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

Architecture of the distal Piedmont-Ligurian rifted margin in NW-Italy: hints for a flip of the rift system polarity

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Keywords: Rift architecture of fossil Alpine margins, upper plate of magma-poor rifted margin, flip in rift asymmetry

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 sub-continental 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 palaeogeographic evolution of the Alpine orogen.

Keywords: Southalpine domain, Briançonnais domain, Magma-poor rifted margins, Rift flip, Palaeogeographic reconstruction of the Alps.

1 Introduction

Remnants of the fossil rifted-margins preserved in the Alps show evidence for a Mesozoic polyphase magma-poor rift evolution [e.g. *Gaetani*, 2010; *De Graciansky et al.,* 2011] that shaped the complex boundary among Africa/Gondwana-derived microplates and Europe [e.g. *Handy et al.,* 2010; *Stampfli et al.,* 2002](Fig 1C). These margins formed as a consequence of hyperextension and exhumation of sub-continental mantle along extensional detachment faults, culminating in the opening of the Piedmont-Ligurian basin (Alpine Tethys Ocean Auct.) during late Middle Jurassic [e.g. *Decandia and Elter,* 1969; *Bezzi and Piccardo,* 1971; *Lemoine et al.,* 1987; *Froitzheim and Manatschal*, 1996; *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 [*Sutra et al.*, 2013; *Tugend et al.*, 2014; *Haupert et al.*, 2016]. 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: *Haupert 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]. Margin-derived units rest on either side of the major ophiolite belt (Piedmont-Ligurian units, Fig 1B)[e.g. *Schmid et al.,* 2004; *De Graciansky et al.,* 2011; *Pfiffner,* 2014]. The northwestern rifted margin, formerly belonging to the European plate, is preserved in the Helvetic-Dauphinois-Provençal units (proximal margin, Fig. 1) and in the Briançonnais and Prepiedmont units (distal margin, Fig. 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] (Fig. 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; *Elter et al.,* 1966; *Sturani*, 1973; *Kalin & Trumpy*, 1977; *Berra et al*, 2009].

2.2 The concept of hyperextended margins applied to the Alps

The Jurassic Alpine Tethys rifted margins were shaped by two discrete extensional phases [*Froitzheim and Manatschal*, 1996; *Berra et al.*, 2009; *Decarlis et al.*, 2015] that lead to a localization of the deformation from the proximal margin (1st phase: Hettangian-Sinemurian) towards the distal margin (2nd 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. Manatschal and Bernoulli*, 1999; *Manatschal*, 2004; Haupert et al., 2016]. These comparative studies led to the introduction of a conceptual model that may explain the evolution of magma-poor rifted margins [*Lavier and Manatschal*, 2006]. The model considers three phases of extension: an initial "*stretching phase*" (Fig. 2A/B) that is mainly accommodated in the upper crust by the formation of wide, distributed half-graben systems; a "*thinning phase*" (Fig. 2B/C), leading to the formation of a hyperextended crustal sector (Fig. 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]; an "*exhumation phase*" related to the exhumation of subcontinental mantle rocks at the seafloor (Fig. 2C-D).

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 (Fig. 2C). At this stage, the keystone formed during necking ["H-block" in *Lavier and Manatschal*, 2006] is laterally delaminated, leading to the formation of extensional

107 allochthons lying on the lower plate. The residual, not delaminated part of the H-block
108 forms the residual H-block ($H_{(r)}$: Fig. 2C) that is the diagnostic feature of an upper plate
109 rifted margin.
110 In the example of the Alpine Tethys margins, the initial stretching phase took place during
111 Hettangian/Sinemurian times [*Froitzheim and Manatschal*, 1996; *Berra et al.*, 2009;
112 *Decarlis et al.*, 2015], the necking occurred during Pliensbachian/Toarcian [Mohn et al.,
113 2012; *Decarlis et al.*, 2015] and was followed by mantle exhumation and onset of
114 emplacement of Mid Ocean Ridge basalts during Callovan/Bathonian time [*e.g. De*
115 *Graciansky et al.*, 2011, *cum ref.*]. *Decarlis et al.* [2015, and references therein] proposed
116 that the Briançonnais units (distal European margin) forms an upper plate margin and the
117 Lower Austroalpine units (distal Northern Adria margin) the lower plate margin (Fig 1C-D).
118 This interpretation was based on both the analysis of the tectono-stratigraphic record and the
119 recognition of primary rift structures that escaped most of the orogenic overprint in the distal
120 margin [cfr: *Mohn et al.*, 2012; *Masini et al.*, 2013; *Decarlis et al.*, 2015; *Haupert et al.*,
121 2016]. The split and left-lateral shift of the two margins has been attributed to the late
122 transpressive evolution of the chain [*Decarlis et al.*, 2015].
123 The fossil rifted margin preserved in the Southern Alps has been analyzed in detail by
124 several authors and has been interpreted as a proximal margin [e.g. *Bertotti et al.,* 1993;
125 *Masini et al.,* 2013], with the exception [*Elter et al.,* 1966; *Sturani*, 1973] of the
126 westernmost area (Cusio-Biellese zone) that rested in the distal domain [*see*: *Beltrando et*
127 *al.,* 2015a; *Berra et al.,* 2009]. *Ferrando et al.* [2004] analyzed the Canavese Zone and
128 proposed a close similarity with the Lower Austroalpine units exposed in Grisons (SE
129 Switzerland). These authors proposed that the distal Southern Adria margin (i.e. the
130 Canavese Zone) formed as a lower plate margin, too (cfr Fig. 1D).
131

3 Polarity of final rifting: geometry and terminology

Haupert 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 (Fig.2-3A). 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. *Haupert et al.* [2016] introduced "terraces" (T1, T2 and T3; Fig. 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, 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±5 km-thick; Fig. 3A). Wide, fault-bounded half-graben basins hosting thick syn-tectonic successions [cfr. STS1: Syn Tectonic Sequence of *Decarlis et al.,* 2015] (Fig. 3B; type 1 basins in Fig. 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 oceanwards by a crustal-scale fault system that developed during the thinning phase, forming a morphologic ramp [referred to as **R1** by *Haupert et al.,* 2016]. This zone corresponds to the "necking zone" (see ϕ faults in Fig 3B-C) [*Mohn et al.*, 2012].

157 Sedimentary rocks accumulated during the early development of R1, may account for
158 relatively shallow depositional environments, but they may also be characterized by peculiar
159 features. In fact, differently from half-graben master faults in the T1 domain, the necking
160 fault system forms simultaneously with conjugate fault systems in the lower crust ["coupled
161 domain": see *Sutra et al.,* 2013]. As a consequence, these faults may allow the advection of
162 deep-seated fluids and they are linked to thermal anomalies and to rapid exhumation of mid-
163 crustal rocks (e.g. heating-cooling cycles) [*Beltrando et al.,* 2015a]. In a rift system, R1
164 marks the boundary between the proximal and the distal margin.
165 The most peculiar feature of upper plate margins is the occurrence of a residual "H-block"
166 [e.g. *Lavier and Manatschal*, 1996], that is up to 50-80 km wide [*Chenin et al.*, 2017] and
167 15-20 km thick. The top of this block is referred to as **T2** [*Haupert et al*., 2016]. In the T2
168 terrace, the pre-rift section is only affected by minor brittle high-angle normal faults and the
169 basement is made of upper crust. The syn-rift succession is reduced due to the syn-rift uplift
170 that may generate emersion (see Fig. 3D, type 2 basins).
171 Oceanwards, the T2 is limited by a big morphologic ramp (**R2**), formed by a major normal
172 fault system (φ fault in Fig. 3) accommodating the bathymetric transition to the T3 domain.
173 Along the R2 escarpment, upper crustal rocks (and potentially also remnants of mid-crustal
174 rocks) are exposed. Faulting produces a diffused source for detritic sediments that are
175 collected in new fault-bounded, open-flank basins (Fig. 3C; type 3-4 basins in Fig. 3D) and
176 constitute the typical sedimentary product associated to the thinning phase (syn-tectonic
177 sequence 2: STS2) [*Decarlis et al.*, 2015]. Along R2, the continental crust is split in several
178 tilted blocks, progressively reducing in thickness while approaching the exhumation area
179 (Fig. 3C). The **T3** consists of blocks of pre- and early syn-rift that overlie exhumed lower
180 crust or mantle rocks [see *Masini et al*., 2011; *Decarlis et al*., 2015].

181 *Haupert et al.* [2016] proposed that the remnants of the European Tethys margin exposed in
182 the Western Alps record key structures of an upper plate system. In this example, the T1
183 corresponds to the Dauphinois units exposed today in the external parts of the Western Alps
184 (Fig. 1D). The rift structures in this domain formed during the stretching phase (Hettangian-
185 Sinemurian). The T2 is best preserved in the Briançonnais units (Fig. 1D), that experienced
186 a pronounced uplift during the thinning phase of the Alpine rifting (Pliensbachian-Toarcian)
187 leading to a deep erosion of the substratum that generated a characteristic stratigraphic gap.
188 T3 corresponds to the Prepiedmont and Piedmont units (Fig. 1D), characterized by a
189 complete stratigraphic succession and by a clastic infill during the thinning phase [see: STS2
190 in *Decarlis et al.,* 2015]. It is important to note that in the Austroalpine units of Grisons,
191 considered to be the conjugate margin of the above-mentioned upper plate section [Decarlis
192 et al., 2015], the T2 domain does not exist and the T3 is directly passing to the proximal
193 margin (T1: Middle and Upper Austroalpine units; Fig. 1D).
194
195 **4 Southern Adriatic margin**
196 Most of the successions of the Southalpine units contain evidence for a thick stratigraphic
197 record (Fig 4) deposited on basins formed on top of 30±5 km thick continental crust
198 [*Bertotti et al.,* 1991, 1993; *Turrini et al.,* 2014]. During Early Jurassic, half-graben
199 structures developed [e.g. Generoso basin: *Bernoulli*, 1964] and hosted thick syn-tectonic
200 carbonate sequences (Moltrasio and Domaro lms, Medolo group: Hettangian/Sinemurian)
201 [*Berra et al*., 2009] followed by a suite of pelagic carbonate rocks (Rosso Ammonitico,
202 Concesio Fm: Pliensbachian/Toarcian) [*Berra et al*., 2009] that draped the topography and
203 marked the passage to a local tectonic quiescence. This area can be therefore interpreted as a
204 typical proximal margin [see *Masini et al.,* 2013].

