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## Tectonics

### RESEARCH ARTICLE

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#### Key Points:

- The Adriatic Jurassic rifted margin preserved in the Alps is related to an upper plate geometry
- The Jurassic Alpine rifting system was characterized by a major rift-flip zone reactivated during the convergence phases of the orogeny

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## Architecture of the Distal Piedmont-Ligurian Rifted Margin in NW Italy: Hints for a Flip of the Rift System Polarity

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**Abstract** The Alpine Tethys rifted margins were generated by a Mesozoic polyphase magma-poor rifting leading to the opening of the Piedmont-Ligurian “Ocean.” This latter developed through different phases of rifting that terminated with the exhumation of subcontinental mantle along an extensional detachment system. At the onset of simple shear detachment faulting, two margin types were generated: an upper and a lower plate corresponding to the hanging wall and footwall of the final detachment system, respectively. The two margin architectures were markedly different and characterized by a specific asymmetry. In this study the detailed analysis of the Adriatic margin, exposed in the Serie dei Laghi, Ivrea-Verbano, and Canavese Zone, enabled to recognize the diagnostic elements of an upper plate rifted margin. This thesis contrasts with the classic interpretation of the Southalpine units, previously compared with the adjacent fossil margin preserved in the Austroalpine nappes and considered as part of a lower plate. The proposed scenario suggests the segmentation and flip of the Alpine rifting system along strike and the passage from a lower to an upper plate. Following this interpretation, the European and Southern Adria margins are coevally developed upper plate margins, respectively resting NE and SW of a major transform zone that accommodates a flip in the polarity of the rift system. This new explanation has important implications for the study of the pre-Alpine rift-related structures, for the comprehension of their role during the reactivation of the margin and for the paleogeographic evolution of the Alpine orogen.

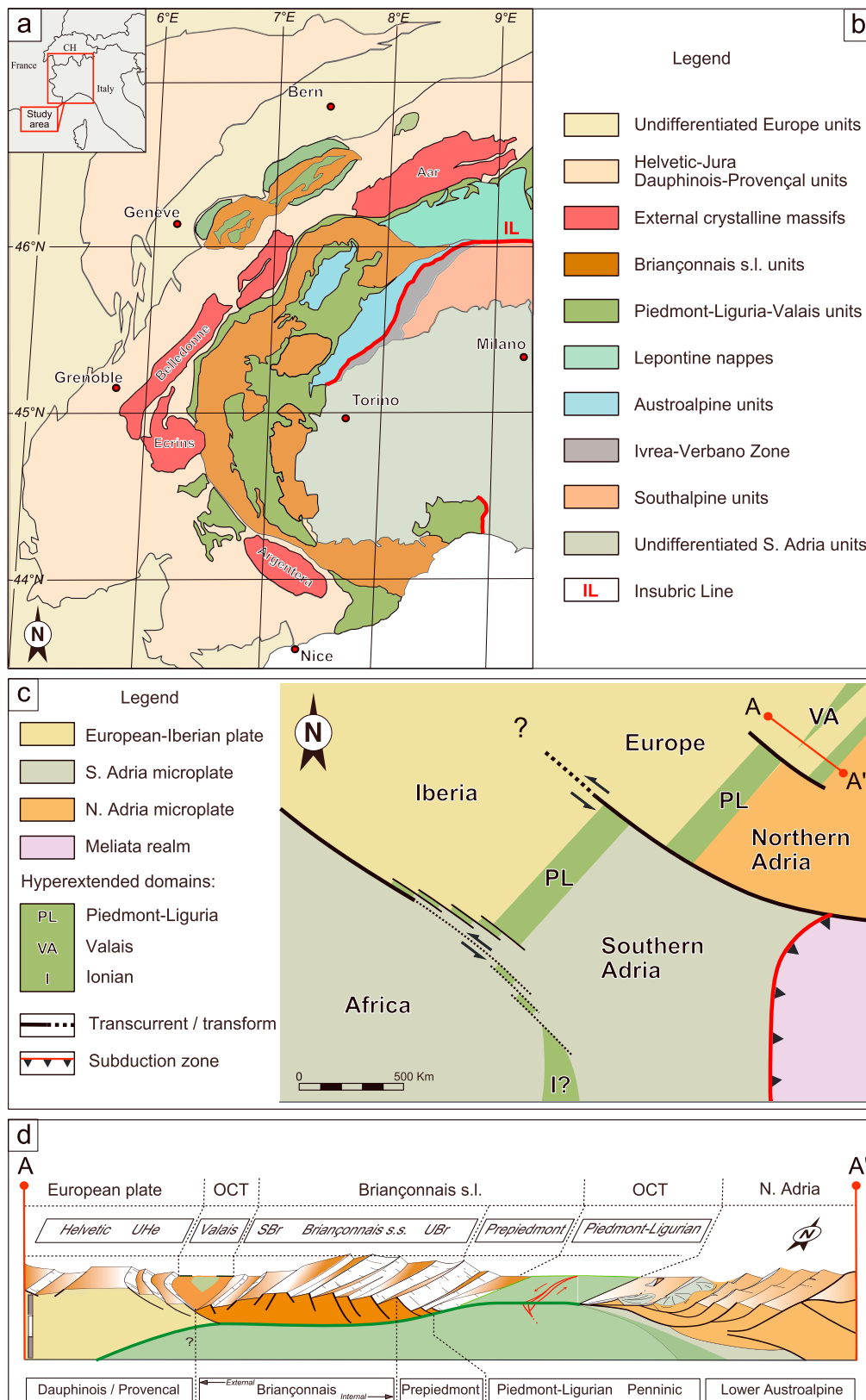
### 1. Introduction

Remnants of the fossil rifted-margins preserved in the Alps show evidence for a Mesozoic polyphase magma-poor rift evolution (e.g., De Graciansky et al., 2011; Gaetani, 2010) that shaped the complex boundary among Africa/Gondwana-derived microplates and Europe (e.g., Handy et al., 2010; Stampfli et al., 2002; Figure 1c). These margins formed as a consequence of hyperextension and exhumation of subcontinental mantle along extensional detachment faults, culminating in the opening of the Piedmont-Ligurian basin (Alpine Tethys Ocean Auct.) during late Middle Jurassic (e.g., Bezzi & Piccardo, 1971; Decandia & Elter, 1969; Froitzheim & Manatschal, 1996; Lemoine et al., 1987; Mohn et al., 2012). The well-preserved Alpine stratigraphic record and its link to extensional rift structures have been widely investigated and compared with seismic images of modern analogues (i.e., Iberia-Newfoundland margins; e.g., Manatschal & Bernoulli, 1999). In the past few years a conceptual framework for magma-poor margins, which includes a specific nomenclature, has been developed (Hauptert et al., 2016; Sutra et al., 2013; Tugend et al., 2014). It accounts for field- and seismic-scale observations made in the Alpine-Pyrenean fossil margins and in the present day Atlantic and east India magma-poor rifted margins. In this study, after a short review on the Alpine Tethys margins, we apply these new concepts and terminology to the Southern Adria sector exposed in NW Italy. The main goal is to investigate the Jurassic syn-rift sedimentary record and the crustal structures preserved in the Southalpine units to identify the rifting geometry in terms of upper and lower plate (for definitions, see Hauptert et al., 2016). Results will be used to decipher the general rift architecture and segmentation in the Alpine Tethys system and to discuss the related plate kinematic implications.

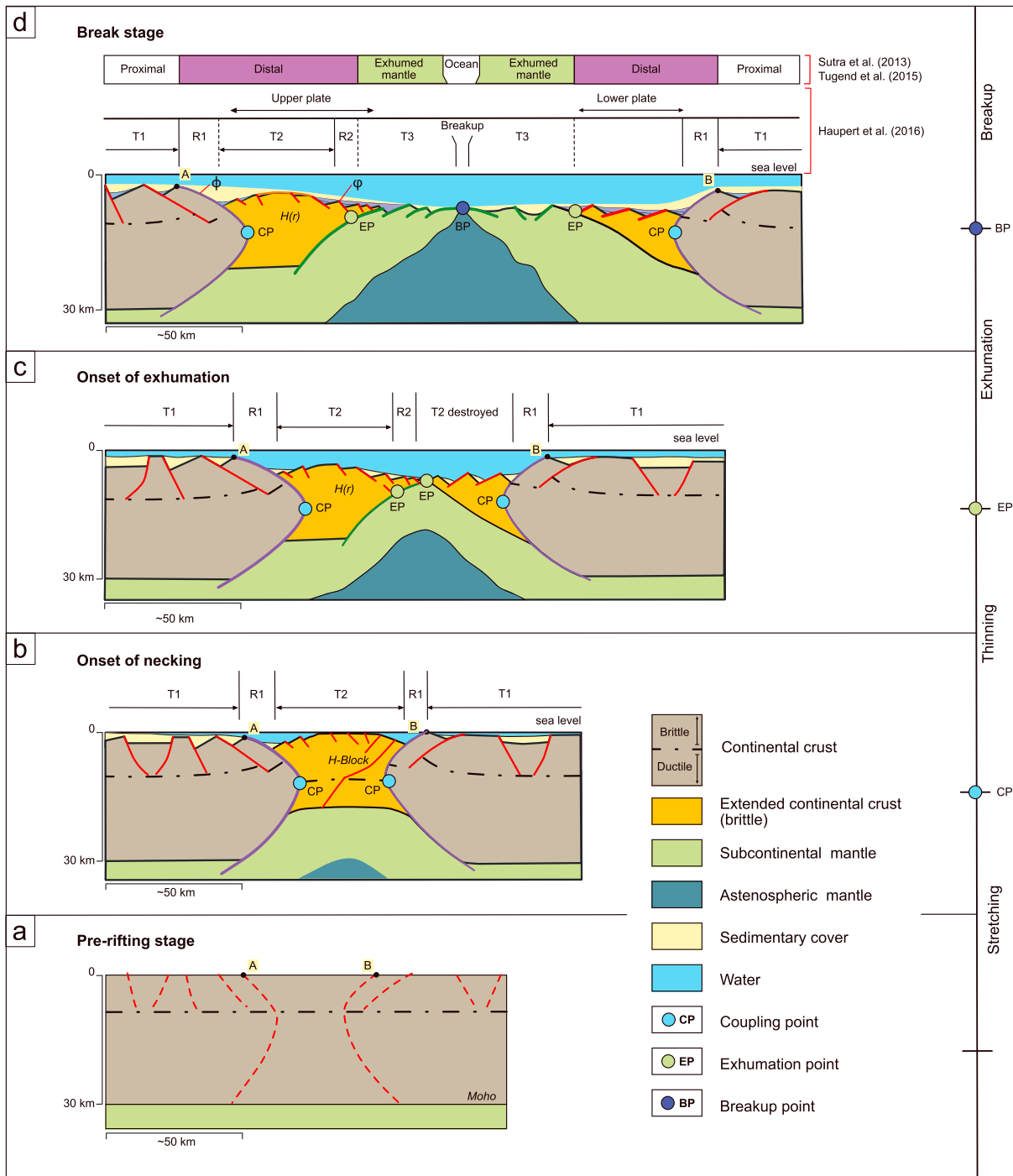
### 2. Review on the Alpine Tethys Rifted Margins

