the Apennines) and in particular the Cravasco-Voltaggio-Montenotte Unit crystalline limestones or calc-schist (equivalent of the *Calcaires Pointillés*). We can have a panoramic view of the mesostructure on a vertical quarry front (the quality of the view depends on the season and vegetation cover) to the south of the main road and observe directly the characteristics of the metamorphic foliations and structures in a abandoned quarry to the north of the road. In the Cravasco-Voltaggio-Montenotte Unit at least 3 deformation events with syn-metamorphic foliations have been described (Hoogerduijn Strating, 1991; Crispini & Capponi, 2001, see Fig. 32).

From a structural geological point of view at the regional scale, we are on the eastern flank of a pluri-metric anticline with blueschist metagabbros and meta-pillow lava at the core, with an axial plane steeply dipping to the E-SE and fold axis ca. 40° plunging to N-NW. The axis is represented by spectacular mullions structures at the contact between limestone beds and intercalations of pelitic schists (Fig. 33).

At the base of the succession, the crystalline limestones are characterised by a level several metres thick that is rich in microcrystalline quartz, which is alternating with layers rich in white micas, chlorite and ankerite, and intercalations of centimetric to metric pelitic levels.

On the fresh fracture surfaces, darker spots give a character-

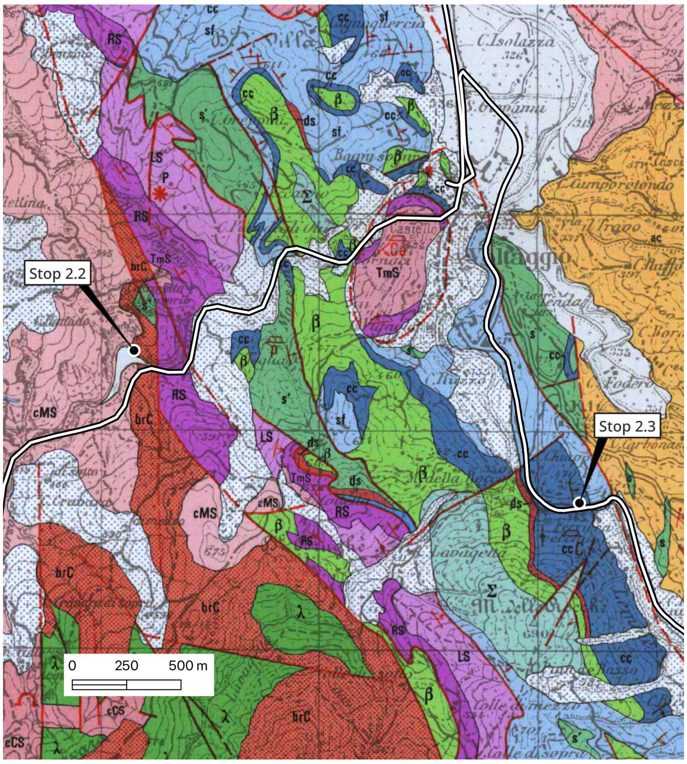


Fig. 29 – Location of Stop 2.2 and Stop 2.3, geological map by Cortesogno & Haccard (1984).

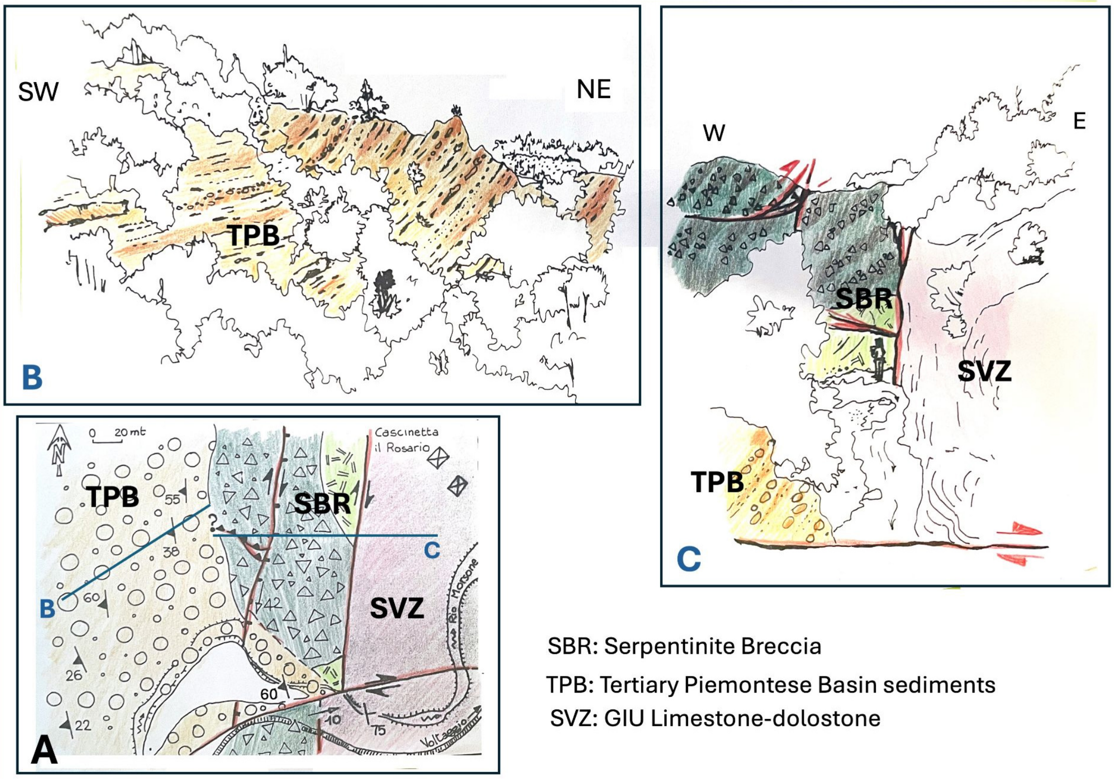


Fig. 30 – Geologic Sketch map of the Stop 2.2 with the cross sections traces B and C.

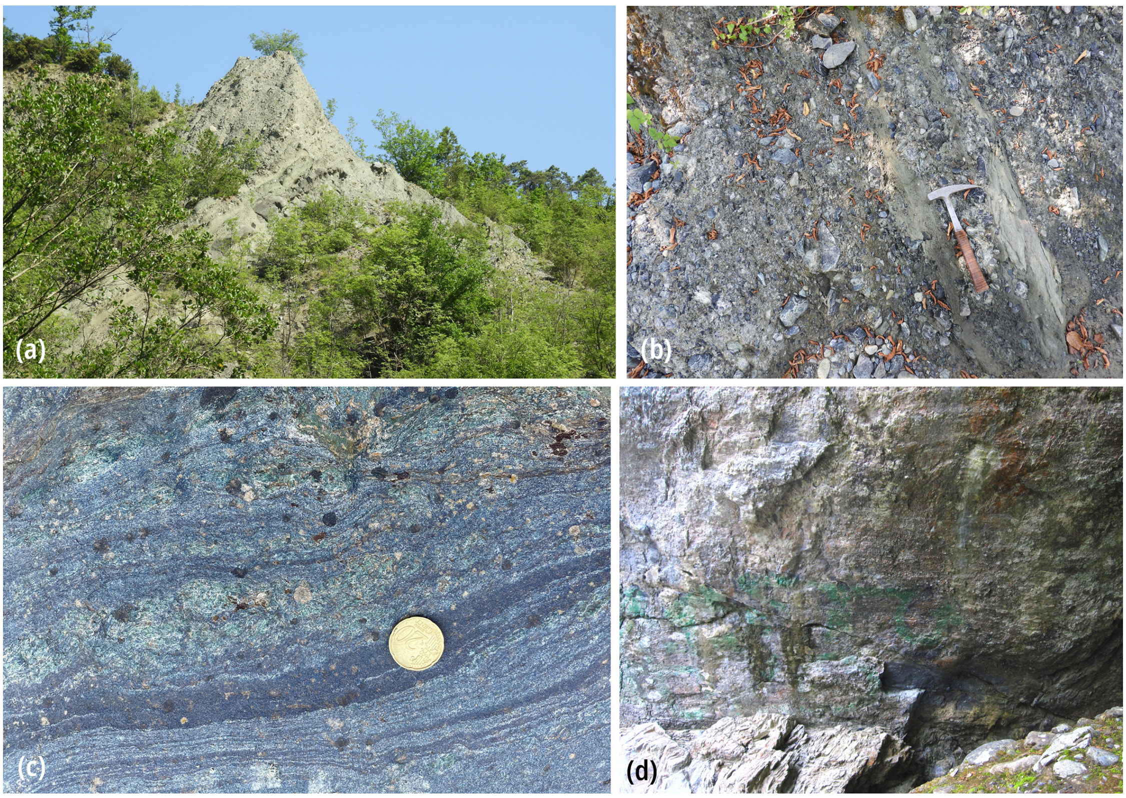


Fig. 31 – (a) Panoramic view of the TPB conglomerates with steeply dipping bedding (detail of the section B of Fig. 30. (b) Tilted Bedding (dip 60 to the west) in the TPB sediments close to fault zone. (c) Detail of HP-LT metagabbro (eclogite-blueschist Voltri Unit) boulders in the Morsone river (possibly derived from clasts of the TPB basal sediments). (d) E-W strike slip fault in dolomitic limestone of the Gazzo-Isoverde Unit.)

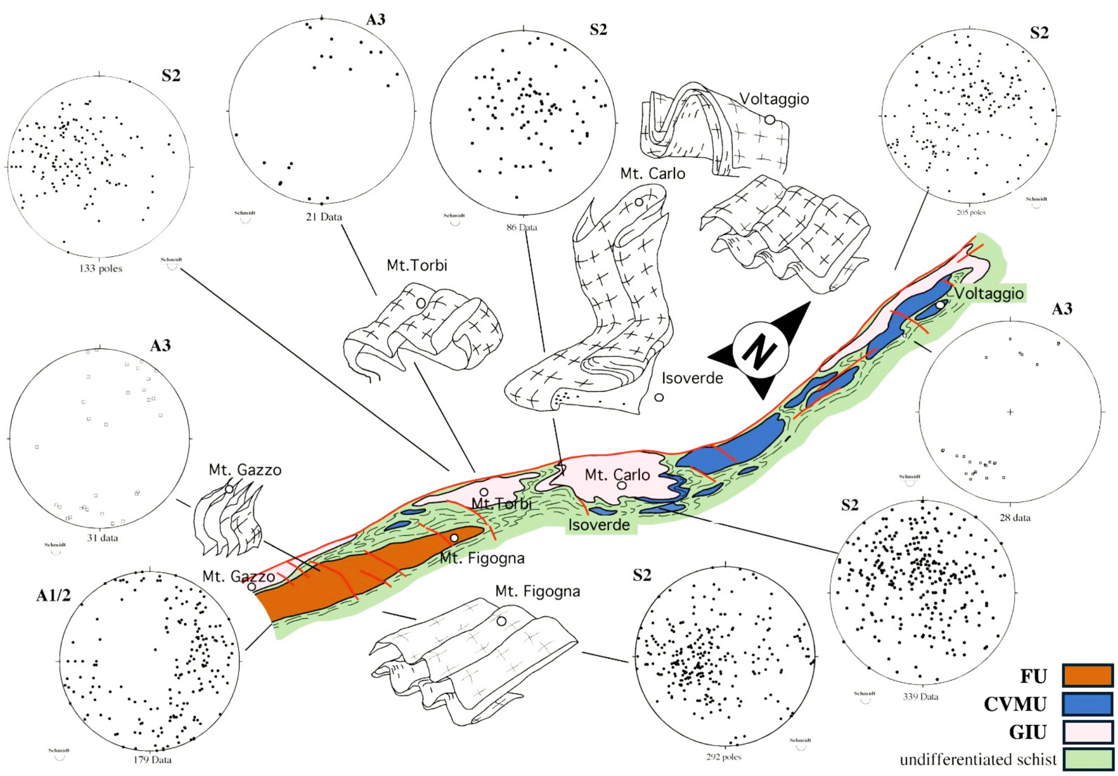


Fig. 32 – Simplified reconstruction of the structures that characterize the main outcrops of the three units in the Sestri-Voltaggio Zone. Stereograms summarize the main structural elements of the Zone. 3D-cartoon are not to scale (after Crispini & Capponi, 2001).

istic dotting, hence the term used by French authors of *Calcaires pointillés* (Fig. 33). The dots are in places aligned and elongated forming a stretching lineation.

At the microscale, deformed 30-40 micron calcite grains are observed, immersed in a microcrystalline matrix, relicts of an original detrital pellet texture or relicts of crinoid segments In some samples, red-orange radiolarian shells were found, which in contrast to the carbonate matrix appear undeformed. They are concentrated along thin phyllosilicate films or at intergranular sites where dissolution is concentrated.

In the sheared siliceous limestones, quartz concentrated in small lenses parallel to the foliation and locally shows a weak oblique grain shape fabric.

Stop 2.4

Locality: Ponte San Giorgio, along the SP160 road, South of Voltaggio
44.591445, 8.858338
Topic: Composition and structures of the Metamorphic Oceanic units: multiphase deformation and metamorphism of the alpine orogenic cycle in blueschist facies metagabbro.

In this Stop (Fig. 14, Fig. 34) we observe the characteristics of metagabbro of the blueschist facies of the Cravasco-Voltaggio-Montenotte Unit. it is possible to observe structures formed during metamorphic conditions of the HT-LP ocean floor, foliations produced during metamorphic conditions of the Alpine Pumpellyite-Blueschist facies and late alpine brittle structures.

The outcrop consists of a metamorphic coarse to fine grained Fe-Ti Oxide-gabbro which preserve cross-cutting relations between primary (igneous) and secondary plastic (pre-alpine and alpine) and brittle deformation structures. The primary foliation is cut by a basaltic dyke (Fig. 35).

The Cravasco-Voltaggio-Montenotte Unit igneous basement is mainly composed by Ol-Gabbro and Fe-Ti Oxide- gabbro with dykes/veins of diorite and plagiogranite, by ophiolitic tectonic breccia and by pillow lava. The Ponte San Giorgio is one of the most extensive body of metagabbro in the SVZ enclosed in foliated serpentinite and metasediments (Fig. 36).

It is composed in general by Fe-Ti oxide gabbro with subordinate dioritic compositions; it shows a compositional and/or grain size layering (varying from centimeter to millimeter) and a texture varying from isotropic to protomylonite and blastomylonite. Polyphasic intrusions of dykelets/veins with quartz-dioritic to plagiogranitic composition are frequent. The dykelets are in places deformed by HT-LP ("ocean floor metamorphism") plastic shear zone (Cortesogno & Haccard, 1984), or may cut the HT-LP foliation.

Doleritic dykes up to plurimetric in thickness, associated with brown hornblende/epidote veins, often contain fragments of the host foliated gabbro. The Alpine HP-LT mineralogical association consists of albite + Na-anfibole +/- Na- and Na-Ca-clinopyroxene +/- chlorite +/- lawsonite +/- epidote +/- pumpellyite +/- titanite and is generally well developed (Cabella *et alii*, 1994; Cortesogno *et alii*, 2002) along shear zones (Fig. 37) or mimetically replacing original igneous minerals (e.g.; fine grained Alpine albite and lawsonite preserve the crystallographic orientation of the primary plagioclase).

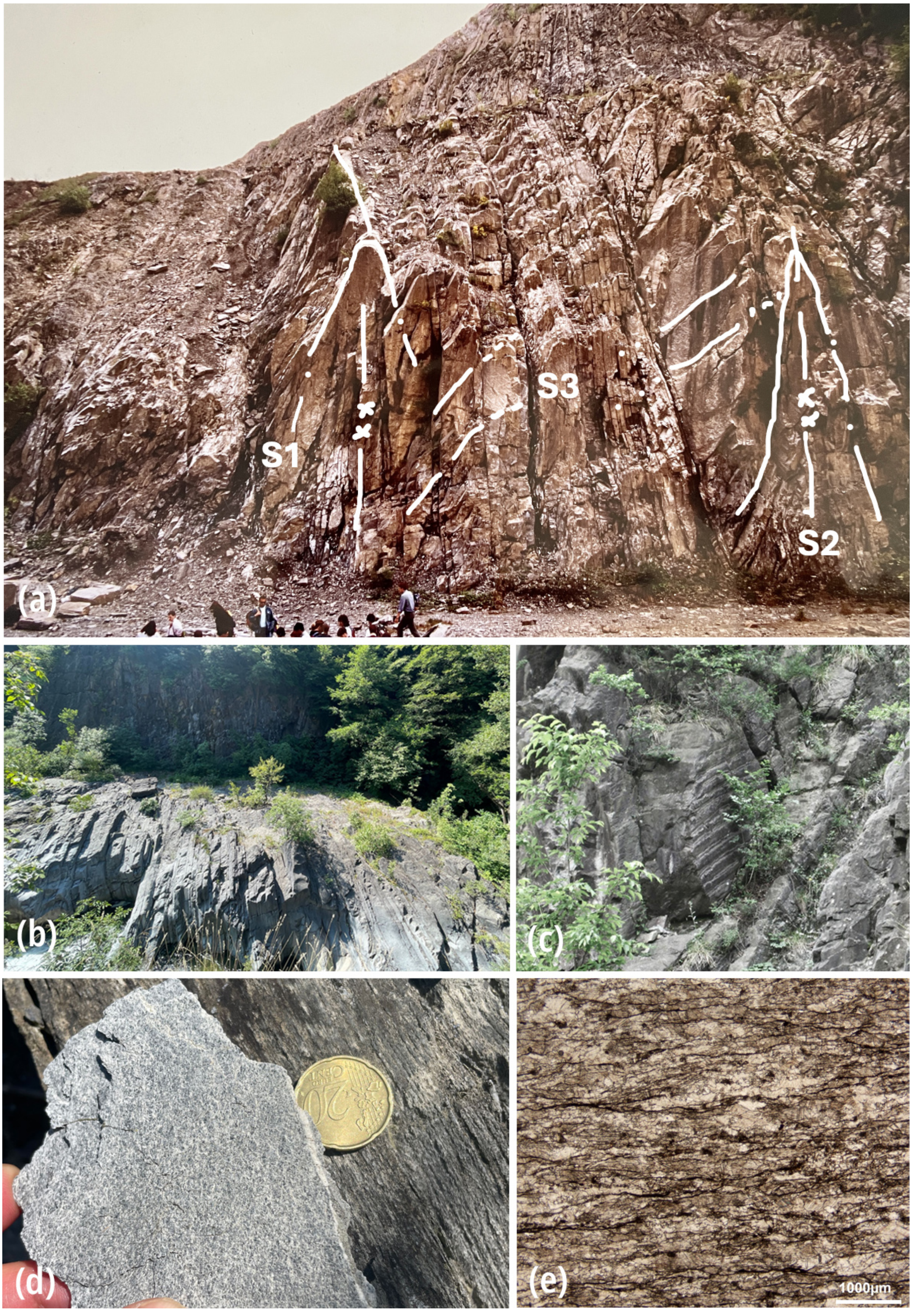


Fig. 33 – (a) Panoramic view of folded and foliated metamorphic crystalline limestone on the front of a disused quarry (Cava Cementir, 1996) view to the south. S1 to S3 refers to the main foliations described in the Cravasco-Voltaggio-Montenotte Unit. (b) Cravasco-Voltaggio-Montenotte Unit Low-T blueschist limestone with steeply dipping regional foliation (composite foliation). (c) Meter scale mullions parallel to fold axis. (d) Detail of the Cravasco-Voltaggio-Montenotte Unit limestone: Foliation surface with dark grey spots hence the name *Calcaire pointillés* of French Alpine literature). (e) Thin section photomicrograph of the calc-schist. Multiple foliation is composed by fine grained white micas, calcite, opaque minerals. The mica outline a composite S1 and S2 foliation.

