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Research Paper

Multistage tectono-stratigraphic evolution of the Canavese Intracontinental Suture Zone: New constraints on the tectonics of the Inner Western Alps

Gianni Balestro[a], Andrea Festa[a,b,*], Sara De Caroli[c], Edoardo Barbero[b], Alessandro Borghi[a], Franco Gianotti[a]

[a] Department of Earth Sciences, University of Torino, Torino, Italy
[b] National Research Council of Italy, Institute of Geosciences and Earth Resources, Torino, Italy
[c] School of Earth and Environmental Sciences, Cardiff University, Cardiff, Wales, UK

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ABSTRACT

The Canavese Intracontinental Suture Zone (CISZ) within the Inner Western Alps represents the remnant of a long-lived minor subduction zone involving a narrow, thinned continental crust/oceanic lithosphere seaway between two continental domains of the Adria microplate (i.e., the Sesia Zone and the Ivrea-Verbano Zone). As opposed to many suture zones, the CISZ mostly escaped pervasive tectonic deformation and metamorphism, thus preserving the original stratigraphy and allowing the relationships between tectonics and sedimentation to be defined. Through detailed geological mapping (1:5000 scale), structural analysis, stratigraphic and petrographic observations, we document evidences for the late Paleozoic to late Cenozoic tectonic evolution of the CISZ, showing that it played a significant role in the context of the tectonic evolution of the Inner Western Alps region from the early to late Permian Pangea segmentation, to the Jurassic Tethyan rifting, and up to the subduction and collisional stages, forming the Western Alps. The site of localization/formation of the CISZ was not accidental but associated with the re-use of structures inherited from regional-scale wrench tectonics related to the segmentation of Pangea, and from the subsequent extensional tectonics related to the Mesozoic rifting, as documented by crosscutting relationships between stratigraphic unconformities and tectonic features. Our findings document that evidences derived from stratigraphy, facies indicators, and relationships between tectonics and sedimentation in the shallow crustal portions of suture zones, such in the CISZ, are important to better constrain the tectonic history of those metamorphic orogenic belts around the world in which evolutionary details are commonly complicated by high-strain deformation and metamorphic transformations.

1. Introduction

Suture zones represent sites in orogenic belts whereby ancient oceanic lithosphere was obliterated by subduction and recycled, resulting in the final intracontinental welding of continental masses along highly deformed mountain belts (Dewey, 1977). Although the subduction of significant portions of oceanic lithosphere may be recorded by an ophiolite-bearing suture or a cryptic suture, minor sutures (i.e., of secondary order) with a wide variety of origins may also occur within the same collisional belt (Dewey and Bird, 1970; Dewey, 1977; Moores, 1981), documenting different evolutionary stages. Both major and minor suture zones commonly preserve the record of a complex tectonic evolution related to the superposition of oceanic rifting, subduction, and collisional processes, the latter of which can be preceded by collision of intraoceanic arcs, oceanic plateaus, microcontinents/extensional allochthons and related trenches. The superposition of these processes contributes to the internal structural complexities of suture zones along and across strike and, therefore, making challenging to decipher their tectonic and tectono-stratigraphic history (see Dewey and Bird, 1970; Dewey, 1977; Moores, 1981; Dilek, 2021).

Stratigraphy, facies indicators, and relationships between tectonics and sedimentation that developed at shallow crustal levels

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* Corresponding author at: Department of Earth Sciences, University of Torino, Torino, Italy.

E-mail address: andrea.festa@unito.it (A. Festa).

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in suture zones, and therefore not overprinted and reworked by high-strain deformation and metamorphic transformations, can be used for constraining their evolution and to derive information on the tectonic history of the orogenic belts in which they occur.

In the Western Alps, the major (i.e., first order) suture zone, marking the late Eocene – early Oligocene collision site between the Europe plate and the Adria microplate, is recorded by exhumed Jurassic metaophiolite (i.e., the Piemontese Zone in Fig. 1) derived from the downgoing Alpine Tethys oceanic lithosphere (i.e., the Ligurian-Piedmont oceanic basin; see, e.g., Dal Piaz et al., 2003; Schmid et al., 2004; Rosenbaum and Lister, 2005; Balestro et al., 2019; Handy et al., 2021 and references therein). However, the occurrence of scattered mantle rock slivers, juxtaposed to (and/or welded with) continental masses and/or mixed with them to form mélange zones in different sectors of the Western Alps, likely mark the site of minor (i.e., secondary order) suture zones (see, e.g., Compagnoni et al., 1977; Stampfli et al., 2002; Michard et al., 2007; Balestro et al., 2020; Festa et al., 2022). This is the case of the here named Canavese Intracontinental Suture Zone (i.e., the Canavese Shear Zone of Festa et al., 2020a; the Canavese Zone, see, e.g., Elter et al., 1966; Ahrendt, 1972; Wozniak, 1977; Borghi et al., 1996; Biino and Compagnoni, 1989; Ferrando et al., 2004; Barnes et al., 2014) in the Inner Western Alps (Fig. 1B, C), in which serpentinized peridotite slivers represent remnants of a long lived tectonic history from the Jurassic opening of a narrow oceanic basin (i.e., the Lanzo oceanic basin; see, e.g., Pognante et al., 1985; Lagabrielle et al., 1989; Pelletier and Müntener, 2006) to Late Cretaceous – early Eocene subduction, and late Eocene – early Oligocene collision between two different portions of the Adria microplate (i.e., the Sesia Zone and the Ivrea-Verbano Zone). We interpret the Canavese Intracontinental Suture Zone (CISZ hereafter) as an "intracontinental suture" within the Inner Western

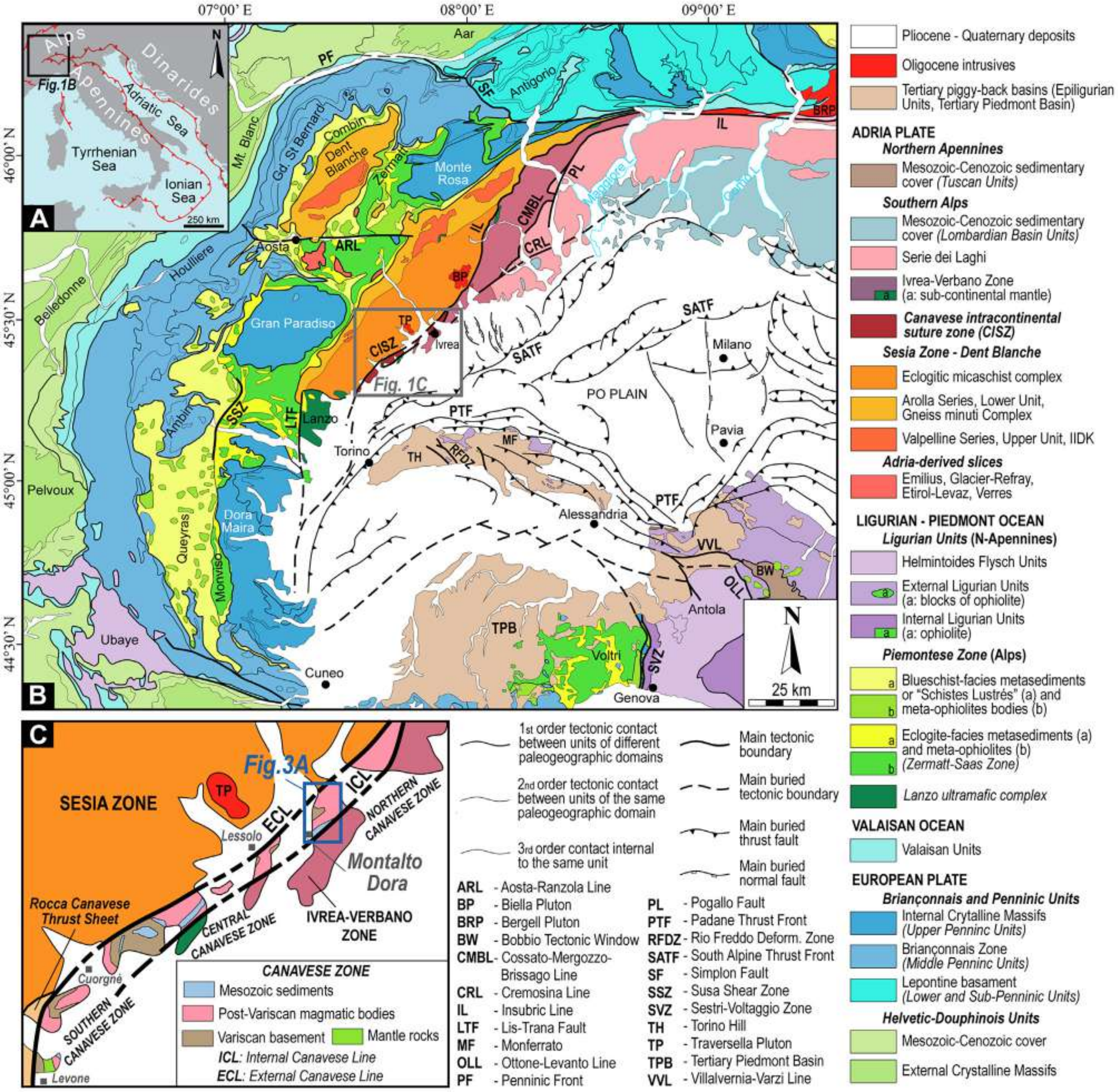


Fig. 1. (A) Sketch of the Alps-Apennine orogenic system and location of the map shown in Fig. 1B. (B) Tectonic map of the Western Alps and the Northern Apennines (modified from Balestro et al., 2015) with location of the sketch shown in Fig. 1C. (C) Simplified structural map of the Canavese Intracontinental Suture Zone (CISZ).

Alps, according to the definition by Michard et al. (2007), as it represents the result of a minor subduction zone involving a narrow, thinned continental crust/oceanic lithosphere seaway between two continental domains. The CISZ, already interpreted as suture zone (see Compagnoni et al., 1977; Pleuger et al., 2007), is located at the southern ending of the Insubric Line (Fig. 1B), which represents a major intracontinental fault zone, according to Schmid et al. (1987).

In the following, we present evidence for the late Paleozoic to late Cenozoic multistage tectonic and tectono-sedimentary evolution of the CISZ in the frame of the tectonic evolution of the Inner Western Alps, based on structural analysis, stratigraphic and petrographic observations, and the documentation of relationships between tectonics and sedimentation. We outline that these analyses and observations are strongly constrained on a new detailed geological mapping (1:5,000 scale) of a sector in which the last official geological map was realized more than one century ago at 1:100,000 scale (see Franchi et al., 1912). We focus on the Montalto Dora sector, which corresponds to the northern sector of the CISZ (Fig. 1B, C), to both avoid repetitions with our previous published data to the SE (i.e., central, and southern sectors of the Canavese Shear Zone of Festa et al., 2020a) and to provide complementary information to the complex evolution of this intracontinental suture zone with respect to our published data. We also compare results of our structural data with the Cenozoic tectono-stratigraphic evolution of the Tertiary Piedmont Basin and Northern Apennines (Fig. 1B), to support the lack of stratigraphic constraints younger than Middle Jurassic in most of the CISZ. In contrast with classical suture zones, in which the overprinting and reworking by high-strain deformation and metamorphic transformations commonly complicate a detailed definition of tectonic and tectono-stratigraphic stages, the CISZ mostly escaped pervasive Alpine deformation and metamorphism, thus preserving stratigraphy, facies indicators, and relationships between tectonics and sedimentation. Our definition and discrimination between the superposition and juxtaposition of different tectonic and tectono-sedimentary processes, which occurred at shallow structural levels (i.e., prehnite-pumpellyite facies conditions, see Biino and Compagnoni, 1989; Borghi et al., 1996) during the long-lived multistage evolution of the CISZ, may contribute to better understanding both the tectonic history of the Inner Western Alps, and the internal complexities which characterize the tectono-stratigraphic evolution of suture zones around the world.

2. Regional geological setting

The CISZ consists of a NE-striking deformation zone, few kilometers wide and several tens of kilometers long, marking the tectonic boundary between the blueschist- to eclogite-facies Sesia Zone of the Austroalpine Domain, to the NW, and the upper amphibolite to granulite facies Ivrea-Verbano Zone of the Southern Alpine Domain, to the SE (Fig. 1B, C). These two Zones, which show different internal architecture and tectono-metamorphic evolution (see, e.g., Dal Piaz et al., 2003 and references therein), were separated during the Mesozoic rifting, resulting in the Alpine Tethys (i.e., the Ligurian-Piedmont oceanic basin; Fig. 2), by a narrow and elongated basin (i.e., the Lanzo Oceanic Basin) along which mantle spread out (see, e.g., Aubouin et al., 1977; Mattauer et al., 1987; Froitzheim et al., 1996). Bounded by the two passive margins on the Sesia and Ivrea sides, the Lanzo oceanic basins, which now corresponds to the exhumed Lanzo Ultramafic Complex (Piccardo, 2010 and references therein; see Fig. 1B), developed as a branch of the Alpine Tethys (Fig. 2), gradually widening toward SW (present-day coordinates).