#### 2.1. Geological Setting

Remnants of the distal Jurassic rifted margins were stacked during Late Cretaceous to Eocene time, forming the present day internal parts of the Central Alps (e.g., De Graciansky et al., 2011; Pfiffner, 2014).



**Figure 1.** (a) Location and (b) structural map of the Western-Central Alps (from Schmid et al., 2004, mod.). Yellow frame indicates the study area. (c) Simplified paleogeographic setting of the Alpine domain during Late Jurassic, showing the main plates involved in the Ligurian-Piedmont rifting. (d) Cross section across the Alpine Tethys illustrating the main Alpine paleogeographic structural domains and rifting domains; OCT: ocean-continent transition zone (from Decarlis et al., 2015).



**Figure 2.** Conceptual kinematic model for magma-poor rifted margin evolution in time (from Hauptert et al., 2016) from (a) pre-rift to (d) breakup stage. Details of the evolutionary stages and nomenclature description in the text. Note the formation of the “H-block” (Lavie & Manatschal, 2006) and its uplift at the beginning of thinning phase (b) before being drowned after the onset of the main detachment fault. (c) Then it lies dissected (“residual H-block”:  $H(r)$ ) at one side of the system as a major indicator for upper plate geometry (see also Figure 3);  $\Phi$ : necking faults;  $\phi$ : R2 fault;  $\Psi$ : main detachment fault; A, B: reference points for extension rate. Vertical exaggeration: 1.6.

Margin-derived units rest on either side of the major ophiolite belt (Piedmont-Ligurian units, Figure 1b; e.g., De Graciansky et al., 2011; Pfiffner, 2014; Schmid et al., 2004). The northwestern rifted margin, formerly belonging to the European plate, is preserved in the Helvetic-Dauphinois-Provençal units (proximal margin; Figure 1) and in the Briançonnais and Prepiedmont units (distal margin; Figure 1). Its southeastern counterpart is preserved in the Austroalpine and Southalpine units. Remnants preserved in the Austroalpine units are considered to be derived from the northern segment of the Adria microplate (Handy et al., 2010, cum ref.). This margin has been interpreted as a conjugate of the European one and is at present separated from the southern segment of Adria, which remnants constitute the Southalpine units, by a major fault zone dividing the south-vergent and almost non-metamorphic part of the chain to the south from a more complex domain to the north (e.g., Schmid et al., 1989; Figure 1b). The Southalpine units, object of the present study, belong to the Southern Adria microplate and preserve remnants for both the proximal and distal parts of the former rifted margin (e.g., Bernoulli, 1964; Berra et al., 2009; Elter et al., 1966; Kalin & Trümpy, 1977; Sturani, 1973).

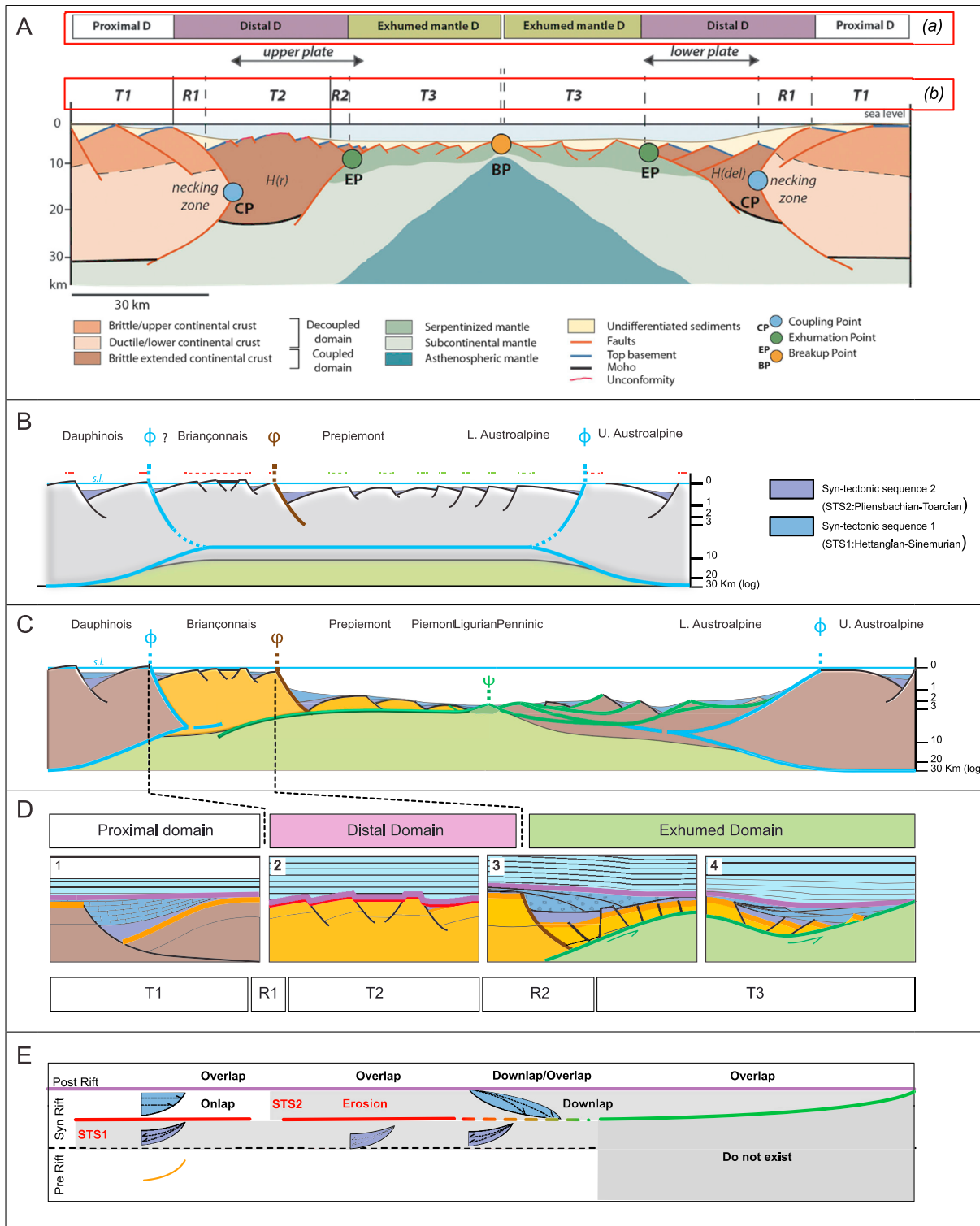
## 2.2. The Concept of Hyperextended Margins Applied to the Alps

The Jurassic Alpine Tethys rifted margins were shaped by two discrete extensional phases (Berra et al., 2009; Decarlis et al., 2015; Froitzheim & Manatschal, 1996) that lead to a localization of the deformation from the proximal margin (first phase: Hettangian-Sinemurian) toward the distal margin (second phase: Pliensbachian to Callovian/Bajocian). During this second phase, the crust was severely thinned, and the subcontinental mantle was exhumed at the seafloor. The geological record of rifting in the Alpine domain has been compared to the evolution of the seismically imaged and drilled Iberia-Newfoundland margins that are considered as the archetypes of upper and lower plate magma-poor rifted margins (e.g., Hauptert et al., 2016; Manatschal, 2004; Manatschal & Bernoulli, 1999). These comparative studies led to the introduction of a conceptual model that may explain the evolution of magma-poor rifted margins (Lavie & Manatschal, 2006). The model considers three phases of extension: an initial “stretching phase” (Figures 2a and 2b) that is mainly accommodated in the upper crust by the formation of wide, distributed half-graben systems; a “thinning phase” (Figures 2b and 2c), leading to the formation of a hyperextended crustal sector (Figure 3A) bounded by necking zones (see Mohn et al., 2012) that separate the future distal margin from the tectonically inactive proximal margin (definitions in Sutra et al., 2013; Tugend et al., 2014); and an “exhumation phase” related to the exhumation of subcontinental mantle rocks at the seafloor (Figures 2c and 2d).

