METAMORPHIC OPHIOLITES OF THE LIGURIAN ALPS: STATE OF THE ART ON AN EXHUMED SUBDUCTION INTERFACE

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ABSTRACT

The metamorphic ophiolites of the central Ligurian Alps, primarily exposed in the Voltri Massif and the Sestri-Voltaggio Zone, preserve an extensive record of Jurassic oceanic lithosphere subducted to high-pressure (HP) and locally ultrahigh-pressure (UHP) conditions during Alpine orogenesis. This review synthesizes published structural, petrological, geochronological and geophysical data on the main tectono-metamorphic units of these metamorphic ophiolites. Their protoliths derived from the Ligurian-Piedmont Ocean, a branch of the western Tethys formed within a magma-poor margin and ocean-continent transition setting characterized by mantle exhumation and MORB-type magmatism.

The metamorphic evolution records a cold subduction regime, with peak conditions spanning from pumpellyite-actinolite to eclogite-facies. In the Voltri Unit, the best constrained in terms of P-T-t, peak eclogite-facies conditions reached ca. 1.8-2.5 GPa and 450-550 °C, whereas the recent discovery of coesite indicates localized UHP conditions of at least ca. 2.8 GPa. Geochronological data constrain the main eclogite-facies event between ca. 50 and 40 Ma, followed by exhumation-related cooling and a widespread greenschist-facies overprint at ca. 34-29 Ma.

The regional structural architecture reflects a polyphase deformation history: early structures formed during subduction, composite fabrics developed during initial exhumation, and later transpressional reactivation accompanied Alps-Apennine interaction at the “Ligurian collisional knot”. Current tectonic interpretations debate the relative role of serpentinite-hosted subduction channel processes versus the exhumation of large coherent slices. Available geological and geophysical evidence suggests that both mechanisms operated at different scales within a fossil plate interface marked at depth by a shallow Adriatic mantle wedge and a hydrated low-velocity zone. The Ligurian meta-ophiolites thus provide a key natural laboratory for investigating subduction-interface dynamics and tectonic reorganization at the Alps-Apennines junction.

INTRODUCTION

Metamorphic ophiolites exposed in Liguria, i.e. in the Ligurian Alps (Fig. 1a, b), represent one of the most complete and best-studied records of oceanic lithosphere subducted to high-pressure (HP) and locally ultra-high-pressure (UHP) conditions and subsequently exhumed during Alpine orogenesis (e.g., Dal Piaz, 1974, 1999; Messiga and Scambelluri, 1991; Liou et al., 1998; Desmons et al., 1999; Starr et al., 2020; Scambelluri et al., 2019; Alismo et al., 2025). These meta-ophiolites are mainly preserved within the Voltri Massif and the Sestri-Voltaggio Zone (hereafter SVZ, Fig. 2) and consist of mantle- and crust-derived rocks originating from the Jurassic Ligurian-Piedmont Ocean, a branch of the western Tethys that separated the European and Adriatic margins (e.g., Lemoine et al., 1986; Vanossi et al., 1984; Stampfli et al., 1998; Handy et al., 2010; Molli et al., 2010). Their metamorphic evolution documents the progressive transformation of oceanic lithosphere within a cold subduction regime, dominated by HP-LT metamorphism and pervasive fluid-rock interaction (e.g., Messiga and Scambelluri, 1991; Federico et al., 2005; Vignaroli et al., 2005; Haws et al., 2021).

The Ligurian Alps are located at the junction between the Western Alps and the Northern Apennine (Fig. 1a, b), an area of long-lasting tectonic interaction commonly referred to as the Ligurian collisional knot (e.g., Biella et al., 1988; Laubscher et al., 1992; Crispini et al., 2009; Molli et al., 2010; Maino et al., 2013; Federico et al., 2014; Amadori et al., 2023; Manna et al., 2023; Molli et al., 2024). Detailed implications are discussed in Section 7.

This region records the superposition of Alpine subduction, continental collision, and later Apenninic tectonics, resulting in a highly complex three-dimensional architecture. This architecture is characterized by multiple deformation phases, diachronous coupling of tectonic units, and significant late-stage transpressional reactivation (Spagnolo et al., 2007; Vignaroli et al., 2008; Crispini et al., 2009; Schmid et al., 2017). In this framework, the meta-ophiolites of the Ligurian Alps provide a unique opportunity to investigate subduction-related metamorphic processes, as well as the mechanisms of exhumation and tectonic reworking occurring at the transition between two major orogenic systems (Molli et al., 2010; Malusà and Balestrieri, 2012; Eva et al., 2020).

Over the past five decades, the Ligurian Alps meta-ophiolites have been the focus of numerous structural, petrological, and geochronological studies (e.g., Chiesa et al., 1975, Cortesogno et al., 1981; Piccardo, 1984; Messiga and Scambelluri, 1991; Hoogerduijn Strating, 1991; Cortesogno and Haccard, 1984; Crispini and Capponi, 1997, 2001; Capponi and Crispini, 2002; Federico et al., 2005; Vignaroli et al., 2009a; Vignaroli et al., 2010). These works have documented a wide range of pressure-temperature conditions (Table 1), from pumpellyite-actinolite to eclogite-facies, and have shown that exhumation occurred through a prolonged and composite history, recorded by pervasive greenschist-facies overprints and late brittle-ductile deformation (e.g., Desmons et al., 1999; Federico et al., 2005; Vignaroli et al., 2010; Crispini et al., 2009; Malatesta et al., 2012a).

Recent studies highlight the importance of serpentinite, metasomatic rocks (e.g. rodingites and ophicarbonates), and fluid-rock interaction along the subduction interface, suggesting a key role of rheological contrasts during subduction and exhumation processes (Federico et al., 2007a,b;

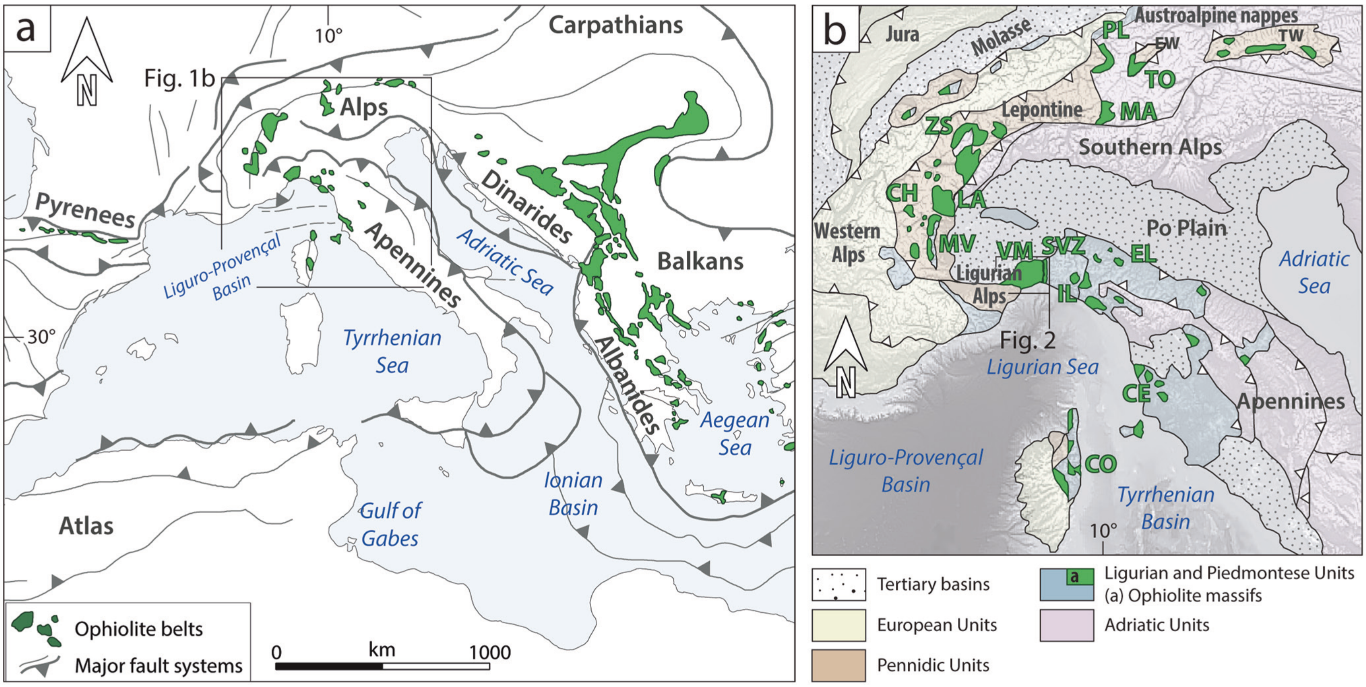

Fig. 1 - (a) Simplified tectonic map of the central Mediterranean region showing the distribution of the Alpine ophiolite belts derived from the Tethys Oceanic domain. Map modified after Najafi et al. (2026). (b) Geological sketch with the location of the major ophiolite massifs in the Central, Western and Ligurian Alps, Northern Apennines and Corsica. Abbreviations: TO, Totalp; MA, Malenco; PL, Platta; ZS Zermatt-Saas; LA, Lanzo; CH, Chenaillet; MV, Monviso; VM, Voltri Massif; SVZ: Sestri-Voltaggio Zone; EL, External Ligurides; IL, Internal Ligurides; CE, Cecina; CO, Corsica. Redrawn and modified after Guarnieri et al. (2012).

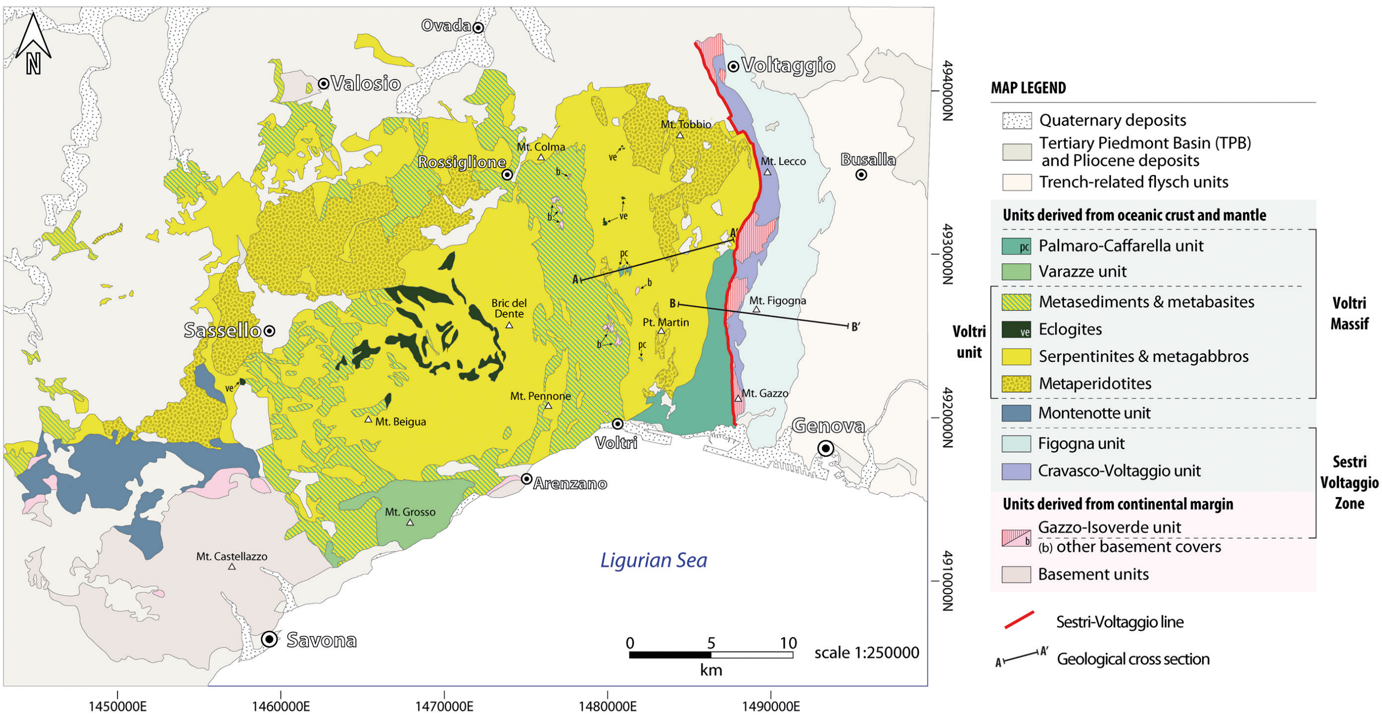

Fig. 2 - Sketch map of the metamorphic ophiolites of the Ligurian Alps, subdivided by paleogeographic pertinence (i.e., units derived from oceanic crust/mantle and units derived from the continental margin). The units belonging to the Voltri Massif and Sestri-Voltaggio Zone are indicated by square brackets. Map recompiled after Capponi et al. (2016), Capponi and Crispini (2008a), Giammarino et al. (2002) and Chiesa et al. (1975).

Scambelluri et al., 2016; Haws et al., 2021; Cannaò et al., 2020; Cannaò, 2025).

Despite the large amount of data accumulated so far, interpretations of the tectonic and metamorphic evolution of the Ligurian Alps remain partly fragmented and, in some aspects, still poorly constrained. In particular, the role of the SVZ within the subduction system, as well as the relative timing and mechanisms of exhumation of the different lithological

Table 1 - Tectono-metamorphic units of the Ligurian Alps meta-ophiolites: acronyms, main lithologies, peak metamorphic grade, and selected references

Sector	Name	Metamorphic peak	Main lithologies (*investigated for P-T estimate)	P-T estimate method/methods	Selected references
Voltri Massif	Voltri Unit - VOU	Eclogite facies	Metaperidotite, *serpentinite, *ophicarbonate rocks, *metagabbro, metabasite, Qtz-schist, calcschist	Facies assemblages; Experimental phase equilibria; Grt–Cpx thermobarometry	Liou et al. (1998)
				Facies assemblages; Grt–Cpx–Ph thermobarometry	Federico et al. (2004)
				Grt zoning + Amp–Ep–Pg–Tlc–Cpx inclusions; THERMOCALC thermobarometry	Vignaroli et al. (2005)
				Facies assemblages; compiled thermobarometry	Capponi et al. (2016)
				Facies assemblages; Perple_X thermobarometry	Starr et al. (2020)
				Facies assemblages; Perple_X thermobarometry	Scambelluri et al. (2016)
Voltri Massif	Varazze Unit - VAU	Greenschist facies	Serpentinite, *metagabbro	Facies assemblages	Chiesa et al. (1975)
				Facies assemblages; mineral-chemistry thermobarometry	Desmons et al. (1999)
Voltri Massif	Palmaro-Caffarella Unit - PCU	Blueschist facies (HP)	Serpentinite, *metagabbro, metabasalt, Qtz-schist, metalimestone, calcschist	Facies assemblages	Cortesogno et al. (1979)
				Facies assemblages; Cpx composition; Grt–Cpx/Grt–Phe thermometry	Cabella et al. (1994)
				Grt-Cpx geothermometry; Perple_X thermobarometry	Malatesta et al. (2012a)
Sestri-Voltaggio zone	Cravasco-Voltaggio Unit CVU	Blueschist facies (LP)	Serpentinite, *metagabbro, *metabasalt, *Si-rich metasediment, *metalimestone, phyllade	Facies assemblages; compiled thermobarometry	Cortesogno and Haccard (1984)
				Facies assemblages; Cpx composition; Grt–Cpx/Grt–Phe thermometry	Cabella et al. (1994)
				Facies assemblages; Cal Geothermometer	Crispini (1996)
				Facies assemblages; mineral-chemistry thermobarometry	Desmons et al. (1999)
				Illite crystallinity	Leoni et al. (1996)
Sestri-Voltaggio zone	Figogna Unit - FU	Pumpellyite-actinolite facies	Serpentinite, *metagabbro, *pillow metabasalt, metabreccia, *Si-rich metasediment, *metalimestone, slate	Facies assemblages; compiled thermobarometry	Cortesogno and Haccard (1984)
				Cal–geothermometry	Crispini (1996)
				Facies assemblages; mineral-chemistry thermobarometry	Desmons et al. (1999)
	Montenotte Unit - MU	Blueschist facies (LP)	Serpentinite, *metagabbro, *metabasalt, *Si-rich metasediment, *metalimestone, phyllade	Facies assemblages	Cortesogno and Haccard (1984)
				Facies assemblages; Cpx composition; Grt–Cpx/Grt–Phe thermometry	Cabella et al. (1994)
				Facies assemblages; mineral-chemistry thermobarometry	Desmons et al. (1999)
				Perple_X thermobarometry	Malatesta et al. (2018)

Abbreviations: Amp, amphibole; Cal, calcite; Cpx, clinopyroxene; Ep, epidote; Grt, garnet; Pg, paragonite; Ph, phengite; Tlc, talc; HP, high pressure; LP, low pressure associations, are still debated. Different exhumation models, ranging from serpentinite-hosted subduction channels to the exhumation of large, relatively coherent slices along the plate interface, have been proposed, but no consensus has yet been reached (Brouwer et al., 2002; Federico et al., 2007a,b; Malatesta et al., 2012a; Starr et al., 2020; Smye et al., 2021). In this paper, we present a critical review of the current state of knowledge on the metamorphic ophiolites of the central Ligurian Alps, with a focus on the Voltri Massif and the SVZ. We synthesize published data on lithologies, metamorphic conditions, deformation history, geochronology, and fluid-rock interaction, and discuss their implications for subduction dynamics and the exhumation of oceanic lithosphere (e.g., Molli et al., 2010; Vignaroli et al., 2009a, 2010; Capponi et al., 2016; Starr et al., 2020; Smye et al., 2021). This review aims to provide an updated reference framework for future studies on Alpine meta-ophiolites and, more broadly, on fossil oceanic subduction interfaces.

