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GEOLOGICAL SETTING OF THE SOUTHERN TERMINATION OF WESTERN ALPS

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Abstract

A revision of the stratigraphic and tectonic setting of the southern termination of the Western Alps, at the junction of the Maritime Alps with the westernmost Ligurian Alps, is proposed.

In response to the Alpine kinematic evolution a number of tectonic units formed on the deformed palaeo-European continental margin and were arranged in a NW–SE striking anastomosed pattern along the north-eastern boundary of the Argentera Massif. Because these tectonic units often cut across the paleogeographical subdivision of the Alpine literature and show only partial affinity with their distinctive stratigraphic features, new attributions are proposed. The Subbriançonnais domain is here intended as a "deformation zone" and its tectonic units have been attributed to Dauphinois and Provençal domains; furthermore, the Eocene Alpine Foreland Basin succession has been interpreted, based on the affinity of its lithologic characters and age, as a single feature resting above all the successions of the different Mesozoic domains.

The Cretaceous tectono-sedimentary evolution of the studied domains was characterized by intense tectonic controls on sedimentation inducing lateral variations of stratigraphic features and major hydrothermal phenomena. Since the early Oligocene, transpressional tectonics induced a NE–SW shortening, together with significant left- lateral movements followed by (late Oligocene–middle Miocene) right-lateral movements along E–W to SE–NW striking

shear zones. This induced the juxtaposition and/or stacking of Briançonnais, Dauphinois and Ligurian tectonic units characterized by different metamorphic histories, from anchizonal to lower greenschist facies. This evolution resulted in the arrangement of the tectonostratigraphic units in a wide “transfer zone” accomodating the Oligocene WNW-ward movement of portions of the palaeo-European margin placed at the south-western termination of Western Alps and the Miocene dextral shearing along SE-striking faults that bound the Argentera Massif on its NE side.

Keywords

Briançonnais, Provençal and Dauphinois successions, Maritime Alps, Western Ligurian Alps, Alpine-orogen transpression, pre-Alpine tectonic inheritance

1. INTRODUCTION

The southern termination of the Western Alps, in the region of Maritime and Western Ligurian Alps (between Col de Larche to the West and the upper Tanaro Valley to the East) is characterized by a complex transpressive tectonic system comprised between the External Briançonnais Front (Michard et al. 2004; Tricart 2004), the boundary fault systems of the Argentera Massif (Sanchez et al. 2011a with references therein) and the recently identified Limone-Viozene zone (Piana et al. 2009) **(Fig. 1).** This region, in which the transition from internal high pressure metamorphic rocks to external very low grade and non-metamorphic rocks occurs, consists of an assemblage of juxtaposed tectonic units aligned on average ESE–WNW direction (Malaroda 1970; Gidon 1972). These units were inferred to be geometrically arranged within a regional-scale strike-slip zone referred to as the “Stura couloir” or “Stura Fault” (Laubscher 1971; Guillaume 1980, Giglia et al. 1986). The occurrence, age, and kinematics of this major structure, however, were postulated almost exclusively on the basis of regional models invoking the development of a strike-slip fault zone at the southern boundary of the Western Alps arc starting from the Oligocene (e.g. Dumont et al. 2012). Despite a supposed important Kinematic role in the post-Eocene

53 evolution of the Western Alps, its direct evidence is still very poorly documented (see
54 discussion below). The main purpose of this work is therefore to fill such a knowledge gap
55 providing a critical revision of the stratigraphic and structural data available and an
56 exhaustive description of the tectonic units throughout the Maritime–Ligurian Alps junction.
57 The original data presented below allow to characterize the stratigraphic and structural
58 setting of each of the units, in order to revise their palaeogeographic position and give new
59 constraints for the interpretation of the kinematic evolution of the southern termination of the
60 Western Alps.
61 These goals have been pursued through: i) the individuation and precise mapping of km-
62 extended macroscale tectonic features that effectively bound the tectonic units (here
63 intended as rock bodies mappable at least at 1:250,000 scale); ii) the evaluation of the
64 affinity of the stratigraphic successions of the proposed units with those of the main
65 palaeogeographic domains of the Alpine geological literature.
66 In the Alpine geological literature the assumption that palaeogeographic units commonly
67 coincide with the main tectonic subdivisions has been widely adopted (e.g., Debelmas and
68 Kerckhove 1980, Lemoine et al. 1986). Since in the study region this is not always the case,
69 a revision of the customary terms and labels has been necessary, as well as a precise
70 localization of the main boundaries of the tectonic units.
71 Based on new tectonic maps (**Fig. 2, 3, 4)** and the detailed analysis of the stratigraphic
72 successions, we reconstruct the pre-Alpine and Alpine geologic history of the tectonic units
73 and we identified their main boundary faults[1].

74 *2. GENERAL STRATIGRAPHIC FEATURES OF SW-ALPS*

75 *PALAEOGEOGRAPHIC DOMAINS*

76 The Alpine tectonic units described in this work mostly consist of Mesozoic successions
77 resting on continental basement rocks and on Carboniferous–Permian volcanic and

1 *The original data of this work regard mostly the areas south of the Stura Valley (the Gesso, Sabbione, Vermenagna, upper Roya, Argentina and upper Tanaro valleys, Tenda Pass area and the Marguareis range) while for the northern part of the study area (Gardetta Pass–Demonte area) a careful revision of available data has been done, in order to homogenize, from NW to SE, the criteria on which the geological schemes are grounded.*

78 sedimentary rocks, and are overlain by middle Eocene–lower Oligocene Alpine Foreland
79 Basin successions. All these units are overthrust by Lower Cretaceous–lower Paleocene
80 Western Ligurian Flysch units that are also affected by steep transpressive shear zones
81 (Piana et al. 2009; 2014). The Mesozoic successions of the tectonic units were attributed
82 (Boillot et al. 1984; Lemoine et al. 1986) to the Briançonnais, Subbriançonnais, Dauphinois
83 and Provençal palaeogeographic domains, individualized during the Late Triassic–Middle
84 Jurassic rifting in the newly forming European passive continental margin.

85 ## 2.1 The Mesozoic succession of the Dauphinois and Provençal Domains

86 The Dauphinois Domain, together with its southern continuation, i.e. the Provençal Domain,
87 represents the more internal part of the European proximal margin (Debelmas and
88 Kerchove, 1980; Mohn et al. 2010) developed above continental crust (External Crystalline
89 Massifs, i.e. the Argentera Massif in the study area). The succession starts with Lower
90 Triassic coastal deposits resting on Carboniferous–Permian continental sediments, followed
91 by Middle Triassic peritidal carbonates and Upper Triassic pelites. Starting from the Late
92 Triassic–Early Jurassic, the Dauphinois Domain was affected by intracontinental rifting and
93 partitioned into fault-bounded rift-basins (Lemoine et al. 1986). From Early Jurassic to Early
94 Cretaceous the Dauphinois Domain progressively subsided and thick successions of deep
95 water marls, limestones and shales with interbedded resedimented calcirudites and
96 calcarenites were deposited, while the Provençal Domain remained in shallow water
97 conditions with the development of a carbonate platform (Faure.Muret 1955).
98 In the study area the Dauphinois succession continues with an Upper Cretaceous unit
99 composed of several hundred meters of hemipelagic marly limestones including platform-
100 derived bioclastic layers in the western sector (Sturani 1962; Bersezio et al. 2002) and layers
101 rich in siliciclastic or dolomite clasts in the eastern sector (Malaroda 1963; Barale et al.
102 2015). In the Provençal Domain, the Upper Cretaceous hemipelagic marly limestones bear
103 very scarse detrital levels (Lanteaume 1968; Varrone 2004; Varrone and d'Atri 2007).

2.2 The Mesozoic succession of the Briançonnais Domain (and Ligurian Briançonnais Domain)

The Briançonnais Domain represents a portion of the European continental margin located between the Mesozoic Ligurian–Piemonte basin and the Dauphinois and Provençal Domains. In the northern part of the Alps the Briançonnais Domain was separated from the proximal margin by the Valais oceanic basin that progressively wedged out toward the south (Mohn et al. 2010; Masini et al. 2013) finally disappearing in the SW Alps.

The stratigraphy of the Briançonnais starts with Lower Triassic fluvial to littoral conglomerates, quartzarenites and lagoonal mudrocks, followed by a Middle Triassic peritidal carbonate succession. This is overlain by an unconformity corresponding to a Late Triassic to Middle Jurassic stratigraphic hiatus due to a regional uplift and related subaerial exposure during the Tethyan syn-rift stage (Decarlis and Lualdi 2008, Lemoine et al. 1987; Claudel and Dumont 1999). The succession continues with Middle Jurassic outer platform carbonate sediments and Upper Jurassic pelagic plateau limestones, followed by a mineralized hard ground — another important stratigraphic hiatus spanning the Early Cretaceous — and by Upper Cretaceous hemipelagic sediments.

The southeasternmost part of the Briançonnais Domain, outcropping in the present Ligurian Alps, is known as Ligurian Briançonnais Domain. While the external sectors of the Ligurian Briançonnais are characterized by a Mesozoic stratigraphy similar to the one of the rest of the Briançonnais (Bertok et al. 2011), the internal sectors show a more reduced succession, with a wider hiatus associated with the syn-rift Late Triassic to Middle Jurassic unconformity (Vanossi 1974; Vanossi et al. 1984).

2.3 The Mesozoic succession of the Subbriançonnais Domain

The Subbriançonnais is a term given to a number of tectonic slices occurring between the Briançonnais and Dauphinois/Provençal Domains, often interpreted as a distinct palaeogeographic domain both in the study area (Malaroda 1970) and in sectors of the Western Alps located further north (Barbier 1948; Barfety et al. 1995; Fügenschuh et al.

1999). The Subbriançonnais did not experience the Late Triassic–Early Jurassic emersion characteristic of the Briançonnais Domain, and is characterized by strong lateral variations of the Mesozoic succession (Debelmas and Kerckhove 1980; Mohn et al. 2010). The basement of the Subbriançonnais units is not known because the succession is everywhere detached along weak Triassic mudrocks. The oldest outcropping term of the stratigraphic succession is represented by Middle–Upper Triassic peritidal carbonates and Lower Jurassic bioclastic and cherty limestones.

The Middle Jurassic succession varies significantly from NW to SE. In the upper Stura Valley area **(Fig. 2)** it consists of deep-water facies (Carraro et al. 1970) whereas in the Tenda Pass **(Fig. 2,)** it is composed of a thick platform limestone succession, locally dolomitized (Barale et al. 2013, 2015). The Cretaceous interval, mainly made up of marly limestones, also shows important lateral variations in thickness, from more than one hundred meters (Roaschia Valley, Zappi 1960) to nil in the Tenda pass area and NW of Valdieri in the Gesso Valley (**Fig. 2).**

In the study area, the Subbriançonnais successions were mapped by Malaroda (1970) from the upper Stura Valley southeastward to the Colle di Tenda area between the Ligurian Briançonnais units to NE and the Dauphinois and Provençal units to SW and labelled as Colle di Tenda unit. In this paper the term Subbriançonnais will not be used to describe a distinct palaeogeographic domain, since the tectonic units individuated in the former Subbriançonnais outcropping area do not really show distinct stratigraphic features, but conversely belong either to the Dauphinois or Provençal Domain (see section 4.1).

2.4 The Alpine Foreland Basin

In all the palaeogeographic domains the top of the Mesozoic successions is truncated by a regional discontinuity surface, corresponding to an important hiatus (latest Cretaceous–middle Eocene), due to a prolonged subaerial exposure related to a significant uplift of the Mesozoic European margin during the first stages of Alpine collision (Crampton and Allen 1995). The subsequent lithospheric flexure produced the Alpine Foreland Basin where a

158 middle Eocene–lower Oligocene succession was unconformably deposited (Sinclair 1997;
159 Ford et al. 1999; Varrone and Clari 2003; Varrone and d'Atri 2007): it consists of
160 discontinuous continental to lagoonal deposits followed by ramp sediments, hemipelagic
161 marls and a thick turbidite succession.

162 2.5 The Western Ligurian Flysch

163 The *Helminthoides* Flysch units (Carraro et al. 1970; Sagri 1980, 1984; Vanossi 1991), also
164 known as "Embrunais–Ubaye nappes" north of the Argentera Massif (Kerckhove 1969;
165 Dumont et al. 2012), are a stack of tectonic units (here named Western Ligurian Flysch
166 units) composed of Lower Cretaceous–lower Paleocene deep-water sediments detached
167 from their original basement and referred to the Ligurian Domain. In the study area the
168 Western Ligurian Flysch units are thrust over the Alpine Foreland Basin succession.

169 2.6 The Argentera Massif

170 The Argentera Massif, here thought as exposed analogue of the subsurface basement of the
171 above described Mesozoic successions, is composed of Variscan migmatites with abundant
172 relicts of pre-anatectic rock types (Compagnoni et al. 2010). It consists of the Gesso–Stura–
173 Vésubie (GSV) Terrane to the NE and of the Tinée Terrane to the SW, which are separated
174 by the NW–SE Ferriere–Mollières shear zone (100 to 1000 m thick) that includes
175 metasedimentary rocks and mylonites derived from high-grade metamorphic rocks
176 (Bogdanoff 1986). The Argentera Massif underwent a tectonic uplift since 33 Ma which could
177 be induced, at least since 22 Ma (Sanchez et al. 2011a; 2011b), by the transcurrent
178 movements along the major NW-SE striking, right lateral ductile to brittle faults in response
179 to N–S shortening. At 22–20 Ma basement rocks now exposed at the surface were still being
180 exhumed in the ductile regime (below the annealing zone of the zircon; Bigot-Cormier et al.
181 2006). Apatite fission track and (U–Th)/He data suggest that the Argentera Massif
182 experienced ongoing exhumation between 12 and 5 Ma with a transition from
183 transpressional to transtensional regimes at 8–5 Ma, according to Sanchez et al. (2011a), or
184 between 6 and 3.5 Ma (Bigot-Cormier et al. 2006).

3. STRUCTURAL SETTING

In this chapter a brief description of the structural setting at the southern termination of the Western Alps (section 3.1.) and the relevant deformation events (section 3.2.) is provided. In section 3.3. the tectonic units resulting from the evolution delineated above are described in detail.

3.1. Structural setting at the southern termination of the Western Alps.

At the crustal scale (down to the depth of about 15 km) the structural setting of the southern termination of the Western Alps can be depicted as a double vergent tectonic system. The main thrusts and transpressive fault systems NE-vergent to the north of the External Briançonnais Front and SW-vergent to the south of it. The development of the main tectonic structures of the region, as well as its present seismicity, have also been related to the presence at depth of a high-density rock body, known as "Ivrea Body" (Schreiber et al. 2010). In map view, the External and Internal Briançonnais Fronts, as well as the Piemonte Zone Front, get closer to each other from West to East, while changing their directions from NW-SE to West-East, almost merging together in the Stura valley, East of Aisone (**Fig. 1, 2**). This marked deflection of tectonic fronts and the strong reduction of thickness of the main structural domains are so relevant in map-view (**Fig. 1**) that several authors were induced since the early ‘70s to evoke the presence of a regional-scale shear zone known as the “Stura couloir” or “Stura Fault” (Laubscher, 1971; Guillaume, 1980). The “Stura Fault” should have represented the left-lateral “*southern disengaging lineament”* (Giglia et al. 1986) necessary for the westward indentation of Adria promontory and subsequent formation of the Western Alps arc. Furthermore, Giglia et al. (1986) interpreted the “Stura couloir *Auctorum*" as a 40 km long, 5–7 km wide zone where several tectonic lines display a sinistral strike-slip component. The strong telescoping of the Briançonnais units, which have been reduced to a total width of a few kilometers (**Fig. 1**), should be an evidence that the “Stura couloir" acted as a shear zone. This should be demonstrated also by the rotation of the Briançonnais front, which strikes N–S in the Pelvoux area, N150 in the Ubaye area, to a N100–110 in the upper

212 Stura Valley and resumes a N140–150 strike in the Western Ligurian Alps (**Fig.1**). However,
213 the effective structural configuration (or even the existence!) of the Stura Fault is not evident
214 in the field. The two geological maps available for the region (Malaroda 1970; Gidon 1972)
215 do not report or refer to this feature. On the other hand, some field evidence of the Stura
216 Fault-related shearing are given by E–W sinistral strike-slip faults, by a marked N110 striking
217 schistosity reactivated by sinistral strike-slip movements and by asymmetric folds with
218 vertical axes (Ricou 1981). Another important feature is the WNW–ESE striking fault known
219 as “Preit scar" (Lefèvre 1983, location in **Fig. 2**), which should have juxtaposed distinct
220 internal Briançonnais units with a sinistral offset of some tens of kilometers.
221 In this section we will go beyond the debate on the Stura Fault existence, describing the
222 structure and composition of the juxtaposed tectonic units that crop out from the Col de
223 Larche in the Maritime Alps (NW) to the upper Tanaro Valley (SE) in the Western Ligurian
224 Alps. The problem of the Stura Fault structural setting and kinematics will be addressed
225 below, also in relation with two adjoining major deformation zones (**Fig. 2**): the Demonte–
226 Aisone Zone already mapped (although not explicitly described) in Malaroda (1970) and the
227 Limone–Viozene Zone of Piana et al. (2009) (see **Fig. 3, 4**).