For the present study it is important to note that after major crustal thinning, when the residual crust does not contain anymore ductile levels, the rift system becomes asymmetric. Major in-sequence detachment faults split the crust into an upper plate (the hanging wall of the detachment) and a lower plate, formed by the exhumed footwall of the detachment system (Figure 2c). At this stage, the keystone formed during necking (“H-block” in Lavie & Manatschal, 2006) is laterally delaminated, leading to the formation of extensional allochthons lying on the lower plate. The residual, not delaminated part of the H-block forms the residual H-block ( $H_{(r)}$ ; Figure 2c) that is the diagnostic feature of an upper plate rifted margin.

In the example of the Alpine Tethys margins, the initial stretching phase took place during Hettangian/Sinemurian times (Berra et al., 2009; Decarlis et al., 2015; Froitzheim & Manatschal, 1996), the necking occurred during Pliensbachian/Toarcian (Decarlis et al., 2015; Mohn et al., 2012), and this was followed by mantle exhumation and onset of emplacement of Mid Ocean Ridge basalts during Callovian/Bathonian time (e.g., De Graciansky et al., 2011, cum ref.). Decarlis et al. (2015, and references therein) proposed that the Briançonnais units (distal European margin) form an upper plate margin and the Lower Austroalpine units (distal Northern Adria margin) the lower plate margin (Figures 1c and 1d). This interpretation was based on both the analysis of the tectono-stratigraphic record and the recognition of primary rift structures that escaped most of the orogenic overprint in the distal margin (cf. Decarlis et al., 2015; Hauptert et al., 2016; Masini et al., 2013; Mohn et al., 2012). The split and left-lateral shift of the two margins has been attributed to the late transpressive evolution of the chain (Decarlis et al., 2015).

The fossil rifted margin preserved in the Southern Alps has been analyzed in detail by several authors and has been interpreted as a proximal margin (e.g., Bertotti et al., 1993; Masini et al., 2013), with the exception (Elter et al., 1966; Sturani, 1973) of the westernmost area (Cusio-Biellese zone) that rested in the distal domain (see Beltrando, Stockli, et al., 2015; Berra et al., 2009). Ferrando et al. (2004) analyzed the Canavese Zone and proposed a close similarity with the Lower Austroalpine units exposed in Grisons (SE Switzerland). These authors



**Figure 3.** (A, B) Interpretative sections across the Alpine conjugate margins of Europe and Northern Adria during syn-tectonic sequence 1 and sequence 2 deposition (STS<sub>1</sub> and STS<sub>2</sub>; Decarlis et al., 2015). (C) Toarcian; logarithmic vertical scale; from Decarlis et al. (2015). (D) Conceptual basin-types developing along an idealized rifted margins section (from Decarlis et al., 2015): 1, half-graben basin of the proximal margin with STS<sub>2</sub> progressively sealing the topography; 2, uplifted sector of the distal margin almost completely lacking the whole syn-tectonic succession; 3, drowned sector of the distal margin characterized by the thick clastic STS<sub>2</sub>; 4, supra-detachment basin, characterized by the occurrence of exhumed basement/mantle and continental derived clast. Note the allochthonous block on the right (see text). (E) Key features of the STS<sub>1</sub> and STS<sub>2</sub> sedimentation along rifted margin section.

proposed that the distal Southern Adria margin (i.e., the Canavese Zone) formed as a lower plate margin, too (cf. Figure 1d).

### 3. Polarity of Final Rifting: Geometry and Terminology

Hauptert et al. (2016) introduced, based on previous studies of Sutra et al. (2013) and Tugend et al. (2014), a specific nomenclature for upper plate magma-poor rifted margins (Figures 2 and 3A). This nomenclature is of particular relevance for the aim of this paper as it introduces simple morpho-tectonic elements (terraces and ramps) that can be used on seismic sections to recognize the polarity of a rift/detachment system and, therefore, to define upper and lower plate margins. Hauptert et al. (2016) introduced “terraces” (T1, T2, and T3; Figure 2) as characteristic features of upper plate margins and discussed them using both fossil (e.g., European-Briançonnais margins of the Alpine Tethys) and present day examples (East India and Newfoundland margins). Terraces are separated by “ramps” (R1 and R2) that correspond to major fault systems formed during the thinning and exhumation phases.

In detail, **T1** corresponds to the proximal margin, resting on non-extended or slightly stretched continental crust ( $30 \pm 5$  km thick; Figure 3A). Wide, fault-bounded, half-graben basins hosting thick syn-tectonic successions (cf. STS1: syn-tectonic sequence of Decarlis et al., 2015; Figure 3B; type 1 basins in Figure 3D) are the key features of this domain. The bounding faults of these basins typically sole out into a *decollement* level in the middle crust (see Bertotti et al., 1991, 1993). Since T1 became inactive when deformation focused in the future distal margin, post-tectonic sediments draped the half-grabens. Thus, the syn-tectonic sequence in the T1 domain predates, by definition, the necking stage and overlies pre-rift successions or upper crust basement only (rift-related exhumation faults do not occur in the T1 domain).

The T1 domain is limited oceanward by a crustal-scale fault system that developed during the thinning phase, forming a morphologic ramp (referred to as R1 by Hauptert et al., 2016). This zone corresponds to the “necking zone” (see  $\phi$  faults in Figures 3B and 3C; Mohn et al., 2012). Sedimentary rocks accumulated during the early development of R1 may account for relatively shallow depositional environments, but they may also be characterized by peculiar features. In fact, differently from half-graben master faults in the T1 domain, the necking fault system forms simultaneously with conjugate fault systems in the lower crust (“coupled domain”: see Sutra et al., 2013). As a consequence, these faults may allow the advection of deep-seated fluids, and they are linked to thermal anomalies and to rapid exhumation of midcrustal rocks (e.g., heating–cooling cycles; Beltrando, Stockli, et al., 2015). In a rift system, R1 marks the boundary between the proximal and the distal margins.

The most peculiar feature of upper plate margins is the occurrence of a residual “H-block” (e.g., Lavier & Manatschal, 2006) that is up to 50–80 km wide (Chenin et al., 2017) and 15–20 km thick. The top of this block is referred to as T2 (Hauptert et al., 2016). In the T2 terrace, the pre-rift section is only affected by minor brittle high-angle normal faults, and the basement is made of upper crust. The syn-rift succession is reduced due to the syn-rift uplift that may generate emersion (see Figure 3D, type 2 basins).

Oceanward, the T2 is limited by a big morphologic ramp (R2), formed by a major normal fault system ( $\phi$  fault in Figure 3) accommodating the bathymetric transition to the T3 domain. Along the R2 escarpment, upper crustal rocks (and potentially also remnants of midcrustal rocks) are exposed. Faulting produces a diffused source for detritic sediments that are collected in new fault-bounded, open-flank basins (Figure 3C; types 3 and 4 basins in Figure 3D) and constitute the typical sedimentary product associated to the thinning phase (syn-tectonic sequence 2: STS2; Decarlis et al., 2015). Along R2, the continental crust is split in several tilted blocks, progressively reducing in thickness while approaching the exhumation area (Figure 3C). The T3 consists of blocks of pre- and early syn-rift that overlie exhumed lower crust or mantle rocks (see Decarlis et al., 2015; Masini et al., 2011).

Hauptert et al. (2016) proposed that the remnants of the European Tethys margin exposed in the Western Alps record key structures of an upper plate system. In this example, the T1 corresponds to the Dauphinois units exposed today in the external parts of the Western Alps (Figure 1d). The rift structures in this domain formed during the stretching phase (Hettangian–Sinemurian). The T2 is best preserved in the Briançonnais units (Figure 1d), which experienced a pronounced uplift during the thinning phase of the Alpine rifting (Pliensbachian–Toarcian) leading to a deep erosion of the substratum that generated

a characteristic stratigraphic gap. T3 corresponds to the Prepedmont and Piedmont units (Figure 1d), characterized by a complete stratigraphic succession and by a clastic infill during the thinning phase (see STS2 in Decarlis et al., 2015). It is important to note that in the Austroalpine units of Grisons, considered to be the conjugate margin of the abovementioned upper plate section (Decarlis et al., 2015), the T2 domain does not exist and the T3 is directly passing to the proximal margin (T1: Middle and Upper Austroalpine units; Figure 1d).

#### 4. Southern Adriatic Margin

Most of the successions of the Southalpine units contain evidence for a thick stratigraphic record (Figure 4) deposited on basins formed on top of  $30 \pm 5$  km thick continental crust (Bertotti et al., 1991, 1993; Turrini et al., 2014). During Early Jurassic, half-graben structures developed (e.g., Generoso basin: Bernoulli, 1964) and hosted thick syn-tectonic carbonate sequences (Moltrasio and Domaro lms, Medolo group: Hettangian/Sinemurian; Berra et al., 2009) followed by a suite of pelagic carbonate rocks (Rosso Ammonitico, Concesio Fm: Pliensbachian/Toarcian; Berra et al., 2009) that draped the topography and marked the passage to a local tectonic quiescence. This area can be therefore interpreted as a typical proximal margin (see Masini et al., 2013).

Portions of the distal Southern Adriatic margin crop out in the westernmost sector of the Southalpine units (e.g., Beltrando, Stockli, et al., 2015) in two different sectors that are here separately described: the Serie dei Laghi–Ivrea–Verbano Zone and the Canavese Zone (Figure 4).

