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UNIVERSITÀ DEGLI STUDI DI TORINO

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1	Structural evolution of different tectonic units across the Austroalpine-Penninic
2	boundary in the middle Orco Valley (Western Italian Alps)
3	
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14	Abstract. A structural study along the Orco Valley, which represents a geological
15	section through the Alpine belt (western Italy), is reported. A Lower Tectonic Element,
16	composed of units with eclogite facies relics (Gran Paradiso and Zermatt-Saas-like
17	Unit) and an Upper Tectonic Element, made of greenschist facies units (Combin-like
18	Unit and Gneiss Minuti Complex of the Sesia-Lanzo Zone) have been distinguished.
19	These two elements show a different main Alpine tectono-metamorphic event (D_1) and
20	are separated by a mylonitic contact (D2-event) developed under greenschist facies
21	conditions (Orco Shear Zone). This regional scale shear zone was responsible for the
22	exhumation of the deeper eclogitic units, and has been inferred as the continuation of
23	the Combin Fault south of the Aosta Valley. From D ₃ event onward, the same tectono-
24	metamorphic evolution was recorded in all units. The following extensional crenulation

cleavage (D_4 event) occurs mostly along a NNE-SSW deformation zone about 1 km thick at the base of the Upper Tectonic Element which leads to a further exhumation of the Lower Tectonic Element.

28

Key-words: structural evolution, tectonic coupling, exhumation, shear zone, Western
Italian Alps.

31

32 **1. Introduction**

33

34 The axial portion of the Western Italian Alps (Austroalpine and Pennidic Domains) 35 represents a fossil subduction complex developed during the Alpine orogenic cycle. In 36 the last twenty years, many geological transects (e.g. Pognante et al. 1987; Inger and 37 Ramsbotham, 1997; Bucher et al., 2004) have improved our knowledge of the structural 38 and metamorphic framework of the Western Alps. This has subsequently-brought to a 39 better insight on the geodynamic evolution of the Alpine mountain belt and has lead 40 many workers to suggest different exhumation mechanisms for HP rocks (Platt, 1993; 41 Ballèvre & Merle, 1993; Reddy et al., 1999). However, some questions about the timing 42 of tectonic coupling between oceanic and continental units still remains controversial. 43 About this debate, Lapen et al. (2007), on the base of geochronological data and PTt path analysis, have proposed that the Monte Rosa-Gran Paradiso Massifs and the 44 45 Zermatt-Saas Unit have been coupled during eclogite-facies tectono-metamorphic stage 46 and have been exhumed together by a buoyancy-driven process. Instead Kassem & Ring 47 (2004) proposed that the Gran Paradiso has been coupled to the Zermatt-Saas Unit early 48 during subduction under brittle conditions. Finally Pleuger et al. (2005) suggested 49 tectonic coupling of the Monte Rosa Massif and the Zermatt-Saas Unit before the50 greenschist facies metamorphic re-equilibration.

In this paper we present the tectono-metamorphic evolution of a geological transect trough different paleogeographic units along the middle Orco Valley, Western Italian Alps (Fig. 1). The Orco Valley represents a poorly studied key-area to unravel the structural and metamorphic evolution of oceanic versus continental tectonic units because it is a natural section through the Alpine mountain belt. Indeed, the valley trends E-W and is perpendicular to both tectonic and lithological boundaries, and to the regional metamorphic foliation.

58 This work is based on structural analysis of an area of 35 km² and take into 59 consideration three tectonic units differing for paleogeographic position and Alpine 60 metamorphic evolution. From W to E and in ascending structural order, they are: the 61 continental crust of the Gran Paradiso Unit generally attributed to the European paleo-62 margin, the Piedmont Zone that represents the remnants of the Tethys Ocean and the 63 Sesia-Lanzo Zone belonging to the African paleo-margin also known as Adria microplate (Dal Piaz, 1999; Schmid et al., 2004). Detailed structural and petrographic 64 65 analysis allowed to establish new insights on the relative timing of the tectonic contacts between the different studied units. In particular, the time of coupling between oceanic 66 and continental crust units and of eclogite versus greenschist facies units has been 67 68 established.

69

- 70 **2. Geological background**
- 71

72 2.1. The Gran Paradiso Unit (GP)

The Gran Paradiso Unit (Fig. 1) is mainly composed of augen-gneisses (Gneiss Occhiadini Complex, Compagnoni et al., 1974) derived from Permian (270 ± 5 Ma) porphyric granitoids (Bertrand et al., 2000; Ring et al., 2005), intruded into a metasedimentary high-T Variscan complex (Gneiss Minuti Complex, Compagnoni et al., 1974). Intrusive contacts are reported at the Lake of Teleccio, where relicts of the intrusive Variscan structures and sillimanite paragneisses have been preserved from Alpine reworking (Callegari et al., 1969; Compagnoni and Prato, 1969).