228 ## 3.2. Deformation events in the study region

229 Following N-S Africa-Europe convergence and the related subduction-accretion phase
230 during the Eocene (Schwartz et al. 2000; Lanari et al., 2014) the southwestern Alps were
231 affected by a contractional tectonic evolution characterized by SW-vergent thrusting onto the
232 European foreland (Ford et al. 2006) active since the early Oligocene (Simon-Labric et al.
233 2009), and back-thrusting onto the hinterland (Michard et al. 2004).
234 The first tectonic event (and related “D1” deformational events) is here intended as a long-
235 lasting composite stage resulting from both the subductive–accretionary processes. During
236 this stage the tectonic units experienced different grades of metamorphism depending on
237 their position within the orogenic wedge (Michard et al. 2004; Seno et al. 2005). These first
238 collisional exhumation processes were responsible for the piling up of the Briançonnais SW-

239 vergent thrusts and transpressive shear zones described by Brizio et al. (1983) and
240 Carminati and Gosso (2000) for the Western LIgurian area and Michard et al. (2004) for the
241 Acceglio zone (**Fig. 1** for location).
242 Two later stages (D2 and D3 deformational events, characterized by plastic-to-frictional
243 shearing in lower greenschist metamorphic conditions) developed at progressively higher
244 structural levels and, especially as regards the study area, mostly in a dextral transpressive
245 setting (Michard et al. 2004; Tricart 2004; Piana et al. 2009; Sanchez et al. 2011a; 2011b).
246 This paper, although supported by a revision of the geological setting of the whole Maritime-
247 West Ligurian Alps junction (e.g. Barale et al., 2015), focuses mainly on the geometry and
248 kinematics of the boundaries of the several newly defined tectonic units (see below). This
249 choice was made not only for the sake of brevity, but also because the present setting of the
250 study area is essentially due to syn-D2 and D3 shear zones or shear planes, generally
251 steep, that are responsible for alignement of the units along an average WNW–ESE
252 direction (with a slightly anastomesed pattern, **Fig. 2**). This occurred in many places,
253 although the internal structural setting of the units can be more complex in certain
254 stratigraphic levels (e.g. upper Cretaceous succession), where the superposed F1 and F2
255 folding events can generate a more complex rock distribution. The syn-D2–D3 shears are in
256 turn displaced, but with minor extent, by later purely brittle fault systems. Some original
257 mesostructural data are also reported (**Fig. 5**) that refer solely to the main deformation zone
258 of the study area, the LiVZ (see also Piana et al., 2009), since it seems to summarise most
259 of the kinematic features of the above cited tectonic boundaries.
260 The main structural associations of the three deformational events are described as follows
261 (see **Fig. 6** for details):
262 *Deformational event D1-*
263 D1 generated the oldest composite tectonic foliation (S1, Brizio et al. 1983), locally axial-
264 planar to F1 macroscale recumbent folds (**Fig. 6a**) and syn-D1 shear zones ("*charriages*"
265 *Auctorum*; Gidon, 1972; Lèfevre,1983). In the External Briançonnais an earliest foliation
266 (S0), generated by pressure dissolution processes along bedding planes also occurs,

267 probably resulting from pre-tectonic, iso-oriented lithostatic load (Piana et al. 2009). Within
268 the main shear zones of the study area the S1 foliation formed mostly steep and parallel to
269 the boundary shear planes and was successively reactivated by the development of the sub-
270 parallel S2. The sense of shear along the main shear zones during the D1 event was mainly
271 reverse and sinistral (**Fig. 5**). Since the D1 affect all the terms of the stratigraphic
272 successions, we can infer that this event could be at least early Oligocene in age, thus
273 originated mainly during the early Oligocene transpressive tectonics that, in the SW Alps,
274 has been interpreted (Dumont et al. 2012) as coeval with NW-ward regional tectonic
275 transport.
276 *Deformational event D2 -*
277 The folding phase D2, particularly well-exposed in the Briançonnais units, folded the D1
278 duplexes and reactivated the D1 steep transpressive shear zones. The F2 folds, mostly NE-
279 vergent, display rather constant NW-trending axes, gently dipping to NW or SE, and axial
280 surfaces mainly dipping to SW. A well developed spaced crenulation cleavage (S2) is
281 associated to F2 folds. S2 planes are in several places reactivated and re-oriented by shear
282 deformation kinematically consistent with D2 phase that often induced the displacement or
283 partial transposition of F2 folds hinge zones (Brizio et al. 1983; Piana et al. 2009). In the
284 major transpressive shear zones (LiVZ) the S1 and S2 surfaces are almost subparallel and
285 often form a composite foliation (**Fig. 6d**). Within these highly strained domains the S2
286 foliation is steepened and lies almost parallel to the F2 fold axial surfaces (**see Fig. 5**), while
287 the fold axes are only partially rotated on a vertical plane roughly perpendicular to the fold
288 axial planes average strike. This suggests that within the main transpressive shear zones
289 the F2 folds did not form as strike-slip drag folds, but as compressional folds resolving the
290 contractional component within the shear zone, then passively rotated and steepened during
291 the progressive shearing stages (see also Piana et al., 2009).
292 It is here assumed that the D2 event originated mainly during the Chattian-Aquitanian (26–
293 20 Ma), since this is the first contractional events recorded at regional scale (in the Ligurian
294 Alps and in the adjoining syn-tectonic basin) after the early Oligocene re-organization of the

295 Alpine belt (the "Oligocene revolution" of Dumont et al., 2012). This age-span could
296 correspond, in the Maritime Alps and Western Ligurian Alps, to the switch from sinistral
297 tectonics to a compressional one (Maino et al. 2013), while the Tertiary Piemonte Basin
298 Oligocene outer shelf and slope sediments underwent contraction and a general uplift,
299 passing to inner shelf conditions in late Aquitanian–early Burdigalian times (Piana et al.
300 1997; Dela Pierre et al. 2003; Piana et al. 2006). This event induced the dextral reactivation
301 of the main NW–SE striking shear zones at regional scale (Sanchez et al. 2011a; Rolland et
302 al. 2012; Bauve et al. 2014), although in the study area sinistral movements are still locally
303 recorded along the D2 event (**see Fig. 5**) with shear reactivation of the S2 foliation (**Fig. 6b**).
304 *Deformational event D3* -
305 This deformation phase generated open folds (**Fig. 6c**) and mainly SW-vergent thrusts
306 (Barale et al., 2015). Regional foliations did not develop during D3, apart from a cm-spaced
307 dissolution cleavages that became, along syn-D3 reverse shear zones, a pervasive slip-
308 cleavage that can locally transpose the primary rock-fabric (**Fig. 6d**). During D3, shearing
309 effects along the LiVZ decreased as the boundary of the syn-S1+S2 are not always
310 reactivated by layer-parallel shearing, but locally displaced by syn-D3 reverse shear zones
311 and further by later NE-SW right-lateral faults.
312 It is here assumed that D3 could have originated during persistent middle Miocene
313 compressional regime characterized by N–S directed shortening (Jourdon et al., 2014)
314 corresponding to the deformation of the early Miocene succession and North-ward shifting of
315 the depocenters of Tertiary Piemonte Basin that occurred in late Serravallian times (Falletti
316 et al., 1995).
317 The relations between the above depicted kinematic evolution and the macro- and meso-
318 structural setting of the study area have been ideally sketched in **Fig. 7**, since a detailed
319 description of the actual configurations observed in the field are beyond the purpose of the
320 paper.

321 ## 3.3. Main tectonic units

A number of tectonic units are here defined on the basis of original field work and careful analysis of literature (Malaroda 1970; Carraro et al. 1970; Gidon 1972; Ricou 1981; Brizio et al. 1983; Lefèvre 1983; Lanteaume 1990; Carminati and Gosso 2000; Michard et al. 2004) and described below. The readers should refer to **Fig. 2 and Fig. 8** for map-view and stratigraphic correlation respectively.

Description starts with the list of the main tectonic contacts[2] which effectively bound the distinguished units and follows with the description of their internal setting.

3.3.1. Main boundary faults.

The structural evolution described in chapter 3.1 gave origin to several and different-orders tectonic structures, which represent the present boundary faults of the main units (see Fig. 2). These faults mostly consist of ductile to brittle shear zones developed during the D1-D2 tectonic stages and often reactivated in a purely frictional regime during D3 and post-D3 tectonic stages. Although the fundamental geometric relations between the units (superposition and/or juxtaposition) were probably achieved during the D1 deformational event, consistent with a general transpression and left-lateral shearing along the main WNW-ESE regional structural trend, the present-day geometric setting is probably mainly the result of the D2 and D3 deformational events, which ultimately defined the position and lenght of the geological contacts between the main units.

3.3.1.1. Piemonte Units Front (PmF)

The PmF corresponds to the external tectonic front of the Piemonte–Ligurian Units, consisting of ophiolite-bearing metasediments (*Schistes Lustrés Auct.*), Upper Triassic dolostones and Lower Jurassic calcareous breccias (Lemoine 1967; Michard 1967; Lemoine et al. 1986). The Briançonnais units are overthrust by or juxtaposed with various units of the Piemonte–Ligurian Domain along the PmF (**Fig. 2**). This regional contact correspond to a metamorphic gap between low-grade, blueschist metamorphism (meta-ophiolites, Michard et

2 *In some cases (e.g. Limone–Viozene Zone, Demonte–Aisone Zone and Refrey Zone) a main regional shear zone can be thought both as an individual macroscale tectonic feature and as a wide deformed rock volume ("Deformation Unit " sensu GeoSciML Information Model, CGI-IUGS, http://www.cgi-iugs.org/tech_collaboration/geosciml.html). To avoid repetition, these instances have been described only once, in the "Main boundary faults" section.*

347 al. 2004) and low green-schists facies metamorphism (sensu Goffé et al. 2004) of
348 Briançonnais successions, but data on metamorphism in the region comprised between
349 Stura Valley and Varaita Valley are too scarce to allow for a reliable interpretation of the role
350 of the PmF on the metamorphic facies distribution.

351 **3.3.1.2. Internal Briançonnais Front (IBF)**

352 In the western part of the study area (Gardetta Pass–Stura Valley) the IBF can be identified
353 in a NW–SE striking fault system that separates a domain (Internal Briançonnais, to NE) with
354 prevailing volcanics and siliciclastic rocks of Permian to Early Triassic age, from another one
355 (External Briançonnais, to SW) mostly made up of detached Mesozoic carbonate
356 successions partially overlain by sediments of the Alpine Foreland Basin. A number of
357 individual ductile to brittle shear zones mark the IBF, among which are the SE prosecution of
358 the Houerts Fault (Fig. 2), that roughly corresponds to the boundary between HP–low grade
359 metamorphic units and low-grade greenschists units of the External Briançonnais (Michard
360 et al. 2004) and the Esischie Fault (Fig. 2), here intended as the tectonic contact between
361 foliated Permian quartz bearing arenites to the north and the Mesozoic carbonate
362 succession of the Viridio Unit to the south of it (left side of the upper Arma valley).
363 Between the Stura Valley and Vermenagna Valley, the ideal prolongation of IBF corresponds
364 to the inner boundary of the LiVZ (Piana et al. 2009).
365 In the Ligurian Alps the IBF coincides with the boundary (Verzera Fault *sensu* Piana et al.
366 2009) between the External Ligurian Briançonnais (ELB) units, characterized by very low to
367 anchizonal metamorphism, and the Internal Ligurian Briançonnais units (ILB) that show low-
368 grade metamorphic transformation. The eastern prolongation (down to the Tanaro Valley) of
369 the Verzera fault can be found in the Pian Bernardo Fault (Bonini et al. 2010), although
370 these authors placed the ELB/ILB boundary in a slightly southern position.
371 As far as the Pennidic Front is thought as the boundary between intensively strained and/or
372 green-schists to eclogite metamorphic units that underwent marked transposition within the
373 Alpine tectonic wedge (“Alpine Axial Belt” sensu Beltrando et al. 2010) on one side, and non-

374 to very-low grade metamorphic units on the other side, the IBF can be here considered as
375 the expression of the Pennidic Front in the Maritime-Ligurian Alps junction.

376 **3.3.1.3 Gardetta Deformation Zone (GAZ)**

377 This deformation zone (known as “bande siliceuse de la Gardetta” sensu Gidon 1972) runs
378 from NW to SE for several kilometres within the western part of the External Briançonnais
379 domain. It is bounded by steep, reverse and probably strike-slip faults and shear zones and
380 it involves several hm-to km-scale detached slices of the Carboniferous-Permian volcanic
381 and Lower Triassic sedimentary rocks of the Briançonnais domain, as well as major gypsum
382 rock bodies and cargneules (Gidon, 1972; 1978).

383 **3.3.1.4 External Briançonnais Front (EBF)**

384 The EBF is an important tectonic contact bounding to S and SW the External Briançonnais
385 Domain (**Fig. 2**): in the western part of the study area it consists of an assemblage of ductile-
386 to-brittle, steep shear zones that runs from the Bersezio Fault (West) to M. Piconiera and M.
387 Salè and then continues in the Arma Valley to the East. The EBF bounds to NE an
388 assemblage of km-scale tectonic slices (M.Giordano, M.Piconiera, M.Savi units and others)
389 all referred in the literature (Malaroda 1970**;** Carraro et al. 1970; Gidon 1972) as
390 Subbriançonnais units and here labelled as Giordano–Savi Unit (**Fig. 9a, c**). Along the EBF
391 major rock bodies of gypsum and anhydrites are widely exposed (Valcavera Pass and
392 Gardetta plateau, **Fig. 9b**). These are intensively folded and sheared and detached from
393 their original substratum and thus suggesting that the EBF is a first-order structure in terms
394 of amount of displacement.
395 Out of the study area (to the NW, beyond the northwestern tip of the Bersezio Fault, **Fig. 2**),
396 the EBF, also known in this region as the “Frontal Briançonnais Thrust” (Tricart et al. 2004)
397 or “Frontal Pennine Fault” (Ford and Lickorish 2004), coincides with the tectonic contact
398 between the Briançonnais Domain and the *Helminthoides* Flysch Unit of the Embrunais–
399 Ubaye (Parpaillon Unit). The EBF here marks the boundary between greenschist facies

400 metamorphic units and very-low grade metamorphic units that were affected by anchizonal
401 metamorphism with T <300°C (Michard et al. 2004).
402 In the central part of the study area, SE of the Gesso Valley, the EBF corresponds to the
403 inner boundary of the Roaschia Unit, whereas more to the East it enters the LiVZ, where it
404 turns into a system of multiple transpressive sinistral faults (Fig.3, Palanfrè-Bec Baral area).
405 The LiVZ itself can be thus viewed as the expression of the EBF in the Ligurian Briançonnais
406 Domain.

407 **3.3.1.5. Bersaio–Nebius Fault - BNF ("Autochthonous Boundary Fault" Auct.)**

408 **and Serra Garb Thrust - SGT**

409 The Giordano–Savi unit is bounded to the South by a tectonic contact (BNF) that separates
410 it from the Sambuco Unit consisting of Dauphinois and Alpine Foreland Basin successions
411 (**Fig. 9C, 10**). The BNF is here generally very steep and has a narrow contact zone; it is very
412 persistent since it runs continuously from Bersezio (NW) to M. Bersaio–M. Nebius to merge
413 eastward with the Demonte–Aisone Zone inner boundary. SE of the Stura and Gesso
414 valleys, an ideal continuation of the BNF can be viewed in the Serra Garb Thrust (SGT) (**Fig.**
415 **11**), a low-angle reverse fault (**Fig. 12**) running for several kilometers from Valdieri in the
416 Gesso Valley to the SE until it enters the LiVZ fragmented domain (**Fig. 3**). This thrust
417 surface overrides the Roaschia Unit onto the Alpine Foreland Basin succession of the
418 Entracque Unit and it has been often interpreted as a segment of the Pennidic Thrust Front
419 (Carraro et al. 1970). The SGT consists of a tens of meters thick, low angle shear zone
420 along which the hanging wall Jurassic carbonates underwent partial dissolution and re-
421 cementation to give origin to marbly fault rocks, while the pelites of the footwall (belonging to
422 the Alpine Foreland Basin turbidite succession) are strongly strained and dragged parallel to
423 the main shear zone (Barale et al. 2015). The SGT merges at its SE termination with some
424 steeply dipping strike-slip faults of the LiVZ, whereas it is truncated by fault segments
425 belonging to the Demonte–Aisone Fault Zone (see below) on its northwestern edge (SE of
426 Demonte) (**Fig. 2. 3**).