##### 4.1. Serie dei Laghi–Ivrea–Verbano Zone: Basement

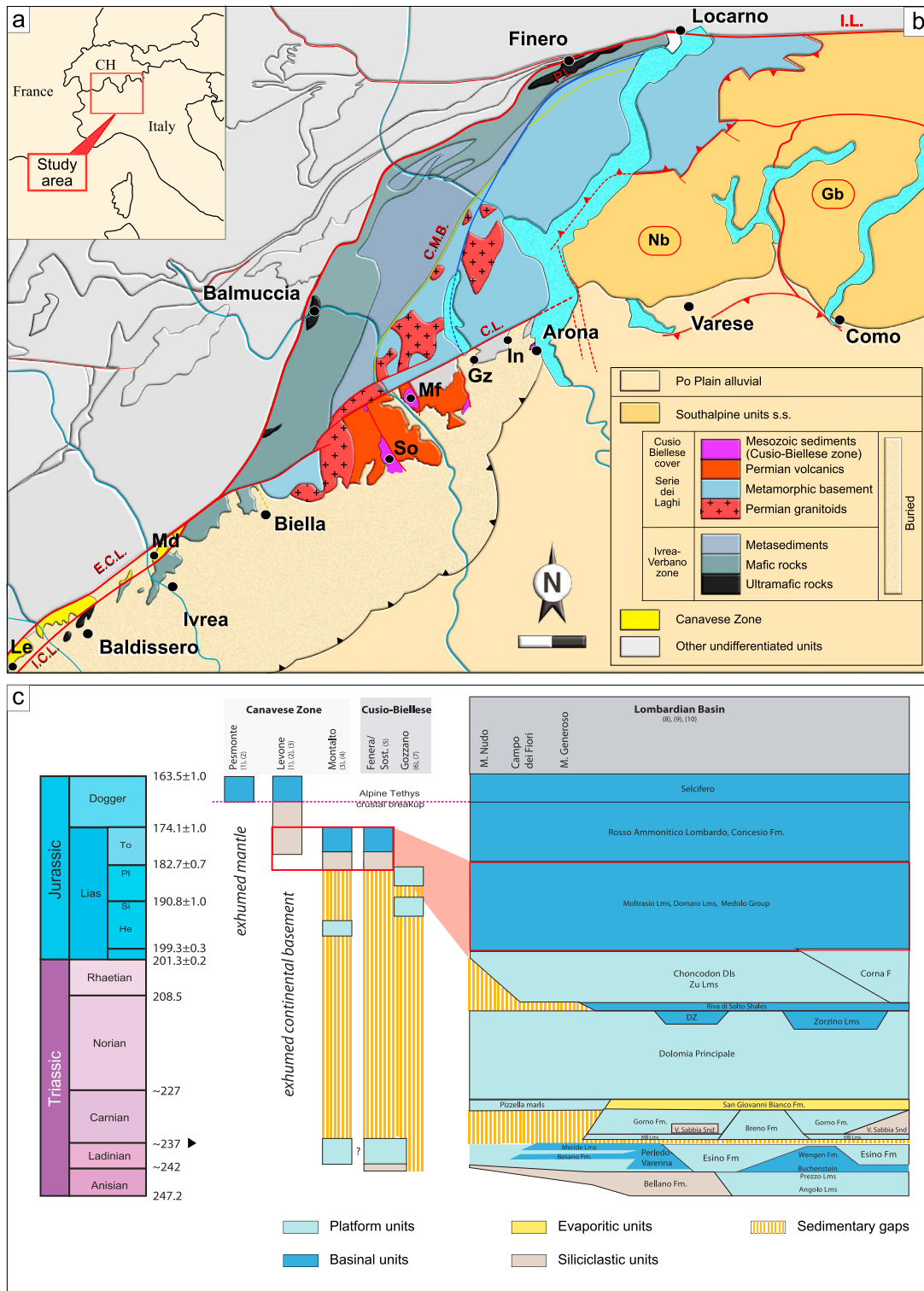
The Southalpine basement in northwestern Italy is mostly made up of igneous and metamorphic rocks cropping out west of the Southalpine thrusts (Figure 4; Pfiffner, 2016).

Upper crustal rocks (Serie dei Laghi; Boriani & Giobbi, 2004) and middle-to-lower crustal rocks (Ivrea–Verbano zone; e.g., Siegesmund et al., 2008, cum ref.) are exposed at present at the surface as a result of an extensive regional tilting that affected the area during the Alpine orogenic cycle (Schmid et al., 1987).

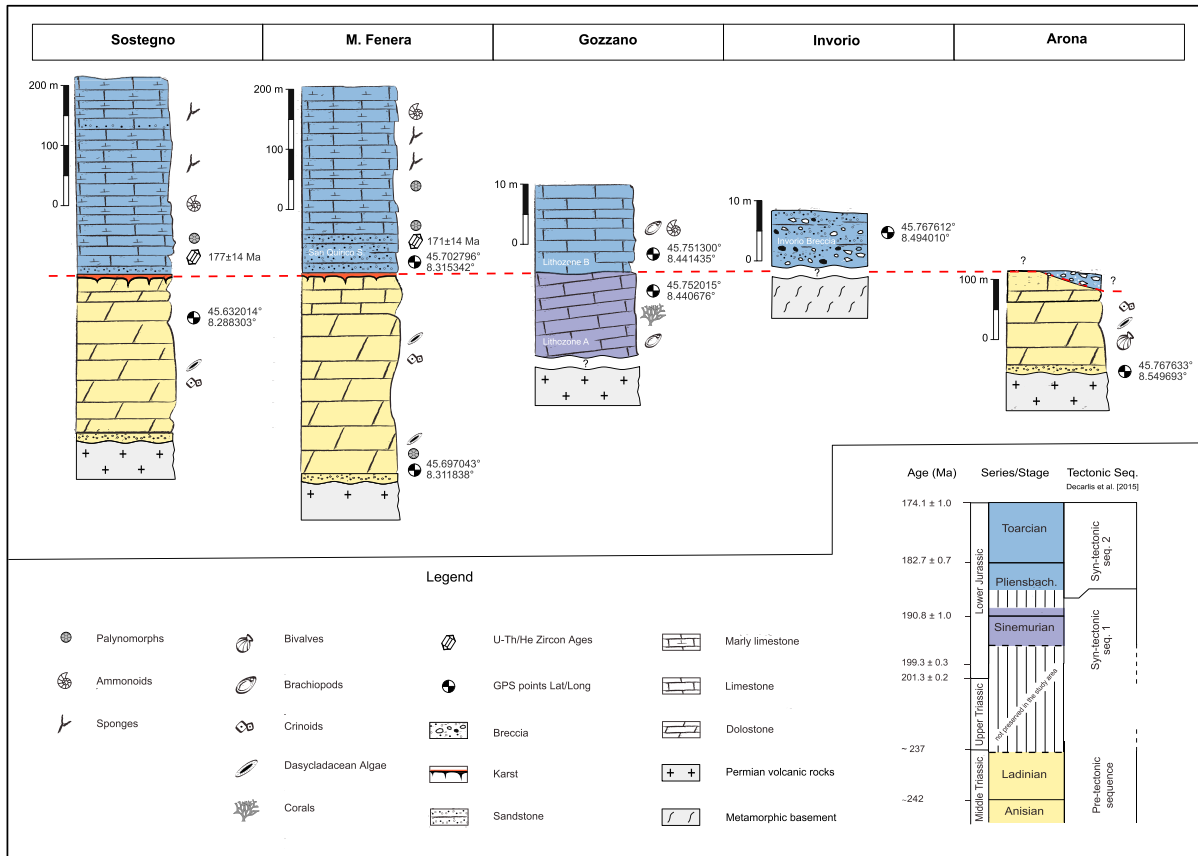
The basement of the Serie dei Laghi is composed of a complex association of Paleozoic meta-arenites, amphibolites with relicts of gabbros, ultramafites and paragneisses, meta-pelites, and ortogneisses (Boriani & Giobbi, 2004). These rocks were intruded by voluminous granitoid bodies during Early Permian (Boriani et al., 1988) and represent a portion of the upper crust since Paleozoic times.

The Ivrea–Verbano Zone is a pre-Jurassic middle/lower crustal unit that is composed of high-temperature amphibolite to granulite facies rocks. It includes kinzigites that represent former metasedimentary to meta-volcanic successions (Novarese, 1929), partly intruded by a Permian large mafic complex (Pfiffner, 2014; Rivalenti et al., 1981; Voshage et al., 1990, and references therein). West of the mafic complex, isolated bodies of subcontinental mantle rocks occur (Figure 4: Balmuccia, Finero, Baldissero; Garutti et al., 1979; Hartmann & Wedepohl, 1993; Rivalenti et al., 1981; Shervais, 1979; Voshage et al., 1988). Lowermost levels of the Ivrea–Verbano Zone are separated from the Sesia–Lanzo Zone by the fault system of the Insubric Line that reached anchizone to low-greenschist facies conditions. Important structures, relevant for the interpretation of the Jurassic Adriatic margin, occur near the stratigraphic top of the Ivrea–Verbano Zone. The Cossato–Mergozzo–Brissago Line is a NE–SW striking fault zone that marks the contact between the Serie dei Laghi and the Ivrea–Verbano Zone (CMB: Figure 2; Handy, 1987). It consists of high-temperature mylonites associated with migmatites and dykes related to Early Permian extension (Ar/Ar age  $271 \pm 1$  Ma; Boriani & Villa, 1997; and Ru/Sr  $275 \pm 8$  Ma; Pinarelli et al., 1988). The Cossato–Mergozzo–Brissago Line is overprinted by a younger fault system, the Pogallo Line (PL: Figure 2; Handy, 1987). The latter is a ductile shear zone, characterized by subvertical foliation with SW–NE strike and NE plunging stretching lineations with a left-lateral sense of shear. It consists of mylonites developed under amphibolite to greenschist facies conditions, striking NE–SW in the northern branch and roughly N–S toward the south (Figure 4). The age of the Pogallo Line has been constrained to 200–180 Ma by Zingg et al. (1990). The late stage of faulting occurred under lower greenschist conditions and close to the brittle–ductile transition and has been related to Early Jurassic (Zingg, 1990, cum ref.). It has been interpreted as an east dipping, midcrustal extensional listric fault that accommodated extension during Jurassic rifting (Handy et al., 1999).