2.1. The Sesia Zone

The Sesia Zone (Fig. 1B), which is classically subdivided into three sub-units (i.e., the Gneiss Minuti Complex, the II Diorite-Kinzigite Zone, and the Eclogitic Micaschists Complex), consists of a polyphasic meta-sedimentary basement intruded by granitoid and gabbroic bodies of Carboniferous and Permian age (Dal Piaz et al., 1972; Compagnoni et al., 1977). It is interpreted as an Adria-derived extensional allochthon (Fig. 2B; see, e.g., Froitzheim et al., 1996), floating within the Ligurian-Piedmont oceanic basin that rifted and drifted away from the thinned passive margin of the Adria microcontinent during the opening of the Alpine Tethys in the Jurassic Period (see, e.g., Froitzheim et al., 1996; Pleuger et al., 2007; Schmid et al., 2017 and references therein). The allochthon was involved in the Late Cretaceous to early Cenozoic accretionary-subduction processes associated with the southeastward subduction of the Ligurian-Piedmont oceanic basin (Froitzheim et al., 1996; Babist et al., 2006, Pleuger et al., 2007; Handy et al., 2010), up to reach eclogite-facies conditions in the period 85–60 Ma (Regis et al., 2014). These processes formed a composite unit consisting of different slices of Adria continental crust metamorphosed under blueschist- to eclogite-facies conditions (e.g., Compagnoni et al., 1977; Spalla et al., 1991; Manzotti et al., 2014; Giuntoli and Engi, 2016; Vho et al., 2020). Evidence of the contact between the accreted Sesia Zone and the rocks of the CISZ occurs in the Rocca Canavese Thrust Sheet (see, e.g., Pognante, 1989, Spalla and Zulbati, 2003; Zucali et al., 2012) in the southern part of the Sesia Zone (Fig. 1C), which consists of a tectonic mélange, formed by the mixing of mantle-derived lithologies (serpentinized lherzolite) and crustal rocks (pre-Alpine granulite, metagranitoids, and glaucophane-bearing schists; see Roda et al., 2018, Roda et al., 2020). During the early Oligocene Epoch, the Sesia Zone was locally intruded by magmatic bodies (i.e., the Biella Volcanic suite, and the Traversella pluton in Fig. 1B; see, e.g., Rossetti et al., 2007; Zanoni et al., 2008, 2021; Berger et al., 2012a, 2012b; Kapferer et al., 2012).

2.2. The Ivrea-Verbano Zone

The Ivrea-Verbano Zone (Southern Alpine Domain) corresponds to a section of the Adriatic lower crust (Fig. 1B and 2) and consists of an upper amphibolite- to granulite-facies Variscan basement (the Kinzigite Formation *Auct.*; Zingg, 1983), which was intruded by lower Permian gabbro and diorite bodies (the Mafic Complex *Auct.*; see Zingg et al., 1990; Quick et al., 2003). It represented the upper plate during the Late Cretaceous subduction of the accreted units of the Sesia Zone in the lower plate (e.g., Babist et al., 2006). The Ivrea-Verbano Zone is tectonically juxtaposed to the Serie dei Laghi (Fig. 1B, see Boriani and Sacchi, 1974; Mulch et al., 2002), which represents a section of the Adriatic upper crust in the Southern Alps. It consists of an amphibolite-facies Variscan basement, which was intruded by lower Permian granitoids and covered by volcanic rocks and late-Carboniferous to Cretaceous sediments (Boriani et al., 1990; Bertotti et al., 1993; Quick et al., 2009). The Ivrea-Verbano Zone is deformed at depth by SE-verging thrusts developed in the retro-wedge hinterland of the Alps since the collisional stage and indentation of the Adria mid-lower lithosphere against the rear of the wedge, and by subsequent southeastward migration of the South Alpine thrust fronts, which are now sealed by late Miocene deposits and buried below the alluvial deposits of the Po Plain (e.g., Laubscher, 1991; Zanchetta et al., 2015).

2.3. The Canavese intracontinental suture zone (CISZ)

The stratigraphic succession involved in the deformation of the CISZ (Fig. 1B, C) consists of a Variscan Basement and lower Permian

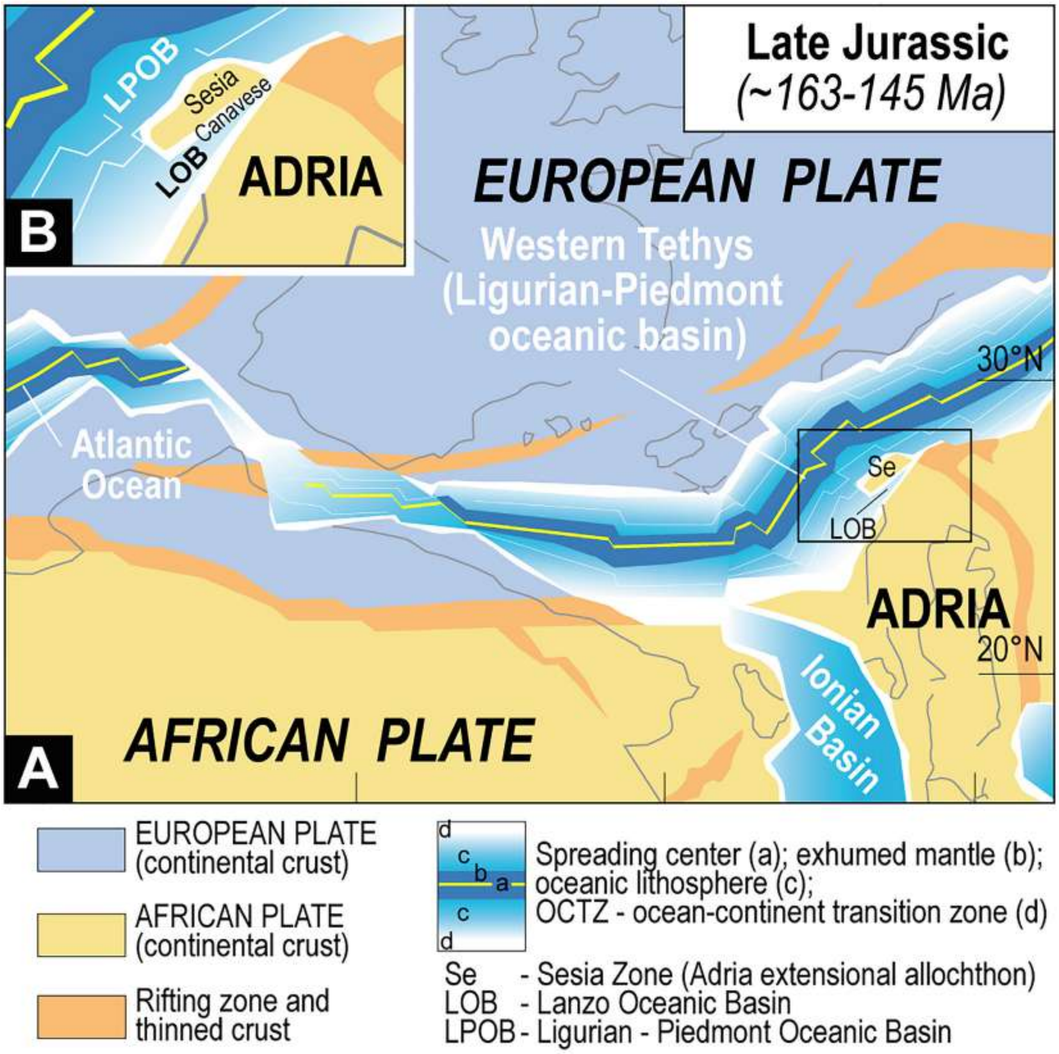


Fig. 2. (A) Paleogeographic reconstruction of the Alpine Tethys (Ligurian-Piedmont Oceanic Basin – LPOB) in the Late Jurassic (modified from Stampfli and Kozur, 2006; Schettino and Turco, 2011; Festa et al., 2021), showing (B) the location of Canavese sector in the ocean-continent transition zone (OCTS) between the Lanzo Oceanic Basin (LOB) and Sesia Zone (Se), which represents an extensional allochthon of the Adria microplate.

igneous bodies, overlain by Permian to Lower Cretaceous sediments, which represent the product of the deposition occurred at the ocean-continental transition zone between the Lanzo oceanic basin and the bounding rifted passive margins of the Adria microplate (Fig. 2; see, e.g., Elter et al., 1966; Ahrendt, 1972; Wozniak, 1977; Biino and Compagnoni, 1989; Borghi et al., 1996; Ferrando et al., 2004; Berra et al., 2009; Barnes et al., 2014; Festa et al., 2020a; Barale et al., 2021). This succession mostly escaped from pervasive Alpine deformation and metamorphism, and was poorly recrystallized under prehnite-pumpellyite facies conditions (Biino and Compagnoni, 1989; Borghi et al., 1996).

The Variscan basement includes a lower and an upper unit (Baggio, 1965b; Ferrando et al., 2004; Festa et al., 2020a). The lower unit consists of micaschist and orthogneiss metamorphosed under amphibolite-facies conditions during the Variscan orogeny, and partly transformed into migmatitic gneiss during the Permian high-temperature metamorphic event. The upper unit consists of a metasedimentary succession with a Variscan metamorphic overprinting, varying from the amphibolite-facies to the greenschist-facies (Wozniak, 1977; Biino and Compagnoni, 1989; Borghi et al., 1996; Sacchi et al., 2007). The two basement units were intruded by post-Variscan plutons and hypabyssal dykes of both mafic to acidic composition and, together, are overlain by Permian volcanic and volcanoclastic rocks (Fenoglio, 1931; Baggio, 1963; Sturani, 1964; Elter et al., 1966; Ahrendt, 1972; Wozniak, 1977; Ferrando et al., 2004). The following late Paleozoic – Mesozoic sedimentary succession is classically subdivided into pre- (i.e., late Carboniferous – Middle Triassic), syn- (i.e., Early Jurassic), and post- (i.e., Early Cretaceous) extensional deposits, which record different stages of the Jurassic rifting of the Alpine Tethys (e.g., Elter et al., 1966; Ferrando et al., 2004, Beltrando et al., 2014; Festa et al., 2020a; Barale et al., 2021). Importantly, the whole Canavese stratigraphic succession shows significant variations in both thickness and facies since the upper Carboniferous terms (see Festa et al., 2020a and references therein). This documents a long-lived tectonic control on sedimentation, with Late Paleozoic - Permian structural inheritances playing a significant role in the localization of both the Jurassic rifting of the Alpine Tethys and the convergent tectonics (see Festa et al., 2020a and references therein).

The structure of the CISZ is characterized by the interlacing of anastomosing faults, NE- to E-striking, which isolate and juxtapose lenticular tectonic slices of Variscan metamorphic basement, post-Variscan intrusives, and different terms of the late Paleozoic to Mesozoic cover succession, as well as of serpentinized peridotite wrenched from the Lanzo mantle rocks (Fig. 1B, C). The latters crop out in the southern portion of the CISZ (Levone sector; Fig. 1C), and mainly consist of massive serpentinite with a very low degree of melt depletion (see Barnes et al., 2014 for details), thus showing a fertile character well-comparable with the one of many peridotites from the Alps and Northern Apennines (e.g., Rampone et al., 1995; Müntener et al., 2010; Saccani et al., 2015). The CISZ is bounded by two regional-scale, first order, faults, the External and Internal Canavese Lines (see Biino and Compagnoni, 1989), about NE-striking and steeply dipping (Fig. 1C). The External Canavese Line (ECL hereafter), which corresponds to the southeastern termination of the Insubric Line (see Fig. 1B, see also Lanza, 1984; Berger et al., 2012a), developed in the Oligocene-early Miocene times under brittle conditions, also driving the exhumation of the Sesia Zone. The Internal Canavese Line (ICL hereafter), which is marked by mylonite rocks developed under low grade metamorphic conditions (Zingg et al., 1976; Schmid et al., 1987), is considered an older left-lateral ductile fault zone, controlling the Late Cretaceous subduction of the Sesia Zone and subsequent collision and exhumation of the Ivrea-Verbano Zone (e.g., Schmid et al., 1987; Biino and Compagnoni, 1989, and references therein).

3. Stratigraphy of the CISZ in the Montalto Dora sector

In the Montalto Dora sector (i.e., the northern sector of CISZ, see Fig. 1B), the stratigraphic succession derived from the detailed geological mapping presented in this work consists of (i) Variscan basement, (ii) post-Variscan intrusive bodies and volcanic rocks, (iii) Mesozoic sediments, and (iv) lower Oligocene dykes (Fig. 3A, B). These different lithological units are locally covered by Pleistocene glacigenic sediments, belonging to the Ivrea end-moraine system (Gianotti et al., 2015), and by Holocene alluvial and debris flow deposits (Fig. 3A).

3.1. The Variscan basement

The Variscan metamorphic basement mainly consists of micaschist and gneiss, which are juxtaposed to each other along an ENE-striking fault, and both show primary relationships with the post-Variscan intrusives and the volcanic sequence (Fig. 3A; see below). The micaschist is about a few hundreds of meters in thickness and it is dark grey in color and fine-grained. Its mineral assemblage consists of quartz, white mica, albite, Mn-rich garnet, chlorite, and graphite. The gneissic rocks are several tens of meters thick and mainly consist of medium-grained paragneiss, which is composed of white mica, quartz, albite, chlorite and minor biotite and graphite. The white mica is of muscovite composition (average Si^{4+} content = 3.18 *a.p.f.u.*; see Supplementary Data, Table S1 and Fig. S1). They are interlayered by decimeters-thick levels of medium-grained leucocratic orthogneiss (Fig. 4A), which consists of K-feldspar porphyroclasts in a matrix of abundant quartz, white mica and albite, with minor chlorite. Metabasite and garnet-bearing quartzite levels within the paragneiss have also been described by Biino and Compagnoni (1989). Textural and mineral relics, together with field relationships between paragneiss and orthogneiss, suggest that pre-Variscan sediments were originally interlayered by levels of volcanic rocks of intermediate to acidic composition.