81 FIG. 1

82 The metasedimentary rocks have been reworked by Alpine orogeny that transforms 83 them into a polymetamorphic complex, made of paragneisses and micaschists with 84 lenses of eclogites, interpreted as pre-Alpine amphibolites (Compagnoni and Lombardo, 85 1974) or Variscan gabbros (Biino and Pognante, 1989). Eclogitic assemblages in the 86 metabasites have been used to estimate minimum PT conditions for the eclogitic event 87 at P > 12-14 kbar and T of 500-550 °C (Ballèvre, 1988; Brouwer et al., 2002). Within 88 orthogneisses, layers of whiteschists that developed in metasomatic shear zone during 89 eclogitic event also occur (Compagnoni and Lombardo, 1974). For these rocks PT 90 conditions of 21-23 kbar and 540-570 °C have been reported by Wei and Powell (2003, 91 2004) and Meffan-Main et al (2004). Conditions of 18-20 kbar and 490° C are reported 92 for the Gneiss Minuti Complex (Le Bayon et al., 2006). The high-P event is followed by 93 a late stage of re-equilibration at 4-6 kbar and 500-550 °C, interpreted as a re-heating 94 stage occurred after an initial cooling during decompression (Borghi et al., 1996; 95 Brouwer et al., 2002, 2004).

Geochronological data, obtained with Rb-Sr microsampling on white mica, suggest that the eclogite-facies event occurred at 43 ± 0.5 Ma (Meffan-Main et al., 2004), whereas the greenschist-facies metamorphism spread at about 34-38 Ma (Rb-Sr on white mica, Freeman et al., 1997; Meffan-Main et al., 2004). The final stages of exhumation are recorded by U-Pb fission tracks on zircon (30 ± 1 Ma at 225 ± 25 °C) and apatite (20-24Ma at 100 ± 20 °C) (Hurford and Hunziker, 1989).

102

103 2.2. The Piedmont Zone

104

105 The Piedmont Zone, representing the remnant of the Tethys Ocean, consists of two 106 main zones, the lower and the upper one, respectively known as Zermatt-Saas Unit and 107 Combin Unit in the southern Valais and Aosta Valley (Bearth, 1967; Dal Piaz, 1974; 108 Dal Piaz and Ernst, 1978; Dal Piaz, 1999). Zermatt-Saas Unit is composed of slivers of 109 oceanic crust, mainly represented by serpentinites with minor peridotites, including 110 discontinuous bodies of Mg-Al to Fe-Ti rich metagabbros and overlaid by metabasalts. 111 Locally a thin metasedimentary cover composed of impure quartzites, micaschists, 112 marbles and calcschists is preserved. Mafic and metasedimentary rocks display a well-113 preserved eclogite facies metamorphism.

114 Combin Unit is made of calcschists with intercalations of metabasalts and serpentinites; 115 all lithologies mainly show a greenschist facies metamorphic overprinting, with 116 blueschist facies relics.

117 PT conditions for different tectonic slivers belonging to Zermatt-Saas decrease from

118 north (P > 15-20 kbar and 550-600 °C) to south (10-18 kbar and 450-500 °C; for review

see: Spalla et al., 1996; Desmons et al., 1999a, 1999b). Occurrence of coesite is reported

120 for the Cignana Unit, in Valtournenche, indicating P of 26-28 kbar and T of 600°C 121 (Reinecke, 1991, 1998). Messiga et al. (1999) reported conditions of 24 kbar at $600 \pm$ 122 50 °C for the Monviso ophiolites. The greenschist facies metamorphic overprinting develops at 425-450 °C and 4-5 kbar and is concentrated along top to SE shear zones 123 124 (Barnicoat et al., 1995; Cartwright and Barnicoat, 2002). The high-P event is dated at 125 40-50 Ma (Rb-Sr white mica, Duchêne et al., 1997; U-Pb zircon with SHRIMP, Rubatto et al., 1998; Sm-Nd garnet, Amato et al., 1999; Rb-Sr and ⁴⁰Ar-³⁹Ar white mica, Dal 126 Piaz et al., 2001; Rb-Sr white mica, Cartwright and Barnicoat, 2002) while greenschist 127 128 re-equilibration spread from 36 to 42 Ma (Rb-Sr whole rock-white mica, Amato et al., 129 1999; Cartwright and Barnicoat, 2002).

In the Combin Unit the high-P event developed under blueschist facies conditions (1213 kbar and 425-475°C, Cartwright and Barnicoat, 2002) while the re-equilibration
event developed under greenschist facies conditions (P < 9kbar and T of 300-450°C,
Reddy et al. 1999) at around 34-38 Ma (Rb-Sr white mica, Inger and Ramsbotham,
134 1997).