205 Portions of the distal Southern Adriatic margin crop out in the westernmost sector of the
206 Southalpine units [e.g. *Beltrando et al.,* 2015a] in two different sectors that are here
207 separately described: the Serie dei Laghi-Ivrea Verbano Zone and the Canavese Zone (Fig
208 4).
209
210 4.1 Serie dei Laghi – Ivrea-Verbano zone: basement
211 The Southalpine basement in northwestern Italy is mostly made up of igneous and
212 metamorphic rocks cropping out west of the Southalpine thrusts (Fig. 4) [*Pfiffner*, 2016].
213 Upper crustal rocks (Serie dei Laghi) [*Boriani and Giobbi,* 2004] and middle-to-lower
214 crustal rocks (Ivrea-Verbano zone) [e.g. *Siegesmund et al.*, 2008 *cum ref.*] are exposed at
215 present at the surface as a result of an extensive regional tilting that affected the area during
216 the Alpine orogenic cycle [*Schmid et al.*, 1987].
217 The basement of the Serie dei Laghi is composed of a complex association of Palaeozoic
218 meta-arenites, amphibolites with relicts of gabbros, ultramafites and paragneisses, meta-
219 pelites and ortogneisses [*Boriani and Giobbi*, 2004]. These rocks were intruded by
220 voluminous granitoid bodies during Early Permian [*Boriani et al*., 1988] and represent a
221 portion of the upper crust since Paleozoic times.
222 The Ivrea-Verbano Zone is a pre-Jurassic middle/lower crustal unit that is composed of
223 high-temperature amphibolite to granulite facies rocks. It includes kinzigites that represent
224 former metasedimentary to metavolcanic successions [*Novarese*, 1929], partly intruded by a
225 Permian large mafic complex [*Rivalenti et al*., 1981; *Voshage et al*., 1990; *Pfiffner,* 2014
226 and ref. therein]. West of the mafic complex, isolated bodies of subcontinental mantle rocks
227 occur (Fig. 4: Balmuccia, Finero, Baldissero) [*Rivalenti et al.* 1981; *Garutti et al.* 1979;
228 *Shervais,* 1979; *Voshage et al.,* 1988; *Hartmann & Wedepohl,* 1993]. Lowermost levels of
229 the Ivrea-Verbano Zone are separated from the Sesia-Lanzo Zone by the fault system of the

230 Insubric Line that reached anchizone to low-greenschist facies conditions. Important
231 structures, relevant for the interpretation of the Jurassic Adriatic margin, occur near the
232 stratigraphic top of the Ivrea-Verbano Zone. The Cossato-Mergozzo Brissago Line is a NE-
233 SW striking fault zone that marks the contact between the Serie dei Laghi and the Ivrea-
234 Verbano Zone (CMB: Fig. 2) [*Handy*, 1987]. It consists of high-temperature mylonites
235 associated with migmatites and dykes related to Early Permian extension (Ar/Ar age: 271±1
236 Ma) [*Boriani and Villa*, 1997] (Ru/Sr; 275±8 Ma) [*Pinarelli et al.,* 1988]. The Cossato-
237 Mergozzo-Brissago Line is overprinted by a younger fault system, the Pogallo Line (PL:
238 Fig. 2) [*Handy,* 1987]. The latter is a ductile shear zone, characterized by subvertical
239 foliation with SW-NE strike and NE plunging stretching lineations with a left-lateral sense
240 of shear. It consists of mylonites developed under amphibolite to greenschist facies
241 conditions, striking NE-SW in the northern branch and roughly N-S toward the south (Fig.
242 4). The age of the Pogallo Line has been constrained to 200-180 Ma by *Zingg et al.* [1990].
243 The late stage of faulting occurred under lower greenschist conditions and close to the
244 brittle-ductile transition and has been related to Early Jurassic [*Zingg,* 1990 cum ref.]. It has
245 been interpreted as an east dipping, mid-crustal extensional listric fault that accommodated
246 extension during Jurassic rifting [*Handy et al.*, 1999].
247
248 4.2 Serie dei Laghi: sedimentary cover
249 Toward the south, the Serie dei Laghi is crossed by an E-W fault system with a right lateral
250 and a vertical component (Cremosina Line: CL: Fig 4) [*Boriani and Sacchi*, 1973]. As a
251 result of this latter structure, the sedimentary cover of the Serie dei Laghi is only preserved
252 south of the Cremosina Line. Scarce remnants of Mesozoic sedimentary rocks actually crop
253 out in between Lago Maggiore and Sostegno (Fig 4), but most of them are buried further to
254 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 [*Berra et al.*, 2009; *Fantoni et al.*, 2003; *Beltrando et al.*, 2015a]. 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 (Fig. 5).

- *Arona (*Fig. 5; Fig. 6a*):* a thin succession of Early to Middle Triassic sandstones onlaps Permian volcanic rocks. Sandstones are overlain by Middle Triassic Dolostones (San Salvatore Dolostones) [*Zanin Buri, 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 (Fig. 6e) and that are considered Jurassic [*Fantoni et al.,* 2003; *Berra et al.*, 2009]. 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.

- *Invorio* (Fig. 5; Fig. 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].

279 - *Gozzano* (Fig. 5; Fig.6c,d)*:* at this locality a few tens of meters of a Jurassic succession
280 probably laying on the Permian volcanic rocks can be observed [*Montanari*, 1969].
281 However, this boundary in not visible at present. The Jurassic succession is formed by
282 calcarenites, microbreccias and calcilutites with brachiopods, corals and crinoids (here
283 informally named Lithozone"A") overlain by nodular limestones and calcarenites with
284 ammonoids and molluscs (Lithozone "B"). The whole succession was affected by important
285 fluid activity that led to the formation of widespread calcite-dolomite veins. Lithozone "A"
286 has been ascribed to the Upper Sinemurian-Lower Pliensbachian (?), Lithozone "B" to the
287 Upper Pliensbachian on the base of a rich fossil fauna [*Sacchi Vialli and Cantaluppi*, 1967;
288 *Montanari*, 1969]. *Montanari* [1969] reported that Upper Pliensbachian sedimentary rocks
289 were filled with neptunian dikes that opened inside the lithozone "A" and described an
290 angular unconformity between the two lithozone suggesting that a tectonic pulse occurred
291 during Late Early Jurassic. The Jurassic succession at Gozzano has been interpreted as
292 deposited on top of a submarine high [*Berra et al.,* 2009].
293 - *Monte Fenera and Sostegno* (Fig. 5)*:* at these localities more complete Mesozoic
294 successions are preserved. Permian volcanic rocks are overlain by a thin succession of
295 sandstones and conglomerates that predate the deposition of Middle Triassic dolostones
296 [see: Fantoni *et al.,* 2003; Berra *et al*., 2009]. The top of Ladinian carbonate rocks is
297 characterized by a widespread unconformity, locally accompanied by karstified levels and
298 followed by a thin succession of dolomitic breccias, conglomerates and micro-
299 conglomerates with oxidized reddish matrix both at Fenera and Sostegno (Fig 6e).
300 Sedimentary dykes filled of the same reddish material and of dolomitic breccias can be
301 frequently found (Fig. 6f). The unconformity has been interpreted as a complex surface,
302 probably related to a prolonged erosion and karstification event leading to the deposition of
303 reworked palaeosoils and breccias [*Fantoni et al.*, 2003; *Berra et al.,* 2009].

304 A 50 meter-thick succession of lithic sandstones (San Quirico Sandstone) composed of
305 dolomitic, volcanic and basement-derived grains [*Fantoni et al.,* 2003; *Berra et al.,* 2009]
306 overlays the breccia. The depositional age for these sandstones has been determined by
307 palinomorphs as Pliensbachian-Toarcian [Berra *et al.,* 2009]. Interestingly, (U-Th)/He
308 analysis on zircons in volcanic grains of the sandstone gave comparable absolute cooling
309 ages (171±14 Ma and 177±14 Ma respectively for Fenera and Sostegno) [*Beltrando et al.*,
310 2015a]. These data demonstrate that the process of exhumation, cooling, erosion and
311 sedimentation was very rapid. San Quirico Sandstone is overlain by some hundred of meters
312 of spongolitic limestone of Plienbachian?-Toarcian age.
313
314 4.3 Canavese Zone
315 The Canavese Zone [Argand, 1909] is a structural unit, about 2 km wide and 40 km long,
316 bounded by two main SW–NE faults: the External Canavese Line (ECL: Fig 4) to the
317 northwest, and the Internal Canavese Line (ICL: Fig. 4) to the southeast [*Biino et al.,* 1988;
318 *Biino and Compagnoni*, 1989] (Fig 4). The External Canavese Line, or the Canavese Line
319 s.s., is the southwestern branch of the Insubric Line. The Internal Canavese Line is a ductile
320 shear zone producing very low-grade Alpine mylonites separating the Canavese Zone from
321 the granulite-facies rocks of the Ivrea Verbano Zone [*Biino et al*., 1988; *Biino and*
322 *Compagnoni*, 1989]. Upper, middle and lower crustal rocks are present in the Canavese
323 Zone, although their relationships are often not easy to decipher.

324 - The upper crust outcrops near Montalto (Fig. 4A) and is composed of a Palaeozoic
325 association of paragneiss, phyllites, banded albite-epidote-actinolite metabasics and augen-
326 gneiss [*Baggio*, 1965a; *Biino et al*., 1988; *Biino and Compagnoni*, 1989]. The metamorphic
327 suite is locally intruded by Permian plutonic rocks [*Biino et al*., 1988; *Biino and*

328 *Compagnoni*, 1989] and is overlain by Permian volcanic rocks similar to those found in the
329 Fenera-Sostegno area.
330 - Mid crustal rocks outcrop near Baldissero (Fig. 4A) and are composed of a
331 heterogeneous assemblage of amphibolite-facies rocks, such as amphibolites, biotite-
332 gneisses ± garnet, and muscovite-biotite schist with garnet ± fibrolitic sillimanite [*Baggio*,
333 1965b; *Wozniack,* 1977; *Borghi et al*., 1996; *Ferrando et al.*, 2004].
334 - Lower crustal rocks outcrop near Baldissero and Levone (Fig. 4A) and are composed
335 of migmatites with transitional contacts to anatectic leucogranite [*Baggio*, 1965b; *Wozniak*,
336 1977; *Ferrando et al*., 2004]. The lower crustal rocks have never been observed to be
337 intruded by the post-Variscan intrusive rocks. On the contrary, they locally include
338 fragments of mafic granulites similar to those of the Ivrea-Verbano Zone [*Wozniak*, 1977;
339 *Ferrando et al.,* 2004].
340 The pre-rift sedimentary succession mainly outcrops near Montalto Dora (Fig. 4). It is
341 formed by conglomerates and sandstones (Permian-Early Triassic in age) followed by
342 Triassic dolostones. The age of the carbonate rocks remains uncertain, due to the lack of
343 fossils, but they have been compared in the literature [*Baggio*, 1965a] to those found at
344 Arona and Fenera-Sostegno and interpreted as Middle Triassic on the basis of the facies and
345 lithologic features. Dolostones are cut by several neptunian dykes and sills filled by a
346 reddish/greenish matrix and by clasts derived from the underlying lithologies [*Biino et al.*,
347 1988; *Biino & Compagnoni*, 1989]. Dolostones are locally overlain by red calcarenites dated
348 as Early Sinemurian by ammonoid occurrence [*Sturani*, 1964]. Breccias can be observed
349 directly laying on the Triassic carbonates. They are formed by dolostones and reddish
350 calcarenite clasts in a reddish or greenish matrix similar to the filling of the neptunian dykes.
351 Syn- to post-rift sedimentary rocks have been reported to directly lie on top of the
352 migmatites in the areas near Baldissero e Levone (Fig. 4) [*Ferrando et al.,* 2004]. These