3.3.1.6. Demonte–Aisone Zone (DAZ)

The Demonte–Aisone Zone is a strongly strained domain elongated on E–W direction in which slices of Argentera crystalline rocks are tectonically juxtaposed with portions of intensively recrystallized Mesozoic carbonate rocks belonging to the Provençal and Dauphinois Domains, and of weakly metamorphosed Alpine Foreland Basin sediments (Demonte–Aisone Flysch Unit, Carraro et al. 1970).

3.3.1.7. Limone–Viozene Zone (LiVZ)

The External Briançonnais Front bounds to SE and South, from Gesso Valley to the upper Tanaro Valley, a deformation zone (Limone–Viozene Zone, Piana et al. 2009) running for some tens of kilometers (**Fig. 2, 4**), which consists of fault-bounded tectonic units (**Fig. 13, 14**) with successions derived from different palaeogeographic domains, presently arranged in an anastomosed or en-échelon setting (Bertok 2007; Piana et al. 2009; Barale et al. 2015). This setting was achieved not only during the last faulting stages, but partially during the D2 and D3 regional tectonic events, in a confined domain where foliation-parallel shearing was prevalent over folding deformations (see the distribution of the foliations and shear planes in **Fig. 5** and **fig. 9** in Piana et al. 2009). The tectonic units preserve at least two generations of fold axial surfaces due to polyphase folding events (Brizio et al. 1983; Carmignani and Gosso 2000), often reactivated or dragged by reverse-left-lateral shearing (**fig. 6b; see also Piana et al. 2009**). Furthermore, a spaced cleavage related to D3 folding and later shearing and faulting events **(Fig. 7)** is observed.

The LiVZ corresponds to a km-wide zone where the fold axial plane foliations are steeper than in adjacent regions and the stretching directions are subparallel to the strike of the main tectonic contacts and to the main regional foliation (**Fig. 5)**. The LiVZ has been interpreted as a transpressive deformation zone that partitioned the deformation at regional scale during both the D1-D2 flexural folding and the D3 fold-and-thrust events. Tectonic slices of the Briançonnais succession are involved in the LiVZ together with km-scale portions of red pelites and limestones of Western Ligurian Flysch Units as well as fragments of the Alpine

Foreland Basin successions. The LiVZ also involved slices of the Provençal Domain succession previously incorporated into the “Colle di Tenda Unit” and referred to the Subbriançonnais Domain (Carraro et al. 1970) (see section 4.1). The LiVZ can be depicted as an asymmetric flower structure (**Fig. 13, 15**) consisting of: (i) an axial zone with rock slices stretched along-strike and embedded in a very steep foliation, (ii) a SW branch with thrust faults and associated fault bend folds or drag folds, and (iii) a NE branch less affected by strike-parallel shearing but where the regional foliation (S2) and most of the D2–D3 shear planes have opposite dip (toward NE) with respect to the SW branch (**Fig. 5**).

3.3.1.8. Refrey Zone (REZ)

The Refrey Zone is formed by a stack of tectonic slices mainly derived from the Provençal Domain and the Alpine Foreland Basin (**Fig. 3, 4**). The Refrey Zone, bounded at its bottom by the Tenda Tunnel Thrust (TTT, see below), corresponds to the footwall of the southwestern branch of the LiVZ (see text above and **Fig. 13, 15**) and is characterized by a SW-vergent reverse shear zones that repeatedly occur with an average spacing in the order of some tens of meters. These shear zones embedded hm-sized tectonic slices made up of rocks belonging to both the Alpine Foreland Basin and the Provençal successions (Refrey Valley, **Fig. 16**). The Refrey Zone also involves upper Eocene–lower Oligocene sedimentary mélanges that include olistoliths made up of Eocene and Triassic–Jurassic Provençal rocks, as well as Western Ligurian Flysch ones (TOM member of the Grès d’Annot Fm. *sensu* Perotti et al. 2012). These mélanges were intensively sheared close to the TTT and deformed by flexural-slip, open to tight folds consistent with those of the underlying Provençal succession. Finally, the REZ involves hm-scale slices of granitoids which were found close to the TTT in the Roya Valley (French exit of the Tenda railroad tunnel, Baldacci and Franchi 1900) and near the boundary of the REZ with the Argentera Massif (Malaroda 1970).

3.3.1.9. The Tenda-tunnel thrust (TTT)

The steeply dipping faults of the LiVZ outer boundary are connected in subsurface to the Tenda-tunnel thrust (TTT) that crops out some kilometers to the SW of the LiVZ as a set of low- to medium-angle reverse faults that superpose the Refrey Zone (see section 3.3.1.8) onto the Upper Roya Unit (**Fig. 3, 4**). From NW to SE, this West-vergent fault system propagates into different stratigraphic levels of the Provençal succession and also involves large slices of the Alpine Foreland Basin succession, to finally merge eastwards with the main thrust surfaces at the base of the Western Ligurian Flysch of San Remo–M. Saccarello Unit (HFT, see below). The TTT is a first-order tectonic feature, as observed in the subsurface of the Tenda Pass and particularly along both the old Tenda railway-tunnel (Baldacci and Franchi 1900) and the bore holes for the new road tunnel (Cavinato et al. 2006), where the Provençal succession, with its Upper Triassic anhydrite and gypsum levels, is overthrust onto the Alpine Foreland Basin succession (**Fig. 13, 14, 17**).

3.3.1.10. The basal thrust of the Western Ligurian Flysch Units (HFT)

In the southeastern sector of the study area, the Western Ligurian Flysch is represented by the San Remo–Monte Saccarello unit (Sagri 1980; 1984; Vanossi 1991). At the base of this unit a low-angle contractional shear zone clearly displaces the underlying Alpine Foreland Basin succession resting on the Provençal Domain (**Fig. 15, 16**), and develops a ten-meters-thick shear zone mostly made up of intensively sheared scaly clays. The HFT is vergent to S and SW and can be followed laterally for several kilometers.

3.3.1.11. Argentera boundary fault system (ABF)

The Argentera Massif is bounded on its northeastern side by several km-long faults mostly striking NW–SE (**Fig. 2, 3**), interconnected with minor NE–SW and E–W fault segments (Perello et al. 2001; Tricart 2004; Baietto et al. 2008; Sanchez et al. 2009). All these structures are here considered as a whole and named the Argentera boundary fault system (ABF). The ABF truncates and drags the regional metamorphic foliation of the crystalline rocks, the bedding and the tectonic foliation S1 and S2 of the adjoining sedimentary successions. The ABF is subparallel or merge with mylonite shear zones developed within

the Argentera massif and is, in many places, associated with cargneules, gypsum-bearing fault rocks or recemented cataclasites that can reach the thickness of several tens of meters (Carraro et al. 1970). The NW–SE faults are mainly dextral and their activity has been inferred to begin in the early Miocene (22 Ma; Corsini et al. 2004; Sanchez et al. 2011b). These faults are mylonitic shear zones reactivated in a brittle regime (Baietto et al. 2008) and exhumed from a depth of 10 to 15 km during the last 6 Ma (Bigot-Cormier et al. 2006, Sanchez et al. 2011a; 2011b). Recent and ongoing activity of the NW–SE dextral faults was evidenced by Sanchez et al. (2010; 2011b) and Bauve et al. (2014), and is underlined by current seismicity, which is mostly of strike-slip character as shown by focal mechanisms (Sanchez et al. 2009). Important hydrothermal activity occurred, and locally still occurs, along the ABF (Perello et al. 2001; Baietto et al. 2008).

3.3.2. Stratigraphic features and structural setting of the main tectonic units.

In this section a description is given for each of the tectonic units to allow for comparisons and correlations at regional scale. In addition to original field data, the main reference works are the following: Malaroda (1970); Carraro et al. (1970); Gidon (1972); Gidon et al. (1994); Michard et al. (2004), as well as the Geological Map of France (“Feuille Larche” at 1:50,000 scale; Gidon, 1978) and the Geological Map of Italy (“Foglio Argentera-Dronero” at 1:100,000 scale; Abiad et al. 1970). Data on metamorphism come from Michard et al. (2004) for the northwestern sectors and are extrapolated from adjoining areas placed some kilometers to the west of the study region. For the central part of the study area original data are taken from Piana et al. (2014) while for the eastern sectors data on metamorphism refer to the work of Seno et al. (2004) with references therein. The Briançonnais units are here subdivided into internal and external ones mainly on the basis of their metamorphic features.

3.3.2.1. Internal Briançonnais Units

In the north-western part of the study area the Internal Briançonnais Units are the Ceillac–Chiappera Unit and Marinet Unit (Fig.2). They consist of Permian volcanics, Permian–Lower

534 Triassic quartzites and a Middle Triassic–Cretaceous carbonate succession. The
535 metamorphic degree of the Chiappera Unit is referred to low-grade blueschist facies
536 (carpholite–lawsonite, Michard et al. 2004). The overall setting of these units is a very steep
537 fan-like structure (**Fig. 9b**), which has been interpreted as the result of backward syn-D2
538 deformation of D1 duplexes, affected by coeval NW-trending folds and longitudinal strike-slip
539 and reverse faults (Gidon 1972; Michard et al. 2004). In the central part of the study area, on
540 the left side of the Stura Valley, the Internal Briançonnais is represented by the M. Grum
541 Unit, mainly made up of detached Permian volcanic rocks and chlorite-rich quartzites. In the
542 south-eastern part of the study area the Internal Ligurian Briançonnais Units comprehend
543 both basement and sedimentary cover units. The basement is represented by a poly-
544 metamorphic complex involved in the Variscan orogenesis, followed by Carboniferous–
545 Permian volcanic and volcanoclastic rocks on which a detached Mesozoic carbonate
546 succession rests over wide parts of the domain. Metamorphism progressively decreases from
547 the inner units, where blue-schist facies developed both in basement rocks and sedimentary
548 covers (P max about 1.3 GPa, T≦ 450 °C; Messiga et al. 1982; Goffé 1984; Cabella et al.
549 1991), to the outer units, where chlorite–albite paragenesis developed in basement and
550 Carboniferous–Permian rocks, pointing to T of about 350 °C and P≦ 0.4 GPa (Messiga et al.
551 1982).

552 **3.3.2.2. External Briançonnais Units**

553 Generally detached on Upper Triassic evaporites, the tectonic units that form the north-
554 western part of the study area (left side of Stura Valley, Arma Valley and Gardetta plateau;
555 see **Fig. 2** for the names and location of the tectonic units) are represented by Mesozoic,
556 mainly carbonate, successions, intensely displaced and folded by WNW–ESE transpressive
557 shear zones (**see Fig. 10**, Gidon 1972; Ricou 1981) that caused the juxtaposition of several
558 tectonic slices showing different internal structural settings. The internal setting of these units
559 is generally complex, as they consist of well-preserved slices bounded by low-angle thrusts
560 and associated tight or recumbent folds, or of steep, intensely fractured slices showing very

narrow truncated folds with sub-vertical axial planes (see geological sections on Malaroda 1970 and Gidon 1972).

All the carbonate units show a Middle Triassic to Upper Cretaceous typical Briançonnais succession and are locally covered by remnants of the Alpine Foreland Basin sediments. SE of the Stura Valley (between Gesso and Vermenagna valleys) the External Briançonnais Units, studied in detail by Malaroda (1957), are bounded to SE by the LiVZ.

East of Tenda pass the Marguareis Unit (MU) occurs. It is composed of a mainly carbonate Mesozoic succession (Bertok et al. 2011; Bertok et al. 2012), largely detached from underlying volcanic and volcanoclastic Carboniferous–Permian rocks, and overlain by the Alpine Foreland Basin succession. The MU was affected by an anchizonal metamorphism (Piana et al. 2014). The Cretaceous succession was affected by intensive shearing and transposition (Brizio et al. 1983; Gosso and Carminati 2000), whereas the Triassic–Jurassic succession experienced only minor deformation. The latter was affected only by minor low-angle faults along the weakest stratigraphic layers. This allowed the preservation of most of the primary features (Piana et al. 2009; Bertok et al. 2011, 2012; Martire et al. 2014) such as Cretaceous palaeoescarpments and palaeofaults that controlled the partitioning of the Alpine deformation, leading to the individuation of different-order sub-units.

3.3.2.3. Dauphinois–Provençal Units

To the south of the External Briançonnais Front a number of tectonic slices is present all along the study area (Puriac Unit to NW of the Stura Valley and Giordano–Savi and Sambuco Units to NE of it; Roaschia, Entracque and Upper Roya Units in the south-eastern part of the study area; **Fig. 2, 3, 4**). The stratigraphic successions of the more internal of these units (Giordano–Savi and Roaschia Units) were attributed in previous works (Malaroda 1970; Gidon 1972) to the Subbriançonnais Domain (Giordano–Savi Unit) and to the Dauphinois ("Autochthonous") Domain (Puriac and Sambuco Units); in this work they are all attributed to the Dauphinois–Provençal Domain since they share the same Dauphinois–Provençal-type succession.

Giordano–Savi Unit (GSU)

The Giordano–Savi Unit comprehends several minor tectonic units (M.Giordano, Bodoira, M.Piconiera, M.Salè, M.Savi) described by Gidon (1972), that have been grouped here into one super-unit (**Fig. 2**). In the western sector (M. Giordano) the Jurassic-Cretaceous deposits consist of deep water limestones that can be thus attributed to the Dauphinois succession (see section 2.2), laterally passing to roughly coeval Provençal-type dolomitized platform limestones in the eastern sector (Rocce Forni-M. Salè). In the westernmost part of the unit, the Mesozoic succession is followed by the Alpine Foreland Basin succession. The Giordano–Savi composite unit is intensively deformed by double-vergent (SW- and NE-ward) narrow folds and displaced by strike-slip and steep reverse faults roughly parallel to the main boundary faults (see geological sections on Gidon, 1972).

Puriac (PUU) and Sambuco (SMU) Units

These units consist of Upper Triassic–Cretaceous deposits showing a typical Dauphinois succession (Carraro et al. 1970) overlain by the Alpine Foreland Basin succession.

The Puriac and Sambuco Units are presently separated by the NW–SE striking Bersezio Fault (**Fig. 2**) that runs sub-parallel to the Stura Valley and merges with the ABF near Bersezio.

The Puriac Unit has an almost continuous and complete Mesozoic succession (Sturani, 1962), detached from the Argentera Massif along cargneule levels. It is regularly dipping to the North and is overthrust by the Western Ligurian Flysch of the Parpaillon Unit (see below).

The Sambuco Unit is deformed by open to tight km-scale large folds, mostly back-vergent to NE (M. Nebius, Punte Chiavardine; Malaroda 1970) together with the overlying Alpine Foreland Basin succession which mainly dips toward NE (**Fig. 10**). The latter is directly overthrust by the Giordano–Savi unit along the BNF, that generally displaced the NE-vergent fold systems generating SW-vergent narrow folds along the main contractional shear planes.

Roaschia Unit (ROU)

615 The Roaschia Unit consists of Jurassic-earliest Cretaceous shallow water sediments and
616 Cretaceous hemipelagic deposits referable to the Provençal succession, overlain by the
617 Alpine Foreland Basin succession (Barale, 2014). The Roaschia Unit succession was folded
618 and thrusted by at least two deformational events that gave origin to NW–SE trending tight
619 folds (successively rotated and steepened) and then to sub-parallel, SW-vergent, open fault-
620 bend folds. It overrode the Entracque Unit along the Serra Garb Thrust (**Fig. 11, 12**). In its
621 southern part the Roaschia Unit progressively changes its setting to a zone consisting of
622 anastomosed tectonic slices bounded by NW–SE steep transpressive faults of the adjoining
623 LiVZ (Barale et al. 2015).