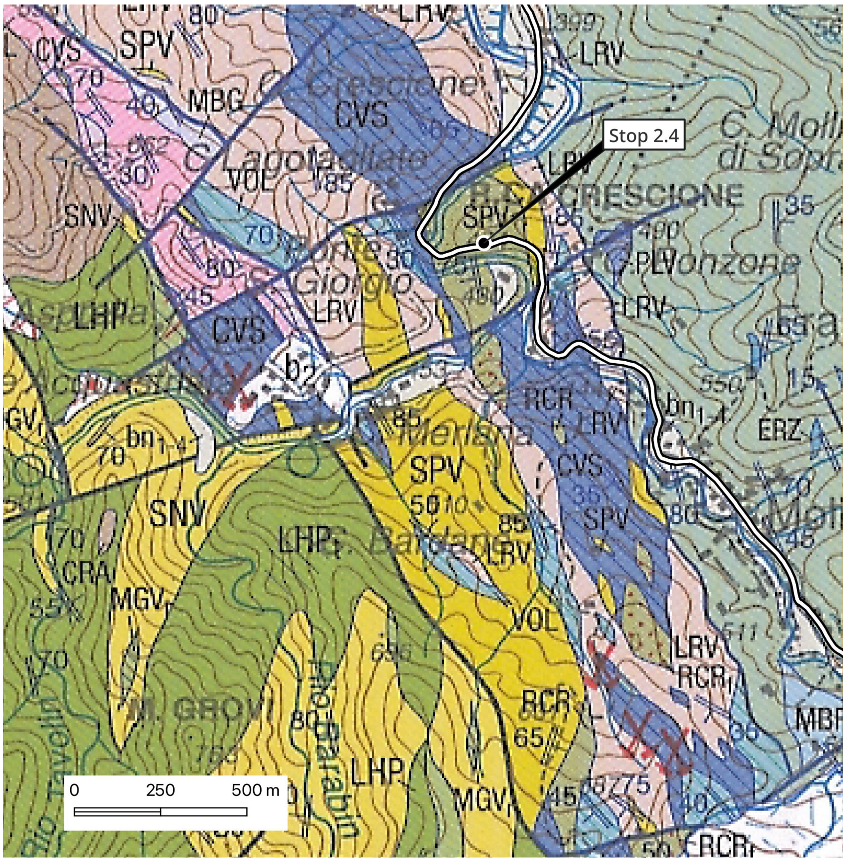


Fig. 34 – Location of Stop 2.4, geological map by Capponi & Crispini (2008).

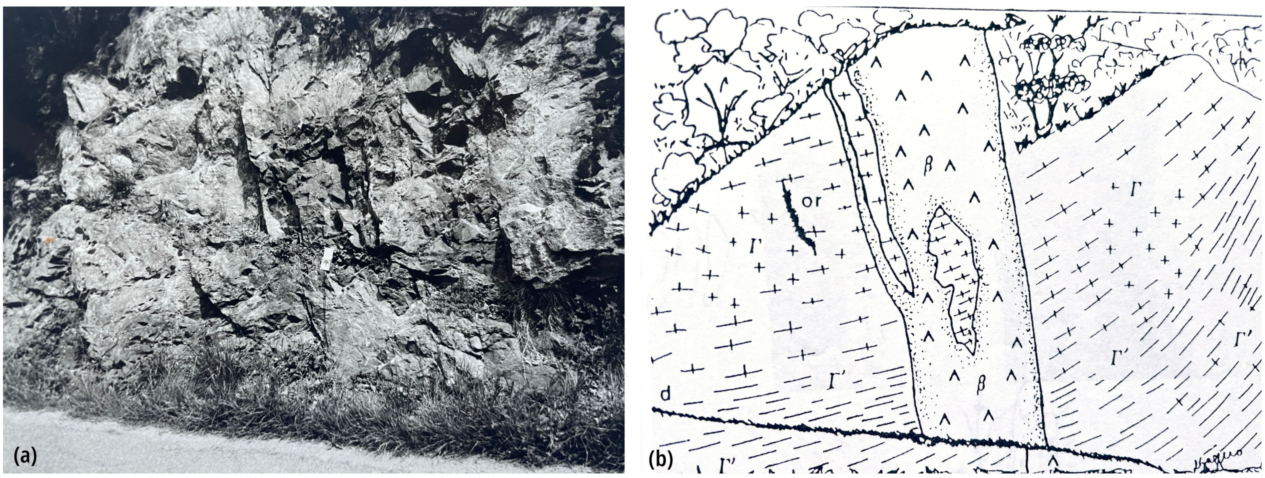


Fig. 35 – (a) Historic photo ('90) of the E-W road cut wall. (b) Sketch of the metagabbro structures (drawing by L. Cortesogno '90).

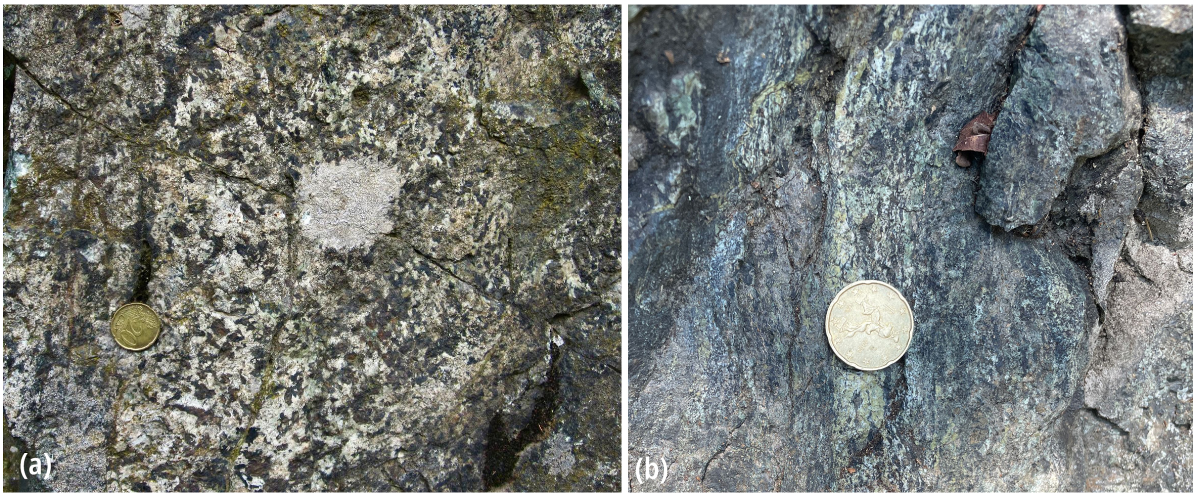


Fig. 36 – Varitextured metagabbro of the Cravasco-Voltaggio-Montenotte Unit with details of different textures and degree of deformation. (a) Magmatic porphyroclastic structure. (b) Ultramylonitic structure.

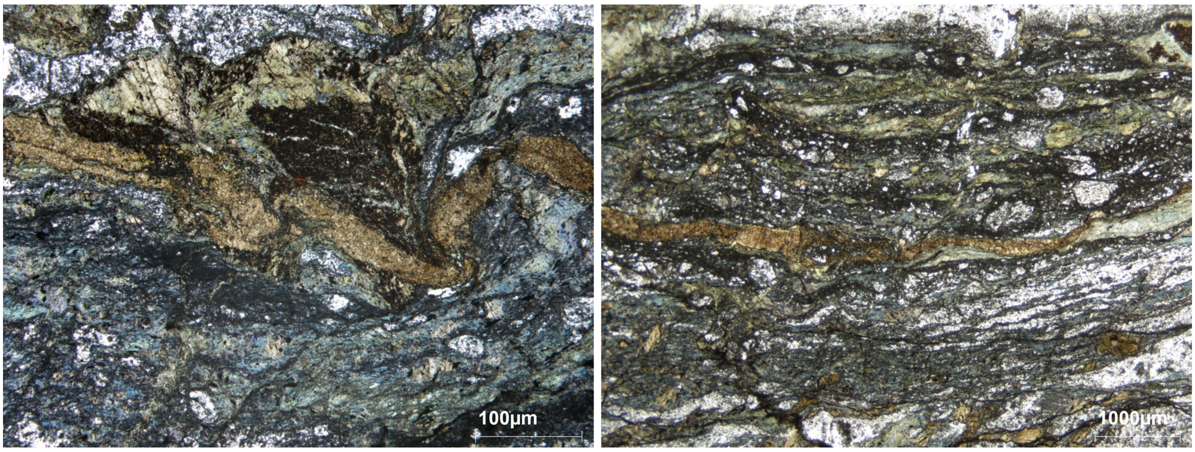


Fig. 37 – Photomicrograph of the mylonitic structure of the Ponte San Giorgio metagabbro (PPL).

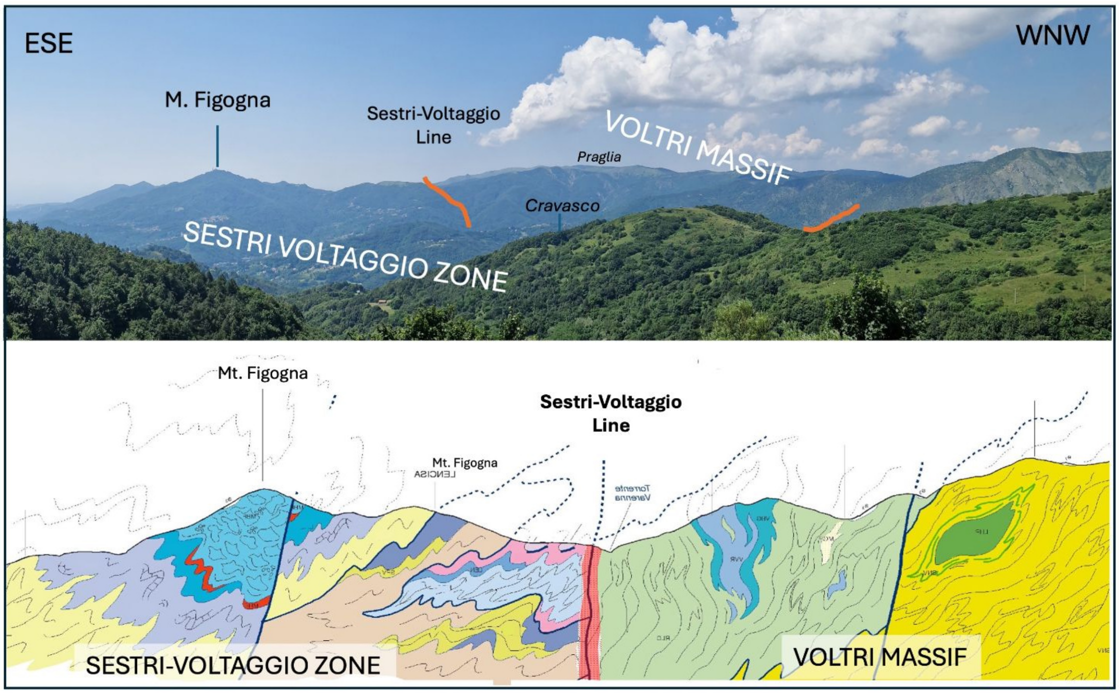


Fig. 38 – Panoramic view across the SVZ looking towards SW.

Stop 2.5

Locality: Bocchetta Pass, panoramic viewpoint.
44.550165, 8.888145
Topic: Panoramic view across the Sestri-Voltaggio Zone (lunch).

The purpose of this Stop (Fig. 14, Fig. 38) is to take a panoramic view of the section through the collisonal knot and have lunch! The stop is characterized by schist of the pumpellyite-actinolite facies Figogna Unit, i.e. the low metamorphic equivalent of the Palombini shale in the oceanic cover sequence. In the area the Figogna Unit shale enclose meter to decameter-scale lenses of pillow lava, associated to metacherts and limestone.

Stop 2.6

Locality: Lencisa-Ceranesi.
44.493179, 8.849983
Topic: SVZ Tectonic unit of the continental margin: metamorphic limestone and dolostone of the Gazzo Isoverde Unit and its contact with Blueschist oceanic unit (serpentinite and pillow basalt).
Limestone: 44.491422, 8.845844 ; Serpentinite 44.492639, 8.850960

The aim of this Stop (Fig. 14, Fig. 39) is to make observations and discussions on the geological features and structural architecture of the Gazzo-Isoverde Unit unit and its contact with boundary units. From the village of Lencisa we descend along the main road toward the south where we find various limited exposition of limestone and dolomitic limestone.

The Lencisa-Mt. Torbi represents one of the 4 areas within the SVZ where the Gazzo-Isoverde Unit sedimentary succession outcrops with the best continuity along the slopes of Mt. Torbi. The Gazzo-Isoverde Unit unit is characterized by a Mesozoic (Trias-Lias) continental shelf sequence (Cortesogno & Haccard, 1984; Lualdi, 1991; Capponi & Crispini, 2008) of neritic dolostone ("dolomie di Monte Gazzo" formation, Upper Carnian?-Norian) overlain by an alternation of thick, partially recrystallized, fossiliferous limestone beds with thin shale layers ("calcari di Gallaneto" formation, Rhaetian-Hettangian) grading upward into massive, partially recrystallized limestone beds with chert nodules ("calcari di Lencisa" formation, Sinemurian-Pliensbachian). This turbiditic sequence is covered by hemipelagic black shales with thin recrystallized calcareous interbeds ("metargilliti di Bessega" Formation, Middle Liassic-Malm?) (Fig. 39).

The structures and deformation phases are the same described for the Cravasco-Voltaggio-Montenotte Unit. The bulk chemical composition and low-T metamorphism preclude the growth of good diagnostic metamorphic minerals in the Gazzo-Isoverde Unit lithologies, so the available evaluation of the PT conditions has been deduced from the structural and cartographic relationships with the neighboring oceanic units or from microstructures in calcite.

The main regional structure of the Lencisa-Mt. Torbi Gazzo-Isoverde Unit has been interpreted as a major synclinal antiform (D2 or D3) with N-S (0° to 30°) trending fold axis with variable dip, and with the axial plane dipping to the E. The structural architecture is complicated by shear and fault zones commonly present at the dolostone-limestone contact. At outcrop scale, the more calcareous lithologies, despite their more or less extensive recrystallisation, preserve the original sedimentary features and remnants of fossiliferous forms.

The marly and dolomitic limestone beds display a spaced pressure solution cleavage (Fig. 40), pelitic interbeds show a penetrative axial-planar slaty cleavage. The more recrystallised limestone (Calcari di Lencisa) shows zones of high strain concentration with extensive shear deformation occurring in the limbs of the main folds. In these zones we can observe transposition of isoclinal/intrafoliar folds along the main regional foliation and mylonitic structures, such as asymmetric foliation boudinage, domino structures, sheath folds (Fig. 41). At the microscale, the micritic limestone is dynamically recrystallized with evidence of grain size reduction and rotation recrystallization, twinned calcite ribbons are enclosed in a matrix of fine grained calcite showing oblique grain shape fabrics. Calcite fibers occur in pressure fringes around opaques minerals and quartz grains.

Going back to Lencisa Moving eastwards along the road cut, strongly foliated serpentinite with a cataclastic to mylonitic structure can be observed for a few metres (Fig. 42), with the main foliation subvertical to strongly dipping towards the east, in contact with metabasalts (pillow lava) alternating with phyllite schists belonging to the Crevasco-Voltaggio-Montenotte unit.

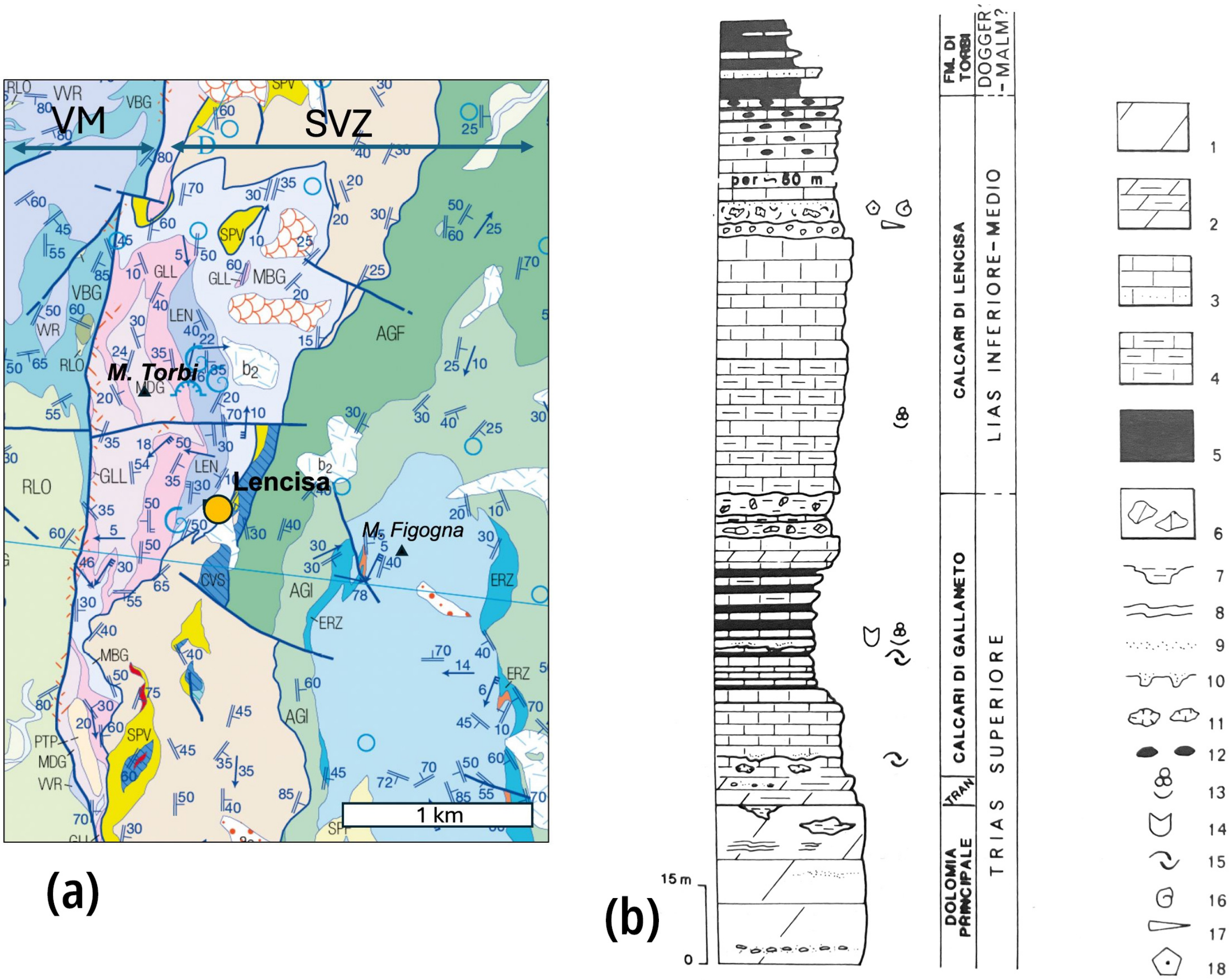


Fig. 39 – (a) Geological map with the location of Stop 2.6 (orange dot) (after Capponi & Crispini, 2008). (b) Stratigraphic column of the Gazzo-Isoverde Unit sequence, after Vanossi (1991).