3.2. The post-Variscan intrusives and the volcanic sequence

The Variscan basement is intruded by a kilometer wide pluton, mainly consisting of diorite and granite, with minor bodies of gabbrodiorite, quartz-bearing diorite, and tonalite. The diorite is medium-grained and massive, and shows a magmatic mineral assemblage of plagioclase, amphibole, relics of pyroxene, biotite, and minor quartz. It is widely crosscut by fine-grained microgranite dykes, decimeters- to meters in size (Fig. 4B). The granite is leucocratic, medium- to coarse-grained, and shows a porphyritic texture including K-feldspar, quartz, albite, white mica, and biotite.

The post-Variscan intrusives, and the hosting Variscan basement, are both unconformably overlain by a volcanic and volcanoclastic sequence post-Varsican in age (Fig. 3B and 4C), which can be referred to the Lower member of the Collio Formation *Auct.* (*sensu* Cadel et al., 1996; Cassinis et al., 2012 and references therein), as also described in the central sector of CISZ (i.e., in the Cuorgnè area; Fig. 1C; see Festa et al., 2020a). Volcanics and volcanoclastic deposits show important thickness variations (Fig. 3B), ranging from about 100 m to more than 350 m, in sectors juxtaposed along ENE- to NE-striking faults. Volcanic rocks are purple red to greenish grey in color and consist of fine-grained porphyritic andesite and rhyolite (Fig. 4D). The former is mainly made up of plagioclase phenocrysts embedded in an aphanitic groundmass, whereas the rhyolite consists of quartz, K-feldspar, and minor biotite phenocrysts. Discontinuous volcanoclastic deposits, ranging in thickness from meters to about one hundred meters, are interfingered at different stratigraphic levels within the volcanic sequence. They are medium- to coarse-grained, reddish to light grey in color (Fig. 4D) and characterized by a matrix-supported texture with millimeters to pluri-centimeters sized angular clasts of volcanic glass, andesite, rhyolite, micaschist and quartzite, as well as crystals of quartz, plagioclase, and white mica.

The above described post-Variscan intrusives and the volcanic sequence can be overall compared to the Lower Permian magmatic suite widely occurring in the Southern Alps (see e.g., Quick et al., 2009, and references therein).

3.3. The Mesozoic sediments

The CISZ Mesozoic succession is classically subdivided into pre-extensional and *syn*-extensional deposits in relation to the Jurassic rifting of the Alpine Tethys (Fig. 3; see Elter et al., 1966; Ferrando et al., 2004; Festa et al., 2020a). Above the volcanic rocks of the Collio Formation, the pre-extensional succession starts with a greenish coarse-grained sandstone (Fig. 4E), ranging in thickness from few decimeters to about 2 m. It consists of clasts, up to millimeters in size, of metasandstone and metavolcanic rocks sourced from the Variscan basement and from volcanic rocks of the Collio Formation, which are embedded in a matrix mainly made up of chlorite. It is important to note that no clasts or lithics of dolostone occur within this sandstone, suggesting a correlation with the Lower Triassic Servino Formation of the Southern Alps (see, e.g., Cadel et al., 1996). This sandstone, which has been documented for the first time in the Montalto Dora sector, also is an excellent comparison with analogous horizons observed in the central CISZ above the upper Permian Verrucano (see Festa et al., 2020a). Through a depositional hiatus, the Servino Formation passes upward to the Middle Triassic (Ladinian, see Berra et al., 2009) San Salvatore Dolostone (Fig. 3B), which consists of light grey, fine-grained, massive dolostone and dolomite limestone (Fig. 5A), up to several tens of meters thick. This stratigraphic contact is exposed only to the North of Mt. Crovero (see Fig. 3A), which represents the only sector in which the stratigraphic relationships among the pre-extensional lithostratigraphic units (i.e., Servino Formation and San Salvatore Dolostone) are preserved and not modified/overprinted by tectonics.

The San Salvatore Dolostone is followed by heterogeneous Lower to Middle Jurassic *syn*-extensional deposits of the Muriaglio Formation (*sensu* Festa et al., 2020a), whose base marks a new depositional hiatus, corresponding to Late Triassic – Early Jurassic. This lithostratigraphic unit is subdivided into four mappable members (i.e., Clastic, Arenaceous, Siltitic-arenaceous and Limestone members, from the lower to the upper one; see Fig. 3B). The Clastic Member (i.e., the Macchia Vecchia breccia of Baggio, 1965a, 1965b)

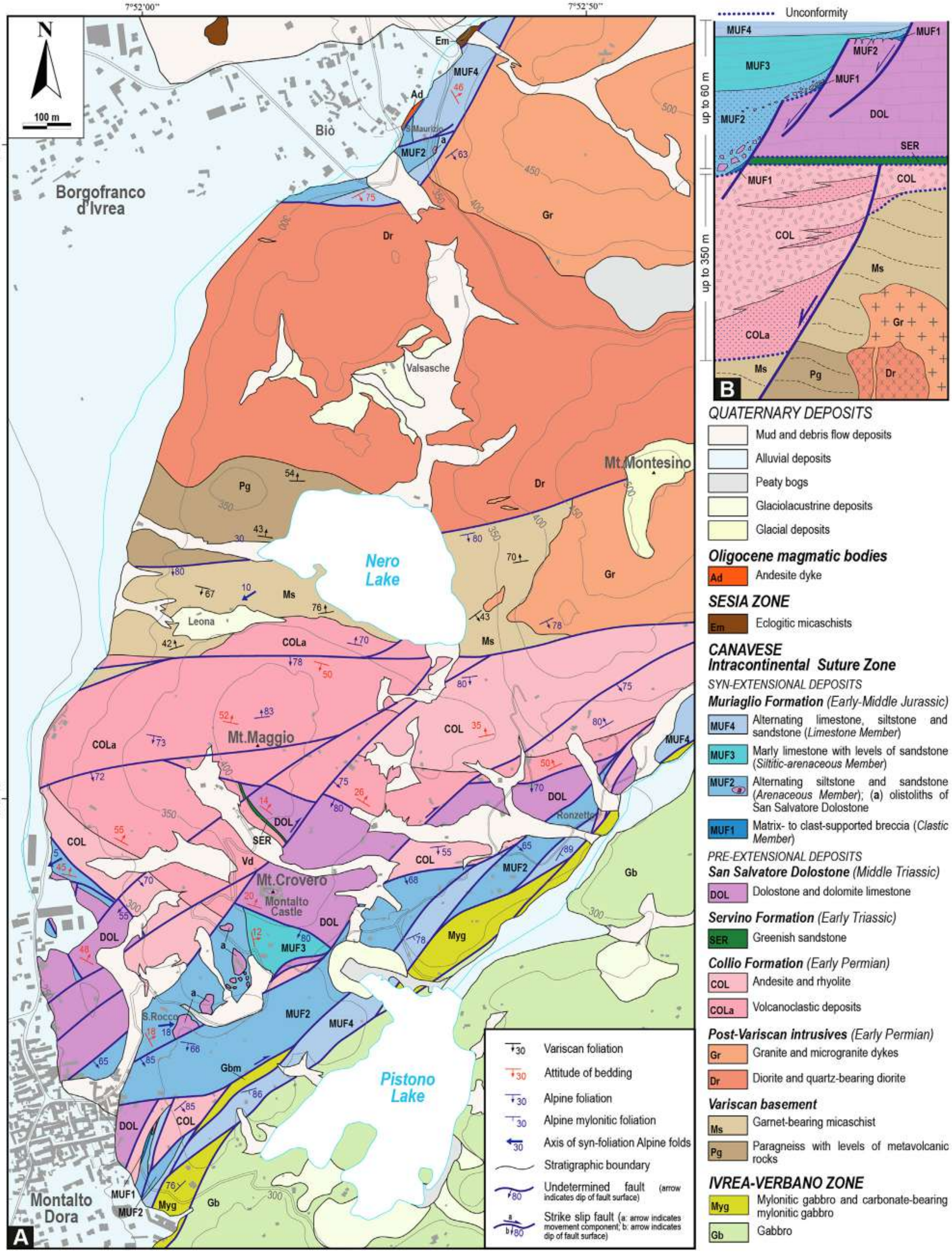


Fig. 3. (A) Geological map of the CISZ in the Montalto Dora sector (location of the map in Fig. 1C). (B) Stratigraphic columnar section of the stratigraphic succession within the CISZ in the Montalto Dora sector.

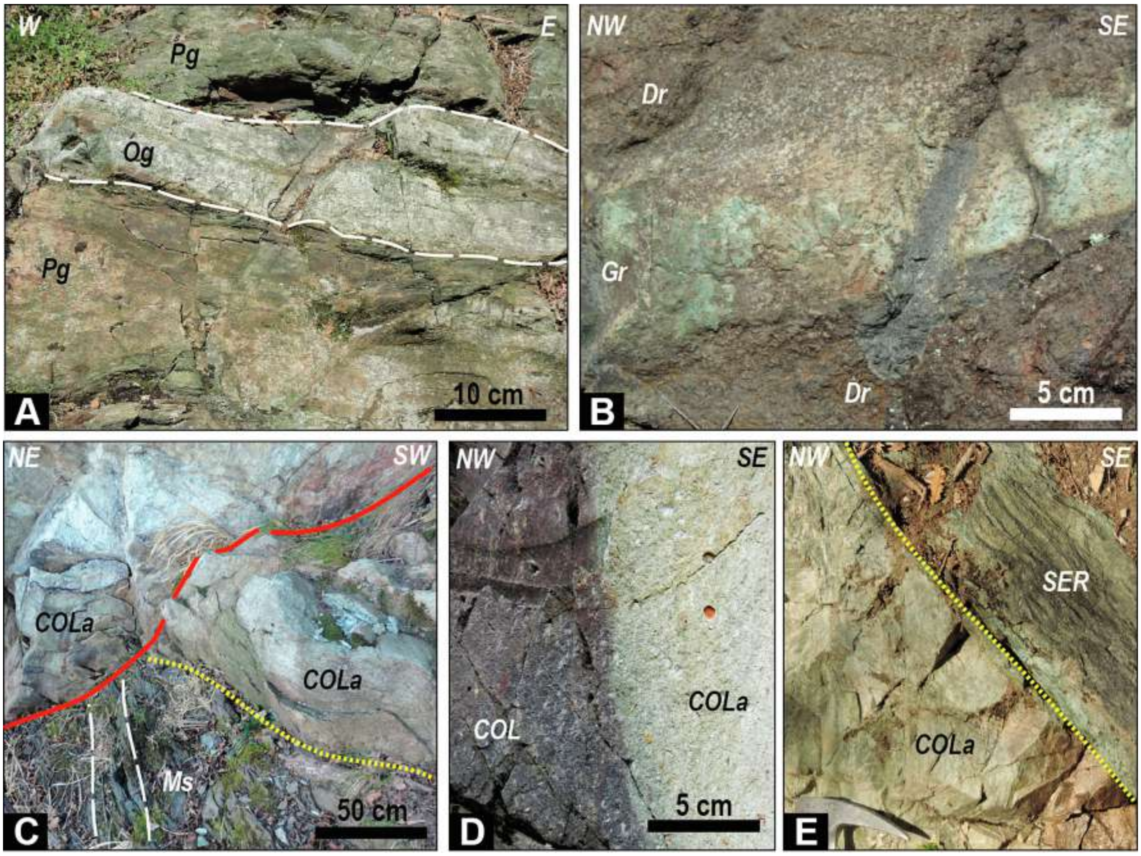


Fig. 4. Field images of the Paleozoic lithostratigraphic units. (A) Close up view of a Variscan Paragneiss (Pg) interlayered by leucocratic orthogneiss (Og) (dashed white lines mark both the contact lithological contacts and the trending of the Variscan foliation; northwestern side of Nero Lake). (B) Close up view of diorite (Dr) crosscuts by a microgranite (Gr) dyke (West of Mt. Montesino). (C) View of the stratigraphic contact (dotted yellow line) between the early Permian volcanoclastics of the Collio Formation (COLa) and the Variscan micaschist (Ms); the contact is displaced by an NNE-striking fault (red line); dashed white lines mark the Variscan foliation (southwestern side of the Nero Lake). (D) Close up view of a stratigraphic contact between the volcanic (COL) and volcanoclastic (COLa) rocks of the Collio Formation (West of Mt. Maggio). (E) Close up view of the stratigraphic contact (dotted yellow line) between the Early Triassic sandstone of the Servino Formation (SER) and the early Permian volcanoclastics of the Collio Formation (COLa) (North of Mt. Cravero). Hammer for scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

represents a Sinemurian – Toarcian(?) condensed succession (Sturani, 1964; Elter et al., 1966) deposited on morphological and/or structural highs, which gradually opens away from the platform dolostone, from decimeters to few meters (Fig. 3A, B). It consists of a matrix- to clast-supported breccia with clasts of whitish dolostone and minor pink limestone, centimeters to decimeters in size, embedded in a greyish to reddish siltitic-arenaceous matrix (Fig. 5B). Locally (i.e., West of Pistono Lake), this breccia directly overlain both the lower Permian volcanic rocks (Fig. 5B) and the Middle Triassic San Salvatore Dolostone, also filling Neptunian dykes (e.g., south of the Mt. Crovero; Fig. 5C) at the top of the platform dolostone (see also Sturani, 1964; Elter et al., 1966; Berra et al., 2009; Barale et al., 2021).