135

136 2.3. The Sesia-Lanzo Zone (SL)

137

The Sesia-Lanzo Zone consists of a pre-Alpine basement thrusted above the Piedmont Zone and involved in the orogenic accretionary wedge. It is made of three tectonic units that, from top to bottom and from E to W, consists of the Eclogitic Micaschists Complex (EMC), the II Dioritic-Kinzigitic Zone (II DK) and the Gneiss Minuti Complex (GMC) (Compagnoni et al., 1977; Pognante, 1989). The EMC is a high-T Variscan complex made of paragneisses, marbles, amphibolites and granulites intruded by late-Variscan gabbros and granitoids, that developed widespread eclogite facies assemblages during Alpine orogenic cycle (Lardeaux and Spalla, 1991). The II DK is a high-T Variscan metasedimentary complex poorly affected by high-P and greenschist facies Alpine overprinting. The GMC also comprises pre-Alpine rocks pervasively transformed into greenschist facies lithologies: mainly orthogneisses, subordinate micaschists and metabasites, with minor Mesozoic calcschists. On the east side of the GMC some relicts of blueschist facies conditions are preserved (Spalla et al., 1996).

151 The EMC reached conditions of 15-18 kbar and 550-620 °C (Pognante et al., 1980,

152 1987; Lardeaux et al., 1982; Pognante, 1989; Lardeaux and Spalla, 1991) dated 65-80

153 Ma (Rb-Sr white mica, Inger et al., 1996; Duchêne et al., 1997; Rubatto et al., 1999).

154 The GMC, instead, has been pervasively equilibrated at P < 13 kbar and 450-500°C

155 (Williams and Compagnoni, 1983; Pognante et al., 1987; Pognante, 1989; Spalla et al.,

156 1996) at about 37-39 Ma (Hunziker et al., 1993; Inger et al., 1996).

157

158 **3. Tectono-stratigraphic setting**

159

160 According to their different structural and metamorphic evolution, the tectonic units 161 outcropping in the study area (Fig. 2) have been grouped in two main Tectonic 162 Elements. From NW to SE they are: I) a Lower Tectonic Element (LTE) preserving 163 relics of eclogite facies metamorphism and consisting of the Gran Paradiso Unit and 164 oceanic tectonic slices referred to the Zermatt-Saas Unit according to lithostratigraphic 165 and metamorphic affinities; II) an Upper Tectonic Element (UTE) made of greenschist 166 facies units devoid of eclogitic relics consisting of a Combin-like unit and the Gneiss 167 Minuti Complex of the Sesia-Lanzo Zone. These two Tectonic Elements are separated

168	by a tectonic contact of regional importance. A detailed summary of the metamorphic
169	assemblages and the tectono-metamorphic relationships of the different studied units are
170	respectively reported in Tables 1 and 2.
171	
172	FIG. 2
173	TABLE 1
174	TABLE 2
175	3.2. Lower Tectonic Element (LTE)
176	
177	In the Lower Tectonic Element the GP continental crust represents the deepest tectonic
178	unit of the study area, thrusted by a tectonic mélange of oceanic affinity referred to the
179	Zermatt-Saas Unit.
180	The Gran Paradiso Unit consists of orthogneisses, a polymetamorphic basement and
181	rare Mesozoic covers (quartzites and dolomitic marbles) preserved near the tectonic
182	contact with oceanic units. The orthogneisses are heterogeneously deformed ranging
183	from isotropic rocks with magmatic structures perfectly preserved, to augen-gneisses
184	and flaser-gneisses. Locally thin layers of whiteschists which grade to augen-gneisses
185	are present. The polymetamorphic basement is mainly composed of micaschists hosting
186	metabasites bodies. They consist of up to 1 metre-sized lenses or layers of fine grained
187	and felsic eclogites, and up to 100-150 m thick fine to medium-grained foliated
188	metagabbros, that locally preserve the eclogite facies assemblage. A late metamorphic
189	greenschist facies overprinting developed under static conditions in both micaschists
190	and metabasites.

The oceanic units consist of a tectonic mélange formed by ultrabasic and metabasic rocks with minor carbonatic-pelitic cover sequences. The ultrabasic bodies mainly consist of serpentinites that envelop 10 to 100 m thick lenses of metamorphosed spinellherzolites, showing a well developed tectonic foliation. Small bodies of metagabbros rarely occur within the ultrabasic rocks. The metabasic bodies consist of epidote-albite amphibolites and of metagabbros, which locally preserve eclogitic relics.

197 Cover sequences are subordinate with at most 5 to 10 m thickness and are represented 198 by marbles, silicates marbles, calcschists, micaschists and impure quartzites. These 199 lithologies are transitional to each other and locally are interlayered at the decimetre-200 size scale.

201

202 3.3. Upper Tectonic Element (UTE)

203

The Upper Tectonic Element consists of a lower unit showing Combin affinity and an
upper unit of continental basement rocks referred to the Gneiss Minuti Complex of the
Sesia-Lanzo Zone.

The Combin-like unit is mainly composed of calcschists with up to 50-100 m thick
bodies of greenstones and serpentinites/ophicalcites.

