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# Anatomy and kinematic evolution of an ancient passive margin involved into an orogenic wedge (Western Southern Alps, Varese area, Italy and Switzerland)

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## Abstract

We make use of own geological mapping, interpretations of seismic reflection profiles and deep geophysical data to build a lithospheric-scale cross-section across the European Western Southern Alps (Varese area) and to model a progressive restoration from the end of Mesozoic rifting to present-day. Early phases of Alpine orogeny were characterized by Europe-directed thrusting, whereas post-Oligocene shortening led to basement-involving crustal accretion accompanied by backfolding, and consistent with the kinematics of the adjoining Ivrea Zone. Wedging was favored by a significant component of reactivation of the inherited Adriatic rifted margin. Our results also suggest that, during the collisional and post-collisional tectonics, lithosphere dynamics drove diachronically the onset of tectonic phases (i.e., wedging and slab retreat), from east to west, across the Western Southern Alps.

**Keywords:** Southern Alps, Accretionary wedge, Passive margin, Inheritance

## 1 Introduction

The European Southern Alps represent a noteworthy example of an ancient passive margin that was later involved into an orogenic wedge, from initial subduction to continental collision and indentation (e.g., Butler, 1986; Handy et al., 1999; Manzotti et al., 2014; Schmid et al., 2017). Here, we document first-order field observations related to the Mesozoic rifted margins of Europe and Adria, (e.g., Bernoulli, 1964) and on their later involvement in the orogenic belt (Bertotti, 1991). The role of rift inheritance in shaping Alpine chain has been explored in detail (Butler, 1986, 2013) and new insights have been lighted up with the better understanding of hyperextension and mantle exhumation processes leading (or not)

to oceanization (e.g., Agard & Handy, 2021; Butler, 2013; Lescoutre & Manatschal, 2020; McCarthy et al., 2021; Mohn et al., 2010, 2011).

Nonetheless, the internal architecture of the Southern Alps orogenic wedge is still debated. Two apparently opposite interpretations for the involvement of the upper plate lithosphere are presently considered: a lithospheric detachment model (sensu Butler & Mazzoli, 2006), applied to the Central Southern Alps (e.g., Laubscher, 1985; Roeder, 1992; Rosenberg & Kissling, 2013; Schönborn, 1992) as opposed to buttressing and backfolding as documented for the Ivrea Zone, in the Western Southern Alps (e.g., Schmid et al., 2017; Zingg et al., 1990; Fig. 1). In detail, the Ivrea Zone represents an upright section of exhumed lenses of upper mantle and lower continental crustal rocks. At depth, these lenses have been correlated with a denser body of mantle rocks (i.e., the so-called Ivrea Geophysical Body; Fig. 1), interpreted as the north-western tip of Adria's upper mantle indented into the inner arc of

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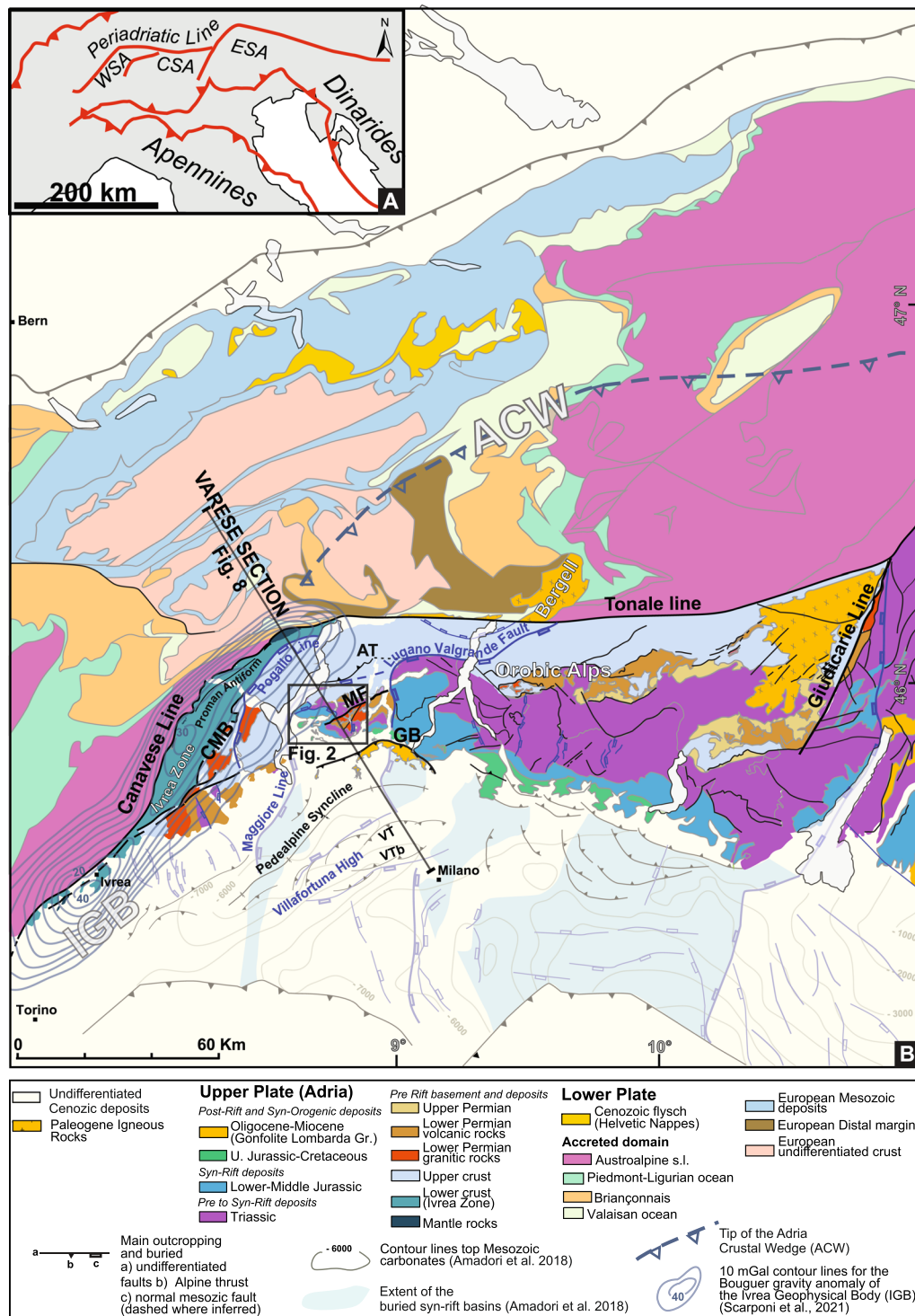
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**Fig. 1** **a** Tectonic scheme of the Alps (Codes: CSA, Central Southern Alps; ESA, Eastern Southern Alps; WSA, Western Southern Alps); **b** simplified geological map of the Central and Western Southern Alps with emphasis on the Alpine and rift-related structures (i.e., Maggiore Line, Pogallo Line and Lugano Valgrande Fault, in blue); the extent of the Ivrea Geophysical Body (IGB), the surface projection of the Adria Crustal Wedge tip (ACW) and the extent of the Varese Ara (black box) are also indicated; Fault Codes: AT: Arosio thrust; CMB: Cossato–Mergozzo Line; GB: Gonfolite backthrust; IGB: Ivrea Geophysical Body; MF: Marzio Fault; VT and VTb: Villafortuna-Treccate thrust and backthrust, respectively (sources for the maps: Amadori et al., 2019; Fantoni et al., 2002, 2004; Mazzucchelli et al., 2014; Rosenberg & Kissling, 2013; Scardia et al., 2015; Scarponi et al., 2021; Schmid et al., 2017; Zanchi et al., 2019 and this study for the Varese area)

the Western Alps at upper crustal depths (e.g., Handy et al., 1999; Schaltegger & Brack, 2007; Schmid et al., 2017). In our area of investigation, since cover units are not exposed, kinematic constraints are few and limited to those recorded in high-grade metamorphic rocks and mantle slivers (e.g., Schmid et al., 1989). However, extensive Permian-Mesozoic cover units crop out to the east where the Southern Alps have been mostly interpreted as a tapered tectonic wedge composed of stacked thin slices of basement and cover units (Pfiffner, 2016; Rosenberg & Kissling, 2013; Schumacher et al., 1997). The interpretation of stacking in our area of research, i.e., the Western Southern Alps, is mainly based on the interpretation of deep seismic reflection profiles (see e.g., the NRP-20 and EGT results in Laubscher, 1985; Roeder, 1992; Schönborn, 1992; Schumacher et al., 1997), even though not directly constrained by deep wells or shallow seismic reflection data. So far, detachment-dominated models have also been adopted for the Western Southern Alps (e.g., Pfiffner, 2016; Rosenberg & Kissling, 2013; Schumacher et al., 1997), resulting in poorly consistent geometries of the orogenic wedge that try to consider both the exhumed lower crustal units in the Ivrea Zone and the presence of a thick stack of thrust sheets. Moreover, the extent to which the backfolding of the Adriatic crust can be traced towards the Central Southern Alps (Fig. 1), is also unknown, apart from the evidence that upturned Mesozoic crustal faults (i.e., the Lugano-Valgrande Fault; Fig. 1) continue east of Lake Como (e.g., Bertotti et al., 1999). These two apparently opposite views could probably reflect an important along-strike transition between different structural levels, namely a transition from the involvement of mantle, lower crust and Paleozoic basement in the Western Southern Alps to a shallower stack including Mesozoic rocks and thin upper crustal slices, to the east. This along-strike change offers an opportunity to integrate all these observations into a geometrically and kinematically consistent evolutionary model.

In this contribution, we focus on the Varese area (Fig. 1 and Additional file 1), a relatively overlooked region located in between the two aforementioned sectors. We mapped in detail the Mesozoic cover and its autochthonous upper crustal basement and integrated available geophysical data to provide a new lithospheric-scale cross section. We then perform a sequential structural restoration to decipher timing and partitioning of deformation among different crustal levels, which allows defining an alternative model for the evolution of this part of the European Alps.

## 2 Geological setting

The European Western and Central Southern Alps are located at the north-western border of the Adria plate and are bound by segments of the Periadriatic Lineament (e.g., Schmid et al., 1989): the Canavese Line to the north-west, the Tonale Line to the north, and the Giudicarie Line to the east (Fig. 1b). The Western Southern Alps include a series of tectono-metamorphic units assembled during the Variscan orogeny: lower crustal units (Ivrea Zone) are represented by high-grade metamorphic rocks and upper crustal units consists of schists and gneisses, outcropping more to the east (e.g., Boriani & Villa, 1997; Boriani et al., 2003; Di Paola et al., 2001; Diella et al., 1992; Siletto et al., 1993; Spalla et al., 2006). During the early Permian, all these crustal levels were intruded by basic-to-acid igneous bodies (i.e., 280–285 Ma; Karakas et al., 2019; Lardeaux & Spalla, 1991; Marotta & Spalla, 2007; Roda et al., 2019; Spalla et al., 2014) and were covered by volcanogenic deposits (e.g., Kälin & Trümpy, 1977; Schaltegger & Brack, 2007) synchronous to the exhumation of lower crustal rocks (Boriani & Sacchi, 1973; Boriani et al., 1990; Handy, 1987; Handy et al., 1999; Rutter et al., 1993; Sinigoi et al., 2010; Zingg, 1983) along the Cossato-Mergozzo-Brissago shear zone in the Ivrea Zone (Fig. 1b; Mazzucchelli et al., 2014; Schaltegger & Brack, 2007).

During the late Permian–Middle Triassic, a regional transgression affected the area with the deposition of siliciclastic and carbonate deposits (Bernoulli et al., 1990; Bertotti et al., 1993; Lemoine & Trümpy, 1987). Late Triassic to Jurassic rifting led to the formation of the Alpine Tethys passive margin and dismembered the Adriatic crust into a series of asymmetrical basins and swells separated by mainly N–S striking listric normal faults (e.g., Bernoulli, 1964; Berra et al., 2009; Bertotti, 1991; Bertotti et al., 1993; Fantoni & Scotti, 2009; Winterer & Bosellini, 1981): the Pogallo Line, Maggiore Line and the Lugano-Valgrande fault (Fig. 1).

During Early Jurassic, rifting localized along a system consisting of a few and newly developed listric normal faults that accommodated significant extension (Bertotti et al., 1993). Rift localization occurred during a second pulse of crustal attenuation and exhumation of the lower and middle crust that resulted in the deposition of thick syn-rift sequences (e.g., Bernoulli, 1964; Berra et al., 2009; Handy & Stünitz, 2002; Handy & Zingg, 1991; Handy et al., 1999; Jadoul et al., 2005; Winterer & Bosellini, 1981).

The Southern Alps developed as a south verging retro-wedge of the Alpine chain (e.g., D'Adda et al., 2011; Doglioni & Bosellini, 1987; Mitterpergher et al., 2021; Zanchetta et al., 2011, 2012, 2015). During the post-Oligocene Europe-Adria indentation (see Fig. 1 for a trace of

the external tip of the Adria crustal wedge), the lower and upper crustal sectors and slices of mantle of the Western Southern Alps were tilted, overturned and exhumed along shear zones presently steeply dipping (Berger et al., 2012; Handy et al., 1999; Schmid et al., 1989, 1996, 2017; Siegesmund et al., 2008; Wolff et al., 2012). Close to the Canavese Line, the deeper crustal levels of the Western Southern Alps are presently exposed in a large-scale box fold (i.e., the Proman Antiform; Fig. 1; Brodie & Rutter, 1987; Rutter et al., 2007; Schmid, 1967; Schmid et al., 1987). The fold's northwestern limb is sheared off against the Canavese Line and the axial trace is truncated to the SW, probably by the latest movement of the Canavese Line. To the southeast of the Proman Antiform hinge zone, the succession is involved into regional backfolding, exposing progressively shallower crustal levels to the SE, toward the Varese Area. As a result of backfolding, the inherited Early Jurassic normal faults were back-tilted as well (e.g., the Maggiore Line and Lugano-Valgrande Fault; Zingg et al., 1990; Bertotti et al., 1991; Fig. 1b), and locally overturned (i.e., the Pogallo Line; Handy, 1987; Handy & Zingg, 1991; Hodges & Fountain, 1984). Some secondary thrusts (e.g., the Arosio thrust, AT in Fig. 1b), have been mapped in the basement north of the Varese area, based on well-developed cataclastic zones at the surface and imaged at depth in seismic reflection profiles (Schumacher, 1997).