**Figure 4.** (a, b) Location and simplified geological structural map of the study area (from Schumacher, 1997, modified; Siegesmund et al., 2008). Key location cited in the text: In: Inverio; Gz: Gozzano; Mf: Monte Fenera; So: Sostegno; Md: Montalto Dora; Le: Levone. Main structural lines: I.L.: Insubric Line s.l.; C.M.B.: Cossato-Mergozzo-Brissago Line; P.L.: Pogallo Line; C.L.: Cremosina Line; E.C.L.: External Canavese Line; I.C.L.: Internal Canavese Line. Additional elements of the Southalpine domain: Nb: Monte Nudo basin; Gb: Monte Generoso basin. (c) Stratigraphic scheme of the sedimentary cover of the Southern Alps (from Beltrando, Stockli, et al., 2015). Red boxes indicate the two main Jurassic phases of the Alpine rifting respectively acting in the proximal (Lombardian basin) and distal margin (Cusio-Biellese-Canavese). References for the stratigraphy of the different sectors: (1) Elter et al. (1966), (2) Beltrando, Stockli, et al. (2015), (3) Ferrando et al. (2004), (4) Sturani (1964), (5) Berra et al. (2009), (6) Casati (1978), (7) Montanari (1969), (8) Bertotti et al. (1993), (9) Berra et al. (2009), and (10) Berra and Carminati (2010).

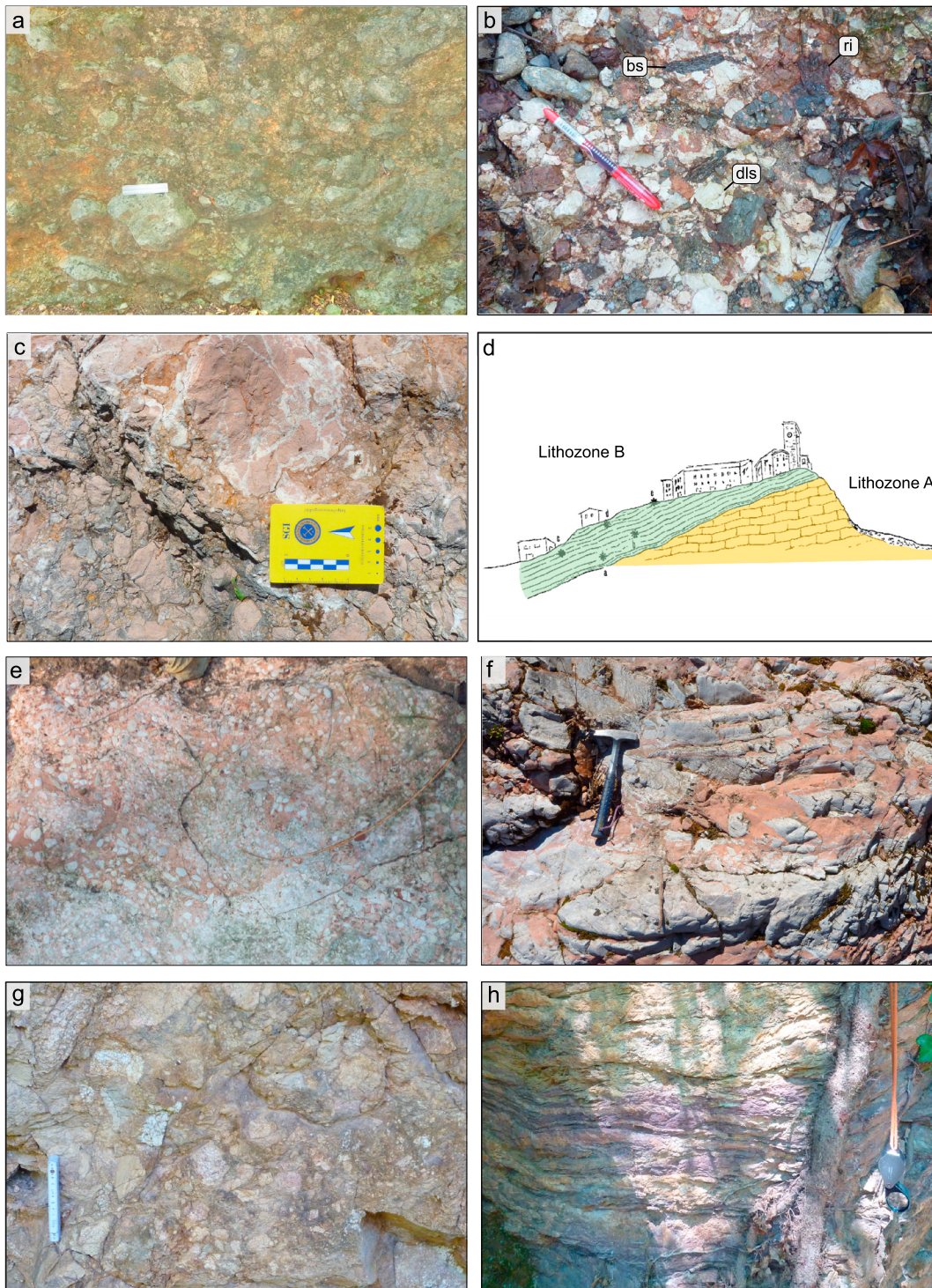


**Figure 5.** Stratigraphic sections of the main western Southalpine outcrops west of Lago Maggiore, drawn on the base of the cited literature and of personal field observations. For locations see Figure 4. See text for detailed description. Relevant GPS points are indicated in lat/long decimal degrees. Please note the different scales.

#### 4.2. Serie dei Laghi: Sedimentary Cover

Toward the south, the Serie dei Laghi is crossed by an E-W fault system with a right lateral and a vertical component (Cremonina Line: CL: Figure 4; Boriani & Sacchi, 1973). As a result of this latter structure, the sedimentary cover of the Serie dei Laghi is only preserved south of the Cremonina Line. Scarce remnants of Mesozoic sedimentary rocks actually crop out in between Lago Maggiore and Sostegno (Figure 4), but most of them are buried further to the south under the Po plain alluvials and are only imaged by seismic profiles (Fantoni et al., 2003; Pfiffner, 2014, 2016). The Mesozoic sedimentary record of the western Southalpine is extremely lacunous if compared to the successions of the Lombardian basin. This marked difference has been described in the literature (Beltrando, Stockli, et al., 2015; Berra et al., 2009; Fantoni et al., 2003). The syn-rift sequence is visible only at selected locations. A brief description of the key stratigraphic features of the most relevant outcrops based on personal observations and on the cited literature is described below (Figure 5).

1. **Arona** (Figures 5 and 6a): A thin succession of Early to Middle Triassic sandstones overlies Permian volcanic rocks. Sandstones are overlain by Middle Triassic Dolostones (San Salvatore Dolostones; Zanin, 1965). A widespread monogenic breccia body can be observed draping the dolostones at the top and laterally. It is almost exclusively composed of angular clasts of Triassic dolostones, but some rare fragments of reddish pelites with small rounded dolomite clasts can be found. Reddish pelite clasts were probably eroded from paleokarsts similar to those found in the Fenera-Sostegno area (Figure 6e) and that are considered Jurassic (Berra et al., 2009; Fantoni et al., 2003). In our interpretation, the Arona breccia was generated by a rock-fall depositional process during Early Jurassic rifting, testifying the dismantling of the Triassic sediments in a subaerial environment.



**Figure 6.** (a) Monogenic breccia with centimeter to decimeter clasts of Triassic dolostones and sparse fragments of reddish pelite (paleosol?); Arona. (b) Polygenic breccia with dolostone (dls), basement (bs), and riolite (ri) clasts; Inorio. (c) Reddish calcarenite of Lithozone A, with widespread evidences for diffused fluid circulation; Gozzano. (d) Interpretative sketch from Montanari (1969) of the angular unconformity between U. Sinemurian–L. Pliensbachian (Lithozone A) and U. Pliensbachian (Lithozone B) deposits; Gozzano. (e) Micro-conglomerate with dolomitic clasts at the top of the Triassic dolostones at Monte Fenera, interpreted as a reworked Jurassic paleosol deposited in a shallow water basin. (f) Sedimentary dikes with reddish pelites infill and dolomitic breccia inside the Ladinian dolostones at Sostegno. Breccia derives from the karstification of the top of the Ladinian platform. White clasts ranging from subcentimeter to decimeter in size are formed by dolostone. (g) Tectono-stratigraphic breccia found at Bric Filia (Canavese Zone) locally directly overlying the lower crust migmatites (not in photo). Clasts and matrix are formed by differently sized debris of lower crust substratum. Only at the top sparse dolomitic clasts occur. (h) Middle Jurassic siliceous schists associated to the radiolarite formation near Bric Filia (Canavese Zone).