353 successions are characterized by a stratigraphic transition from the cataclastic lower crust to
354 a clast-supported tectono-sedimentary breccia [*Manatschal*, 1999] (Fig 6g) and finally,
355 toward the top, to a polymictic breccia (clasts of both lower and middle crusts, intrusive and
356 volcanic rocks and phyllonites) [*Ferrando et al., 2004*; *Beltrando et al.,* 2015b]. A
357 Pliensbachian to Bajocian age has been proposed for the breccia/arkosic-pelitic sequence
358 because of the marked similarity with the syn-rift Saluver Formation of the Austroalpine
359 nappes of the Grisons in SE-Switzerland [*Carraro and Sturani,* 1972; *Ferrando et al.,*
360 2004]. In the Levone area (Fig. 4), the tectono-sedimentary breccias are dissected by shear
361 zones associated to a characteristic chromium-rich fault gouge [Beltrando et al. 2015b].
362 Similar fault-rocks have been described in the Lower Austroalpine Err nappe in Grisons
363 along extensional detachment faults [*Manatschal, 1999*]. These fault-rocks have been shown
364 to result from the alteration by mantle-derived fluids along exhumation faults that penetrated
365 and exhumed the subcontinental mantle to the Jurassic seafloor. This similarity drove
366 *Beltrando et al.* [2015b] to suggest the same interpretation for the Canavese gouges of the
367 Levone sector, where they crop out close to the large serpentinized peridotite body of
368 Pesmonte.
369 Post-rift sedimentary rocks mainly outcrop near Baldissero (Fig. 4) and are made of
370 Radiolarites (Fig. 6h), micritic limestones of the Maiolica formation (Tithonian-Berriasian)
371 [*Baggio*, 1963] and marly limestones considered to be equivalent to the Palombini Shales
372 [*Ferrando et al.*, 2004]. These sediments, most likely of Early Cretaceous age, represent the
373 youngest sedimentary rocks found in the Canavese Zone.

374 **5 Discussion**

375 **5.1** Interpretation of the architecture of the Southern Adria distal margin

376 In the following, we apply the classification criteria and diagnostic features used by *Tugend*
377 *et al.* [2014] and *Haupert 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 [*Haupert et al.,* 2016]. The Canavese Zone was interpreted as an analogue for the Lower Austroalpine Err unit in Grisons [*Ferrando et al.*, 2004], *i.e*. 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-Verbano 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-Biellese zone) led *Berra et al.* [2009] to interpret it as part of the distal margin of Southern Adria.

The boundary between the proximal and the most distal margin corresponds, as shown in Fig. 3, to the necking zone, a system of convex-concave faults respectively dissecting the upper-to-middle and the middle-to-lower crust. 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 (Fig. 4).

-The upper necking fault system (N1: Fig. 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 (Fig. 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 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

403 exposed basement formed syn-rift sandstones accumulations to the west (San Quirico
404 Sandstone at M. Fenera and Sostegno). These sandstones preserve evidence for their
405 peculiar heating-cooling history, never found elsewhere in the Southalpine units. U-Th/He
406 analysis on zircons from these sandstones provided ages comparable with those of their
407 deposition (Pliensbachian-Toarcian) [*Beltrando et al.,* 2015a]. This suggests that: (i) source
408 rocks were exhumed and cooled along major crustal faults, (ii) they were rapidly eroded and
409 (iii) sandstones were deposited in shallow water basins. Therefore we interpret Arona and
410 Invorio to lie close or on top of the emerged upper necking fault system (N1: Fig. 7)
411 footwall, whereas Gozzano remained into an isolated but tectonically active submerged
412 environment.
413 -The lower part of the necking system (Fig. 7: N2) is formed by a concave crustal-scale fault
414 that, by definition, intersects the upper system N1 in the Coupling Point (Fig. 3: CP). In a
415 3D view the coupling point becomes a line (see Fig. 7). In this study we propose that the
416 northern part of the Pogallo Fault Zone may correspond to the east dipping lower part of the
417 necking fault system (N2 in Fig. 7). Toward the south, close to the Orta Lake (Fig. 4), the
418 fault possibly reaches the coupling point. This southern segment of the Pogallo Line may
419 thus represent the projection of the coupling point in a map view (*i.e.* a NE dipping coupling
420 line).
421 Thus, north of the Cremosina Line, the Pogallo fault system separates two distinct crustal
422 blocks owing to the distal (to the west) and to the proximal margin (to the east). Their
423 basement rocks preserve evidence for a complex pre-Alpine evolution of the Southalpine
424 units [*Boriani et al.,* 2004], but also for a Jurassic shear and/or tectono-magmatic activity in
425 the Pogallo Fault [*Handy*, 1999] and in the Ivrea-Verbano Zone [*Zanetti et al.,* 2013].
426 Based on this interpretation, the domain exposed west of the Lago Maggiore corresponds to
427 a R1-T2 [*Haupert et al.*, 2016], *i.e*. it is in an equivalent position to the Briançonnais domain

428 along the European margin (see Fig. 8). Direct evidence comes from the sedimentary record
429 preserved in Cusio-Biellese zone that is crucial for this interpretation. In fact, sedimentary
430 rocks testify a stage of emersion during rifting with deep erosion and karstification of the
431 substratum (M. Fenera and Sostegno), followed by deposition of shallow water sediments
432 during the thinning phase. Low organic matter maturity data suggest that the sedimentary
433 cover experienced a moderate thermal gradient with temperatures in the sedimentary rocks
434 never exceeding 60-70 °C [*Fantoni & Scotti,* 2003]. These data place this sector relatively
435 "high" along a hypothetic passive margin profile (i.e. with low burial temperature). In
436 addition, Mesozoic sedimentary basins seismically imaged further south underneath the Po
437 plain [*Fantoni et al.,* 2003] are relatively thin and localized, suggesting that moderate
438 deposition and erosion are not exclusive features of the Serie dei Laghi cover exposed at the
439 surface, but can be extended to the whole sedimentary sequence further to the southwest.
440 Further, but indirect evidence comes from the preserved width of the Serie dei Laghi distal
441 margin, that can be tentatively estimated in the order of 50-60 km. Since during alpine
442 compressional phases this area was only shortened N-S, perpendicular to the strike of the
443 margin, we assume that these 50 to 60 km roughly correspond to the original width of the
444 interpreted Adria T2. A global estimation of T2 compiled from different margins by *Chenin*
445 *et al.* [2017] is in the order between 50-80 km. Moreover, restorations of the Briançonnais
446 domain (also interpreted as a T2) [*Haupert et al.,* 2015] are in the order of 50-60 km [*Mohn*
447 *et al.,* 2010 *cum ref.*].
448 More critical is the interpretation of the Canavese Zone that can be described as a complex
449 unit formed by several tectonic elements in which the convergence and orogenic phases of
450 the Alpine cycle probably juxtaposed portions of the R2 (Montalto Dora) and the transition
451 to the T3 (Levone).
452

5.2 Palaeogeographic 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; *Haupert et al.*, 2016] and distal Southern Adria margins were upper plate systems (Fig. 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 palaeogeographic map of the Alpine realm (Fig. 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 Fig. 8) and one, incomplete, to the south (T1: Southalpine s.s., T2: Serie dei Laghi – Ivrea-Verbano Zone, R2-T3 Canavese zone; Fig. 8) separated by a major tectonic system locally represented by the Insubric Line. Conjugate pairs 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 type of transfer zones [*Peron-Pinvidic et al.*, 2017].

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

An important consequence of this interpretation is related to the position of the Corsica-Sardinia block in the proposed palaeogeographic reconstruction (Fig. 8), that 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 palaeogeographic position to that proposed by *Thierry et al.* (2000a,b). This would place the Sardinia-Corsica-Briançonnais block on the SW edge of the European plate. According to this configuration, the Jurassic palaeo-Insubric transfer zone merged the plate boundary between Europe and Iberia to the NW.

After the rifting and drifting phase, the palaeo-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 Palaeozoic 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 palaeogeography.

7 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 *Haupert 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, that respectively represent T2 and R2-T3 domains of *Haupert 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 palaeogeographic evolution since the Mesozoic.

Acknowledgements

We gratefully thank Giancarlo Molli, Adrian Pfiffner and Gideon Rosenbaum for helpful reviews that significantly improve the manuscript. The research was supported by Torino University Grant (Torino_call2014_L1_202; Resp. S.F.) and by MM4 consortium (Margin

Modelling Phase 4: Liverpool & Strasbourg University), taking benefits from useful discussions with colleagues from the academic and industrial partners. The data supporting this paper are available within figures 5-7.

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771

772 **Captions**

Fig. 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 palaeogeographic 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 palaeogeographic structural domains and rifting domains; OCT: ocean-continent transition zone [from Decarlis et al., 2015].

Fig. 2: Conceptual kinematic model for magma-poor rifted margin evolution in time [from *Haupert et al.*, 2016] from pre-rift (**a**) to breakup stage (**d**). Details of the evolutionary stages and nomenclature description in the text. Note the formation of the "H-block" [*Lavier and Manatschal*, 2006] and its uplift at the beginning of thinning phase (**b**) before being drowned after the onset of the main detachment fault. Then it lies dissected ("residual H Block": $H_{(r)}$) at one side of the system as a major indicator for upper plate geometry (**c**; see also Fig 3); Φ: Necking faults; φ: R2 fault; Ψ: Main detachment fault; A-B: reference points for extension rate. Vertical exaggeration: 1.6.

Fig. 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_1 and STS_2) [*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_2 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_2; *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 STS1 and STS2 sedimentation along rifted margin section.

Fig. 4: (**a-b**): Location and simplified geological-structural map of the study area [from *Siegesmund et al.*, 2008; *Schumacher*, 1997; modified]. Key location cited in the text: In: Invorio; 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 et al.*, 2015a]. 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 et al.* [2015a], (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].

Fig. 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 Fig. 4. See text for detailed description. Relevant GPS points are indicated in Lat/Long decimal degrees. Please note the different scales.