The Gneiss Minuti Complex represent an heterogeneous continental crust unit with subordinate Mesozoic covers. It mainly consists of orthogneisses whose protholites range from monzodiorite to granodiorite and minor leuco-gneisses, greenstones, metagabbros and micaschists. The latter have been interpreted as a pre-Alpine basement for the presence of relict, coarse grained, red biotite. The Mesozoic covers are made of 214 rare quartzites and of calcschists interlayered with thin meta-carbonatic and meta-pelitic215 levels.

216

217 *3.4. Mylonitic rocks along tectonic contacts*

218

Mylonitic rocks occur along the main tectonic contacts between the different studied units. Their peculiar mineral assemblages are indicative of the metamorphic conditions under which they were developed and resulted of great importance in reconstructing the tectono-metamorphic evolution of the area. For this reason a brief description of the metamorphic assemblages is here reported.

224 The tectonic contact between the Gran Paradiso and the Zermatt-Saas-like Unit is 225 characterized by the presence of sheared Mesozoic covers belonging to both units. 226 Where metasediments are absent serpentinites become mylonitic (Srp + Mg-Chl + Ol + 227 Di; mineral abbreviations according to Kretz, 1983), eclogites are re-equilibrated under 228 blueschist facies conditions (Gln + Ep + Bt + Spn), while orthogneisses are transformed into micaschists (Qtz + Wm + Mg-Chl + Ab + Mg-Cld). On the southern side of the 229 230 Orco Valley, a mylonitic foliation that envelops eclogites boudins has been observed. 231 This foliation is made of Act-Chl-Wm-schists and preserves portions of an older 232 foliation defined by blue Am + Chl + Wm which suggests that the tectonic contact 233 developed under blueschist facies conditions and was reworked during later decreasing 234 P. The thickness of the deformation zone varies between 1-5 meters where competent 235 rocks are in contact, to 10-50 metres where Mesozoic covers are present.

236 Tectonic contact between the Gneiss Minuti Complex of the Sesia-Lanzo Zone and the
237 Combin-like unit is marked by mylonitic rocks deriving from both units and developed

under greenschist facies conditions. Locally Chl-schists (at the expense of greenstones)and Tlc-schists (at the expense of metabasites or serpentinites) are also present.

240 Finally, the regional tectonic contact between eclogitic LTE and greenschist UTE is 241 marked by a mylonitic zone which thickness-ranges from some meters up to 50-100 242 metres. Along this shear zone mylonitic calcschists and gneisses are widespread and 243 locally Chl-Act-schists (derived from metabasites and serpentinites) are developed, 244 which envelop blocks of eclogites, metasediments and Sesia-Lanzo gneisses. This 245 regional scale shear zone represents the boundary between the eclogite facies units in 246 the footwall and the greenschist facies units in the hangingwall and has been defined as 247 Orco Shear Zone.

248

249 4. Structural and metamorphic evolution

250

251 Three different Alpine tectono-metamorphic events at the regional scale (D_1, D_2, D_3) , 252 followed by two ductile to brittle events (D_4, D_5) have been distinguished. The study 253 area is marked by a regional transposed foliation concordant with the lithological 254 boundaries, dipping 40-50° towards E to SE. However, the regional foliation developed under different metamorphic conditions (Table 2) and in different time through the two 255 256 main tectonic elements. In the following sections, we will refer to S_1 as the main 257 regional foliation of each tectonic element, which is not synchronous across the whole 258 area. The mineral assemblages related to the different deformation events are 259 summarized in Table 1 for the main rock types.

260

261 *4.1. D₁ structures and metamorphism in the Lower Tectonic Element*

263 In the Gran Paradiso Unit S₁ foliation dips 35-70° toward SE with some poles in the 264 opposite quadrant (Fig. 3a). D₁ folds are isoclinal to rootless in the paragneisses, 265 isoclinal and asymmetric in meta-aplites within orthogneisses. At the microscale, D_1 266 folds transpose an early pre-S₁ foliation rarely preserved in relict hinges. Fold axes 267 show similar orientation to stretching lineations (L_1) that plunge mainly 10-45° towards 268 050-095 with some scattering due to subsequent reorientation. L₁ is defined by oriented 269 K-feldspar porphyroclasts in the augen-gneisses, by quartz + white mica + horneblende 270 in paragneisses and by Ca-Na amphibole + zoisite in metabasites. D₁ is associated with 271 top to W sense of shear, which is proved by widespread σ -shaped K-feldspars 272 porphyroclasts in orthogneisses (Fig. 4a). The occurrence of non-linear intersection 273 lineations on S_1 foliation planes according to the parallelism between L_1 and A_1 on the 274 regional scale, suggest that D_1 event mainly develops under simple-shear regime, 275 causing non-cylindrical folding (Fig. 4b).