GEOLOGICAL SETTING

Peri-Mediterranean and Alps-Apennine Ophiolite

The metamorphic ophiolites of the Ligurian Alps represent lithospheric remnants of the Jurassic Ligurian-Piedmont Ocean, preserved within the Alpine-Apennine orogenic system and classically interpreted as fragments of a Mesozoic Tethyan oceanic domain between Europe and Adria/Apulia (e.g., Chiesa et al., 1975; Principi and Treves, 1984; Vanossi et al., 1984; Nicolas et al., 1990; Hunziker et al., 1992; Martin et al., 1994; Le Breton et al., 2021). Very early syntheses on the Voltri-Ligurian meta-ophiolites emphasized their role as key archives for reconstructing oceanic lithosphere evolution and subsequent Alpine subduction/exhumation, within the broader "Calcescisti con Pietre Verdi" Auctt. framework (Chiesa et al., 1975; Chiesa et al., 1977).

While terminology varies (e.g., Western/Alpine Tethys, Ligurian Tethys), classic reconstructions and regional reviews framed the basin as part of the Western Tethyan realm and discussed alternative large-scale plate configurations through time (e.g., Ricou, 1994; Dal Piaz, 1999; Jolivet, 2023).

Recent kinematic reconstructions provide quantitative constraints on the rift-to-drift history of the Ligurian-Piedmont Basin, supporting a multi-stage evolution that includes: (i) rifting of proximal margins (ca. 200-180 Ma), (ii) hyperextension of distal margins (ca. 180-165 Ma), (iii) development of an ocean-continent transition (OCT) with mantle exhumation and MORB-type magmatism (ca. 165-154 Ma), and (iv) limited mature seafloor spreading mainly in the Late Jurassic (ca. 154-145 Ma), followed by a decrease in spreading rates and possible cessation by ~130 Ma (e.g., Le Breton et al., 2021; Frasca et al., 2024).

These domains subsequently evolved into ocean-type basins (e.g., the Ligurian-Piedmont and Valaisan basins), characterized by mantle peridotites, variably developed mafic crust, pelagic sedimentary covers and, locally, sedimentary mélanges recording ocean-continent transition processes, separating paleo-Europe from Adria/Apulia (e.g., Dal Piaz, 1999; Marroni et al., 2017; Handy et al., 2010; Le Breton et al., 2021).

Adria is commonly regarded as an African promontory in plate reconstructions, although its independent motion relative to Africa and Europe has also been discussed (e.g., Platt et al., 1989; Rosenbaum and Lister, 2004; Rosenbaum et al., 2004).

These oceanic basins were later involved in Alpine subduction, accretion and exhumation during convergence between Europe (lower plate) and Adria (upper plate), from Late Cretaceous through Cenozoic times (e.g., Schmid et al., 2004; Handy et al., 2010; Marroni et al., 2017; Le Breton et al., 2021).

Alpine convergence and the resulting subduction-collision history are commonly linked to the north- to northwest-directed motion of Adria with respect to Europe in the Late Cretaceous-Cenozoic framework (Platt et al., 1989; Schmid et al., 2004; Handy et al., 2010; Le Breton et al., 2021), consistent with early interpretations based on Alpine tectonic syntheses (Dal Piaz, 1999).

This convergence allowed accretion and exhumation of high-pressure to ultrahigh-pressure oceanic rocks, including newly documented coesite-bearing units and UHP plate-interface remnants in the Western Alps (e.g., Reinecke, 1991; Groppo et al., 2009; Angiboust et al., 2009; Scaramuzzo et al., 2026).

A major feature of the circum-Mediterranean orogenic system (Fig. 1a) is the so-called "Tethyan ophiolite duality", originally introduced following the works of Miyashiro (1973), Pearce et al. (1981) and Alabaster et al. (1982). This concept distinguishes Jurassic, magma-poor ophiolites of the western Tethyan realm (e.g., the former Ligurian-Piedmont and Valaisan oceans) from Late Cretaceous supra-subduction zone (SSZ) ophiolites developed in the eastern Mediterranean domains (e.g., the former Vardar Ocean, partly preserved in the Dinarides and Albanides; Rocci et al., 1975; Robertson, 2002). However, more recent studies have shown that this dual scheme may be oversimplified, as several ophiolitic sequences record transitional or polygenetic histories, reflecting the progressive evolution from continental rifting to subduction initiation. In this perspective, a more complex framework includes: (i) magma-poor, rift-related ophiolites associated with exhumed subcontinental mantle; (ii) supra-subduction zone ophiolites formed in intra-oceanic convergent settings; and (iii) hybrid or transitional ophiolites recording overprinting of subduction-related magmatism on pre-existing oceanic or hyperextended lithosphere.

Within this framework, western Alpine-Apennine ophiolites (Fig. 1b) are commonly linked to hyperextended margins and OCT domains, being locally associated with continental slices and/or preserving subcontinental lithospheric signatures in mantle sections (e.g., Marroni et al., 1998; Manatschal and Müntener, 2009; Rampone et al., 1995; Müntener et al., 2004; Montanini et al., 2012; Rampone and Sanfilippo, 2021 and ref. therein). The Ligurian-Piedmont domain is distinctive in preserving embryonic oceanic lithosphere generated in magma-poor OCT and slow- to ultraslow-spreading settings (e.g., Lagabrielle and Cannat, 1990; Tribuzio et al., 1995; Sanfilippo and Tribuzio, 2011) later involved in Alpine subduction and HP metamorphism. Some successions resemble OCT analogues such as Iberia-Newfoundland, whereas others compare with slow/ultraslow ridge lithosphere, including depleted peridotites intruded by MOR-type gabbro bodies, locally interpreted as oceanic core-complex-type associations (e.g., Lagabrielle and Cannat, 1990; Tribuzio et al., 1995, 1999; Rampone et al., 1996, 1997, 2009; Rampone and Hofmann, 2012; Principi et al., 2004; Sanfilippo and Tribuzio, 2011, 2013; Alt et al., 2012; Schwarzenbach et al., 2012; Rampone and Sanfilippo, 2021).

Based on geological, petrographic and geochemical data, as well as direct comparisons with modern oceanic crust-mantle sections, several schematic palaeogeographic reconstructions have been proposed for the distribution of Alpine-Apennine ophiolite massifs within the Ligurian-Piedmont ocean during the Late Jurassic (e.g., Manatschal and Müntener, 2009; Müntener et al., 2005; Müntener et al., 2010; Handy et al., 2010; Marroni et al., 2017; Vissers et al., 2013; Le Breton et al., 2021).

Palaeogeographic reconstructions propose margin-proximal to distal positions for different Alpine-Apennine massifs within the Late Jurassic Ligurian-Piedmont ocean, with the Voltri peridotitic complex occupying a debated position that may include exhumed subcontinental mantle related to Europe-Adria rifting (e.g., Handy et al., 2010; Manatschal and Müntener, 2009; Piccardo et al., 1994; Piccardo and Guarnieri, 2011; Marroni et al., 2010).

Comparative stratigraphic and sedimentological analyses indicate that Jurassic ophiolites in the Ligurian Alps and Northern Apennines record broadly synchronous processes during Middle-Late Jurassic seafloor spreading in the Ligurian-Piedmont ocean basin but metamorphic imprints differ across the system: Apennine ophiolites (External/Internal Ligurides) typically record low-grade oceanic metamorphism (prehnite-pumpellyite) and cool orogenic deformation, whereas Alpine ophiolites (Ligurian Alps) record high-P, low-T metamorphism up to blueschist- to eclogite-facies conditions (e.g., Cortesogno et al., 1975; Leoni et al., 1996; Ellero et al., 2001; Sanità et al., 2024).

The metamorphic ophiolite in the Ligurian Alps and the Alps-Apennine junction

From a regional perspective, the Ligurian Alps form the southern termination of the Italian Western Alps and occupy a key position at the transition toward the Northern Apennines. This Western Alps-Northern Apennines junction is characterized by pronounced three-dimensional structural interference, along-strike changes in transport direction and vergence, and repeated reactivation of inherited tectonic boundaries (Fig. 3). Rather than a discrete tectonic line, the junction is therefore better regarded as a broad interference zone in which Alpine and Apenninic nappe contacts, metamorphic boundaries, basin margins, and late strike-slip to transpressive structures overlap in space and time (Elter and Pertusati, 1973; Laubscher et al., 1992; Spagnolo et al., 2007; Crispini et al., 2009; Molli et al., 2010; Mosca et al., 2010; Malusà and Balestrieri, 2012; Schmid et al., 2017).

At first order, this junction includes three interconnected morphostructural domains (Fig. 4a): (i) the Ligurian Sea and the Liguro-Provençal-northern Tyrrhenian back-arc region; (ii) the S-shaped mountain belt extending from the Cottian-Maritime Alps through the Ligurian Alps into the Northern Apennines; and (iii) the western Po Plain, together with the Tertiary Piedmont Basin and related Cenozoic depocentres (e.g., Molli et al., 2010 and ref. therein). The development of the Liguro-Provençal back-arc system and its link with Oligocene-Miocene plate-boundary reorganization and rotation/drift of the Corsica-Sardinia block are widely framed in rollback/back-arc reconstructions and plate-kinematic models for the western Mediterranean (Rosenbaum et al., 2002; Rosenbaum and Lister, 2002; Schettino and Turco, 2006). These domains record the superposition of Mesozoic palaeogeographic inheritance, Alpine subduction and collision, and an Oligocene-Miocene reorganization of the plate boundary, expressed by major crustal discontinuities and transpressional zones in the "Ligurian knot"/Alps-Apennines interference region (e.g., Laubscher et al., 1992; Crispini et al., 2009; Mosca et al., 2010; Molli et al., 2024). Their architecture is broadly double-vergent, with southwest-vergent structures affecting the external Alpine side and northeast- to east/northeast-vergent structures involving the innermost units and their boundary with Po-side basinal domains (Fig. 4b, c). This geometry has been interpreted as the result of late-stage transpression superposed on an earlier Alpine nappe stack, with Oligocene-Miocene brittle transpression and strain partitioning in the Ligurian knot (Crispini et al., 2009; Spagnolo et al., 2007; Molli et al., 2010 and 2024), and has also been discussed in the context of slab kinematics and polarity changes at the Western Alps-Northern Apennines junction (Vignaroli et al., 2008).

The Ligurian Alps are characterized by metamorphic ophiolites mainly exposed in the Voltri Massif, the SVZ and the Montenotte Unit (Fig. 2). These are dominated by serpentinite-rich successions, with associated mantle peridotites, metagabbros and metabasalts, locally overlain by metamorphosed sedimentary covers including calcschists, marbles and metapelagic deposits (Capponi et al., 2016; Principi et al., 2004). The magmatic crustal component is generally discontinuous and poorly developed, being represented mainly by isolated gabbroic bodies, basaltic dykes and rare plagiogranites rather than by a complete sheeted-dyke and lava sequence (Figs. 5 and 6). This architecture is consistent with the magma-poor Tethyan ophiolite framework described for Alpine-Apennine ophiolites (e.g., Manatschal and Müntener, 2009; Rampone and Sanfilippo, 2021) and supports lithostratigraphic and palaeogeographic correlations

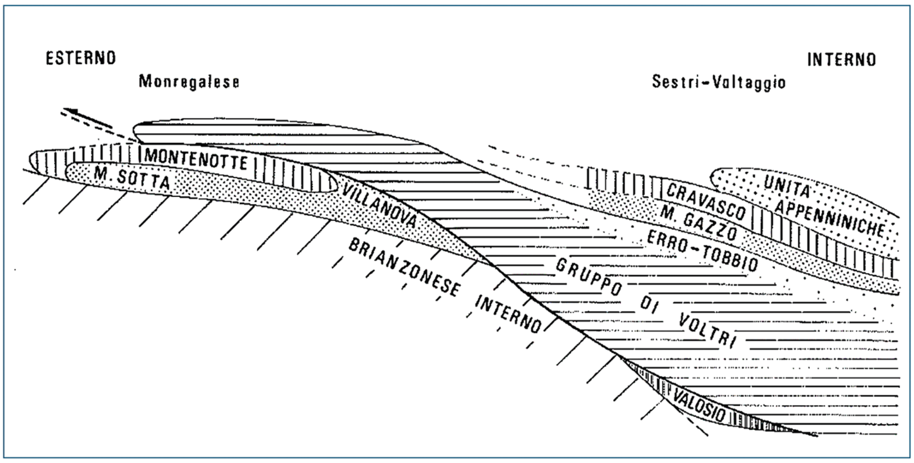

Fig. 3 - Historical sketch summarizing the tectonostratigraphic relationships among the main units of the Voltri Massif and the Sestri-Voltaggio Zone in the Alpine-Apennine junction. The diagram illustrates the relative position of the Voltri Massif units (Gruppo di Voltri and Erro-Tobbio Auctt.) and the Sestri-Voltaggio Zone units (i.e., Cravasco and M. Gazzo units Auctt.) with respect to the Briançonnais domain and the Apennine units. External (Monregalese) and internal (Sestri-Voltaggio Zone) sectors are distinguished, highlighting the overall structural framework and large-scale tectonic relationships. From Vanossi et al. (1984).