### 3 Methods and datasets

The approach that we adopt here is based on the integration of several data sources (Fig. 3), characterized by different reliability and spatial resolutions, into a single interpretative model at lithospheric scale. We proceed, by means of a top-down approach, from surface geology (Fig. 2) to deeper sectors, thanks to a comparison with published geophysical and seismological data (Fig. 3; Additional files 2 and 3). We underline that the mapped area is characterized by poor outcrop conditions, a dense vegetation cover and is dominated by karstified carbonates: conditions that somehow hampered the geological surveying. Mapped units are referred to the main tectono-sedimentary cycles recognized in the Southern Alps (e.g., Gaetani et al., 1998) and their equivalents in the subsurface traced by means of seismic imaging in the Po Plain area to the south (Fantoni & Franciosi, 2008; Fantoni et al., 2002, 2004; Turrini et al., 2014).

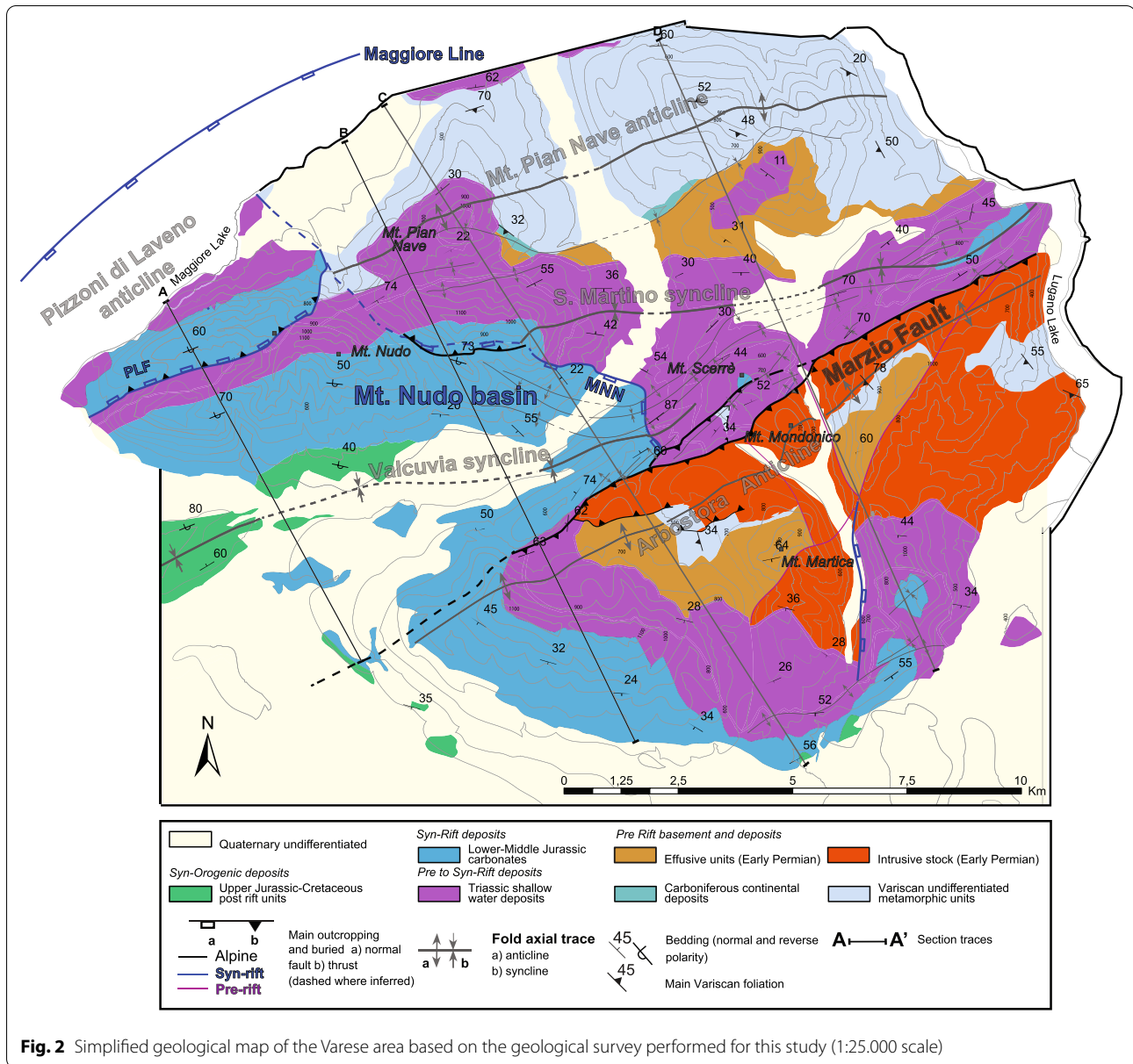
Structural measurements were analysed regarding their orientation thanks to a classical  $\pi$ -diagram approach for folds and the structural measurements of faults' kinematics were grouped and inverted for paleostress orientation, using the WinTensor structural software (Delvaux, 1993) and the Right Dihedra approach. The mapped units include: a Triassic shallow-water deposits, followed by a

Jurassic syn-rift deep-water carbonates succession sealed by Upper Cretaceous syn-orogenic terrigenous deposits. Basement in the Varese area consists of Variscan-related metamorphic units covered by an early Permian volcanic succession and intruded by an almost coeval granitic stock (e.g., Bakos et al., 1990; Schaltegger & Brack, 2007).

The geophysical dataset is composed of: (i) three deep tomographic sections (blue lines in Fig. 3) derived from a 3D velocity model below the Alps (see Additional file 3\_S3) (Diehl et al., 2009, 2017; Rosenberg & Kissling, 2013), (ii) three crustal seismic reflection profiles (see Additional file 2\_S2) from the NRP-20 Project (green lines in Fig. 3; Pfiffner & Heitzmann, 1997; Schumacher, 1997 in Pfiffner et al., 1997), (iii) two already published seismic reflection lines (fn\_02 and fn\_10 in Fig. 3; Fantoni et al., 2002; Fantoni & Franciosi, 2010), adopted with the original interpretations down to the depth of the top of basement, (iv) one seismic reflection profile that we re-interpreted and provided with line drawing of the main reflectors (mc\_13 in Fig. 3; Michetti et al., 2012) and (v) six deep exploration wells (Fig. 3; Videpi project <https://www.videpi.com/videpi/videpi.asp>; and Fantoni et al., 2002). Additionally, we added the Moho depth map from Spada et al. (2013) and the well-constrained earthquake foci for the 1985 to 2020 period (ISIDe Database at <http://terremoti.ingv.it/search>) within a 30 km wide corridor (see Additional file 4\_S4). All the datasets have been integrated into the structural geology modelling software MOVE™ to build a new crustal-scale geological cross-section that integrated all the datasets described above (i.e., the Varese Section, see trace in Fig. 1).

We restored the Varese section using the 2D Move-on-fault and 2D Unfolding modules of the MOVE™ suite. Fault propagation folds have been restored by means of a trishear numerical code (i.e., Erslev, 1991; Hardy & Ford, 1997; Zehnder & Allmendinger, 2000). The trishear model describes the deformation induced by a growing fault as a triangular zone of shear emanating from the tip of a propagating fault (Fig. 4). The algorithm deforms beds in a single (homogenous trishear), or series of nested, triangular zone(s) of shear (heterogeneous trishear), where the magnitude of slip is varied from a user defined value at the top of the zone to zero at the base of the zone and the direction of slip is varied from parallel to the fault dip at the top of the zone to parallel to the base of the zone at the lower boundary of the zone (Hardy & Ford, 1997). We adopted only a homogenous trishear model: the only parameter defining the triangular velocity field is the trishear angle offset (Fig. 4). This value indicates the fraction of the triangular area comprised between the fault projection and the upper trishear boundary. Other variables that can be controlled are the apical angle (or angle between the boundaries of



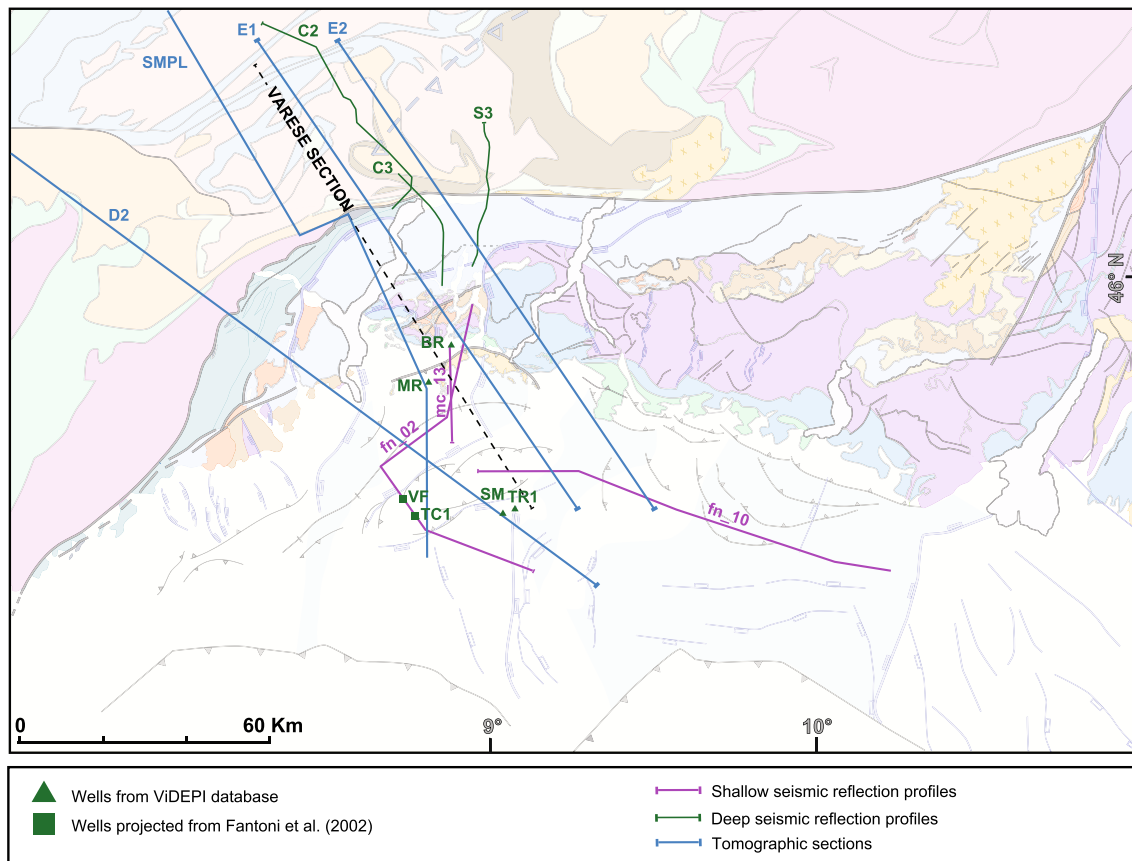


the trishear zone; “a” in Fig. 4), fault dip (“b” in Fig. 4), slip and the propagation to slip ratio (“p/s ratio” in Fig. 4). Area is preserved within the zone during deformation thus assuring that the section is balanced.

Given a fault or a fault-related fold of a certain geometry, the slip is determined by the structural relief of a reference horizon across the structure (“h” in Fig. 4) and outside the trishear zone whereas the remaining parameters (i.e., “apical angle”, “b”, “p/s ratio” and “trishear angle”; Fig. 4) need to be fine-tuned in order to restore the reference horizon to a viable pre-deformation geometry. We moved the hanging wall sector of each fault

according to a fault-parallel flow model (Egan et al., 1997; Kane et al., 1997). This algorithm assumes particle flow parallel to the fault surface and parallel to the plane of cross-section (plane strain assumption). Compared to other geometric construction models like those predicted by fault bend fold theory, the fault parallel flow is not restricted to simple ramp-flat-ramps with a dip less than 30° thus, may be better applied to faults with a complex geometry or curved hinge sectors.

Our kinematic approach, that was firstly thought for basement-cored structures (Allmendinger, 1998; Erslev, 1991), is intended for providing a bulk description of a



**Fig. 3** Datasets and sources used for the building of the Varese Section, including: deep seismic reflection profiles (C2 and S3: Schumacher, 1997; C2: Pfiffner & Heitzmann, 1997), shallow seismic reflection profiles (mc\_13: Michetti et al., 2012; fn\_02: Fantoni et al., 2002; fn\_10: Fantoni & Franciosi, 2010), tomographic sections (E1, E2 and D2: Diehl et al., 2009, 2017; SMPL: Simplicon section after Rosenberg & Kissling, 2013), well logs BR: Brenno; MR: Morazzone; SM: Settimo Milanese; TC 1: Trecate 1; TR1: Trenno 1; VF: Villa Fortuna). Same Fig. 1 legend

deforming zone, without dictating any specific structural geometry and/or processes by which those strains occur (e.g., duplex thickening in an anticlinal stack or passive roof duplex can be both modelled with trishear). Instead, it is useful in the prediction of gross structural geometries in areas of poor (or non-existent) subsurface data (Allmendinger, 1998). Trishear, in fact, has previously been used for the modelling of basement-involved fault-propagation folds (Hardy & Finch, 2007; Mitra & Miller, 2013).

Note that the trishear kinematic model provides non-unique balanced solutions for the considered geometries but, conversely, includes only weak validations on the structural interpretations. In the result section we will discuss the procedure that led to the selection of the appropriate parameters during restoration. For unfolding, we adopted a flexural shear algorithm that uses a pin and a slip-system parallel to the template bed to control the unfolding of the remaining horizons.