276

FIG. 3

In the main lithologies of the GP (paragneisses, metabasites, orthogneisses) the S_1 regional foliation (Fig. 5a,b) is defined by metamorphic assemblages (Table 1) indicative of upper-greenschist to epidote-albite amphibolite facies conditions (subsequently reported as medium PT conditions), following pre- S_1 event/events (Fig. 5b) developed under eclogite facies conditions.

- 282
- 283

FIG. 4

FIG. 5

In the Zermatt-Saas-like Unit, the main foliation S_1 (Fig. 3b) dips in SE quadrant with a more obvious scattering with respect to the Gran Paradiso Unit, probably due to the

presence of great volumes of serpentinites strongly and easily deformed by subsequent 286 287 events. Folds are isoclinal in eclogites and rootless in serpentinites (Fig. 5c) and 288 metasediments. The mineral lineations are defined by Ca-Na amphibole + zoisite in 289 metagabbros and in re-equilibrated eclogites and by magnetite aggregates in 290 serpentinites. Both fold-axes and stretching lineations plunge to E and show a 291 substantial parallelism like in the Gran Paradiso Unit (Fig. 3b). Locally a well-preserved 292 pre-S₁ eclogitic foliation occurs in metabasites and metagabbros. In meta-peridotites a relic foliation defined by olivine + chlorite + amphibole + meterite is preserved. The 293 294 following D₁ event developed a new axial surface defined by medium PT conditions.

The tectonic contact between the Gran Paradiso and the Zermatt-Saas units was deformed by D_1 top to W non-cylindrical folds (Figs. 6, 7 and 8, cross section B-B'). The presence of Mg-chlorite + albite +Mg-chloritoid micaschists and glaucophane + epidote + rutile blueschists along the contact suggests tectonic coupling under blueschist facies conditions.

300

FIG. 6

301

302 *4.2. D*₁ structures and metamorphism in the Upper Tectonic Element

303

In both units of the Upper Tectonic Element the main regional foliation S_1 (Fig. 3d-f) dips 25-65° towards SE with some planes in other quadrant owing to the following deformation phases. D₁ folds (Fig. 4c) are isoclinal to rootless with axes plunging 25-60° towards 060-110 which are sub-parallel to the stretching lineations, defined by quartz + white mica in calcschists and by quartz + albite + white mica ± actinolite in gneisses.

311 In both the Combin-like Unit (Fig. 5d,e) and the Gneiss Minuti Complex of the Sesia-312 Lanzo Zone (Fig. 5f,g), the main foliation S_1 is underlined by greenschist facies 313 conditions.

Pre-S₁ relic foliations are preserved both in the Sesia-Lanzo gneisses and in the Combin
calcschists and are defined by greenschist facies assemblages too.

- 316 D_1 event deforms the mylonitic contacts between the two tectonic units of the UTE and 317 is mainly responsible for their lithological repetition at the regional scale (Figs. 2, 7 and 318 8).
- 319

320 *4.3. D*₂ structures and metamorphism

321

322 D_2 event deforms D_1 structures in all tectonic units, but its structural imprinting affected 323 differently LTE and UTE. Indeed, in the former, D₂ structures are developed only at the 324 mesoscale while, in the latter, macroscale folds are also present and D₂ structures are 325 very common. D₂ develops polyharmonic and asymmetric folds that show close to 326 isoclinal profile, but rarely an axial plane foliation occurs at the mesoscale (Fig. 4d, e). 327 Axial planes dip 30-60° towards E to SE while the axes are scattered on the average 328 maximum circle of the foliation planes (Fig. 3g, h) showing the presence of noncylindrical structures developed during non-coaxial deformation. Therefore, A_2 axes 329 330 show a variable angle respect to the stretching lineations L₂ which plunge concordantly 331 towards E. The asymmetric Z folds (looking to N) present on the long limbs have an 332 enveloping surface dipping to the E more than S2 surfaces. These features of the meso to 333 macroscale D₂ structures indicate a top to E sense of shear (Fig. 8 cross sections A-A',

C-C') according to the structural relationship described by Inger & Ramsbotham (1997)
for the Eclogitic Micaschists Complex of the Sesia-Lanzo Zone outcropping to the E of
the study area.

337 At the microscopic scale S_2 developed under greenschist facies conditions and is 338 defined by a crenulation cleavage (Fig. 5b-d) in all lithologies of the studied units 339 (Table 1).

340

341 *4.4. D₃ structures and metamorphism*

342

343 D_3 phase develops box folds with open to close profiles which indicate a prevalent top 344 to SE asymmetry. Axial planes dip mainly NW by a range of inclination from 30° to 345 sub-vertical with some data in the opposite quadrant, indicating polyclinal profile 346 typical of box folds (Figs. 3i and 4f). Rarely C'-type conjugate shear bands, with 347 reverse-slip movement is developed at the mesoscale in calcschists (Fig. 4f), 348 serpentinites and subordinately in the Sesia-Lanzo gneisses, with a stretching lineations 349 L₃ defined by quartz and calcite fibres and by striations. L₃ on C'-type surfaces and 350 shear bands geometry indicate both top to NW and top to SE sense of shear pointing to 351 a NW-SE directed compression. Axes plunge equally 10-30° towards NE and SW while 352 the scattering of at least 60° is due to D₅ deformation phase.