Fig 6: (**a**): Monogenic breccia with cm to dm clasts of Triassic dolostones and sparse

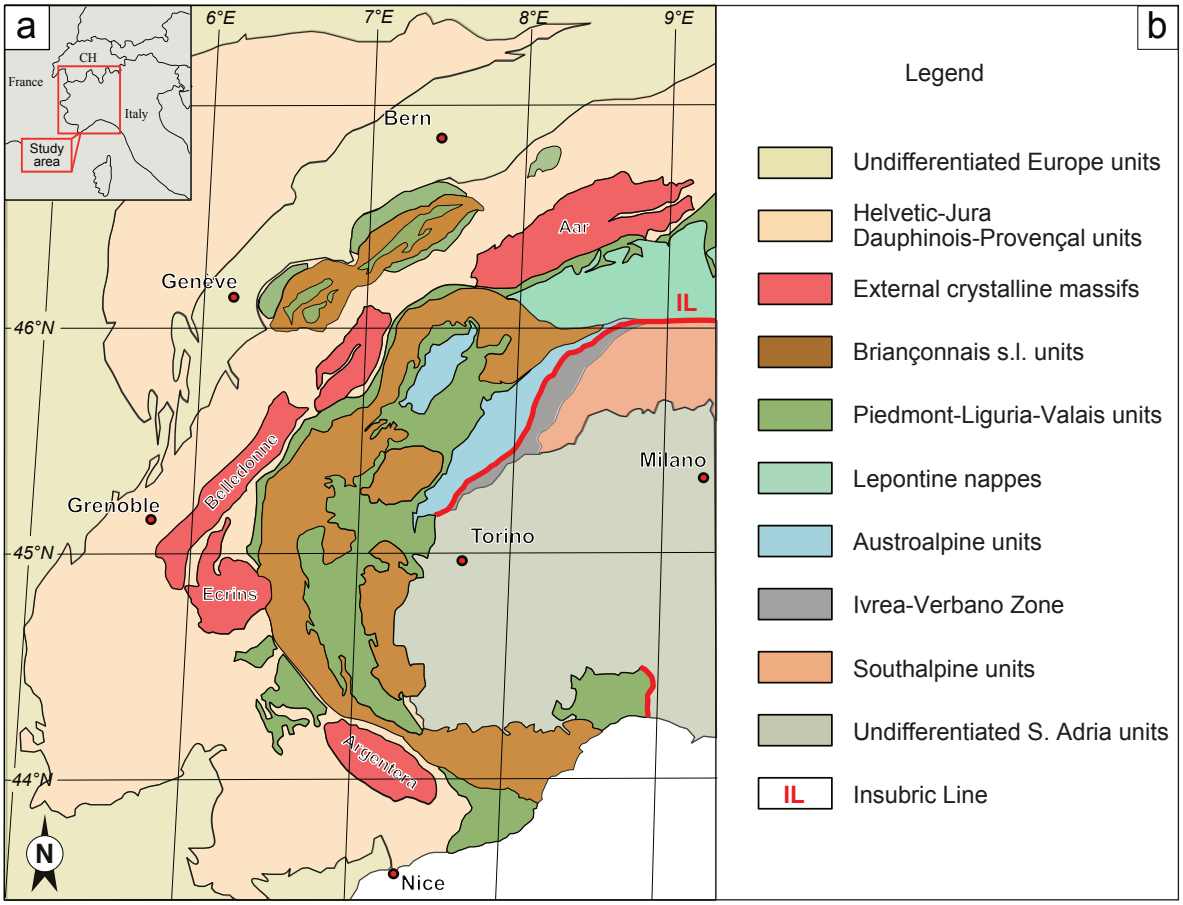
fragments of reddish pelite (palaeosol?); Arona. (**b**): Polygenic breccia with dolostone (dls), basement (bs) and riolyte (ri) clasts; Invorio. (**c**): Reddish calcarenite of Lithozone A, with widespread evidences for diffused fluid circulation; Gozzano. (**d**): Interpretative sketch from *Montanari* [1969] of the angular unconformity between U. Sinemurian - L. Pliensbachian (Lithozone A) and U. Pliensbachian (Lithozone B) deposits; Gozzano. (**e**): Microconglomerate 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 sub-cm to dm in size are formed by dolostone. (**g**): Tectonostratigraphic 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 occurr. (**h**): Middle Jurassic siliceous schists associated to the Radiolarite Formation near Bric Filia (Canavese Zone).

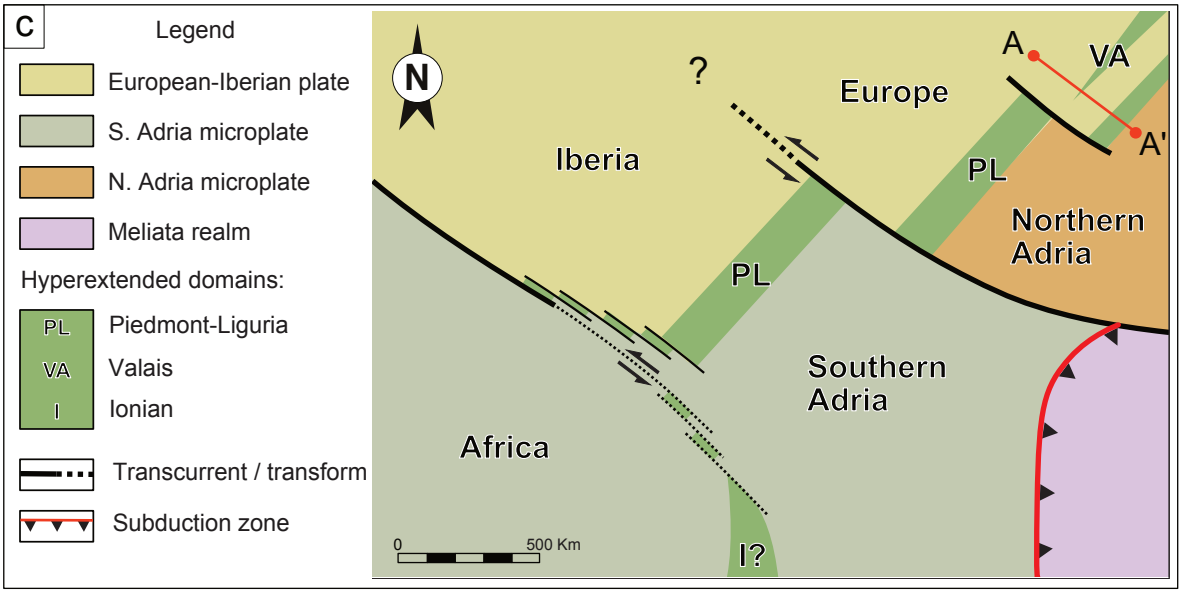
Fig. 7 (a) Simplified reconstruction of the Adriatic margin during the Middle Jurassic from Lombardy basin to the Canavese Zone, from *Beltrando et al.* [2015], mod. For locations see Fig. 4. (b) Conceptual 3D model of the distal sector of the Southern Adria margin. See text for detailed explanation. Locations and fault abbreviations as in Fig. 4. (**b**): 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 inheredited line.

Fig. 8 (**a**-**b**): Location and interpretative map of the Alps where major tectonic units are mapped as rifting domain [*Haupert 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.

Figure 1.


a
6°E
7°E
8°E
9°E
CH
France
Italy
Study area
Bern
Aar
Genève
IL
46°N
Milano
Grenoble
Belledonne
Torino
45°N
Ecrins
Argentera
44°N
N
Nice
b
Legend
Undifferentiated Europe units
Helvetic-Jura
Dauphinois-Provençal units
External crystalline massifs
Briançonnais s.l. units
Piedmont-Liguria-Valais units
Lepontine nappes
Austroalpine units
Ivrea-Verbano Zone
Southalpine units
Undifferentiated S. Adria units
IL
Insubric Line


c
Legend
European-Iberian plate
S. Adria microplate
N. Adria microplate
Meliata realm
Hyperextended domains:
PL
VA
I
Piedmont-Liguria
Valais
Ionian
Transcurrent / transform
Subduction zone
N
?
Europe
A
VA
A'
Iberia
PL
Northern
Adria
PL
Southern
Adria
Africa
0
500 Km
I?

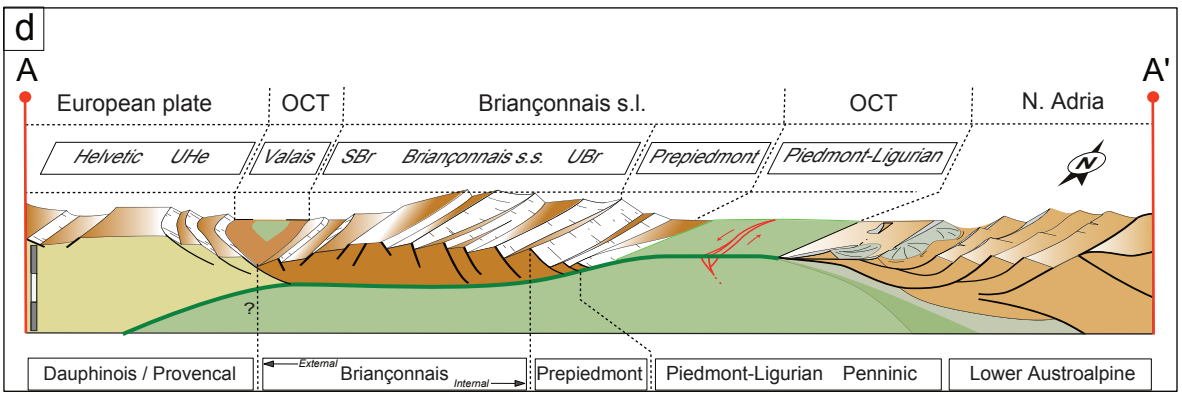

d
A
A'
European plate
OCT
Briançonnais s.l.
OCT
N. Adria
Helvetic
UHe
Valais
SBr
Briançonnais s.s.
UBr
Prepiedmont
Piedmont-Ligurian
N
?
Dauphinois / Provencal
External
Briançonnais
Internal
Prepiedmont
Piedmont-Ligurian
Penninic
Lower Austroalpine

Figure 2.