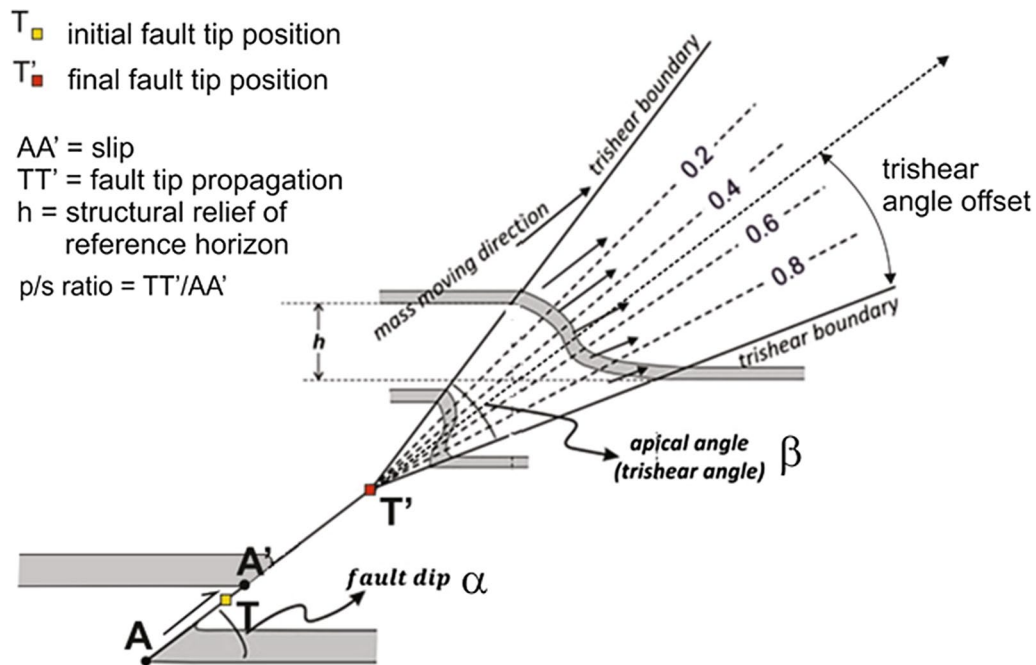
## 4 Results

### 4.1 Structural and geological field data

Thanks to our new geological map of the Varese Area (see Additional file 1\_S1 for the full resolution map), we compiled a series of shallow geological cross-sections (Fig. 5) and analyzed the structural data of faults and folds (Fig. 6).

Cover units, together with the underlying basement, are involved into a series of NE-SW striking folds. We recognize two sets of folds, with opposite-dipping axial surfaces, related to Alpine deformation.

The folds belonging to Set 1 (Fig. 6a) are N60E striking, with the axis gently plunging to the SW, and they indicate a tectonic transport to the NW. This set is mainly represented by the Arbostora Anticline, a large wavelength fold that entirely occupies the southern sector of the Varese Area (Sections C and D in Fig. 5). The Arbostora Anticline is an asymmetric, kink-type open fold with a forelimb steeply dipping to the NW and a large



**Fig. 4** The trishear kinematic model (modified after Pei et al., 2014), based on Erslev (1991)

monoclinical back-limb. The axial plane of this large fold dips N147/77 with an axis plunging N231/25.

The axial trace of the Arbostora Anticline runs parallel to the Marzio Fault, a NE-SW striking fault, vertical at the surface, that puts in contact the Permian and basement units, outcropping in the core of the Arbostora Anticline, with the deep water syn-rift limestone north of it. These two structures can be interpreted as a high-angle fault-propagation fold system, whose tectonic transport direction, deduced from the dip direction of the fold axial surface and by its asymmetry, is to the NW.

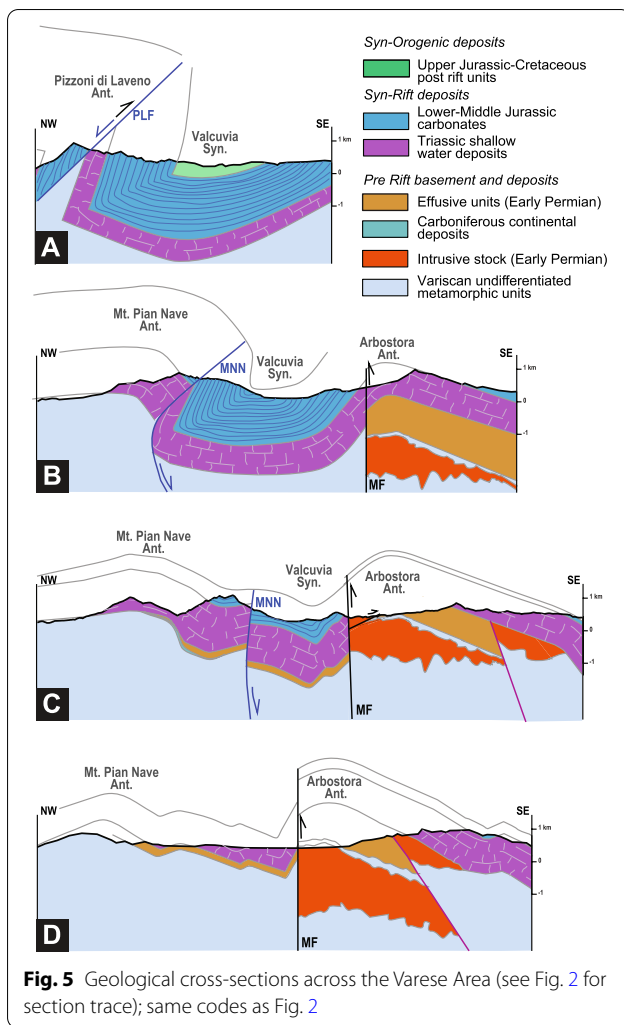
The folds belonging to Set 2 (Fig. 6b) show a N80E strike, an axial surface moderately dipping to the NNW, and an axis plunging at low angle to NE. These structures, indicating a ca. N-S compression with a tectonic transport direction to the south, are mainly located in the north-western sector of the Varese area. Here, a couple of SSE-verging recumbent folds, namely the Pizzoni di Laveno Anticline and the Valcuvia Syncline, crop out (Section A in Fig. 5).

The Pizzoni di Laveno Anticline, mostly eroded and submerged beneath the Maggiore Lake, is preserved only in its overturned frontal limb, with an axial plane dipping N354/38 and an axis plunging N54/21. The Valcuvia syncline deforms a thick sequence of syn-rift lower Jurassic limestones, into a close and recumbent fold with an axial plane dipping N354/38 and with an axis plunging N55/20. It is noteworthy that the Mesozoic Monte Nudo

Fault (i.e., MNN in Figs. 2 and 5), bounding a syn-rift basin to the east, was not inverted during contraction but it was rather folded into the Valcuvia syncline, instead.

The Valcuvia and Pizzoni di Laveno folds are separated by the Pizzoni di Laveno Fault, a reverse structure dipping steeply to the NW. This fault puts in contact the overturned Lower Jurassic limestones of the southern limb of the Pizzoni di Laveno Anticline in the hanging wall against the overturned flank of the Valcuvia syncline, here represented by shallow water Triassic carbonates, in the footwall. The present-day younger-on-older tectonic relationship across the Pizzoni di Laveno Fault (Section A in Fig. 5) can be explained if interpreted as an inherited normal fault that was positively inverted during Alpine tectonics. The fault nucleated during the Mesozoic rifting stage and cumulated a normal throw of ca. 1000 m, based on a minimum thickness estimation, by extrapolating the top of the syn-rift units from the Valcuvia sector to the hanging wall of the Pizzoni di Laveno Fault.

Field measurements of fault slip data provided two sets of reverse and strike slip structures (Fig. 6) with a rotation of the compressive direction in between. Consistently with the distribution of the two sets of folds, also the data populating the two sets of faults are located at the two sides of the Marzio Fault, that acted as a rigid backstop during contraction. As a consequence, direct observations on the crosscutting relationships of faults are rare or non-conclusive. Only a few field observations provide

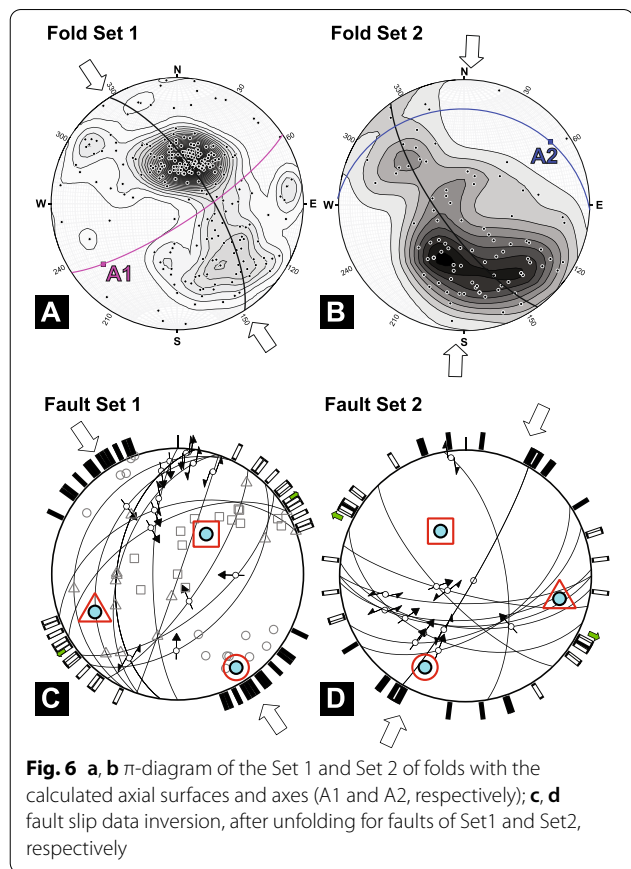


evidence of a polyphase reactivation along the Marzio Fault zone, with strike-slip slickenlines overprinting the down-dip ones and suggesting that Set 2 postdated Set 1.

From the data above, we infer that, in the Varese area, a progressive clockwise rotation of the maximum compressive stress (i.e., from NNW to NNE) happened during Alpine tectonics, with an associated set of north-verging folds predating the development of south-verging ones, and marking a change in the structural style of Alpine contraction through time.

#### 4.2 The Varese section

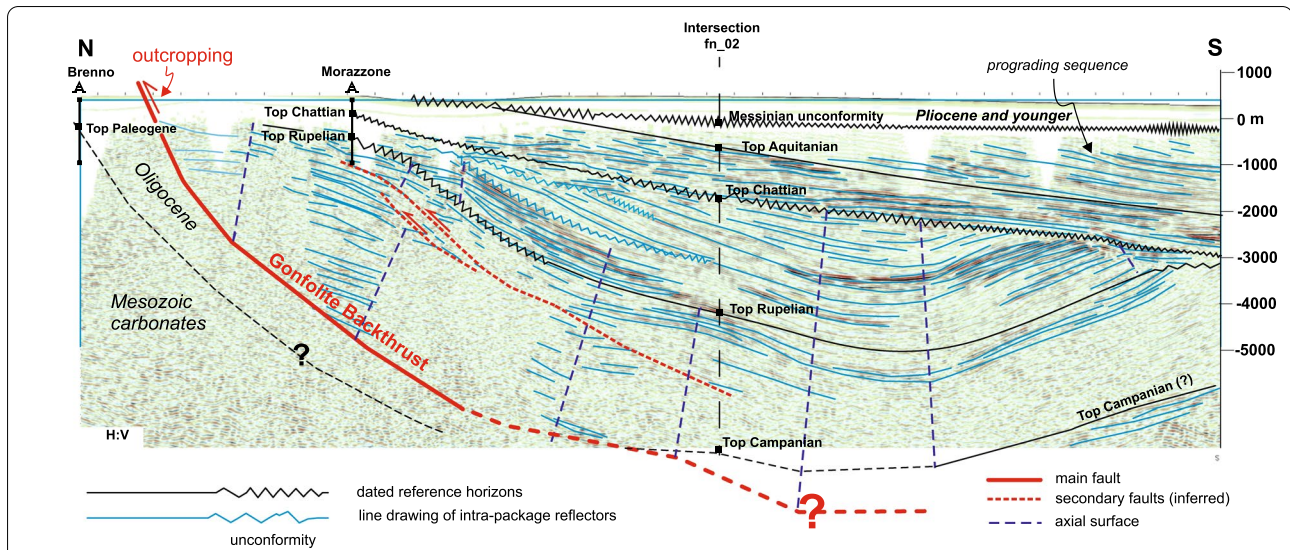
In a first step, we integrated surface geology (Fig. 2) with shallow seismic reflection profiles (Fig. 3), tied to available well logs. The geometry of the syn-orogenic sequence (Gonfolite Gr.) in the Pedéalpine syncline has been constrained by interpreting the mc\_13 seismic reflection profile (Fig. 7; see section trace in Fig. 3). The



location of the Gonfolite backthrust is constrained at the surface, and the projected Morazzone and Brenno wells, together with the intersection of the published fn\_02 section, provide the constraints to the interpreted horizons. The sequence stratigraphy records the major unconformities at the northern margin of the Pedéalpine syncline, consistently with a syn-growth architecture of the sequence, during backthrusting and backfolding. A regional unconformity is recorded at the top of Chattian, extended over the entire basin and sealing the main phase of folding. Some secondary thrusts, with flat-ramp-flat geometries, are interpreted in the Rupelian sequence, based on the downward termination of axial surfaces. These faults, resembling flexural slip faults due to their apparent lack of a deep rooting, are in line with a secondary backthrust in the Gonfolite Group, as pointed out by Bernoulli et al. (1993). The root of the Gonfolite backthrust and the geometry of the top of carbonates to the north are only supposed and not directly imaged at depth.

In a second step, we integrated some deeper-reaching geophysical data, including a 3-D high-resolution P-wave tomography of the Alpine crust (Diehl et al., 2009, 2017, Rosenberg & Kissling, 2013; Figs. 3 and 8)





**Fig. 7** Depth-migrated seismic section mc\_13 imaging the Gonfolite Lombarda Gr. of the Pedalpine syncline to south of the Varese area (re-interpreted after Michetti et al., 2012). Intersection with section fn\_02 and projected well logs are shown (see Fig. 3 for data locations)

into the Varese Section. Following Diehl et al. (2009), we define the boundary between lower and upper Adria crust by the 6.5 km/s Vp contour line, where other external constraints are lacking. The Triassic cover units, unconformably overlying the metamorphic basement and Permian intrusive bodies, have a thickness of *ca.* 2–3 km and are overlain by a syn- to post-rift sequence up to 3 km of thickness.