353 At the microscale, C'-type shear bands developed under low-grade metamorphic 354 conditions. D_3 event deforms the tectonic boundary between LTE and UTE and all other 355 previous structures (Fig. 8 cross sections B-B', C-C').

- **FIG. 7**
- 357 **FIG. 8**

359 4.5. D₄ Extensional Crenulation Cleavage (ECC)

360

Extensional Crenulation Cleavage (as defined by Platt & Vissers, 1980) is well 361 362 developed in calcschists and locally in serpentinites at the mesoscale (Fig. 4g). It is 363 underlined by centimetric to millimetric spaced surfaces which mostly occur along a 364 NE-SW belt less than one kilometre thick within the calcschists and subordinately in the Sesia-Lanzo gneisses of the UTE. S₄ surfaces dip mainly to SE by 60° to sub-vertical 365 366 with down-dip lineations defined by quartz and calcite fibres and by striations indicating top to SE normal shear. Axes plunge less than 30° towards NE and SW (Fig. 31). 367 368 Locally at the contact between calcschists and gneisses, ECC steps gradually into 369 frictional structures in the latter lithologies, suggesting that this deformation event took 370 place under the brittle-ductile transition regime. ECC shows a significant grain-size reduction (Fig. 5e,g,h) suggesting high parain-rate and is defined by low-grade 371 372 metamorphic conditions.

Field observations at the western border of the Gran Paradiso Unit, on the watershed
separating the Orco Valley from the Isère Valley, confirm the presence of ECC dipping
to NW with top to NW normal shear.

376

377 4.6. *D*₅ structures and frictional deformation regime

378

379 D_5 event is only detected at the macroscale analyzing variation in orientation of 380 previous structures. It is responsible for undulations of S₁ with 10 to 100-200 meter 381 wavelength Axial planes strike between 100-160 and dip in opposite quadrant with high angle, while axes scatter from 080 to 150 N with variable inclination. The scattering of geometric features indicate the presence of conjugate and anastomosing axial surfaces that coincide with a conjugate high angle fracture system striking 120-150 N.

386

387 **5. Discussion**

388

389 5.1 Coupling of the Gran Paradiso versus the Zermatt-Saas

390

391 In the Gran Paradiso Unit the development of the S_1 at the expense of garnet + 392 omphacite + glaucophane assemblages in metabasites, indicates that main foliation 393 occurred during exhumation under medium PT conditions (Table 1). Eclogitic-peak pre-394 D₁ event in orthogneisses was recorded only along thin shear bands where whiteschists 395 developed, while surrounding rocks remain in metastable conditions probably because 396 of H₂O deficiency that prevents the activation of metamorphic reactions and 397 recrystallization into denser rocks (Austrheim et al., 1997; Proyer, 2003). On the base of 398 bibliographic data, a maximum age of 43 ± 0.5 Ma (Meffan-Main et al., 2004) at 21–23 399 kbar and 540-570 °C (Wei and Powell, 2003, 2004) can be assigned to the eclogite 400 facies pre-D₁ event for the Gran Paradiso Unit.

401 In the Zermatt-Saas-like Unit an eclogitic pre-S₁ foliation is locally well preserved 402 while metagabbros and most metabasites are extensively re-equilibrated during D_1 403 event, which is characterised by medium PT conditions.

404 The tectonic contact between the Gran Paradiso and the Zermatt-Saas-like units is 405 deformed by D_1 event (Figs. 8, 9 and 10a,b) and is defined by blueschist assemblages

406	(see § 3.5). This tectonic contact is deformed by a macro-scale fold showing an anvil-
407	shaped section (Mies, 1993) as reported in structural map of Fig. 7. This geometry,
408	linked to the parallelism between L_1 and A_1 (Fig. 3a-c), is referred to the development
409	of sheath folds whose structure is sketched in Fig. 9. The structural evidence that
410	eclogite facies pre-S1 foliation of the Zermatt-Saas metabasites is truncated by the
411	tectonic contact and is folded by D_1 event (Fig. 6) implies that the coupling between the
412	Gran Paradiso and the Zermatt-Saas-like units developed after pre-S1 eclogite facies
413	event but before D_1 event, suggesting nappes emplacement during exhumation.
414	FIG. 9
415	D_1 event developed during top to W compressional regime (Figs. 4c and 8) and could be
416	related to the top to NW shearing event of Inger and Ramsbotham (1997), dated at 38-
417	40 Ma, within Gran Paradiso Unit W of Locana. On the base of structural and
418	petrographic features, the main foliation S ₁ of the Gran Paradiso Unit can be related to
419	the regional fabric decribed by Brouwer et al. (2002) west of the study area, for which
420	they suggest metamorphic conditions of 10-12 kbar and 500-550°C.
421	FIG. 10
422	
423	5.2 Coupling of the Sesia-Lanzo GMC and the Combin Unit
424	
425	Both the greenschist facies units are pervasively deformed during D_1 event that
426	developed the main regional foliation under greenschist facies conditions (Figs. 7 and
427	10b). The presence of rare pre- D_1 , zoisite + rutile assemblages, in little deformed lithons
428	within Sesia-Lanzo orthogneisses indicates an older metamorphic event, but evidences