Fig. 40 – Gazzo-Isoverde Unit limestone along the main road. Fold hinge zone show high angle relationships between two foliations (S2 and S0+S1).

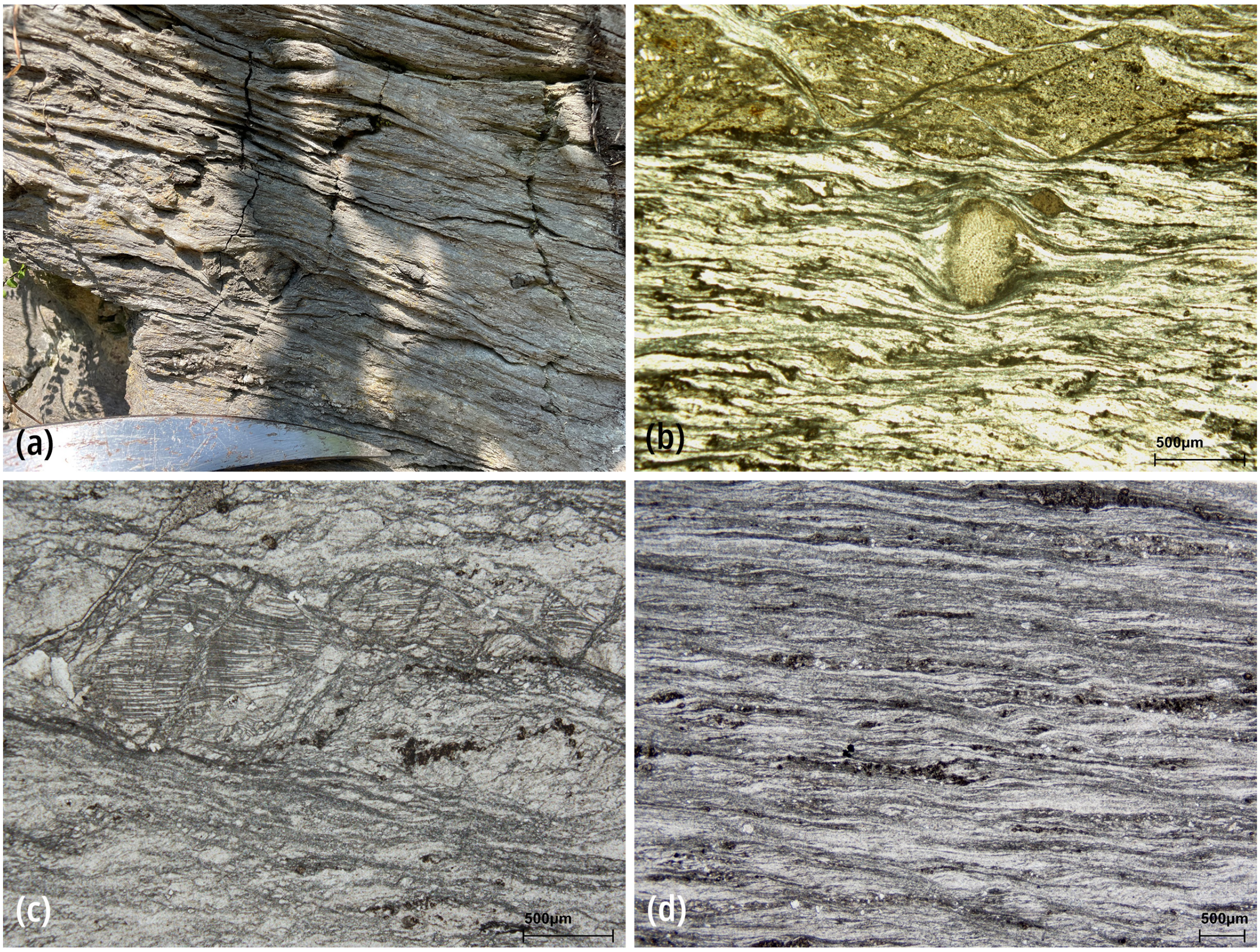


Fig. 41 – High strain zones in limestones of the Gazzo-Isoverde Unit. (a) Mylonitic foliation and foliation boudinage ate the outcrop scale. (b) - (d) Photomicrographs of mylonitic structures in the recrystallised Gazzo-Isoverde Unit micritic limestone in high strain zones.

Fig. 42 – Highly deformed foliated serpentinite with folds and S-C structures.

Day 3 : The Ligurian ophiolites and the inner Northern Apennines

Giancarlo Molli[1], Laura Crispini[2], Laura Federico[2]

Field Trip Route

Varese Ligure - Passo del Bracco - Montaretto - Bonassola - Rocchetta Vara (Fig. 43).

Topics

Introduction to geology of the Bracco area, orogenic structures of the ophiolitic unit, ophiolite stratigraphy, petrology and pre-orogenic deformation, ophicalcite quarries.

In this third day of excursion we will have the opportunity to see some character of the uppermost units of the NA and in particular of the Internal Ligurian units along the coast and in the hinterland of La Spezia. This area represents the part of Apennines with the longest "modern" geological investigation dating back to the early 19th century. We present an introduction to geology of the Bracco area, orogenic structures of the ophiolitic unit, ophiolite stratigraphy, petrology and pre-orogenic deformation, including the visit of a ophicalcite quarry.

The east Liguria represents a key region for the studies of the Ligurian Tethys ophiolites having a special role in the historical and modern geological knowledge. The area was visited by Brongniart (1821) and one century later by Steinmann (1927).

In the early 1960s Bailey & McCallien (1963) analyzed the local geology following the problems related to the original association of pillow lava, serpentinites and cherts at that time recognized as the "Steinmann Trinity", (Bernoulli *et alii*, 2003). Later, Abbate (1969), and above all Decandia & Elter (1969, 1972), addressed the peculiarity of the Ligurian ophiolites. They described a major unconformity between mantle rocks and overlying basalts, tectonosedimentary breccias (ophicalcites and ophigabbros) and sediments. Moreover, Decandia & Elter (1969) firstly suggested the interpretation of mantle and gabbro tectonic fabrics as related to low-angle extensional shearing and mantle exhumation connected with tectonic processes predating the emplacement of basalts, being therefore at the forefront of the concepts that are today proposed to understand continental breakup at magma-poor rifted margins and ultra slows spreading ridges (Boillot & Winterer, 1987; Manatschal & Müntener, 2009; Molli, 2020). The Bracco-Levanto and nearby areas were furthermore the object of key papers on the petrology of mantle (Bezzi & Piccardo, 1971; Piccardo, 1977; Rampone *et alii*, 1998; Piccardo *et alii*, 2014), geochemistry of ophiolitic magmatism (Ferrara *et alii*, 1976; Beccaluva *et alii*, 1980; Serri, 1980), ocean-floor metamorphism (Spooner & Fyfe, 1973; Cortesogno *et alii*, 1975, 1994; Bonatti *et alii*, 1976; Cortesogno & Lucchetti, 1984; Tribuzio *et alii*, 1997) and stratigraphy-sedimentology of ocean-floor deposits and mineralizations and their connection with the tectonic environment (Bonatti *et alii*, 1976; Barrett & Spooner, 1977; Folk & McBride, 1978; Barrett, 1982; Cortesogno *et alii*, 1987; Zaccarini & Garuti, 2008).

The geology of the Bracco-Levanto area, ground of the first three stops of the day, is represented in the map of Fig. 44.

Stop 3.1

Locality: Mattarana quarry.
44.2472144,9.5881516
Topic: introduction to the main lithotypes of the Bracco area.

The main lithotypes in the Bracco area are represented by gabbroic cumulates and serpentinized mantle peridotites (Fig. 45). Primary contacts between the plutonic rocks and the peridotite testify the intrusive character of the gabbro body within mantle rocks.

The cumulates are mainly represented by olivine-bearing gabbros (as observed along the road), but also by olivine-rich cumulates like in this quarry.

In this first outcrop, two lenses of ultramafic cumulates are interlayered with olivine-bearing gabbros. The quarry consists of pl+cpx-bearing dunites to mela-troctolites and troctolites, in which the primary igneous structures are observable. Spinel and clinopyroxene are commonly preserved, whereas olivine and plagioclase are partially or totally replaced by serpentine + Fe-oxide phases + chlorite ± tremolite and prehnite + chlorite ± hydrogrossular, respectively.

[1]University of Pisa, Italy
[2]University of Genova, Italy

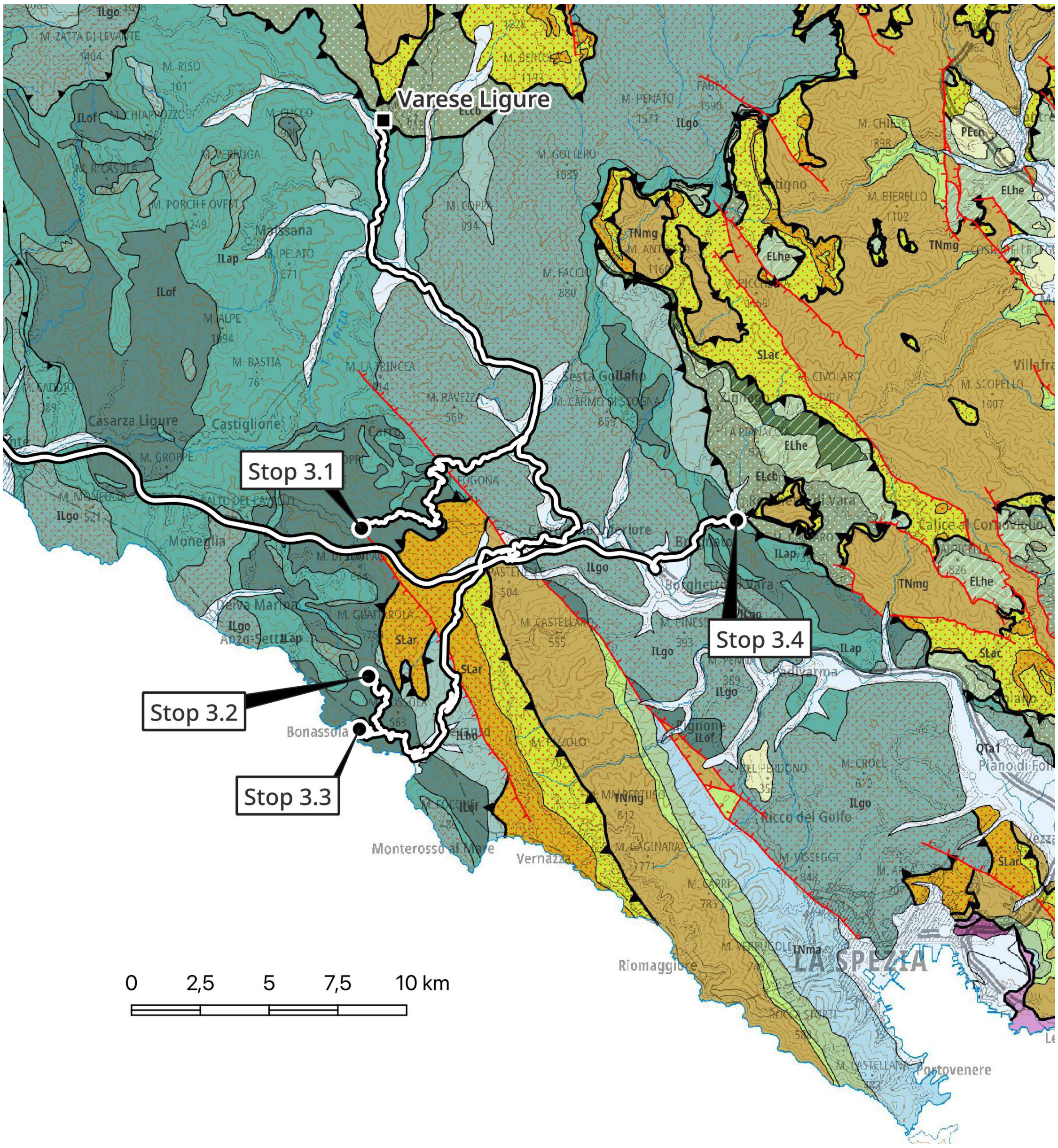


Fig. 43 – Geological map of eastern Liguria, with Itinerary and Day 3 stops.

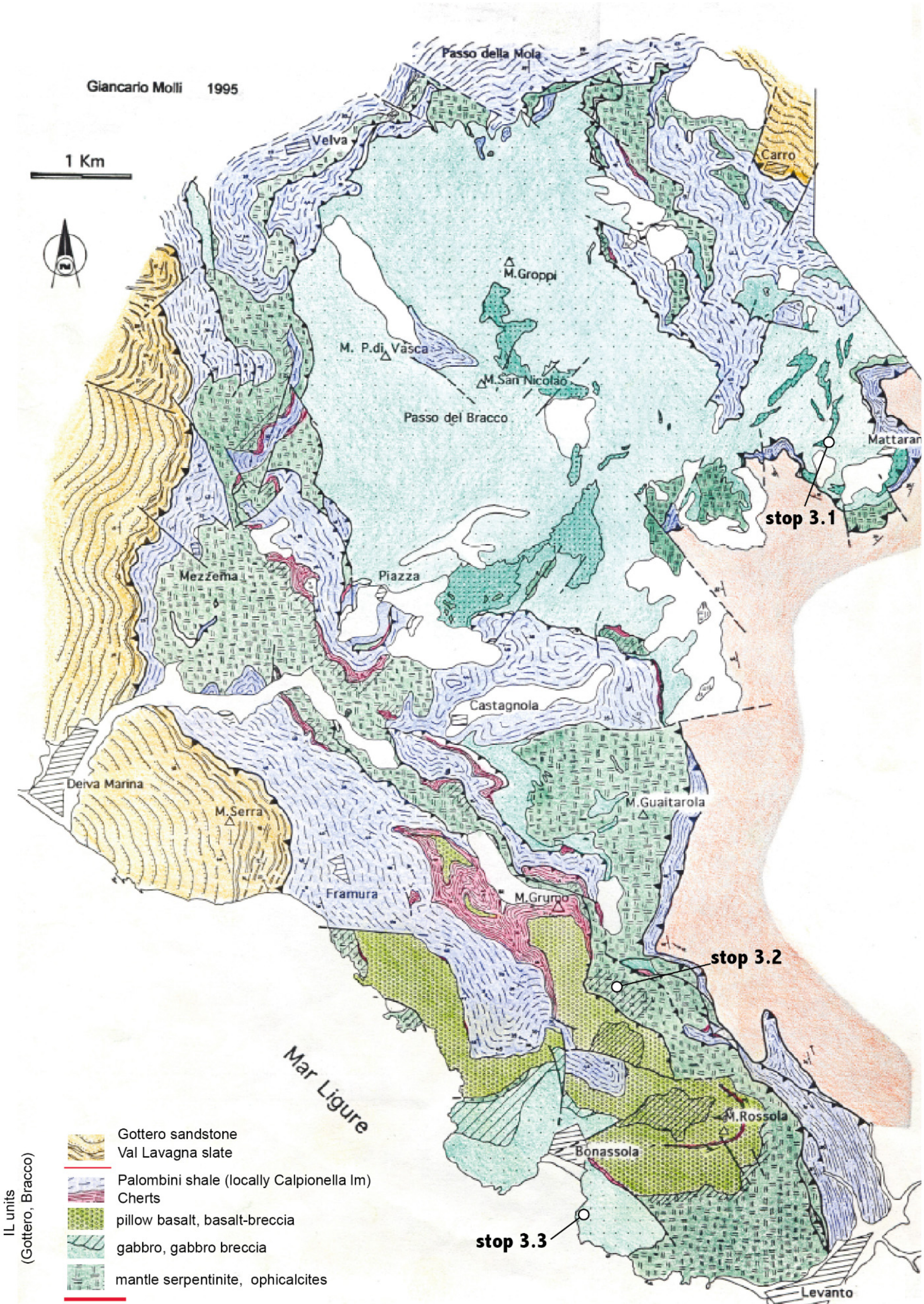


Fig. 44 – Geological map of the Bonassola-Levanto area. Based on 1:5000 scale GM mapping (1990-1994), Decandia & Elter (1972) and Cortesogno *et alii* (1987), with stop locations.