2. *Invorio* (Figures 5 and 6b): In this location clast-supported polygenic breccia (“Invorio Breccia”; Casati, 1978) was likely directly deposited on the Serie dei Laghi basement. Breccias correspond to local accumulations with poor evidence for bedding or relevant sedimentary structures. It is composed of centimetric to decimetric clasts of Serie dei Laghi basement, Permian volcanic fragments, and Triassic dolostones. The limited extension of the outcrops and the lack of sharp upper and lower stratigraphic boundaries do not allow to properly correlate the Invorio breccias, nevertheless it has been interpreted as a continental deposit of Jurassic age (Casati, 1978).
3. *Gozzano* (Figures 5, 6c, and 6d): At this locality, a few tens of meters of a Jurassic succession probably laying on the Permian volcanic rocks can be observed (Montanari, 1969). However, this boundary is not visible at present. The Jurassic succession is formed by calcarenites, microbreccias, and calcilitites with brachiopods, corals, and crinoids (here informally named Lithozone “A”) overlain by nodular limestones and calcarenites with ammonoids and molluscs (Lithozone “B”). The whole succession was affected by important fluid activity that led to the formation of widespread calcite–dolomite veins. Lithozone “A” has been ascribed to the Upper Sinemurian–Lower Pliensbachian (?), Lithozone “B” to the Upper Pliensbachian on the base of a rich fossil fauna (Montanari, 1969; Sacchi Vialli & Cantaluppi, 1967). Montanari (1969) reported that Upper Pliensbachian sedimentary rocks were filled with neptunian dikes that opened inside the lithozone “A” and described an angular unconformity between the two lithozone suggesting that a tectonic pulse occurred during Late Early Jurassic. The Jurassic succession at Gozzano has been interpreted as deposited on top of a submarine high (Berra et al., 2009).
4. *Monte Fenera and Sostegno* (Figure 5): At these localities, more complete Mesozoic successions are preserved. Permian volcanic rocks are overlain by a thin succession of sandstones and conglomerates that predate the deposition of Middle Triassic dolostones (see Berra et al., 2009; Fantoni et al., 2003). The top of Ladinian carbonate rocks is characterized by a widespread unconformity, locally accompanied by karstified levels and followed by a thin succession of dolomitic breccias, conglomerates, and microconglomerates with oxidized reddish matrix both at Fenera and Sostegno (Figure 6e). Sedimentary dykes filled of the same reddish material and of dolomitic breccias can be frequently found (Figure 6f). The unconformity has been interpreted as a complex surface, probably related to a prolonged erosion and karstification event leading to the deposition of reworked paleosoils and breccias (Berra et al., 2009; Fantoni et al., 2003).

A 50 m-thick succession of lithic sandstones (San Quirico Sandstone) composed of dolomitic, volcanic, and basement-derived grains (Berra et al., 2009; Fantoni et al., 2003) overlays the breccia. The depositional age for these sandstones has been determined by palynomorphs as Pliensbachian–Toarcian (Berra et al., 2009). Interestingly, (U-Th)/He analysis on zircons in volcanic grains of the sandstone gave comparable absolute cooling ages ( $171 \pm 14$  Ma and  $177 \pm 14$  Ma, respectively, for Fenera and Sostegno; Beltrando, Stockli, et al., 2015). These data demonstrate that the process of exhumation, cooling, erosion, and sedimentation was very rapid. San Quirico Sandstone is overlain by some hundreds of meters of spongolitic limestone of Pliensbachian–Toarcian age.

### 4.3. Canavese Zone

The Canavese Zone is a structural unit, about 2 km wide and 40 km long, bounded by two main SW–NE faults: the External Canavese Line (ECL: Figure 4) to the northwest and the Internal Canavese Line (ICL: Figure 4) to the southeast (Biino & Compagnoni, 1989; Biino et al., 1988; Figure 4). The External Canavese Line, or the Canavese Line s.s., is the southwestern branch of the Insubric Line. The Internal Canavese Line is a ductile shear zone producing very low-grade Alpine mylonites separating the Canavese Zone from the granulite-facies rocks of the Ivrea-Verbano Zone (Biino et al., 1988; Biino & Compagnoni, 1989). Upper, middle, and lower crustal rocks are present in the Canavese Zone, although their relationships are often not easy to decipher.

1. The upper crust outcrops near Montalto (Figure 4a) and is composed of a Paleozoic association of paragneiss, phyllites, banded albite–epidote–actinolite metabasics, and augen-gneiss (Baggio, 1965a; Biino et al., 1988; Biino & Compagnoni, 1989). The metamorphic suite is locally intruded by Permian plutonic rocks (Biino et al., 1988; Biino & Compagnoni, 1989) and is overlain by Permian volcanic rocks similar to those found in the Fenera-Sostegno area.

2. Midcrustal rocks outcrop near Baldissero (Figure 4a) and are composed of a heterogeneous assemblage of amphibolite-facies rocks, such as amphibolites, biotite-gneisses  $\pm$  garnet, and muscovite-biotite schist with garnet  $\pm$  fibrolitic sillimanite (Baggio, 1965b; Borghi et al., 1996; Ferrando et al., 2004; Wozniak, 1977).
3. Lower crustal rocks outcrop near Baldissero and Levone (Figure 4a) and are composed of migmatites with transitional contacts to anatectic leucogranite (Baggio, 1965b; Ferrando et al., 2004; Wozniak, 1977). The lower crustal rocks have never been observed to be intruded by the post-Variscan intrusive rocks. On the contrary, they locally include fragments of mafic granulites similar to those of the Ivrea-Verbanò Zone (Ferrando et al., 2004; Wozniak, 1977).

The pre-rift sedimentary succession mainly outcrops near Montalto Dora (Figure 4). It is formed by conglomerates and sandstones (Permian-Early Triassic in age) followed by Triassic dolostones. The age of the carbonate rocks remains uncertain, due to the lack of fossils, but they have been compared in the literature (Baggio, 1965a) to those found at Arona and Fenera-Sostegno and interpreted as Middle Triassic on the basis of the facies and lithologic features. Dolostones are cut by several neptunian dykes and sills filled by a reddish/greenish matrix and by clasts derived from the underlying lithologies (Biino et al., 1988; Biino & Compagnoni, 1989). Dolostones are locally overlain by red calcarenites dated as Early Sinemurian by ammonoid occurrence (Sturani, 1964). Breccias can be observed directly laying on the Triassic carbonates. They are formed by dolostones and reddish Calcarenite clasts in a reddish or greenish matrix similar to the filling of the neptunian dykes.

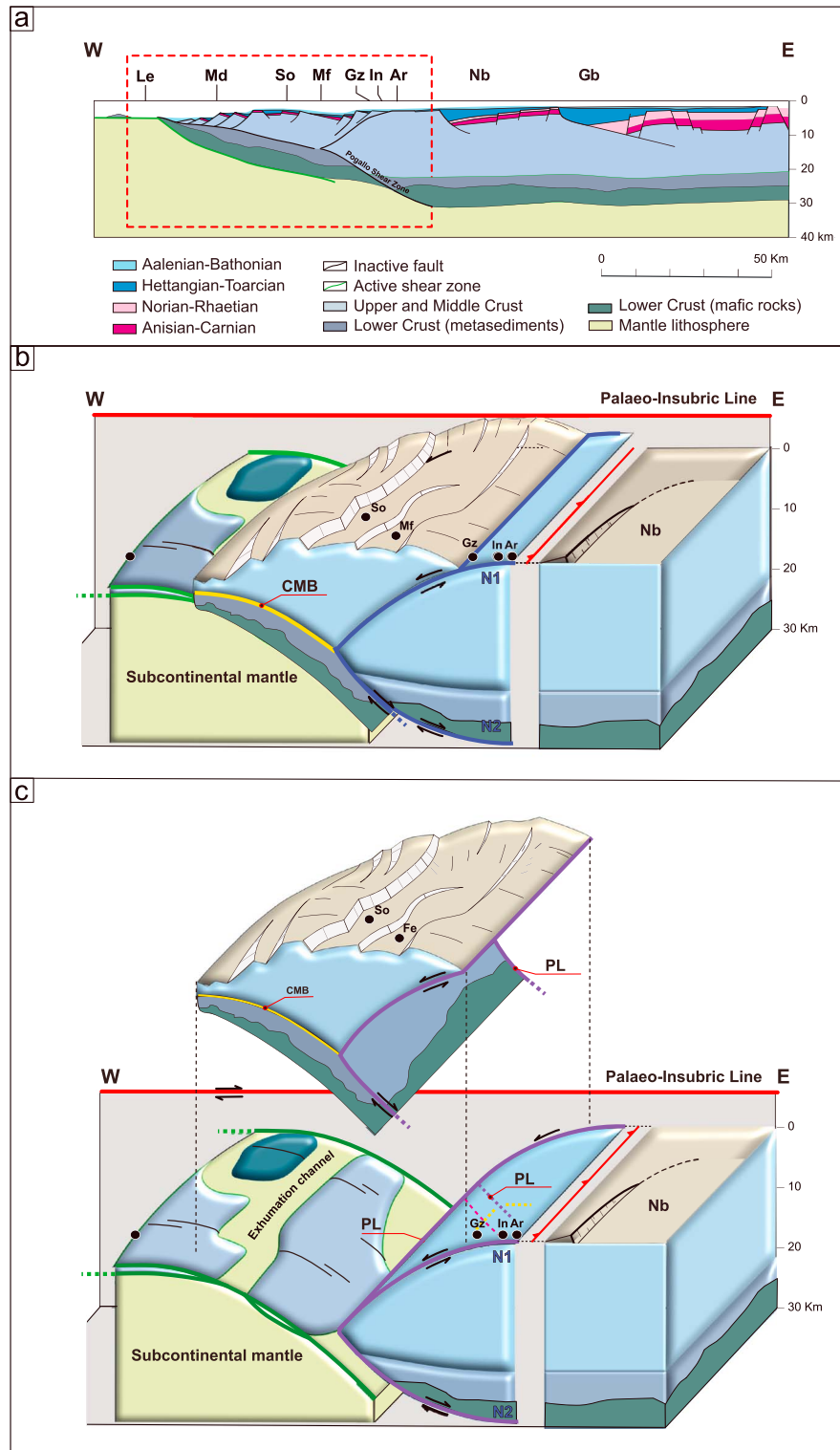
Syn- to post-rift sedimentary rocks have been reported to directly lie on top of the migmatites in the areas near Baldissero e Levone (Figure 4; Ferrando et al., 2004). These successions are characterized by a stratigraphic transition from the cataclastic lower crust to a clast-supported tectono-sedimentary breccia (Manatschal, 1999; Figure 6g) and finally, toward the top, to a polymictic breccia (clasts of both lower and middle crusts, intrusive and volcanic rocks, and phyllonites; Beltrando, Compagnoni, et al., 2015; Ferrando et al., 2004). A Pliensbachian to Bajocian age has been proposed for the breccia/arkosic-pelitic sequence because of the marked similarity with the syn-rift Saluver Formation of the Austroalpine nappes of the Grisons in SE Switzerland (Ferrando et al., 2004). In the Levone area (Figure 4), the tectono-sedimentary breccias are dissected by shear zones associated to a characteristic chromium-rich fault gouge (Beltrando, Compagnoni, et al., 2015). Similar fault rocks have been described in the Lower Austroalpine Err nappe in Grisons along extensional detachment faults (Manatschal, 1999). These fault rocks have been shown to result from the alteration by mantle-derived fluids along exhumation faults that penetrated and exhumed the subcontinental mantle to the Jurassic seafloor. This similarity drove Beltrando, Compagnoni, et al. (2015) to suggest the same interpretation for the Canavese gouges of the Levone sector, where they crop out close to the large serpentized peridotite body of Pesmonte.