The Clastic member gradually passes upward and laterally to the Arenaceous member (Fig. 3A, B), which consists of a fining-upward sequence of alternating pelite and medium- to coarse sandstone, interbedded by dark to reddish argillite levels (Fig. 5A), millimeters in thickness, and local intercalations of matrix-supported conglomerate horizons with centimeters-sized clasts of quartz composition (Fig. 5D). To the WSW of Mt. Crovero, the Arenaceous member embeds irregular shaped blocks (i.e., olistoliths) of the San Salvatore Dolostone, ranging in size from a few meters up to tens of meters, forming an olistolith field (*sensu* Festa et al., 2016; Ogata et al., 2020) over an area of several hundreds of meters square (Fig. 3A, B). Olistoliths, which range in shape from tabular to angular and are pervasively veined, locally preserve the stratigraphic contact with the Clastic member of the Muriaglio Formation, documenting that at least in part they are sourced from the topmost portion of the San Salvatore Dolostone. They show a random distribution within the arenaceous matrix and seem to be sealed by the Siltitic-arenaceous member (Fig. 3A, B). The latter consists of tens of meters thick pinkish marly limestone with crinoid fragments, and greenish to reddish and yellow fining-upward sandstone (Fig. 5E), in centimeters thick levels, interbedded by black pelite and sandstone levels with sub-rounded clasts, centimeters in size, of yellowish quartz-rich arenite. The age of this member is considered Sinemurian by Sturani (1964), based on the paleontological content. Although the direct stratigraphic relations between the Siltitic-arenaceous member and the Arenaceous member are not observed in the studied sector, observations from the central and southern CISZ (see Festa et al., 2020a) document that commonly the latter passes upward and laterally to the former one.

The Muriaglio Formation ends with the Limestone member (i.e., the Pistono Schist and Biò Schist of Biino and Compagnoni, 1989, and references therein), which consists of alternating white to grey limestone and fine-grained siltstone and sandstone in decimeters thick beds (Figs. 3 and 5F). As for other members, the Limestone member locally rests unconformably onto both the San Salvatore Dolostone and the Clastic and Arenaceous members. The occurrence of interbedded quartzite horizons, possibly deriving from cherts, suggests a Middle Jurassic age for this Member (Sturani,

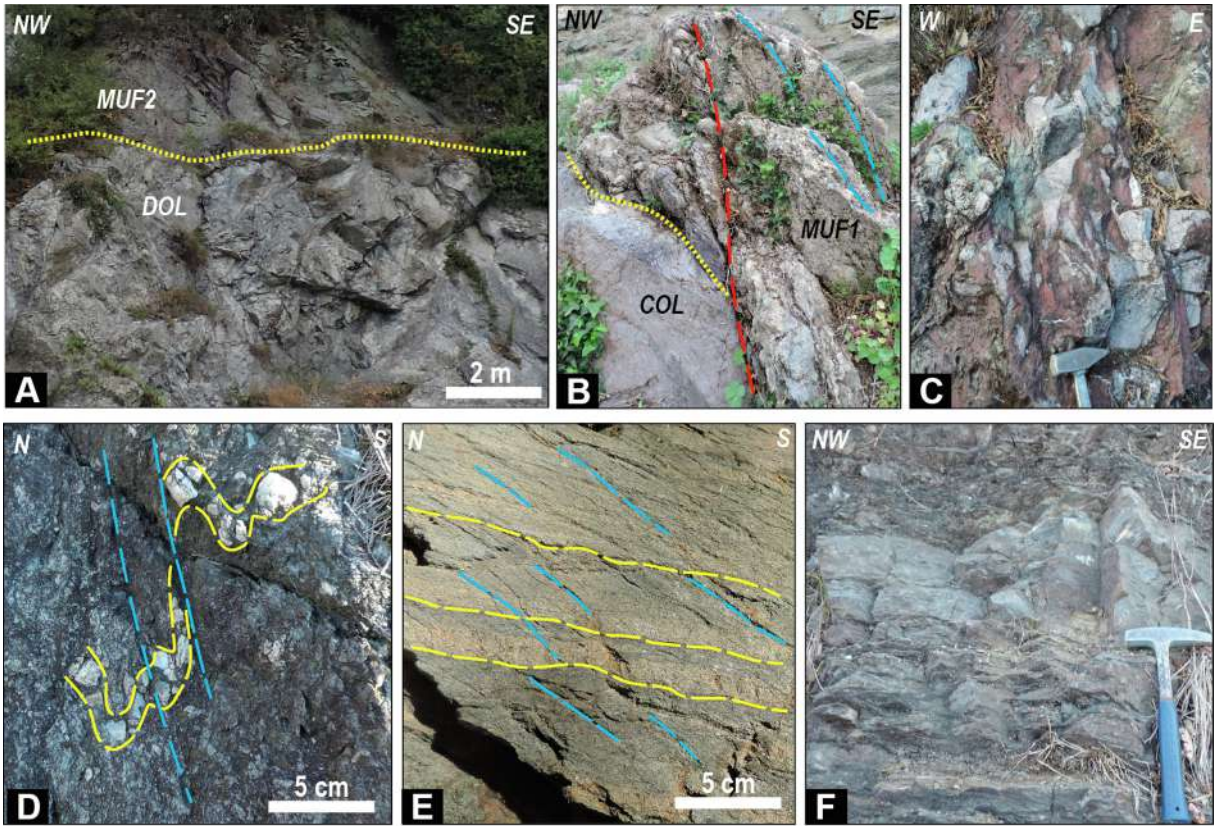


Fig. 5. Field images of Mesozoic lithostratigraphic units. (A) Panoramic view of the stratigraphic contact (dotted yellow line) between the the San Salvatore Dolostone (DOL) and alternating siltstone and sandstone of the Muriaglio Formation (Arenaceous Member, MUF2) (North of Montalto Dora). (B) Close up view of the stratigraphic contact (dotted yellow line) between volcanic rocks of the Collio Formation (COL) and breccia of the Muriaglio Formation (Clastic Member, MUF1); the contact is crosscut by a NE-striking alpine fault (dashed red line) (Montalto Dora) and clasts are elongated parallel to the Alpine foliation (dashed light blue lines). (C) Close up view of a neptunian dyke (i.e., the Macchia Vecchia breccia; Clastic Member of the Muriaglio Formation) filled with breccias in a reddish siltitic matrix (SE of Mt. Crovero). (D) Close up view of a conglomeratic horizon with clasts of quartz occurring in the Arenaceous Member of Muriaglio Formation; original bedding surfaces (dashed yellow lines) are deformed by close folds with axial panes corresponding to the Alpine foliation (dashed light blue lines) (S. Rocco). (E) Close up view of alternating yellowish siltstone and sandstone levels of the Siltitic-arenaceous Member (Muriaglio Formation); dashed yellow and light blue lines mark the bedding surfaces and the Alpine foliation, respectively (South of Mt. Crovero). (F) Close up view of alternating limestone and siltstone levels of the Limestone Member (Muriaglio Formation) (S. Maurizio; hammer for scale). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1975). Therefore, the age of the whole Muriaglio Formation ranges from the upper part of the Early Jurassic to the Middle Jurassic Period (see Elter et al., 1966 and references therein).

3.4. The lower Oligocene dykes

A meter-sized andesite dyke occurs along the ECL, between the eclogitic micaschist of the Sesia Zone and the Jurassic sediments of CISZ (Fig. 3A). It is bluish green in color and characterized by a porphyritic texture with altered phenocrysts of plagioclase and amphibole embedded in a very fine-grained groundmass. Considering its textural features and its tectonostratigraphic position, the dyke can be referred to the early Oligocene (late-orogenic) Periadriatic magmatism (see Kapferer et al., 2012, and references therein). The occurrence of similar dykes has been also described by Biino et al. (1988).

4. Structure of the CISZ in the Montalto Dora sector

The CISZ in the Montalto Dora sector currently corresponds to a structurally complex and polyphasic, Alpine-age, strike-slip deformation zone (Fig. 3A), about NE-striking and up to a few kilometers wide, internally made up of the interlacing of high-angle anastomosed faults. These faults isolate lenticular tectonic slices of different lithostratigraphic units and lithologies, in each of which primary relationships between different terms of the stratigraphic succession are locally preserved (Fig. 3A). Locally, the CISZ also preserves structural features inherited from the (i) Variscan orogeny, (ii) pre-Alpine tectonics, and (iii) Alpine orogeny, which are currently superposed by the younger Alpine deformational events.

4.1. Variscan tectonic features

The main feature of Variscan tectonic deformation consists in the occurrence of a main foliation (Fig. 4A), which characterizes the micaschist and paragneiss of the Variscan basement at both the micro- and *meso*-scale. It is mainly transpositive, corresponding to the axial plain of tight to isoclinal folds, and dips toward NNW at moderate angle, and locally toward South (Fig. 6B), in a parallel fashion to the lithological contacts between the different rock types. Its scattered distribution is coherent with an E-striking fold axis, which can be related to the subsequent Alpine folding (see below). At the microscale, the Variscan foliation is mostly defined by oriented lepidoblasts of white mica of muscovite composition (average Si^{4+} content = 3.18 *a.p.f.u.*; see Supplementary data, Table S1 and Fig. S1) foliation is axial planar to tight to isoclinal folds.

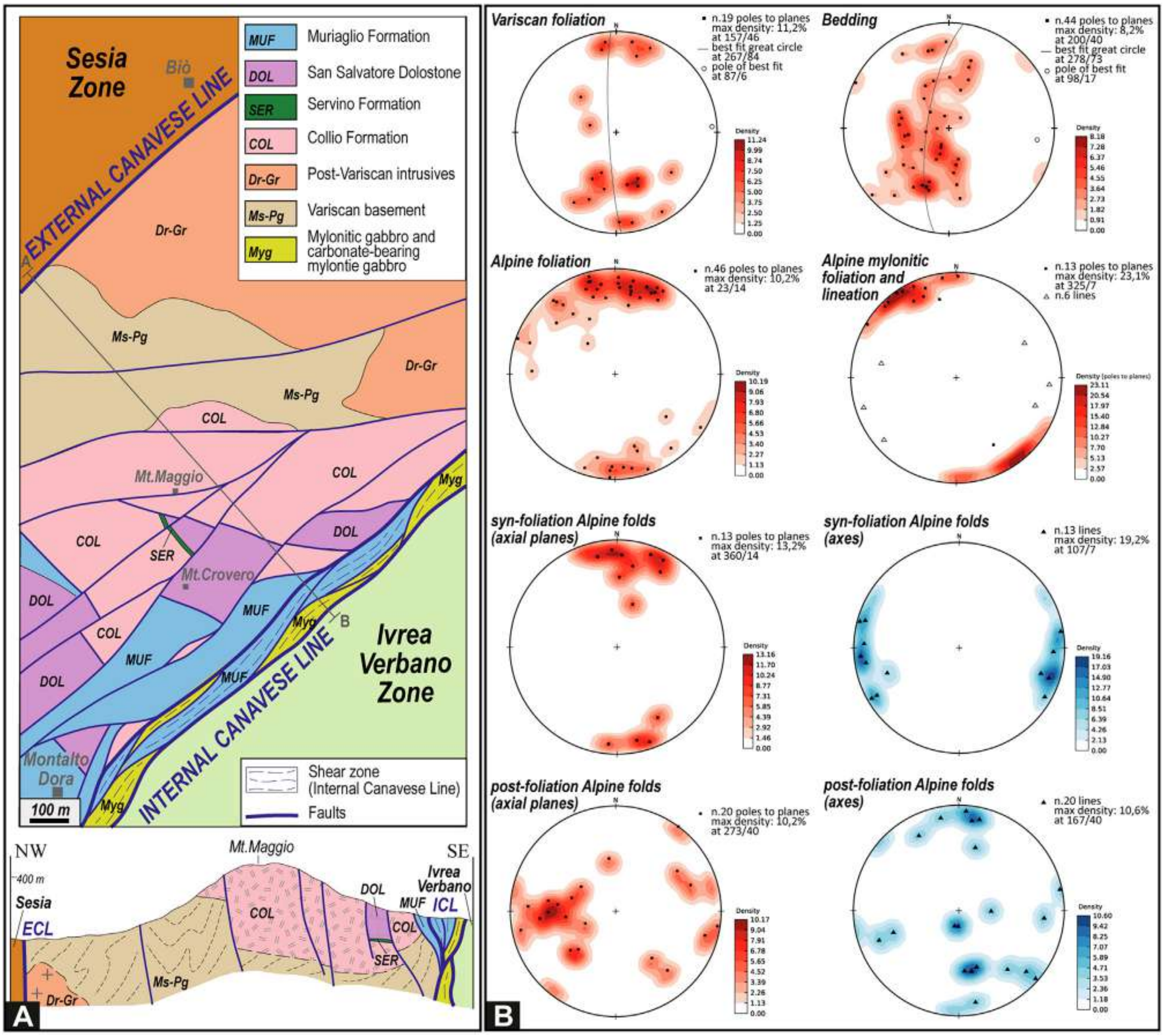


Fig. 6. (A) Tectonic sketch and cross-section of the CISZ in the Montalto Dora sector. (B) Stereographic projections of mesoscale structural data (Schmidt net, lower hemisphere; n.: number of data; counting method: Fisher distribution; best fit method: Bingham axial distribution).