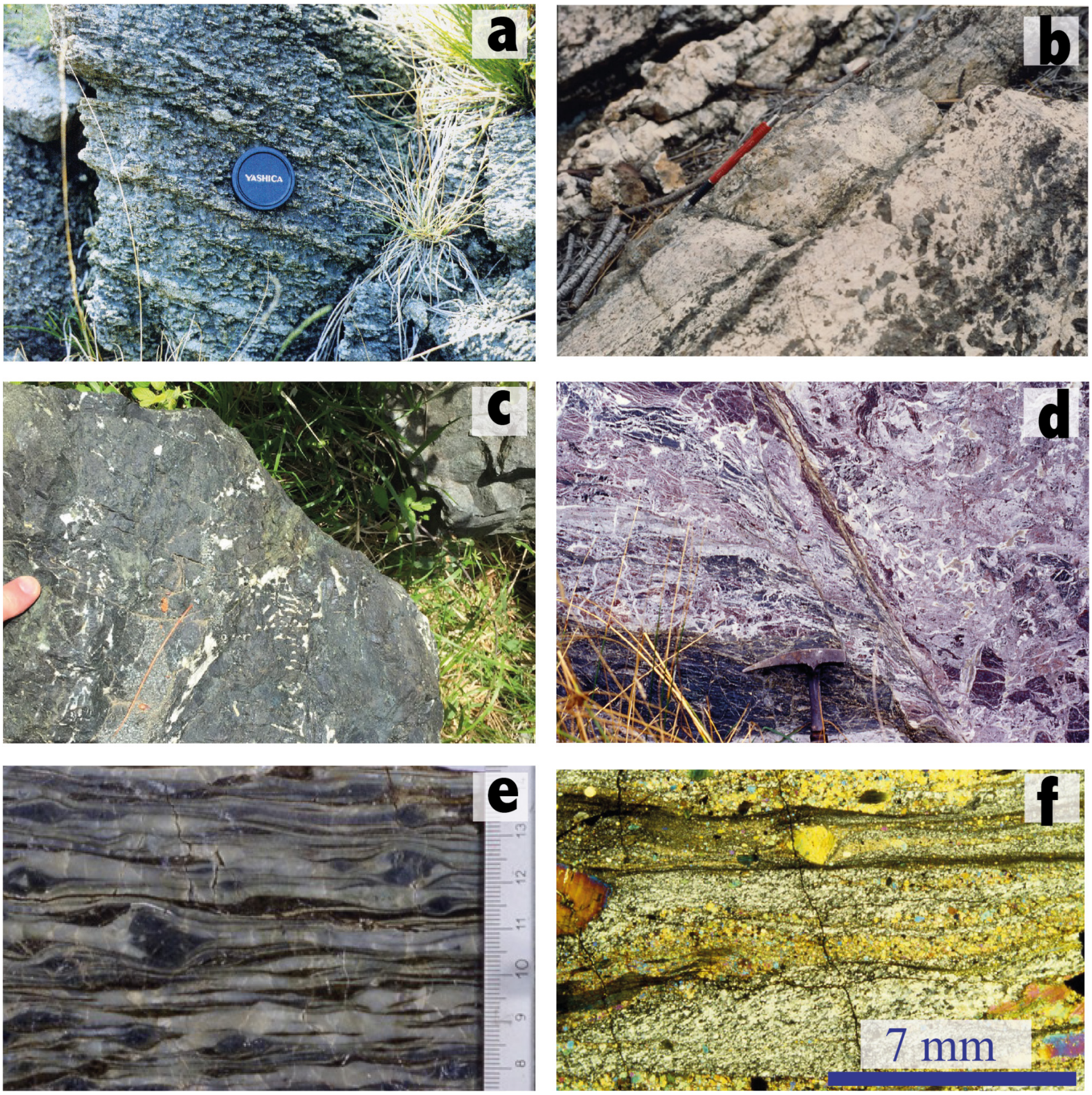


Fig. 45 – a) Serpentinized lherzolite showing tectonite-fabric at an angle with pirossenite-rich layers. Deformation fabric related to mantle shear zones pre-dating the gabbro, 165 Ma old intrusions; b) gabbro showing magmatic layering defined by clinopiroxene, olivine and plagioclase-rich layers; c) ultramaphic cumulate (melatroctolite); d) typical ophicalcite, polyphasic fault rock, related to pre-orogenic "oceanic" detachment fault; e,f) high temperature gabbro-mylonite showing gneissic porphyroclastic structures defined by cpx-rich and plagioclase-rich layers, f) at microscopic-scale, cross-polarized light.

Ultramafic cumulates have olivine (commonly about 85 % by volume) and accessory spinel as cumulus phases, and minor poikilitic plagioclase and clinopyroxene. Mafic minerals are highly magnesian: olivine has 88 forsterite mol% and clinopyroxene has mg# value (Mg/Mg+Fe_{tot}) of 90. These cumulates are the early products of a fractional crystallization process starting from N-MORB-type liquids (Serri, 1980; Serri *et alii*, 1989; Tribuzio *et alii*, 2000, 2016).

Igneous layering made up by grain-size variations of the cumulus olivine can be observed,together with thin chromite grains parallel to the layering and huge clinopyroxene crystals. Igneous layering is also in places shown by variations in olivine modal percentages. In pegmatoid patches, cumulates locally develop harrisitic structures (“Christmas-tree”, Bezzi & Piccardo, 1971. These magmatic structures, defined by skeletal symmetric parallel olivine intergrown, are interpreted as a result of decreasing diffusion rate and increasing growth rate, as it is commonly found in rapidly cooling magmas.

Stop 3.2

Locality: Montaretto.
44.1975385, 9.5885825
Topic: phicalcite quarries and supra-ophiolite sedimentary cover.

Close to village of Montaretto (north of Levanto) we may observe the character of Ligurian sedimentary cover (Cherts and Palombini limestone) locally covering basaltic breccias and pillow lava but also elsewhere gabbros or serpentinites (Fig. 45). Moving back we’ll see in a quarry a typical Ligurian ophicalcite.

The ophicalcites (Fig. 45d) locally known as Levanto breccias (but also by the commercial names of Rosso or Verde Levanto) represent the uppermost part of serpentinites. Ophicalcites consist of two main components occurring in variable amounts: subangular to subrounded serpentinite (or rarely gabbro, or rodingite) clasts and a white or pink carbonate matrix. Near the underlying serpentinites the matrix is scarse and the clast distribution indicates that the fragments are in-situ or were little reworked. Higher levels show a more abundant matrix, sometimes with dispersed clasts; grading, lamination and imbrication of clasts suggest their sedimentary transport (Framura breccia, Abbate *et alii*, 1980). The serpentinite clasts are often red due to oxidation of magnetite to hematite. Most of the pink matrix is a microcristalline calcite (and more rarely dolomite and ankerite) and scattered hematite, filling the fissures and wide fractures among or within the serpentinite blocks (sedimentary or neptunian dykes). Sedimentary features of the carbonate mud can be recognized (e.g. grading, lamination and geopetal structures) but no micro- or macro-fossils have been found so far. The present interpretation of the carbonate matrix suggests that it was a muddish marine sediment, in part remobilized by hydrothermal processes.

From the structural point of view, the most interesting features of the ophicalcite can be observed within some clasts in the uppermost "sedimentary" levels, and even better in the lowermost parts just at the top of the serpentinite body. Two different types of structures can be recognized, both characterized by polyphasic evolution. The early generation of structures is represented by plastic shear zones, whereas the latter consists of polyphasic fracturing. According to Cortesogno et al. (1987), Molli (1995) and Treves and Harper (1996), the general evolution of ophicalcites can be reconstructed as follows (Fig. 46):

- intrusion of gabbroic dykes and bodies in peridotite (previously affected by mantle deformation in shear zone) (at 165-161 Ma Tribuzio et al., 2016);
- early “crustal” shearing (T> 800°C): mylonitic foliation (Ol + Cpx + Ti-Prg + Pl in ultramafics and Pl + Cpx ± Ti-Prg? ± Ol in metagabbros);
- onset of serpentinization and second generation of shearing (T< 550 °C): mylonitic serpentinite-structures (Serp + Ta ± Tr ± Chl ± Mag) in ultramafics and rodingitic mineral assemblages in gabbros;
- fractures systems; the older veins are filled with serpentine, whereas the most diffuse contain calcite with less abundant hematite, talc, chlorite, andradite and tremolite, developed under hydrothermal conditions;
- development of sedimentary breccias, neptunian dykes. Hydrothermal fenomena were still active, together with sedimentary reworking.

The overall evolution of these rocks showing plastic to brittle deformation during progressively lower temperature and pressure conditions suggests their genesis as fault rocks during the uprise of the mantle toward the ocean floor. This interpretation of the ophicalcite was drawn and discussed in the frame of a low angle normal faulting at the beginning of the Seventies (Decandia and Elter, 1969) and it is now recognized at slow- or ultra-slow spreading mid-ocean ridges (in the so called “oceanic core complex”, Whitney *et alii*, 2013 and references therein).

Stop 3.3

Locality: Bonassola.
44.1803756, 9.5843923
Topic: gabbros with high temperature shear zones crosscut by hornblende veins and albitite.

The stop winds along the eastern shoreline of Bonassola village. Map and cross section Fig. 47 shows the main geologic features of the area. The large scale deformation geometries consist of an open north-east facing syncline (cross-sections in Fig. 48) dissected by later high angle normal and oblique-slip faults.

The gabbroic massif of Bonassola displays intrusive contacts with serpentinized mantle rocks, which crop out along the coast toward Levanto. Both gabbros and serpentinites are covered by ophiolitic mono- and polygenic breccias well exposed in the M.Rossola area. The outcrop consists of Mg-gabbros which evidence cross-cutting relations between igneous, plastic and brittle deformation structures. The dominant rock-type consists of coarse grained gabbros composed of euhedral plagioclase (about 55%) and olivine (minor than 20% in volume), and subhedral to poikilitic clinopyroxene. Plagioclase-rich pegmatoid patches are frequently found.

Compositional layering characterized by modal and/or grain size variations is recognizable in some places (Fig. 49a). A pervasive high temperature foliation at low angle with respect to the compositional layering can be observed (Fig. 49b). In particular, the most widespread rock type is a porphyroclastic coarse-grained protomylonite. Dragging of the foliation in higher strain

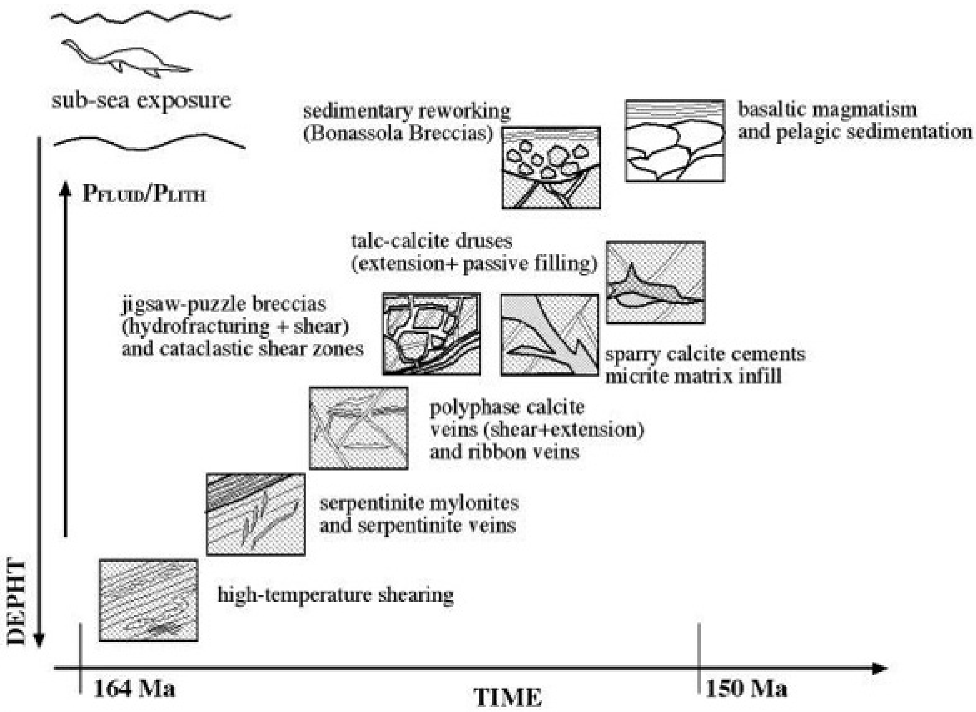


Fig. 46 – The ophicalcite-structure evolution record of exhumation of "oceanic" detachment fault with progressive increase of fluid-rock hydrothermal interaction.

zones, asymmetric porphyroclasts and mylonitic folds can be locally recognized (Fig. 49c).

At microscopic scale the foliation is defined by recrystallized pyroxene and plagioclase grains. Arrays of systematic fractures filled with amphibole (± plagioclase) are widespread throughout the area (Fig. 49d). The sets strike quite uniformly NW-SE and dip steeply to NE and SW. Most veins are nearly planar and range in length from a few millimeters to decimeters, whereas their width generally does not exceed a few millimeters.

The amphibole veins are mainly of mode-2 (hybrid-type cracks) with displacement up to few millimeters. When cross-cut by amphibole veins, the igneous clinopyroxene in the wall-rock is partially replaced by amphibole, due to fluid diffusion away from fracture (up to few centimeters). In particular this transformation is well evident when amphibole veins crosscut the pegmatoid gabbros (Fig. 49e).

Locally albitite dykelets (commonly of centimetric thickness) with irregular contacts (Garzetti *et alii*, 2009) characterized by coarse-grained hornblende rich reaction zones (Fig. 49f). These dykelets represent residual melts that were injected before complete solidification of the host gabbro. The albitites with sharp planar boundaries are inferred to have formed subsequently, when the host gabbro was under a brittle tectonic regime. U-Pb zircon dating by laser ablation ICP-MS provides evidence for two distinct albitite pulses separated by a period of magmatic inactivity of the order of millions of years (Garzetti *et alii*, 2009). The long time interval between solidification of the gabbro and its uplift to sub-seafloor conditions, dated by the first and second generation of albitites, respectively, indicates a slow exhumation rate for the host gabbro.

Late fractures filled with quartz (± Fe-sulphides) can be observed and locally reworks the amphibole veins. Sporadic calcite ± prehnite fractures crosscut both amphibole and quartz veins.

Stop 3.4

Locality: Rocchetta Vara.
44.2478061, 9.7547667
Topic: Ligurian sopra-ophiolitic sedimentary sequence.

In this stop we can observe lithotypes referable to the Bracco unit (Fig. 50), resting below the overlying Gottero unit in the eastern limb of a regional scale synform structures in which the Vara valley is cut.

The locality was visited (Fig. 51) and firstly figured by Brongniart (1821) in his famous paper "S*ur le Gisement ou position relative des Ophiolites, Euphotides, Jaspes, etc. dans quelques parties des Apennins*". In this paper the term Ophiolite was introduced in the geological literature.

The area is the site of a past quarrying activity on cherts. It is possible to observe an overturned sequence formed by serpentinized ultramafics, ophicalcites, ophiolitic breccias called M.Zenone Breccia, cherts, Calpionella limestone and Palombini shales. The M. Zenone breccia is interpreted as a debris flow deposit locally thick one hundred metres. It is made of monogenic gabbroic clasts of variable size, surrounded by sandy or silty gabbroic chloritic matrix. Some of the gabbros clasts show evidence of HT shearing. The sedimentary contact with the overlaying cherts is witnessed by the intercalation of ophiolitic debris, arenitic in size, within the cherts (Fig. 52). At the top of ophiolitic breccias Baumgartner (1984) recognized an early to late Callovian radiolarian assemblage, whereas a late Oxfordian assemblage is recognized by Chiari *et alii* (2000) in the quarry (20 m up to the base of cherts).

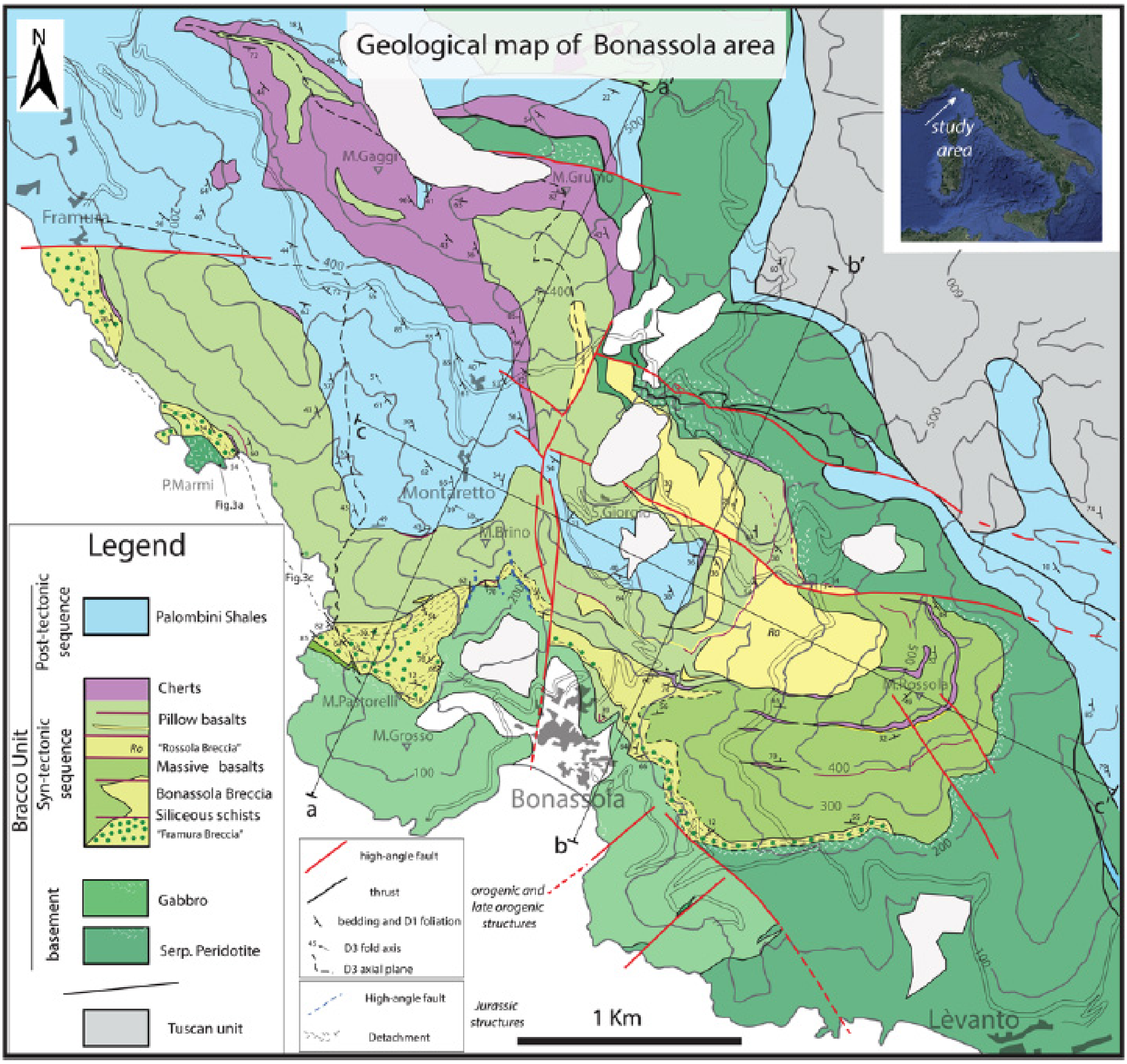


Fig. 47 – Geological map of the Bonassola-Levanto area. Based on 1:5000 scale author's mapping (1990-1994), Decandia & Elter (1972) and Cortesogno *et alii* (1987), in Molli (2020).