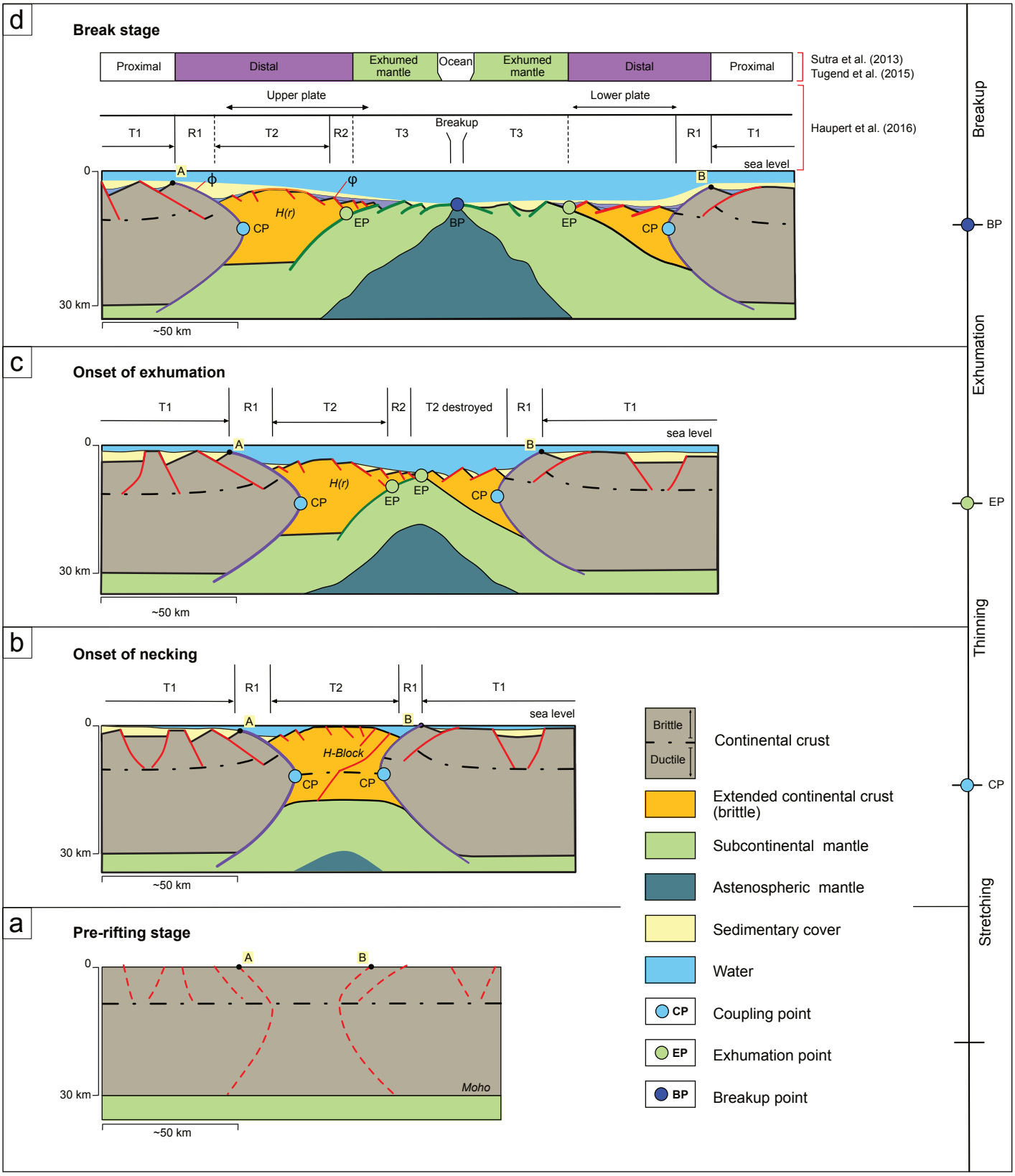

d
Break stage
Proximal
Distal
Exhumed mantle
Ocean
Exhumed mantle
Distal
Proximal
Sutra et al. (2013)
Tugend et al. (2015)
Upper plate
Lower plate
T1
R1
T2
R2
T3
Breakup
T3
R1
T1
Haupert et al. (2016)
sea level
0
A
B
ϕ
φ
H(r)
CP
EP
BP
EP
CP
30 km
~50 km
c
Onset of exhumation
T1
R1
T2
R2
T2 destroyed
R1
T1
sea level
0
A
B
H(r)
CP
EP
EP
CP
30 km
~50 km
b
Onset of necking
T1
R1
T2
R1
T1
sea level
0
A
B
H-Block
CP
CP
30 km
~50 km
a
Pre-rifting stage
0
A
B
30 km
Moho
~50 km
Brittle
Ductile
Continental crust
Extended continental crust (brittle)
Subcontinental mantle
Astenospheric mantle
Sedimentary cover
Water
CP
Coupling point
EP
Exhumation point
BP
Breakup point
Breakup
BP
Exhumation
EP
Thinning
CP
Stretching

Figure 3.

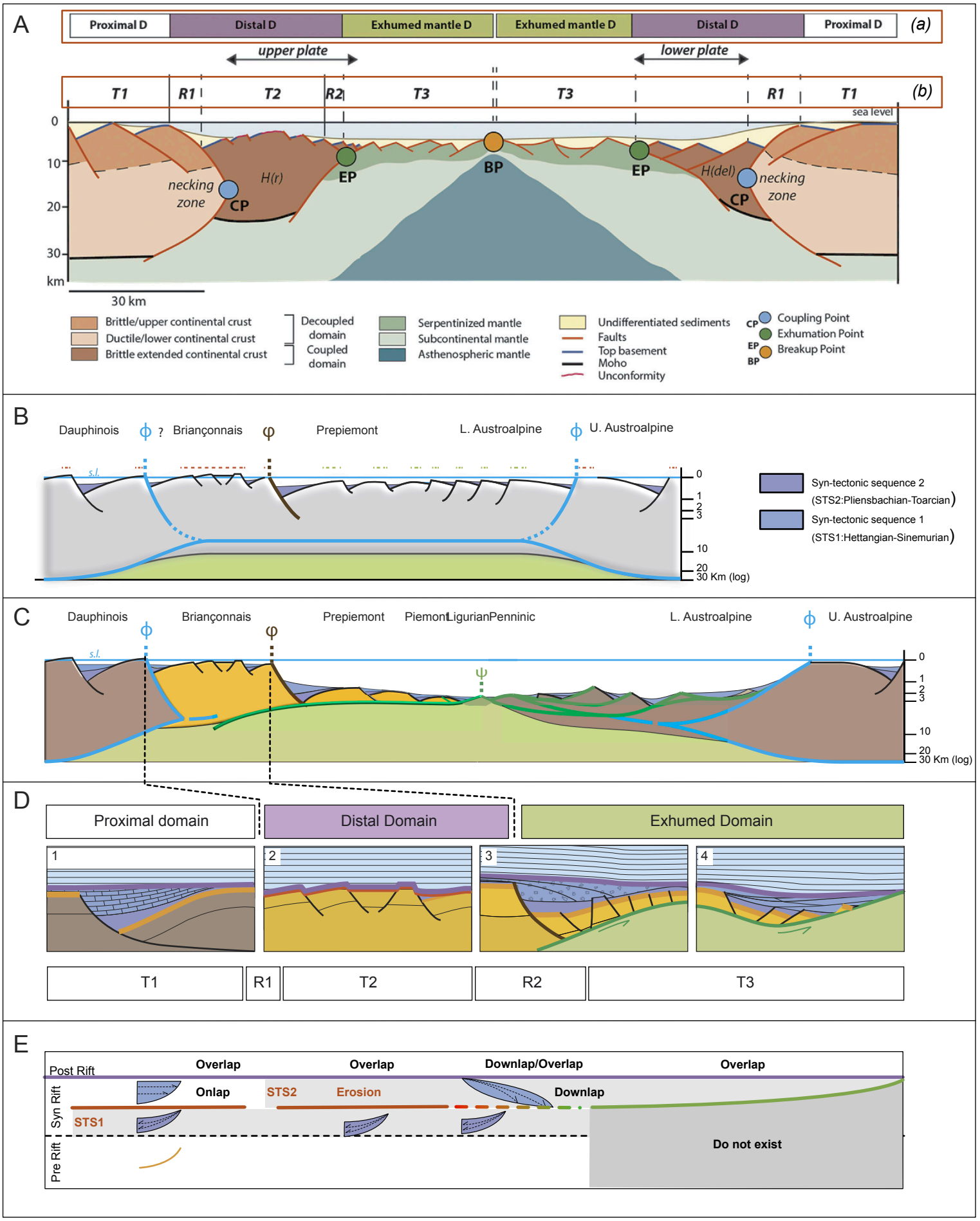
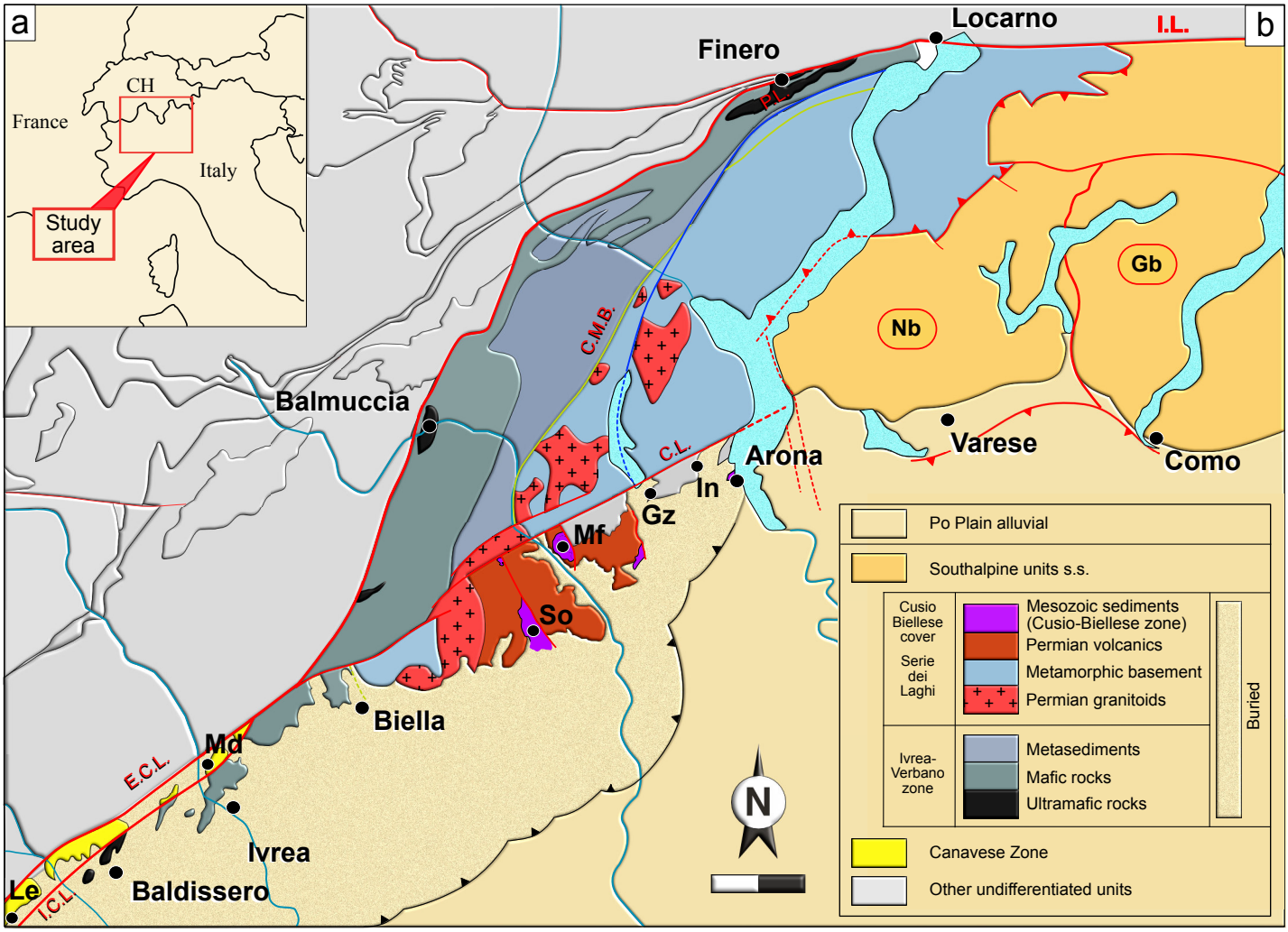