4.2. Post-Variscan – pre-Late Cretaceous (i.e., pre-Alpine) tectonic features and/or related stratigraphic evidence

Pre-Alpine tectonic features, although existing, are mainly overprinted and reactivated by later (i.e., Alpine) tectonic deformation (see below). Therefore, evidence of pre-Alpine (i.e., post-Variscan – pre-Late Cretaceous) tectonics is mainly documented by significant changes of both facies and thickness of the lower Permian – Middle Jurassic succession in sectors bounded by both NE- and WNW-striking faults. This evidence allows to recognize and distinguish the early Permian-Early Triassic tectonic features and/or their direct control on sedimentation from Late Triassic-Early Jurassic ones, as in the following.

4.2.1. Early Permian – Early Triassic tectono-stratigraphic features

The main evidence of tectonic activity during this time interval is documented by both the significant variation in both thickness and facies of the lower Permian Collio Formation in sectors juxtaposed along ENE- to NE-striking faults (see Section 3.2) and restoration of the pre-Triassic fault offset. Fig. 7 clearly shows that the stratigraphic boundary at the base of the Servino Formation (Early Triassic) and that one between the volcanoclastic deposits and volcanic rocks of the Collio Formation (early Permian) are cut off with opposite sense of movement (i.e., left-lateral vs right-lateral, see black and red arrows in Fig. 7A, respectively) and/or different magnitude of displacement. re-attaining the juxtaposition of the stratigraphic boundary at the base of the Servino Formation (Early Triassic) through the restoration of the left-lateral component of movement (black arrows in Fig. 7A) along the NE-striking fault, allows to locate the "null point" there (black dot in Fig. 7B), according with inversion tectonics criteria. As a result, the stratigraphic boundary within the volcanoclastic deposits and volcanic rocks of the lower Permian succession to the NE and SW of the "null point" (see red hemispheres and red arrows in Fig. 7B) clearly remain in net horizontal (i.e., right-lateral) displacement along the same, NE-striking, fault system. The same result is also shown by locating the "null point" in the point of re-attained juxtaposition of the same tectonic contact, such as the WNW-striking fault (see Fig. 7A), which likely corresponds to a Jurassic fault system as documented in the next section (see Sec-

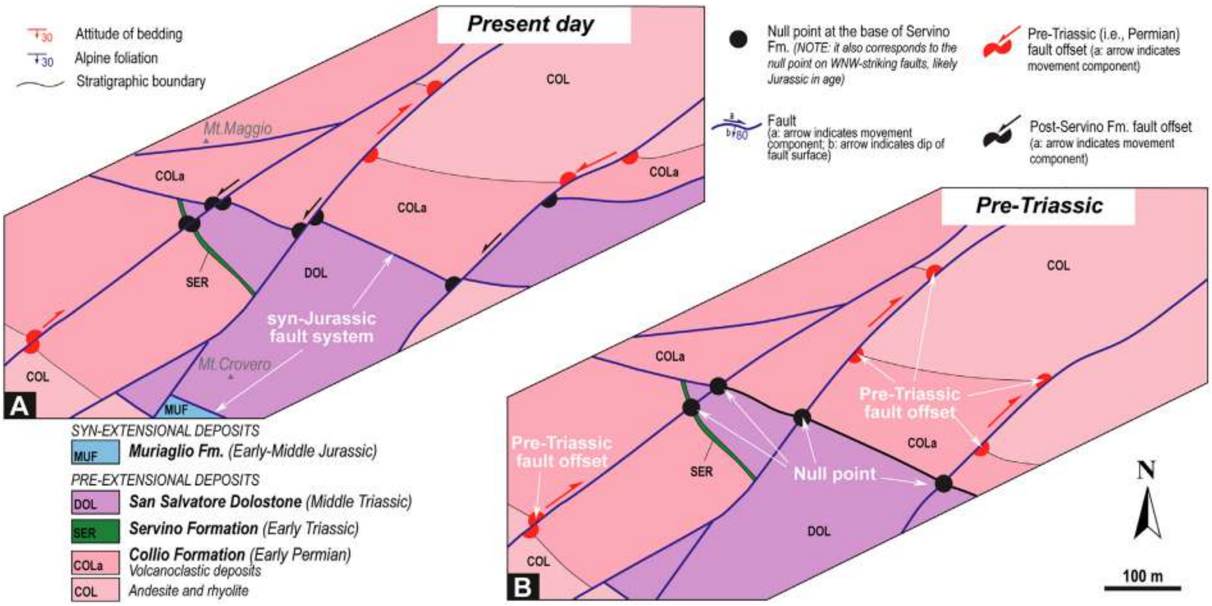


Fig. 7. Tectonic sketch of the central part of the study area (A), reconstructing the pre-Triassic (i.e., Permian) fault offset (B) of NE-striking faults before the deposition of the Servino Formation (Early Triassic). The "null point" (black dot), which is defined as the point of re-attained juxtaposition of the same stratigraphic boundary, is located at the base of the Servino Formation and/or, alternatively, along the WNW-striking fault that is interpreted as *syn*-Jurassic faults. After re-attaining the juxtaposition of the stratigraphic boundary at the base of the Servino Formation (Early Triassic) through the restoration of the left-lateral component of movement (black hemisphere and black arrows) along the NE-striking faults, the stratigraphic boundary between the volcanoclastic deposits and volcanic rocks of the Collio Formation (early permian) documents right-lateral offsets (red hemisphere and red arrows) inherited from a pre-Triassic (i.e., Permian) faulting stage. See text for a detailed explanation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tion 4.2.2). Application of inversion tectonics criteria allows, therefore, to clearly document that the NE-striking fault system represent pre-early Triassic inherited (i.e., Permian) right-lateral (and locally left-lateral) faults, which were reactivated with opposite sense of movement (left-lateral) after the deposition of the Early Triassic Servino Formation and the Middle Triassic San Salvatore Dolostone (Fig. 3A).

Another minor indirect evidence for Early Permian tectonics is the local alignment of microgranite dykes to major ENE-striking high-angle fault, which displace the diorite to the north of Nero Lake (Fig. 3A), suggesting that a fracture network parallel to this fault likely represented one of the preferential pathways for dyke intrusions.

4.2.2. Late Triassic – Middle Jurassic tectono-stratigraphic features

Evidence of tectonic activity during Jurassic age is indirectly documented by the occurrence, distribution, and internal organization of the heterogeneous Lower-Middle Jurassic Muriaglio Formation. The most notable evidence occurs close to the Montalto Dora village to West of the Pistono Lake, and SW of Mt. Crovero (Fig. 3A). In the first sector, although the contacts are partially reworked by Alpine deformation (see below Section 5.3), the Muriaglio Formation pinches out toward volcanic deposits. Here, the Clastic member of the Muriaglio Formation, which mainly consists of dolostone clasts, drapes the remnants of a primary tectono(?)-morphological scarp, probably dipping toward ESE (present day coordinates), according to the progressive thickening of the *syn*-extensional succession toward the same direction. The unconformable deposition of different terms of the Muriaglio Formation (i.e., from the Siltitic-arenaceous member to the Limestone member) directly above the Collio Formation and/or on the San Salvatore Dolostone in sectors separated by both NE- and WNW-striking faults (Fig. 3A), well agrees with the evidence that primary structural and/or morphological highs characterized the Jurassic depositional setting.

In the second sector (i.e., SW of Mt. Crovero), the occurrence of an olistolith field with blocks of San Salvatore Dolostone randomly distributed within the Arenaceous member of the Muriaglio Formation (Fig. 3A), provides additional evidence of *syn*-sedimentary tectonics. Blocks were likely sourced by a tectonic or tectonometamorphic scarp now corresponding to the southwestern side of the Mt. Crovero - Mt. Maggio hill. Evidence that the olistolith field is bounded between NE-striking strike-slip faults, tentatively suggests a primary role of those faults in controlling the basin physiography (see below Section 5).

4.3. Alpine tectonic features

4.3.1. Foliation

The earliest Alpine-related tectonic feature is represented by a discontinuous foliation, which shows different characteristics and pervasiveness degrees, depending on the rock rheology and texture. Pervasive planar surfaces, millimeters spaced, characterize the fine-grained portions of the Muriaglio Formation (Fig. 5E), also showing an alignment coherent with the long axis of elongated clasts within both the Collio Formation and the Clastic Member of the Muriaglio Formation. In the coarse-grained volcanic rocks, granite, diorite, and Variscan basement rocks, the foliation is only locally developed, corresponding to a centimeters spaced cleavage and to microscale shear zones (Fig. 8). These shear zones crosscut the Variscan foliation and are mainly defined by preferred orientation of white mica of phengitic composition (average Si^{4+} content = 3.36 *a.p.f.u.*; see Supplementary Data, Table S2 and Fig. S1; see also Fig. 8B) and of chlorite of ripidolite to pychnochlorite composition in the micaschist, and by growth of oriented crystals of epidote, chlorite, and white mica in the plutonic and volcanic rocks. The white mica results of phengite composition (average Si^{4+} content = 3.49 *a.p.f.u.*; see Supplementary Data, Table S3 and Fig. S1; see also Fig. 8A) in the granite, highlighting that greenschist-facies P - T conditions developed along those Alpine shear zones.

The Alpine foliation is on average E-striking and mainly steeply southward dipping (Fig. 6B), although it shows slightly different

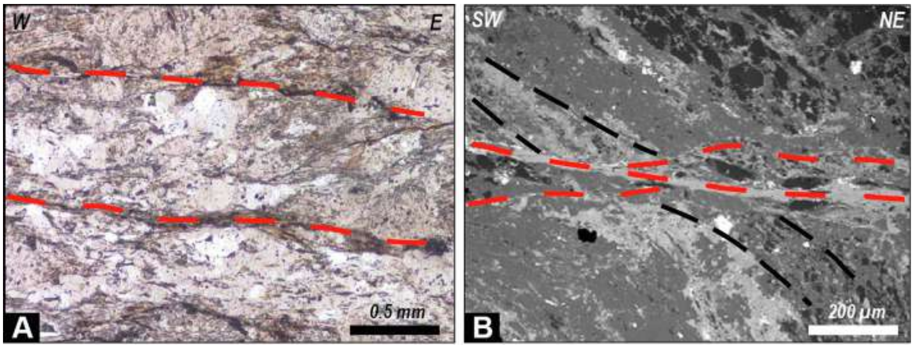


Fig. 8. (A) Thin section image (plane polarized light) of the Alpine foliation (dashed red lines) in the granite (post-Variscan intrusives); (B) SEM image of an Alpine microscale shear zone (dashed red lines) crosscutting the Variscan foliation (dashed black lines) in the micaschist (Variscan basement). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

orientations and deflections in sectors separated by ENE- to NE-striking strike-slip faults (see below). It roughly matches with the orientation of axial surfaces of close to open folds (Fig. 5D), whose axes are double-plunging toward both East and West at very low angle (Fig. 6B), and partially reorient both the Variscan foliation and bedding surfaces of the Paleozoic-Mesozoic succession (Fig. 5D, E). The bedding is mainly WNW-striking and both North and South dipping at moderate angle (Fig. 6A, B), and its scattered distribution is coherent with the orientations of early Alpine fold axes.

The early Alpine foliation, as well as the Variscan foliation and bedding surfaces, is further poorly deformed by superposed open to gentle folds, showing straight limbs and sharp hinges. Axes and axial planes are scatterly distributed, however they are mostly N- and S-plunging, and E- and W-dipping at high angle (Fig. 6B), respectively.

4.3.2. The mylonite shear zone

A tens of meters wide Alpine shear zone (Fig. 6A), NE-striking and both NW- and SE-dipping at high angle, marks the contact between CISZ and the Ivrea-Verbano Zone, corresponding to the ICL of Biino and Compagnoni (1989). It is characterized by a mylonitic fabric, associated with rootless isoclinal folds and the transposition of pre-existing planar features (e.g., bedding, veins), which result strongly parallelized to the shear zone boundaries. The shear zone, and the related mylonitic foliation, are characterized by a roughly E- and WSW-plunging stretching lineation (Fig. 6B). Asymmetries of folds, boudins and layer transposition, weakly indicate left-lateral kinematics (Fig. 9B). Rocks involved in this deformation correspond to portions of both the Muriaglio Formation and gabbro of the Ivrea-Verbano Zone. The former mainly pertains to the Siltitic-arenaceous Member, wherein quartz-rich layers are strongly elongated and recrystallized, and to the Limestone Member, wherein greyish to whitish carbonate layers are pervasively folded and transposed (Fig. 9C). The pyroxene- and plagioclase-bearing gabbro of the Ivrea-Verbano Zone, is epidote- and chlorite-rich and partly foliated. Remarkably, the gabbro is locally associated to a mylonitic rock consisting of gabbro fragments embedded in a greyish to whitish pervasively foliated carbonate matrix, likely sourced from pre-existing calcite veins. The gabbro occurs both as highly transposed and boudinaged layers, and as sub-angular to rounded aggregates, up to decimeters in size. The mineral assemblage of this mylonitic rock consists of diopside, albite, chlorite, epidote, calcite and abundant titanite.