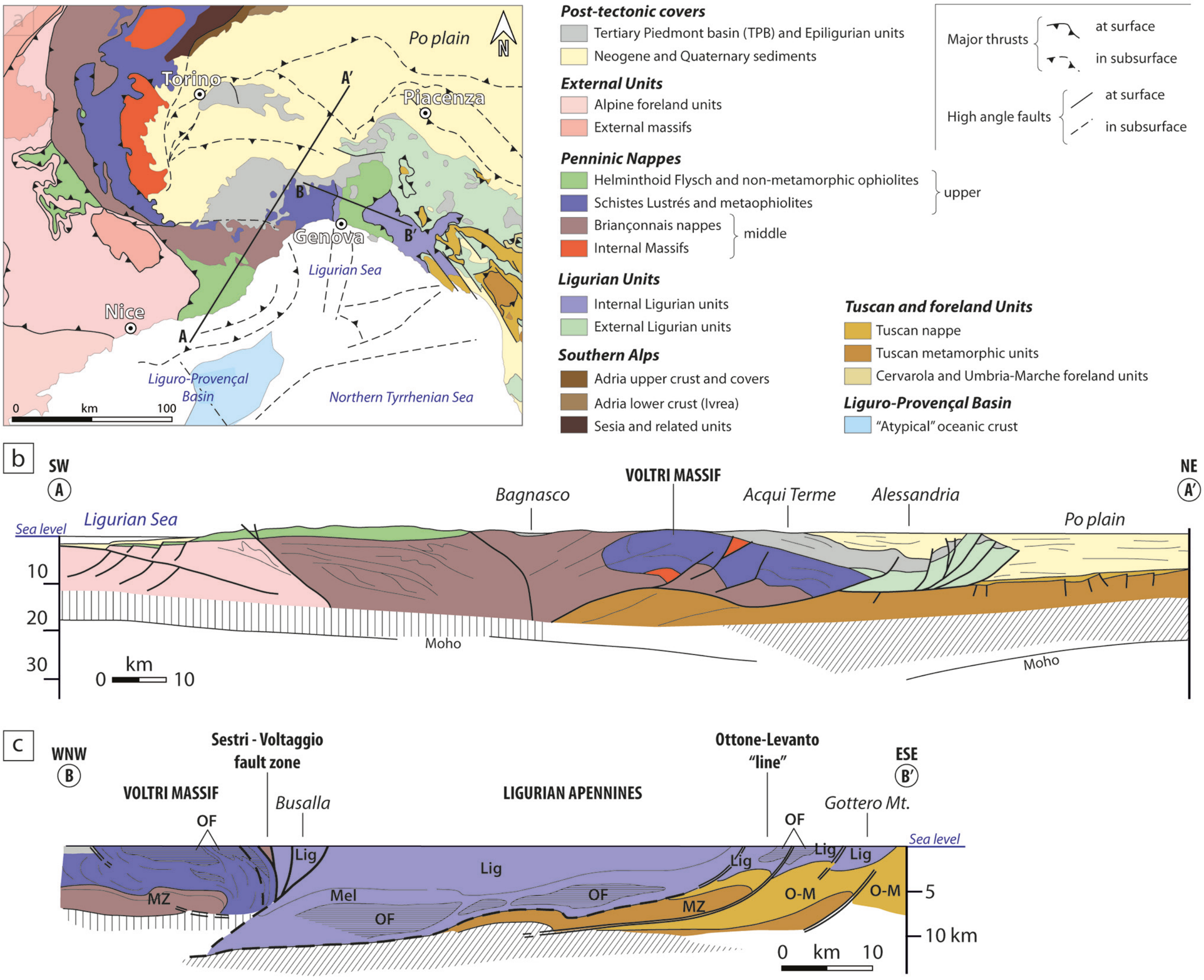

Fig. 4 - Tectonic map and regional-scale cross-sections across the Western Alps and Northern Apennines junction area (redrawn from Molli et al., 2010). (a) Tectonic map of Western Alps/Northern Apennine junction area, with the major thrusts and high angle faults. See Molli et al. (2010) and refs. therein, offshore tectonic structures derived from Morelli et al. (2022). (b) Geological cross-section from the Liguro-Provençal basin (SW) to the Po plain (NE) redrawn after Molli et al. (2010). (c) General crustal-scale cross section from the Voltri Massif (WNW) to the Mt. Gottero (ESE); enlightened the Sestri-Voltaggio zone (SVZ). Structural data and units are redrawn and modified after Biella et al. (1988) and Molli et al. (2010). Abbreviations: OF, ophiolites; MZ, Meso-Cenozoic successions; Lig, Ligurian units; Mel, ophiolite mélange; O-M, Oligo-Miocene deposits of the Tertiary Piedmont Basin.

with the non-metamorphic ophiolitic successions of the Internal and External Ligurian Units in the Northern Apennines. Accordingly, the metamorphic ophiolites of the Ligurian Alps and the non-metamorphic Ligurian Units may represent different crustal levels, tectonic positions and metamorphic trajectories of the same oceanic lithosphere, reflecting variable involvement in Alpine subduction and later orogenic reworking (e.g., Decandia and Elter, 1972; Marroni et al., 2010; Beltrando et al., 2014; Lagabrielle et al., 2015; Capponi et al., 2016 and references therein).

Peak metamorphic conditions of Ligurian Alps ophiolites range from pumpellyite-actinolite to blueschist to eclogite-facies, followed by retrograde low grade to greenschist-facies overprinting (Cortesogno and Haccard, 1984; Messiga and Scambelluri, 1991; Desmons et al., 1999; Capponi and Crispini, 2002; Federico et al., 2005; Molli et al., 2010; Vignaroli et al., 2010). The Ligurian metamorphic ophiolites preserve a polyphase history in which relic eclogite-facies foliations and rootless isoclinal folds are attributed to subduction processes, whereas Na-amphibole-bearing greenschist-facies folds and schistosities are related to exhumation and nappe stacking. These fabrics are overprinted by upper-crustal deformation expressed by systems of brittle-ductile and brittle structures (e.g., Spagnolo et al., 2007; Crispini et al., 2009; Molli et al., 2010).

As mentioned above, the divide between the metamorphic and the unmetamorphosed Ligurian ophiolites is ideally represented by the SVZ (Figs. 1b and 2), which forms a kilometre-wide, north-south-trending high-strain corridor along the eastern margin of the Voltri Massif (Figs. 2, 4 and 5). The SVZ is bounded to the west by the Sestri-Voltaggio Line, a steeply dipping fault separating it from the High-P low-T meta-ophiolites of the Voltri Massif, and to the east by very low-grade Ligurian flysch units and the unmetamorphosed Antola Unit (Figs. 2 and 4; Cortesogno and Haccard, 1984; Capponi and Crispini, 2002; Molli et al., 2010). Since

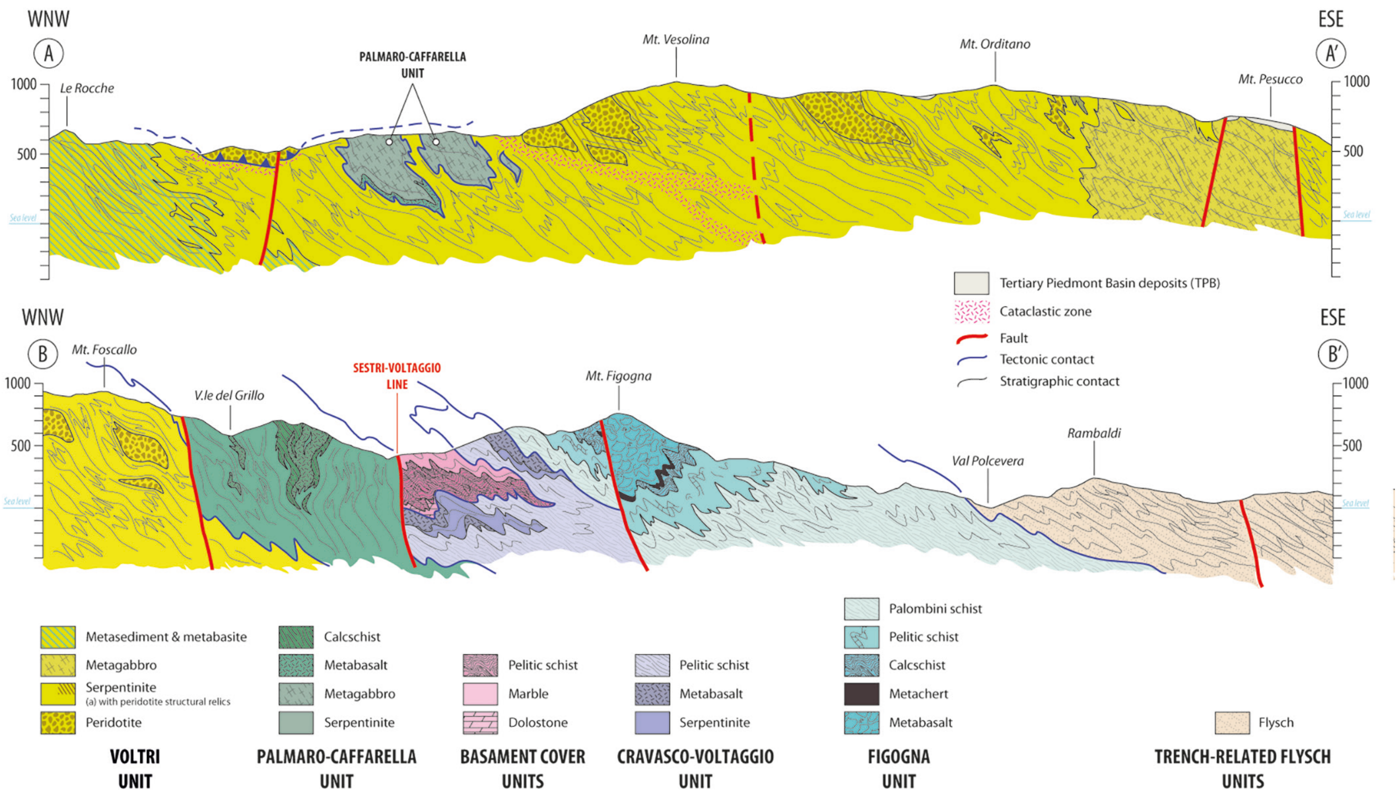

Fig. 5 - Geological cross-sections (traces in Fig. 2) showing the complex structural architecture of the area across the innermost sectors of the Ligurian Alps (i.e., the Voltri Massif, Sestri-Voltaggio Zone and trench-related flysch units). Units name and colour code as in Fig. 2. Cross-sections are redrawn and modified after the Geological Map CARG Sheet "230-GENOVA" (scale 1:50.000) and Capponi and Crispini (2008a).

the earliest interpretations of the Alps-Apennine boundary, the SVZ has played a central role in discussions of Alpine-Apenninic relationships. Its significance has progressively shifted from that of a discrete plate boundary to that of a polyphase high-strain zone: an early nappe contact later reworked at shallow crustal levels, marked today by steep tectonic contacts, intense shearing and fracturing, folded shear zones, and repeated strike-slip reactivation (Elter and Pertusati, 1973; Cortesogno and Haccard, 1984; Crispini and Capponi, 1997, 2001; Spagnolo et al., 2007; Crispini et al., 2009; Molli et al., 2010).

In the context of the Ligurian metamorphic ophiolites, the SVZ is particularly important because it juxtaposes oceanic-derived units that experienced contrasting pressure-temperature conditions and preserves a complex record of subduction-related deformation, exhumation and late reactivation. Regional top-to-the-east/northeast backthrusting affected both the metamorphic basement and Oligocene deposits of the Tertiary Piedmont Basin (e.g., Fig. 4b, c), and subsidiary structures indicate that activity along the "Sestri-Voltaggio Line" persisted into the late Oligocene-early Miocene (e.g., Cortesogno and Haccard, 1984; Crispini et al., 2009; Molli et al., 2010; Piana et al., 2006). Collectively, these features define the Ligurian collisional knot of Laubscher et al. (1992): a structurally congested domain in which Alpine and Apenninic tectonic processes are not merely adjacent, but superposed and mechanically intertwined. This concept captures the dual nature of the region as both the southern termination of the Western Alps and the northwestern entrance into the Northern Apennines (Laubscher et al., 1992; Crispini et al., 2009; Molli et al., 2010).

LITHOLOGICAL FRAMEWORK OF THE LIGURIAN ALPS METAMORPHIC OPHIOLITES

The largest body of metamorphic ophiolites in the Ligurian Alps, and one of the most extensive meta-ophiolitic complexes of the Alpine chain, is the Voltri Massif (also referred to as the "Voltri Group" in older literature; e.g., Chiesa et al., 1975). It is commonly interpreted to represent a fragment of the Ligurian-Piedmont oceanic domain that was involved in subduction and then exhumed.

The Voltri Massif is characterized by pronounced lithological, structural and metamorphic heterogeneity, and both metamorphic re-equilibrations and deformation structures are distributed unevenly within and among the different lithologies. This complexity has resulted in the proposal of several alternative tectonic subdivisions and groupings, as well as different evolutionary and geodynamic models (e.g., Chiesa et al., 1975; Messiga et al., 1983; Hoogerduijn Strating, 1991; Capponi et al., 1994; Vignaroli et al., 2010; Malatesta et al., 2012a; Capponi et al., 2016; Starr et al., 2020).

The lithologies of the Voltri Massif (Figs. 2 and 3) have been historically grouped in units using different criteria and various names (e.g. Chiesa et al., 1975; Messiga et al., 1983, Hoogerduijn Strating, 1991, Capponi et al., 1994, Capponi et al., 2016). A comprehensive review of this literature can be found in Capponi et al., (2016) where the Authors propose a simplified-comprehensive classification, based on the tectonic and metamorphic evolution where the Voltri Massif meta-ophiolites are divided into three units using tectono-metamorphic criteria (see also Table 1):

- the eclogitic-facies Voltri Unit (VOU hereafter), mainly composed of metamorphosed serpentinite that contains Fe-Ti-oxides rich metagabbro bodies (eclogite in Fig. 2; "Beigua Unit or Beigua-Ponzema Unit and San Luca-Colma Unit Auctt."), in addition to associated oceanic metasediments that include micaschists, quartz-schists and calcschists (e.g. Capponi et al., 2016; Chiesa et al., 1975; Cortesogno et al., 1977; Hoogerduijn-Strating, 1991; "Voltri-Rossiglione, Ortiglieto, Alpicella Units Auctt.") and to partly serpentinized metaperidotite (originally mainly spinel and plagioclase lherzolites) intruded by metagabbroic dykes that records an Alpine subduction history (e.g. Capponi and Crispini, 1990; Piccardo et al., 1988; Scambelluri et al., 1991, 1995; "Erro-Tobbio Unit Auctt.");
- the blueschist-facies Palmaro - Caffarella Unit (PCU hereafter; Cortesogno et al., 1979; Cabella et al., 1994; Malatesta et al., 2012a), characterized by metamorphosed serpentinite, with bodies of metagabbro and by a metamorphosed volcano-sedimentary sequence (metabasalts, quartz-schist and calcschist);
- the greenschist-facies Varazze Unit (VAU hereafter; Capponi et al., 2016; Chiesa et al., 1975), made up of metamorphosed ultramafite and metagabbro.

The Voltri Massif is bounded (Figs. 2 and 5), (i) to the east, by the SVZ (see below) that separates the HP Voltri Massif from the low-grade to non-metamorphic sequences of the Northern Apennine (Cortesogno and Haccard, 1984); (ii) to the west, by the Hercynian basement of the Briançonnais (Arenzano and Savona Crystalline Massifs; e.g., Allasinaz et al., 1971, Capponi, 1990) and by the meta-ophiolitic sequences of the Montenotte Unit (Vanossi et al., 1984); and (iii) to the north, by the Valosio Crystalline Massif and the Tertiary Piedmont Basin (TPB). The TPB contains Upper Eocene to Miocene sedimentary successions deposited at the top of the already exhumed Alpine belt (Gelati et al., 1998; Ghibaudo et al., 2019). High pressure and eclogitic meta-ophiolitic clasts are reported from the lowermost conglomeratic levels of the TPB (e.g. Cortesogno and Haccard, 1984; Federico et al., 2004).

The SVZ was originally defined by Görler (1962) and Görler and Ibbeken (1964) as a complex of rocks, extending from Sestri Ponente to Voltaggio (Figs. 2 and 4) in a 5-6 km-wide N-S strip (Görler & Ibbeken, 1964). This area has long attracted scientific interest and discussion because of its intermediate position between the deeply subducted oceanic lithosphere of the Voltri Massif and the shallower portions of the Northern Apennines domain (e.g.: Elter and Pertusati, 1973; Cortesogno and Haccard, 1984; Hoogerduijn Strating E.H., 1991; Crispini and Capponi, 2001; Molli et al., 2010 for a review). Accordingly, the western contact of the SVZ (commonly referred to as the Sestri-Voltaggio Line) has historically been regarded, for many years, as the boundary between the Alps and the Northern Apennines (since Rovereto, 1939).

In this framework, the SVZ is composed of tectonically juxtaposed slices (along folded foliations, shear zones and faults) preserving different peak metamorphic assemblages and foliations (from blueschist- to pumpellyite-actinolite-facies, variably overprinted), organized in a high-strain, composite structural framework that can be described as a mélange-like domain or a km-scale shear zone (Cortesogno & Haccard, 1984; Hoogerduijn Strating, 1991; Crispini and Capponi, 2001; Molli et al., 2010).