A
Proximal D
Distal D
Exhumed mantle D
Exhumed mantle D
Distal D
Proximal D
(a)
upper plate
lower plate
T1
R1
T2
R2
T3
T3
R1
T1
(b)
sea level
0
10
20
30
km
necking zone
H(r)
CP
EP
BP
EP
H(del)
CP
necking zone
30 km
Brittle/upper continental crust
Ductile/lower continental crust
Brittle extended continental crust
Decoupled domain
Coupled domain
Serpentinized mantle
Subcontinental mantle
Asthenospheric mantle
Undifferentiated sediments
Faults
Top basement
Moho
Unconformity
CP Coupling Point
Exhumation Point
EP
BP Breakup Point
B
Dauphinois
?
Briançonnais
Prepiemont
L. Austroalpine
U. Austroalpine
s.l.
0
1
2
3
10
20
30 Km (log)
Syn-tectonic sequence 2
(STS2:Pliensbachian-Toarcian)
Syn-tectonic sequence 1
(STS1:Hettangian-Sinemurian)
C
Dauphinois
Briançonnais
Prepiemont
Piemont
Ligurian
Penninic
L. Austroalpine
U. Austroalpine
s.l.
0
1
2
3
10
20
30 Km (log)
D
Proximal domain
Distal Domain
Exhumed Domain
1
2
3
4
T1
R1
T2
R2
T3
E
Post Rift
Syn Rift
Pre Rift
Overlap
Overlap
Downlap/Overlap
Overlap
Onlap
STS2
Erosion
Downlap
STS1
Do not exist

Figure 4.


a
CH
France
Italy
Study area
b
Locarno
I.L.
Finero
P.L.
C.M.B.
Balmuccia
C.L.
Arona
In
Gz
Mf
So
Biella
Md
E.C.L.
Ivrea
Le
I.C.L.
Baldissero
Gb
Nb
Varese
Como
N
Po Plain alluvial
Southalpine units s.s.
Cusio Biellese cover
Serie dei Laghi
Mesozoic sediments (Cusio-Biellese zone)
Permian volcanics
Metamorphic basement
Permian granitoids
Buried
Ivrea-Verbano zone
Metasediments
Mafic rocks
Ultramafic rocks
Canavese Zone
Other undifferentiated units

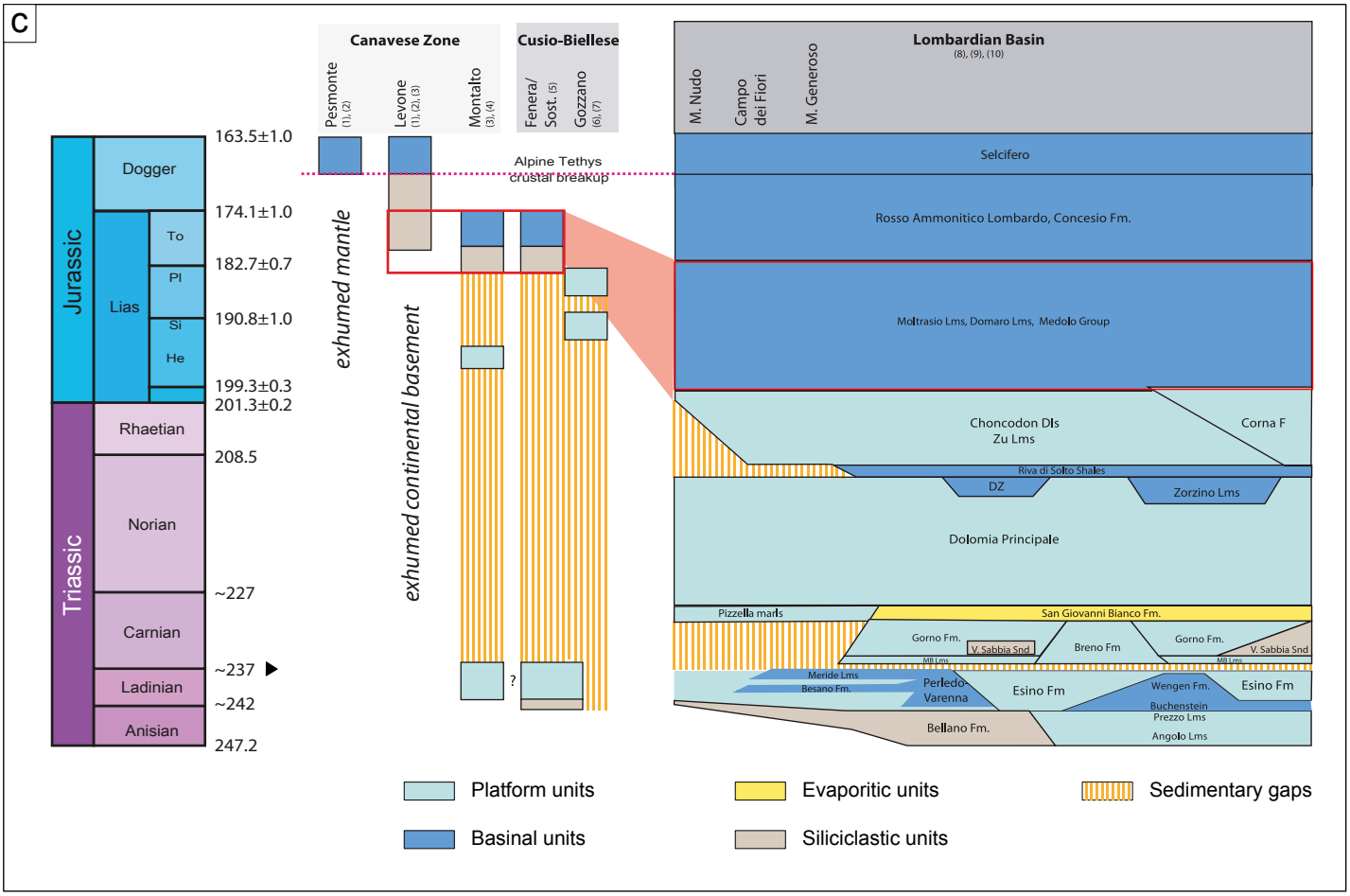

c
Canavese Zone
Cusio-Biellese
Pesmonte (1), (2)
Levone (1), (2), (3)
Montalto (3), (4)
Fenera/ Sost. (5)
Gozzano (6), (7)
Lombardian Basin (8), (9), (10)
M. Nudo
Campo dei Fiori
M. Generoso
Jurassic
Triassic
Dogger
Lias
To
Pl
Si
He
Rhaetian
Norian
Carnian
Ladinian
Anisian
163.5±1.0
174.1±1.0
182.7±0.7
190.8±1.0
199.3±0.3
201.3±0.2
208.5
~227
~237
~242
247.2
Alpine Tethys crustal breakup
exhumed mantle
exhumed continental basement
Selcifero
Rosso Ammonitico Lombardo, Concesio Fm.
Moltrasio Lms, Domaro Lms, Medolo Group
Choncodon Dls
Zu Lms
Corna F
Riva di Solto Shales
DZ
Zorzino Lms
Dolomia Principale
Pizzella marls
San Giovanni Bianco Fm.
Gorno Fm.
V. Sabbia Snd
MB Lms
Breno Fm
Meride Lms
Besano Fm.
Perledo-Varenna
Esino Fm
Wengen Fm.
Buchenstein
Prezzo Lms
Angolo Lms
Bellano Fm.
Platform units
Basinal units
Evaporitic units
Siliciclastic units
Sedimentary gaps

Figure 5.