4.3.3. Strike-slip faults

The left-lateral mylonite-bearing shear zone, as well as the pre-Alpine and early Alpine tectonic features, are crosscut and displaced by ENE- to NE-striking faults, up to several kilometers in length, which increase in pervasiveness toward the ICL (Fig. 3A). These faults, which in most of the cases oveprint pre-existing faults (see above), show horizontal displacements ranging from tens to hundreds of meters (see Figs. 3 and 6A), accumulated during different stages of strike-slip tectonics (see Section 5). They define a complex fault zone, up to several hundreds of meters wide in map, which consists of the interlacing of anastomosing NE- and ENE-striking fault surfaces (Fig. 3A). Along these fault zone, lenticular to sigmoidal tectonic slices of different lithostratigraphic units (e.g., Muriaglio Formation, Collio Formation, San Salvatore Dolostone, etc.) are juxtaposed, depicting an up to hundreds of meters wide flower structures in section (Fig. 6A). Fault slip data show a left-lateral (and partly transpressive) component of shear, which is consistent with a roughly sub-horizontal NNE-SSE oriented shortening direction (Fig. 9A).

Brittle kinematic indicators (e.g., slickenlines, mineral slickenfibers and disjunctive shear surfaces) overprint left-lateral transpressive movements showing a right-lateral reactivation of the NE- and ENE-striking fault surfaces, which is consistent with a low angle roughly WNW-ESE oriented shortening direction (Fig. 9A). Depending on the dip of reactivated faults, the main displacement component ranges from transtensive to transpressive. It is worth to point out that right-lateral faults also displace the above-described mylonite-bearing shear zone (Fig. 9D) (i.e., the ICL of Biino and Compagnoni, 1989), which juxtaposes the boundary of the CISZ and the Ivrea-Verbano Zone and deforms the Oligocene andesite dyke located along the ECL (Fig. 9E), providing an excellent temporal constraint to this faulting stage (see below).

Discrete and very localized NNE-striking faults (Fig. 4C), dipping at medium to high angle, displace with extensional and transtensional movements all the above-described Alpine tectonic features. They represent evidence for the last observed faulting-related deformation, which is consistent with a sub-vertical shortening direction (Fig. 9A).

5. Discussion: Structural and stratigraphic constraints of the CISZ to the tectonic evolution of the Inner Western Alps

Our field data allows to show in the following that the tectonic evolution of the CISZ was characterized by different tectonic stages within a long-standing tectono-stratigraphic history. Late Paleozoic – Mesozoic structural inheritances significantly controlled the formation/location of the CISZ and, consequently, the subsequent tectonic evolution of the Inner Western Alps (Fig. 10). We show that crosscutting relationships between stratigraphic unconformities and tectonic features provide excellent constraints for the definition of those different tectonic stages during the late

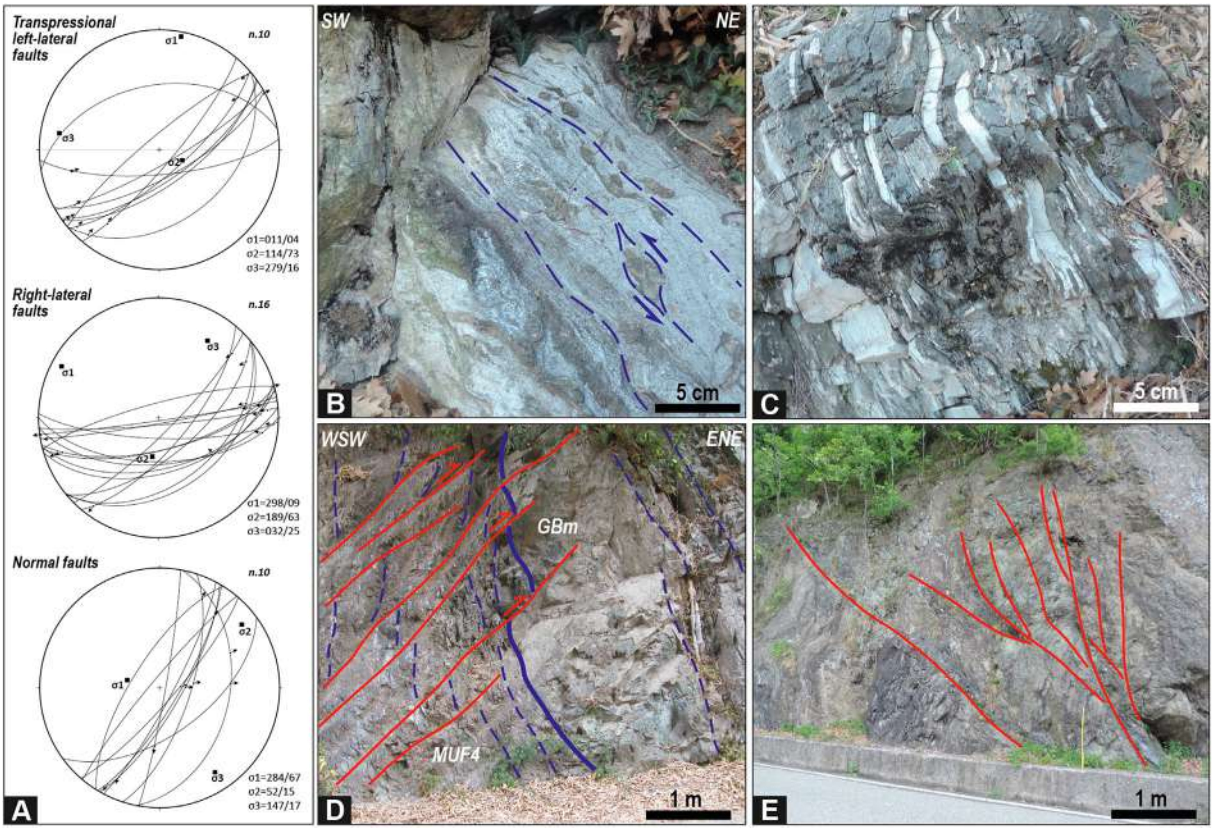


Fig. 9. (A) Stereographic projections of mesoscale faults (Schmidt net, lower hemisphere; n: number of data; σ1, σ2 and σ3 indicate the maximum, intermediate and minimum shortening axes, respectively; axes calculated through Linked Bingham analysis). (B) Close up view of mylonitic rocks of the Ivrea-Verbano Zone occurring along the Internal Canavese Line (ICL); the mylonite consists of fragments of sheared gabbro embedded in a whitish carbonate matrix, showing left-lateral kinematics (dashed blue lines mark the mylonitic foliation) (NE of Montalto Dora). (C) Close up view of mylonitic rocks of the Limestone Member of Muriaglio Formation occurring along the Internal Canavese Line (ICL); the mylonite structure is defined by pervasively transposed whitish carbonate layers (NE of Montalto Dora). (D) View of the Internal Canavese Line - ICL (thick blue line) at Montalto Dora, juxtaposing the mylonitic gabbro of the Ivrea-Verbano Zone (GBm) to mylonitic limestone and siltstone of the Limestone Member of the Muriaglio Formation (MUF4); the mylonitic contact is displaced by brittle right-lateral transpressional faults (red lines). Dashed blue lines mark the mylonitic foliation. (E) View of a transtensional flower structure within the shear zone of the External Canavese Line - ECL at S. Maurizio (red lines mark NE- and ENE-striking faults). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Paleozoic – Mesozoic time interval. We make up for the lack of stratigraphic constraints to Cenozoic tectonic stages, which is due to the lack of a succession younger than Middle Jurassic, with the comparison between the characteristics of the different faulting pulses recognized in the study area and in the close Tertiary Piedmont Basin and Northern Apennines. In these last sectors, stratigraphic constraints to tectonic stages are well-documented (see, e.g., Piana, 2000; Dela Pierre et al., 2002, 2003, 2011; Festa et al., 2009, 2013, 2015a, 2020b; Mosca et al., 2010; Piazza et al., 2016; Barbero et al., 2017, 2020, and references therein).

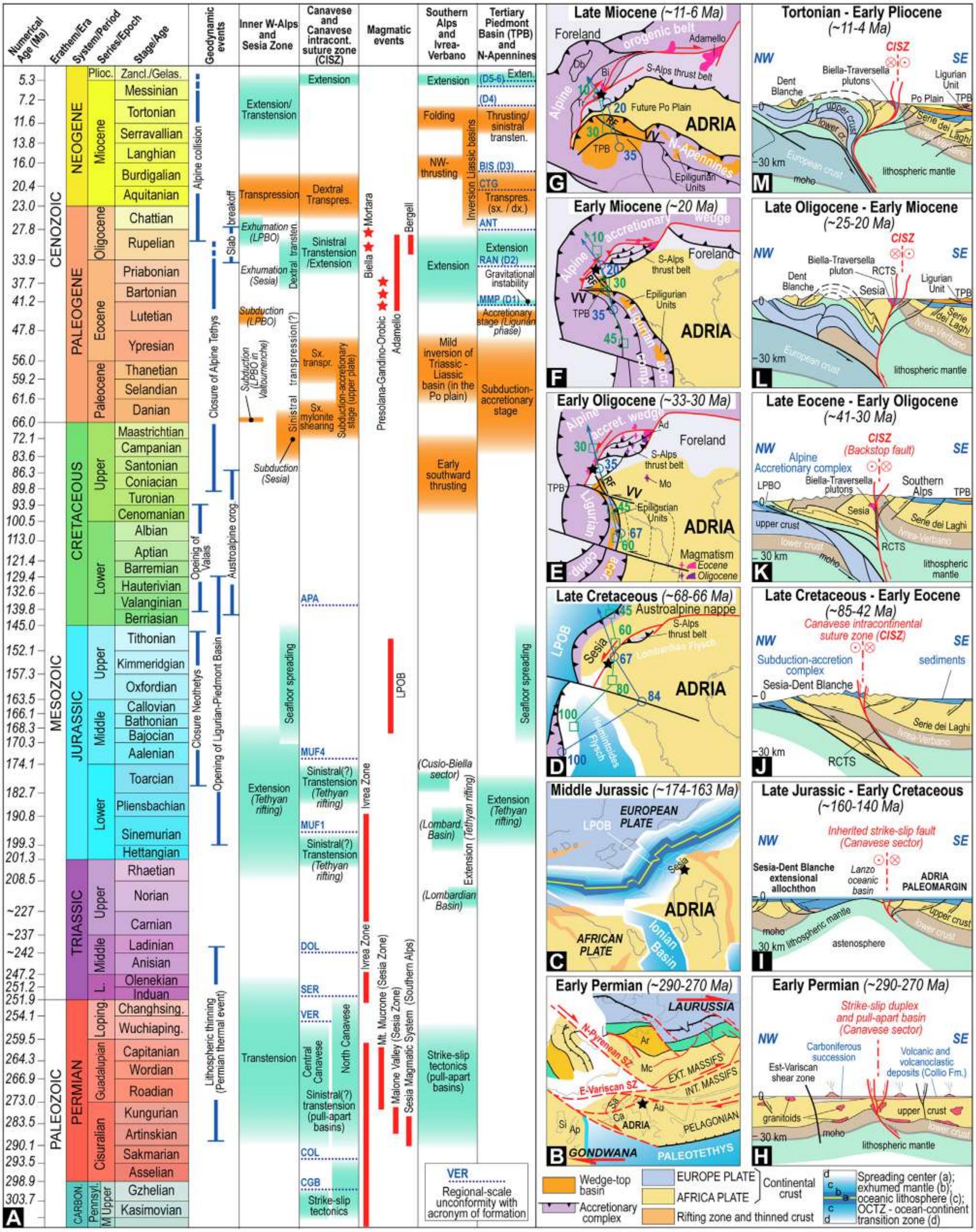
5.1. Pre-Early Permian tectonic stage

The oldest tectonic stage is defined by the main Variscan foliation, which results parallel to the lithological contacts between the micaschist and the gneiss of the Variscan basement with interlayered meta-volcanic horizons. The locally preserved primary compositional banding and the absence of pre-Variscan mineral relics, suggest that this basement corresponds to a monometamorphic unit, which was metamorphosed under greenschist-facies conditions during the Variscan orogeny, as highlighted by the occurrence of muscovite and Mn-rich garnet in the mineral assemblages. The occurrence of a low-grade Variscan basement (see also Biino et al., 1988) has been also described SW of the study area (i.e., in the central sector of CISZ; see Fig. 1C) by Borghi et al. (1996). The Variscan basement of CISZ has been overall compared with the one of the Serie dei Laghi (Borghi et al., 1996; Sacchi et al., 2007; Festa et al., 2020a), which represents a section of the Adriatic upper crust exposed in the Southern Alps.