429 of eclogitic or blueschist facies assemblages laek. Inger et al. (1996) reported an age of

430 37.5 ± 1 Ma for the contact between the Gneiss Minuti Complex and the Combin-like 431 calcschists in Soana Valley north of the study area.

432

433 5.3 Coupling of LTE vs UTE: the Orco Shear Zone

434

435 Time constraining of the tectonic contact between Upper and Lower Tectonic Element 436 (Orco Shear Zone) is not simple. The geometric and structural relationships show that 437 this tectonic contact cut D₁ structures both in LTE (HP units) and UTE (LP units) and is 438 folded by D₃ event (see Figs. 2, 7 and 8). The evidence of a top to E sense of shear (Fig. 439 4h) in the mylonitic foliation along the contact between LTE and UTE is in agreement 440 with D_2 tectonic transport. Particularly, D_2 structures are slightly different in LTE and 441 UTE: the main axial plane surface differs by at least 25° of orientation (Fig. 3g, h) and 442 moreover D₂ structures are better developed in the UTE, suggesting that the contact can 443 be related to late- D_2 event (Fig. 10c). Therefore, the Orco Shear Zone represents a 444 metamorphic gap between the two Tectonic Elements accommodating exhumation of 445 the Lower one, and stopped working before the onset of D_3 event (see Figs. 2, 7 and 8). 446 This regional scale structure is responsible for the disappearing of Zermatt-Saas-like oceanic units ards N, in Soana Valley (see Fig. 8 of Inger & Ramsbotham, 1997) 447 448 where GP orthogneisses are directly in contact with the calcschists of the Combin-like 449 Unit. The disappearing of the oceanic crust can be attributed to a delamination process 450 during exhumation along this tectonic contact, for which Inger and Ramsbotham (1997) 451 suggest an age of 34-39 Ma.

452 In summary the Orco Shear Zone shows the following features: i) consist of a late 453 ductile tectonic contact developed under greenschist facies conditions; ii) juxtaposes

454 eclogites-bearing units to greenschist ones; iii) at present, dips towards ESE and shows 455 top to SE normal sense of shear. In the Western Alps, similar regional scale shear zones have been reported by many thors (Combin Fault: Ballèvre and Merle, 1993; 456 Gressoney Shear Zone; Reddy et al., 1999). Both the Combin Fault and the Gressoney 457 458 Shear Zone represent the tectonic contact between HP and overlying LP units 459 outcropping in the northern area of the Aosta Valley. Since the Orco Shear Zone occurs 460 in the same structural position (HP-LP boundary), it can be considered the southern 461 continuation of these structures. According to Ballèvre and Merle (1993) the Combin 462 Fault is mainly an Early Tertiary detachement fault reactived as thrust during 463 Oligocene. Ring (1995) interpreted the Combin Fault as an out-of-sequence NW 464 directed thrust (Late Eocene) subsequently reactived as SE directed backthrust (Early 465 Oligocene). Reddy et al. (1999, 2003) suggest for the Gressoney Shear Zone an early 466 compressional history followed by pervasive SE extension between 45 and 36 Ma. 467 Therefore the interpretation of these shear zones is very ambiguous. On the base of our 468 structural and metamorphic data we suggest for the Orco Shear Zone a main top to SE 469 extensional component at a shallow crustal level, even if an older top to NW 470 compressional displacement (before D_2) cannot be excluded.

471

472 *5.4 Late structural and metamorphic evolution*

473

474 After D_2 event a metamorphic stage under static conditions was recorded in all the 475 studied units. It is characterized by albite + biotite in Gran Paradiso paragneisses and 476 Sesia-Lanzo gneisses and by albite + green amphibole + epidote ± biotite in Gran 477 Paradiso and Zermatt-Saas metabasites. Afterward D_3 event developed and locally caused activation of reverse-slip C'-type shear bands only in less competent lithologies such as calcschists, serpentinites and Sesia-gneisses. Microstructural observations indicate recrystallization coupled with grain-size reduction, suggesting high strain deformation in low-grade metamorphic conditions. D_3 event deformed the contact between LTE and UTE (Figs. 7 and 10d) and may be responsible for the doming of the Gran Paradiso.