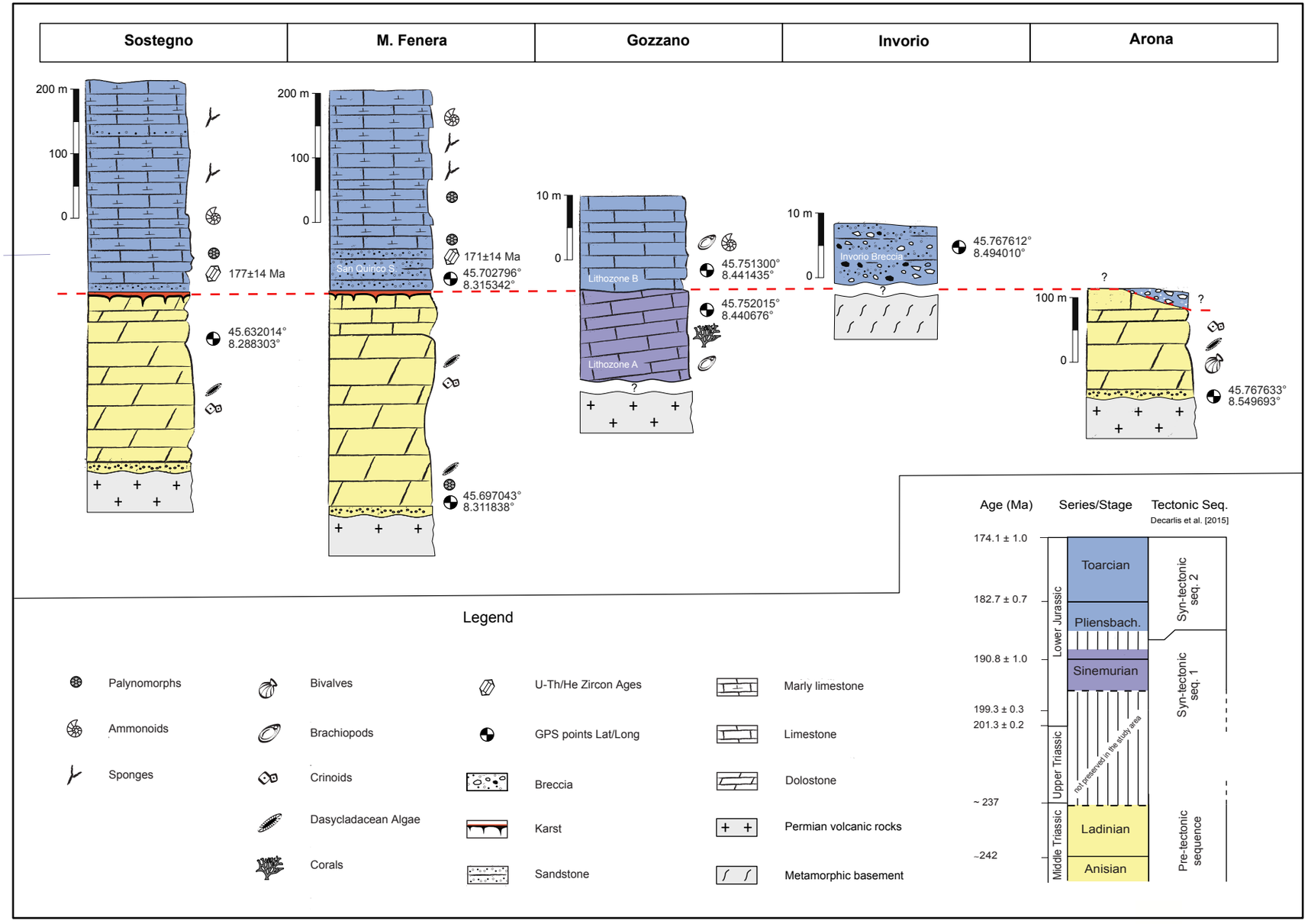
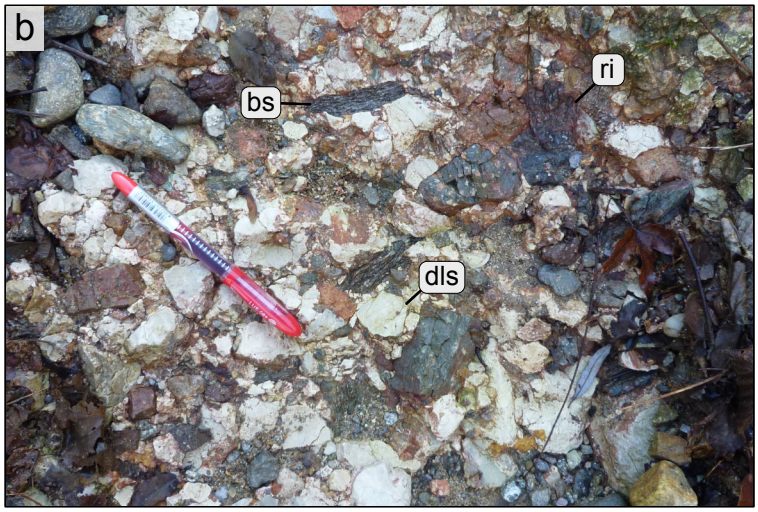
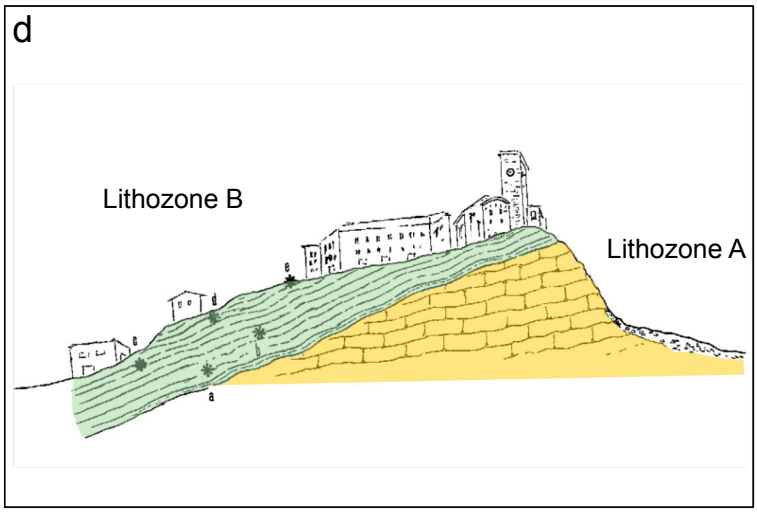

Sostegno
M. Fenera
Gozzano
Invorio
Arona
200 m
100
0
177±14 Ma
45.632014°
8.288303°
171±14 Ma
45.702796°
8.315342°
45.697043°
8.311838°
San Quirico S.
10 m
Lithozone B
Lithozone A
45.751300°
8.441435°
45.752015°
8.440676°
Invorio Breccia
45.767612°
8.494010°
100 m
45.767633°
8.549693°
Legend
Palynomorphs
Ammonoids
Sponges
Bivalves
Brachiopods
Crinoids
Dasycladacean Algae
Corals
U-Th/He Zircon Ages
GPS points Lat/Long
Breccia
Karst
Sandstone
Marly limestone
Limestone
Dolostone
Permian volcanic rocks
Metamorphic basement
Age (Ma)
Series/Stage
Tectonic Seq.
Decarlis et al. [2015]
174.1 ± 1.0
182.7 ± 0.7
190.8 ± 1.0
199.3 ± 0.3
201.3 ± 0.2
~ 237
~242
Lower Jurassic
Upper Triassic
Middle Triassic
Toarcian
Pliensbach.
Sinemurian
Ladinian
Anisian
not preserved in the study area
Syn-tectonic seq. 2
Syn-tectonic seq. 1
Pre-tectonic sequence

Figure 6.


a


b
bs
ri
dls


c


d
Lithozone B
Lithozone A


e


f


g

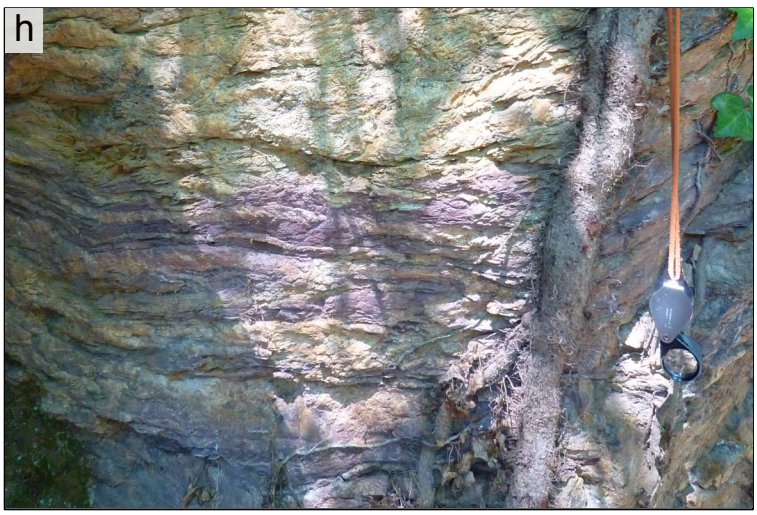

h

Figure 7.