Post-rift sedimentary rocks mainly outcrop near Baldissero (Figure 4) and are made of radiolarites (Figure 6h), micritic limestones of the Maiolica formation (Tithonian-Berriasian; Baggio, 1963), and marly limestones considered to be equivalent to the Palombini Shales (Ferrando et al., 2004). These sediments, most likely of Early Cretaceous age, represent the youngest sedimentary rocks found in the Canavese Zone.

## 5. Discussion

### 5.1. Interpretation of the Architecture of the Southern Adria Distal Margin

In the following, we apply the classification criteria and diagnostic features used by Tugend et al. (2014) and Hauptert et al. (2016) to characterize the architecture of the Southern Adria margin. The Southalpine successions of the Orobic and Lombardic nappes have been classically ascribed to a proximal margin (Bertotti et al., 1993; Masini et al., 2013, cum ref.), or a T1 terrace (Hauptert et al., 2016). The Canavese Zone was interpreted as an analogue for the Lower Austroalpine Err unit in Grisons (Ferrando et al., 2004), that is, as a part of the lower plate. At present, these sectors are preserved within different tectonic units separated by large-scale structural contacts. The Serie dei Laghi-Ivrea-Verbanò Zone basement complex is placed in between these two units and exposes a deep crustal section at the surface due to orogenic tilting. This area assumes a key role as indicator for the polarity of the rift system. The peculiar stratigraphic record associated to the scarce, starved sedimentary cover of the Serie dei Laghi (Cusio-Biellesse zone) led Berra et al. (2009) to interpret it as part of the distal margin of Southern Adria.



**Figure 7.** (a) Simplified reconstruction of the Adriatic margin during the Middle Jurassic from Lombardy basin to the Canavese Zone, from Beltrando, Stockli, et al. (2015), mod. For locations see Figure 4. (b) Conceptual 3-D model of the distal sector of the Southern Adria margin. See text for detailed explanation. Locations and fault abbreviations as in Figure 4. (c) Same view with the “H-block” (T2) exploded to highlight the complex fault bounded structure and the suggested relationships with the outcropping faults. Pogallo Line (PL) may represent at the surface either the lower necking system or the coupling line. Note that Cossato Mergozzo Brissago Line (CMB) do not necessary correspond to the Jurassic upper-lower crustal boundary over all the section, as it represents an inherited line.

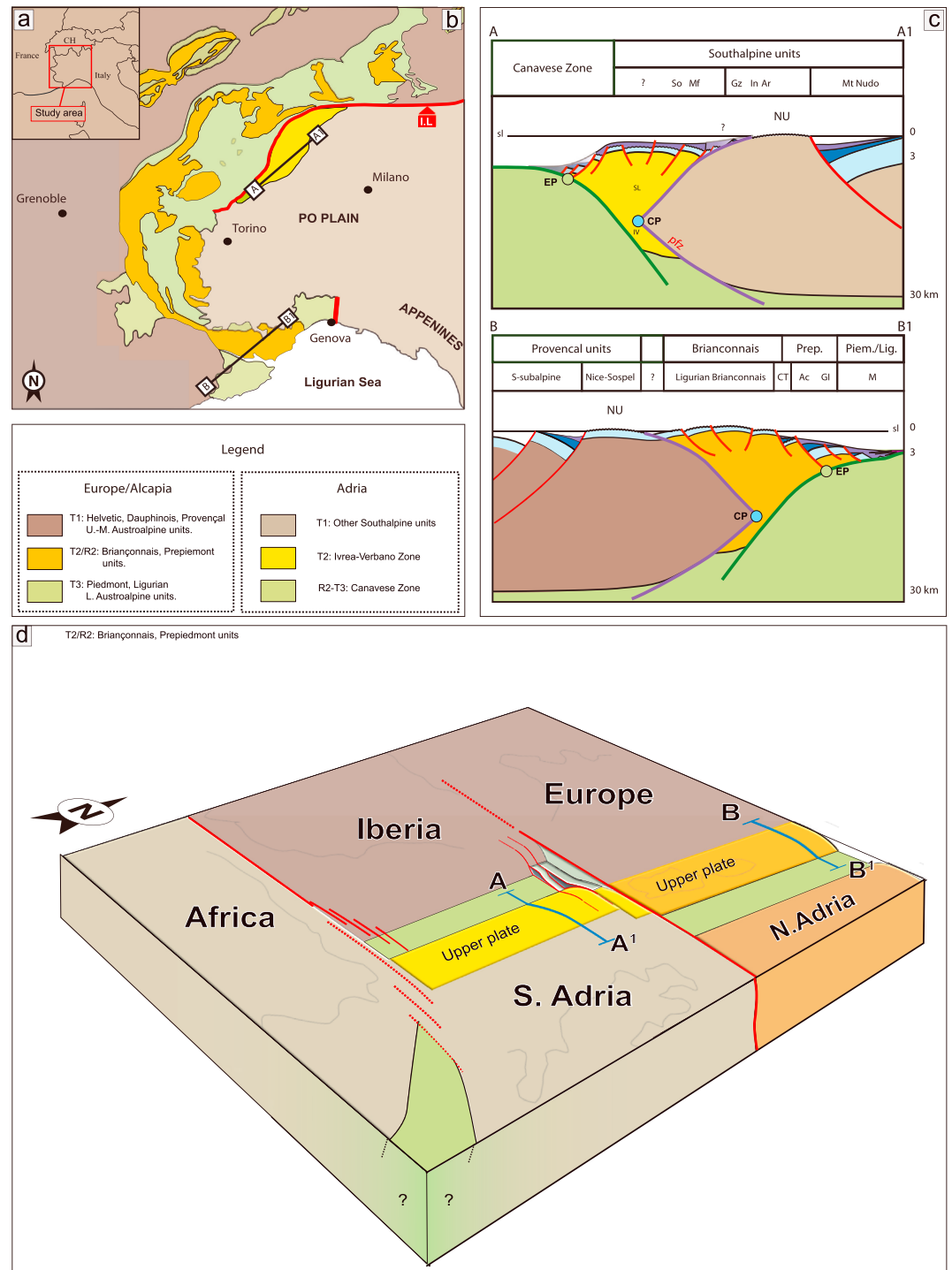
The boundary between the proximal and the most distal margin corresponds, as shown in Figure 3, to the necking zone, a system of convex–concave faults respectively dissecting the upper-to-middle and the middle-to-lower crusts. For the case of the Southern Adria margin, the conjugate necking faults may be located inside the Serie dei Laghi–Ivrea-Verbano Zone, and due to its tilting along a horizontal axis, they must mainly crop out respectively south and north of the Cremosina Line (Figure 4).