Lithologies in the SVZ are commonly grouped into three main tectono-metamorphic units: the Cravasco-Voltaggio Unit (CVU hereafter), the Figogna unit (FU hereafter) and the Gazzo - Isoverde units (e.g., Cortesogno and Haccard, 1984; Desmons et al., 1999; Crispini and Capponi, 2001; Capponi et al., 2016). Earlier studies proposed alternative subdivisions, including the Timone-Teiolo Unit (internally composed of the Timone and Tejolo elements) defined as an independent ophiolitic unit (e.g., Marini, 1977, 1984, 1998), and the interpretation by Hoogerduijn Strating (1991) who defined the western Lavagna Nappe as a separate unit from the SVZ (composed only by CVU and Gazzo Isoverde Unit).

The CVU comprises meta-ophiolites and associated metasediments, whose lithostratigraphic features suggest that it is derived from the Ligurian-Piedmont oceanic domain (Jurassic - Cretaceous in age). Similarly, the FU comprises meta-ophiolites and related metasediments, but it records metamorphic peak conditions in pumpellyite - actinolite facies.

The Gazzo - Isoverde Unit is not an ophiolite (it is made up of dolostone, limestone and schist, of Triassic - Lower Jurassic age and continental shelf or OCT origin), but shares part of the same syn-orogenic deformations of the CVU; this structural evidence points to a Low-T blueschist-facies equilibration also for the Gazzo - Isoverde Unit. This interpretation is further supported by calcite deformation microstructures indicating a T>300°C (Crispini, 1996).

The Montenotte Unit (MU) comprises a meta-ophiolitic sequence, from serpentinite to slate, characterized by a metamorphic peak in blueschist-facies; it crops out to the west of the Voltri Massif (Fig. 2) and generally tectonically overlies it. MU has traditionally been correlated with the CVU, based on strong similarities in both stratigraphy and metamorphic evolution (e.g., Haccard and Lemoine, 1970). Moreover, like the CVU, it is associated with a carbonatic unit of continental margin affinity (Monte Sotta Unit; Capponi et al., 2013 and references therein). As a consequence, some Authors grouped the two meta-ophiolitic units into the "Cravasco-Voltaggio-Montenotte Unit" (CVMU; i.e. Cortesogno and Haccard, 1984, Vanossi et al., 1984 and Cabella et al., 1994) owing to convergent lithological and metamorphic characteristics, although they may differ from a tectonic and possibly geochronological perspective. For the sake of brevity, we will follow this tradition below and we describe their lithological and metamorphic features together; i.e., CVU+MU= CVMU.

The lithostratigraphy of the various tectono-metamorphic units is summarized in Fig. 6.

Ultramafic rocks: metamorphic peridotites and serpentinites

The most common ultramafic rocks, exposed in all meta-ophiolitic units are serpentinites, which locally preserve mineralogical and/or textural relics of their peridotitic protoliths.

High-Pressure metamorphism in serpentinite is not always easily recognizable in the field; nevertheless, systematic variations in serpentine mineralogy are observed among the different units.

In the lowest-grade FU, serpentinites are dominated by chrysotile and lizardite, whereas antigorite appears and becomes increasingly abundant in the higher-grade units. Antigorite is well developed in the CVMU and PCU, and dominant or even exclusive in the VOU. In VOU higher-grade domains, antigorite is typically associated with magnetite, metamorphic olivine, chlorite, and Ti-clinohumite, reflecting equilibration under HP-LT conditions (Hoogerduijn Strating et al., 1993; Scambelluri et al., 1995, 1997; Capponi and Crispini 2008a; 2008b); but they record a polyphase evolution, with prograde low-grade chrysotile-lizardite replaced by antigorite and then

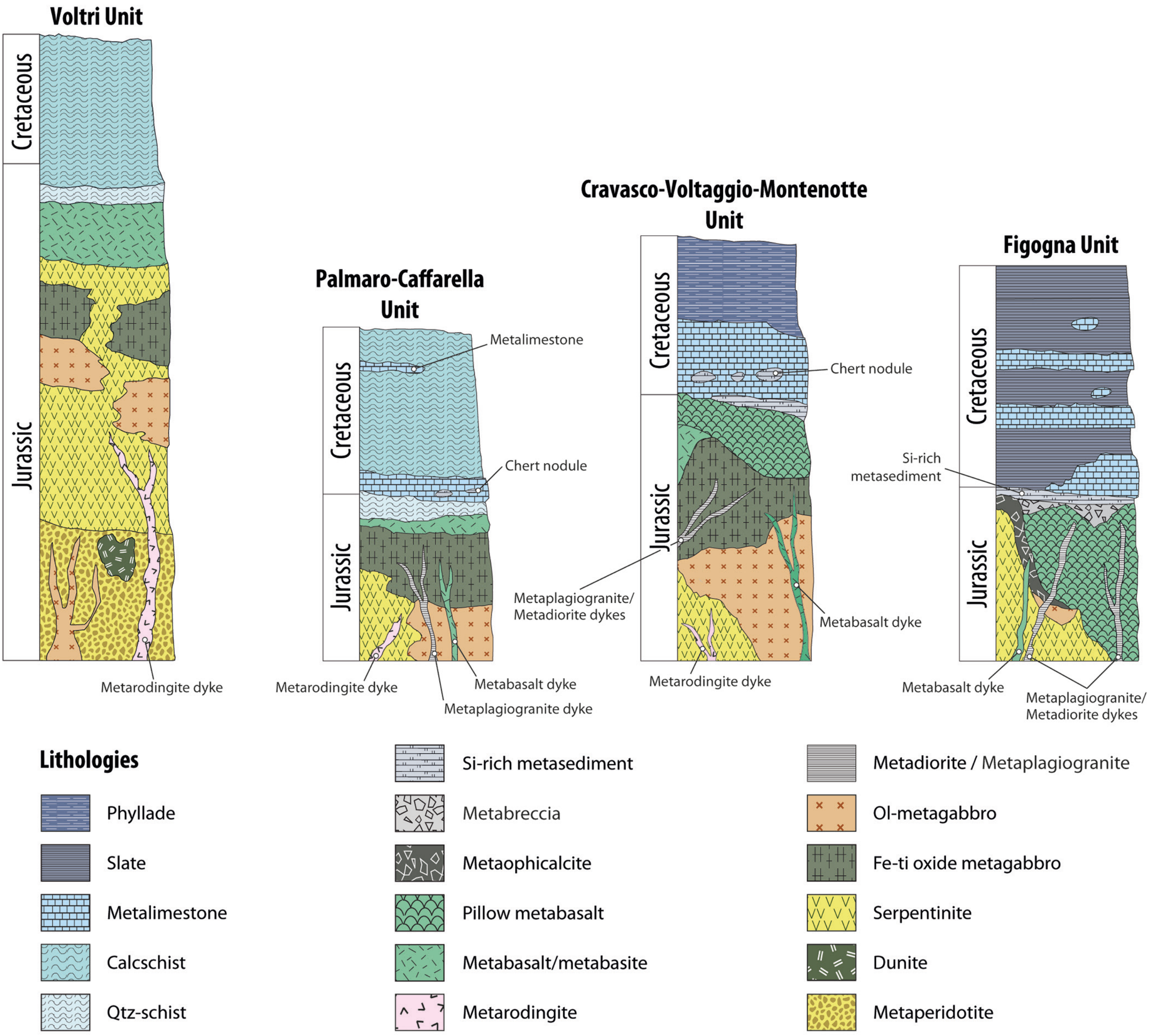

Fig. 6 - Simplified lithostratigraphic columns of the meta-ophiolite units from the Voltri Massif, not to scale. The adopted colour code distinguishes between different lithologies and is not referred to single units as in Fig. 2. The columns are modified from: Cortesogno and Haccard (1984), Principi et al. (2004) and Capponi and Crispini (2008a; 2008b).

by olivine-bearing metamorphic assemblages (Cimmino et al., 1979; Scambelluri and Rampone, 1999).

Metarodingite dykes occur in all units and derive from metasomatic transformation of basaltic or gabbroic dykes intruded into the ultramafic protoliths. Their metamorphic associations are variable, but commonly include grossular ± vesuvianite ± chlorite ± diopside ± clinozoisite (Capponi and Crispini 2008b).

Beyond serpentinite and serpentinized peridotite, in the VOU the other well-represented ultramafic rocks are metaperidotite (Fig. 2). These rocks were traditionally grouped within the Erro-Tobbio Unit or Erro-Tobbio peridotite (e.g., Chiesa et al., 1975, Scambelluri et al., 1991, Piccardo et al., 1992, Borghini et al., 2007), but are more recently included in the Voltri tectono-metamorphic Unit (see Capponi et al., 2016).

Metaperidotite consists mainly of spinel-bearing lherzolites and harzburgites with local dunite and pyroxenite layers and troctolite-gabbro intrusions.

Peridotites display granulitic, tectonic and mylonitic textures, reflecting different stages of mantle deformation prior to Alpine subduction.

Previous petrological and structural studies describe, for the pre-Alpine evolution, a decompressional tectono-metamorphic history from deep lithospheric conditions (>15-20 kbar) to shallow levels (<5 kbar), with progressive re-equilibration from spinel- to plagioclase- and amphibolite-facies conditions. Exhumation likely occurred in an extensional regime, with development of shear zones producing spinel tectonites and a spectrum of mylonites (plagioclase-, hornblende- and chlorite-bearing, as well as serpentinite mylonites). This extension-related unroofing was accompanied by repeated melt percolation and intrusions (e.g., Hoogerduijn-Strating et al., 1990, 1993; Vissers et al., 1991; Rampone et al., 2005).

This evolution is interpreted as related to proximity of the subcontinental mantle peridotites to the Jurassic ocean floor of the Ligurian-Piedmont basin and is likely the result of lithospheric-scale extensional shear zones active during the embryonic stages of a slow to ultraslow spreading system. In this setting, mantle exhumation, melt impregnation and detachment faulting led to the construction of a highly heterogeneous oceanic lithosphere, analogous to modern oceanic core complexes and magma-poor rifted margins (Lagabrielle and Cannat, 1990; Manatschal and Müntener, 2009; Rampone and Borghini, 2008; Padovano et al., 2015; Rampone and Sanfilippo, 2021). The VOU mantle rocks were tectonically coupled with the oceanic crust and thus shared a common metamorphic evolution during the Alpine subduction and exhumation.

As a consequence of strong strain partitioning, large volumes of peridotites locally preserve almost intact primary textures and mineral assemblages despite Alpine metamorphic overprint (Drury et al., 1990; Hoogerduijn Strating et al., 1990; Scambelluri et al., 1991).

Such an apparent lack of metamorphic and structural reactivation in the Alpine cycle initially drove some authors to interpret the Erro-Tobbio peridotites as mantle slices that had largely escaped Alpine subduction-related reworking and were only emplaced onto the Voltri units during late Alpine tectonics (e.g., Chiesa et al., 1975). This "weakly reworked mantle slice" perspective has also been implicitly adopted in some regional-scale geodynamic reconstructions of the Alps-Apennines junction (e.g., Vignaroli et al., 2008), but the associated structural/exhumation scenario has been debated in subsequent discussion (Capponi et al., 2009; see also Vignaroli et al., 2009b).

Various authors showed the occurrence of eclogite-facies Alpine metamorphic re-equilibration in the Erro-Tobbio rocks, particularly well-developed in metagabbro dykes, emplaced in peridotites, as well as by olivine- and Ti-clinohumite-bearing veins documenting fluid circulation along the subduction interface (e.g., Capponi and Crispini, 1990; Messiga et al., 1995; Hoogerduijn Strating et al., 1990; Scambelluri et al., 1991; Scambelluri et al., 1995).

Metaperidotites are locally transformed into carbonate-bearing ultramafic rocks (meta-ophicalcite, meta-ophicarbonates and listvenites), which occur as meter- to decameter-scale bodies interlayered with serpentinite and associated oceanic metasedimentary rocks (e.g., Cortesogno et al., 1981; Molli, 1996; Principi et al., 2004; Scambelluri et al., 2016, Collins et al., 2015; Cannaò et al., 2020; Spagnolo et al., 2007; Locatelli et al., 2024).

In general, metamorphic ophicarbonate may represent (i) oceanic tectono-hydrothermal breccias to mylonite (e.g., listvenite) formed during mantle exposure, (ii) oceanic sedimentary ophiolitic breccias produced by reworking of ultramafic/mafic debris, or (iii) Alpine tectonic breccias to mylonite generated during subduction-exhumation-related deformation and fluid-rock interactions (e.g., listvenites). Accordingly (as also observed in the Ligurian Apennines) ophiolitic breccias (including ophicalcite-bearing levels) may either directly drape serpentinized ultramafics in 'reduced' successions, or occur higher in the crustal sequence, e.g., preceding and/or overlying basaltic flows in 'complete' successions reflecting strong lateral variability in ocean-floor architecture and subsequent tectonic overprint. Ophicarbonate become strongly sheared and recrystallized during prograde subduction metamorphism from pumpellyite-actinolite to blueschist and eclogite-facies. Carbonate fabrics and veins, including their oxygen-isotope signatures, may be variably overprinted and reset during Alpine metamorphism and fluid-rock interaction (e.g., Früh-Green et al., 1990; Marroni et al., 2001; Collins et al., 2015; Cannaò et al., 2020; Bernoulli and Weissert, 2021).

In FU are relatively abundant decametric to kilometre-scale bodies of meta-ophicalcite, made up of serpentinite breccia, and minor basaltic pillow/breccia horizons, cemented by carbonates, cited in literature as "Verde Polcevera" and "metaoficalciti di Pietralavezzara" Fm. (e.g., Cortesogno and Haccard, 1984; Capponi and Crispini, 2008b). They are interpreted as seafloor-related tectonic and sedimentary breccias.

In the CVMU, ophiolitic breccias occur both as pillow-/pillow-breccia metabasalts and as cataclastic serpentinite breccias and fault rocks (cataclasites to gouge) within the ultramafic domain.

Metagabbros and associated metaplagiogranites

Metagabbros occur in variable proportions and volumes, in all the meta-ophiolitic units. The FU includes only scarce metagabbro occurrences (Capponi et al., 2016) whereas in the CVMU, PC and VOU metagabbros comprise either relatively less differentiated typologies (i.e.: Ol-gabbros and -Pl-Cpx gabbros derivates) or more evolved Fe-Ti-oxide-rich metagabbros, locally separated in distinct mapped lithologies. By contrast, the VAU mainly contains metamorphic Ol-gabbros.

Gabbros of the VOU display tholeiitic compositions with N-MORB affinity (e.g., Bocchio and Mottana, 1975). The less differentiated products (like those from the Erro-Tobbio Unit Auct.) have primitive N-MORB affinities, reflecting their origin from depleted mantle sources during lithospheric extension (e.g., Piccardo, 1984; Borghini et al., 2007). This geochemical signature is similar to the one of the non-metamorphic gabbros of the Ligurian Units, thus confirming the common origin within the Ligurian-Piedmont ocean (e.g., Tribuzio et al., 1996; 2004).

In general, primary features (i.e.; magmatic texture, HT-oceanic foliations, mineralogical assemblages and veins) are best preserved in the units with metamorphic peaks at lower P and T conditions, i.e. in decreasing order, in the CVMU, PCU and VAU and VOU.

In the meta-Ol-gabbros and meta-plagioclase+ clinopyroxene gabbros of the CVMU, VAU and PCU the pristine texture, with large-to-medium grain size, is still preserved; in the same units the Fe-Ti-oxide-rich metagabbros are crosscut by dolerite, diorite and plagiogranite dykes. Both gabbro types show evidence of assemblages developed during ocean-floor HT metamorphism (diopside and brown hornblende), overprinted by HP parageneses that are more pervasive in the PCU.

In the VOU the primary mineralogy is completely overprinted by metamorphic minerals, whereas the textural relics of the magmatic phase are still locally present. The variety rich in Fe-Ti oxides (usually referred to simply as "eclogites"; see Fig. 2) usually gives rise to lower-variance assemblages with respect to the Ol-gabbro one and therefore have been long studied to derive P-T-t constraints (see par. 4.1). They frequently show tectonic and mylonitic varieties, with omphacite porphyroclasts.