624 **Entracque Unit (ENU)**

625 The NW part of the Entracque Unit consists of a Mesozoic succession that can be attributed
626 to the Dauphinois domain (**Fig. 2**). It consists of Middle? Jurassic–Lower Cretaceous
627 hemipelagic/pelagic sediments, with resedimented carbonate breccias in the upper part, and
628 by Aptian–Upper Cretaceous hemipelagic sediments which contain important siliciclastic
629 inputs in the upper part (Carraro et al., 1970; Barale et al., 2015). The south-eastern part is
630 on the contrary made up mostly of Middle (?) Jurassic–Berriasian (?) platform carbonates,
631 locally dolomitized, referable to the Provençal succession and Cretaceous sediments are
632 commonly missing; in both sectors, the Mesozoic succession is truncated by a discontinuity
633 surface, overlain by the Alpine Foreland Basin succession (Carraro et al., 1970; Barale et al.,
634 2015). The transition between the Dauphinois basin and the Provençal platform successions
635 occurs at Caire di Porcera, a few kilometres SE of Entracque (**Fig. 18a, b**). This boundary,
636 mapped by Malaroda (1970) and described as a tectonic contact by Carraro et al. (1970),
637 has been recently reinterpreted as a depositional escarpment, separating the top of the
638 drowned Provençal platform from the Dauphinois basin during the Cretaceous (Barale 2014;
639 Barale et al. 2015).
640 The northern slope of Caire Porcera consists of Middle (?) Jurassic–Berriasian (?) platform
641 carbonates, representing the northernmost outcrop of the Provençal succession in the

642 Entracque unit, replaced towards the NW by the Jurassic–Cretaceous Dauphinois
643 succession. These platform carbonates are covered by a few-metres-thick Lower
644 Cretaceous condensed succession represented by pebbly mudstones with clasts of
645 Provençal platform carbonates (**Fig. 18a**), followed by belemnite-bearing marly limestones.
646 The northern slope of Caire di Porcera has been interpreted as part of a depositional slope
647 that connected the Provençal platform and the Dauphinois basin in the Early Cretaceous
648 (Barale, 2014; Barale et al. 2015). The thin hemipelagic succession deposited on this slope,
649 containing clasts coming from the adjoining platform, has its equivalent in the resedimented
650 beds that characterize the Lower Cretaceous Dauphinois succession of the Entracque sector
651 (Barale, 2014; Barale et al., 2015). The paleoslope was later onlapped by the Upper
652 Cretaceous hemipelagic succession; onlap geometric relationships of this succession with
653 the condensed sediments overlaying the Caire di Porcera northern slope, even if not directly
654 observable, are clearly inferred from map evidence (Barale et al. 2015). Even though the
655 direct evidence of the Provençal–Dauphinois transition in Jurassic times cannot be
656 observed, stratigraphic features and map evidence document that this boundary should have
657 been placed close to the earlier described Lower Cretaceous palaeoslope, as already
658 described in Barale (2014).
659 The Jurassic–Cretaceous succession of the north-western sector of the Entracque Unit is
660 affected by polyphase folding (NW–SE trending, open overturned folds that were refolded by
661 drag and fault-bend folds). The geometrical upper part consists everywhere of the intensively
662 folded and sheared turbidite succession of the Alpine Foreland Basin, in some places
663 doubled by reverse faults propagated as synthetic footwall-splays of the main Serra Garb
664 Thrust. As for the Roaschia Unit, also the Entracque Unit progressively passes, to the SE, to
665 a zone consisting of anastomosed tectonic slices bounded by NW–SE steep transpressive
666 faults of the adjoining LiVZ. (**Fig. 3, 11**). The Entracque Unit is displaced on its southern side
667 by the boundary fault system of the Argentera Massif, consisting of steep strike-slip and
668 normal faults in some places associated with meter-thick fault rocks.
669 **Upper Roya Unit (RYU)**

The Permian–Mesozoic succession of the Provençal Domain that crops out in the upper part of the Roya Valley is here named “Upper Roya Unit”. The RYU also include the sediments of the Alpine Foreland Basin succession which overlain the Provençal Permian–Mesozoic succession.

In the NW sector, close to the border of the Argentera massif, the succession is composed by Permian volcanoclastic sediments, followed by a Triassic–Jurassic Provençal-type succession. The top of the Upper Jurassic platform limestones, locally intensively dolomitized, is bounded by a regional unconformity directly overlain by the Paleogene Alpine Foreland Basin succession; only locally a few meters of Lower Cretaceous marly limestones with belemnites are preserved (Punta Bussaia). Differently, in the Roya Valley and in Argentina Valley the Upper Cretaceous marly limestone succession is hundreds of meters thick (Lanteaume 1968; Varrone and d’Atri 2007).

3.3.2.4. Western Ligurian Flysch Units

The Western Ligurian Flysch units, deeply involved in the LiVZ and sandwiched between the Briançonnais and Provençal units, widely overthrust the Alpine Foreland Basin successions resting on the Dauphinois/Provençal units. At the northwestern edge of the Argentera Massif the Western Ligurian Flysch units are known as Parpaillon Unit (Kerchove 1969), while in the southeastern part of the study area they are represented by the San Remo-Monte Saccarello Unit (Vanossi et al. 1984) (**Fig. 1, 2, 15, 16**). These units, interpreted as a detached nappe made up of internal Ligurian units (Kerchove 1969), are presently bounded at their base by a low-angle shear zone (**Fig. 15, 16**), striking NW-SE over several kilometers, which was active since the D1 deformational stage (Maino et al., 2015) but whose final emplacement is due to the D3 tectonic stage.

Parpaillon Unit (PAU)

The Parpaillon Unit is the uppermost unit of the “Ubaye Embrunais nappes” and consists of a thin interval of dark shales at the base overlain by thick Upper Cretaceous fine-grained turbidite limestones (Kerchkove 1969). It is deformed by two main superposed deformation

phases, characterized by large-scale recumbent folds with NW-ward and SW-ward vergence respectively (Merle and Brun 1984).

San Remo–Monte Saccarello Unit (SRU)

This unit is made up of carbonate-poor, thin-bedded varicoloured pelites (the so called "basal complex") interpreted as basin plain deposits; thick-bedded, coarse-grained sandstones interbedded with thin layers of dark shales deposited in internal deep-sea fans; thick-bedded, fine-grained turbidite sandstones and limestones deposited in elongated and constricted basins (Sagri 1984). The whole succession has a Barremian–Maastrichtian age (Manivit and Prud'homme 1990; Cobianchi et al. 1991).

The San Remo–Monte Saccarello Unit is deformed by large scale, open south–vergent folds (Lanteaume 1968) and related thrust surfaces (Vanossi et al. 1984 with references therein). Three main deformation phases are recorded: a first S-ward-verging phase that generated E–W narrow folds and related thrust faults dismembering the unit into minor tectonic sub-domains (Galbiati et al. 1983; Galbiati 1986 and 1987); a second phase, roughly coaxial with the previous one but with an opposite N-ward vergence, that produced more open, often faulted, folds; a third S-ward-verging phase that gave origin to open folds and thrusts (Brizio et al. 1983; Di Giulio 1992, Piana et al., 2014) related to the final emplacement of the unit along the HTF (**Fig. 15, 16**).

4. DISCUSSION

During the early Eocene, significant plate convergence between Europe and Adria must have occurred to allow subduction of the internal Alpine units (internal Briançonnais units of the palaeo-European crustal margin and Ligurian ophiolites with related sediments) to HP conditions (Goffé and Chopin 1986; Michard et al. 2004; Bousquet et al., 2008). Because between 50 Ma and 35 Ma about two hundreds km of N–S convergence occurred in the central Alps (Schmid et al. 1996; Schmid and Kissling 2000), a component of NW–SE oblique convergence of more than one hundred km is therefore estimated along the EBF in the Maritime Alps in the same time span (Ford et al. 2006).

724 During the middle–late Eocene, the internal Alpine units were exhumed to shallow levels and
725 tectonically superposed on the continental margin, together with detached Ligurian
726 sediments (Western Ligurian Flysch) (Kerchove 1969; Dumont et al. 2012), while the Alpine
727 Foreland Basin was already formed and progressively migrated toward the NNW in the
728 northern sectors of the Alpine realm (Ford et al. 2006) and toward WSW in the southern
729 ones.
730 In the early Oligocene, the motion vector of the Adria microplate with respect to Europe
731 changed from N-ward to WNW-ward (Schmid et al. 1996; Handy et al. 2010), inducing a
732 west-ward indentation of Adria that was kinematically resolved, in the SW Alps, by
733 anticlockwise rotation of the tectonic units with respect to stable Europe (Thomas et al. 1999;
734 Collombet et al. 2002) and by the onset of a general sinistral transpressional regime (Ford et
735 al. 2006). As a consequence of this new tectonic regime, SW-ward overthrusting of the
736 Brianconnais units onto the Dauphinois ones occurred (Kerckhove 1969; Merle 1982;
737 Coward and Dietrich 1989; Fry 1989; Michard et al. 2004), together with left-lateral
738 juxtaposition of different tectonic units belonging to both domains (Lemoine et al. 2000; Ford
739 et al. 2006; Piana et al. 2009).
740 Since about 26 Ma a transpressional regime coherent with regional N-S shortening
741 directions induced right-lateral movements of the NW–SE and E–W oriented fault systems
742 displacing the Argentera Massif (Sanchez et al. 2011b), while in the adjacent internal syn-
743 orogenic basins (Tertiary Piemonte Basin) significant uplifting occurred at about 20 Ma,
744 controlled by N–S to NE–SW compressional tectonic regime (Festa et al. 2005; Piana et al.
745 2006; Maino et al. 2013) and recorded by regional unconformities (Piana et al. 1997, d'Atri
746 et al. 2002, Dela Pierre et al. 2003) and by the on-set of new depocenters (Rossi et al.
747 2009).
748 In middle–late Miocene, the exhumation of the Argentera Massif occurred and was driven by
749 alternating transtensional and transpressional right-lateral movements along a main NW–SE
750 regional fault system, with ongoing strike-slip deformation (Tricart 2004; Bigot-Cormier et al.
751 2006; Sanchez et al. 2011b).

In the above described evolutionary frame, a number of tectonic units were individuated and arranged in a roughly anastomosed pattern from SE to NW along the NE boundary of the Argentera Massif. Our analyses showed that these tectonic units in many places cut across the palaeogeographic subdivisions of the Alpine literature; consequently, new attributions and subdivisions have been proposed and discussed in the following. Furthermore, the revision of the overall stratigraphic and tectonic setting allows the discussion of an integrated geo–structural framework for the study area.

4.1 The Provençal–Dauphinois transition, the Subbriançonnais paradigm and the "Colle di Tenda Unit".

The transition between the Dauphinois and the Provençal palaeogeographic domains has been recently recognized in the study area within the Entracque Unit (Caire di Porcera area, see also Barale 2014; Barale et al. 2015), where an important structural and physiographic threshold developed and persisted from the Early–Middle Jurassic up to the Early Cretaceous, causing a differentiation of the basin in a shallow-water sector (Provençal) and a basinal one (Dauphinois).

Some tectonic units of the study area (Giordano-Savi and Roaschia units), interposed between units with Briançonnais-type stratigraphic successions and units showing Dauphinois- and Provençal-type stratigraphic successions, were previously attributed to the Subbriançonnais palaeogeographic domain (Malaroda 1970; Gidon 1972). This study shows, however, that their stratigraphic successions do not show specific features such as to justify the attribution to a distinct palaeogeographic domain. Consequently, the Giordano-Savi and Roaschia units, previously referred to the Subbriançonnais Domain, have been here attributed to the Dauphinois Domain (the western part of the Giordano-Savi Unit, characterized by a Jurassic-Cretaceous deep-water succession) or to the Provençal one (the eastern part of the Giordano-Savi Unit and the Roaschia Unit, characterized by shallow-water Middle Jurassic-Early Cretaceous succession).

Between the lower Stura Valley (NW) and the Tenda pass (SE) Carraro et al. (1970) distinguished the “Colle di Tenda Unit”, whose attribution to the Subbriançonnais Domain was maintained in the Geological Map of Italy at 1:100,000, Foglio Demonte (Abiad et al. 1970; Crema et al. 1971), in Lanteaume (1958; 1968) and Guillaume (1962). Also in this case the analogy between the stratigraphic successions of the Colle di Tenda Unit and those of the adjacent units made up of Provençal-type successions do not justify the attribution to distinct palaeogeographic domains, being all characterized by comparable thickness and very similar facies of the Jurassic succession as already highlighted by Lanteaume (1958), Campanino Sturani (1967), and Crema et al. (1971). The southeastern part of the “Colle di Tenda Unit”, at present represented by an assemblage of hm-scale tectonic slices, has been here incorporated into the LiVZ and in the REZ, while the northwestern part corresponds to the Roaschia Unit (**Fig. 2**).

The interpretation of the Subbriançonnais as a merely structural domain was already proposed by Maury and Ricou (1983), who questioned the existence of the Subbriançonnais as a Meso-Cenozoic palaeogeographic domain and argued that it actually corresponded to a Eocene strike-slip zone, made up of slices of the Briançonnais, Dauphinois and Provençal domains. A similar interpretation of the Subbriançonnais domain has been proposed also by Dumont et al. (2012) which, on the base of stratigraphic comparisons, argued an important NW-ward displacement of the Briançonnais units placed to the North of the Argentera Massif.

4.2 The “common” Alpine Foreland Basin succession.

The history of the European passive margin ends between the Late Cretaceous and the Paleogene, when the Tethyan oceanic crust, together with its sedimentary cover, was involved in the Alpine accretionary wedge that overthrust the European margin. The lithospheric flexure resulting from collision acted upon the previously stretched continental margin and produced the Alpine Foreland Basin (Ford et al. 1999).

804 During the middle Eocene–early Oligocene, the sedimentary succession of the Alpine
805 Foreland Basin was deposited above the different Mesozoic sectors of the European passive
806 margin (Briançonnais, Dauphinois and Provençal Domains) with the same main features: a
807 basal discontinuity surface related to an emersion, in turn related to the forebulge uplift,
808 overlain by continental deposits (locally), mixed ramp sediments, slope marls and a thick
809 turbidite succession (Sinclair 1997; Allen et al. 1991).
810 In this paper we stress the uniformity of such succession resting above all the Mesozoic
811 successions which points to the development of a single basin above the different Domains
812 (Briançonnais, Dauphinois and Provençal) of the passive margin, as already proposed by
813 Ceriani et al. (2011) for more northern sectors of the Western Alps. This led us to consider
814 the Alpine Foreland Basin succession as a single map-entity. For these reasons the Alpine
815 Foreland Basin succession is here considered "ubiquitous" and to be kept apart from the
816 underlying successions of the different Mesozoic Domains.

817 **4.3 The presence of a long-lived regional shear zone along the EBF and**

818 **the "Alpine SW Transfer".**

819 At the southern termination of the Western Alps arc, and all along the EBF, a relatively
820 complex arrangement of tectonostratigraphic units (or simply of several tectonic slices)
821 occurs. This structural setting is the result of the anastomosed branching of multiple tectonic
822 contacts corresponding to the Internal/External Briançonnais boundary zone (partially
823 corresponding with the "*Stura couloir" Auct.*), the Demonte–Aisone shear zone, the boundary
824 faults of NE border of the Argentera Massif and the Limone–Viozene transpressive zone
825 (with associated minor thrusts) developed along the External Briançonnais Front in the
826 Maritime and westernmost Ligurian Alps. This articulated structural setting took place
827 through at least three main deformational stages (D1–D3, see section 3.2) in anchizonal
828 and/or diagenetic conditions (Piana et al. 2014) since the early Oligocene likely up to the
829 beginning (middle Miocene) of the Argentera Massif uplifting tectonics (Sanchez et al.
830 2011b). The overall resulting fault network seems to depict a wide deformation zone (mostly

transpressional), active through all the stages of the Alpine tectonics, into which also some Western Ligurian Flysch units were involved since the late Eocene as slices tectonically juxtaposed along the European palaeomargin (Perotti et al. 2012).

The crustal-scale structural roots of this deformation zone can be found in the fault and fracture network that since the Early Cretaceous hosted a huge hydrothermal circulation widespread for tens of km along the NE boundary of the Argentera Massif and adjoining sedimentary successions, as recently described by Barale et al. (2013; 2015), and that also strongly controlled the tectono-sedimentary evolution of the Briançonnais (Bertok et al. 2012) and Dauphinois-Provençal Domains (Barale et al. 2015). Consequently, the presence of a major kinematic "transfer zone" (Ligurian sinistral transfer, LST in fig. 19) at the southern termination of the Western Alps arc could be envisaged as a major crustal feature that may have provided the left-lateral "*southern disengaging lineament"* (Giglia et al., 1986) necessary for the Oligocene westward indentation (Dumont et al. 2012) and counterclockwise rotation (Collombet et al. 2002; Rolland et al., 2012) of Adria promontory, as invoked in literature during the last decades (see section 3.1 for details), and roughly described as "Stura couloir" or Stura Fault.

5. CONCLUSIONS

At the southwestern termination of the Western Alps arc the present tectonic setting is the result of the following factors:

- pre-Alpine syn-sedimentary tectonics that induced a complex distribution of basinal areas, slopes and structural highs so that the classical subdivisions of the European palaeomargin (i.e. Briançonnais, Provençal, Dauphinois Domains) can show strongly different stratigraphic features from NW to SE, from the northwestern edge of the Argentera Massif to the Ligurian Alps (see also Maury and Ricou 1983; Bertok et al. 2012, Perotti et al. 2012). This syn-sedimentary tectonics seems to have been mainly driven by strike-slip faults that also induced widespread hydrothermal activity at regional scale along the NE boundary of the Argentera Massif (Barale et al. 2013);

- development of a single syn-tectonic basin (middle Eocene–lower Oligocene Alpine Foreland Basin) unconformably deposited above the different Domains (Briançonnais, Dauphinois and Provençal) of the European palaeomargin;
- transpressional multistage tectonics that induced not only shortening but also a significant relative lateral movement along E–W to SE–NW direction, that could have been mainly sinistral in the first stages (late Cretaceous–Oligocene: Maury and Ricou 1983; Tricart 2004; Piana et al. 2009; Dumont et al. 2012) and dextral in later (Miocene) times (Sanchez et al. 2011a; 2011b; Bauve et al. 2014). These tectonic events induced juxtaposition and/or stacking of tectonic units characterized by a different metamorphic history, from anchizonal to lower greenschist facies (Michard et al. 2004; Piana et al. 2009, 2014). This evolution resulted in a relatively complex arrangement of tectonostratigraphic units aligned in a wide transfer zone developed at the southern termination of the Western Alps arc, that could have acted as an Oligocene (Chattian) left-lateral major crustal fault, necessary for the post-Eocene westward indentation of Adria promontory and, since early–middle Miocene, as a dextral fault systems allowing the uplifting of the Argentera Massif.