Exhumation of the monometamorphic Variscan basement took place before the early Permian Period as constrained by the unconformable deposition of the Lower member of the Collio Formation (Fig. 10A). However, comparison with the central CISZ, where the Upper Carboniferous-Lower Permian fluvial deposits of the Basal Conglomerate overlain the monometamorphic basement in angular unconformity (i.e., the Hercynian unconformity, see Festa et al., 2020a), does not exclude an older exhumation age also in the studied sector where these continental deposits are lacking.

5.2. Early – Late Permian tectonic stage: Setting the scene of structural inheritance for the location of CISZ

The intrusion within the Variscan metamorphic basement of plutonic rocks of diorite and granite composition, which are not affected by Variscan-related deformation and metamorphic recrystallization, is well comparable with the magmatic activity described for the Sesia Magmatic System in the Southern Alps, to the NE of the studied sector (e.g., Peressini et al., 2007; Quick et al., 2009 and references therein; see also Pin, 1986; Mayer et al., 2000). In that sector, as well as in the central and southern CISZ, the magmatic activity affected both the upper crust of the Serie dei Laghi (i.e., the Graniti dei Laghi *Auct.*) and the lower crust of the Ivrea-Verbano Zone (i.e., the Mafic Complex *Auct.*) with different pulses of mafic to acid plutonic, and volcanic activity between 290 and 280 Ma (i.e., early Permian) (Fig. 10A, B, H). Direct relationships with strike-slip tectonics are suggested by the abrupt change of facies and thickness within the Collio Formation in sectors juxtaposed along NE- to ENE-striking faults. This strike-slip tectonics favored the deposition of the Collio Formation within ENE- to NE-elongated transtensional pull-apart basins, accordingly with observations from the Southern Alps (Fig. 10H; e.g., Handy and Zingg, 1991; Cadel et al., 1996; Handy et al.,



1999; Spalla et al., 2014; Marotta et al., 2018) and in the central and southern CISZ (Festa et al., 2020a).

Although in the Montalto Dora sector the primary kinematics of this faulting stage is overprinted by subsequent reactivations, both right- and left-lateral transtensive movements can be reconstructed (see Fig. 7), also by comparison with those documented to NE of the studied sector (see Handy et al., 1999) for the Cossato-Mergozzo-Brissago Line, and to the SW (see Festa et al., 2020a) in the central and southern CISZ. Evidence from the central CISZ (see Festa et al., 2020a) and Southern Alps (see Handy et al., 1999), clearly show that the early Permian strike-slip faulting activity overprinted and reactivated late Carboniferous – early Permian faults (Fig. 10B, H), also contributing to modify the stratigraphic relationships between the Variscan basement and the Permian succession before the onset of rifting, and subsequent formation of the Ligurian-Piedmont oceanic basin (e.g., Marroni and Pandolfi, 2007; Vissers et al., 2013; Marotta et al., 2018; Festa et al., 2020a, 2021). At regional scale, this strike-slip transtensive stage can be roughly related to the Permian HT metamorphic event (e.g., Schuster and Stüwe, 2008; Spalla et al., 2014), which is well documented in the Southern Alpine domain and along the Cossato-Mergozzo-Brissago Line.

In the Montalto Dora sector, the unconformable deposition of the Lower Triassic Servino Formation and of the Middle Triassic San Salvatore Dolostone onto the Collio Formation, represents the uppermost temporal constrain to this transtensional strike-slip stage (Figs. 7 and 10A). However, comparison with both the central and southern CISZ (see Festa et al., 2020a) and the Southern Alps (see, e.g., Handy et al., 1999; Marotta et al., 2018; Roda et al., 2019, and references therein), where the alluvial deposits of the Verrucano (late Permian) unconformably overlain different portions of the Collio Formation, which are juxtaposed to each other along faults, suggests that this faulting stage was likely characterized by different tectonic pulses (Fig. 10A), whose temporal constraints were only in part recorded in the studied sector.

5.3. Late Triassic – Middle Jurassic tectonic stage: The rifting stage

The strongly articulated tectono-stratigraphic setting defined by the late Paleozoic tectonic stage represents the structural inheritance which drove the onset of the Early Jurassic continental break-up and Alpine Tethys formation (Fig. 10C, I). The occurrence of a Late Triassic stratigraphic hiatus suggests that the studied sector corresponded to a structural/morphological high in which subaerial conditions without deposition and erosion were prevailing, such as in the Monte Fenera sector in the Southern Alps, to the NE (see Barale et al., 2021 and references therein), and locally in the central CISZ (see Festa et al., 2020a for details). Tectonics and sedimentation relationships clearly show that the deposition of the heterogeneous Muriaglio Formation, which represents the *syn*-extensional (e.g., *syn*-Jurassic rifting) succession, was strongly controlled by this inherited physiography, and by the reactivation of both NE- to ENE-striking and WNW- to NW-striking fault systems. Stratigraphic data show, in fact, main changes of facies and thickness, forming different Early Jurassic types of succession (i.e., completed, condensed, and reduced) within the Muriaglio Formation (see Fig. 3B). Relationships between tectonics and sedimentation, and the architecture of fault systems, suggest deposition in elongated basins bounded by ENE- to NE-structural faults. This is well documented by the evidence that the olistolith field sourced from the tectonic and/or tectono-morphological structural high, now corresponding with the Mt. Crovero – Mt. Maggio hill, is laterally bounded by ENE- to NE-striking transcurrent faults, likely forming elongated transtensional pull-apart basins (Fig. 3A). Although the reactivation and overprinting of faults by Alpine tectonics did not allow preserving primary Jurassic fault kinematic indicators (or they are doubly preserved), the interpreted basin physiography well agrees with the role inferred to transtensional left-lateral tectonics in controlling the formation of Late Triassic – Early Jurassic elongated pull-apart basins to both the NE (Handy and Zingg, 1991; Handy et al., 1999) and SW (Festa et al., 2020a) of the studied sector. This fits well with oblique rifting controlled by the S- to SE-orientation of motion vectors between Europe and Adria plates in the time interval 200–165 Ma (see, e.g., Le Breton et al., 2021). The limited (i.e., meters to tens of meters) vertical displacement documented along Jurassic faults, also suggests that a late Carboniferous to Permian-Early Triassic extension is, therefore, required to explain the observed Early Jurassic crustal extension, thinning and mantle exhumation (see, e.g., Handy et al., 1999; Spalla et al., 2014; Marotta et al., 2018; Roda et al., 2019; Festa et al., 2020a).

Different pulses of strike-slip tectonics (Fig. 10A) agree with results of the detailed work by Barale et al. (2021) in the Montalto Dora sector, which document a polyphase (i.e., Late Triassic-Early Jurassic, and Pliensbachian – Toarcian) history of host-rocks fracturing in vein systems cemented by calcite, dolomite and quartz

Fig. 10. Timetable of late Palaeozoic-Cenozoic tectonic stages in the northern sector of Adria microplate and palegeographic reconstructions. (A) Timetable comparing geodynamic events (from Handy et al., 2010) with tectonic stages in the Canavese Intracontinental Suture Zone (Northern Canavese from this study; Central and Southern Canavese from Festa et al., 2020a), Inner sector of Western Alps and Sesia Zone (from Babist et al., 2006; Handy et al., 2010; Manzotti et al., 2014; Spalla et al., 2014; Malusà et al., 2015; Perrone et al., 2015; Giuntoli and Engi, 2016; Zanoni et al., 2016; Schmid et al., 2017; Rebay et al., 2018; Roda et al., 2018, 2019; Luoni et al., 2020; Vho et al., 2020), Southern Alps and Ivrea-Verbano Zone (from Cadel et al., 1996; Handy et al., 1999; Berra et al., 2009; Zanchetta et al., 2015 and references therein), Tertiary Piedmont Basin and Northern Apennines (from Piana, 2000; Dela Pierre et al., 2002, 2003, 2007; Festa et al., 2005, 2013, 2015a, 2020a; Piazza et al., 2016; Barbero et al., 2017, 2020 and references therein), and with main Magmatic events (from Pin, 1986; Berger et al., 2012a; Zanetti et al., 2013 and references therein). (B–G) Paleogeographic reconstructions (in map) of (B) the Variscan Belt in the early Permian Period (modified from Ballèvre et al., 2018, and from Stampfli et al., 2002; Schettino and Turco, 2011), (C) the northern margin of the Adria microplate and the Alpine Tethys (Ligurian-Piedmont Oceanic Basin – LPOB) in the Middle Jurassic Period (modified from Stampfli et al., 2002; Schettino and Turco, 2011; Festa et al., 2021); (D) the Alpine accretionary wedge in the Late Cretaceous Period (modified from Michard et al., 2002; Stampfli et al., 2002; Handy et al., 2010, 2015; Schettino and Turco, 2011; Festa et al., 2013, 2020a; Barbero et al., 2020); (E–G) the Western Alps – Northern Apennines belts from early Oligocene to late Miocene Epochs (modified from Castellarin, 1994; Mosca et al., 2010; Festa et al., 2015b;). In all figures, the location of the Canavese Zone is indicated by a black star. Motion paths of Northern Adria back to 100 Ma (time steps indicted in millions of years) from and Van Hinsbergen et al. (2020, in green color) and Le Breton et al. (2021, in blue color). (H–M) Simplified cross-sections, showing the location of the Canavese sector and the tectonic role played by the Canavese Intracontinental Suture Zone (CISZ) from early Permian to early Pliocene (modified from Manzotti et al., 2014; Festa et al., 2020a). Acronyms: Ad: Adamello Pluton, Ap – Apulia, Ar – North and Central Armorican, Au - Austroalpine, Bi – Biella Pluton, Ca – Calabria, Db – Dent Blanche, Mc – Massif Central, CISZ – Canavese Intracontinental Suture Zone, LPBO – Ligurian - Piedmont Oceanic Basin, Mo – Mortara, RCTS – Rocca Canavese Thrust Sheet, RF – Rio Freddo Deformation Zone, Sa – Sardinia, Si – Sicily, TPB – Tertiary Piedmont Basin, Tr – Traversella Pluton, VVL – Villalvernia-Varzi Shear Zone. Acronyms for regional-scale uncoformities (from Dela Pierre et al., 2002, 2003; Festa et al., 2009; 2015a, 2020a; Barbero et al., 2017), from older to younger one: CGB – Basal conglomerate, COL – Collio Formation, VER – Verrucano, SER – Servino, DOL – San Salvatore Dolostone, MUF1 – Muriaglio Formation (clastic member), MUF4 – Muriaglio Formation (limestone member), APA – Palombini shale, MMP (D1) – Monte Piano marls, RAN (D2) – Ranzano Formation, ANT – Antognola Formation, CTG – Contignaco Formation, BIS (D3) – Bismantova Group, (D4) – unconformity at the base of the Vena del Gesso Group, (D5–6) – unconformity at the base of the Late Messinian chaotic succession and Pliocene succession. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with fluids, sourced from different sources and depth (e.g., carbonate- and silica-bearing fluids). The occurrence of fluids from different sources and depths, may document an active fluid circuit, cyclically subjected to pressure rises and drops, and permeability changes during a seismic cycle (e.g., Sibson, 1992, 2013, 2017; Fagereng et al., 2010; Cerchiari et al., 2020). Deep fluids, external to the system (e.g., fluids likely sourced from mantle rocks in Barale et al., 2021), and shallow ones internal to the system (i.e., carbonate-rich fluids in Barale et al., 2021), may therefore document different stages of a seismic cycle (e.g., Sibson, 1992, 2013, 2017; Fagereng et al., 2010; Cerchiari et al., 2020), which occurred during the Early Jurassic *syn*-rift tectonics in the studied sector.

5.4. Late Cretaceous – Middle Eocene tectonic stage: From subduction to the onset of the CISZ

The earliest stage of Alpine deformation is documented by the foliation developed under low grade metamorphic conditions, as also documented in the central sector of CISZ (Borghi et al., 1996). The occurrence of prehnite and pumpellyite in the Alpine mineral assemblage (Biino and Compagnoni, 1989), together with growth of chlorite and epidote, indicate sub-greenschist to low greenschist *P-T* conditions (T = 300–350 ℃ and P = 0.2–0.4 GPa). Remarkably, our data on phengite composition (up to 3.49 *a.p.f.u.* Si^{4+} content in the granite) suggest that along localized Alpine shear zones, the upper part of the greenschist facies conditions (Bousquet et al., 2012) developed. The Alpine foliation has been dated at the latest in Cretaceous - early Paleocene times (60–72 Ma; see Zingg et al., 1976), showing a good agreement with temperatures of around 350 °C documented for Paleocene (65 ± 16 Ma) *syn*-metamorphic veins which crosscut the San Salvatore Dolostone (see Barale et al., 2021 for details).