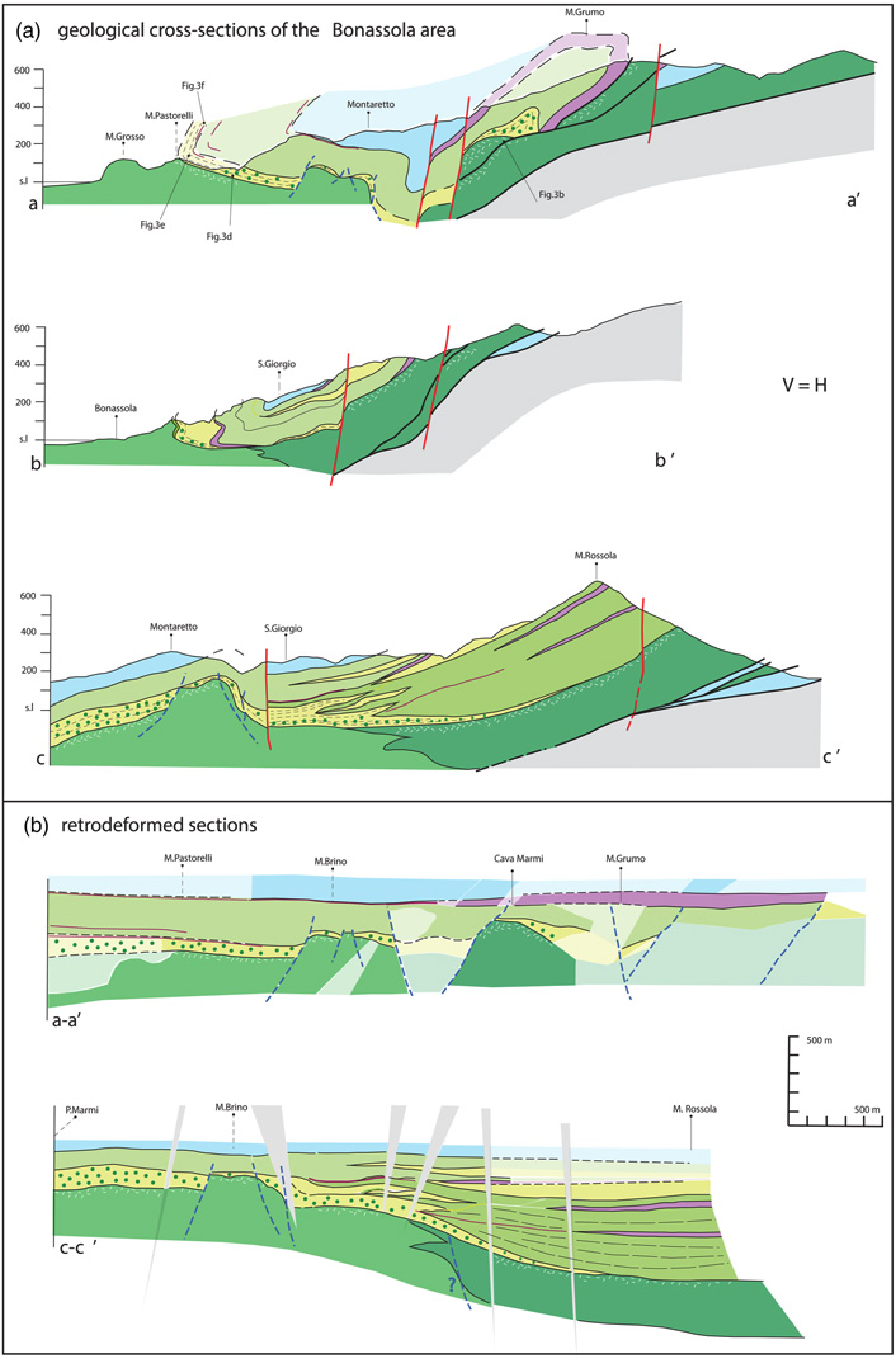


Fig. 48 – (a) Geological cross-sections for trace see Fig. 47; (b) Reconstructed interpretative sections of the former OCT at the time of deposition of Palombini shales (early Cretaceous) based on retrodeformation of the geological structures in the Bonassola-Levanto area. Vertical and horizontal scale based on observed thickness of lithologies and retrodeformation of the orogenic and late orogenic structures.

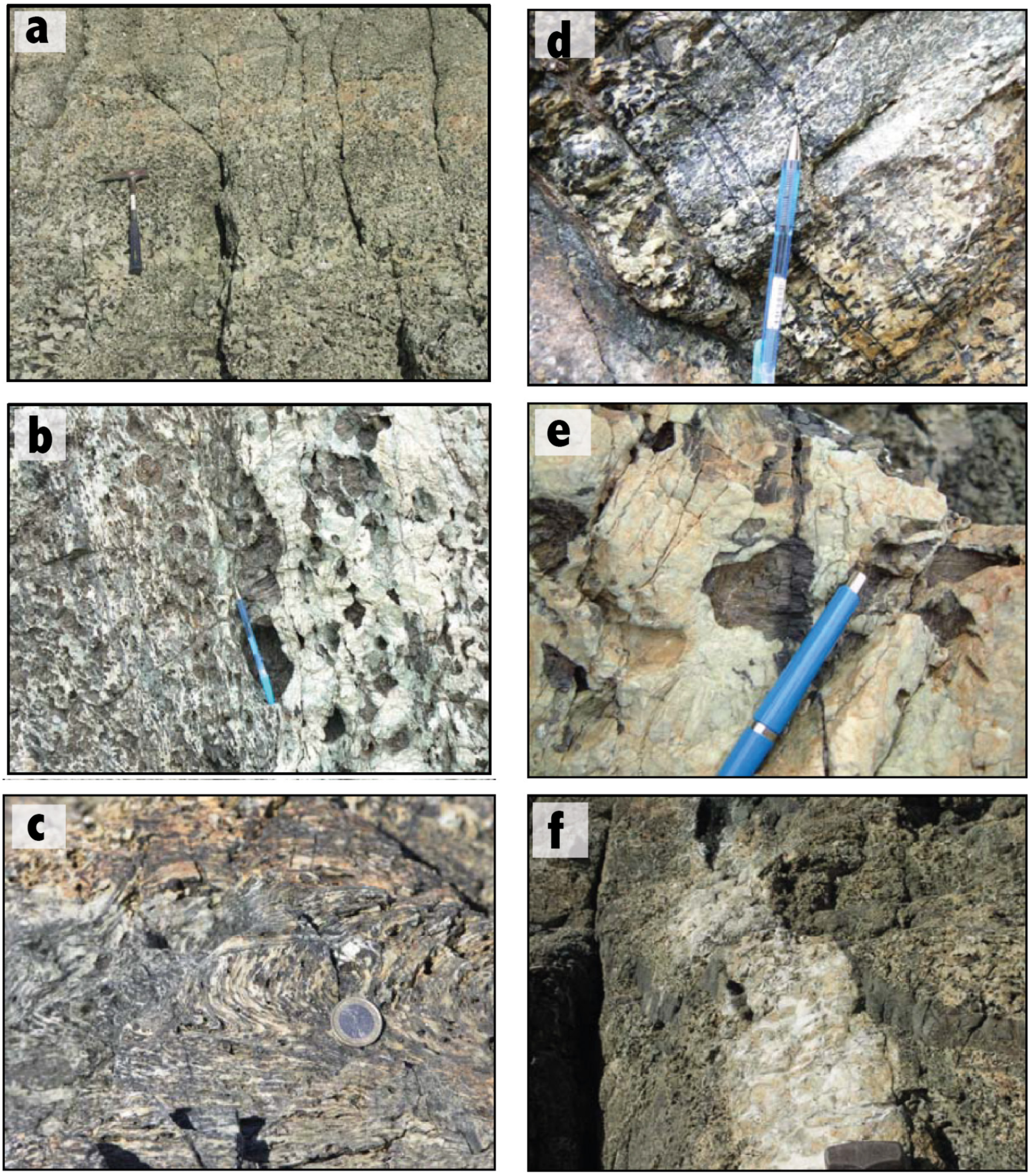


Fig. 49 – (a) Coarse-grained clinopyroxene rich gabbros with a weak modal and grain size layering. (b) HT mylonitic foliation sub-parallel to the igneous layering of the gabbro. (c) Mylonitic fold in a high strain domain of the gabbro body. (d) Parallel fracture-sets filled with hornblende, crosscutting at high angle the HT foliation of the host gabbro. Hornblende is also found as coronas around (sheared) clinopyroxenes in the gabbro; (e) Hornblende vein crosscutting a pegmatoid gabbro. Clinopyroxene of the host gabbro is replaced by hornblende for a few mm due to fluid diffusion away from the fracture. (f) Elongated albitite body showing sharp planar boundaries with the host gabbro. The albitite crosscuts the microgabbro body in the host gabbro at a high angle.

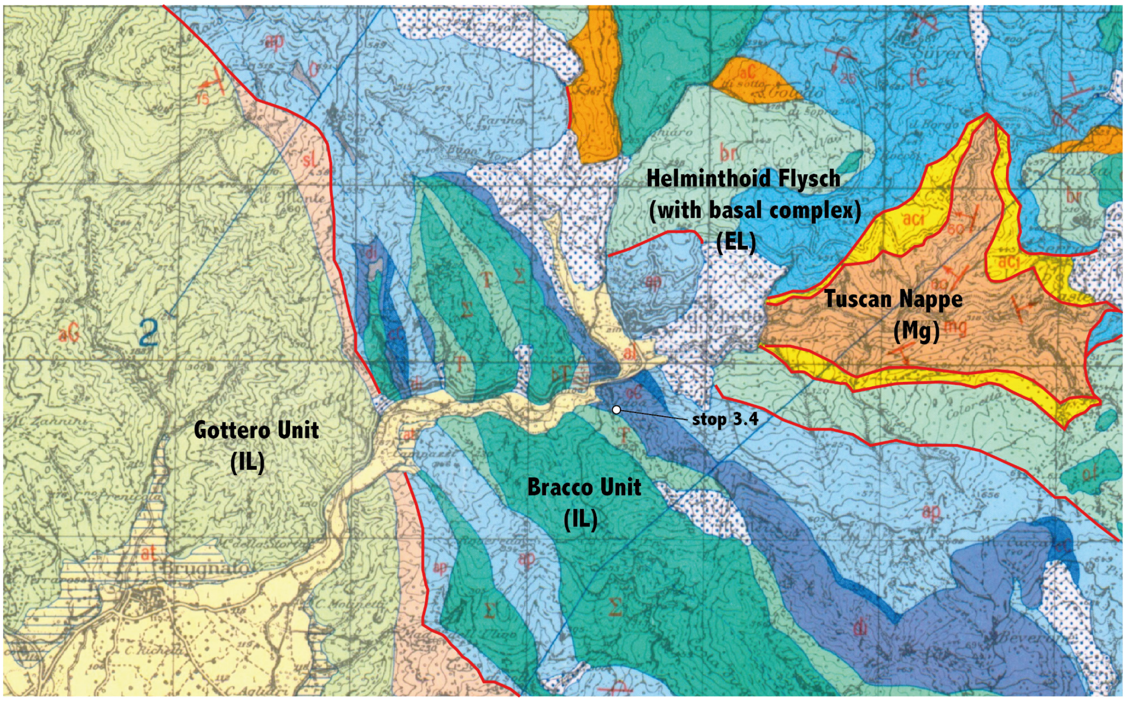


Fig. 50 – Geological map of the Brugnato-Rocchetta Vara area. After Monteforti & Raggi (1975).

Fig. 51 – Profile and present view of the right side of the Gravignola creek published in Brongniart (1821). On the left (SW) the highest ridge is made up of serpentinite, the saddle on gabbro and gabbro breccia whereas the clift on the right (NE-side) is within a 170 m thick radiolarian cherts.

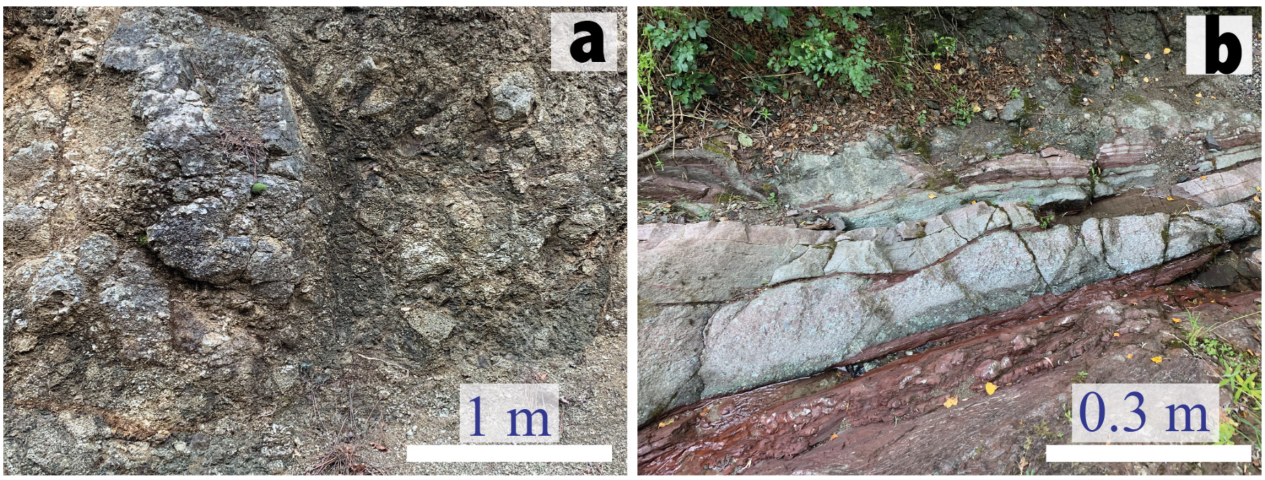


Fig. 52 – (a) Gabbro-breccia made up of poor-sorted gabbro debris including clasts of undeformed coarse grained gabbro (*eufotidi Auctt.*) and high temperature gabbro-mylonite in an fine grained gabbro-derived matrix (M. Zenone breccia). (b) Stratigraphic contact between ophiolites here represented by ophiolitic sandstone, mainly gabbro-derived) and radiolarian cherts in an overturned sequence.

References

Abbate E. (1969) - *Geologia delle Cinque Terre e dell'entroterra di Levanto (Liguria orientale).* Memorie della Società Geologica Italiana, **8**, 923–1014.

Abbate E., Bortolotti V. & Principi G. (1980) - *Apennine ophiolites: a peculiar oceanic crust.* Ofioliti, **5** (1), 59–96.

Abbate E. & Sagri M. (1984) - *Le unità torbiditiche continentali della Tetide.* Memorie dalla Società Geologica Italiana, **24**, 359–375.

Advokaat E.L., van Hinsbergen D.J., Maffione M., Langereis C.G., Vissers R.L., Cherchi A., Schroeder R., Madani H. & Columbu S. (2014) - *Eocene rotation of Sardinia, and the paleogeography of the western Mediterranean region.* Earth and Planetary Science Letters, **401**, 183–195.

Allasinaz A., Gelati R., Gnaccolini M., Martinis B., Orombelli G., Pasquarè G. & Rossi P.M. (1971) - *Carta Geologica d'Italia, Foglio 82 - Genova.* Scala 1:100.000, Servizio Geologico d'Italia, Roma.

Amorosi A., CENTINEO M.C. & d'Atri A.a. (1997) - *Lower Miocene glauconybearing deposits in the SE Tertiary Piedmont Basin (northern Italy).* Rivista Italiana di Paleontologia e Stratigrafia, **103**, 101–110.

Argand E. (1924) - *La Tectonique de L'Asie.* Compte-Rendu du XIII Congrès Géologique International Bruxelles 1922, Imprimerie Vaillant-Carmanne, Liége, 372 pp.

Argnani A. (2012) - *Plate motion and the evolution of Alpine Corsica and Northern Apennines.* Tectonophysics, **579**, 207–219.

Bailey E.B. & McCallien W.J. (1963) - *Liguria nappe; northern Apennines.* Transactions - Royal Society of Edinburgh, **65** (13), 315–333.

Barrett T.J. (1982) - *Review of stratigraphic aspects of the ophiolitic rocks and pelagic sediments of the Vara complex, North Apennines, Italy.* Ofioliti, **7**, 3–45.

Barrett T.J. & Spooner E.T.C. (1977) - *Ophiolitic breccias associated with allochthonous oceanic crustal rocks in the East Ligurian Apennines, Italy—a comparison with observations from rifted oceanic ridges.* Earth and Planetary Science Letters, **35** (1), 79–91.

Baumgartner P.O. (1984) - *A Middle Jurassic-Early Cretaceous low-latitude radiolarian zonation based on Unitary Assosiations and age of Tethyan radiolarites.* Eclogae Geologicae Helvetiae, **77**, 729–837.

Beccaluva L., Piccardo G.B. & Serri G. (1980) - *Petrology of the Northern Apennines ophiolites and comparison with other Tethyan ophiolites.* In: A. Panayiotou (Ed.), *Proceedings of the International Ophiolite Symposium, Cyprus*, pp. 314–330. Geological Survey Department, Nicosia.

Bellinzona G. & Boni A. (1971) - *Stratigrafia e tettonica della zona tra il T. Scrivia e il T. Sisola.* Atti dell'Istituto di Geologia dell'Università di Pavia, **21**, 121–137.

Bernoulli D., Manatschal G., Desmurs L. & Müntener O. (2003) - *Where did Gustav Steinmann see the trinity? Back to the roots of an Alpine ophiolite concept.* Geological Society of America Special Paper, **373**, 93–110.

Bertotti G., Mosca P., Juez J., Polino R. & Dunai T. (2006) - *Oligocene to Present kilometres scale subsidence and exhumation of the Ligurian Alps and the Tertiary Piedmont Basin (NW Italy) revealed by apatite (U–Th)/He thermochronology: Correlation with regional tectonics.* Terra Nova, **18** (1), 18–25.

Beucher R., van der Beek P., Braun J. & Batt G.E. (2012) - *Exhumation and relief development in the Pelvoux and Dora-Maira massifs (Western Alps) assessed by spectral analysis and inversion of thermochronological age transects.* Journal of Geophysical Research: Earth Surface, **117**, F03030. doi:10.1029/2011jf002240.

Bezzi A. & Piccardo G.B. (1971) - *Structural features of the Ligurian ophiolites: petrologic evidence for the 'oceanic' floor of the Northern Apennines geosyncline.* Memorie dalla Società Geologica Italiana, **10**, 53–63.

Biella G., Polino R., de Franco R., Rossi P.M., Clari P., Corsi A. & Gelati R. (1997) - *The crustal structure of the western Po Plain: reconstruction from integrated geological and seismic data.* Terra Nova, **9**, 28–31.

Biella G.C., Gelati R., Lozej A., Rossi P.M. & Tabacco I. (1988) - *Sezioni geologiche nella zona limite Alpi occidentali-Appennino settentrionale ottenute da dati geofisici.* Rendiconti della Società Geologica italiana, **11** (2), 287–292.

Bigi G., Cosentino D., Parotto M., Sartori R. & Scandone P. (1990) - *Structural Model of Italy, Sheet n. 1.*

Bigot-Cormier F., Sosson M., Poupeau G., Stéphan J.F. & Labrin E. (2006) - *The denudation history of the Argentera Alpine External Crystalline Massif (Western Alps, France-Italy): an overview from the analysis of fission tracks in apatites and zircons.* Geodinamica Acta, **19** (6), 455–473.

Boillot G. & Winterer E.L.e. (1987) - *Proceedings of the Ocean Drilling Program, Initial Reports, 103.* Ocean Drilling Program,, College Station, TX,. doi: 10.2973/odp.proc.ir.103.1987.

Bonatti E., Zerbi M., Kay R. & Rydell H. (1976) - *Metalliferous deposits from the Apennine ophiolites: Mesozoic equivalents of modern deposits from oceanic spreading centers.* Geological Society of America Bulletin, **87** (1), 83–94.

Boni A. (1961) - *Per la geologia dell'Appennino settentrionale a W della linea La Spezia-Piacenza.* Atti dell'Istituto di Geologia dell'Università di Pavia, **12**, 63–196.

Boni A. (1962) - *Ligues et problemes tectoniques du secteur nord-ouest de l'Apennin Septentrional.* Bulletin de la Société Géologique de France, **4** (5), 644–656.

Boni A. (1969) - *Carta Geologica d'Italia alla scala 1:100.000 "Foglio 71 - Voghera".* Servizio Geologico d'Italia, Roma.