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CAPTIONS

Fig. 1: Geological sketch of the southern termination of the Western Alps. The main tectonic domains are represented with different colours. The black dashed rectangle corresponds to the study area of Fig. 2. Thick red lines indicate the tectonics contacts described in this paper; all others tectonic contacts are represented as thin red lines. Legend: ARG: Argentera Massif (GSV: Gesso–Stura–Vésubie terrane; TIN: Tinée terrane); EBr: External Briançonnais Domain; IBr: Internal Briançonnais Domain; Pm+PPm: Piemonte and Pre-Piemonte Domains; DM: Dora–Maira Domain; DauPro: Dauphinois–Provençal Domain; ExLBr: External Ligurian Briançonnais Domain; ILBr: Internal Ligurian Briançonnais Domain; WestLF: Western Ligurian Flysch Domain; TPB: Tertiary Piemonte Basin; PQ: Plio-Quaternary deposits; IBF: Internal Briançonnais Front; EBF: External Briançonnais Front; ABF: Argentera Boundary Fault system; LiVZ: Limone–Viozene Zone; DAZ: Demonte–Aisone Zone; REZ: Refrey Zone; HFT: *Helminthoides* Flysch Basal Thrust; TTT: Tenda-tunnel Thrust. Geological boundaries redrawn from the Geological Map of France at 1:1,000,000 (Chantraine and Clozier 2003); coordinate system RGF93/Lambert-93.

Fig. 2: Geological sketch map of the Maritime–Ligurian Alps junction, at the southern termination of the Western Alps. The main tectonic units are represented referring to their different paleogeographic pertinence (different colours) and geometrical position with respect to the main tectonic boundaries and deformation zones. The location of the geological cross-section of Fig. 10 (section A–A'), Fig. 12 (section B–B'), Fig. 13 (section C–C') and Fig. 15 (section D–D') is here reported. The Internal Briançonnais Front (IBF) here corresponds to the external boundary of the green-schist to eclogite facies metamorphic axial belt of the Alps (sensu Beltrando et al., 2010) and can be thus considered as the surface expression of the Pennidic Front.

Fig. 3: Geological sketch map of the central-northern sector of the study area (see location in Fig. 2), modified from Barale et al. (2015). Legend: 1: Argentera crystalline basement; 2: Permian continental sediments; 3: Lower Triassic coastal deposits; 4: Middle Triassic

peritidal carbonates; 5: Upper Triassic pelites; 6: Jurassic hemipelagic sediments (Dauphinois); 7: Jurassic platform carbonates (Provençal); 8: Lower Cretaceous condensed succession; 9: Upper Cretaceous hemipelagic succession; 10, 11: Alpine Foreland Basin succession (10: ramp sediments and hemipelagic marls; 11: turbidite succession); 12 Western Ligurian Flysch; 13: Tectonic breccias (Carnieules Auct.); 14: main tectonic contacts (a: faults; b: thrusts); 15: minor tectonic contacts (a: faults; b: thrusts). ARG: Argentera Crystalline Massif; ENU: Entracque Unit; ROU: Roaschia Unit; LiVZ: Limone–Viozene Zone; REZ: Refrey Zone; RYU: Upper Roya Unit. ABF: Argentera boundary fault system; TTT: Tenda-tunnel Thrust; SGT: Serra Garb Thrust; $LiVZ_f$: external boundary faults of the LiVZ. The location of geological cross section of Fig. 13 is reported (CC').

Fig. 4: Geological sketch map of the central-eastern sector of the study area (see location in Fig. 2). Legend: 1: Permian volcanoclastic sediments; 2: Lower Triassic coastal deposits; 3: Middle Triassic peritidal carbonates; 4: Middle–Upper Jurassic limestones (Briançonnais); 5: Jurassic platform carbonates (Provençal); 6: Upper Cretaceous hemipelagic succession; 7,8: Alpine Foreland Basin succession (7: ramp sediments and hemipelagic marls; 8: turbidite succession); 9: Western Ligurian Flysch; 10: minor tectonic contacts; 11: main faults. 11: main thrust surfaces. ExLBr: External Ligurian Briançonnais; IBr: Internal Briançonnais; WestLF: Western Ligurian Flysch; LiVZ: Limone–Viozene Zone; REZ: Refrey Zone; RYU: Upper Roya Unit. TTT: Tenda-tunnel Thrust; $LiVZ_f$: boundary faults of the LiVZ; HFT: *Helminthoides* Flysch basal Thrust; IBF: Internal Briançonnais Front.

Fig. 5: Stereonets of the main structural features within the LiVZ northern, central and eastern sectors. The structural associations related to the D2 event are characterised by almost parallelised features along an average NW–SE direction (the S2 foliation, the F2 fold axial planes and the reverse and left-lateral shears reactivating the S2 foliation or the S1+S2 composite foliation). The low-angle dip of the F2 axes, as well as the distribution of F2 fold axial planes along girdles representing a wide range of dip values suggest that, even in the mostly sheared domains, the F2 folds did not form as strike-slip drag folds but as compressional folds whose axial surfaces were progressively rotated toward the parallelism

with the shear zone boundaries. These conditions are coherent with strain partitioning of distinct domains within a major, NW–SE oriented, sinistral transpressive zone.

Fig. 6: Mesostructural features. (a): Sedimentary bedding (Ss - Briançonnais Upper Jurassic pelagic carbonates/Cretaceous hemipelagic sediments boundary, M.Mongioie, western side, Marguareis Unit) deformed by F1 narrow fold; (b): D2 shearing (forming the S2sh composite foliation) developed along the Ss (lithological bands) dragging the S2 foliation (the older S1 foliation is still well recognizable), Cretaceous hemipelagic sediments, Colle del Pas, Marguareis Unit; (c): S2 foliation folded by open D3 folds in Cretaceous hemipelagic sediments dm-thick layers (the older S1 foliation is still well recognizable) close to Pian Ambrogi; (d): composite foliation (S2sh + syn-D3 shearing) within a plurimeters-thick shear zone active at least until the D3 deformational stage (Selle Vecchie, Eocene Foreland Basin succession, Limone–Viozene Zone); (e) sketch representing the multistage deformational evolution as observed at the mesoscale: see text for explanation (after Piana et al., 2009).

Fig. 7: Conceptual sketch of the main structural associations and relative cross-cutting relations observed in the study area. The "S2 shears" (i.e. shear zones reactivating the S2 foliations) or the D3 shear planes (usually low-angle reverse faults, e.g. Serra Garb Thrust), as well as the syn-D3 dextral faults, represent in most cases the NW–SE oriented mechanical boundaries of the described tectonic units. Later (D4) individual faults can locally displace these boundaries. More complex distribution of lithologic units can occur within the main tectonic units, especially in the Upper Cretaceous calcareous-marly succession, due to superposition of F1 and F2 folding events.

Fig. 8: Schematic stratigraphic logs of the Dauphinois, Provençal, and External Ligurian Briançonnais Domains. Since the Provençal succession shows important lateral variations in the study area, two end-member logs are here represented (Upper Roya Unit and SE sector of the Entracque Unit).

Fig. 9: Geological landscapes on the northern side of the Stura Valley. (a): the structural setting of the Giordano–Savi Unit (GSU), consisting of very steep tectonic slices often corresponding to sheared antiform- or synform-fold flanks of the Provençal–Dauphinois

Jurassic succession. The GSU is comprised between the External Briançonnais Front (EBF) to the North (Col Salé, where gypsum and anhydrites slices are present) and the Bersaio–Nebius Fault (BNF) to the South, that separates it from the Sambuco Unit (SMU), see also the geological section of Fig. 10. Image taken from Chiaffrea Valley (44°22'19'' N, 7°06'03'' E), looking SE. (b): Gypsum and anhydrite masses of the Valcavera Pass, placed within the External Briançonnais Domain between the M.Omo Unit (to the South) and the Cima di Test Unit. In the inset is a detail of the folding deformation that widely affects the whole gypsum rock mass. Image taken from the northern side of Monte Omo (44°22'33'' N, 7°06'45'' E), looking NW. (c): view of the External Briançonnais (M.Omo) and Dauphinois–Provençal (Giordano–Savi and Sambuco) units of the northern flank of the Upper Stura Valley, north of Demonte. The dotted green lines indicate the bedding of Cretaceous limestones, folded at the macroscopic scale and displaced by NW–SE faults (red dotted line) sub-parallel and very close to the Argentera boundary fault system (see Fig. 2). EBF: External Briançonnais Front, BNF: Bersaio–Nebius Fault. Image taken from Monte Bersaio (44°21'14'' N, 7°04'42'' E), looking ENE.

Fig. 10: Geological cross section across the External Brianconnais Front (modified from Gidon, 1972). Location in Fig.2. SMU: Sambuco Unit; SMU_{For}: Foreland Basin succession of the Sambuco Unit; GSU: Giordano–Savi Unit; OMO: Monte Omo Unit; TES: Cima Test Unit; GAZ: Gardetta Zone; BNF: Bersaio–Nebius Fault; EBF: External Briançonnais Front.

Fig. 11: Geological landscape in the Maritime Alps, eastern side of the Bousset Valley. The Roaschia Unit (ROU) overthrust the Eocene Foreland Basin succession (For) of the Entracque Unit (ENU), along the Serra Garb low-angle thrust (SGT). Following the dotted red line one can realize the progressive SE-ward steepening of the Roaschia Unit succession while approaching to the LiVZ boundary (see Fig. 2–3 and geological cross-section of Fig. 12). Image taken from Mont Pianard (44°12'25" N, 7°27'55" E), looking NNW.

Fig. 12: Geological cross section across the Serra Garb low-angle thrust (modified from Barale et al., 2015). Location in Fig.2, photographic details in Fig.11. GSV: Gesso–Stura–

Vésubie terrane; ENU: Entracque Unit; ENU_{For}: Foreland Basin succession of the Entracque Unit; ROU: Roaschia Unit; ABF: Argentera boundary fault system; SGT: Serra Garb Thrust.

Fig. 13: Geological cross section across the LiVZ northern branch (modified from Barale et al., 2015). Location in Fig. 2 and 3, photographic details in Fig.14. RYU: Upper Roya Unit; REZ: Refrey Zone; REZ_{For}: Foreland Basin succession of the Refrey Zone; LiVZ: Limone–Viozene Zone; $LiVZ_{For}$: tectonic slices of Foreland Basin succession involved in the Limone–Viozene Zone; $LiVZ_{HF}$: tectonic slices of Western Ligurian Flysch Unit involved in the Limone–Viozene Zone; TTT: Tenda-tunnel Thrust; $LiVZ_f$: external boundary faults.

Fig. 14: (a) Landscape of the southern part of the study area; $LiVZ_f$: SW boundary of the LiVZ; T1,T2,T3: minor transpressive faults within the LiVZ; in the inset is the area of Fig. 14c. Image taken from the northern side of Cime du Bec Roux (44°09'13" N, 7°35'14" E), looking WNW. (b) intensively sheared, steepened bed of Triassic pelites and carbonate levels in the T1 shear zone (the precise location of the observation point is marked by a grey filled circle in Fig.14c). (c) detailed view of Fig. 14a showing the Bec Matlas (BMT) and Bec Baral (BBA) tectonic slices within the LiVZ, mainly made up of very steep Jurassic limestones and sheared Triassic pelites.

Fig. 15: Geological cross section across the LiVZ southern branch. Location in Fig. 2. RYU_{For}: Foreland Basin succession of the Upper Roya Unit; SRU: San Remo–Monte Saccarello Unit; LiVZ: Limone–Viozene Zone; $LiVZ_{HF}$: tectonic slices of Western Ligurian Flysch Unit involved in the Limone–Viozene Zone; MAU: Monte Marguareis Unit; HFT: *Helminthoides* Flysch basal Thrust; $LiVZ_f$: LiVZ external boundary fault; EBF: External Briançonnais Front.

Fig. 16: Geological landscapes in Maritime–Ligurian Alps junction (Refrey Valley); (a) the HFT thrust superposes the S.Remo–M.Saccarello Unit (SRU, Western Ligurian *Helminthoides* flysch) onto the Refrey deformation zone (REZ) characterized by an assemblage of tectonic slivers (represented in the background, in yellow colour, as a whole deformed unit) made up of Eocene Foreland Basin sediments (REZ For) resting on Cretaceous levels (REZ K) of the Provençal Domain (see details in the foreground, black-

and-white view). Image taken from Rochers de Servia (44°07'16" N, 7°37'45" E), looking NW. (b) deformed Cretaceous levels within the Refrey Deformation Zone: a tectonic foliation (St) originated by diffuse pressure-dissolution processes is folded and sheared by reverse, SW vergent slip planes (Sh) developed along the axial zone of dm-scale folds. Bedding is moderately transposed and roughly parallel to the Sh surfaces. In the inset is a detail of the St/Sh geometrical relations.

Fig. 17: Geological landscape in Maritime–Ligurian Alps junction (Tenda Pass zone); in the background is the Ciotto Mieu Pass–Bec Matlas range represented in detail in Fig. 13 and Fig. 14. To the East (right) of the Tenda Pass a tectonic slice of the Refrey Deformation Zone (REZ) is overthrust, along a splay-fault of the Tenda Tunnel Thrust (TTT), onto a stratified marly-calcareous succession of the Eocene Foreland Basin. This tectonic slice is characterized by the lack of the Cretaceous succession and direct, unconformable superposition of the Eocene succession onto the Jurassic carbonates of the Provençal Domain, as reported and discussed in section 4.1 (see the inset to the left for a detailed view of the Jurassic (J) - Eocene (For) discontinuity surface, marked by a yellow dotted line). Image taken from the southern side of Cime du Bec Roux (44°08'37" N, 7°35'12" E), looking NW.

Fig. 18: Caire di Porcera paleomargin. (a): view of the northern side Caire di Porcera (image taken from 44°12’37’’ N, 7°26’51’’ E, looking S), showing the massive Middle (?) Jurassic–Berriasian (?) Provençal platform carbonates (PPC) covered by a few metres of evenly bedded Lower Cretaceous pebbly mudstones (PM), containing clasts of the underlying Provençal carbonates (see inset). (b): interpretative scheme of the Caire di Porcera paleomargin in the earliest Cretaceous. Legend: 1: Argentera crystalline basement; 2: Lower Triassic coastal deposits; 3: Middle Triassic peritidal carbonates; 4: Middle (?) Jurassic–Berriasian (?) Provençal platform carbonates; 5: Middle (?) Jurassic–Berriasian (?) Dauphinois hemipelagic succession (a: intraformational mudstone clasts; b: clasts of Middle Triassic peritidal carbonates); 6: Lower Cretaceous pebbly mudstones on the Caire di

1374 Porcera paleomargin and laterally equivalent sediments of the Dauphinois succession (a:
1375 intraformational mudstone clasts; b: clasts of Provençal platform carbonates).
1376 Fig. 19 - Schematic tectonic sketch showing the Oligocene geodynamic setting of the
1377 southwestern Alps, the Ligurian, Provençal and Dauphinois domains, and the Alpine syn-
1378 tectonic basins (Alpine Foreland Basin and Tertiary Piemonte Basin, see text for further
1379 explanations). The Ligurian-Maritime Alps and Corsica are restored to their original position
1380 prior to the post-Aquitanian counterclockwise rotation (Gattacceca et al., 2007; Maffione et
1381 al., 2008). The Ligurian-Maritime Alps and Tertiary Piemonte Basin (TPB) were involved in a
1382 regional-scale left-lateral shear zone accommodating the different motion of the WNW-
1383 directed Adria (Handy et al., 2010) and SW-Alps (Dumont et al. 2012: Maino et al. 2013) with
1384 respect to the ENE-directed Ligurian-Corso-Sardinian block (Elter 1975; Merle and Brun
1385 1984; Principi and Treves 1984; Molli 2008). In the same time span the emplacement of the
1386 Apennines belt and formation of the Liguro-Provençal basin began (Molli et al. 2010 with
1387 references therein). In this period (i.e. Late Rupelian-Early Chattian time span), the study
1388 area was comprised between the Internal Briançonnais Front (IBF) to the north and an
1389 inferred large-scale, left-lateral shear zone, here labelled as Ligurian sinistral transfer (LST),
1390 to the south. It was thus intensively affected by transpression, as recorded in the Limone-
1391 Viozene deformation Zone (LIVZ), developed roughly along the Briançonnais-
1392 Dauphinois/Provençal boundary and involving slices of Ligurian sediments (*Helminthoides*
1393 Flysch, HF). The IBF-LIVZ system could be thus part of a major, large scale Oligocene left-
1394 lateral shear zone. The effects of the Oligocene regional sinistral shearing are recorded also
1395 in the adjoining TPB (Festa et al. 2005; Maino et al. 2013) and eastern Ligurian Alps, that
1396 were controlled by the activity of the Sestri-Voltaggio fault zone (SV, Cortesogno and
1397 Haccard 1984; Vignaroli et al. 2009) and the Villalvernia-Varzi Line (VVL, Di Giulio and