Metaplagiogranites (metamorphosed plagiogranites) occur as felsic dykes and small intrusive bodies within the serpentinite-gabbro association, and are documented in both the

Voltri Massif and the SVZ (Cortesogno and Haccard, 1984; Borsi et al., 1996; Borsi et al., 1998; Capponi and Crispini, 2008a; 2008b). They are best preserved and described within the PCU (Voltri Massif), and the CVU for the SVZ, where they are associated with metagabbros and locally occur as centimetre- to metre-wide dykes cutting gabbros, serpentinites and mafic dykes (basalt and diorite), up to the lower part of the volcano-sedimentary sequence (Borsi et al., 1996; Serri, 1980; Tiepolo et al., 1997). These rocks are originally magmatic and represent low-K leucocratic late-stage differentiates of ocean-floor tholeiitic to MORB-type basaltic melts, emplaced during Jurassic oceanic magmatism in the Piedmont-Ligurian domain (e.g., Borsi et al., 1998; Castelli et al., 2002; Tribuzio et al., 2016). Alpine subduction metamorphism variably overprinted their primary igneous textures and mineralogy, producing metaplagiogranites in which relict quartz + plagioclase/albite ± amphibole may coexist with metamorphic assemblages dominated by albite + Na-amphibole ± epidote ± titanite under blueschist- to higher-pressure conditions (Borsi et al., 1996). In addition, interaction with ultramafic host rocks and fluid-assisted metasomatism may substantially modify the bulk composition, locally driving plagiogranitic protoliths toward Ca-rich rodingitic assemblages in strongly altered settings (e.g., Borsi et al., 1996; Castelli et al., 2002). Metaplagiogranites are particularly important for the study of metamorphic ophiolites because they commonly contain zircon and thus provide robust U-Pb crystallization ages that directly date oceanic magmatism even where mafic rocks are strongly recrystallized or metamorphically re-equilibrated (e.g., Borsi et al., 1996; Lombardo et al., 2002; Tribuzio et al., 2016). In the Ligurian Alps, zircon U-Pb ages obtained from such rocks constrain Late Jurassic emplacement (~150-153 Ma), thereby providing key time markers for the pre-subduction evolution of the oceanic lithosphere later involved in the Alpine tectono-metamorphic history (Borsi et al., 1996).

Metabasites: volcanic and volcanoclastic sequences

The original volcanic section of the oceanic crust, pertaining to the same tholeiitic sequence as the gabbros, is better preserved in FU, where the pillow structures, although deformed, are still recognizable. They are accompanied by levels of hyaloclastite and volcanic breccia, crosscut by basalt and diorite dykes (Fig. 6).

In the CVMU metabasalts are quite scarce and still preserve their original pillow or dyke shape; however, the pillows are often severely deformed and flattened along the main schistosity, boudinaged and transposed until they are transformed into layered metabasite.

In the PCU the original basaltic texture is no longer recognizable and the volcanics are converted into fine-grained, layered metabasite with alternated yellowish (epidote-rich) and blue-greenish (Na-amphibole-rich) levels.

In the VOU, metabasite ("prasiniti" Auct.) likely derive either from basalts of tholeiitic affinity (Messiga et al., 1977), even if the primary textures are never preserved, or from basaltic breccia or mafic sandstones. Sometimes they show layered texture, with alternating yellowish (epidote-rich) and greenish (Ca-amphibole and chlorite-rich) levels and the typical poikiloblastic albite porphyroblasts.

At the serpentinite-eclogite, serpentinite-metabasite and serpentinite-calcschist contacts, centimetre- to metre-thick layers of hybrid-rocks locally occur. These lithologies consist mainly of chlorite + actinolite ± talc ± calcite and have been commonly cited in literature as "chlorite-actinolite schists" or "SAC" (e.g., Allasinaz et al., 1971; Capponi et al., 2008a; 2008b). They typically show a mylonitic fabric and are interpreted to form through strain localization coupled with fluid-assisted metasomatic exchange between the juxtaposed lithologies.

Metasediments of the Oceanic Crust Cover Sequence

A wide variety of metasedimentary lithologies are present that derive from the oceanic-crust cover sequence, originally composed of chert, limestone, and shale, and subsequently variably metamorphosed and sheared.

In the FU cherty metasediments still preserve their original reddish to green colour (typical of the "Diaspri" Fm. Auctt.) with relics of radiolarian skeletons and radiolarian moulds replaced by secondary minerals. They are underlain by metabreccia with metabasaltic clasts and grade upward into metacalcarenite or metamudstone, followed by slate alternating with metalimestone; the proportion of limestone layers decreases towards the top of the sequence (Fig. 6).

In the CVMU cherty metasediments are also reddish and green and contain variable amounts of phyllosilicates and carbonates, with rare relics of radiolarians and radiolarian moulds replaced by secondary minerals. They are underlain by greenish ophiolitic metasandstone layers. The limestone section consists of crystalline, impure metalimestone, rich in quartz grains ("calcaire pointillés" of French authors). Upsection, layers of slates become progressively more abundant eventually becoming the dominant lithology.

In the PCU the metasedimentary sequence starts with thin and discontinuous layers of quartzschists, locally Mn-rich (with spessartine, piemontite, and Mn-chlorite) or hematite-rich. The most abundant metasedimentary lithology is a calcschist/micaschist, with layers of metalimestone-marble and quartzschists; variations in the relative abundance of white mica, calcite and quartz account for continuous transition between the different lithologies. These rocks are characterized by intense metamorphic layering and schistosities linked to multiple phases of deformation.

In the VOU, the metasedimentary cover starts with quartzite layers, often containing white micas (phengite-muscovite), chlorite and relics of garnets and/or chloritoid. Similar to the PCU, this succession grades to the regionally more abundant calcschist lithology: similarly to the PCU, this formation shows a continuous transition between micaschists, calcschist and quartzschist end-members and is characterized by pervasive schistosity and widespread folding.

METAMORPHISM: P-T CONDITIONS AND METAMORPHIC EVOLUTION

The main P-T data available in the literature for the metamorphic stages are presented in Table 1 and Fig. 7.

Peak metamorphism: blueschist to eclogite-facies

Voltri Unit

The metamorphic evolution of the VOU has been extensively studied since the 1970s, with special emphasis on the Fe-Ti-oxide-rich metagabbros, to which most of the published metamorphic descriptions and pressure-temperature (PT) estimates are referred (e.g. Messiga and Scambelluri

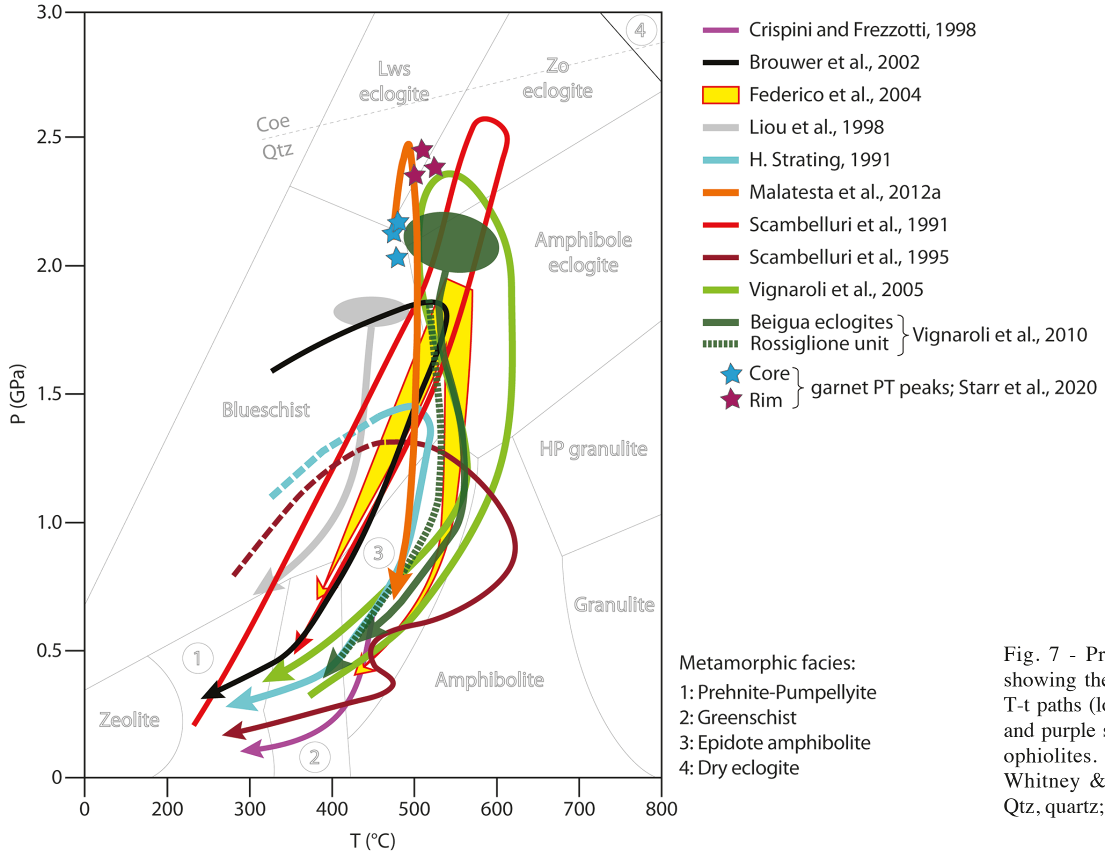

Fig. 7 - Pressure-Temperature diagram showing the diversity of reconstructed P-T-t paths (loop lines) and P-T peaks (blue and purple stars) for the Voltri Unit meta-ophiolites. Minerals abbreviations (from Whitney & Evans, 2010): Coe, coesite; Qtz, quartz; Lws, lawsonite; Zo, zoisite.

1991; Liou et al., 1998; Federico et al., 2004; Vignaroli et al., 2005; Starr et al., 2020). PT conditions summarized here (Fig. 7; Table 1) have been obtained using different methods and datasets (including conventional thermobarometers, pseudosection modelling and mineralogical constraints applied to distinct rock types). As a consequence, numerical values reflect method specific uncertainties and should not be directly compared without caution.

Peak metamorphic estimates on the mafic eclogites, characterized by the high-pressure (HP) association of Na-cpx + grt + rt ± Na-amp ± ep (abbreviations after Kretz, 1983), range between 1.8-2.5 GPa and 450-550 °C (Brouwer et al., 2002; Federico et al., 2007a, b; Malatesta et al., 2012a; Scambelluri et al., 2016; Vignaroli et al., 2005, Starr et al., 2020). Rare occurrence of lenses of lws-bearing eclogites, with metamorphic paragenesis of Ca-Na-px + garnet + gln + rt + ph + lws ± czo and estimated peak conditions within the previously cited range (T = 465-477 °C and P = 20.9-24.4 kbar) has been reported in the NW sector of the Voltri Massif (Roboaro River area, Scarsi et al., 2018) and in its eastern sector (Capponi et al., 2008a; 2008b).

The recent finding of coesite (Alismo et al., 2025) as inclusions in garnet of the eclogites suggests these rocks underwent UHP metamorphism (minimum pressure estimated at 2.8 GPa at 500°C). At present, UHP conditions appear localized and their regional significance remains uncertain.

Other contributions addressed the PT conditions of ultramafic rocks, investigating the transition from antigorite to metamorphic olivine and the growth of Ti-clinohumite (Scambelluri et al., 1991; 1995): they propose a P range between 2.0-2.5 GPa and temperatures between 550 and 650 °C for the metamorphic peak. More recently, similar PT estimates have been proposed for metaophicarbonate rocks (Scambelluri et al., 2016).

Defining peak PT conditions of metasedimentary rocks is more challenging, because the most frequent HP mineral is phengite, which tends to easily turn into lower-Si micas during retrogression. However, estimates between 12-18 kbar and 450-550 °C have been proposed by Vignaroli et al. (2010). Slightly higher peak pressures and comparable temperatures (18-19 kbar, 450-470 °C) are also reported by Federico et al., (2007a) through pseudosection calculations.

Palmaro-Caffarella Unit

This unit shows a blueschist-facies metamorphic climax, as indicated by Cortesogno et al. (1979) and Cabella et al. (1994), with a Na-amph + ep ± lws ± grt ± jd ± Na-cpx assemblage in the Fe-Ti-oxides rich metagabbro (Capponi et al., 2008b; Malatesta et al., 2012a). Malatesta et al. (2012a) supplied a pseudosection study for a Palmaro-Caffarella metagabbro, indicating blueschist-facies peak conditions of 10 < P(kbar) < 15 and 450 < T(°C) < 500; no eclogite relics occur.

Varazze Unit

The Varazze Unit has been comparatively less investigated than the other meta-ophiolitic units of the Ligurian Alps. Available studies, mainly carried out during the 1970s-1990s, indicate that it records a low-grade metamorphic evolution characterized by greenschist-facies assemblages (in the metagabbro ab + sphene + czo + chl + Ca-amph ± ph; Chiesa et al., 1975) with no evidence for earlier high-pressure (eclogite-facies) conditions (Chiesa et al., 1975; Desmons et al., 1999).

Cravasco-Voltaggio and Montenotte Unit

This unit equilibrated in low-temperature blueschist-facies metamorphic peak conditions (T= 300-350° C and Pmin = 0.8-1.1 GPa), with paragenesis at ab + chl + Na-amph ± Na-cpx ± lws ± pump ± ep in the metagabbro (Cabella et al., 1994, Desmons et al., 1999, Hoogerduijn Strating, 1991) with a following metamorphic imprint at lower pressure. Illite crystallinity data suggest T = 300-350°C and P = ca. 7 Kbar (Leoni et al., 1996). Both the pressure peak conditions and the following retrogressive stages are not tightly constrained so far.

In the Montenotte Unit a recent paper by Malatesta et al., (2018) estimated peak conditions of 220-310 °C and 6.5-10 kbar for a mylonitic metabasite at the contact with the Voltri Unit, using the pseudosection approach.

Figogna Unit

The Figogna Unit equilibrated under pumpellyite- actinolite facies metamorphic peak conditions, with pump + act + ab + chl-bearing assemblages in the metagabbro (T = 300-350° C and P = 0.7 GPa, Desmons et al., 1999).

Retrograde evolution and overprints

Voltri Unit

The greenschist facies event in the VOU is more pervasive in the metasediments, for which conditions of T ~ 350° and P ~ 3.5 Kbar (Vignaroli et al., 2010), or T<400°C and P<4 kbar (Cimmino and Messiga, 1979) or in the range of 1-3 Kbar (Federico et al., 2005) have been proposed (Fig. 7). Higher PT conditions (~1.2 GPa and 550 °C) for the epidote blueschist-facies and for the amphibolite- to greenschist- facies transition (~ 0.8 GPa and 480 °C) have been suggested by Vignaroli et al., (2005) in the partially retrogressed HP metagabbros. Comparable temperature estimates of ca. 400-450 °C, and locally down to 350-400 °C during later retrograde stages, were also inferred from syntectonic quartz veins in metasediments of the Voltri Massif (VOU) by Crispini and Frezzotti (1998), supporting a metamorphic evolution within the blueschist- to lower-grade retrograde field.

STRUCTURAL FEATURES AND TECTONIC EVOLUTION OF THE LIGURIAN ALPS OPHIOLITE

Deformation sequence and fabrics

Voltri Massif

The Voltri Massif is a natural field laboratory for linking HP-LT metamorphism, polyphase deformation and exhumation in the Alps-Apennine system.

Its structural evolution has been progressively constrained by regional geological-structural mapping and subsequent syntheses, from early frameworks on the "Voltri Group" and Ligurian Alps tectonics to the recognition of a pervasive composite/transposition fabric and the strong overprint of tectonic boundaries during greenschist-facies retrogression (e.g., Chiesa et al., 1975; Vanossi et al., 1984; Capponi et al., 1986; Capponi, 1991; Capponi et al., 1994; Capponi and Crispini, 1997, 2002). More recent studies refined the tectono-metamorphic unit framework and proposed complementary mechanisms for exhumation, ranging from extensional/detachment-driven interpretations to serpentinite-rich mélange/subduction-channel scenarios, together with late transpressional reworking at upper-crustal levels in the Ligurian Knot (Vignaroli et al., 2009a; Spagnolo et al., 2007; Federico et al., 2009; Federico et al., 2022).