1. The upper necking fault system (N1: Figure 7) is located in the easternmost area of the Serie dei Laghi–Ivrea-Verbano zone, south of the Cremosina Line and between the Lago Maggiore and M. Fenera (Figure 4). Although anthropization and widespread quaternary deposits prevents the exposure of the upper necking fault system in the field, indirect evidences for its occurrence are represented by the “Jurassic faults” dissecting N–S of the Permian volcanic rocks and the Serie dei Laghi (Sbisà, 2010). Moreover, this area was exposed at the surface during rifting, as subaerial syn-rift sedimentary rocks directly overlap basement or slice of reduced pre-rift successions (Invorio and Arona). The erosion of the exposed basement formed syn-rift sandstones accumulations to the west (San Quirico Sandstone at M. Fenera and Sostegno). These sandstones preserve evidence for their peculiar heating–cooling history, never found elsewhere in the Southalpine units. U-Th/He analysis on zircons from these sandstones provided ages comparable with those of their deposition (Pliensbachian-Toarcian; Beltrando, Stockli, et al., 2015). This suggests that (i) source rocks were exhumed and cooled along major crustal faults, (ii) they were rapidly eroded, and (iii) sandstones were deposited in shallow water basins. Therefore, we interpret Arona and Invorio to lie close or on top of the emerged upper necking fault system (N1: Figure 7) footwall, whereas Gozzano remained into an isolated but tectonically active submerged environment.
2. The lower part of the necking system (Figure 7: N2) is formed by a concave crustal-scale fault that, by definition, intersects the upper system N1 in the Coupling Point (Figure 3: CP). In a 3-D view the coupling point becomes a line (see Figure 7). In this study we propose that the northern part of the Pogallo Fault Zone may correspond to the east dipping lower part of the necking fault system (N2 in Figure 7). Toward the south, close to the Orta Lake (Figure 4), the fault possibly reaches the coupling point. This southern segment of the Pogallo Line may thus represent the projection of the coupling point in a map view (i.e., a NE dipping coupling line).

Thus, north of the Cremosina Line, the Pogallo fault system separates two distinct crustal blocks owing to the distal (to the west) and to the proximal margin (to the east). Their basement rocks preserve evidence for a complex pre-Alpine evolution of the Southalpine units (Borioni & Giobbi, 2004) but also for a Jurassic shear and/or tectono-magmatic activity in the Pogallo Fault (Handy et al., 1999) and in the Ivrea-Verbano Zone (Zanetti et al., 2013).

Based on this interpretation, the domain exposed west of the Lago Maggiore corresponds to a R1-T2 (Haupt et al., 2016); i.e., it is in an equivalent position to the Briançonnais domain along the European margin (see Figure 8). Direct evidence comes from the sedimentary record preserved in the Cusio-Biellesse zone that is crucial for this interpretation. In fact, sedimentary rocks testify a stage of emersion during rifting with deep erosion and karstification of the substratum (M. Fenera and Sostegno), followed by deposition of shallow water sediments during the thinning phase. Low organic matter maturity data suggest that the sedimentary cover experienced a moderate thermal gradient with temperatures in the sedimentary rocks never exceeding 60–70°C (Fantoni & Scotti, 2003). These data place this sector relatively “high” along a hypothetical passive margin profile (i.e., with low burial temperature). In addition, Mesozoic sedimentary basins seismically imaged further south underneath the Po plain (Fantoni et al., 2003) are relatively thin and localized, suggesting that moderate deposition and erosion are not exclusive features of the Serie dei Laghi cover exposed at the surface but can be extended to the whole sedimentary sequence further to the southwest.

Further, indirect evidence comes from the preserved width of the Serie dei Laghi distal margin, which can be tentatively estimated in the order of 50–60 km. Since during alpine compressional phases this area was only shortened N–S, perpendicular to the strike of the margin, we assume that these 50 to 60 km roughly correspond to the original width of the interpreted Adria T2. A global estimation of T2 compiled from different margins by Chenin et al. (2017) is in the order between 50 and 80 km. Moreover, restorations of the Briançonnais domain (also interpreted as a T2; Haupt et al., 2016) are in the order of 50–60 km (Mohn et al., 2010, cum ref.).



**Figure 8.** (a, b), Location and interpretative map of the Alps where major tectonic units are mapped as rifting domain (Hauptert et al., 2016). (c) Schematic interpretative sections through the upper plates sections of Southern Adria (A-A1: see text in this paper) and Europe-Northern Adria rifted margins (B-B1; Decarlis et al., 2015). (d) Paleogeographic reconstruction of the western Mediterranean during Late Jurassic. The proposed distribution of different upper plates and lower plates in the Alpine domains suggests the existence of a major “transfer” fault cutting apart southern from northern Adria and possibly Europe from Iberia.



More critical is the interpretation of the Canavese Zone that can be described as a complex unit formed by several tectonic elements in which the convergence and orogenic phases of the Alpine cycle probably juxtaposed portions of the R2 (Montalto Dora) and the transition to the T3 (Levone).

## 5.2. Paleogeographic Implications

The identification of a T2 domain in the distal margin of Southern Adria implies that it has to be interpreted as an upper plate margin during the opening of the Piedmont-Ligurian basin. Thus, the tectono-stratigraphic analysis of the rifted margins of the Alps suggests that both the distal European (Decarlis et al., 2015; Hauptert et al., 2016) and distal Southern Adria margins were upper plate systems (Figure 8). On the contrary, the Northern Adria margin exposed north of the Insubric Line in the Austroalpine nappes and considered to be conjugate to the European margin (Decarlis et al., 2015) was interpreted as a lower plate (Manatschal, 2004).

If these margins are plotted into a paleogeographic map of the Alpine realm (Figure 8), it becomes clear that two conjugate pairs can be identified: one to the north (T1: Provençal, T2: Briançonnais, R2-T3: Pre-Piedmont and Piedmont-Ligurian, destroyed T2: Lower Austroalpine, T1: Upper Austroalpine; see Figure 8) and one, incomplete, to the south (T1: Southalpine s.s., T2: Serie dei Laghi-Ivrea-Verbano Zone, R2-T3 Canavese Zone; Figure 8) separated by a major tectonic system locally represented by the Insubric Line. Conjugate pair remnants are thus flipped in the Alpine rift geometry.

Such configuration can be compared with those observed in core complex systems (Lister et al., 1986), in which the rifting geometry flips across “transfer faults” that accommodate the different dips of contiguous detachment faults. Lister et al. (1986) also proposed that the mechanism of detachment faulting is part of the continental extension process and that thus similar geometries are to be expected in passive margins.

In fact, along strike variations in the distribution of upper and lower plate systems have been recently observed in seismic profiles of the Western Africa margins of the Atlantic Ocean. In the Angola-Gabon rifted margin, upper and lower plates alternate, and the change of polarity is accommodated by different types of transfer zones (Peron-Pinvidic et al., 2017).

We propose that a similar transfer zone had to be active during Jurassic time along the Paleo-Insubric Line system (Figure 8).

An important consequence of this interpretation is related to the position of the Corsica-Sardinia block in the proposed paleogeographic reconstruction (Figure 8), which deviates from the Handy et al. (2010) model. In fact, as Corsica and Sardinia have been usually interpreted as the southern continuation of the Briançonnais realm and display a marked tectono-stratigraphic affinity with this domain (e.g., Costamagna, 2016, cum ref.), they can be considered as part of an upper plate system. For this reason they rested toward the north in respect to the suggested transfer fault and in a similar paleogeographic position to that proposed by Thierry (2000a, 2000b). This would place the Sardinia-Corsica-Briançonnais block on the SW edge of the European plate. According to this configuration, the Jurassic Paleo-Insubric transfer zone merged the plate boundary between Europe and Iberia to the NW.

After the rifting and drifting phases, the Paleo-Insubric transfer system was then reactivated during the successive stages of the Alpine cycle, accommodating the oblique convergence and the continental collision during Cretaceous and Cenozoic.

We also suggest that the Jurassic transfer zone may have superimposed on a pristine major fault system. In fact, several studies hypothesized a widespread transcurrent-extensional activity during Late Paleozoic and Triassic in the Alps (e.g., Muttoni et al., 2003: Southalpine; Doglioni, 1987: Dolomites; Decarlis et al., 2013, cum ref.: Ligurian Alps). This suggests that major transcurrent discontinuities at an orogen-scale (e.g., the Insubric system) may be inherited from former rift events and can survive and control later orogenic phases. This interpretation may open new interesting questions about the role of rifting-related inheritance during orogenic evolution and may help to better define the kinematic evolution of the strongly debated Alpine paleogeography.

## 6. Conclusion

The tectono-stratigraphic setting of the Southern Adria rifted margin preserved in NW Italy suggests that this sector can be interpreted as an upper plate system. The proximal margin (T1 in Hauptert et al., 2016) is

preserved in the central-eastern Southalpine units, while distal parts of the former margin crop out in the Serie dei Laghi–Ivrea-Verbano Zone and Canavese Zone, which respectively represent T2 and R2-T3 domains of Hauptert et al. (2016). This observation is not in agreement with the classic interpretation of the Alpine rifted margins that account for an NW located upper plate (European plate) and a SE lower plate (Northern and Southern Adria) throughout the whole Alpine rift system. The proposed configuration accounts for two distinct type sections across the Alpine rifted margins that exhibit a flip of the distal geometry of the Alpine Tethys margins. As reported by Decarlis et al. (2015), the upper plate along the Europe-Northern Adria margins is located to the NW and corresponds to the Briançonnais Zone. In the studied Southern Adria margin, the upper plate is located to the SE. This setting requires that a major flip occurred along strike of the Piedmont-Ligurian rifting system. The present study proposes that these two sectors are separated by a tectonic system comparable to the “transfer faults” proposed by Lister et al. (1986) and observed at present day margins. This fault zone probably survived the rifting stage and was reactivated during the whole orogenic cycle forming a key crustal discontinuity that conditioned the large-scale kinematics of the Western Mediterranean and its paleogeographic evolution since the Mesozoic.

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