Fig. 1

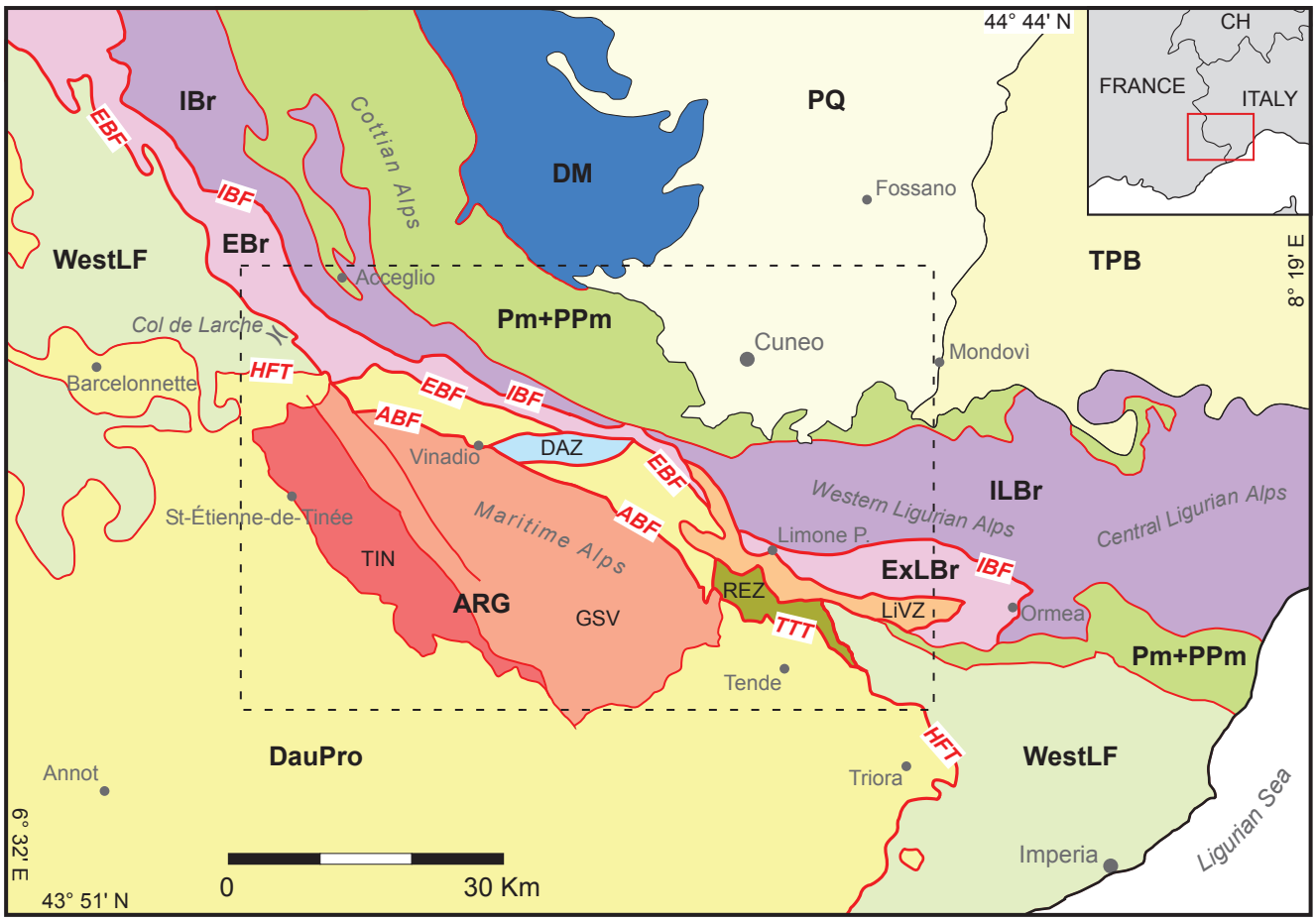

Figure 2

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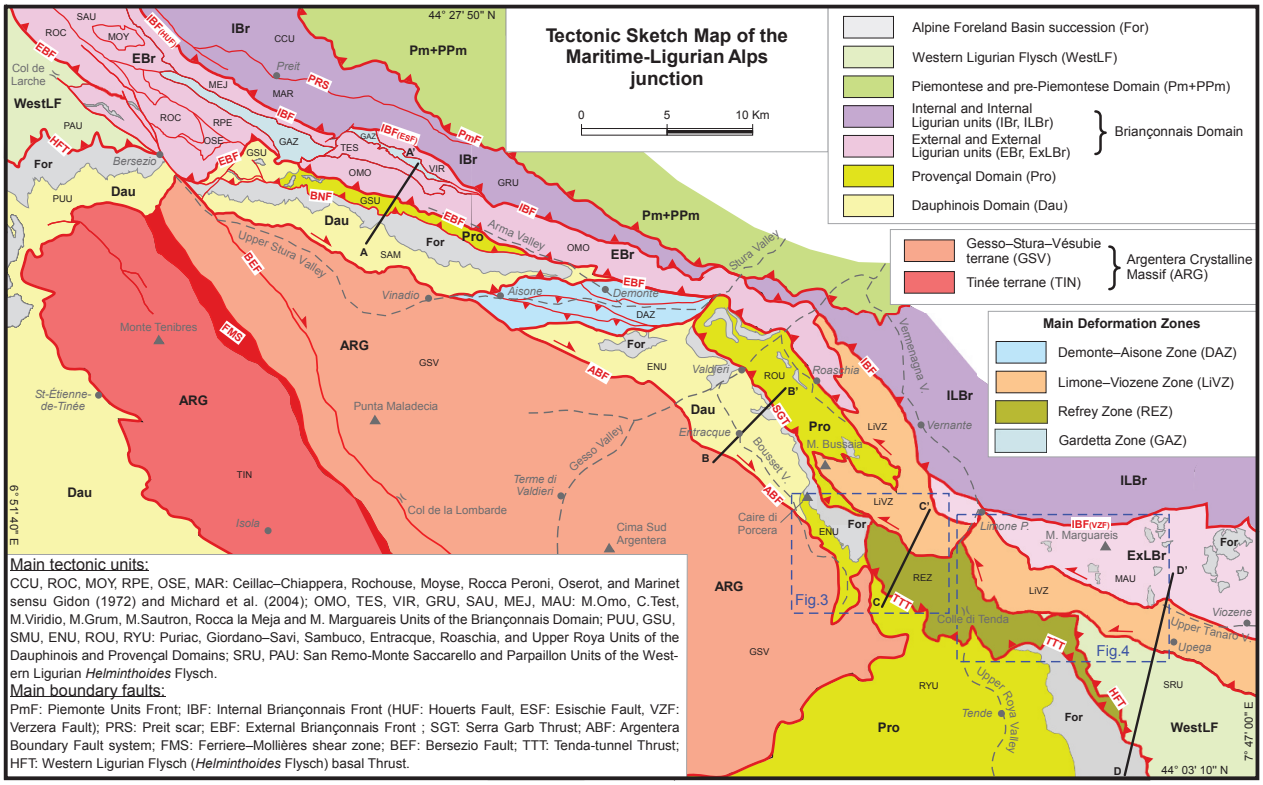

Figure 3

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Fig. 3

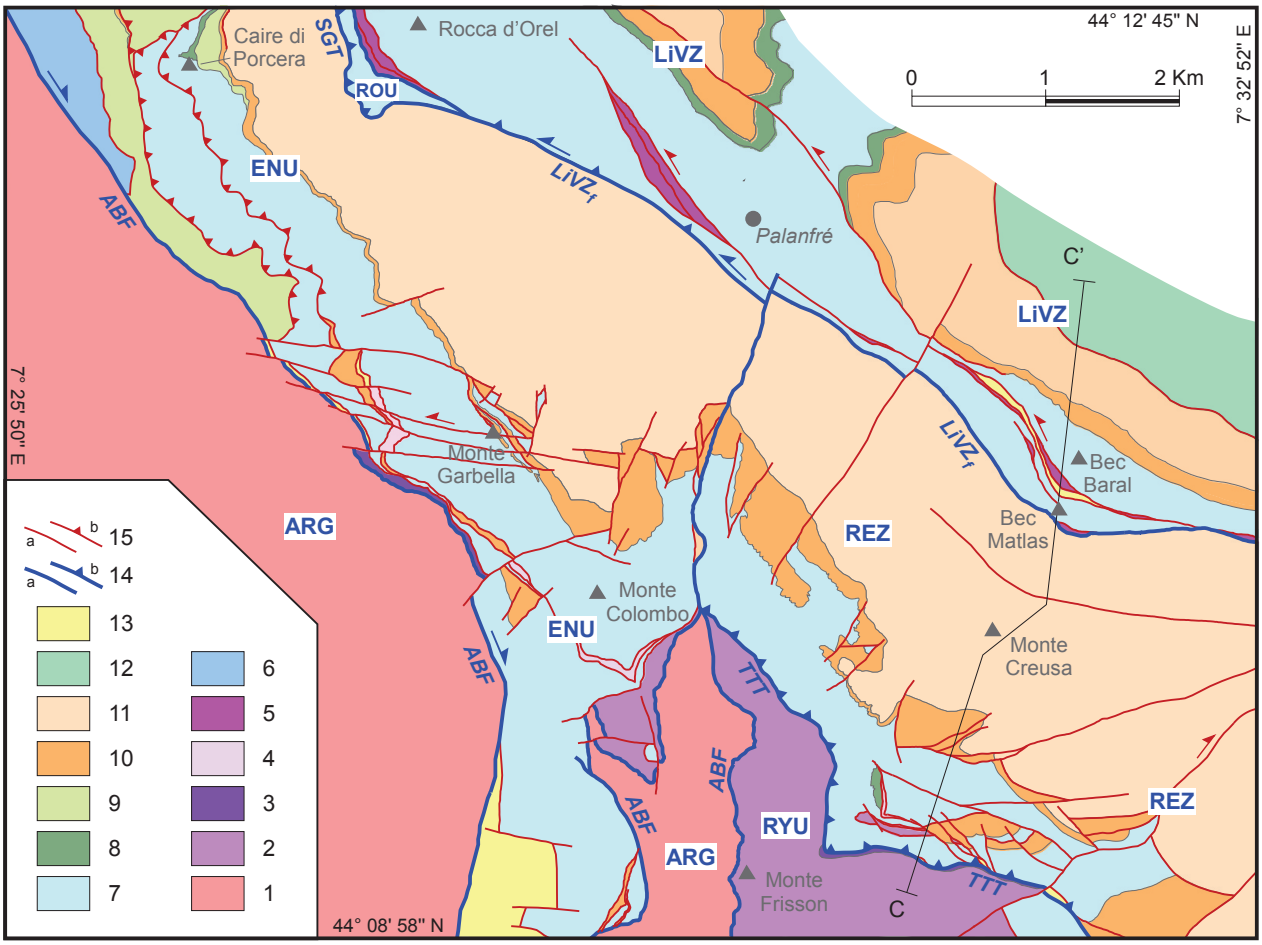

Figure 4

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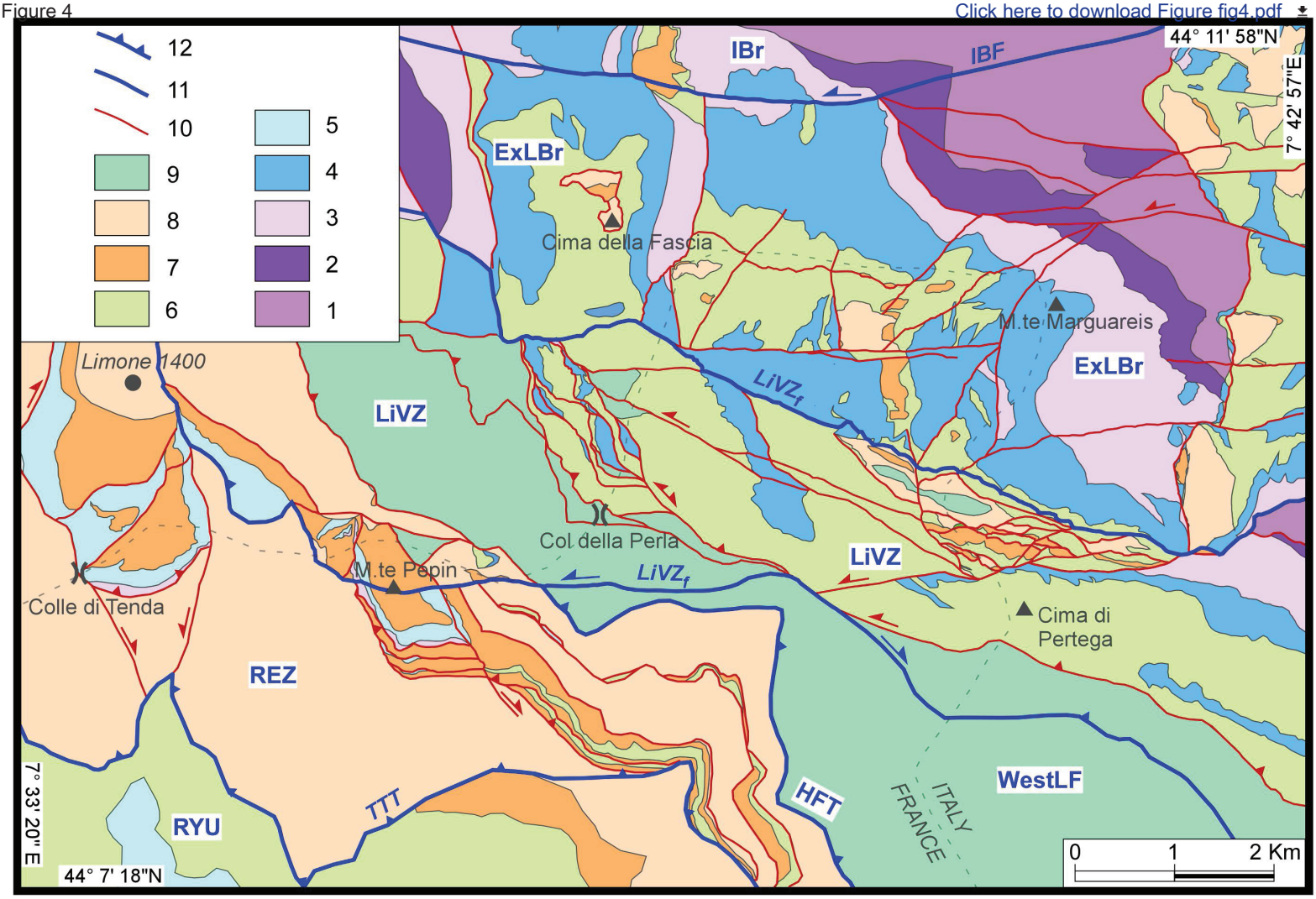