The structural evolution of the Voltri Massif (VOU and PCU) is characterized by a complex, polyphase deformation history linked to Alpine subduction and subsequent exhumation. The main deformation phases are generally divided into D1, D2, and D3 (with a later D4 event often reported), each associated with specific metamorphic conditions and structural sets, but the phase numbering may be different in each contribution. However, a first deformation phase (D1 for Vignaroli et al., 2010; pre-D1 for Capponi and Crispini, 2002) is usually associated with the subduction event and HP-metamorphism (eclogite to blueschist-facies conditions). This phase is characterized by a penetrative foliation and rootless hinges of isoclinal folds which have no regional continuity. Kinematic indicators are often obliterated by later phases; according to Vignaroli et al. (2005) some relics suggest early top-to-the-north/NNW tectonic transport.

The D2 Phase is the most prominent deformation phase, producing the main regional foliation, which is a composite fabric (CF, see Fig. 8a) resulting from the transposition of earlier surfaces (S1 + S2 of Capponi and Crispini, 2002). It is associated with isoclinal folds and distinctive sheath folds. A well-developed stretching lineation (L2) is prevalent, defined by minerals like tourmaline, quartz, albite, feldspar and phengite in metasedimentary rocks (Capponi and Crispini, 2002; Vignaroli et al., 2010). The attitude is variable, but generally subhorizontal in the western part of the massif and moderately to steeply-dipping to the east in the eastern part of the massif (Fig. 8b; Capponi and Crispini, 2002). This deformation phase (and also the D1 for Capponi and Crispini, 2002) occurred during decompression and cooling, evolving from Na-amphibole-greenschist to greenschist facies s.s. and is shared between VOU and PCU, thus indicating a coupling between them before or syn-greenschist facies. Regional-scale interference patterns of type 3 (Ramsay, 1967) between D1 and D2 folds are locally reported, especially in metasedimentary rocks (Capponi and Crispini, 2002; 2008a; 2008b; Capponi et al., 2013).

A D3 phase, characterized by more open folds, chevron folds, and a rough fracture cleavage or crenulation, typically refolds the D2 mylonitic fabric. Fold axes generally plunge toward the NNE and SSW, with sub-horizontal axial planes (Capponi and Crispini, 2002). This phase is coeval with low-grade greenschist conditions and is usually interpreted as an extensional/collapse phase involving vertical shortening and horizontal extension (Capponi and Crispini, 2002). An important constraint on the structural evolution of PCU metasediments comes from Crispini and Frezzotti (1998), who linked three syntectonic vein generations to F1, F2 and F3 (i.e. D1, D2, D3) folds and showed that the first two folding events likely belong to a progressive retrograde deformational history (from glaucophanic to greenschist s.s. facies), whereas F3 marks a later, lower-grade stage.

The overall deformational history results in a markedly different architecture in the eastern and western sectors of the Voltri Massif (see Figs. 8a and 9). In the eastern sector, in both the VOU and the PCU, the dominant lithology is serpentinite, enclosing 10 to 100 m-sized bodies of metagabbro and lenses of metaperidotite, metabasalt and minor metarodingite (Capponi et al. 2008a; 2008b; Malatesta et al., 2012a) elongated along the regional foliation (Capponi et al., 2008a; Cortesogno et al., 1975; Hoogerduijn Strating, 1991). Deformation partitioning inside metagabbro bodies allows the

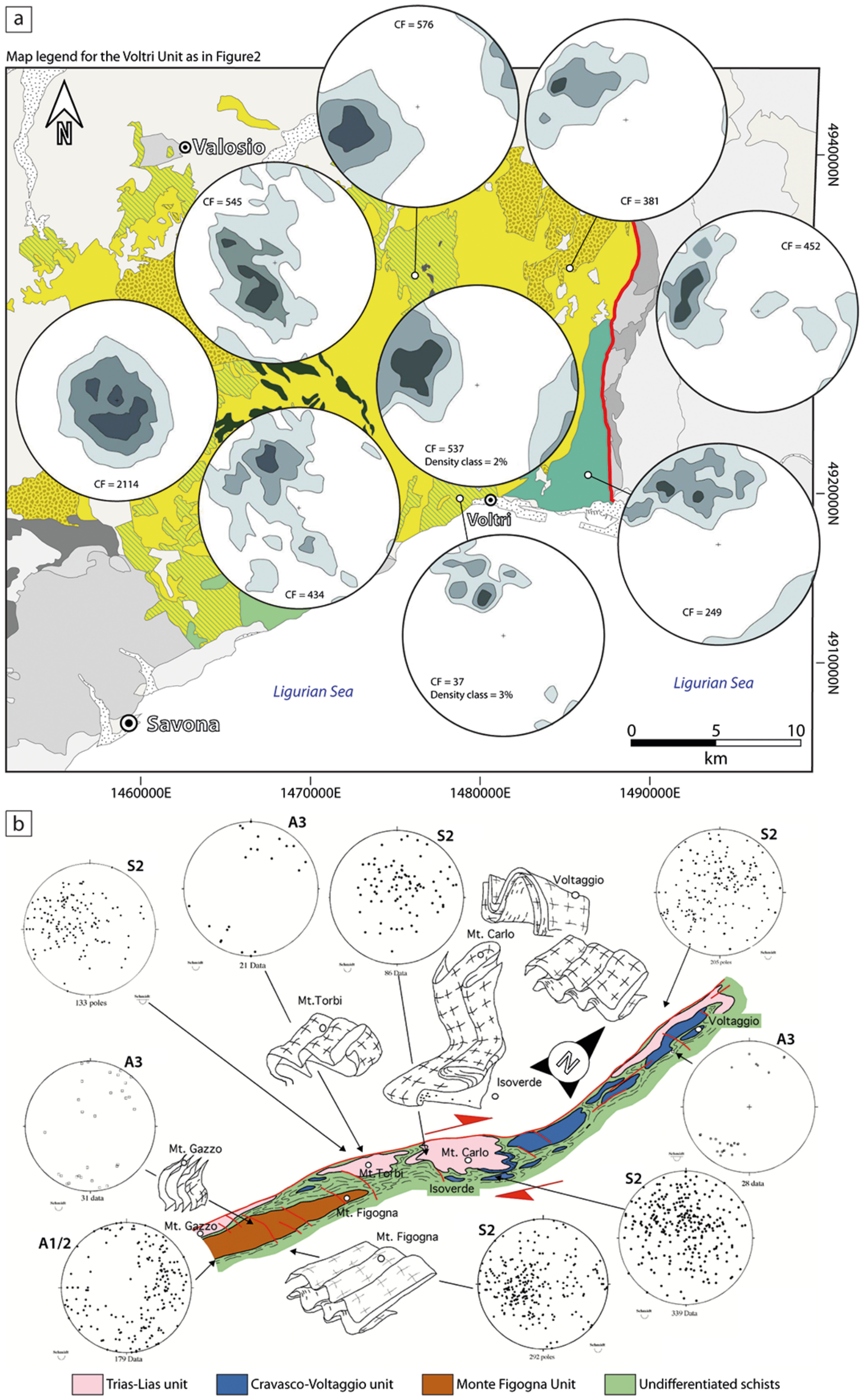

Fig. 8 - Compilation of structural data. (a) Regional schistosity (i.e., composite fabric) of the Voltri Massif. Data derived from Capponi and Crispini (2002), Capponi and Crispini (2008a; 2008b) and Capponi et al. (2013). (b) Simplified model of the tectonic structures and architecture across the Sestri-Voltaggio Zone (SVZ); 3D drawings not to scale. Stereograms summarize the main structural elements of the Sestri-Voltaggio Zone. Fig. modified after Crispini and Capponi (2001).

preservation of texture related to the magmatic or to the LP-HT (low pressure-high temperature) oceanic metamorphic stage; the deformation is localized at the contact with the host-rock or in shear zones (Liou et al., 1998; Messiga et al., 1995; Malatesta et al., 2012a). This structural architecture led to the interpretation of the eastern part of the Voltri Massif as a tectonic mélange (Malatesta et al., 2012a).

In the western sector the eclogite bodies are larger (up to km-scale; Fig. 2), more abundant and better preserved, due to an apparent less severe greenschist-facies retrogression, but still embedded within serpentinite (Vignaroli et al., 2005; Messiga and Scambelluri, 1991). Here large metaperidotite bodies usually occur topographically at the top of the meta-ophiolitic sequence. The contact with the underlying serpentinite can either be transitional or by means of thrust faults (Capponi et al., 2013): this is probably due to the high competence contrast between serpentinite and metaperidotite, that makes their contact a preferential site for fault nucleation/reactivation. This contact has also been described as a first-order ductile-to-brittle shear zone, separating two tectonic complexes with the higher one characterized by the absence of a retrogressive (syn-exhumation) fabric (Vignaroli et al., 2009a).

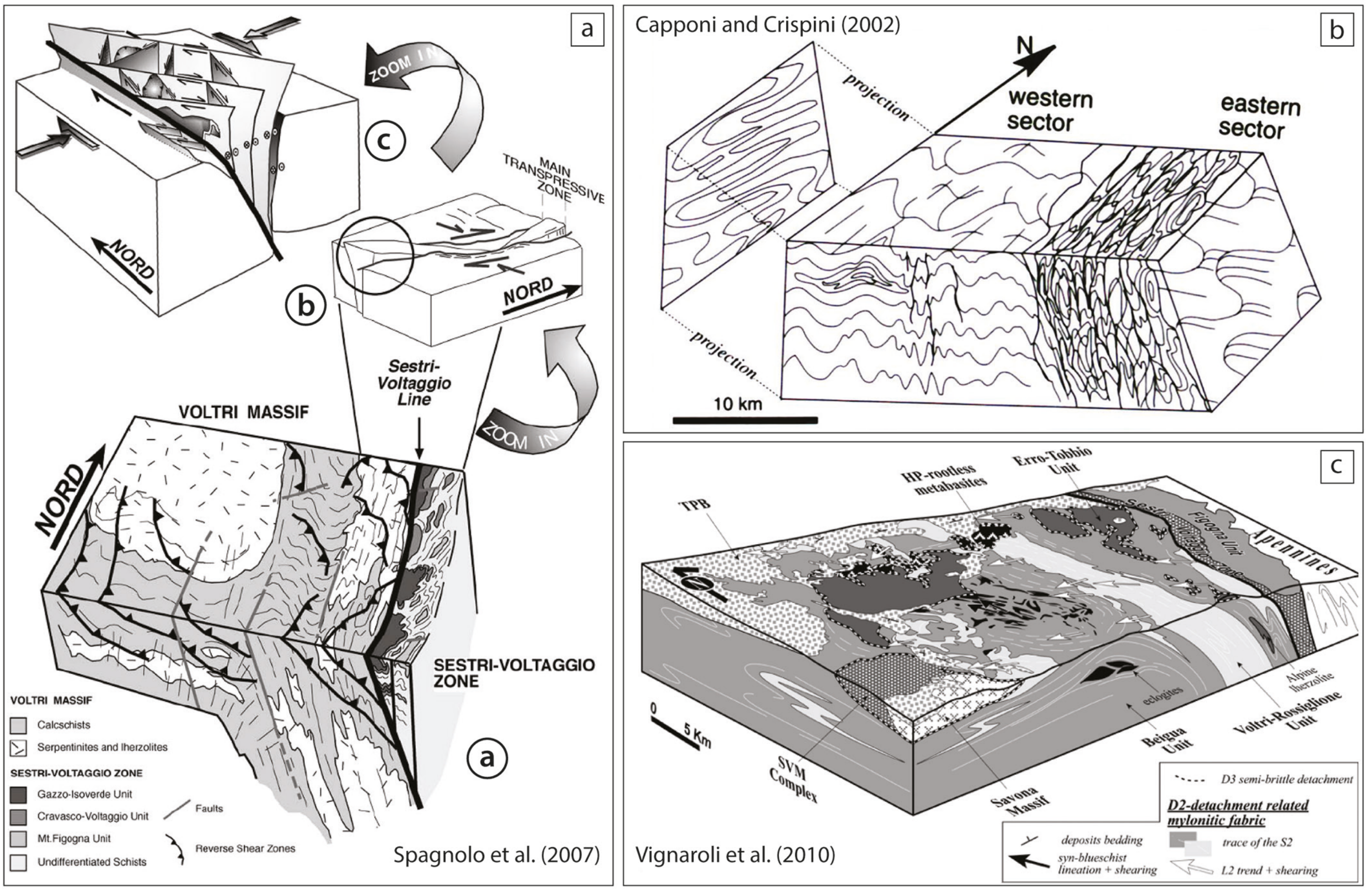

Fig. 9 - (A) Three-dimensional reconstruction of the structural relationships between the Voltri Massif and the Sestri-Voltaggio Zone, highlighting the Sestri-Voltaggio Line as the main transpressive shear zone and showing the distribution of major lithological units and shear zones (after Spagnolo et al., 2007). Insets (b-c) illustrate schematic kinematic interpretations of the deformational system and associated transfer structures. (B) Block diagram showing the structural architecture of the western and eastern sectors, emphasizing along-strike variations in deformation style, folding patterns, and foliation geometries (after Capponi and Crispini, 2002). (C) Three-dimensional tectonic model of the main tectono-metamorphic units (Voltri Unit, with metaperidotite; i.e. Erro-Tobbio Unit Auctt., Savona Massif) and their tectonic contacts, including D2 detachment-related mylonitic fabrics and later D3 brittle deformation, with indication of stretching lineations and shear directions (after Vignaroli et al., 2010). Overall, these models highlight the key role of the Sestri-Voltaggio Line in controlling the tectonic segmentation and polyphase deformation of the Voltri Massif in the Alpine-Apennine junction zone.

This structural architecture has been interpreted in literature with different models: an overturned lithospheric megafold with a NNE-SSW horizontal axis (Capponi, 1991); an exhumed metamorphic dome exposed as a consequence of a ductile-to-brittle extensional event (Vignaroli et al., 2009a); the consequence of alternating extensional and compressional (Hoogerduijn Strating, 1994) or of polyphase compressional phases (e.g. Chiesa et al., 1975; Cortesogno & Haccard, 1984; Vanossi et al., 1984) possibly in the context of a subduction channel (Federico et al., 2007a, b; Malatesta et al., 2012a).

A last deformation stage (D4) produced open folds and thrust faults with top-to-the-E/NE sense of shear (e.g., Capponi and Crispini, 2002; Crispini et al., 2009; Spagnolo et al, 2007; Federico et al., 2009) that have been related to the counterclockwise rotation of the Corsica-Sardinia block during the Early Miocene and the overthrusting of Apennine Units.

Sestri-Voltaggio Zone (SVZ)

For the purpose of this paragraph, the Cravasco-Voltaggio Unit and the Montenotte Unit will be described separately because, even if they share a common stratigraphy and metamorphic evolution, it is still unclear whether they experienced a common and coeval structural evolution. In addition, they are exposed in different sectors of the Ligurian Alps and are located in different tectonic positions with respect to the Voltri Massif (Fig. 2).

The CVU is characterized by the superposition of two folding phases (F1 and F2) related to the peak blueschist conditions, followed by a F3 coeval with albite-chlorite-epidote recrystallization in the mafic rocks (Hoogerduijn Strating, 1991, Crispini, 1996). The F1 and F2 folds are isoclinal and develop an axial plane schistosity with blastesis of phengite+calcite+quartz in the metasediments. F1 and F2 folds are not distinguishable in the field in the absence of interference patterns and therefore commonly cited as "F1/F2 folds". F3 folds are subcylindrical and with m- to dam-wavelength; they are associated to a crenulation cleavage or pressure solution cleavage in the limestone and growth of pumpellyite, chlorite, albite and epidote in veins or fractures in metabasic rocks.

The superposition of multiple folding events, penetrative shear zones and later thrust- and fault-related deformation results in a highly dismembered internal architecture of the CVU, characterized by strong strain partitioning, tectonic repetition of lithological successions and local loss of primary stratigraphic relationships. This structural complexity gives the SVZ a "chaotic" appearance at outcrop and map scale, which reflects intense polyphase tectonic reworking rather than sedimentary mélange formation (Crispini, 1996; Crispini and Capponi, 1997, 2001).