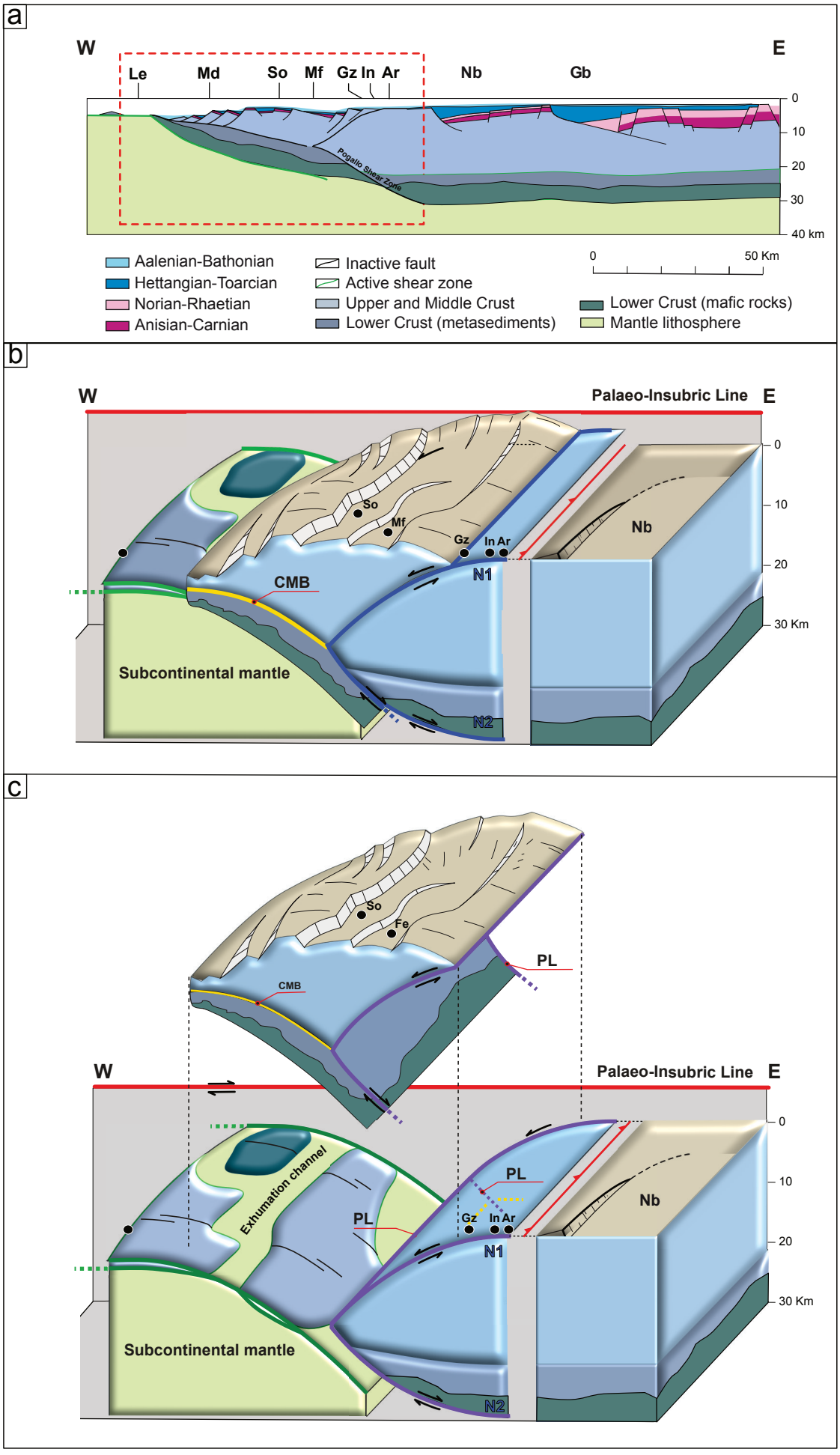
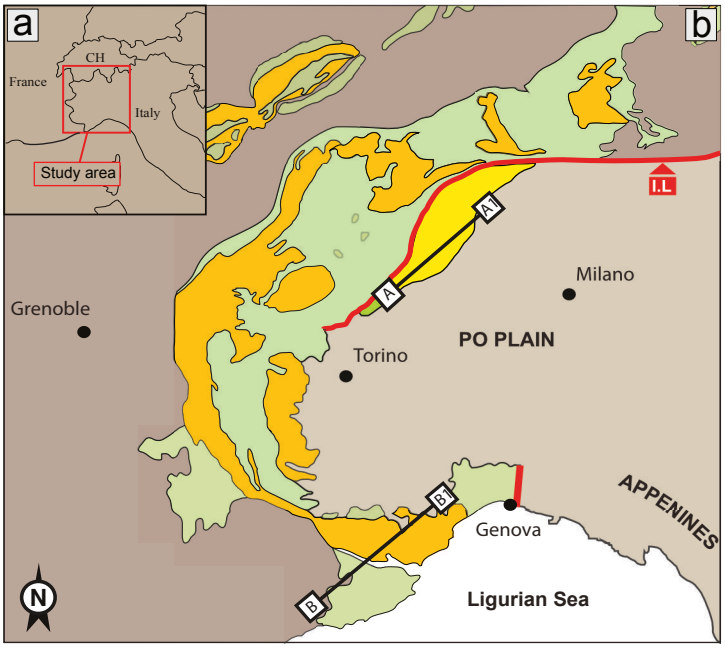
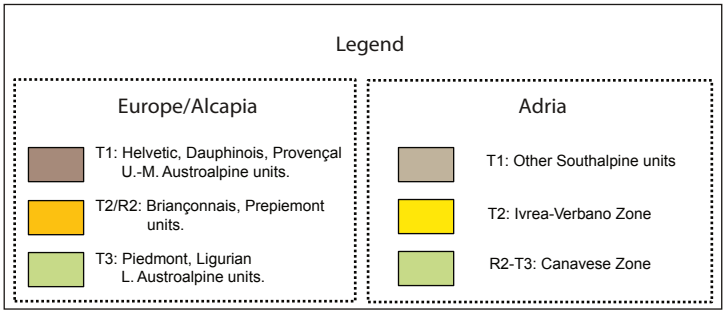
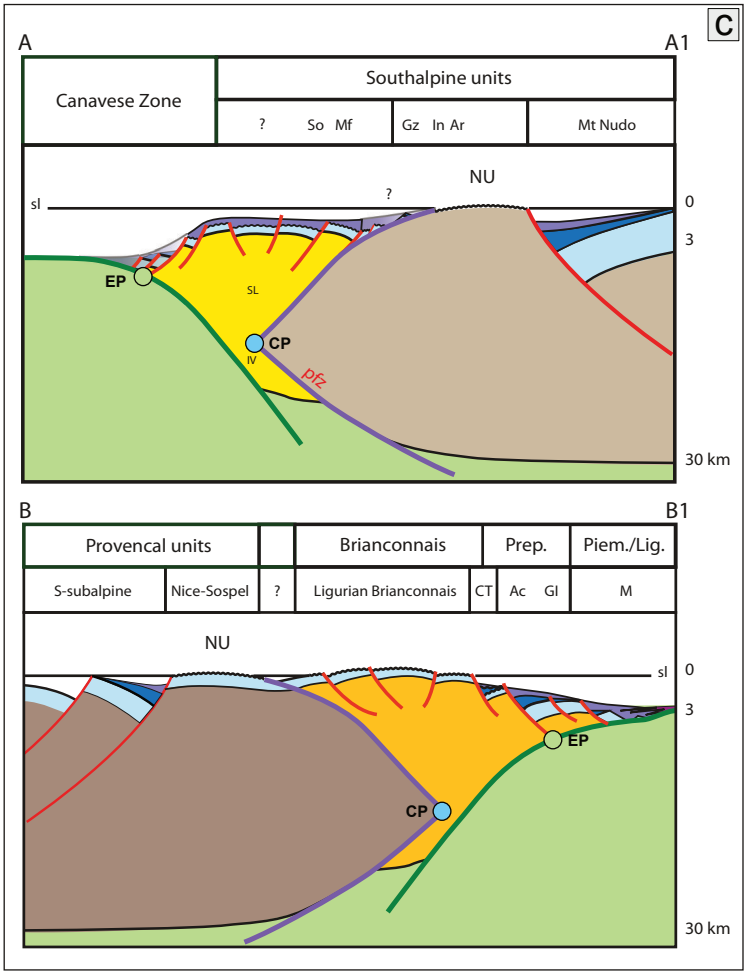
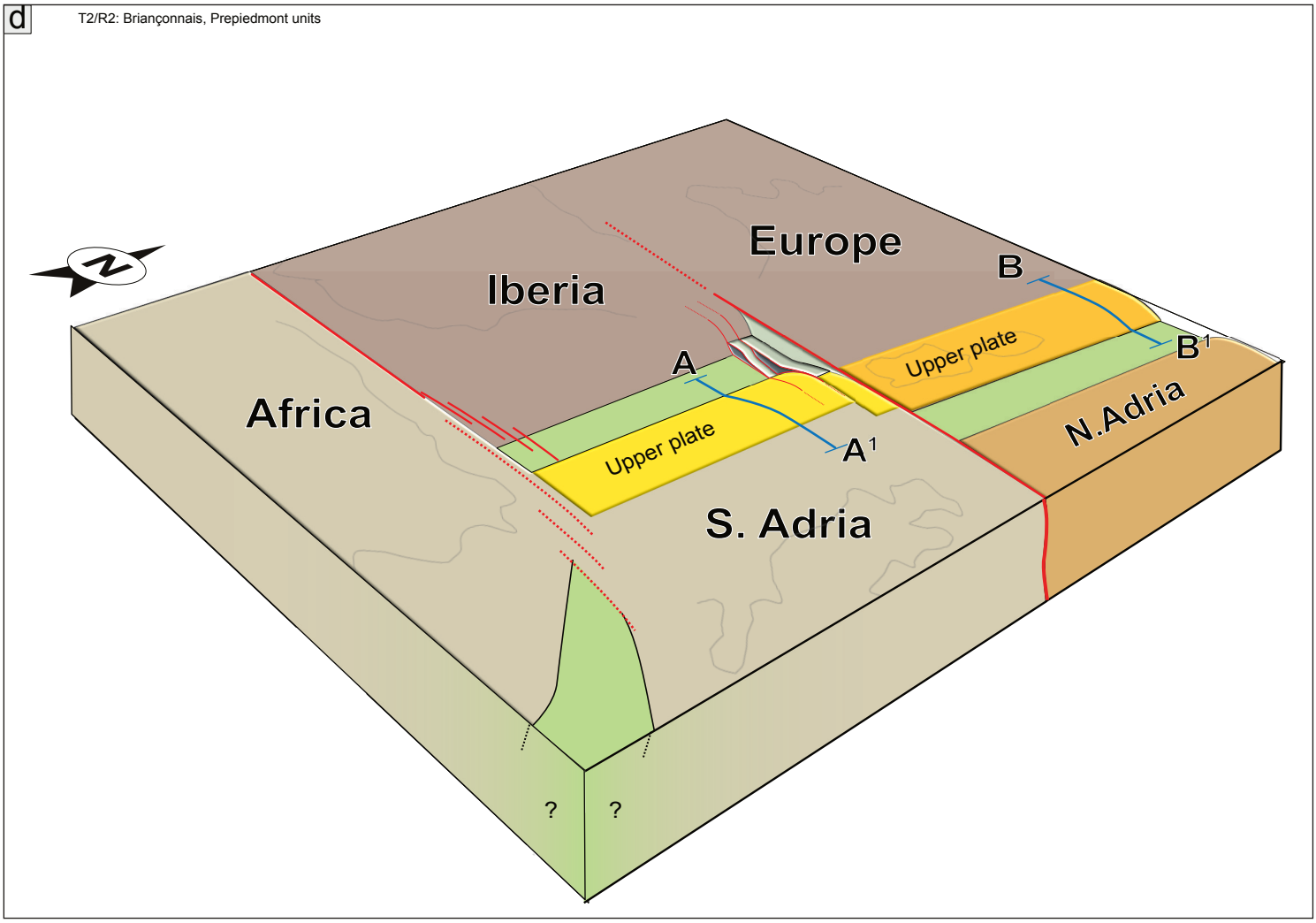

a
W
E
Le
Md
So
Mf
Gz
In
Ar
Nb
Gb
Pogallo Shear Zone
0
10
20
30
40 km
0
50 Km
Aalenian-Bathonian
Hettangian-Toarcian
Norian-Rhaetian
Anisian-Carnian
Inactive fault
Active shear zone
Upper and Middle Crust
Lower Crust (metasediments)
Lower Crust (mafic rocks)
Mantle lithosphere
b
W
Palaeo-Insubric Line
E
So
Mf
Gz
In
Ar
Nb
CMB
N1
N2
Subcontinental mantle
0
10
20
30 Km
c
So
Fe
PL
CMB
W
Palaeo-Insubric Line
E
Exhumation channel
PL
PL
Gz
In
Ar
Nb
N1
N2
Subcontinental mantle
0
10
20
30 Km

Figure 8.


a
CH
France
Italy
Study area
b
I.L
Milano
Grenoble
Torino
PO PLAIN
APPENINES
Genova
Ligurian Sea
A
A1
B
B1
N


Legend
Europe/Alcapia
T1: Helvetic, Dauphinois, Provençal U.-M. Austroalpine units.
T2/R2: Briançonnais, Prepiemont units.
T3: Piedmont, Ligurian L. Austroalpine units.
Adria
T1: Other Southalpine units
T2: Ivrea-Verbano Zone
R2-T3: Canavese Zone


c
A
A1
Canavese Zone
Southalpine units
? So Mf
Gz In Ar
Mt Nudo
NU
sl
?
0
3
EP
SL
CP
IV
pfz
30 km
B
B1
Provencal units
Brianconnais
Prep.
Piem./Lig.
S-subalpine
Nice-Sospel
?
Ligurian Brianconnais
CT
Ac Gl
M
NU
sl
0
3
EP
CP
30 km


d
T2/R2: Briançonnais, Prepiedmont units
N
Europe
Iberia
Africa
B
A
Upper plate
Upper plate
B1
A1
N.Adria
S. Adria
?
?