Figure 5

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Fig. 5

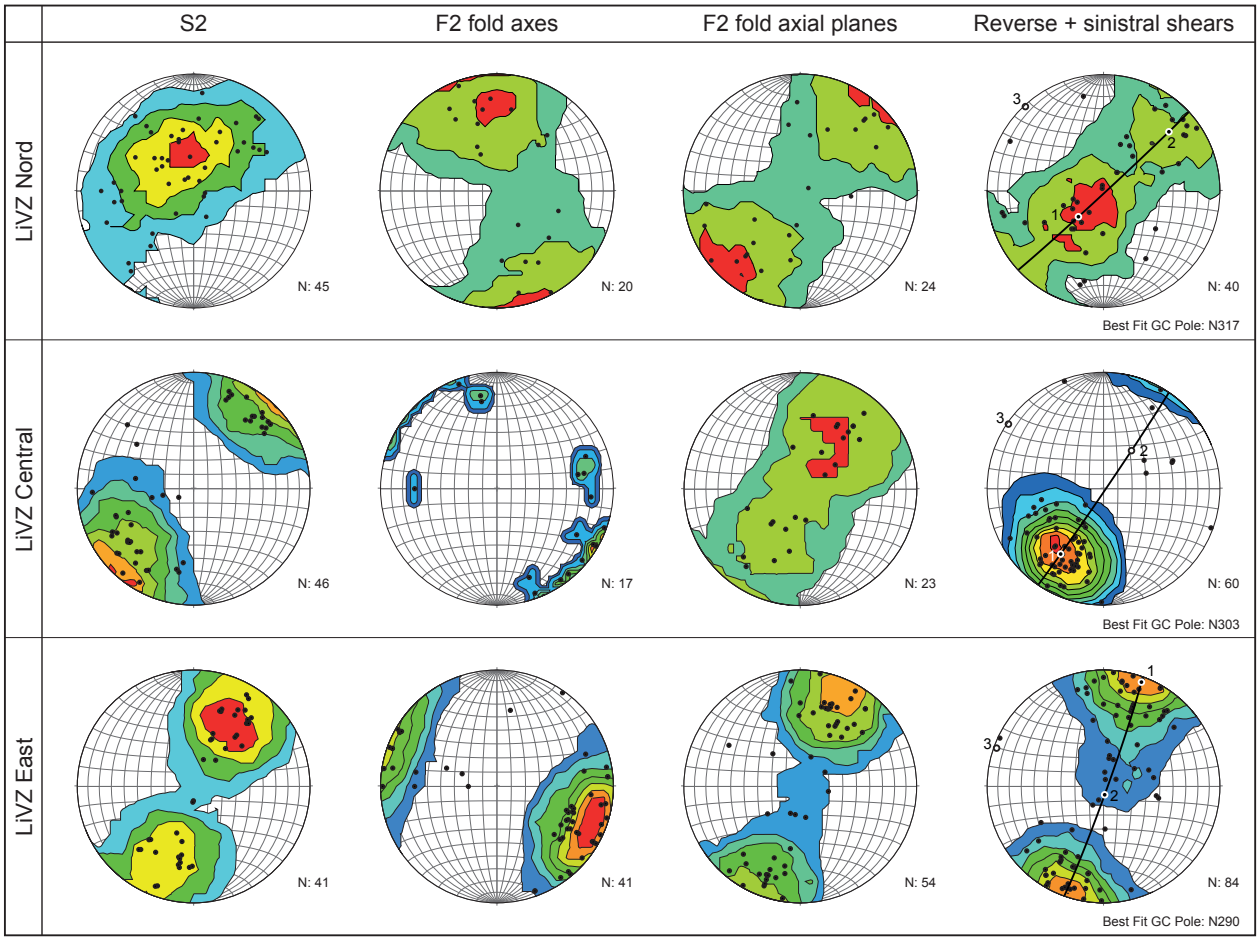

Figure 6

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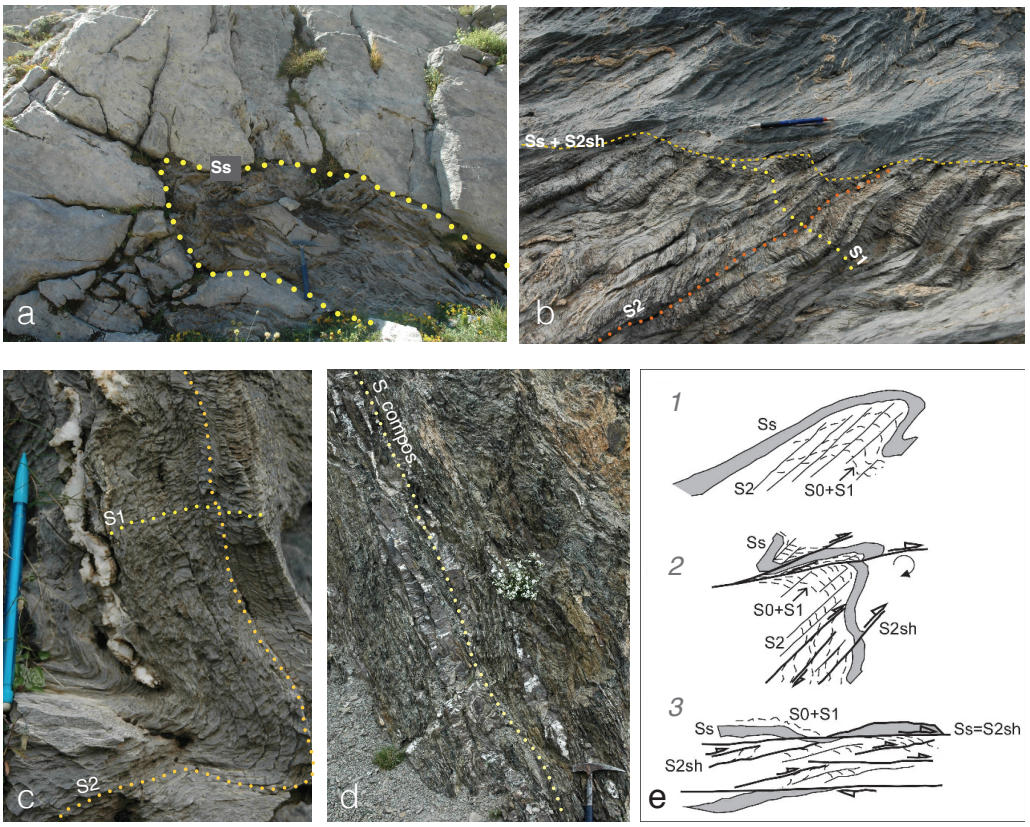

Fig. 6

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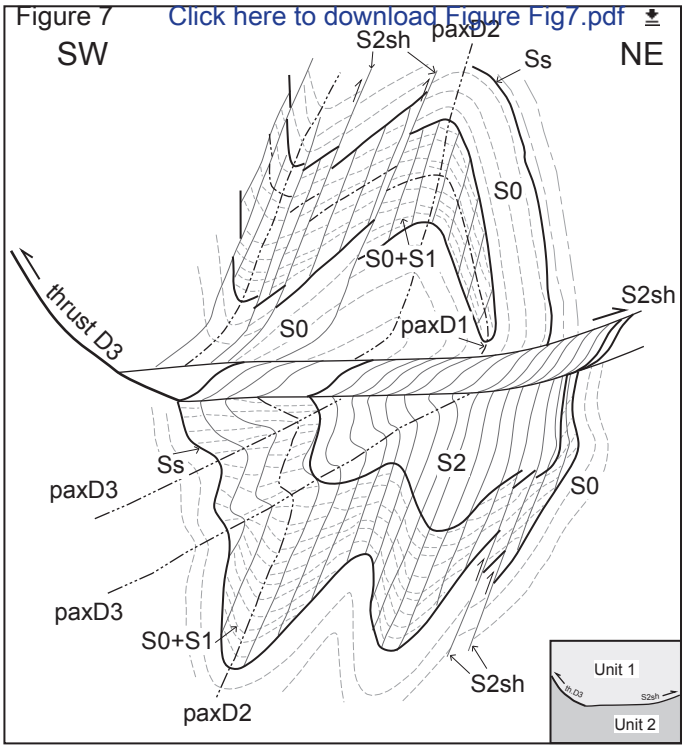
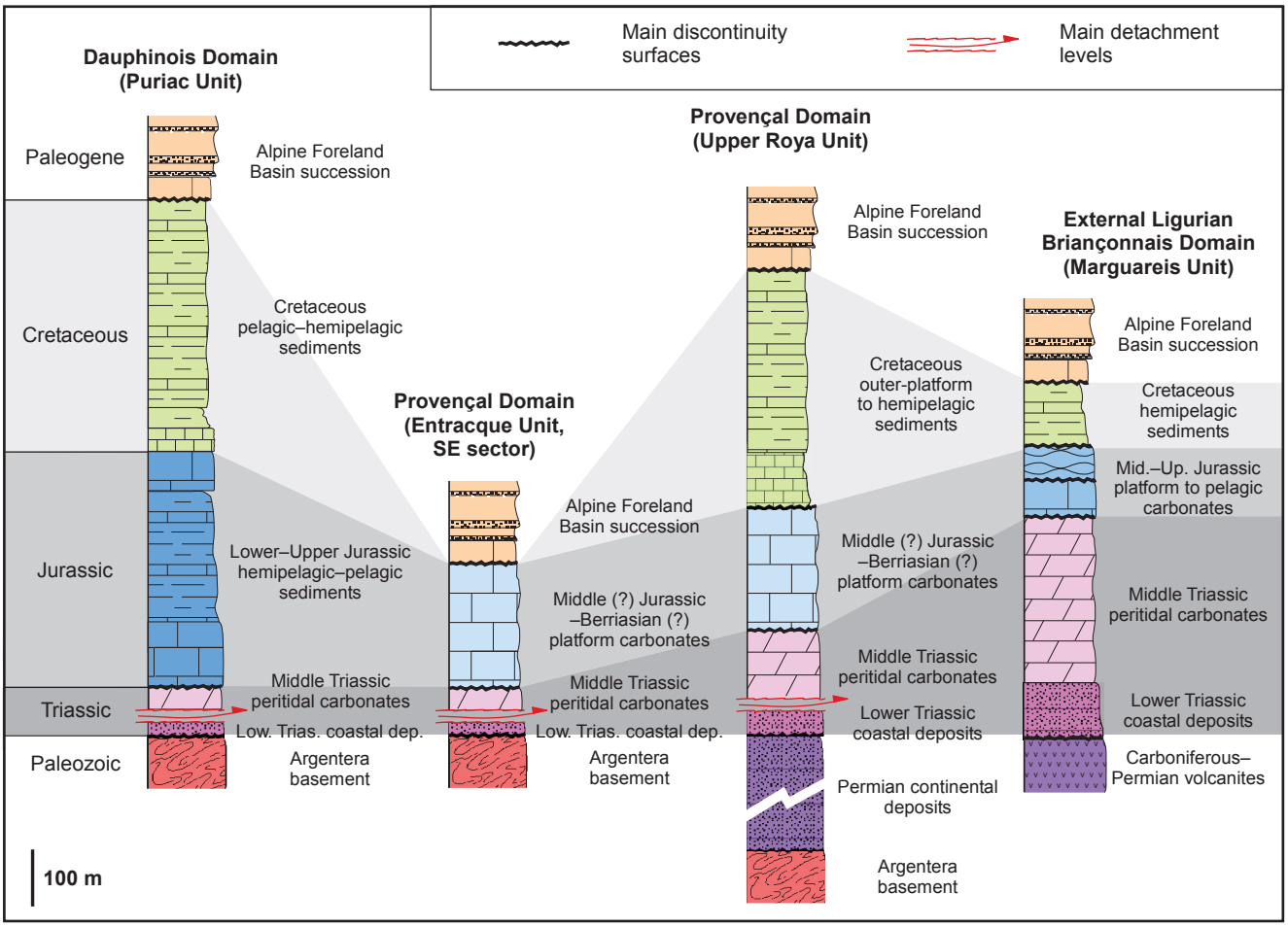


Fig.8



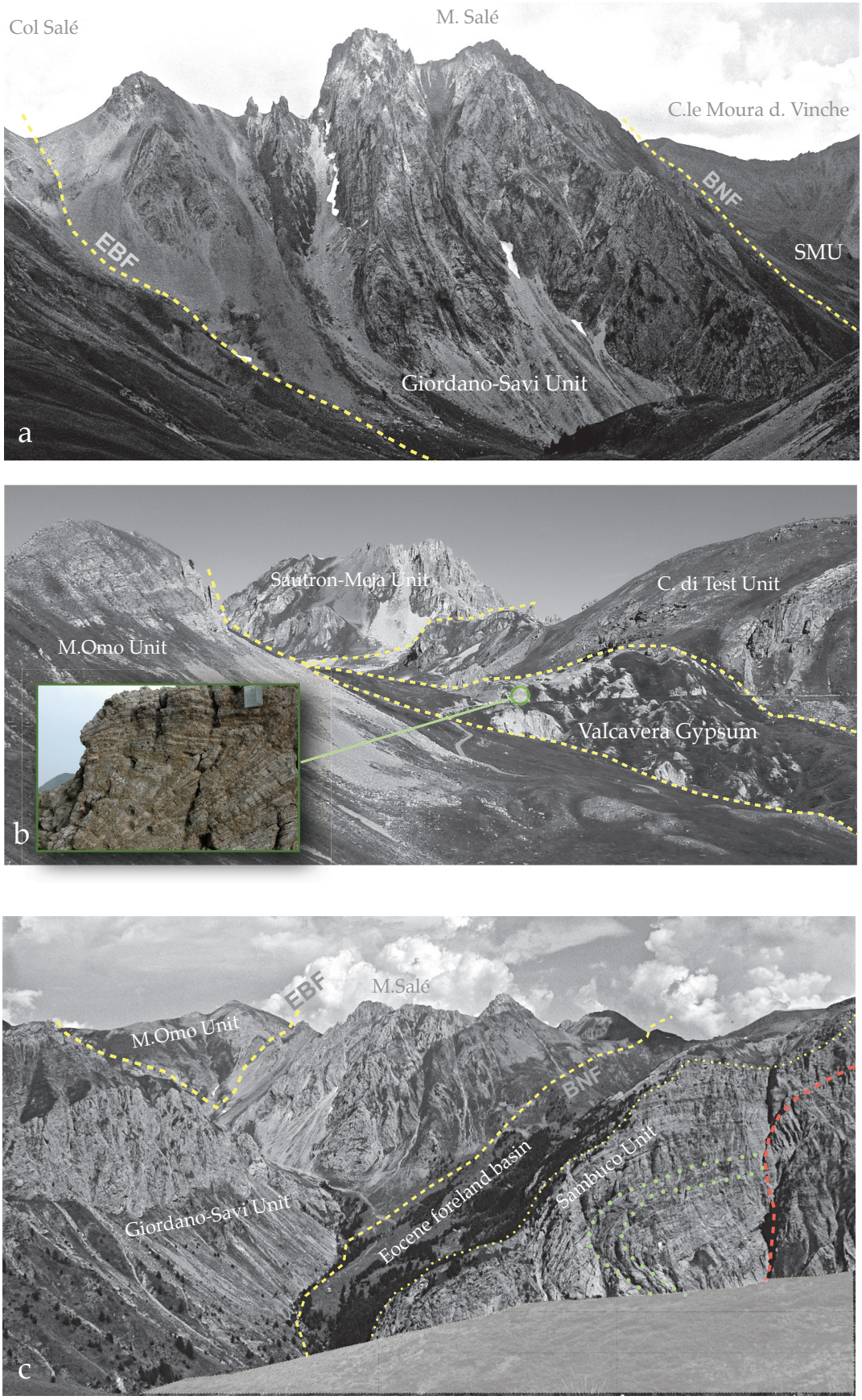


FIG. 9

Figure 10

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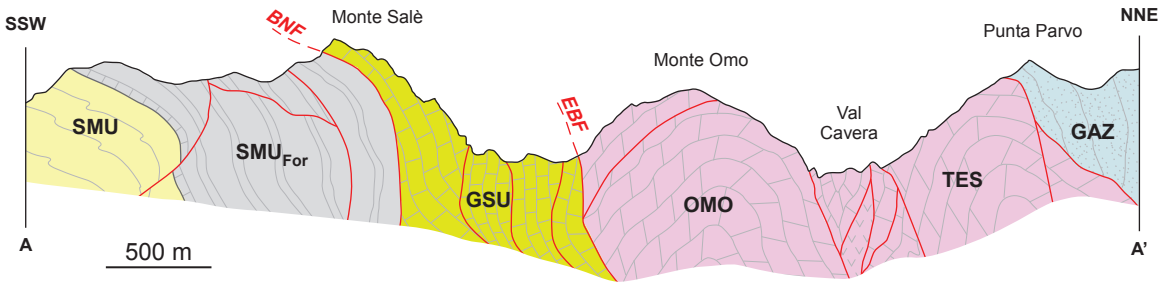
Fig.10