In the Figogna Unit (part of the "Western Lavagna Nappe" according to Hoogerduijn Strating, 1991), the F1 and F2 folds are related to the peak Pumpellyite - Actinolite metamorphic phase and therefore developed at shallower structural levels related to the CVU, despite their similarity in style. The F3 folds, on the contrary, are shared among all the units of the SVZ and are therefore post-coupling between them (Crispini, 1996).

Oligocene-Early Miocene tectonics in the SVZ has been interpreted as involving a dextral transpressive deformation zone, possibly accommodating the northwestward motion of the Adriatic indenter within the broader framework of anticlockwise rotation of the Corsica-Sardinia block. This late tectonic overprint likely contributed to enhancing the structural complexity and internal disruption of the SVZ units, reinforcing their present-day heterogeneous and locally chaotic structural arrangement (Crispini et al., 2009; Molli et al., 2010).

Montenotte Unit

Three deformational events have been described in the Montenotte Unit: two isoclinal transpositive folding phases with axial plane schistosity (D1 and D2) and a D3 characterized by open folding, with rare axial plane cleavages (Anfossi et al., 1984; Beccaluva et al., 1979). The contacts among lithologies are geometrically controlled by the composite foliation (CF) that includes the D1 and D2 related schistosity (F1 and F2 after Anfossi et al., 1984; Capponi et al., 2013); D1/D2 folds are coeval with blueschist-facies metamorphism, whereas D3 folds are coeval with low-grade greenschist metamorphism, with blastesis of albite + chlorite + epidote (Capponi et al., 2013). The D3 folds are shared between Montenotte and VOU and therefore postdate their coupling (Malatesta et al., 2018), which occurred, at least locally, along a blueschist-facies mylonitic shear zone (Federico et al., 2014; Malatesta et al., 2018).

A late-stage backthrusting phase (D4) is shared with the Voltri Massif: these E-NE vergent thrusts have largely reworked and disrupted the earlier mylonitic contacts (Federico et al., 2014).

Crustal scale Structure: Constraints from Geophysical Data

Geophysical data from the Western Alps and the Alps-Apennine junction indicate that the Ligurian collisional knot overlies a highly heterogeneous crustal domain, characterized by strong lateral variations in crustal thickness, anomalously shallow mantle bodies, and inherited plate-interface structures. Seismic refraction, gravity modelling and local-earthquake tomography identify the Ivrea-Verbano geophysical anomaly as a major body of Adriatic upper mantle emplaced at mid- to lower-crustal depths, whose southern continuation beneath the Ligurian Alps governs first-order Moho geometry and crustal architecture (e.g., Kissling, 1993; Diehl et al., 2009; Wagner et al., 2012; Spada et al., 2013; Schmid et al., 2017). Ambient-noise and surface-wave tomography reveal reduced crustal thickness and sharp velocity gradients beneath the Ligurian domain, consistent with attenuation or tectonic omission of the European lower crust adjacent to the Adriatic mantle wedge (e.g., Lu et al., 2018; Kästle et al., 2018; Lu et al., 2020). Receiver-function studies image a low-velocity zone at depths of ~40-70 km, interpreted as a hydrated, serpentinite-rich plate-interface channel separating the downgoing European lithosphere from the Adriatic upper plate (e.g., Malusà et al., 2011; Zhao et al., 2015; Solarino et al., 2018; Zhao et al., 2020). In the synthesis of Schmid et al. (2017), this domain represents a long-lived Alpine subduction interface, providing a geophysical link between mantle-scale processes and the exhumed high-pressure meta-ophiolites of the Voltri Massif and SVZ, interpreted as the crustal expression of a fossil plate interface rather than isolated metamorphic slices. Teleseismic tomography images a continuous south- to southeast-dipping high-velocity slab beneath the Western Alps and Ligurian sector down to 200-300 km depth, arguing against large-scale slab breakoff beneath Liguria during exhumation (e.g., Lippitsch et al., 2003; Piromallo and Morelli, 2003; Zhao et al., 2016; Malusà et al., 2021). Seismic anisotropy shows predominantly belt-parallel fast directions beneath the Ligurian Alps, consistent with inherited mantle fabrics from Jurassic rifting and Alpine subduction, later overprinted by asthenospheric flow related to Apenninic slab rollback (Barruol et al., 2004; Bokelmann et al., 2013; Salimbeni et al., 2018).

From a structural point of view, the available geophysical models consistently depict the Ligurian Alps as the shallow expression of a crust-mantle-scale plate boundary zone.

Overall, available geophysical data indicate that the Alps-Apennines junction in the Ligurian sector is characterized by a shallow Adriatic mantle wedge, corresponding to the southern continuation of the Ivrea-Verbano mantle body, beneath a strongly heterogeneous crust (e.g., Schmid et al., 2017; Lu et al., 2020). The crust in this sector also shows marked lateral thickness variations and sharp Moho gradients, consistent with attenuation and/or tectonic omission of parts of the European lower crust close to the Adriatic mantle wedge (Lu et al., 2018; Lu et al., 2020). Receiver-function and tomographic data further image a low-velocity zone at ca. 40-70 km depth, interpreted as a hydrated and serpentinite-rich plate-interface channel between the downgoing European lithosphere and the Adriatic upper plate (Zhao et al., 2020). At greater depth, teleseismic tomography reveals a continuous south- to southeast-dipping high-velocity Alpine slab beneath the Western Alps-Ligurian sector, arguing against large-scale slab break-off beneath Liguria during exhumation (Zhao et al., 2016; Handy et al., 2021). This deep architecture supports the interpretation of the main meta-ophiolitic bodies (i.e., Voltri Massif) as the exposed fossil record of a mechanically heterogeneous Alpine plate interface, later reactivated during Oligocene-Miocene Alps-Apennines reorganization (e.g., Schmid et al., 2017; Salimbeni et al., 2018; Malusà et al., 2021).

GEOCHRONOLOGY AND RATES: P-T-T SYNTHESIS

Primary ages

Few primary ages are available for some of the meta-ophiolitic units: Sm/Nd dating on plagioclase and clinopyroxene of the VOU peridotite gave Late Carboniferous-Permian ages (273±16 Ma and 313±16 Ma; Rampone et al., 2005). This recrystallization stage marks the tectonic exhumation of the subcontinental lithospheric mantle to shallower levels and indicates that the lithospheric extensional regime leading to the future Ligurian-Piedmont ocean was already active at the end of Palaeozoic. The final exposure of the mantle at the ocean floor probably occurred during Middle-Late Jurassic time. Eclogitic metagabbroes of the VOU have been analyzed through the U/Pb SHRIMP method and Late Jurassic magmatic ages of 160 ± 1 and 161 ± 3 have been obtained (Rubatto and Scambelluri, 2003).

U-Pb dating on zircon from felsic differentiate ("metaplagiogranite" Auct.) associated to metagabbro gave a Late Jurassic age of 153.3±1.0 Ma for the CVU and of 150.1±0.6 Ma for the PCU (Borsi et al., 1996). Sm-Nd ages on metagabbros from the Erro-Tobbio Unit Auct. gave a weighted mean age of 178±5 Ma (Rampone et al., 2014). Similar old ages are only recorded in gabbroic rocks from the External Liguride Units of the Northern Apennines.

Dating peak metamorphism

At the time of this review, geochronological constraints are available only for the lithologies of the VOU, whereas the timing of metamorphic recrystallization in the PCU, VAU, CVMU, and FU is still under investigation.

The main geochronological data available in the literature for the metamorphic stages are presented in Table 2, Fig. 10 and are summarised below.

Voltri Unit

Age of the peak eclogite stage of this unit has been constrained in the range 39 - 50 Ma, based on different radiometric methods (Table 2 and Fig. 10), mostly applied to Fe-Ti rich eclogitic metagabbros, in particular:

– Sm-Nd on garnet (Starr et al., 2020), ranging from 38.15 ± 0.89 Ma to 40.4 ± 1.3 Ma (overall 5 samples) in the central area of the unit (Vara locality) and 49.68 ± 0.35 Ma in the north-western part of the unit.
– ^{40}Ar-^{39}Ar dating of white mica in mafic eclogite clasts within the Oligocene conglomerates of the Tertiary Piedmont Basin ranging between 49.00 ± 0.40 of the most preserved sample and 43.5 ± 1.7 Ma of a sample partially retrogressed in blueschist-facies (Federico et al., 2005); in the north-western part of the VOU (Cascine Parasi area) Federico et al. (2007b) report an age of 43.2 ± 0.5 Ma in an eclogitic quartzschist.
– Rb-Sr on white mica (Smye et al., 2021) of a mafic eclogite sampled in the NW part of the unit show an age of 47.37 ± 0.41 Ma.
– U-Pb (SHRIMP) dating on baddeleyite in a Ti-clinohumite bearing dyke from the central area of the unit (Vara area) records at 33.6 ± 1.0 Ma age (Rubatto and Scambelluri, 2003) interpreted as the age of the HP metamorphic peak.

In addition, a metarodingite dyke from the central part of the unit has been dated through Sm-Nd method by Haws et al. (2021): the authors interpret the age of 40.6 ± 2.9 Ma as a late prograde to peak metamorphic age.

At the present state of knowledge, it appears plausible that different rock volumes or sub-units within the Voltri Massif reached peak eclogite-facies metamorphic conditions at different times. However, available data are still insufficient to constrain the extent, mechanisms, and timing of their tectonic coupling, which therefore remain matters of ongoing investigation.

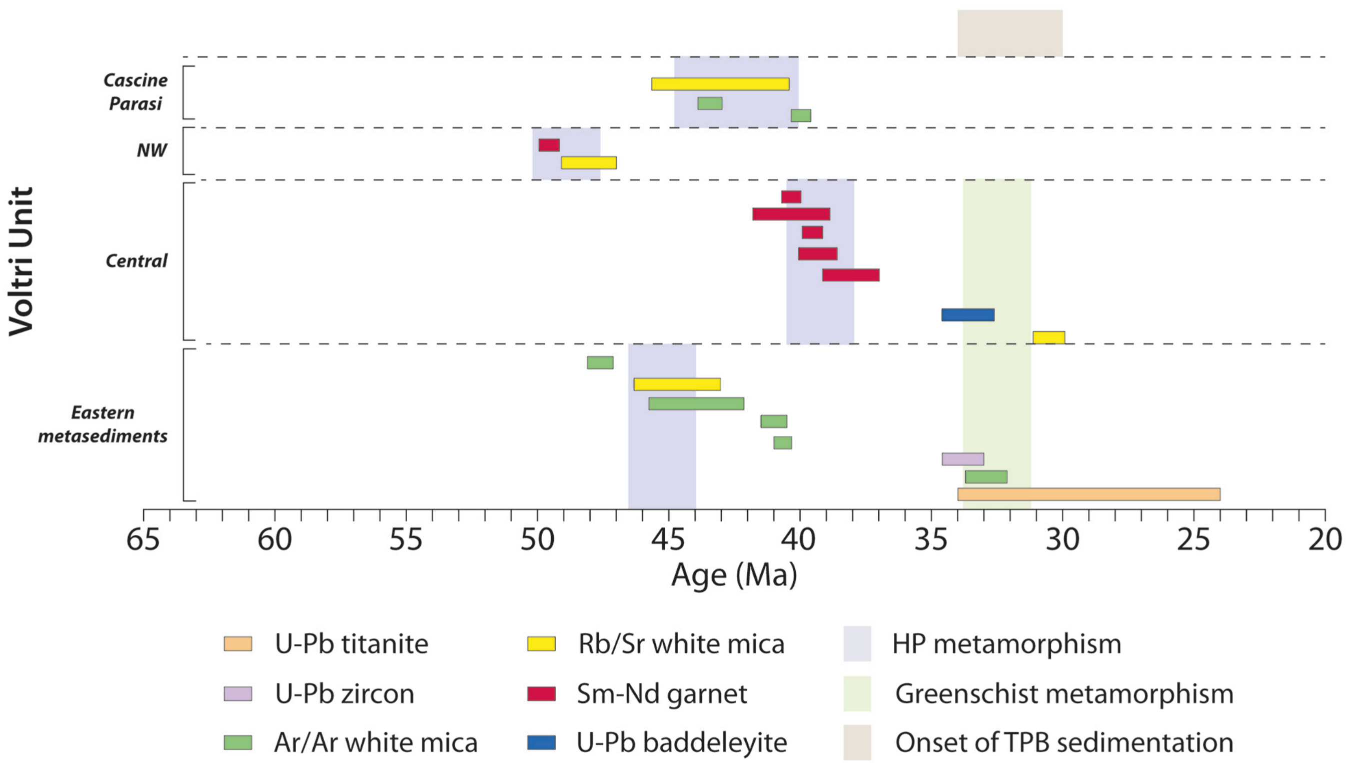

Fig. 10 - Compilation of available geochronological data for the Voltri Unit (modified after Smye et al., 2021). Horizontal bars correspond to 2σ errors. Data sources: U-Pb titanite and zircon (Vignaroli et al., 2010); U-Pb baddeleyite (Rubatto and Scambelluri, 2003); ^{40}Ar-^{39}Ar mica (Barbieri et al., 2003; Federico et al., 2005); Sm-Nd garnet, (Starr et al., 2020), and Rb-Sr white mica, (Smye et al., 2021). Age of onset of TPB sedimentation from Turco et al. (1994) and Gelati et al. (1998).

Dating exhumation and cooling

Voltri Unit

Greenschist facies retrogression has been constrained in micaschists by ^{40}Ar-^{39}Ar dating of white mica at about 32.9 ± 0.8 Ma (Federico et al., 2005). In addition, two blueschist-facies samples from the north-western sector of the unit, yielded ^{40}Ar-^{39}Ar ages of 43.4 ± 0.5 Ma and 39.95 ± 0.37 Ma interpreted as recording cooling during blueschist-facies exhumation (Federico et al., 2007a and b).

Rb-Sr ages obtained by Smye et al. (2021) on white mica cluster between ca. 45 and 40 Ma and are referred to the blueschist-facies exhumation stage of the Voltri eclogites, whereas younger ages around 31-30 Ma are interpreted as recording the greenschist-facies overprint.

- U-Pb (SHRIMP) dating records a 33.8 ± 0.8 Ma age on a zircon rim and a 29 ± 5 Ma age in titanite from a metasedimentary sample (Vignaroli et al., 2010), interpreted as ages of the greenschist-facies retrogression.

These results are consistent with detrital white-mica ^{40}Ar-^{39}Ar ages from the Tertiary Piedmont Basin, which record Eocene-Oligocene cooling signals (ca. 32-50 Ma) attributed to the exhumation of high-pressure units in the Ligurian Alps, including the VOU (Carrapa et al., 2004).

TECTONIC AND GEODYNAMIC INTERPRETATIONS

Exhumation mechanisms for the meta-ophiolites: tectonic mélange versus coherent slices

A central issue in the interpretation of the Ligurian Alpine meta-ophiolites concerns the relative importance of tectonic mixing versus large-scale internal coherence. Early models emphasized regionally continuous fabrics, common greenschist-facies overprint and apparent tectono-metamorphic continuity, favouring interpretation of the Voltri and Palmaro-Caffarella units as coherent slices of subducted oceanic lithosphere (e.g., Chiesa et al., 1975; Cortesogno and Haccard, 1984; Capponi and Crispini, 2002).

Subsequent work has documented a much higher degree of internal heterogeneity. Field, petrological and geochronological data show strong strain partitioning between serpentinite matrices and competent blocks, widespread boudinage and lens-shaped HP rock volumes, and significant variability in peak P-T conditions and metamorphic ages within spatially associated domains (Scambelluri et al., 1995; Federico et al., 2007a, b; Vignaroli et al., 2010; Malatesta et al., 2012a; Starr et al., 2020; Figs. 7, 10 and Tables 1 and 2) . Serpentinite-hosted mélanges containing blocks with distinct P-T-t paths provide compelling evidence for incorporation of tectonic slices with different burial and exhumation histories within a fossil subduction channel.