Bonsignore G. Bortolami G.C., Elter G., Montrasio A., Petrucci F., Ragni U., Sacchi R., Sturani C. & Zanella E. (1969) - *Note Illustrative della Carta Geologica d'Italia alla scala 1:100.000 "Foglio 56 - Torino".* Servizio Geologico d'Italia, Roma, 96 pp.

Bormioli D. & Lanza R. (1995) - *Rotazioni antiorarie nelle rocce terziarie delle Alpi Occidentali e dell'Appennino Settentrionale.* In: R. Polino & R. Sacchi (Eds.), *Atti del Convegno "Rapporti Alpi-Apennino", Peveragno (CN) 31 Maggio - 1 Giugno 1994*, vol. 14, pp. 277–289. Accademia Nazionale delle Scienze detta dei XL, Scritti e Documenti, Roma.

Brongniart A. (1821) - *Sur le gisement ou position relative des ophiolites, euphotides, jaspes, etc. dans quelques parties des Apennins.* Annales des Mines ou recueuil de Mémoires sur l'Exploitation des Mines, **6**, 177–238.

Brunsmann Q., Rosenberg C.L. & Bellahsen N. (2024) - *The Western Alpine arc: a review and new kinematic model.* Comptes Rendus. Géoscience, **356** (S2), 231–263.

Cabella R., Cortesogno L., Gaggero L. & Lucchetti G. (1994) - *Clinopyroxenes through the blueschists facies metamorphisms of the Ligurian Alps:*

compositional variability and miscibility gaps. Atti Ticinensi di Scienze della Terra, Ser. Spec., **1**, 55–63.

Capponi G. (1991) - *Megastructure of the south-eastern part of the Voltri Group (Ligurian Alps); a tentative interpretation.* Bollettino della Società Geologica Italiana, **110** (2), 391–403.

Capponi G. & Crispini L. (2002) - *Structural and metamorphic signature of alpine tectonics in the Voltri Massif (Ligurian Alps, North-Western Italy).* Eclogae Geologicae Helvetiae, **95** (1), 31–42.

Capponi G. & Crispini L. (2008) - *Carta Geologica d'Italia alla scala 1:50.000 "Foglio 213-230 Genova".* Servizio Geologico d'Italia, Roma.

Capponi G., Crispini L., Federico L. & Malatesta C. (2016) - *Geology of the Eastern Ligurian Alps: a review of the tectonic units.* Italian Journal of Geosciences, **135** (1), 157–169. doi:10.3301/IJG.2015.06.

Capponi G., Crispini L., Federico L., Piazza M. & Fabbri B. (2009a) - *Late Alpine tectonics in the Ligurian Alps; constraints from the Tertiary Piedmont Basin conglomerates.* Geological Journal, **44** (2), 211–224.

Capponi G., Crispini L., Piazza M. & Amandola L. (2001) - *Field constraints to the mid-Tertiary kinematics of the Ligurian Alps.* Ofioliti, **26** (2B), 409–416.

Capponi G., Crispini L. & Scambelluri M. (2009b) - *Comment on "Subduction polarity reversal at the junction between the Western Alps and the Northern Apennines, Italy", by G. Vignaroli, C. Faccenna, L. Jolivet, C. Piromallo, F. Rossetti.* Tectonophysics, **465** (1-4), 221–226.

Carmignani L., Conti P., Cornamusini G. & Meccheri M. (2004) - *The internal Northern Apennines, the Northern Tyrrhenian Sea and the Sardinia-Corsica Block.* In: U. Crescenti, S. D'Offizi, S. Merlino & L. Sacchi (Eds.), *Geology of Italy. Special Volume of the Italian Geological Society for the IGC Florence 2004*, pp. 59–77. Società Geologica Italiana, Roma.

Carminati E. & Doglioni C. (2005) - *Mediterranean tectonics.* In: *Encyclopedia of Geology*, vol. 2, pp. 135–146. Elsevier, Amsterdam.

Carminati E., Lustrino M. & Doglioni C. (2012) - *Geodynamic evolution of the central and western Mediterranean: Tectonics vs. igneous petrology constraints.* Tectonophysics, **579**, 173–192. doi:10.1016/j.tecto.2012.01.026.

Carrapa B. (2002) - *Tectonic evolution of an active orogen as reflected by its sedimentary record - An integrated study of the Tertiary Piedmont Basin (internal Western Alps, NW Italy).* Tesi di Dottorato, Vrjie Universiteit, Amsterdam.

Carrapa B., Bertotti G. & Krijgsman W. (2003) - *Subsidence, stress regime and rotation(s) of a sedimentary basin within the Western Alps: the Tertiary Piedmont Basin (Alpinedomain, Northwest Italy).* In: T. McCann & A. Saintot (Eds.), *Tracing Tectonic Deformation Using the Sedimentary Record*, Geological Society London Special Publications, vol. 208, pp. 205–227. Geological Society London.

Carrapa B., Di Giulio A., Mancin N., Stockli D., Fantoni R., Hughes A. & Gupta S. (2016) - *Tectonic significance of Cenozoic exhumation and foreland basin evolution in the Western Alps.* Tectonics, **35** (8), 1892–1912.

Casnedi R. & Mosna S. (1970) - *Segnalazione di una serie miocenica inferiore nel Monregalese (Bacino Terziario Piemontese).* Atti della Accademia Nazionale dei Lincei. Classe di Scienze Fisiche, Matematiche e Naturali. Rendiconti, **48** (6), 636–645.

Cassano E., Anelli L., Fichera R. & Cappelli V. (1986) - *Pianura Padana: Interpretazione Integrata di Dati Geofisici e Geologici.* Agip SpA, Servizi Centrali per l'Esplorazione, Metodologie e Applicazioni Geofisiche, Milano, 27 pp.

Castellarin A. (2001) - *Alps-Apennines and Po Plain-frontal Apennines relations.* In: G.B. Vai & I.P. Martini (Eds.), *Anatomy of an Orogen, The Apennines and Adjacent Mediterranean Basins*, pp. 177–196. Kluwer Academic Publishers, Dordrecht.

Cerrina Feroni A., Martelli L., Martinelli P., Ottria G. & Catanzariti R. (2002) - *Note Illustrative della Carta Geologico-Strutturale dell'Appennino Emiliano-Romagnolo a scala 1:250.000.* Regione Emilia-Romagna, C.N.R., Bologna., 118 pp.

Chamot-Rooke N., Gaulier J.M. & Jestin F. (1999) - *Constaints on Moho depth and crustal thickness in the Liguro-Provençal basin from a 3D gravity inversion: geodynamic implications.* In: B. Durand, L. Jolivet, F. Horvath & M. Séranne (Eds.), *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen*, Special Publications, vol. 156, pp. 37–61. Geological Society of London, London.

Champagnac J.D., Sue C., Delacou B. & Burkhard M. (2004) - *Brittle deformation in the inner NW Alps: From early orogen-parallel extrusion to late orogen-perpendicular collapse.* Terra Nova, **16** (4), 232–242.

Cherchi A., Mancin N., Montadert L., Murru M., Putzu M.T., Schiavinotto F. & Verrubbi V. (2008) - *The stratigraphic response to the Oligo-Miocene extension in the western Mediterranean from observations on the Sardinia graben system (Italy).* Bulletin de la Societe Geologique de France, **179** (3), 267–287.

Chiari M., Marcucci M. & Principi G. (2000) - *The age of the radiolarian cherts associated with the ophiolites in the Apennines (Italy) and Corsica (France): a revision.* Ofioliti, **25** (2), 141–146.

Chiesa S., Cortesogno L., Forcella F., Galli M., Messiga B., Pasquarè G., Pedemonte G.M., Piccardo G.B. & Rossi P. (1975) - *Assetto strutturale ed interpretazione geodinamica del Gruppo di Voltri.* Bollettino della Società Geologica Italiana, **94** (3), 555–581.

Clari P., Dela Pierre F., Novaretti A. & Timpanelli M. (1995) - *Late Oligocene-Miocene sedimentary evolution of the critical Alps/Apennines junction: the Monferrato area. Northwestern Italy.* Terra Nova, **7** (2), 144–152.

Clari P., Proto Decima F., Ricci B. & Sampò M. (1987) - *Facies di piattaforma nell'Oligocene medio del Monferrato.* Bollettino della Società Paleontologica Italiana, **26** (1-2), 109–118.

Comerci V., Morelli M., D'Ambrogi C., Di Manna P., Mallen L. & Nicolò G. (2021) - *Final case study report on subsidence assessment techniques, Po Basin area, Italy, Deliverable 3.3, Hike- GeoERA Report, Horizon 2020 Program.* Technical report, Hike-GeoERA Report, Horizon 2020 Program. 66 pp.

Corsi B., Elter F.M. & Giammarino S. (2001) - *Structural fabric of the Antola Unit (Riviera di Levante, Italy) and implications for its Alpine versus Apennine origin.* Ofioliti, **26** (1), 1–8.

Cortesogno L., Dellagiovanna G., Gaggero L. & Vanossi M. (1993) - *Elements of the Palaeozoic history of the Ligurian Alps.* In: J.F. von Raumer & F. Neubauer (Eds.), *Pre-Mesozoic Geology in the Alps*, pp. 257–277. Springer-Verlag, Berlin.

Cortesogno L., Gaggero L., Lucchetti G. & Cabella R. (2002) - *Compositions and miscibility gap in Na-Ca clinopyroxenes through high-pressure metamorphism.* Periodico di Mineralogia, **71** (1), 1–25.

Cortesogno L., Gaggero L. & Molli G. (1994) - *Ocean floor metamorphism in the Piedmont-Ligurian Jurassic basin: a review.* Memorie dalla Società Geologica Italiana, **48** (1), 151–163.

Cortesogno L., Galbiati B. & Principi G. (1987) - *Note alla "Carta geologica delle ofioliti del Bracco" e ricostruzione della paleogeografia Giurassico-Cretacica.* Ofioliti, **12**, 261–342.

Cortesogno L., Gianelli G. & Piccardo G.B. (1975) - *Pre-orogenic tectonometamorphic evolution of the ophiolite mafic rocks (Northern Apennine and Tuscany).* Bollettino della Società Geologica Italiana, **94** (231-327).

Cortesogno L. & Haccard D. (1984) - *Note illustrative alla Carta geologica della Zona Sestri-Voltaggio.* Memorie dalla Società Geologica Italiana, **28**, 115–150.

Cortesogno L. & Lucchetti G. (1984) - *Ocean floor metamorphism of the volcanic and sedimentary sequences in the Northern Apennine ophiolites: mineralogical and paragenetic features.* Ofioliti, **9** (363-400).

Crispini L. & Capponi G. (2001) - *Tectonic evolution of the Voltri Group and Sestri Voltaggio Zone (southern limit of the NW Alps): a review.* Ofioliti, **26** (2a), 161–164.

Crispini L., Federico L., Capponi G. & Spagnolo C. (2009) - *Late orogenic transpressional tectonics in the «Ligurian Knot».* Italian Journal of Geosciences, **128** (2), 433–441.

Daniele G. & Plesi G. (2000) - *The Ligurian Helminthoid flysch units of the Emilian Apennines: stratigraphic and petrographic features, paleogeographic restoration and structural evolution.* Geodinamica Acta, **13**, 313–333.

d'Atri A. (1990a) - *Analisi sedimentologica, biostratigrafia e sequenziale della successione del Miocene inferiore tra le valli Lemme e Bormida di Spigno (margine sudorientale del Bacino terziario ligure-piemontese).* Tesi di Dottorato, Università di Torino.

d'Atri A. (1990b) - *Facies e sequenze deposizionali nella Formazione di Visone (Miocene inferiore, Bacino terziario ligure piemontese).* Memorie dalla Società Geologica Italiana, **45**, 723–729.

d'Atri A., Irace A., Piana F., Tallone S., Varrone D., Bellino L., Fioraso G., Cadoppi P., Fusetti E., Morelli M., Lanteri L., Paro L., Piccini C., Trenkwalder S. & Violanti D. (2015) - *Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000 "Foglio 194 - Acqui Terme".* Servizio Geologico d'Italia, Roma, 229 pp.

d'Atri A., Piana F., Barale L., Bertok C. & Martire L. (2016) - *Geological setting of the southern termination of Western Alps.* International Journal of Earth Sciences, **105**, 1831–1858.

d'Atri A., Piana F., Tallone S., Bodrato G., Roz Gastaldi M. *et alii* (1997) - *Tettonica oligo-miocenica dell'Alto Monferrato (Bacino Terziario Piemontese) e nel settore nord-occidentale del Gruppo di Voltri (Acqui Terme-Cassinelle, AL).* Atti Ticinensi di Scienze della Terra, Serie Speciale, **5**, 85–100.

d'Atri A. & Tateo F. (1994) - *Volcano-sedimentary beds of Oligocene age from the Tertiary Piedmont Basin (NW Italy): biostratigraphy and mineralogy.* Giornale di Geologia, **56**, 79–95.

Debelmas J. (1974) - *Les Alpes franco-italiennes.* In: J. Debelmas (Ed.), *Géologie de la France*, pp. 21–58. Doin, Paris.

Debelmas J. (1986) - *The Western Alpine Arc: new data and hypothesis.* In: F.C. Wezel (Ed.), *The Origin of Arcs*, Developments in Geotectonics, vol. 21, pp. 233–251. Elsevier.

Decandia F.A. & Elter P. (1969) - *Riflessioni sul problema delle ofioliti dell'Appennino Settentrionale.* Atti della Società Toscana di Scienze Naturali, Memorie, Serie A, **76**, 1–9.

Decandia F.A. & Elter P. (1972) - *La zona ofiolitifera del Bracco nel settore compreso tra Levanto e la Val Graveglia (Appennino Ligure).* Memorie della Società Geologica Italiana, **11**, 503–530.

Decarlis A., Dallagiovanna G., Lualdi A., Maino M. & Seno S. (2013) - *Stratigraphic evolution in the Ligurian Alps between Variscan heritages and the Alpine Tethys opening: A review.* Earth-Science Reviews, **125**, 43–68. doi:10.1016/j.earscirev.2013.07.001.

Dela Pierre F., Clari P.A., Cavagna S. & Bicchi E. (2002a) - *The Parona chaotic complex: a puzzling record of the Messinian (Late Miocene) events in Monferrato (NW Italy).* Sedimentary Geology, **152** (3-4), 289–311.

Dela Pierre F., Piana F. & Clari P. (2002b) - *Il Monferrato.* In: R. Polino (Ed.), *Il Sistema Alpino-Appenninico nel Cenozoico. 81a Riunione Estiva, Guida alle Escursioni*, pp. 116–128. Società Geologica Italiana, Torino.

Dela Pierre F., Piana F., Fioraso G., Boano P., Bicchi E., Forno M.G., Violanti D., Clari P. & Polino R. (2003) - *Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000 "Foglio 157 - Trino".* Servizio Geologico d'Italia, Roma, 147 pp.

Desmons J., Compagnoni R. & Cortesogno L. (1999) - *Alpine metamorphism of the Western Alps: II. High-P/T and related pre-greenschist metamorphism.* Schweizerische Mineralogische und Petrographische Mitteilungen, **79** (1), 111–134.

Di Giulio A. & Galbiati B. (1995) - *Interaction between tectonics and deposition into an episutural basin in the Alps-Apennine knot. Scritti e Documenti dell'Acc.* In: R. Polino & R. Sacchi (Eds.), *Atti del Convegno "Rapporti Alpi-Appennino", Peveragno (CN) 31 Maggio - 1 Giugno 1994*, vol. 14, pp. 113–128. Accademia Nazionale delle Scienze detta dei XL, Scritti e Documenti, Roma.

Doglioni C., Fernandez M., Gueguen E. & Sàbat F. (1999) - *On the interference between the early Apennines-Maghrebides backarc extension and the Alps-Betics orogen in the neogene Geodynamics of the western Mediterranean.* Bollettino della Società Geologica Italiana, **118**, 75–89.

Doglioni C., Gueguen E., Sàbat F. & Fernandez M. (1997) - *The western Mediterranean extensional basins and the Alpine orogen.* Terra Nova, **9** (3), 109–112.

Dumont T., Schwartz S., Guillot S., Simon-Labric T., Tricart P. & Jourdan S. (2012) - *Structural and sedimentary records of the Oligocene revolution in the Western Alpine arc.* Journal of Geodynamics, **56**, 18–38.

Edel J.B., Dubois D., Marchant R., Hernandez J. & Cosca M. (2001) - *La rotation Miocène inférieur du bloc corso-sarde. Nouvelles contraintes plaléomagnétiques sur la fin du mouvement.* Bulletin de la Société Géologique de France, **172** (3), 275–283.

Elter G., Elter P., Sturani C. & Weidmann M. (1966) - *Sur la prolungation du domaine de l'Apennin dans le Monferrat et les Alpes et sur l'origine de la Nappe de la Simme s.l. des Préalpes romandes et chablaisiennes.* Bulletin des Laboratoires de Géologie, Minéralogie et du Musée Géologique de l'Université de Lausanne, **19** (3), 279–377.

Elter P. (1975) - *L'ensemble ligure.* Bulletin de la Société Géologique de France, **17**, 984–997.

Elter P. (1997) - *Detritismo ofiolitico e subduzione: riflessioni sui rapporti Alpi e Appennino.* Memorie dalla Società Geologica Italiana, **49**, 205–215.

Elter P. & Pertusati P.C. (1973) - *Considerazioni sul limite Alpi-Appennino e sulle relazioni con l'arco delle Alpi occidentali.* Memorie della Società Geologica Italiana, **12**, 359–375.

Eva E., Malusà M.G. & Solarino S. (2020) - *Seismotectonics at the transition between opposite-dipping slabs (western Alpine region).* Tectonics, **39** (9), e2020TC006086.

Faccenna C., Becker T.W., Lucente F.P., Jolivet L. & Rossetti F. (2001) - *History of subduction and back-arc extension in the central Mediterranean.* Geophysical Journal International, **145** (3), 809–820.

Faccenna C., Mattei M., Funiciello R. & Jolivet L. (1997) - *Styles of back-arc extension in the Central mediterranean.* Terra Nova, **9**, 126–130. 21.

Falletti P., Gelati R. & Rogledi S. (1995) - *Oligo-Miocene evolution of Monferrato and Langhe related deep structures.* In: R. Polino & R. Sacchi (Eds.), *Atti del Convegno "Rapporti Alpi-Appennino", Peveragno (CN) 31 Maggio - 1 Giugno 1994*, vol. 14, pp. 1–19. Accademia Nazionale delle Scienze detta dei XL, Scritti e Documenti, Roma.

Fanucci F. & Morelli D. (2003) - *The CROP profiles across the Western Mediterranean basins.* Memorie Descrittive della Carta Geologica d'Italia, **62**, 166–170.

Federico L., Capponi G., Crispini L. & Scambelluri M. (2004) - *Exhumation of alpine high-pressure rocks: insights from petrology of eclogite clasts in the Tertiary Piedmontese basin (Ligurian Alps, Italy).* Lithos, **74** (1-2), 21–40.