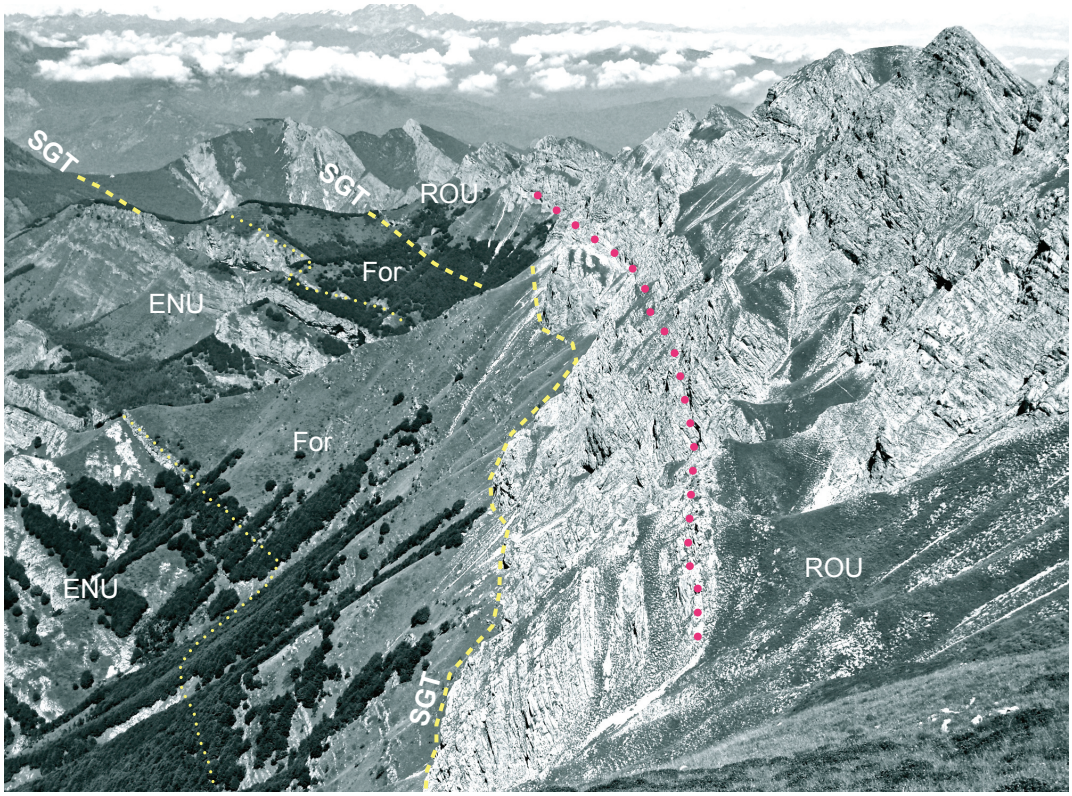


Fig. 11 -

Figure 12

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Fig.12

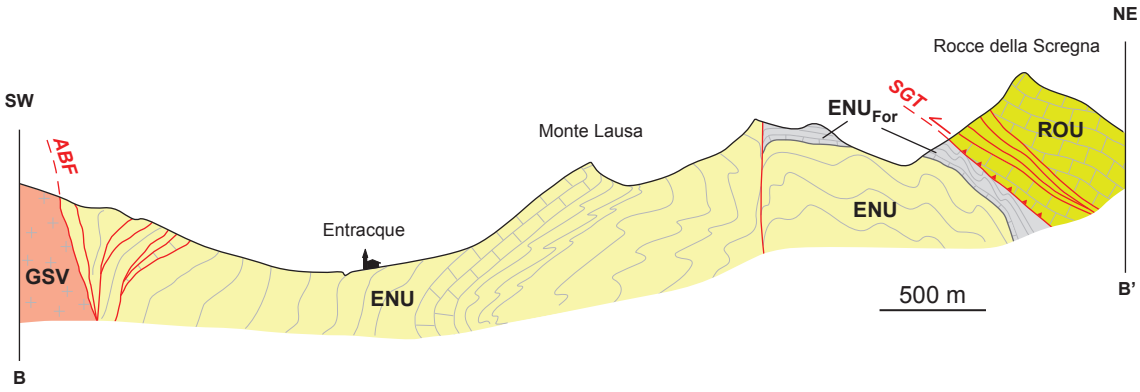

Figure 13

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Fig.13

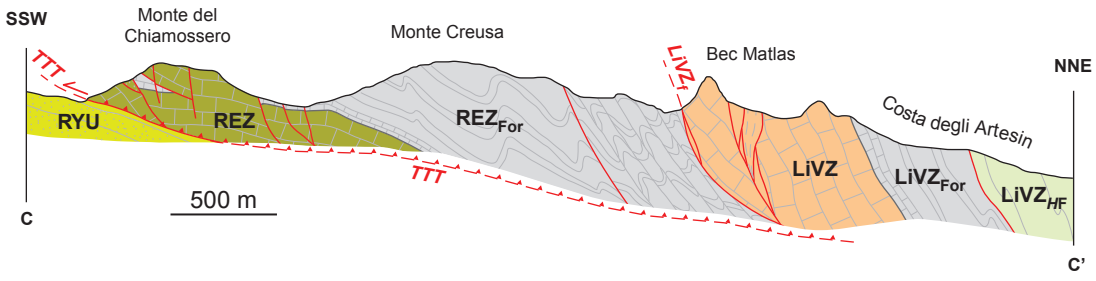

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Fig. 14

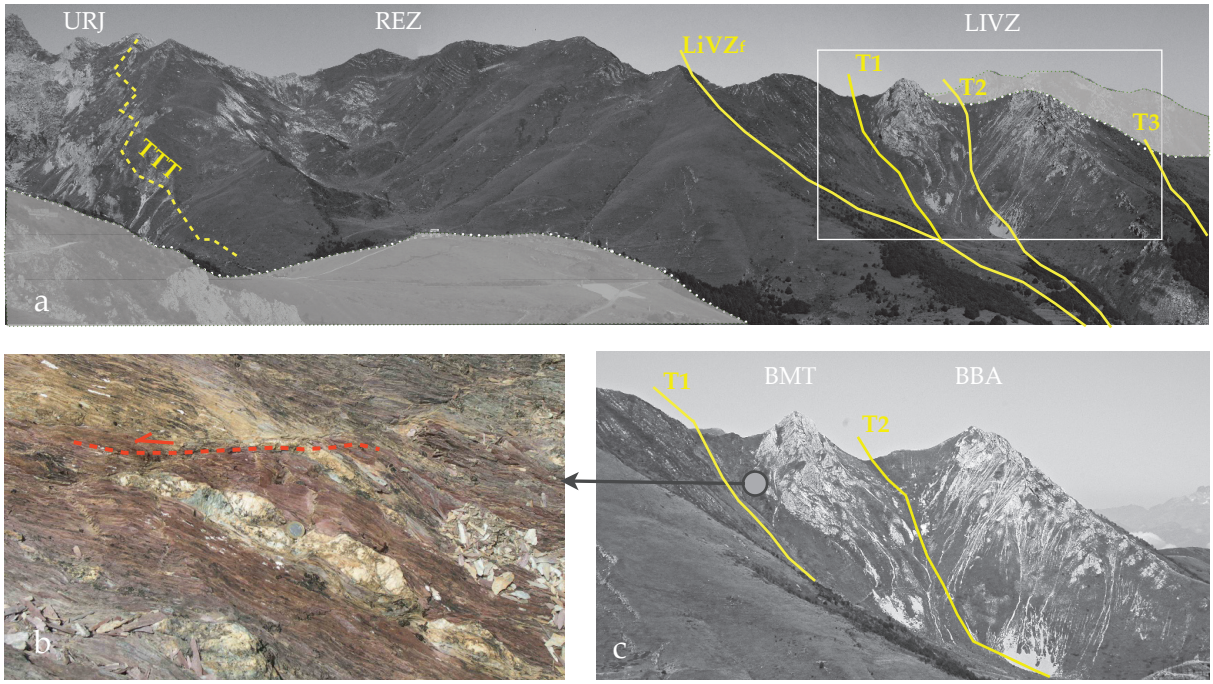

Figure 15

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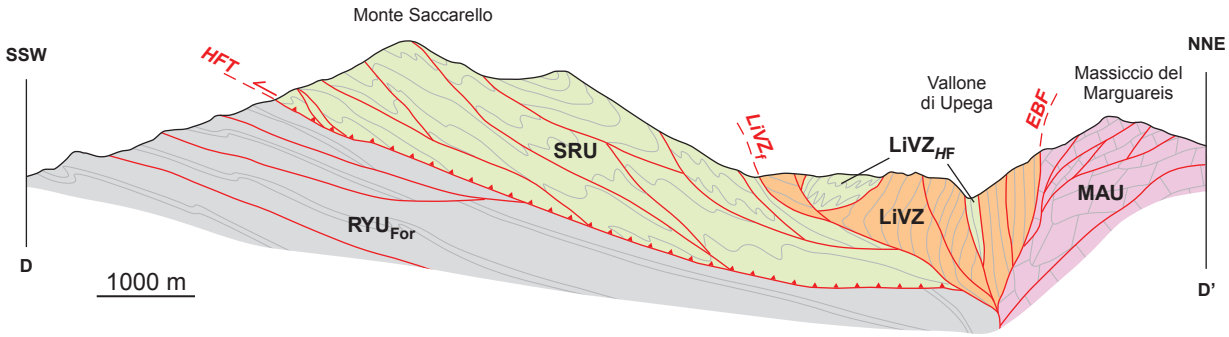
Fig.15



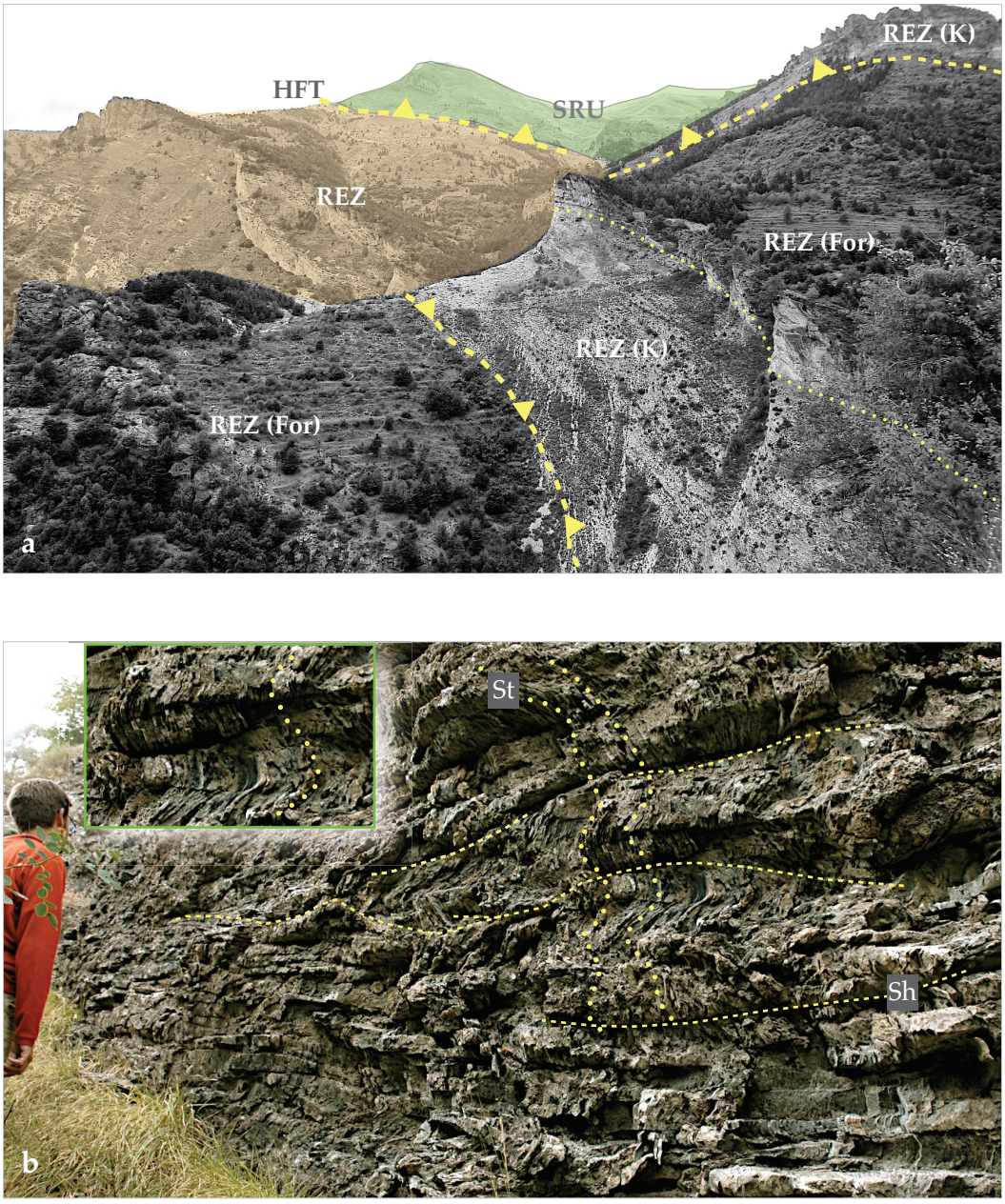


Fig. 16

Figure 17

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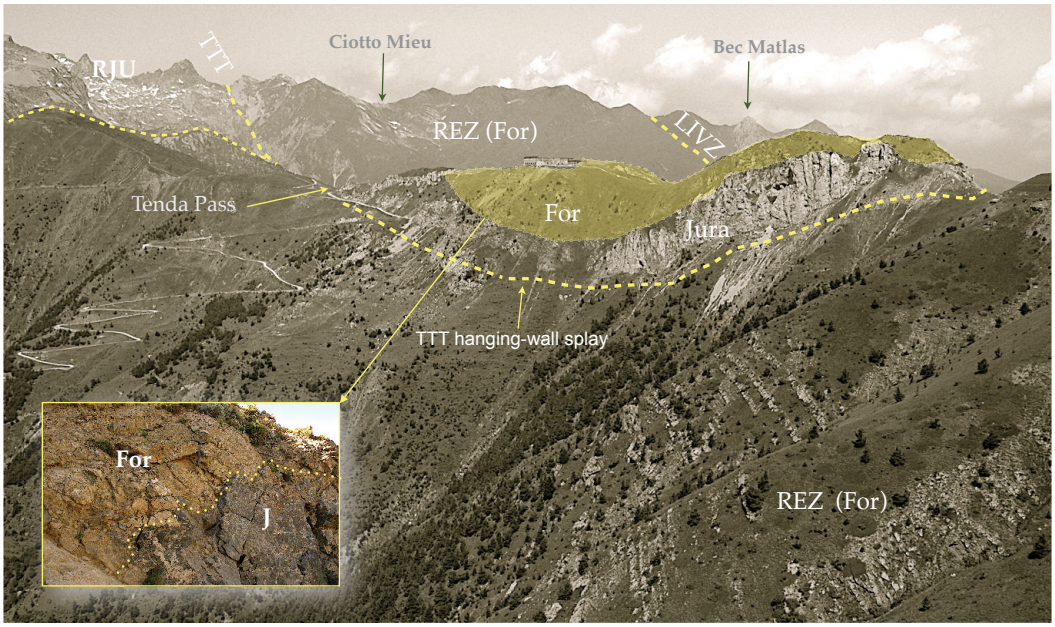

Fig. 17 -

Figure 18

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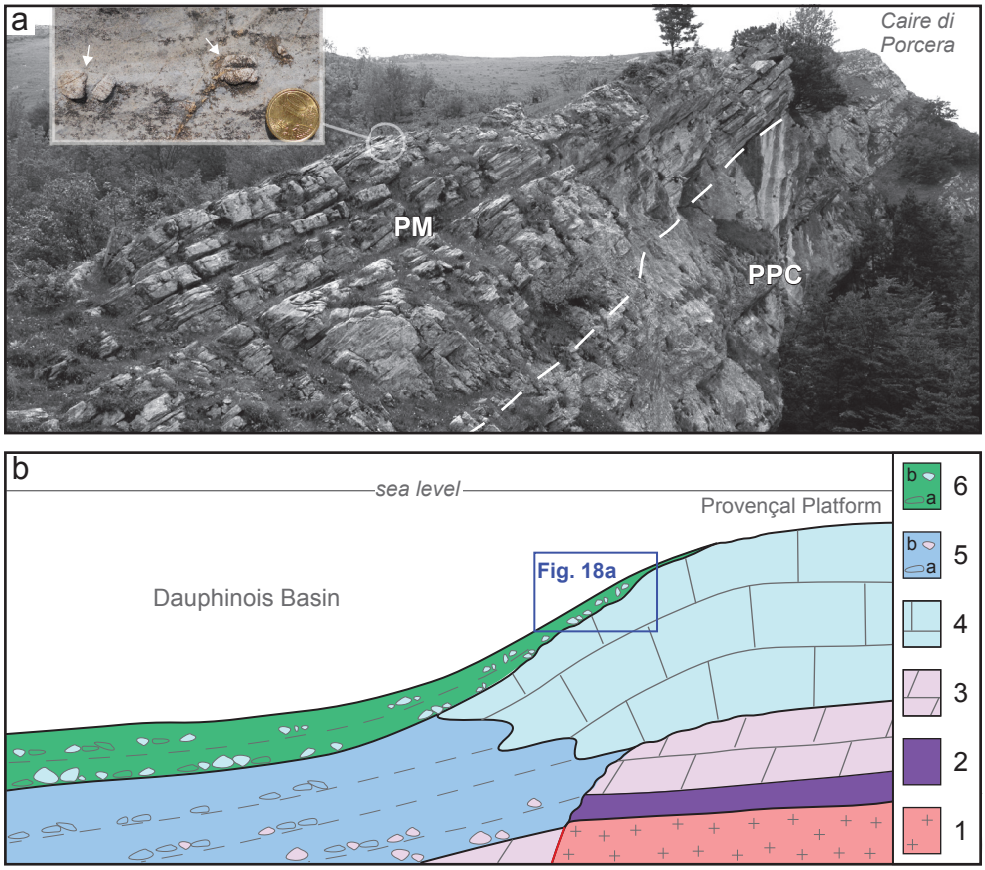

Fig.18

Figure 19

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