At the same time, late-stage deformation under Na-amphibole greenschist- and greenschist-facies conditions promoted regional mechanical coupling of previously decoupled slices, generating map-scale structural coherency (e.g., Capponi and Crispini, 2002; Crispini et al., 2009; Vignaroli et al., 2010). Such coherency therefore reflects syn-exhumational reworking within a weak plate-interface domain rather than preservation of primary tectono-stratigraphic integrity.

Overall, the Voltri Massif and the SVZ are best interpreted as composite tectonic domains, where coherent slices and tectonic mélanges sensu-stricto coexist. The relative expression of coherence versus mixing depends on serpentinite abundance, rheological contrasts, fluid availability and evolving effective viscosity within the subduction channel (Engi et al., 2001; Gerya et al., 2002; Guillot et al., 2009; Malatesta et al., 2012a).

Subduction-channel models invoke the development of a low-viscosity, serpentinite-rich interface between the downgoing slab and the overriding plate, generated by slab dehydration and mantle-wedge metasomatism (e.g., Fig. 11; Gerya et al., 2002; Stöckhert and Gerya, 2005, Guillot et al., 2009). In this context, serpentinite acts as a mechanically weak carrier capable of entraining HP to locally UHP blocks detached from different depths, predicting block-in-matrix relationships, heterogeneous P-T paths and diachronous metamorphic ages, all features well documented in parts of the Voltri Massif (Fig. 11; e.g., Federico et al., 2007a; b; Malatesta et al., 2012a; Scarsi et al., 2018; Locatelli et al., 2023).

Alternative models emphasize exhumation of relatively large, coherent slices within an evolving orogenic wedge, driven by continuous underplating and syn-orogenic extension (Platt, 1986; Brouwer et al., 2002), or by buoyant rise of serpentinite-dominated lithospheric fragments along the plate interface (Starr et al., 2020; Smye et al., 2021). Field and geochronological evidence from the Voltri Massif suggests that both mechanisms may have operated at different scales and stages, with initial distributed channel-style exhumation followed by local aggregation and coherent ascent of selected slices.

Plate-scale framework of the Ligurian Alpine meta-ophiolites

The metamorphic Ligurian ophiolite represents key fragments of the Jurassic Ligurian-Piedmont Ocean. Together with the Internal Ligurian units of the Northern Apennine they are commonly interpreted as parts of the same oceanic domain and its adjacent ocean-continent transition, later incorporated into different segments of the Alpine-Apennine system during convergence (Dal Piaz, 1974, 1999; Molli et al., 2010; Handy et al., 2010).

Closure of the Ligurian-Piedmont Ocean began in the Late Cretaceous with south- to southeast-directed Alpine subduction of oceanic lithosphere beneath Adria. In the Voltri Massif, this evolution is recorded by widespread HP-LT metamorphism, with eclogite-facies peak conditions attained mainly between ca. 50 and 40 Ma, followed by blueschist-facies re-equilibration and pervasive greenschist-facies overprint by the Eocene-Oligocene transition (e.g., Messiga and Scambelluri, 1991; Federico et al., 2005; Vignaroli et al., 2005; Starr et al., 2020; Smye et al., 2021). These ages firmly link the Ligurian Alpine meta-ophiolites to the Alpine subduction cycle, rather than to Apenninic subduction. Geological and geophysical evidence suggests that subduction and exhumation may have occurred along a long-lived, mechanically heterogeneous Alpine plate-interface domain, rather than within a single coherent slab (Figs. 8 and 11; Scambelluri et al., 1995; Federico et al., 2007a; Guillot et al., 2009; Malatesta et al., 2012a; 2012b). At plate scale, this architecture is consistent with exhumation along a long-lived Alpine plate-interface domain (e.g., Engi et al., 2001; Gerya et al., 2002). Crustal- and lithospheric-scale geophysical constraints further support this interpretation, imaging a shallow Adriatic mantle wedge (Ivrea-Verbano body) beneath the Ligurian Alps and a low-velocity, serpentinite-rich interface separating European and Adriatic plates at depth (Wagner et

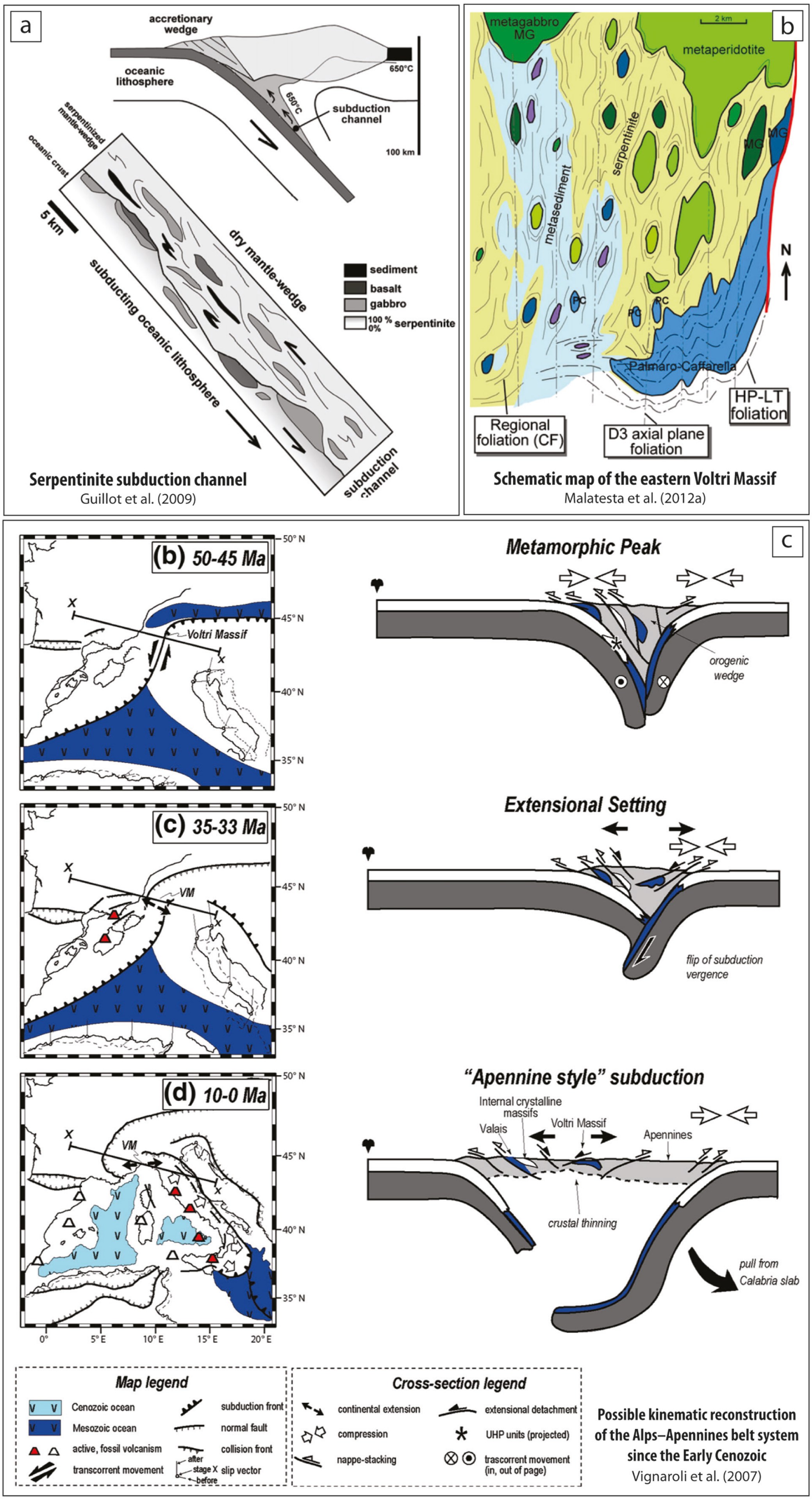

Fig. 11 - A) Simplified sketch of serpentinite subduction channel model (modified after Guillot et al., 2009 and Malatesta et al., 2012a). B) Interpretation of the eastern part of the Voltri Massif as a fossil serpentinite subduction channel. The schematic geologic map shows the bodies of various lithologies and metamorphic peaks enclosed in a foliated serpentinite-metasediment matrix (after Malatesta et al., 2012a). C) Kinematic reconstruction of the Alps-Apennines junction proposed by Vignaroli et al. (2008). It shows coeval double subduction with opposite vergence/polarity and the associated Oligocene extensional regime (35-33 Ma), evolving to a later west-dipping ("Apennine-type") subduction system during Miocene-present (10-0 Ma) driven by slab rollback and outward migration of orogenic fronts.

Table 2 - Published P-T estimates and geochronological constraints for the Voltri Unit and related rocks, with methods and interpreted metamorphic stages

Reference	Unit	Lithology	P–T	Method and Mineral analysed	Age (Ma)	Stage Dated	Uncertainty and Notes
Federico et al. (2005)	TPB Clast	Eclogite	18–19 kbar 530–570° C	40Ar/39Ar Phengite	49.00 ± 0.40	Eclogite stage	High-Si phengites record peak formation age.
Federico et al. (2005)	TPB Clast	Eclogite	8–15 kbar 400–500°C	40Ar/39Ar Phengite	43.5 ± 1.7	Blueschist retrogression	Records partial re-equilibration from eclogite- to blueschist-facies.
Federico et al. (2005)	Voltri Unit (NW area)	Blueschist metabasite	8-15 kbar; 400–550° C	40Ar/39Ar Phengite	39.95 ± 0.37	Blueschist stage	Phengite ages reflect peak blueschist recrystallization.
Federico et al. (2005)	Voltri Unit	Micaschist	<4 kbar <400°C	40Ar/39Ar Muscovite	32.9 ± 0.8	Greenschist paragenesis	Maximum age for the greenschist-facies mica generation.
Federico et al., (2007b)	Voltri Unit (NW area)	Eclogitic qtz-schist	22–24 kbar 565–600°C	40Ar/39Ar Phengite	43.2 ± 0.5	Eclogite stage	Phengite ages reflect peak eclogite recrystallization.
Federico et al., (2007b)	Voltri Unit (NW area)	Blueschist metabasite	20–22 kbar; 510–600° C	40Ar/39Ar Phengite	43.4 ± 0.5	Blueschist stage	Phengite ages reflect peak blueschist recrystallization.
Rubatto and Scambelluri (2003)	Beigua Unit / Voltri Unit	Ti-clinohumite bearing dykes	13 kbar 450–500°C	U-Pb Baddeleyite	33.6 ± 1.0	HP metamorphism	Baddeleyite inclusion evidence points to formation during regional HP metamorphism.
Starr et al. (2020)	Voltri Unit (NW area)	Foliated Fe–Ti metagabbro	-	Sm–Nd Garnet	49.68 ± 0.35	Peak HP metamorphism	Indicates peak HP conditions were attained ~10-12 Ma earlier in the NW sector.
Starr et al. (2020)	Voltri Unit	Foliated Fe–Ti metagabbro	25 kbar 510°C	Sm–Nd Garnet	40.4 ± 1.3	Peak HP metamorphism	Consistent with peak metamorphism occurring around 40 Ma in the central area.
Starr et al. (2020)	Voltri Unit	Massive Fe–Ti metagabbro	24 kbar 525°C	Sm–Nd Garnet	38.15 ± 0.89	Peak HP metamorphism	Younger age likely due to kinetic overstepping and delayed garnet growth in massive samples.
Smye et al. (2021)	Voltri Unit	Eclogite	24–25 kbar 510–530°C	Rb–Sr Phengite	47.37 ± 0.41	HP phengite growth	Minimum age; two-point isochron pairs suggest HP growth closer to 48 ± 1 Ma
Smye et al. (2021)	Voltri Unit	Quartz-mica-schist	12–19 kbar 450–470°C	Rb–Sr Phengite	30.45 ± 0.45	Exhumation stage	Date represents an upper bound for white mica equilibration during decompression.
Vignaroli et al. (2010)	Voltri-Rossiglione / Voltri Unit	Micaschist	-	U-Pb Titanite	29 ± 5	D2 fabric / greenschist stage	Metamorphic growth is interpreted as pre-tectonic to syn-tectonic with respect to S2
Vignaroli et al. (2010)	Voltri-Rossiglione / Voltri Unit	Micaschist	19 kbar 555°C (Max)	U-Pb Zircon rim	33.8 ± 0.8	Greenschist paragenesis	Zircon rims record fluid-enhanced exhumation.

al., 2012; Spada et al., 2013; Zhao et al., 2015; Schmid et al., 2017). These data provide an independent link between mantle-scale processes and the exposed HP meta-ophiolites, reinforcing the interpretation of the Voltri-SVZ system as the fossil record of an Alpine plate interface rather than a simple nappe stack.

The SVZ represents a first-order tectonic element at the southern termination of the Western Alps. Rather than marking a discrete boundary between the Alps and the Apennines, it records the long-term mechanical interaction and strain partitioning between two convergent systems during Paleogene to Neogene plate reorganization (e.g., Crispini and Capponi, 2001; Molli et al., 2010; Schmid et al., 2017). Structural and metamorphic relationships indicate that the main architecture of the SVZ was established during Alpine subduction and early exhumation, through progressive underplating, tectonic slicing and juxtaposition of units derived from both oceanic and continental domains (Fig. 11a b, c; Capponi and Crispini, 2002; Federico et al., 2007a; 2007b; Vignaroli et al., 2010; Scambelluri et al., 2016; Cannaò et al., 2020). Later Apenninic tectonics mainly reactivated pre-existing Alpine structures within this inherited high-strain corridor, without exerting a primary control on the burial and exhumation of the meta-ophiolites.

CONCLUSIVE REMARKS AND OPEN QUESTIONS

The Ligurian Alps meta-ophiolites (Voltri Massif and Sestri-Voltaggio Zone) provide a well-exposed record of an exhumed subduction interface, integrating Jurassic rift-to-drift/oceanic construction with Alpine HP-LT subduction and later orogenic reworking at the Alps-Apennines junction.

Peak metamorphic conditions span from pumpellyite-actinolite to eclogite-facies; the Voltri Unit is the best constrained, with eclogite-facies estimates around 1.8-2.5 GPa and 450-550 °C, and locally documented UHP conditions indicated by coesite.

The main eclogite-facies event is Alpine (ca. 50-40 Ma), followed by cooling/exhumation and a pervasive greenschist-facies overprint near the Eocene-Oligocene boundary (ca. 34-29 Ma).

The regional architecture and fabric development are consistent with a long-lived, mechanically heterogeneous plate-interface domain, where serpentinite-rich volumes promoted strong strain partitioning and local tectonic mixing, while later greenschist-facies deformation enhanced map-scale coupling and apparent coherency.

The Sestri-Voltaggio Zone is best regarded as a polyphase high-strain corridor rather than a single "Alps-Apennines boundary": its main structural assembly reflects Alpine subduction/exhumation, later reactivated in transpression during Paleogene-Neogene plate reorganization in the "Ligurian collisional knot".

Despite these advances, several first-order issues remain unresolved and require further work. Among the open questions:

– How regionally significant is UHP metamorphism in the Voltri Massif? The current evidence suggests localization, but the areal extent and tectonic meaning of UHP domains remain uncertain.
– To what extent are P-T-t paths different and peak ages diachronous within the Voltri Unit, and what does this imply for the size, duration, and efficiency of coupling/decoupling along the interface?
– The Sestri-Voltaggio units and the Montenotte Unit remain comparatively underconstrained in P-T-t terms: improved geochronology and petrochronology are needed to test correlations among slices, timing of coupling, and links to Voltri Massif exhumation.
– What were the relative contributions of subduction-channel style mixing versus exhumation of larger coherent slices through time, and how did this balance evolve during exhumation and late reactivation?
– Fluid-rock interaction (serpentinization/dehydration, carbonation and metasomatism) likely controlled rheology and strain localisation, but quantitative constraints on timing, fluxes, and mechanical effects are still limited.
– A key perspective is to better couple field-based interface records with crustal/lithospheric geophysical images (hydrated low-velocity interface; shallow mantle wedge) to test geometry, thickness, and evolution of the fossil plate interface of the Ligurian Alps.

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