Federico L., Capponi G., Crispini L., Scambelluri M. & Villa I.M. (2005) - *39Ar/40Ar dating of high-pressure rocks from the Ligurian Alps: evidence for a continuous subduction–exhumation cycle.* Earth and Planetary Science Letters, **240** (3-4), 668–680.

Federico L., Crispini L., Scambelluri M. & Capponi G. (2007) - *Different P-T paths recorded in a tectonic mélange (Voltri Massif, NW Italy): implications for the exhumation of HP rocks.* Geodinamica Acta, **20** (1-2), 3–19.

Ferrara G., Innocenti F., Ricci C.A. & Serri G. (1976) - *Ocean-floor affinity of basalts from north Apennine opholites: Geochemical evidence.* Chemical Geology, **17**, 101–111.

Festa A., Dela Pierre F., Irace A., Piana F., Fioraso G., Lucchesi S., Boano P. & Forno M.G. (2009) - *Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000 "Foglio 156 - Torino Est".* Servizio Geologico d'Italia, Roma, 143 pp.

Festa A., Fioraso G., Bissacca E. & Petrizzo M.R. (2015) - *Geology of the Villalvernia -Varzi Line Between Scrivia and Curone valleys (NW Italy).* Journal of Maps, **11** (1), 39–55. doi:10.1080/17445647.2014.959569.

Festa A., Piana F., Dela Pierre F., Malusà M.G., Mosca P., Polino R. *et alii* (2005) - *Oligocene-Neogene kinematic constraints in the retroforeland basin of the Northwestern Alps.* Rendiconti della Società Geologica Italiana, **1**, 107–108.

Folk R.L. & McBride E.F. (1978) - *Radiolarites and their relation to subjacent "oceanic crust" in Liguria, Italy.* Journal of Sedimentary Research, **48** (4), 1069–1102.

Ford M., Lickorish W.H. & Kusznir N.J. (2002) - *Tertiary foreland sedimentation in the Southern Subalpine Chains, SE France: a geodynamic appraisal.* Basin research, **11** (4), 315–336.

Forno M.G., De Luca D., Bonasera M., Bucci A., Gianotti F., Lasagna M., Lucchesi S., Pelizza S., Piana F., Taddia G. *et alii* (2018) - *Synthesis on the Turin subsoil stratigraphy and hydrogeology (NW Italy).* Alpine and Mediterranean Quaternary, **31** (2), 147–170.

Garzetti F., Tribuzio R. & Tiepolo M. (2009) - *Structure and U-Pb geochronology of zircons from the Ligurian ophiolites (Northern Apennine, Italy).* In: *Alpine Ophiolites and Modern Analogues, Abstract Volume.* Parma (Italy), September 30-October 2 2009.

Gattacceca J., Deino A., Rizzo R., Jones D.S., Henry B., Beaudoin B. & Vadeboin F. (2007) - *Miocene rotation of Sardinia; new paleomagnetic and geochronological constraints and geodynamic implications.* Earth and Planetary Science Letters, **258** (3-4), 359–377.

Gelati R. (1968) - *Stratigrafia dell'Oligo-Miocene delle Langhe tra le valli dei fiumi Tanaro e Bormida di Spigno.* Rivista Italiana di Paleontologia e Stratigrafia, **74**, 865–897.

Gelati R., Gnaccolini M. & Petrizzo M.R. (1998) - *Synsedimentary tectonics and sedimentation in the Tertiary Piedmont Basin, northwestern Italy.* Rivista Italiana di Paleontologia e Stratigrafia, **104** (2), 193–213.

Gelati R., Gnaccolini M., Polino R., Mosca P., Piana F. & Fioraso G. (2010) - *Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000 "Foglio 211 - Dego".* Servizio Geologico d'Italia, Roma, 117 pp.

Gelati R. & Pasquarè G. (1970) - *Interpretazione geologica del limite Alpi–Appennini in Liguria.* Rivista Italiana di Paleontologia e Stratigrafia, **76** (4), 513–578.

Ghibaudo G., Clari P. & Perello M. (1985) - *Litostratigrafia, sedimentologia ed evoluzione tettonico-sedimentaria dei depositi miocenici del margine sud-orientale del bacino terziario ligure-piemontese (Valli Borbera, Scrivia e Lemme). In memoria di Carlo Sturani.* Bollettino della Società Geologica Italiana, **104** (3), 349–397.

Ghibaudo G., Massari F., Chiambretti I. & d'Atri A. (2014) - *The Langhe Sub-basin: Sedimentology and Tectono-Sedimentary Evolution (Tertiary Piedmont Basin-Northwestern Italy).* Journal of Mediterranean Earth Sciences, **6** (Special Issue), 144.

Ghibaudo G., Massari F., Chiambretti I., d'Atri A. & Fornaciari E. (2019) - *Birth and tectono-sedimentary evolution of the Tertiary Piedmont Basin (NW Italy).* Journal of Mediterranean Earth Sciences, **11** (Special Issue), 5–112.

Ghielmi M., Rogledi S., Vigna B. & Violanti D. (2019) - *La successione messiniana e plio-pleistocenica del Bacino di Savigliano (settore occidentale del Bacino Terziario Piemontese-Italia.* Geologia Insubrica, **13** (1), 3–141.

Gnaccolini M. (1968) - *Il bacino delle Langhe (Piemonte) durante il Miocene.* Rivista Italiana di Paleontologia e Stratigrafia, **74** (1), 133–142.

Gnaccolini M. & Rossi M. (1994) - *Sequenze deposizionali e composizione delle arenarie nel Bacino Terziario Ligure–Piemontese: osservazioni preliminari.* Atti Ticinesi di Scienze della Terra, **37**, 3–15.

Görler K. & Ibbeken H. (1964) - *Die Bedeutung der Zone Sestri-Voltaggio als Grenze zwischen Alpen und Apennin.* Geologische Rundschau, **53**, 73–84.

Gueguen E., Doglioni C. & Fernandez M. (1998) - *On the post-25 Ma geodynamic evolution of the western Mediterranean.* Tectonophysics, **298** (1-3), 259–269.

Haccard D. & Lorenz C. (1979) - *Les deformations de l'Eocene superieur au Stampien de la terminaison septentrionale de la zone de Sestri-Voltaggio.* Bulletin de la Société Géologique de France, **7** (4), 401–413.

Haccard D., Lorenz C. & Grandjacquet C. (1972) - *Essai sur l'évolution tectogénètique de la liason Alpes-Apennins (de la Ligurie à la Calabrie).* Memorie della Società Geologica Italiana, **11**, 309–342.

Handy M.R., Schmid S.M., Bousquet R., Kissling E. & Bernoulli D. (2010) - *Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps.* Earth-Science Reviews, **102** (3-4), 121–158. doi:10.1016/j.earscirev.2010.06.002.

Handy M.R., Schmid S.M., Paffrath M., Friederich W. & the AlpArray Working Group (2021) - *Orogenic lithosphere and slabs in the greater Alpine area–interpretations based on teleseismic P-wave tomography.* Solid Earth, **12** (11), 2633–2669.

Hoogerduijn Strating E.H. (1991) - *The evolution of the Piemonte-Ligurian ocean. A structural study of ophiolite complexes in Liguria (NW Italy).* Geologica Ultraiectina, **74**, 1–127.

Irace A., Dela Pierre F. & Clari P. (2005) - *"Normal" and "chaotic" deposits in the Messinian Gessoso-Solfifera Fm at the north-eastern border of the Langhe domain (Tertiary Piedmont basin).* Bollettino della Società Geologica Italiana, Volume speciale, **4**, 77–85.

Jolivet L. & Faccenna C. (2000) - *Mediterranean extension and the Africa-Eurasia collision.* Tectonics, **19** (6), 1095.

Jolivet L., Faccenna C., Goffé B., Mattei M., Rossetti F., Brunet C., Storti F., Funiciello R., Cadet J., D'Agostino N. & Parra T. (1998) - *Midcrustal shear zones in postorogenic extension: example from the northern Tyrrhenian Sea.* Journal of Geophysical Research, **103**, 12123–12160.

Jolivet L., Faccenna C. & Piromallo C. (2009) - *From mantle to crust: Stretching the Mediterranean.* Earth and Planetary Science Letters, **285** (1-2), 198–209.

Jolivet L., Romagny A., Gorini C., Maillard A., Thinon I., Couëffé R., Ducoux M. & Seranne M. (2020) - *Fast dismantling of a mountain belt by mantle flow: late-orogenic evolution of Pyrenees and Liguro-Provençal rifting.* Tectonophysics, **776**, 228312.

Jourdan S., Bernet M., Tricart P., Hardwick E., Paquette J.L., Guillot S., Dumont T. & Schwartz S. (2013) - *Short-lived, fast erosional exhumation of the internal western Alps during the late early Oligocene: Constraints from geothermochronology of pro-and retro-side foreland basin sediments.* Lithosphere, **5** (2), 211–225.

Kingston D.R., Dishroon C. & Williams P. (1983) - *Global basin classification system.* American Association of Petroleum Geologists, Bullettin, **67** (12), 2175–2193.

Király Á., Capitanio F.A., Funiciello F. & Faccenna C. (2016) - *Subduction zone interaction: Controls on arcuate belts.* Geology, **44** (9), 715–718.

Kissling E., Schmid S.M., Lippitsch R., Ansorge J. & Fügenschuh B. (2006) - *Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography.* Geological Society, London, Memoirs, **32** (1), 129–145.

Lagabrielle Y. (2023) - *Paleogeography and Architecture of the Alpine Tethys Margins.* In: C. Rosenberg & N. Bellahsen (Eds.), *Geodynamics of the Alps 2. Pre-collisional Processes*, pp. 45–156. ISTE - Wiley.

Laubscher H. (1971) - *The large scale kinematics of the western Alps and the northern Apennines and its palinspastic implications.* American Journal of Science, **271**, 193–226.

Laubscher H. (1988) - *The arcs of the Western Alps and Northern Apennines: an updated view.* Tectonophysics, **146**, 67–78.

Laubscher H., Biella G.C., Cassinis R., Gelati R., Lozej A., Scarascia S. & Tabacco I. (1992) - *The collisional knot in Liguria.* Geologische Rundschau, **81** (2), 275–289.

Le Breton E., Brune S., Ustaszewski K., Zahirovic S., Seton M. & Müller R.D. (2021) - *Kinematics and extent of the Piemont–Liguria Basin - implications for subduction processes in the Alps.* Solid Earth, **12** (4), 885–913.

Le Breton E., Handy M.R., Molli G. & Ustaszewski K. (2017) - *Post-20 Ma motion of the Adriatic plate – new constraints from surrounding orogens and implications for crust-mantle decoupling.* Tectonics. doi:10.1002/2016TC004443.

Lemoine M., de Graciansky P.C. & Tricart P. (2000) - *De l'Océan à la Chaîne de Montagnes: Tectonique des Plaques dans les Alpes.* Société Géologique de France, Collection Géosciences, Gordon and Breach Science Publishers, Paris, 207 pp.

Levi N., Ellero A., Ottria G. & Pandolfi L. (2006) - *Polyorogenic deformation history recognized at very shallow structural levels: the case of the Antola Unit (Northern Apennine, Italy).* Journal of Structural Geology, **28** (9), 1694–1709.

Liou J.G., Zhang R., Ernst W.G., Liu J. & McLimans R. (1998) - *Mineral parageneses in the Piampaludo eclogitic body, Gruppo di Voltri, western Ligurian Alps.* Schweizerische Mineralogische und Petrographische Mitteilungen, **78** (2), 317–335.

Lippitsch R., Kissling E. & Ansorge J. (2003) - *Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography.* Journal of Geophysical Research: Solid Earth, **108** (B8), 2376.

Livani M., Petracchini L., Benetatos C., Marzano F., Billi A., Carminati E., Doglioni C., Petricca P., Maffucci R., Codegone G., Rocca V. & Antoncecchi I. (2023) - *Subsurface geological and geophysical data from the Po Plain and the northern Adriatic Sea (north Italy).* Earth System Science Data Discussions, **15**, 4261–4293.

Lorenz C. (1969) - *Contribution a l'étude stratigraphique de l'Oligocene inferieur des confins Liguro-Piémontais (Italie).* Atti dell'Istituto di Geologia dell'Università di Genova, **6**, 253–888.

Lorenz C. & Rebora G. (1982) - *Les niveaux oligocenes a lignite de Voltaggio (province d'Alessandria, Italie).* Bollettino della Societa Geologica Italiana, **101**, 219–232.

Lualdi A. (1991) - *Il Trias Superiore Lias della zona Sestri-Voltaggio (Unità di M. Gazzo-Isoverde). La sezione di Lencisa-M. dei Torbi.* Atti Ticinensi di Scienze della Terra, **34**, 121–132.

Lustrino M. & Wilson M. (2007) - *The circum-Mediterranean anorogenic Cenozoic igneous province.* Earth-Science Reviews, **81** (1-2), 1–65.

Maffione M., Speranza F., Faccenna C., Cascella A., Vignaroli G. & Sagnotti L. (2008) - *A synchronous Alpine and Corsica-Sardinia rotation.* Journal of Geophysical Research, **113** (B3).

Maino M. (2009) - *Zircon (U-Th)/He dating of collisional stages in Ligurian Alps.* Scientifica Acta, **2**, 35–38.

Maino M., Decarlis A., Felletti F. & Seno S. (2013) - *Tectono-sedimentary evolution of the Tertiary Piedmont Basin (NW Italy) within the Oligo–Miocene central Mediterranean geodynamics.* Tectonics, **32** (3), 593–619.

Malatesta C., Crispini L., Federico L., Capponi G. & Scambelluri M. (2012) - *The exhumation of high pressure ophiolites (Voltri Massif, Western Alps): Insights from structural and petrologic data on metagabbro bodies.* Tectonophysics, **568**, 102–123.

Malusà M.G., Faccenna C., Baldwin S.L., Fitzgerald P.G., Rossetti F., Balestrieri M.L., Danišík M., Ellero A., Ottria G. & Piromallo C. (2015) - *Contrasting styles of (U)HP rock exhumation along the Cenozoic Adria-Europe plate boundary (Western Alps, Calabria, Corsica).* Geochemistry, Geophysics, Geosystems, **16** (6), 1786–1824. doi:10.1002/2015GC005767.

Manatschal G. & Müntener O. (2009) - *A type sequence across an ancient magma-poor ocean–continent transition: the example of the western Alpine Tethys ophiolites.* Tectonophysics, **473** (1-2), 4–19.

Mantovani F., Elter F.M., Pandeli E., Briguglio A. & Piazza M. (2023) - *The Portofino Conglomerate (Eastern Liguria, Northern Italy): Provenance, Age and Geodynamic Implications.* Geosciences, **13** (6), 154.

Marroni M., Molli G., Montanini A. & Tribuzio R. (1998) - *The association of continental crust rocks with ophiolites in the Northern Apennines (Italy): implications for the continent-ocean transition in the Western Tethys.* Tectonophysics, **292**, 43–66.

Martinod J., Daou A.C., Métral L. & Sue C. (2024) - *Did subduction in the western Mediterranean drive Neogene alpine dynamics? Insights from analogue modeling.* BSGF - Earth Sciences Bulletin, **195** (1), 5.

Meneghini F., Di Rosa M., Marroni M., Raimbourg H. & Pandolfi L. (2023) - *Subduction signature in the Internal Ligurian units (Northern Apennine, Italy): Evidence from P–T metamorphic peak estimate.* Terra Nova, **36** (3), 182–190. doi:10.1111/ter.12694.

Menichelli I., De Gori P., Lucente F.P., Improta L. & Chiarabba C. (2023) - *Lithosphere Structure, Processes, and Physical State of the Alpine-Apennine System.* Journal of Geophysical Research: Solid Earth, **128** (4), e2023JB026411.

Messiga B. & Scambelluri M. (1991) - *Retrograde P-T-t path for the Voltri Massif eclogites (Ligurian Alps, Italy): Some tectonic implications.* Journal of Metamorphic Geology, **9** (1), 93–109.

Michard A., Schmid S.M., Lahfid A., Ballèvre M., Manzotti P., Chopin C., Iaccarino S. & Dana D. (2022) - *The Maira-Sampeyre and Val Grana Allochthons (south Western Alps): review and new data on the tectonometamorphic evolution of the Briançonnais distal margin.* Swiss Journal of Geosciences, **115** (1), 19.

Molli G. (1996) - *Pre-orogenic tectonic framework of the northern Apennine ophiolites.* Eclogae Geologicae Helvetiae, **89**, 163–180.

Molli G. (2008) - *Northern Apennine–Corsica orogenic system: an updated overview.* In: S. Siegesmund, B. Fugenschuh & N. Froitzheim (Eds.), *Tectonic Aspects of the Alpine–Dinaride–Carpathian System*, Geological Society of London Special Publications, vol. 298, pp. 413–442. Geological Society of London, London.

Molli G. (2020) - *Discussion on 'Breaking up continents at magma-poor rifted margins: a seismic v. outcrop perspective'Journal of the Geological Society, London, 175, 875–882.* Journal of the Geological Society, **177** (3), 661–667.

Molli G., Crispini L., Malusà M.G., Mosca P., Piana F. & Federico L. (2010) - *Geology of the Western Alps-Northern Apennine junction area: a regional review.* In: M. Beltrando, A. Peccerillo, M. Mattei, S. Conticelli & C. Doglioni (Eds.), *The Geology of Italy: Tectonics and Life Along Plate Margins*, Journal of the Virtual Explorer, vol. 36/10, pp. 1–51. Journal of the Virtual Explorer.

Monteforti B. & Raggi G. (1975) - *Per la geologia dell'entroterra di La Spezia tra Sarzana e Zignano.* Bollettino della Società Geologica Italiana, **94**, 927–943.

Mosca P. (2006) - *Neogene basin evolution in the western Po Plain (NW Italy). Insights from seismic interpretation, subsidence analysis and low temperature (U-Th)/He thermochronology.* Tesi di Dottorato, Vrije Universiteit, Research School Geology (NSG), publ. n. 20060202, Amsterdam.

Mosca P., Polino R., Rogledi S. & Rossi M. (2010) - *New data for the kinematic interpretation of the Alps–Apennines junction (Northwestern Italy).* International Journal of Earth Sciences, **99** (4), 833–849.

Mutti E., di Biase D., Fava L., Mavilla N., Sgavetti M. & Tinterri R. (2002) - *The Tertiary Piedmont Basin - Excursion Notes.* In: E. Mutti, F. Ricci Lucchi & M. Roveri (Eds.), *Revisiting Turbidites of the Marnoso-Arenacea Formation and the Basin margin Equivalents: Problems with Classic Models*, pp. 137–176. Dipartimento di Scienze della Terra, Università di Parma, Eni-Agip Division, 64th EAGE Conference, Florence, 2002.

Mutti E., Papani L., Di Biase D., Davoli G., Mora S., Segadelli S. & Tinterri R. (1995) - *Il Bacino Terziario Epimesoalpino e le sue implicazioni sui rapporti tra Alpi ed Appennino.* Memorie di Scienze Geologiche, **47**, 217–244.

Padovano M., Piccardo G.B. & Vissers R.L. (2015) - *Tectonic and magmatic evolution of the mantle lithosphere during the rifting stages of a fossil slow–ultraslow spreading basin: insights from the Erro–Tobbio peridotite (Voltri Massif, NW Italy).* Geological Society, London, Special Publications, **413** (1), 205–238.