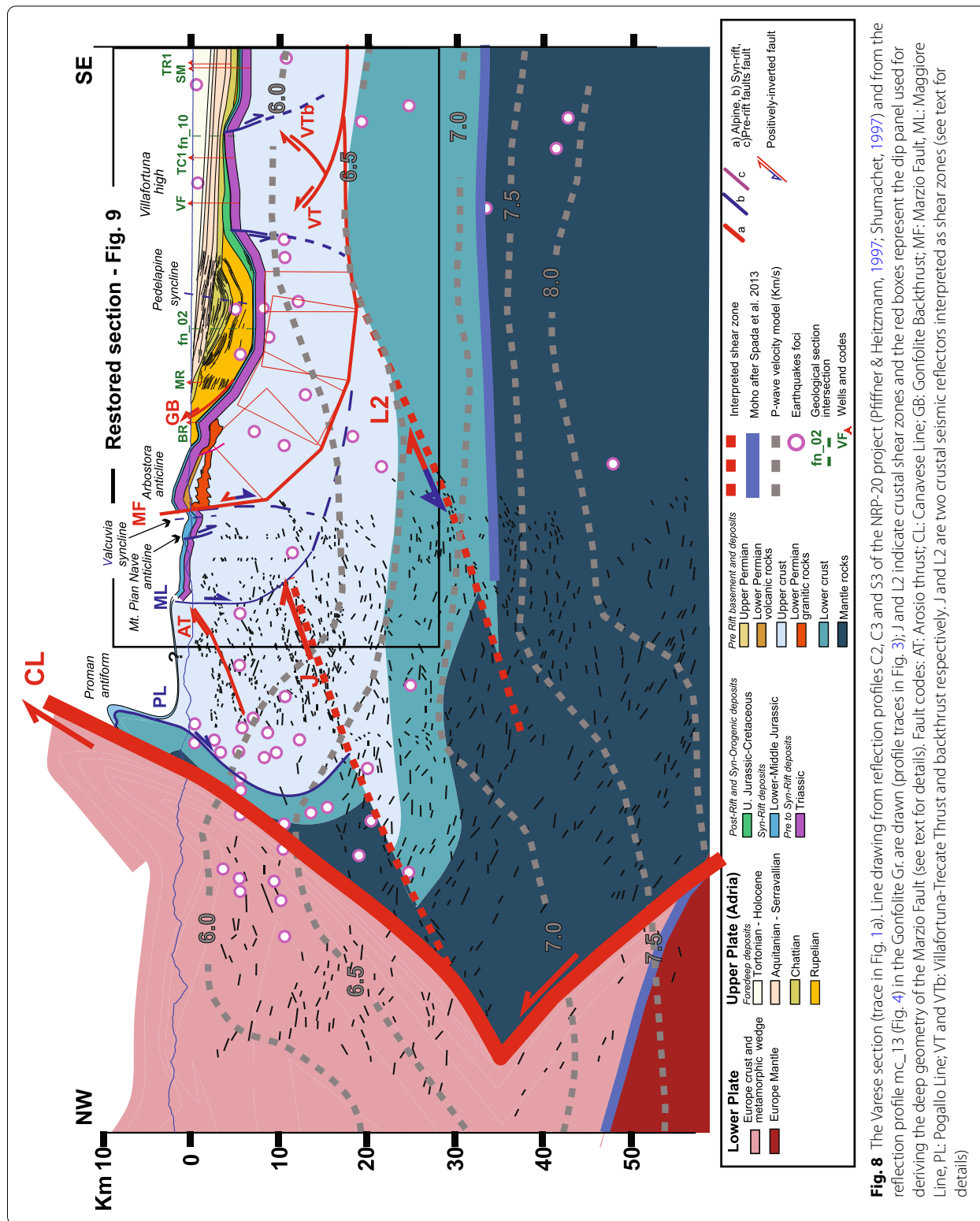
Basement and cover units are involved in a north-verging reverse fault-propagation-fold related to the inversion of the Marzio Fault (Fig. 8). The Marzio Fault represents a long-lived inherited fault that was probably active since Late Carboniferous (Casati, 1978). The Marzio Fault bounds an early Permian sub-volcanic body (Bakos et al., 1990) suggesting a certain structural control for its emplacement. During Triassic and Jurassic, the fault separated two structural blocks that experienced differential uplift, as highlighted by an abrupt change in the thickness of the Mesozoic sequences across the structure (Fig. 6). To the west, the Marzio Fault is concealed in a 2 km-thick zone of distributed deformation within the syn-rift units (Fig. 2).

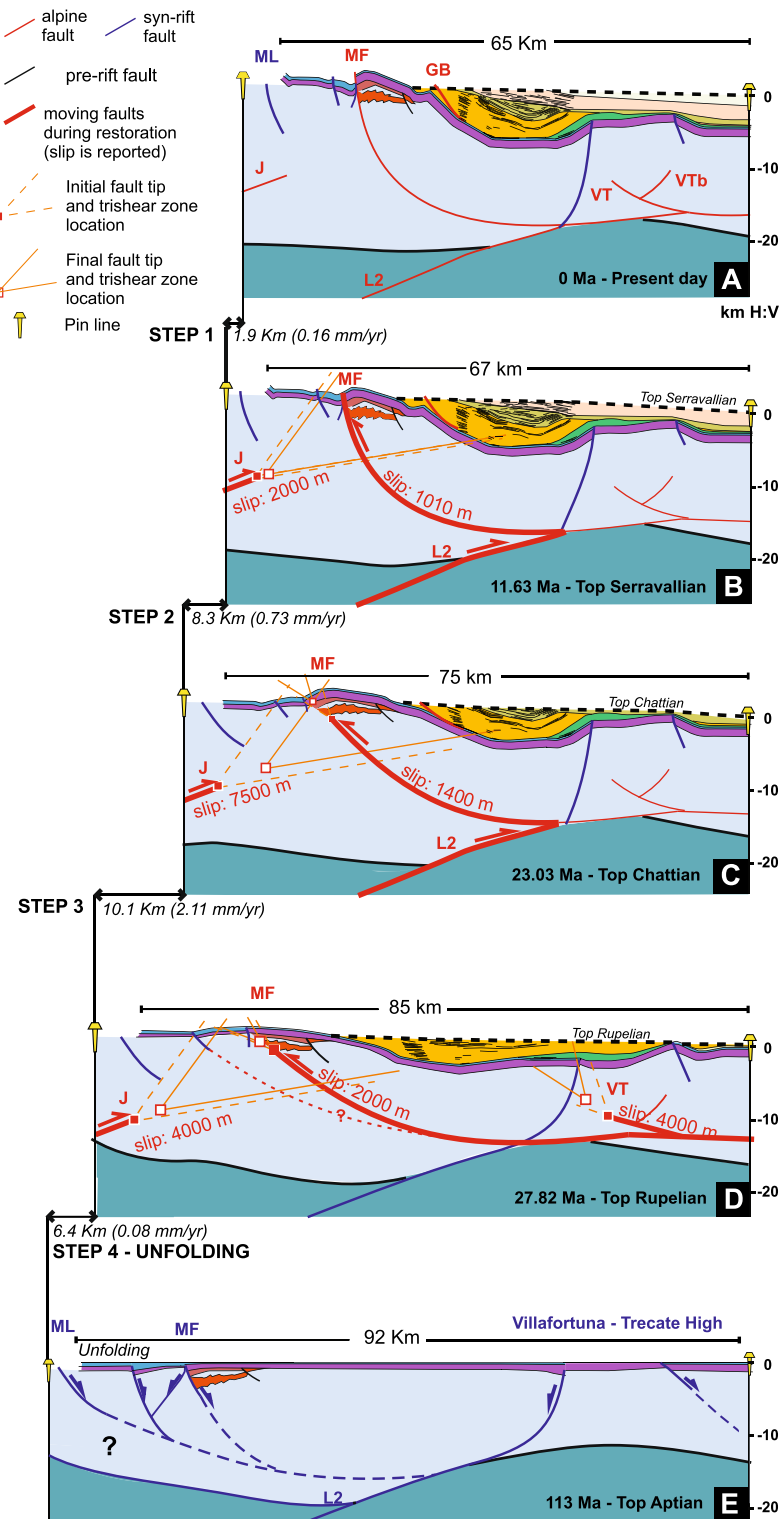
South of the Marzio Fault, the NE-SW trending asymmetric Arbostora anticline runs for more than 20 km along strike, plunging 22° towards N235E. Immediately south, the Pedalpine syncline is buried below the Po Plain recent sediments (Fig. 1), and hosts the Oligocene–Miocene Gonfolite Lombarda Group (e.g., Gelati et al., 1988; Tremolada et al., 2009); this sequence is deformed by shallowly-rooted thrusts, such as the Gonfolite back-thrust (Fig. 6, e.g., Bernoulli et al., 1989, 1993; Fantoni

et al., 2002), formed to accommodate shortening as an out-of-the-syncline back-thrust.

The considerable wavelength of the Arbostora anticline (*ca.* 25 km) and the coupled involvement of cover and basement (Fig. 8) suggest a deep-seated origin for the Marzio Fault. We have tried to constrain the geometry of the Marzio Fault at depth by applying a structural method whereby hanging wall rocks follow displacement trajectories parallel to the fault line at depth (Fig. 8). Based on this approach we obtained a thick-skinned N-verging high-angle reverse fault, with an associated hanging wall harpoon anticline resembling a break-through fault-propagation fold with a maximum structural relief of *ca.* 10 km with respect to the base of the Pedalpine syncline foredeep sequence.

South of the Canavese line, we traced the Proman Antiform, sheared to the south against the Pogallo line, the Arosio thrust (Schumacher, 1997): the extrapolated geometry of the Lower Jurassic syn-rift sequence is purely hypothetical, based on the presence of this unit close to the Canavese line (Brack et al., 2010). We also traced two well-defined deep-seated northwest-dipping seismic reflectors (i.e., J and L2 in Fig. 6). Reflectors J and L2 had been previously recognized and interpreted as shear zones in the deep seismic reflection profile NRP-20 by Pfiffner and Heitzmann (1997) and Schumacher (1997), in sections S3 and C3 (see Fig. 3 for location). We interpreted the Marzio Fault to be linked with the L2 shear zone and constituting a crustal-scale wedge. The L2 shear zone dips northwestwards and crosses the Adriatic Moho boundary, separating domains with differing lower crustal thicknesses. Stacking of thin lower crustal slices





**Fig. 9** Sequential restoration of the Varese section: **a** present-day, **b** top Serravallian, **c** top Chattian, **d** top Rupelian, **e** top Aptian—end of rifting. Fault slip values are listed on Table 1. See further comments on the text

**Table 1** list of the parameters adopted for the Trishear kinematic modelling, during the first three steps of restoration; Step 4 was restored with unfolding only

Restoration steps	Fault code	Apical angle $b$ (degrees)	Trishear angle offset	p/s ratio	Slip (m)
Step 1	J	45	0.73	1.5	2000
Present day—top Serravallian	MF (fault parallel flow)	—	—	—	1010
Step 2	J	50	0.80	1	7500
Top Serravallian—top Chattian	MF	40	0.60	1.5	1400
Step 3	J	46	0.71	1	4000
Top Chattian—top Rupelian	MF	50	0.54	1.5	2000
	VT	37	0.60	1	4000

attached to their corresponding upper crust can also provide a similar up-warping of Vp trajectories below the Ivrea Zone (see Fig. 8).

Seismic reflector J, on the other hand, corresponds to a major shear zone in the core of the presently upright to overturned Adria crust and uppermost mantle slices. Reverse slip along this shear zone would ideally provide both uplift and backfolding of the northern sector, including the inherited Liassic normal faults (i.e., the Pogallo and Maggiore Lines; Fig. 1) and back-tilting/folding of the Marzio Fault and its hanging wall. A late-stage backfolding of the Marzio Fault would explain the present-day steeply dipping geometry of the structure that would not be consistent with a simple fault-propagation fold, if we consider the theoretical field of existence according to kink-band theory (Suppe & Medwedeff, 1990). Crustal stacking and wedging, including the positive reactivation of the Marzio Fault as a back-thrust in the wedge's tip, could have contributed to the formation the Pedalpine syncline, where Oligocene–Miocene syn-orogenic deposits accumulated. A major pulse of uplift related to such crustal wedging is recorded in the Pedalpine syncline by the large erosional unconformity at the base of the Aquitanian, as well as the development of the Gonfolite back-thrust resulting from flexural slipping and out-of-the syncline thrusting (see Tavani et al., 2017).

#### 4.3 Kinematic restoration: insights on the tectonic evolution of the Western Southern Alps

We tested our hypothesis through a sequential restoration of the Varese section (Fig. 9). We restored the section in four steps from present-day to the end of the Jurassic rifting by means of a kinematic approach aided by well-tied and dated reference horizons and well tops belonging to the Gonfolite Lombarda Group within the Pedalpine syncline. The complete parametrization of the trishear restoration modeling for each of the faults that

slipped during each of the restoration steps is provided in Table 1.

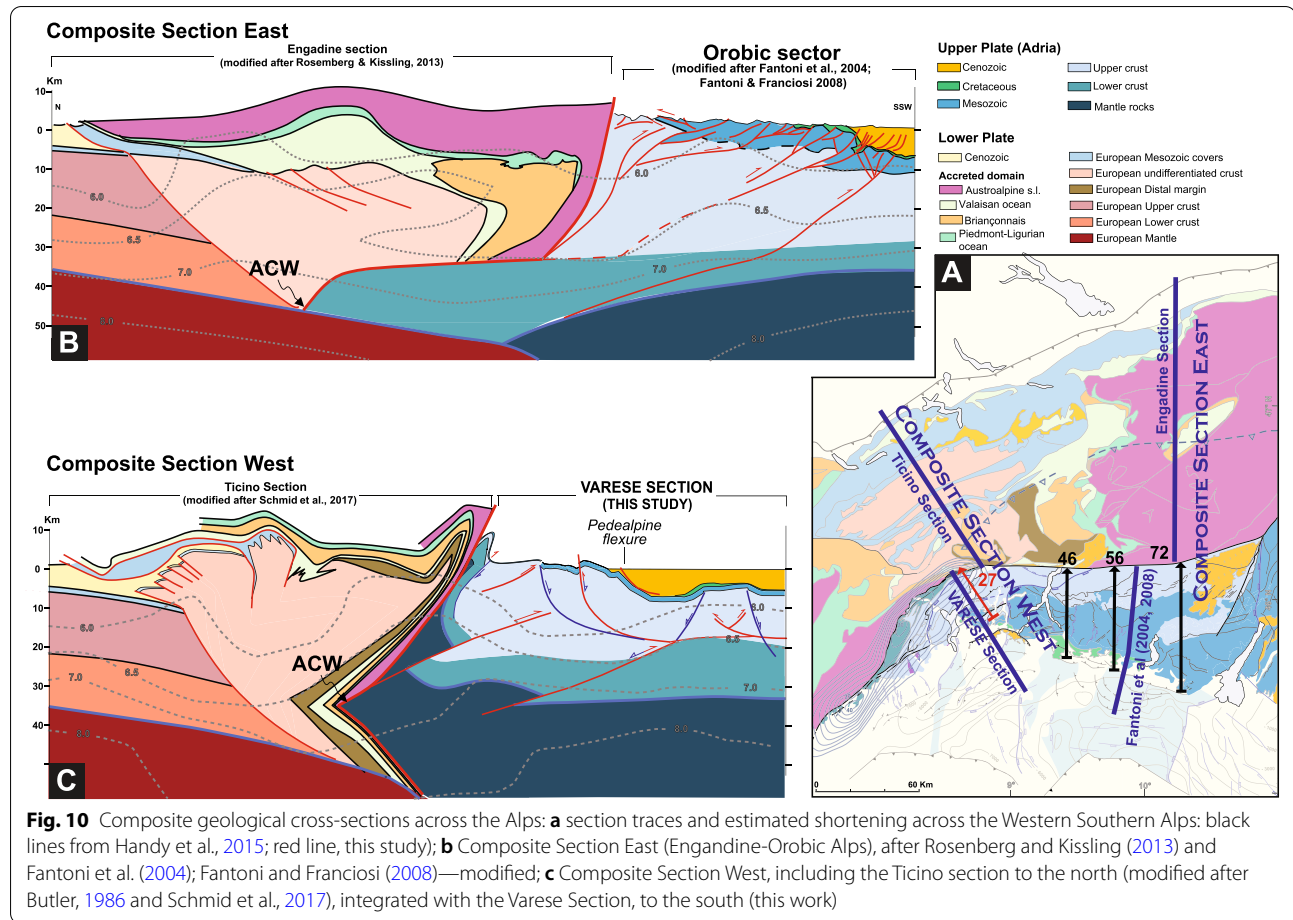
The choice of the parameters for the trishear restoration is mostly guided by the geometry of the reference horizons themselves. Given the position of the fault tip at each of the restoration steps, the apical angle and the trishear angle offset is determined by the position of the anticlinal and synclinal hinges, enclosing the fault-propagation fold front limb, and bounding the triangular zone of deformation. For the first restoration step, we interactively changed the position of the fault tip for J and Vt, along the fault lines, with a trial-and-error approach, resulting in the proposed solution. Conversely, for the MF, we constrained the fault tip position at the base of the cover units, after un-faulting during Step 1.