Development of the Alpine foliation was followed by the mylonitic deformation along a major shear zone, corresponding to the ICL. The latter is interpreted to represent the record of the tectonic juxtaposition between the Canavese succession and the rocks of the Ivrea-Verbano Zone at depth of 5–7 km (Biino and Compagnoni, 1989), at the onset of convergence between Adria microplate (upper plate), and Europe (lower) plate (lower one) (Fig. 10A, D, J). The shear zone, which represents the onset of the CISZ, was characterized by left-lateral kinematics and involved rocks belonging to both the Muriaglio Formation and the Ivrea-Verbano Zone. Therefore, since Late Cretaceous, the above-described late Paleozoic – Jurassic structural inheritances favored the localization of the earliest plate interface of the Alpine system in the Canavese sector (Fig. 10D and J; see also Dal Piaz et al., 1972), which acted as proto-CISZ (i.e., the proto-Canavese shear zone of Festa et al., 2020a). Along this plate interface, the Sesia Zone was subducted following the consumption of the Lanzo oceanic basin, as documented by the occurrence of slivers of serpentinized peridotite within the southern CISZ (see also Babist et al., 2006). The mylonite deformation represents, therefore, the product of tectonic shearing between the OCTZ succession of the Canavese and the Ivrea-Verbano Zone. In this scenario, the occurrence of tectonic slices of mantle rocks and continental crust, which are documented to the SW and NE of the studied sector within both the southern CISZ (e.g., Elter et al., 1966; Ferrando et al., 2004; Berger et al., 2012a; Festa et al., 2020a) and the Rocca Canavese Thrust Sheet of the Sesia Zone (e.g., Roda et al., 2018, 2020), support the interpretation that the Alpine convergent deformation localized at the ocean-continent transition zone (OCTZ) between the Adria passive margin and the Alpine Tethys (Fig. 10J). The reconstructed orientation of the OCTZ (e.g., Stampfli et al., 2002; Handy et al., 2010, 2015; Schettino and Turco, 2011) with respect to the direction of regional shortening, is well in agreement with an oblique subduction of a narrow and elongated basin (i.e., now corresponding to the Lanzo Ultramafic Complex; Piccardo, 2010), gradually widening toward SW (present day coordinates), and characterized by the spreading out of mantle rocks. This oceanic basin was originally interposed between the passive margin of Adria and the Sesia Zone (see Fig. 2; see, e.g., Aubouin et al., 1977; Mattauer et al., 1987; Froitzheim et al., 1996; Manzotti et al., 2014; Festa et al., 2020a), as also documented by data from the northernmost part of the External Ligurian accretionary wedge in the Northern Apennines (e.g., Barbero et al., 2020).

The brittle reactivation of this mylonite shear zone with left-lateral transpressive movements, which are consistent with an NNE-oriented shortening direction also reactivating/displacing the mylonite shear zone, represents a younger and shallower evidence of this convergent stage, which occurred under a significant oblique component of subduction (Fig. 10A). The latter is recorded by different tectonic features (i.e., Alpine foliation, mylonite deformation and brittle faulting), which occurred in a continuum of deformation from deeper to shallower structural levels at the onset of the CISZ. Although the lack of a stratigraphic succession younger than Middle Jurassic does not allow to better constrain in time our structural observations, the time of this deformation well agrees at regional scale with (i) the Late Cretaceous – Middle Eocene N -- S shortening described in the Southern Alps, (ii) the left-lateral transpressive tectonics in the Ivrea-Verbano zone (e.g., Schmid et al., 1989, 2017; Souquière et al., 2011), and (iii) the onset of southwestward thrusting of both the Variscan belt and the Permo-Mesozoic succession in the Alpine retrobelt (Zanchetta et al., 2015; see Fig. 10A, D, J). This regional scale shortening event is coeval with the activation of the “Proto-Insubric line” (Fig. 10D; see Zanchetta et al., 2015), and the closure of the Alpine Tethys with formation of the Alpine subduction-accretionary complex and subduction of the Sesia Zone (i.e., the distal margin of Adria) up to the high pressure metamorphic peaks (Fig. 10J; see, e.g., Schmid et al., 1987, 1989, 2017; Malusà et al., 2011; Vho et al., 2020 and references therein).

5.5. Late Eocene – Rupelian collisional stage: left-lateral transtensional reactivation of CISZ

The occurrence along the ECL fault zone of the andesite dyke, which is referred to the early Oligocene Periadriatic magmatism (see, e.g., Biino et al., 1988; Zanoni et al., 2010; Kapferer et al., 2012), indirectly suggests a correlation with the extensional/transtensional tectonic stage documented to the NE of the studied sector and related to the first half of Rupelian age (Fig. 10A, E, K; see Kapferer et al., 2011; Berger et al., 2012a,b). In the Western and Central Alps, the extensional/transtensional stage, which roughly occurred between 41 Ma and 35 Ma (late Eocene – early Oligocene), was inferred as the result of the degree of displacement vectors between Western Alps (i.e., NW-directed) and Eastern Alps (i.e., *N*-directed), which induced an orogen-parallel extension at around 35 Ma (see Pleuger et al., 2008). During this stage, left-lateral transtensional movements were proposed by Malusà et al. (2015) at the scale of the Western Alps, following the motion of Adria relative to Europe based on Dewey et al. (1989) (Fig. 10E, K).

Soon after, the Balearic rifting affected the Ligurian realm with the formation of NW-striking pull-apart basins in the Northern Apennines and Tertiary Piedmont Basin (Monferrato and Torino Hill sectors; see Piana, 2000; Festa et al., 2005, 2009; Festa and Codegone, 2013), and the left-lateral transtension along the Villalvernia-Varzi fault zone (e.g., Elter and Pertusati, 1973; Festa et al., 2015a). In all these sectors, this faulting stage is documented to have strongly controlled the drowning of the upper Eocene – lower Oligocene shelf sediments (see Mutti et al., 1995; Piana, 2000; Dela Pierre et al., 2003; Festa et al., 2005, 2009; see also Piazza et al., 2016; Barbero et al., 2017 for the Northern Apennines). This occurred in parallel with the onset of the collision between Adria and Europe (Fig. 10A, E, K), and exhumation of high pressure units (e.g., the Sesia Zone, see, e.g., Malusà et al., 2015), which in the Northern Apennines were coeval with the transition between the end of the Ligurian tectonic phase (i.e., Lutetian age in Northern Apennines, see Mutti et al., 1995; Piana, 2000; Festa et al., 2020b) and the onset of the Apenninic phase (the Ligurian phase II of Mutti et al., 1995; Faulting stage A of Piana, 2000; Festa et al., 2005, 2013 in the Monferrato and Torino Hill). During this period (i.e., ca. 42.0 – 41.2 Ma), minor tectonic pulses was documented to have triggered regional scale slope failure (Fig. 10A) in the Northern Apennines (i.e., the Baiso argillaceous breccias) in response to the post-accretionary stress release (i.e., after the Ligurian tectonic phase; see Festa et al., 2020b).

The uppermost temporal constraint to this faulting stage is documented to the NE of the studied sector (i.e., in the Biella sector), where the Sesia Zone and the Ivrea-Verbano Zone, containing the Biella Volcanic suite and the Miagliano pluton, respectively, were juxtaposed at the same crustal level (ca. 5 km depth) and sealed by deposition of Rupelian clastic sediments (see Berger et al., 2012a, 2012b; Kapferer et al., 2012).

5.6. Chattian – pre-Burdigalian tectonic stage: Right lateral reactivation of CISZ

Evidence that the mylonite foliation of the ICL and left-lateral faults were obliquely displaced/reactivated by right-lateral transpressional faults, ENE- to NE-striking, documents a new stage of regional shortening according to WNW-directions (Fig. 10A, F, L). Although the lack of stratigraphic markers does not allow to constrain in detail this faulting stage, it can be attributed to the post-Rupelian because of the tectonic involvement of the lower Oligocene andesite within the fault zone of the ECL (Fig. 10A). The WNW-directed shortening well agrees with the about E-directed regional shortening documented in the Tertiary Piedmont Basin and Northern Apennines (i.e., the Chattian – pre-Burdigalian tectonic stage), which inverted the Rupelian extensional regime (see, e.g., Mutti et al., 1995; Piana, 2000; Dela Pierre et al., 2003; Festa et al., 2005, 2015a; Piazza et al., 2016; Barbero et al., 2017) in response to the NW-propagation of the Apennine thrust front (i.e., the Ligurian phase III of Mutti et al., 1995), and the southeastward migration of the South Alpine thrust front below the Po Plain (see, e.g., Fantoni et al., 2004; Festa et al., 2005; Mosca et al., 2010; Zanchetta et al., 2015). This stage was coeval with the anticlockwise rotation of the Tertiary Piedmont Basin that was accommodated by the strike-slip movements along the Villalvernia-Varzi fault zone (see Festa et al., 2015a and references therein) and by the southeastward rotation of the Sesia Zone and of the Periadriatic magmatic bodies (see e.g., Zanoni et al., 2021, and reference therein).

In the Inner Western Alps this faulting stage corresponded to the main stage of southeastward backtrusting (Fig. 10F, L), which continued with different pulses up to the Late Miocene (see also Balestro et al., 2009; Perrone et al., 2010).

5.7. post-Burdigalian tectonic stage: Transtensional reactivation of CISZ

Unlike the Tertiary Piedmont Basin and the Northern Apennines, in which different subsequent faulting stages (i.e., late Serravallian – Tortonian, and Late Messinian – early Pliocene) can be differentiated, the lack of stratigraphic markers younger than Jurassic does not allow a similar detail in the studied sector. However, extensional- to transtensional movements documented along N- to NNE-striking faults (see Festa et al., 2020a), seem to show a good agreement with the late Messinian – early Pliocene faulting stage (Fig. 10A, G, M) described in the Tertiary Piedmont Basin and Northern Apennines (see, e.g., Piana, 2000; Dela Pierre et al., 2002, 2003, 2007, 2011; Festa et al., 2005, 2013, 2015b; Mosca et al., 2010; Piazza et al., 2016; Barbero et al., 2017), and exhumation of Inner sectors of Western Alps and Po Plain (see, e.g., Fantoni et al., 2004; Balestro et al., 2009; Perrone et al., 2010, 2011), as also described in the central CISZ (see Festa et al., 2020a).

6. Concluding remarks

Detailed geological mapping, structural analysis, and stratigraphic and petrographic observations allowed to define that the CISZ, which controlled the Cenozoic tectonic evolution of the Inner Western Alps and the tectonic juxtaposition of two different tectono-metamorphic Alpine units (i.e., the Sesia Zone and the Ivrea-Verbano Zone), represents the product of a long-lived and multistage tectonic and tectono-stratigraphic evolution. Strike-slip tectonics played a significant role in reactivating late Paleozoic – Mesozoic structural inheritances and related crustal weakness (Fig. 10). The site of localization/formation of this intracontinental suture zone was not accidental but favored by regional-scale wrench tectonics related to the early to late Permian segmentation of Pangea (see, e.g., Muttoni et al., 2003), and subsequent extensional tectonics related to the Mesozoic rifting, as documented by crosscutting relationships between stratigraphic unconformities and tectonic features (Fig. 10A). The magmatic activity occurring along the CISZ (i.e., plutonic rocks of diorite and granite composition), which accompanied the Early to Late Permian segmentation of Pangea, is inferred to represent the product of the connection between wrenching of the upper crust across active tectonic pathways and deep mechanical instabilities in the mantle (e.g., Handy et al., 1999; Muttoni et al., 2003; Spalla et al., 2014; Roda et al., 2018, 2019 and references therein), likely reactivating Variscan orogenic trends (e.g., Matte, 1986; Massari, 1988). Multistage reactivation (i.e., early - late Permian and Late Triassic - Middle Jurassic) of the Permian elongated transtensional pull-apart basins contributed to form regional-scale rheological weakness within the upper crust, likely favoring the onset of the Early Jurassic continental break-up of the passive margin of Adria (see also Festa et al., 2020a for details), and the subsequent oceanic seafloor spreading with exhumation of the Lanzo mantle (i.e., a branch of the Alpine Tethys), separating the Sesia extensional allochthon (i.e., the Sesia Zone) from the Adria passive margin (i.e., Southern Alpine Domain). Since Late Cretaceous, with the onset of convergent tectonics between the European plate and the Adria microplate, the above-described structural inheritance favored the localization of the earliest plate interface of the Alpine system in the Canavese sector (Fig. 10), which acted as proto-CISZ. Along this plate interface, the Sesia Zone was subducted following the consumption of the Lanzo oceanic basin, as documented by the occurrence of slivers of serpentinized peridotite within the southern CISZ (see also Babist et al., 2006). Repeated reactivation of the CISZ (i.e., Late Eocene-Rupelian, Chattian-Burdigalian, and post-Burdigalian), and related fault systems, controlled the subsequent tectonic evolution of the Inner Western Alps in the sector of tectonic juxtaposition with the Southern Alps.

The results of this study document that stratigraphy, facies indicators, and relationships between tectonics and sedimentation that developed at shallow structural levels in suture zones, such in the CISZ, are important to better constrain the tectonic history of those metamorphic orogenic belts in which evolutionary details are commonly complicated by high-strain deformation and metamorphic transformations occurred at deep structural levels. The CISZ, which represent the remnant of the evolution at shallower structural levels of an intracontinental suture zone and of late Paleozoic –

Mesozoic structural inheritances, allowed in fact to better document and constrain different tectonic stages in both time and space, providing additional details to the tectonic evolution of the Inner Western Alps and their juxtaposition to the Southern Alpine Domain (Fig. 10). Therefore, multidisciplinary studies (e.g., structural, stratigraphic, petrological), supported by new and detailed geological maps and the definition of the crosscutting relationships between stratigraphic unconformities and tectonic features (faults, foliations, etc.), are essential to better understand the evolution of complex orogenic belts and suture zones worldwide, and to better constrain analytical data (see also Moores, 1981; Şengör, 2014).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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