Patacca E. & Scandone P. (1989) - *Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab.* In: A. Boriani, M. Bonafede, G.B. Piccardo & G.B. Vai (Eds.), *The Lithosphere in Italy*, Atti dei Convegni Lincei, vol. 80, pp. 157–176. Roma.

Piana F. (2000) - *Structural setting of western Monferrato (Alps-Apennines junction zone, NW Italy).* Tectonics, **19** (5), 943–960.

Piana F., Barale L., Bertok C., d'Atri A., Irace A. & Mosca P. (2021) - *The Alps-Apennines Interference Zone: A Perspective from the Maritime and Western Ligurian Alps.* Geosciences, **11** (5), 185. doi:10.3390/geosciences11050185.

Piana F., Barale L., Compagnoni R., D'Atri A., Fioraso G., Irace A., Mosca P., Tallone S., Monegato G. & Morelli M. (2017a) - *Geological Map of Piemonte Region at 1:250,000 scale; Explanatory notes.* Memorie della Accademia delle Scienze di Torino, Classe di Scienze Fisiche, Matematiche e Naturali, **41**, 3–143.

Piana F., d'Atri A. & Orione P. (1997) - *The Visone formation: a marker for the Early Miocene tectonics in the Alto Monferrato domain (Tertiary Piemonte Basin, NW, Italy).* Memorie di Scienze Geologiche, **49**, 145–162.

Piana F., Fioraso G., Irace A., Mosca P., D'Atri A., Barale L., Falletti P., Monegato G., Morelli M., Tallone S. & Vigna G.B. (2017b) - *Geology of Piemonte region (NW Italy, Alps–Apennines interference zone).* Journal of Maps, **13** (2), 395–405. doi:10.1080/17445647.2017.1316218.

Piana F. & Polino R. (1994) - *La zona transpressiva di Rio Freddo e l'evoluzione convergente della Collina di Torino e del Monferrato durante il Terziario.* Atti Ticinensi di Scienze della Terra, Serie Speciale, **1**, 167–180.

Piana F. & Polino R. (1995) - *Tertiary structural relationships between Alps and Apennines: the critical Torino Hill and Monferrato area, Northwestern Italy.* Terra Nova, **7** (2), 138–143.

Piana F., Tallone S., Cavagna S. & Conti A. (2006) - *Thrusting and faulting in metamorphic and sedimentary units of Ligurian Alps: an example of integrated field work and geochemical analyses.* International Journal of Earth Sciences, **95** (3), 413–430.

Piccardo G.B. (1977) - *Le ofioliti dell'areale ligure: petrologia e ambiente geodinamico di formazione.* Rendiconti della Società Italiana di Mineralogia e Petrologia, Special Issue, pp. 221–252.

Piccardo G.B., Padovano M. & Guarnieri L. (2014) - *The Ligurian Tethys: Mantle processes and geodynamics.* Earth-Science Reviews, **138**, 409–434. doi:10.1016/j.earscirev.2014.07.002.

Piccardo G.B. & Vissers R.L.M. (2007) - *The pre-oceanic evolution of the Erro-Tobbio peridotite (Voltri massif, Ligurian Alps, Italy).* Journal of Geodynamics, **43** (4-5), 417–449.

Principi G. & Treves B. (1984) - *Il sistema corso-appenninico come prisma d'accrezione. Riflessi sul problema generale del limite Alpi-Appennini.* Memorie della Società Geologica Italiana, **28**, 549–576.

Rampone E., Hofmann A.W. & Raczek I. (1998) - *Isotopic contrasts within the Internal Liguride ophiolite (N. Italy): the lack of a genetic mantle–crust link.* Earth and Planetary Science Letters, **163** (1-4), 175–189.

Rehault J.P., Boillot G. & Mauffret A. (1984) - *The Western Mediterranean basin geological evolution.* Marine Geology, **55**, 447–477.

Réhault J.P., Mascle J. & Boillot G. (1984) - *Evolution géodynamique de la Méditerranée depuis l'Oligocène.* Memorie della Società Geologica Italiana, **27**, 85–96.

Rollet N., Déverchère J., Beslier M.O., Guennoc P., Réhault J.P., Sosson M. & Truffert C. (2002) - *Back arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, Western Mediterranean.* Tectonics, **21** (3), 1–23.

Rosenbaum G., Lister G.S. & Duboz C. (2002) - *Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene.* Journal of the Virtual Explorer, **8**, 107–126.

Rossi M. (2017) - *Outcrop and seismic expression of stratigraphic patterns driven by accommodation and sediment supply turnarounds: Implications on the meaning and variability of unconformities in syn-orogenic basins.* Marine and Petroleum Geology, **87**, 112–127.

Rossi M. & Craig J. (2016) - *A new perspective on sequence stratigraphy of syn-orogenic basins: insights from the Tertiary Piedmont Basin (Italy) and* *implications for play concepts and reservoir heterogeneity.* In: M. Bowman, H.R. Smith, T.R. Good, S.R. Passey, J.P.P. Hirst & C.J. Jordan (Eds.), *The value of outcrop Studies in Reducing Subsurface Uncertainty and Risk in Hydrocarbon Exploration and Production*, Special Publications, vol. 436, pp. 93–133. The Geological Society of London, London.

Rossi M., Mosca P., Polino R., Rogledi S. & Biffi U. (2009) - *New outcrop and subsurface data in the Tertiary Piedmont Basin (NW-Italy): unconformity-bounded stratigraphic units and their relationships with basin-modification phases.* Rivista Italiana di Paleontologia e Stratigrafia, **115** (3), 305–335.

Roure F., Bergerat F., Damotte B., Mugnier J.L. & Polino R. (1996) - *The ECORS-CROP Alpine seismic traverse. Programme ECORS-CROP (France).* Mémoires de la Société géologique de France, **170**, 1–113.

Roure F., Howell D.G., Guellec S. & Casero P. (1990) - *Shallow structures induced by deep-seated thrusting.* In: J. Letouzey (Ed.), *Petroleum and Tectonics in Mobile Belts.*, pp. 15–30. Editions Technip, Paris.

Rubatto D. & Scambelluri M. (2003) - *U-Pb dating of magmatic zircon and metamorphic baddeleyite in the Ligurian eclogites (Voltri Massif, Western Alps).* Contributions to mineralogy and Petrology, **146**, 341–355.

Sanità E., Di Rosa M., Marroni M., Meneghini F. & Pandolfi L. (2024) - *Insights into the Subduction of the Ligure-Piemontese Oceanic Basin: New Constraints from the Metamorphism in the Internal Ligurian Units (Northern Apennines, Italy).* Minerals, **14** (1), 64. doi:10.3390/min14010064.

Schmid S.M., Fügenschuh B., Kissling E. & Schuster R. (2004) - *Three lithospheric transects across the Alps and their forelands.* In: W. Cavazza, F. Roure, W. Spakman, G.M. Stampfli & P.A. Ziegler (Eds.), *The TRANSMED Atlas. The Mediterranean Region from Crust to Mantle.* Springer Verlag.

Schmid S.M. & Kissling E. (2000) - *The arc of the western Alps in the light of geophysical data on deep crustal structure.* Tectonics, **19** (1), 62–85.

Schmid S.M., Kissling E., Diehl T., van Hinsbergen D.J.J. & Molli G. (2017) - *Ivrea mantle wedge, arc of the Western Alps, and kinematic evolution of the Alps–Apennines orogenic system.* Swiss Journal of Geosciences, pp. 581–612.

Schmid S.M., Pfiffner O.A., Froitzheim N., Schönborn G. & Kissling E. (1996) - *Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps.* Tectonics, **15** (5), 1036–1064.

Seno S., Dallagiovanna G. & Vanossi M. (2005) - *A kinematic evolutionary model for the Penninic sector of the central Ligurian Alps.* International Journal of Earth Sciences, **94**, 114–129.

Séranne M. (1999) - *The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview.* In: B. Durand, L. Jolivet, F. Horvath & M. Séranne (Eds.), *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen*, Geological Society of London, Special Publications, vol. 156, pp. 15–36. Geological Society of London.

Serri G. (1980) - *Chemistry and petrology of gabbroic complexes from the northern Apennine ophiolites.* In: A. Panayiotou (Ed.), *Proceedings of the International Ophiolite Symposium, Cyprus*, pp. 296–313. Geological Survey Department, Nicosia.

Serri G., Hebert R. & Hékinian R. (1989) - *Mineral chemistry of ultramafic tectonites and ultramafic lo gabbroic cumulates from the major oceanic basins and Northern Apennine ophiolites (Italy).* Chemical Geology, **77**, 183–207.

Sinclair H. (1997) - *Flysch to molasse transition in peripheral foreland basins: The role of the passive margin versus slab breakoff.* Geology, **25** (12), 1123–1126.

Siravo G. & Speranza F. (2024) - *Paleomagnetism of the Peloritan terrane (NE Sicily): From Greater Iberia to the Neo Apennine-Maghrebide Arc.* Tectonics, **43**, e2023TC008128. doi:https://10.1029/2023TC008128.

Speranza F., Villa I.M., Sagnotti L., Florindo F., Cosentino D., Cipollari P. & Mattei M. (2002) - *Age of the Corsica-Sardinia rotation and Liguro-Provençal Basin spreading; new paleomagnetic and Ar/Ar evidence.* Tectonophysics, **347** (4), 231–251.

Spooner E.T.C. & Fyfe W.S. (1973) - *Sub-sea-floor metamorphism, heat and mass transfer.* Contributions to Mineralogy and Petrology, **42**, 287–304.

Stampfli G.M., Borel G.D., Marchant R. & Mosar J. (2002) - *Western Alps geological constraints on western Tethyan reconstructions.* Journal of the Virtual Explorer, **8**, 77.

Stampfli G.M., Mosar J., Marquer D., Marchant R., Baudin T. & Borel G. (1998) - *Subduction and obduction processes in the Swiss Alps.* Tectonophysics, **296** (1-2), 159–204.

Starr P.G., Broadwell K.S., Dragovic B., Scambelluri M., Haws A.A., Caddick M.J., Smye A.J. & Baxter E.F. (2020) - *The subduction and exhumation history of the Voltri Ophiolite, Italy: Evaluating exhumation mechanisms for high-pressure metamorphic massifs.* Lithos, **376**, 105767.

Staub R. (1928) - *Der Deckenbau Korsikas und sein Zusammenhang mit Alpen und Apennin.* Vierteljahresschriften der naturforschenden Gesellschaft Zürich, **73**, 298–348.

Steinmann G. (1927) - *Die ophiolitischen Zonen in den mediterranen Kettengebirgen.* In: *Compte-rendu, XIVe Congrès Géologique International, 1926.* Graficas Reunidas, Madrid.

Stille H. (1924) - *Grundfragen der vergleichenden Tektonik.* Gebrüder Borntraeger, Berlin, 443 pp.

Sturani C. (1973) - *Considerazioni sui rapporti tra Appennino settentrionale ed Alpi occidentali.* Rendiconti dell'Accademia Nazionale dei Lincei, **183**, 119–142.

Tribuzio R., Garzetti F., Corfu F., Tiepolo M. & Renna M.R. (2016) - *U–Pb zircon geochronology of the Ligurian ophiolites (Northern Apennine, Italy): Implications for continental breakup to slow seafloor spreading.* Tectonophysics, **666**, 220–243.

Tribuzio R., Molli G., Riccardi M.P. & Messiga B. (1997) - *Poliphase metamorphism in ophiolitic gabbros from Bonassola (Internal Liguride Units, northern Apennines): A record of western Tethys oceanization.* Ofioliti, **22**, 163–174.

Tribuzio R., Tiepolo M. & Vannucci R. (2000) - *Evolution of gabbroic rocks of the Northern Apennine ophiolites (Italy): comparison with the lower oceanic crust from modern slow-spreading ridges.* In: J. Dilek, E. Moores, D. Elthon & A. Nicolas (Eds.), *Ophiolites and Oceanic Crust: New Insights from Field Studies and Ocean Drilling Program*, Geological Society of America Memoir, vol. 349, pp. 129–138. Geological Society of America, Boulder.

Turrini C., Lacombe O. & Roure F. (2014) - *Present-day 3D structural model of the Po Valley basin, Northern Italy.* Marine and Petroleum Geology, **56**, 266–289.

Van Hinsbergen D.J.J., Torsvik T.H., Schmid S.M., Maţenco L.C., Maffione M., Vissers R.L.M., Gürer D. & Spakman W. (2020) - *Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic.* Gondwana Research, **81**, 79–229.

van Hinsbergen D.J.J., Vissers R.L.M. & Spakman W. (2014) - *Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation.* Tectonics, **33**, 393–419, doi:10.1002/tect.20125.

Vanossi M. (1991) - *Alpi Liguri*, Guide Geologiche Regionali, vol. 2. Società Geologica Italiana, BE-MA Editrice, Milano, 296 pp.

Vigliotti L. & Langenheim V. (1995) - *When did Sardinia stop rotating? New paleomagnetic results.* Terra Nova, **7**, 424–435.

Vignaroli G. (2006) - *Structural-metamorphic evolution of the Voltri Massif (Ligurian Alps, Italy).* Tesi di Dottorato, Università degli Studi di Roma 3, Roma.

Vignaroli G., Faccenna C., Jolivet L., Piromallo C. & Rossetti F. (2008) - *Subduction polarity reversal at the junction between the Western Alps and the Northern Apennines, Italy.* Tectonophysics, **450** (1-4), 34–50.

Vignaroli G., Faccenna C., Rossetti F. & Jolivet L. (2009) - *Insights from the Apennines metamorphic complexes and their bearing on the kinematics evolution of the orogen.* Geol. Soc. London Spec. Publ., **311** (235-256).

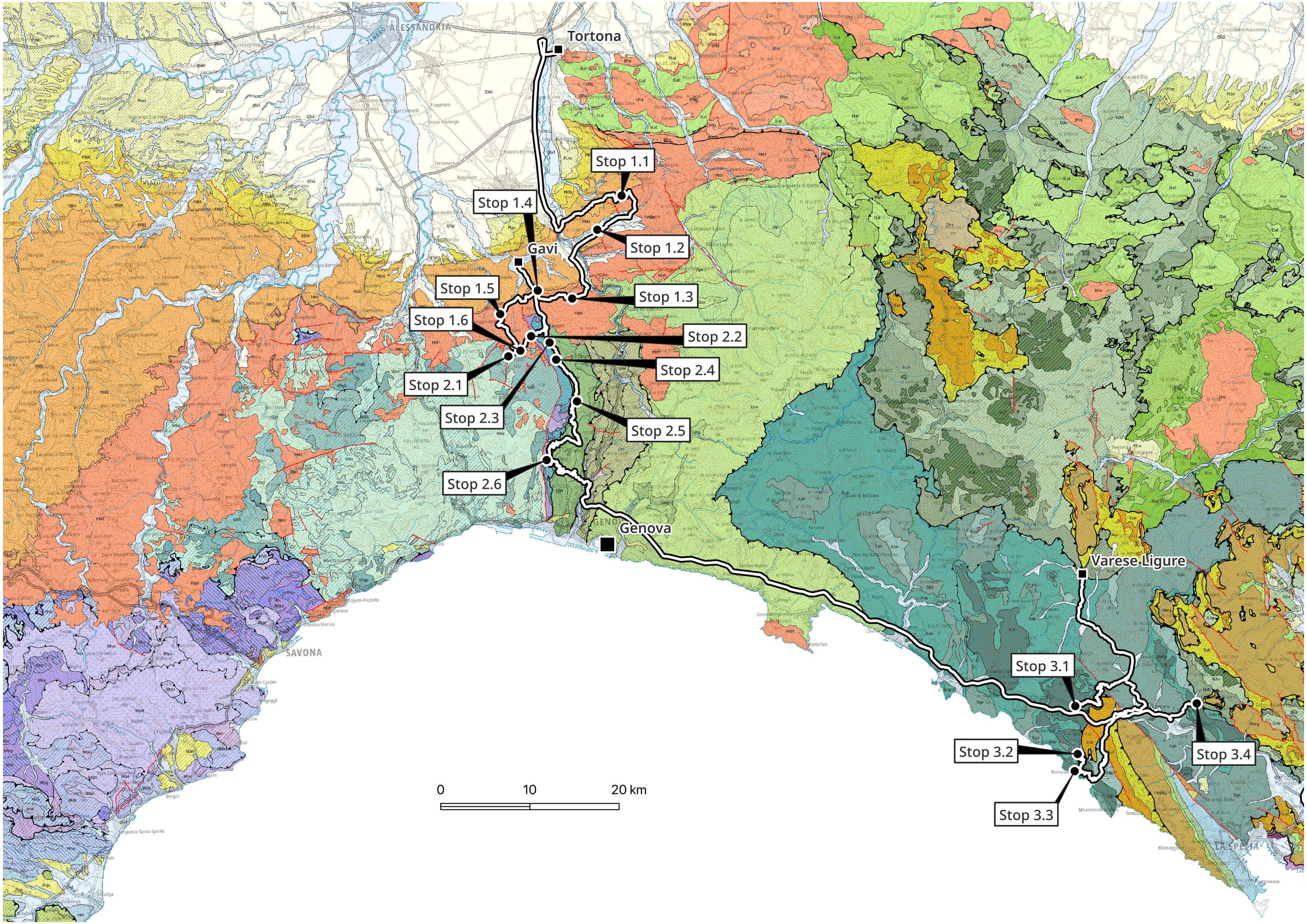
Vignaroli G., Rossetti F., Rubatto D., Theye T., Lisker F. & Phillips D. (2010) - *Pressure-temperature-deformation-time (P-T-d-t) exhumation history of the Voltri Massif HP complex, Ligurian Alps, Italy.* Tectonics, **29** (6), TC6009. doi:10.1029/2009TC002621.

Whitney D.L., Teyssier C., Rey P. & Buck W.R. (2013) - *Continental and oceanic core complexes.* Geological Society of America Bulletin, **125** (3-4), 273–298.

Wildi W. (1985) - *Heavy mineral distribution and dispersal pattern in penninic and ligurian flysch basins (Alps, northern Apennines).* Giornale di Geologia, **47** (1-2), 77–99.

Zaccarini F. & Garuti G. (2008) - *Mineralogy and chemical composition of VMS deposits of northern Apennine ophiolites, Italy: evidence for the influence of country rock type on ore composition.* Mineralogy and Petrology, **94**, 61–83.

Zanzucchi G. (1988) - *Ipotesi sulla posizione paleogeografica delle "Liguridi Esterne" cretacico-eoceniche, nell'Appennino Settentrionale.* Atti Ticinensi di Scienze della Terra, **31**, 327–339.



Tortona
ALESSANDRIA
Stop 1.1
Stop 1.4
Stop 1.2
Gavi
Stop 1.5
Stop 1.3
Stop 1.6
Stop 2.2
Stop 2.4
Stop 2.1
Stop 2.3
Stop 2.5
Stop 2.6
Genova
SAVONA
Varese Ligure
Stop 3.1
Stop 3.2
Stop 3.4
Stop 3.3
0
10
20 km