The remaining two parameters, i.e., slip and p/s ratio, were tested over a range of possible values, with a trial-and-error approach, keeping the combination of the two values that lead to the most geological viable and likely solution. In particular, we rejected p/s ratios higher than ca. 1.5, because they lead to an incomplete restoration of the hanging wall anticlines, and lower than ca. 1.0, because these result in unrealistic hanging wall restorations. The resulting range of the p/s ratio is consistent with other published case studies, reporting a typical range between 1 and 3 (e.g., Pei et al., 2014). Additionally, a slightly higher value for the MF fault is somehow expected, considering the presence of the mechanically strong early Permian granitic stock and volcanic units in the deformation zone of the propagating fault tip.

##### *Step 1 (present day—top Serravallian)*

Fault J had to slip 2000 m in order to place the hanging wall sector at the same elevation of the top Serravallian reference horizon (i.e., no sediment accommodation space in the chain sector). This assumption comes from the consideration that foredeep deposits were not present in these sectors of the chain. We thus adopted a fill-to-the-top approach (i.e., the structural relief of the structure compensated the thickness of the syn-growth





sequence deposited in the basin) thus reaching an estimation of the maximum value of slip for the considered time window.

The Marzio Fault (MF) was restored according to a fault parallel flow model by restoring the offset of the Aptian unconformity (i.e., a reference horizon for the end-of-rifting stage) and by obtaining a viable geometry for the top Serravallian reference horizon.

#### Step 2 (top Serravallian—top Chattian)

Both J and MF were restored by means of a trishear method with the parameters indicated in Table 1. Slip and parameters were estimated in order restore a top Chattian reference horizon and adopting a fill-to-the-top assumption.

#### Step 3 (top Chattian—top Rupelian).

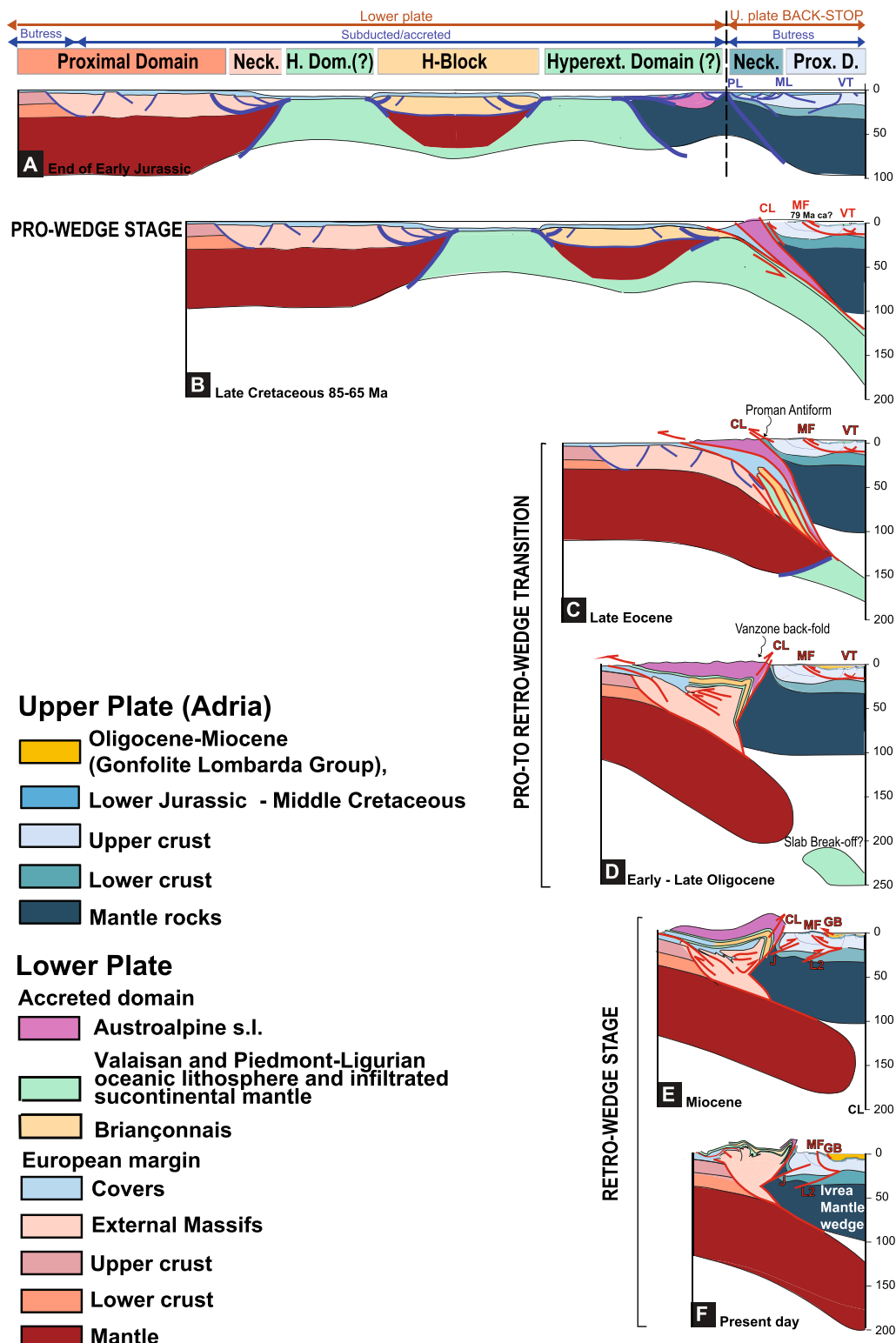
Faults MF, J and VT were restored by means of a trishear kinematic model with the parameters indicated in Table 1. Slip and parameters were estimated in order restore a top Rupelian reference horizon and adopting a fill-to-the-top assumption.

#### Step 4 (top Rupelian—top Aptian; end of rifting)

All the remaining deformation was restored by means of a 2D unfolding approach with a flexural slip method. We restored the upper crust thickness to likely values but realize that the position of the lower crust boundary at depth is not constrained by our restoration.

## 5 Discussion

According to the terminology proposed by Butler and Mazzoli (2006), a detachment-dominated solution for internal wedge anatomy of the Western Southern Alps has been proposed since the 90s (e.g., Schumacher, 1997; Pfiffner 2017). A similar model of thrust sheet stacking of cover units has been assumed for the Varese Area as well (Rosenberg & Kissling, 2013) by importing the surface geology outcropping to the east (Grigne stack, see Schmid et al., 1996). However, this proposal is solely based on the interpretation of deep seismic reflection profiles (i.e., the NRP20 profile in Schumacher et al., 1997), since contrary to the Orobic Alps, the Varese section is devoid of cover units (Figs. 1, 2 and 3). A slightly different interpretation has been provided by Fantoni et al. (2002) and Fantoni



and Franciosi (2008), who traced a stack of south-verging thrusts, ramping up from the basement and detached at a depth of ca. 15 km, but still framed in a detachment-dominated interpretative model.

The lithospheric detachment solutions above imply the stacking of a south verging thrust pile accommodating a significant amount of shortening: close to 100 km, calculated in the Central Southern Alps (e.g., Schönborn, 1992; Schumacher et al., 1997; see Carminati, 2009 for a discussion about this topic and Verwater et al., 2021 for different values calculated across the Giudicarie belt). At a more regional scale, the post-Adamello shortening estimates, calculated across for the Central and Western Southern Alps (Fig. 10a; Handy et al., 2015), decrease westward from ca. 70 km, close to the Giudicarie belt (18 km of Neogene shortening, across the Giudicarie belt alone, according to Verwater et al., 2021) to about 45 km east of Lake Como. According to the proposed detachment-dominated interpretation for the Western Southern Alps of Rosenberg and Kissling (2013), deep-seated structures, including the Marzio Fault, the Valcuvia syncline and the inherited syn-rift normal faults (i.e., such as the Pogallo and Maggiore Lines) are crosscut by the thrust sheets and no clear explanation for their present-day backfolding is offered.

As a matter of fact, the internal wedge architecture has never been verified from direct evidence (i.e., the Varese Area outcrops or wells), and the interpretation of available seismic lines results questionable. The only available well ties in front of the range could also be consistent with a steep regional folding, the Pedevalpine flexure (the so-called “Flessura Pedemontana” *Auct.*; e.g., Castellarin et al., 1992), that has been correlated with the Neoalpine movements.

A deeply different perspective is offered by ramp-dominated solutions, such as that proposed in the present work where lithospheric scale backfolding and upper crust accretion is proposed, resulting in much less shortening than the thrust stack solution (i.e., ca. 21 km of post-Adamello shortening; Fig. 8a).

A comparison of the anatomy of the wedge along different transects across the Southern Alps highlights significant differences in the contractional style (see composite Sections West and East of Fig. 10).

In the Composite Section East (Fig. 10b), located in the middle of the Mesozoic Lombardy basin, the main detachment levels are localized in the weak levels of the cover units, at the top of basement and at the lower–upper crust boundary. Deformation involves the whole crust, but, due to the presence of many rheologically weak layers, it resembles a detachment-dominated style. Note that slip along deeply rooted thrusts (i.e., A and B in Fig. 10b) results in the development of wide anticlines

at shallower levels, and the steepening of cover units at the southern margin of the range (the Pedevalpine flexure; Fig. 10b). The presence of a weak level at the upper–lower crust boundary also results in a pronounced indentation of the Adria crustal wedge into the European crust (ACW in Fig. 10b).

Conversely, at the western margin of the Lombardian basin (i.e., Composite Section West; Fig. 10c), the ductile parts of the crust had been thinned, extracted (*sensu* Froitzheim et al., 2006), with the lower crustal section and uppermost mantle most likely exhumed upon the latest stages of rifting, making the brittle parts of the upper crust and uppermost mantle to become coupled, and importantly, the upper mantle to become serpentized (see Peron-Pinvidic & Manatschal, 2019 and Festa et al., 2020). At the end of rifting (Fig. 11a), the studied area was characterized by a subsiding sector delimited by the Pogallo Line and other detachment faults that would have been located close to the present-day Canavese Line (Fig. 1). These faults were responsible for a pronounced thinning and attenuation of the Adria crust (Ferrando et al., 2004; Handy & Stünitz, 2002) and marked the external limit of the necking domain of Adriatic margin (*sensu* Peron-Pinvidic & Manatschal, 2019).

During convergence, the necking zone delimits the crustal sectors that can act as a buttress (Lacombe & Bellahsen, 2016; Lescoutre & Manatschal, 2020), inhibiting internal stacking.

Up to Rupelian times (e.g., Bersezio et al., 1993; Fig. 11b), we record a period, encompassing the main stages of subduction, when deep-seated Marzio Fault is inverted (ca. 79 Ma; Beltrando et al., 2015). Given the time constraints coming from the Varese section and the lack of reliable horizons older than Rupelian, we can possibly include into this time frame also the pre-Adamello deformation phase (i.e., up to early–middle Eocene). Such a style persisted also during the first stage between proto retro-wedge transition (Schmid et al., 1996; Fig. 9d and Fig. 9c), when the inception of the crustal wedge accretion was accommodated mainly through north-verging thrusts. This first phase was also coupled with the positive inversion of rift-related structures such as the Marzio Fault. Similar and coeval inversions are recorded also in other sectors of the chain, predating the deposition of syn-collisional deposits and the intrusion of the Tertiary bodies (i.e., the so-called pre-Adamello phase, e.g., Zanchetta et al., 2015). Additionally, other lines of evidence, indicate that during the subduction phase of convergence, tectonic stacks developed in the Southern Alps (e.g., Fantoni et al., 2004; Zanchetta et al., 2015),

A dramatic change in the structural style is recorded from the Aquitanian onward (i.e., 23.03 Ma; Figs. 9c and b and 11d and e), when shortening was taken up also by

deeper structures. During this phase we record the inversion of the inherited L2 shear zone and of the Marzio Fault into a crustal-scale wedge, whereas the most external structures were inactive. The internal deformation of the orogenic wedge and crustal accretion was here modeled by the slip on the J structure, whose growth caused the progressive back-tilting of the southern sectors and the closure of the Pedevalpine syncline, including out-of-sequence thrusting.

This change in structural style is consistent with the timing of Adria indentation of the Adriatic plate into the orogenic wedge resulted in the formation of the Vanzone back-fold (Fig. 9e; Keller et al., 2006; Manzotti et al., 2014), as deduced from the cooling of the Lepontine Dome and sediment accumulation within the Adriatic Foredeep basin (e.g., Di Capua et al., 2016; Di Giulio et al., 2001; Garzanti & Malusà, 2008; Gianola et al., 2014; Lu et al., 2019; Schmid et al., 1989). Backthrusting and exhumation of the Central Alps started somewhat earlier than 23 Ma in the Bergell area (e.g., Gianola et al., 2014), as recorded within the sediments accumulated the Adriatic foredeep (Di Giulio et al., 2001; Garzanti & Malusà, 2008; Lu et al., 2019) and progressively migrated westward, with an exhumation period dated at ca. 17–14 Ma in the sector close to the Proman Antiform (Fig. 1). Another indication comes from the geochronological fingerprints of the Adriatic foredeep deposits, that recorded a shift of the Adria indenter at ca. 23–23 Ma (Malusà et al., 2016).

The backfolding of the Adria margin, well-documented in the Ivrea Zone (Zingg et al., 1991), now finds additional evidence in the Varese area, directly linking the upturned lower crustal sectors, outcropping to the west, with folding of the Lugano–Valgrande Fault into a regional syncline (Bertotti, 1991; Fig. 1).

In turn, the shallow accommodation of this folding resulted into flexural slip faulting along the Gonfolite backthrust between Varese and Lake Como (Fig. 1) that is mostly expressed at the surface (i.e., east of Varese; Bernoulli et al., 1989; Bersezio et al., 1993; Sileo et al., 2007) and rooted at depth (Michetti et al., 2012), in the hinge zone of the Pedevalpine syncline, as a thrust flat. Consistently, earthquakes' foci cluster in the sector on top of the J shear zone, and on top of the wedge-related Marzio Fault, where we infer that the most recent crustal deformation focused (i.e., Tortonian–present day). Restoration resulted in 27 km of total shortening (i.e., 29% of a restored section of 92 km) for the stack of structures investigated in the Varese area and with much of the slip being accommodated by uplifting the inner part of the chain through internal deformation, and not by stacking of thin-skinned nappes as previously suggested.

Shortening is documented also in the Orobic Alps, for a pre-Adamello syn-collisional tectonic phase (55–45 Ma:

Zanchetta et al., 2015), and came to an apparent pause during Late Eocene–Early Oligocene (42–30 Ma), when Ji et al. (2019) framed a possible phase of lower slab steepening below the Southern Alps, resulting in a higher dip of the slab to the east (ca. 80°) compared to the Varese area, where it is close to 60° (Zhao et al., 2016). Here, we documented wedging from the Chattian onward, i.e., later than in the Orobic Alps and after ceasing of slab retreat. Such a sequence of events, on a broader perspective, suggests that during the collisional and post-collisional history of orogenesis, lithosphere dynamics diachronically drove the onset of tectonic phases (i.e., wedging and slab retreat), from east to west, across the Southern Alps. Even if based on a structural and kinematic approach alone, our results are consistent with a recent numerical thermo-mechanical modeling (Dal Zilio et al., 2020) demonstrating that the rearrangement of forces after a possible breakoff, bending and rollback of the European slab would result in a compressive stress transferred to the shallow crust.

The wedge structure of the Southern Alps and its evolution can be better framed if we consider that the deeply rooted structures proposed here resulted from a long-lived and polyphase tectonic history where structural inheritance played a primary role. Some of the structures involved during Jurassic rifting (Fig. 9a) were positively inverted during a first phase of deformation that, in our dataset, is possibly also encompassing the Cretaceous development of a north-verging pro-wedge, during the subduction phase of convergence (Fig. 11b). Finally, contemporary to continental collision, and, possibly, a slab breakoff (Manzotti et al., 2014; von Blanckenburg & Davies, 1995), the Western Southern Alps wedge shows an inversion of the tectonic transport direction (Fig. 9d), contemporary to the deposition of a thick syn-collisional deposits (i.e., the Gonfolite Lombarda Group). During the last stages of convergence (Fig. 9e and f) subcontinental mantle of the Ivrea Zone was finally exhumed together with the inversion of crustal rift-related structures.

In summary, the pre-collisional lithospheric configuration was significantly different in the western and eastern margins of the Lombardian basin. In the composite Section West, collision resulted in the involvement of upper mantle lenses, and a thinned lower crustal section; the weak interface represented by the upper and lower crustal levels interpreted for the Orobic Alps section was missing, thus promoting the indentation of the Adriatic upper lithosphere into Europe. Reactivation of deep-seated, probably rift-inherited shear zones (L2 and J reflectors) upon convergence would have transferred slip into the upper crustal section, re-activating Permian and Jurassic faults (i.e., Marzio Fault, Maggiore Line).



## 6 Conclusions

Analyzing and discussing the crustal structure of a key area of the orogenic wedge of the Western Southern Alps we provide a ramp-dominated balanced solution for the accretionary wedge that opposes previously proposed detachment-dominated interpretations (e.g., Fantoni & Franciosi, 2008; Fantoni et al., 2002; Pfiffner, 2016; Rosenberg & Kissling, 2013; Schumacher et al., 1997). The proposed solution depicts the presence of a retro-wedge involving the tip of the north-verging Adria mantle wedge, along with the reactivation of crustal rift-inherited faults and shear zones cutting through previously thinned crustal sectors. The inversion of the deeply rooted normal faults as crustal thrust ramps could relate to the inherited thinning of the ductile parts of the continental crust, and the mechanical coupling between the brittle upper crustal and upper lithospheric mantle sections involved in the orogenic wedge (e.g., Lescoutre & Manatschal, 2020; Tavani et al., 2021). Consistently with Festa et al. (2020), our restoration implies that the Southern Alps acted as a backstop of the subduction-accretion complex and that most of the continental collisional deformation was efficiently accommodated inside the wedge through the thickening of the upper crust.

Finally, in relation to the Orobic stacks in the Central Alps, we do not have any evidence of an eroded upper stack of units in the Varese Area. The integration with the geophysical seismic reflection profiles at the front of the buried chain, shows that the outcropping structures find a good correspondence at depth, below the Po Plain, and the supposed presence of another tectonic stack is definitely not necessary for the section interpretation. Based on these conclusions, we speculate whether a major discontinuity for the change of the basal depth of the contractional wedge could be related to the abrupt increase in the Jurassic syn-rift thickness to east of the Lugano-Valgrande fault, changes in the lower crustal thickness (and strength), and the rheology of the upper and lower crust interface. Such lateral discontinuity could relate to the inherited non-cylindricity of the Adriatic rifted margin, as observed in rifted margins worldwide and collisional orogens developed from those.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s00015-021-00404-7>.

**Additional file 1: S1.** Geological map of the Varese Area.

**Additional file 2: S2.** Line drawing of the Deep Seismic Reflection Profiles\_S3, C2, C3.

**Additional file 3: S3.** Adopted seismic tomographic sections\_E1, E2, SIMPLON, D2.

**Additional file 4: S4.** Earthquakes locations projected on the Varese Section.

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## Authors' contributions

ES and FAL performed the geological survey and calculated the progressive restoration; ES FAL e PG conceptualized the work and built the Varese Section; ADC e RF revised the seismic interpretation; all the authors participated in writing the manuscript. All authors read and approved the final manuscript.

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## Availability of data and materials

Detailed Geological Map of the Varese Area, adopted line drawing of the deep seismic reflection profiles, adopted seismic tomographic sections and earthquakes projected on the Varese Section are available in Additional files. Well Logs can be downloaded at the VIDEPI Project (Visibility of petroleum exploration data in Italy) webportal—Ministry for Economic Development DGRME—Italian Geological Society—Assomineraria; <https://www.videpi.com/videpi/videpi.asp>; last accessed 30th, August 2021.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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## References

- Agard, P., & Handy, M. R. (2021). Ocean subduction dynamics in the Alps. *Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology*, 17(1), 9–16. <https://doi.org/10.2138/gselements.17.1.9>
- Allmendinger, R. W. (1998). Inverse and forward numerical modeling of trishear fault-propagation folds. *Tectonics*, 17(4), 640–656. <https://doi.org/10.1029/98TC01907>
- Amadori, C., Toscani, G., Di Giulio, A., Maesano, F. E., D'Ambrogio, C., Ghielmi, M., & Fantoni, R. (2019). From cylindrical to non-cylindrical foreland basin: Pliocene-Pleistocene evolution of the Po Plain-Northern Adriatic basin

- (Italy). *Basin Research*, 31(5), 991–1015. <https://doi.org/10.1111/bre.12369>
- Bakos, F., Del Moro, A., & Visona, D. (1990). The Hercynian volcano-phitonic association of Ganna (Lake Lugano, Central Southern Alps, Italy). *European Journal of Mineralogy*. <https://doi.org/10.1127/ejm/2/3/0373>
- Beltrando, M., Stockli, D. F., Decarlis, A., & Manatschal, G. (2015). A crustal-scale view at rift localization along the fossil Adriatic margin of the Alpine Tethys preserved in NW Italy. *Tectonics*, 34(9), 1927–1955. <https://doi.org/10.1002/2015TC003973>
- Berger, A., Mercolli, I., Kapferer, N., & Fügenschuh, B. (2012). Single and double exhumation of fault blocks in the internal Sesia-Lanzo Zone and the Ivrea-Verbano Zone (Biella, Italy). *International Journal of Earth Sciences*, 101(7), 1877–1894. <https://doi.org/10.1007/s00531-012-0755-6>
- Bernoulli, D. (1964). Zur Geologie des Monte Generoso (Lombardische Alpen); ein Beitrag zur Kenntnis der südalpinen Sedimente (Doctoral dissertation).
- Bernoulli, D., Bertotti, G., & Froitzheim, N. (1990). Mesozoic faults and associated sediments in the Austroalpine-South Alpine passive continental margin. *Memorie Della Società Geologica Italiana*, 45, 25–38.
- Bernoulli, D., Bertotti, G., & Zingg, A. (1989). Northward thrusting of the Gonfolite Lombarda (South-Alpine Molasse) onto the Mesozoic sequence of the Lombardian Alps: Implications for the deformation history of the Southern Alps. *Eclogae Geologicae Helvetiae*, 82(3), 841–856.
- Bernoulli, D., Giger, M., Müller, D. W., & Ziegler, U. F. (1993). Sr-isotope stratigraphy of the Gonfolite Lombarda Group (South-Alpine Molasse, northern Italy) and radiometric constraints for its age of deposition. *Eclogae Geologicae Helvetiae*, 86(3), 751–767.
- Berra, F., Galli, M. T., Reghellin, F., Torricelli, S., & Fantoni, R. (2009). Stratigraphic evolution of the Triassic-Jurassic succession in the Western Southern Alps (Italy): The record of the two-stage rifting on the distal passive margin of Adria. *Basin Research*, 21(3), 335–353. <https://doi.org/10.1111/j.1365-2117.2008.00384.x>
- Bersezio, R., Fornaciari, M., Gelati, R., Napolitano, A., & Valdisturlo, A. (1993). The significance of the Upper Cretaceous to Miocene clastic wedges in the deformation history of the Lombardian southern Alps. *Géologie Alpine*, 69, 3–20.
- Bertotti, G. (1991). Early Mesozoic extension and Alpine shortening in the western southern Alps: The geology of the area between Lugano and Menaggio (Lombardy, northern Italy). *Memorie Di Scienze Geologiche Padova*, 43, 17–123.
- Bertotti, G., Picotti, V., Bernoulli, D., & Castellarin, A. (1993). From rifting to drifting: Tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. *Sedimentary Geology*, 86(1–2), 53–76. [https://doi.org/10.1016/0037-0738\(93\)90133-P](https://doi.org/10.1016/0037-0738(93)90133-P)
- Bertotti, G., Seward, D., Wijbrans, J., ter Voorde, M., & Hurford, A. J. (1999). Crustal thermal regime prior to, during, and after rifting: A geochronological and modeling study of the Mesozoic South Alpine rifted margin. *Tectonics*, 18(2), 185–200. <https://doi.org/10.1029/1998TC900028>
- Boriani, A., Burlini, L., & Sacchi, R. (1990). The Cossato-Mergozzo-Brissago Line and the Pogallo Line (Southern Alps, Northern Italy) and their relationships with the late-Hercynian magmatic and metamorphic events. *Tectonophysics*, 182(1–2), 91–102. [https://doi.org/10.1016/0040-1951\(90\)90344-8](https://doi.org/10.1016/0040-1951(90)90344-8)
- Boriani, A., & Sacchi, R. (1973). Geology of the junction between the Ivrea-Verbano and Strona-Ceneri Zones. *Memorie Degli Istituti Di Geologia e Mineralogia Della Università Di Padova*, 28, 36.
- Boriani, A., Sassi, F., & Sassi, R. (2003). The basement complexes in Italy, with special regards to those exposed in the Alps: A review. *Episodes*, 26(3), 186–192.
- Boriani, A., & Villa, I. M. (1997). Geochronology of regional metamorphism in the Ivrea-Verbano zone and Serie dei Laghi, Italian Alps. *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 77, 381–401.
- Brack, P., Ulmer, P., & Schmid, S. M. (2010). A crustal-scale magmatic system from the Earth's mantle to the Permian surface: Field trip to the area of lower Valsesia and Val d'Ossola (Massiccio dei Laghi, Southern Alps, Northern Italy). *Swiss Bulletin Für Angewandte Geologie*, 15(2), 3–21.
- Brodie, K. H., & Rutter, E. H. (1987). Deep crustal extensional faulting in the Ivrea Zone of northern Italy. *Tectonophysics*, 140(2–4), 193–212. [https://doi.org/10.1016/0040-1951\(87\)90229-0](https://doi.org/10.1016/0040-1951(87)90229-0)
- Butler, R. W. (2013). Area balancing as a test of models for the deep structure of mountain belts, with specific reference to the Alps. *Journal of Structural Geology*, 52, 2–16. <https://doi.org/10.1016/j.jsg.2013.03.009>
- Butler, R. W. (1986). Thrust tectonics, deep structure and crustal subduction in the Alps and Himalayas. *Journal of the Geological Society*, 143(6), 857–873. <https://doi.org/10.1144/gsjgs.143.6.0857>
- Butler, R. W. H., & Mazzoli, S. (2006). Styles of continental contraction: A review and introduction. In S. Mazzoli & R. W. Butler (Eds.), *Styles of continental contraction*. (Vol. 414). Geological Society of America.
- Carminati, E. (2009). Neglected basement ductile deformation in balanced-section restoration: An example from the Central Southern Alps (Northern Italy). *Tectonophysics*, 463(1–4), 161–166. <https://doi.org/10.1016/j.tecto.2008.09.042>
- Casati, P. (1978). Tettonismo e sedimentazione nel settore occidentale delle Alpi Meridionali durante il tardo Paleozoico, il Triassico e il Giurassico. *Rivista Italiana Di Paleontologia e Stratigrafia*, 84, 313–326.
- Castellarin, A., Cantelli, L., Fesce, A. M., Mercier, J. L., Picotti, V., Pini, G. A., & Selli, L. (1992). Alpine compressional tectonics in the Southern Alps. *Relationships with the N-Apennines. Annales Tectonicae*, 6(1), 62–94.
- D'Adda, P., Zanchi, A., Bergomi, M., Berra, F., Malusà, M. G., Tunesi, A., & Zanchetta, S. (2011). Polyphase thrusting and dyke emplacement in the central Southern Alps (Northern Italy). *International Journal of Earth Sciences*, 100(5), 1095–1113. <https://doi.org/10.1007/s00531-010-0586-2>
- Delvaux, D. (1993). The TENSOR program for paleostress reconstruction: Examples from the east African and the Baikal rift zones. *Terra Nova*, 5(1), 216.
- Dèzes, P., Schmid, S. M., & Ziegler, P. A. (2004). Evolution of the European Cenozoic Rift System: Interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics*, 389(1–2), 1–33. <https://doi.org/10.1016/j.tecto.2004.06.011>
- Di Capua, A., Vezzoli, G., Cavallo, A., & Groppelli, G. (2016). Clastic sedimentation in the Late Oligocene Southalpine Foredeep: From tectonically controlled melting to tectonically driven erosion. *Geological Journal*, 51(3), 338–353. <https://doi.org/10.1002/gj.2632>
- Di Giulio, A., Carrapa, B., Fantoni, R., Gorla, L., & Valdisturlo, A. (2001). Middle Eocene to Early Miocene sedimentary evolution of the western Lombardian segment of the South Alpine foredeep (Italy). *International Journal of Earth Sciences*, 90(3), 534–548. <https://doi.org/10.1007/s005310000186>
- Di Paola, S., Spalla, M. I., & Gosso, G. (2001). New structural mapping and metamorphic evolution of the Domaso CortafoZone (Southern Alps—Lake Como). *Memorie Di Scienze Geologiche, Padova*, 53, 1–14.
- Diehl, T., Kissling, E., & Schmid, S. (2017). High-resolution 3D seismic structure of the Ivrea-Verbano Zone, ICDP Baveno Workshop, May 1–5 2017. <https://doi.org/10.13140/RG.2.2.30166.86088>
- Diehl, T., Husen, S., Kissling, E., & Deichmann, N. (2009). High-resolution 3-DP-wave model of the Alpine crust. *Geophysical Journal International*, 179(2), 1133–1147. <https://doi.org/10.1111/j.1365-246X.2009.04331.x>
- Diella, V., Spalla, M. I., & Tunesi, A. (1992). Contrasting thermomechanical evolutions in the Southalpine metamorphic basement of the Orobic Alps (Central Alps, Italy). *Journal of Metamorphic Geology*, 10(2), 203–219. <https://doi.org/10.1111/j.1525-1314.1992.tb00079.x>
- Dogliani, C., & Bosellini, A. (1987). Eoalpine and mesoalpine tectonics in the Southern Alps. *Geologische Rundschau*, 76(3), 735–754. <https://doi.org/10.1007/BF01821061>
- Egan, S. S., Buddin, T. S., Kane, S. J., & Williams, G. D. (1997). Three-dimensional modelling and visualisation in structural geology: new techniques for the restoration and balancing of volumes. In Proceedings of the 1996 Geoscience Information Group Conference on Geological Visualisation. Electronic Geology Special Volume, 1, 67–82.
- Erslev, E. A. (1991). Trishear fault-propagation folding. *Geology*, 19(6), 617–620. [https://doi.org/10.1130/0091-7613\(1991\)019%3c0617:TFFP%3e2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019%3c0617:TFFP%3e2.3.CO;2)
- Fantoni, R., Bello, M., Ronchi, P., & Scotti, P. (2002). Po Valley oil play: from the Villafortuna-Treccate field to South-Alpine and Northern Apennine exploration. EAGE Conference Florence. Extended Abstracts Book, 1–4.
- Fantoni, R., Bersezio, R., & Forcella, F. (2004). Alpine structure and deformation chronology at the Southern Alps-Po Plain border in Lombardy. *Bollettino Della Società Geologica Italiana*, 123(3), 463–476.
- Fantoni, R., & Franciosi, R. (2008). 8 geological sections crossing Po Plain and Adriatic foreland. *Rendiconti Online Società Geologica Italiana*, 3(2008), 365–366.

- Fantoni, R., & Franciosi, R. (2010). Tectono-sedimentary setting of the Po Plain and Adriatic foreland. *Rendiconti Lincei*, 21(1), 197–209.
- Fantoni, R., & Scotti, P. (2009). Time of hydrocarbon generation vs trap forming age in Mesozoic oil play in Po Plain. *Rendiconti Online Società Geologica Italiana*, 5, 89–92.
- Ferrando, S., Bernoulli, D., & Compagnoni, R. (2004). The Canavese zone (internal Western Alps): a distal margin of Adria. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 84(1–20).
- Festa, A., Balestro, G., Borghi, A., De Caroli, S., & Succo, A. (2020). The role of structural inheritance in continental break-up and exhumation of Alpine Tethyan mantle (Canavese Zone, Western Alps). *Geoscience Frontiers*, 11(1), 167–188. <https://doi.org/10.1016/j.gsf.2018.11.007>
- Froitzheim, N., Pleuger, J., & Nagel, T. J. (2006). Extraction faults. *Journal of Structural Geology*, 28(8), 1388–1395. <https://doi.org/10.1016/j.jsg.2006.05.002>
- Garzanti, E., & Malusà, M. G. (2008). The Oligocene Alps: Domal unroofing and drainage development during early orogenic growth. *Earth and Planetary Science Letters*, 268(3–4), 487–500. <https://doi.org/10.1016/j.epsl.2008.01.039>
- Gelati, R., Napolitano, A., & Valdisturlo, A. (1988). La "Gonfolite Lombarda": stratigrafia e significato nell'evoluzione del margine sudalpino. *Rivista Italiana di Paleontologia e Stratigrafia*, 94(2).
- Gianola, O., Schmidt, M. W., von Quadt, A., Peytcheva, I., Luraschi, P., & Reusser, E. (2014). Continuity in geochemistry and time of the Tertiary Bergell intrusion (Central Alps). *Swiss Journal of Geosciences*, 107(2), 197–222. <https://doi.org/10.1007/s00015-014-0174-8>
- Handy, M. R. (1987). The structure, age and kinematics of the Pogallo Fault Zone; Southern Alps, northwestern Italy. *Eclogae Geologicae Helveticae*, 80(3), 593–632.
- Handy, M. R., Franz, L., Heller, F., Janott, B., & Zurbirgen, R. (1999). Multistage accretion and exhumation of the continental crust (Ivrea crustal section, Italy and Switzerland). *Tectonics*, 18(6), 1154–1177. <https://doi.org/10.1029/1999TC900034>
- Handy, M. R., & Stünitz, H. (2002). Strain localization by fracturing and reaction weakening—a mechanism for initiating exhumation of subcontinental mantle beneath rifted margins. *Geological Society, London, Special Publications*, 200(1), 387–407. <https://doi.org/10.1144/GSL.SP.2001.200.01.22>
- Handy, M. R., Ustaszewski, K., & Kissling, E. (2015). Reconstructing the Alps—Carpathians—Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. *International Journal of Earth Sciences*, 104(1), 1–26. <https://doi.org/10.1007/s00531-014-1060-3>
- Handy, M. R., & Zingg, A. (1991). The tectonic and rheological evolution of an attenuated cross section of the continental crust: Ivrea crustal section, southern Alps, northwestern Italy and southern Switzerland. *Geological Society of America Bulletin*, 103(2), 236–253. [https://doi.org/10.1130/0016-7606\(1991\)103%3C0236:TAREO%3E2.3.CO;2](https://doi.org/10.1130/0016-7606(1991)103%3C0236:TAREO%3E2.3.CO;2)
- Hardy, S., & Finch, E. (2007). Mechanical stratigraphy and the transition from trishear to kink-band fault-propagation fold forms above blind basement thrust faults: A discrete-element study. *Marine and Petroleum Geology*, 24(2), 75–90. <https://doi.org/10.1016/j.marpetgeo.2006.09.001>
- Hardy, S., & Ford, M. (1997). Numerical modeling of trishear fault propagation folding. *Tectonics*, 16(5), 841–854. <https://doi.org/10.1029/97TC01171>
- Hodges, K. V., & Fountain, D. M. (1984). Pogallo Line, South Alps, northern Italy: An intermediate crystal level, low-angle normal fault? *Geology*, 12(3), 151–155. [https://doi.org/10.1130/0091-7613\(1984\)12%3C151:PLSANI%3E2.0.CO;2](https://doi.org/10.1130/0091-7613(1984)12%3C151:PLSANI%3E2.0.CO;2)
- ISIDe Database (Italian Seismological Instrumental and Parametric Data-Base) v. 1.0: <http://terremoti.ingv.it/search> (accessed December 2020).
- Jadoul, F., Galli, M., Calabrese, L., & Gnaccolini, M. (2005). Stratigraphy of Rhaetian to Lower Sinemurian carbonate platforms in western Lombardy (Southern Alps, Italy): paleogeographic implications. *Rivista Italiana di Paleontologia e Stratigrafia*, 111(2), 285–303. <https://doi.org/10.13130/2039-4942/6316>
- Ji, W. Q., Malusà, M. G., Tiepolo, M., Langone, A., Zhao, L., & Wu, F. Y. (2019). Synchronous Periadriatic magmatism in the Western and Central Alps in the absence of slab breakoff. *Terra Nova*, 31(2), 120–128. <https://doi.org/10.1111/ter.12377>
- Kälin, O., & Trümpy, D. (1977). Sedimentation und Paleotektonik in den westlichen Sudalpen: Zur triassisch-jurassischen Geschichte des Monte Nudo Beckens. *Eclogae Geologicae Helveticae*, 70, 295–350.
- Kane, S. J., Williams, G. D., Buddin, T. S., Egan, S. S., & Hodgetts, D. (1997). Flexural-slip based restoration in 3D, a new approach. In 1997 AAPG Annual Convention Official Program A:58.
- Karakas, O., Wotzlaw, J. F., Guillong, M., Ulmer, P., Brack, P., Economos, R., & Bachmann, O. (2019). The pace of crustal-scale magma accretion and differentiation beneath silicic caldera volcanoes. *Geology*, 47(8), 719–723. <https://doi.org/10.1130/G46020.1>
- Keller, L. M., Fügenschuh, B., Hess, M., Schneider, B., & Schmid, S. M. (2006). Simplon fault zone in the western and central Alps: Mechanism of Neogene faulting and folding revisited. *Geology*, 34(4), 317–320. <https://doi.org/10.1130/G22256.1>
- Lacombe, O., & Bellahsen, N. (2016). Thick-skinned tectonics and basement-involved fold-thrust belts: insights from selected Cenozoic orogens. *Geological Magazine*, 153(5–6), 763–810. <https://doi.org/10.1017/S0016756816000078>
- Lardeaux, J. M., & Spalla, M. I. (1991). From granulites to eclogites in the Sesia zone (Italian Western Alps): A record of the opening and closure of the Piedmont ocean. *Journal of Metamorphic Geology*, 9(1), 35–59. <https://doi.org/10.1111/j.1525-1314.1991.tb00503.x>
- Laubscher, H. P. (1985). Large-scale, thin-skinned thrusting in the southern Alps: Kinematic models. *Geological Society of America Bulletin*, 96(6), 710–718. [https://doi.org/10.1130/0016-7606\(1985\)96%3C710:LTITS%3E2.0.CO;2](https://doi.org/10.1130/0016-7606(1985)96%3C710:LTITS%3E2.0.CO;2)
- Lemoine, M., & Trümpy, R. (1987). Pre-oceanic rifting in the Alps. *Tectonophysics*, 133(3–4), 305–320. [https://doi.org/10.1016/0040-1951\(87\)90272-1](https://doi.org/10.1016/0040-1951(87)90272-1)
- Lescoutre, R., & Manatschal, G. (2020). Role of rift-inheritance and segmentation for orogenic evolution: Example from the Pyrenean-Cantabrian system. *BSGF-Earth Sciences Bulletin*, 191(1), 18. <https://doi.org/10.1051/bsgf/2020021>
- Lu, G., Di Capua, A., Winkler, W., Rahn, M., Guillong, M., von Quadt, A., & Willett, S. D. (2019). Restoring the source-to-sink relationships in the Paleogene foreland basins in the Central and Southern Alps (Switzerland, Italy, France): A detrital zircon study approach. *International Journal of Earth Sciences*, 108(6), 1817–1834. <https://doi.org/10.1007/s00531-019-01734-6>
- Malusà, M. G., Anfinson, O. A., Dafon, L. N., & Stockli, D. F. (2016). Tracking Adria indentation beneath the Alps by detrital zircon U-Pb geochronology: Implications for the Oligocene-Miocene dynamics of the Adriatic microplate. *Geology*, 44(2), 155–158. <https://doi.org/10.1130/G37407.1>
- Manzotti, P., Ballevre, M., Zucali, M., Robyr, M., & Engi, M. (2014). The tectono-metamorphic evolution of the Sesia-Dent Blanche nappes (internal Western Alps): Review and synthesis. *Swiss Journal of Geosciences*, 107(2), 309–336. <https://doi.org/10.1007/s00015-014-0172-x>
- Marotta, A. M., & Spalla, M. I. (2007). Permian-Triassic high thermal regime in the Alps: Result of late Variscan collapse or continental rifting? Validation by numerical modeling. *Tectonics*. <https://doi.org/10.1029/2006TC002047>
- Mazzucchelli, M., Quick, J. E., Sinigoi, S., Zanetti, A., & Giovanardi, T. (2014). Igneous evolutions across the Ivrea crustal section: The Permian Sesia magmatic system and the Triassic Finero intrusion and mantle. Goldschmidt conference – Florence, 2013 Geological Field Trips, 6 (2.2), 98. <https://doi.org/10.3301/GFT.2014.05>
- Mccarthy, A., Tugend, J., & Mohn, G. (2021). Formation of the Alpine orogen by amagmatic convergence and assembly of previously rifted lithosphere. *Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology*, 17(1), 29–34. <https://doi.org/10.2138/gselements.17.1.29>
- Michetti, A., Giardina, F., Livio, F., Mueller, K., Serva, L., Sileo, G., Vittori, E., Devoti, R., Riguzzi, F., Carcano, C., Rogledi, S., Bonadeo, L., Brunamonte, F., & Fioraso, G. (2012). Active compressional tectonics, Quaternary capable faults, and the seismic landscape of the Po Plain (N Italy). *Annals of Geophysics*, 55(5), 969–1001. <https://doi.org/10.4401/ag-5462>
- Mitra, S., & Miller, J. F. (2013). Strain variation with progressive deformation in basement-involved trishear structures. *Journal of Structural Geology*, 53, 70–79. <https://doi.org/10.1016/j.jsg.2013.05.007>
- Mitterperger, S., Zanchi, A., Zanchetta, S., Fumagalli, M., Gukov, K., & Bistacchi, A. (2021). Fault reactivation and propagation in the northern Adamello pluton: The structure and kinematics of a kilometre-scale seismogenic source. *Tectonophysics*, 806, 228790. <https://doi.org/10.1016/j.tecto.2021.228790>

- Mohn, G., Manatschal, G., Beltrando, M., & Hapert, I. (2014). The role of rift-inherited hyper-extension in Alpine-type orogens. *Terra Nova*, 26(5), 347–353. <https://doi.org/10.1111/ter.12104>
- Mohn, G., Manatschal, G., Masini, E., & Müntener, O. (2011). Rift-related inheritance in orogens: A case study from the Austroalpine nappes in Central Alps (SE-Switzerland and N-Italy). *International Journal of Earth Sciences*, 100(5), 937–961. <https://doi.org/10.1007/s00531-010-0630-2>
- Mohn, G., Manatschal, G., Müntener, O., Beltrando, M., & Masini, E. (2010). Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. *International Journal of Earth Sciences*, 99(1), 75–101. <https://doi.org/10.1007/s00531-010-0566-6>
- Pei, Y., Paton, D. A., & Knipe, R. J. (2014). Defining a 3-dimensional trishear parameter space to understand the temporal evolution of fault propagation folds. *Journal of Structural Geology*, 66, 284–297. <https://doi.org/10.1016/j.jsg.2014.05.018>
- Peron-Pinvidic, G., & Manatschal, G. (2019). Rifted margins: State of the art and future challenges. *Frontiers in Earth Science*, 7, 218.
- Pfiffner, O. A. (2016). Basement-involved thin-skinned and thick-skinned tectonics in the Alps. *Geological Magazine*, 153(5–6), 1085–1109. <https://doi.org/10.1017/S0016756815001090>
- Pfiffner, O. A., Lehner, P., Heitzmann, P., Mueller, S., & Steck, A. (1997). *Deep structure of the Swiss Alps: results of NRP 20* (p. 380). Birkhäuser.
- Pfiffner, O. A., & Heitzmann, P. (1997). Geological interpretation of the seismic profiles of the central traverse (lines C1, C2 and C3-north). *Deep Structure of the Swiss Alps: Results of NRP 20*, 115–122.
- Roda, M., Regorda, A., Spalla, M. I., & Marotta, A. M. (2019). What drives Alpine Tethys opening? Clues from the review of geological data and model predictions. *Geological Journal*, 54(4), 2646–2664. <https://doi.org/10.1002/gj.3316>
- Roeder, D. (1992). Thrusting and wedge growth, southern Alps of Lombardia (Italy). *Tectonophysics*, 207(1–2), 199–243. [https://doi.org/10.1016/0040-1951\(92\)90478-O](https://doi.org/10.1016/0040-1951(92)90478-O)
- Rosenberg, C. L., & Kissling, E. (2013). Three-dimensional insight into Central-Alpine collision: Lower-plate or upper-plate indentation? *Geology*, 41(12), 1219–1222. <https://doi.org/10.1130/G34584.1>
- Rutter, E. H., Brodie, K. H., & Evans, P. J. (1993). Structural geometry, lower crustal magmatic underplating and lithospheric stretching in the Ivrea-Verbano zone, northern Italy. *Journal of Structural Geology*, 15(3–5), 647–662. [https://doi.org/10.1016/0191-8141\(93\)90153-2](https://doi.org/10.1016/0191-8141(93)90153-2)
- Rutter, E., Brodie, K., James, T., & Burlini, L. (2007). Large-scale folding in the upper part of the Ivrea-Verbano zone, NW Italy. *Journal of Structural Geology*, 29(1), 1–17. <https://doi.org/10.1016/j.jsg.2006.08.013>
- Scardia, G., Festa, A., Monegato, G., Pini, R., Rogledi, S., Tremolada, F., & Galadini, F. (2015). Evidence for late Alpine tectonics in the Lake Garda area (northern Italy) and seismogenic implications. *Bulletin*, 127(1–2), 113–130. <https://doi.org/10.1130/B30990.1>
- Scarponi, M., Hetényi, G., Plomerová, J., Solarino, S., Baron, L., & Petri, B. (2021). Joint seismic and gravity data inversion to image intra-crustal structures: The Ivrea Geophysical Body along the Val Sesia profile (Piedmont, Italy). *Frontiers in Earth Science*. <https://doi.org/10.3389/feart.2021.671412>
- Schaltegger, U., & Brack, P. (2007). Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. *International Journal of Earth Sciences*, 96(6), 1131–1151. <https://doi.org/10.1007/s00531-006-0165-8>
- Schmid, R. (1967). Zur Petrographic und Struktur der Zone Ivrea-Verbano zwischen Valle d'ossola und Val Grande (Prov. Novara, Italien). *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 47, 935–1117.
- Schmid, S. M., Aebli, H. R., Heller, F., & Zingg, A. (1989). The role of the Periadriatic Line in the tectonic evolution of the Alps. *Geological Society, London, Special Publications*, 45(1), 153–171. <https://doi.org/10.1144/GSL.SP.1989.045.01.08>
- Schmid, S. M., Kissling, E., Diehl, T., van Hinsbergen, D. J., & Molli, G. (2017). Ivrea mantle wedge, arc of the Western Alps, and kinematic evolution of the Alps-Appennines orogenic system. *Swiss Journal of Geosciences*, 110(2), 581–612. <https://doi.org/10.1007/s00015-016-0237-0>
- Schmid, S. M., Pfiffner, O. A., Froitzheim, N., Schönborn, G., & Kissling, E. (1996). Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. *Tectonics*, 15(5), 1036–1064. <https://doi.org/10.1029/96TC00433>
- Schmid, S. M., Zingg, A., & Handy, M. (1987). The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Zone. *Tectonophysics*, 135(1–3), 47–66. [https://doi.org/10.1016/0040-1951\(87\)90151-X](https://doi.org/10.1016/0040-1951(87)90151-X)
- Schönborn, G. (1992). Alpine tectonics and kinematic models of the central southern Alps: Memorie di Scienze Geologiche di Padova, 44, 229–393
- Schumacher, M. E., et al. (1997). Geological interpretation of the seismic profiles through the Southern Alps (lines S1–S7, and C3-south). In Q. A. Pfiffner (Ed.), *Deep Structure of the Swiss Alps—Results from the National Research Program 20 (NRP 20)* (pp. 101–114). Birkhäuser.
- Schumacher, M. E., Schönborn, G., Bernoulli, D., & Laubscher, H. P. (1997). Rifting and collision in the Southern Alps. *Deep Structure of the Swiss Alps: Results of the National Research Program*, 20, 186–204.
- Siegesmund, S., Layer, P., Dunkl, I., Vollbrecht, A., Steenken, A., Wemmer, K., & Ahrendt, H. (2008). Exhumation and deformation history of the lower crustal section of the Valstrona di Omegna in the Ivrea Zone, southern Alps. *Geological Society, London, Special Publications*, 298(1), 45–68. <https://doi.org/10.1144/SP298.3>
- Sileo, G., Giardina, F., Livio, F., Michetti, A. M., Mueller, K., & Vittori, E. (2007). Remarks on the Quaternary tectonics of the Insubria Region (Lombardia, NW Italy, and Ticino, SE Switzerland). *Bollettino-Società Geologica Italiana*, 126(2), 411.
- Siletto, G. B., Spalla, M. I., Tunesi, A., Lardeaux, J. M., & Colombo, A. (1993). Pre-Alpine structural and metamorphic histories in the Orobic Southern Alps, Italy. In *Pre-Mesozoic geology in the Alps (585–598)*. Springer, Berlin, Heidelberg.
- Sinigo, S., Quick, J. E., Demarchi, G., & Peressini, G. (2010). The Sesia magmatic system. *Journal of the Virtual Explorer*, 36, 1–33. <https://doi.org/10.3809/jvirtex.2009.00218>
- Spada, M., Bianchi, I., Kissling, E., Agostinetti, N. P., & Wiemer, S. (2013). Combining controlled-source seismology and receiver function information to derive 3-D Moho topography for Italy. *Geophysical Journal International*, 194(2), 1050–1068. <https://doi.org/10.1093/gji/ggt148>
- Spalla, M. I., Diella, V., Pigazzini, N., Siletto, G. B., & Gosso, G. (2006). Significato tettonico della transizione Cld-And nelle metapeliti del Basamento Sudalpino (Alta Val Camonica). *Rendiconti Della Società Geologica Italiana*, 2, 182–183.
- Spalla, M. I., Zanon, D., Marotta, A. M., Rebay, G., Roda, M., Zucali, M., & Gosso, G. (2014). The transition from Variscan collision to continental break-up in the Alps: Insights from the comparison between natural data and numerical model predictions. *Geological Society, London, Special Publications*, 405(1), 363–400. <https://doi.org/10.1144/SP405.11>
- Suppe, J., & Medwedeff, D. A. (1990). Geometry and kinematics of fault-propagation folding. *Eclogae Geologicae Helveticae*, 83(3), 409–454.
- Tavani, S., Granado, P., Corradetti, A., Camanni, G., Vignaroli, G., Manatschal, G., Mazzoli, S., Muñoz, J. A., & Parente, M. (2021). Rift inheritance controls the switch from thin-to thick-skinned thrusting and basal décollement re-localization at the subduction-to-collision transition. *GSA Bulletin*, 133(9–10), 2157–2170. <https://doi.org/10.1130/B35800.1>
- Tavani, S., Granado, P., Arbués, P., Corradetti, A., & Muñoz, J. A. (2017). Syn-thrusting, near-surface flexural-slipping and stress deflection along folded sedimentary layers of the Sant Corneli-Bóixols anticline (Pyrenees, Spain). *Solid Earth*, 8(2), 405–419. <https://doi.org/10.5194/se-8-405-2017,2017>
- Tremolada, F., Guasti, E., Scardia, G., Carcano, C., Rogledi, E. N. I., & Sciunnach, D. (2009). Reassessing the biostratigraphy and the paleobathymetry of the Gonfolite Lombarda Group in the Como area (northern Italy). *Rivista Italiana di Paleontologia e Stratigrafia*.
- Turrini, C., Lacombe, O., & Roue, F. (2014). Present-day 3D structural model of the Po Valley basin, Northern Italy. *Marine and Petroleum Geology*, 56, 266–289. <https://doi.org/10.1016/j.marpetgeo.2014.02.006>
- Verwater, V. F., Le Breton, E., Handy, M. R., Picotti, V., Jozi Najafabadi, A., & Haberland, C. (2021). Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (northern Italy). *Solid Earth*, 12(6), 1309–1334. <https://doi.org/10.5194/se-12-1309-2021>
- von Blanckenburg, F., & Davies, J. H. (1995). Slab breakoff: A model for syn-collisional magmatism and tectonics in the Alps. *Tectonics*, 14(1), 120–131. <https://doi.org/10.1029/94TC02051>



- Winterer, E. L., & Bosellini, A. (1981). Subsidence and sedimentation on Jurassic passive continental margin, Southern Alps. *Italy. AAPG Bulletin*, 65(3), 394–421. <https://doi.org/10.1306/2F9197E2-16CE-11D7-8645000102C1865D>
- Wolff, R., Dunkl, I., Kiesselbach, G., Wemmer, K., & Siegesmund, S. (2012). Thermochronological constraints on the multiphase exhumation history of the Ivrea-Verbano Zone of the Southern Alps. *Tectonophysics*, 579, 104–117. <https://doi.org/10.1016/j.tecto.2012.03.019>
- Zanchetta, S., D'Adda, P., Zanchi, A., Barberini, V., & Villa, I. M. (2011). Cretaceous-Eocene compression in the central Southern Alps (N Italy) inferred from  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of pseudotachylytes along regional thrust faults. *Journal of Geodynamics*, 51(4), 245–263. <https://doi.org/10.1016/j.jog.2010.09.004>
- Zanchetta, S., Garzanti, E., Doglioni, C., & Zanchi, A. (2012). The Alps in the Cretaceous: A doubly vergent pre-collisional orogen. *Terra Nova*, 24(5), 351–356. <https://doi.org/10.1111/j.1365-3121.2012.01071.x>
- Zanchetta, S., Malusà, M. G., & Zanchi, A. (2015). Precollisional development and Cenozoic evolution of the Southalpine retrobelt (European Alps). *Lithosphere*, 7(6), 662–681. <https://doi.org/10.1130/L466.1>
- Zanchi, A., Zanchetta, S., Berio, L., Berra, F., & Felletti, F. (2019). Low-angle normal faults record Early Permian extensional tectonics in the Orobic Basin (Southern Alps, N Italy). *Italian Journal of Geosciences*, 138(2), 184–201. <https://doi.org/10.3301/IJG.2018.35>
- Zehnder, A. T., & Allmendinger, R. W. (2000). Velocity field for the trishear model. *Journal of Structural Geology*, 22(8), 1009–1014. [https://doi.org/10.1016/S0191-8141\(00\)00037-7](https://doi.org/10.1016/S0191-8141(00)00037-7)
- Zhao, L., Paul, A., Malusà, M. G., Xu, X., Zheng, T., Solarino, S., & Zhu, R. (2016). Continuity of the Alpine slab unraveled by high-resolution P wave tomography. *Journal of Geophysical Research: Solid Earth*, 121(12), 8720–8737. <https://doi.org/10.1002/2016JB013310>
- Dal Zilio, L., Kissling, E., Gerya, T., & van Dinther, Y. (2020). Slab rollback orogeny model: a test of concept. *Geophysical Research Letters*. <https://doi.org/10.1029/2020GL089917>
- Zingg, A. (1983). The Ivrea and Strona-Ceneri zones (Southern Alps, Ticino and N-Italy) - a review. *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 63(2–3), 361–392.
- Zingg, A., Handy, M. R., Hunziker, J. C., & Schmid, S. M. (1990). Tectonometamorphic history of the Ivrea Zone and its relationship to the crustal evolution of the Southern Alps. *Tectonophysics*, 182(1–2), 169–192. [https://doi.org/10.1016/0040-1951\(90\)90349-D](https://doi.org/10.1016/0040-1951(90)90349-D)

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