484 The following ECC caused a further differentiated exhumation between the Lower 485 Tectonic Element (the footwall) and the Upper one (the hangingwall) (Fig. 10e). ECC 486 developed in ductile conditions in phillosilicates-rich rocks while in guartz-feldspatic 487 ones is defined by fractures and faults indicating a plastic-frictional transition regime in 488 agreement with deformation at a shallow crustal level. The presence of ECC at the 489 western border of the Gran Paradiso Unit (this work; Rolland et al., 2000; Bucher et al., 490 2003) can be related to an axial culmination of the Alpine mountain belt in this area. 491 corresponding to the outcropping of the deepest eclogitic units of the Western Alps. D₄ 492 probably represents the onset of the gravitational collapse of the Alpine-orogen linked 493 to further exhumation of the Lower Tectonic Element.

494

495 **6.** Conclusions

496

This paper provides new structural and petrographic data in the Orco Valley and allows a better constraint of the tectonic framework within this portion of the Alpine orogen. It also gives more detailed information about the tectono-metamorphic evolution of a keyarea in the Western Italian Alps. <u>At-first-two</u> main Tectonic Elements have been distinguished (Fig. 7): the Lower one composed of eclogite facies units (Gran Paradiso 502 Unit and Zermatt-Saas-like oceanic units) the Upper one made of greenschist facies
503 units (the Combin-like Unit and the Gneiss Minuti Complex of the Sesia-Lanzo Zone).
504 In both Tectonic Elements, the units were independently coupled before the occurrence
505 of the regional schistosity (S₁) which developed under different metamorphic conditions
506 and probably in different time across the two Tectonic Elements.

507 In the Lower Tectonic Element (LTE), Gran Paradiso and Zermatt-Saas-like units were 508 coupled during exhumation after pre-D₁ eclogite facies conditions and then were folded 509 together by D_1 event under medium PT conditions (upper-greenschist to epidote-albite 510 amphibolite facies). Pre-D₁ structural and mineralogical HP relicts are still present at 511 every scale, particularly in the Zermatt-Saas-like Unit where mesoscale eclogitic 512 foliations and macroscale structures are preserved. Additionally this unit consists of 513 different tectonic slices in agreement with the structural setting proposed by Battiston et 514 al. (1984) towards N in Val Soana. Instead, in the Gran Paradiso orthogneisses eclogite 515 facies assemblages occur only along discrete shear zones where whiteschists developed. 516 In the Upper Tectonic Element (UTE), structural and mineralogical evidences of a pre-517 D_1 evolution are preserved, too. However, in these units, both the pre- D_1 metamorphic 518 assemblages and the regional foliation (D_1) developed under greenschist facies 519 conditions.

520 LTE and UTE are separated by a normal-slip tectonic contact represented by a thin 521 mylonitic top to E shear zone that occurred during late- D_2 event. This first order 522 structure (Orco Shear Zone) led to the exhumation of the HP units (LTE) and coupled 523 them with LP ones (UTE). This contact defines the boundary between the Zermatt-Saas-524 like Unit and the Combin-like Unit therefore it can be considered as the continuation of the Gressoney Shear Zone (Reddy et al., 1999) and of the Combin Fault (Ballèvre and
Merle, 1993) further S of the Aosta Valley.

527 From D_3 onward all units followed the same tectono-metamorphic history and the dome 528 structure of the Gran Paradiso takes its final shape. Finally D_4 event (ECC) occurred 529 along a thin belt mainly within Combin-like calcschists, implying a further differential 530 exhumation of LTE (footwall) respect to UTE (hangingwall) at the brittle-plastic 531 transition regime.

The occurrence of a W-dipping normal-slip shear zone between Zermatt-Saas-like Unit (footwall) and Combin-like Unit (hangingwall) at the western border of the Gran Paradiso Unit (Rolland et al., 2000), corresponding to our late- D_2 Orco Shear Zone, suggests the presence of a core complex made of eclogite-bearing units beneath greenschist facies ones. This core complex occurs in the axial position within the Western Alps orogenic wedge and can be responsible for the late exhumation stage of the deeper subducted units.

539

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799	Figures Captions									
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801	Fig. 1. a) Tectonic map of the Western Alps (modified after Schmid et al., 2004). b)									
802	Simplified geological map of the Gran Paradiso Massif and surrounding units (modified									
803	after Compagnoni and Lombardo, 1974).									
804										
805	Fig. 2. Simplified geological map of the study area located at the western border of the									
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Fig. 3. Equiareal projection, lower hemisphere of the main structural features characterizing the four deformation phases identified. The mean surface (e.g.: 127/34) of foliation or axial plane is indicated. A_n: fold axes; L_n: stretching lineation; S_n: foliation or axial surface. For discussion see text.

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813 Fig. 4. Meso-scale structures representing the four deformation phases distinguished in 814 the study area: a) σ -shaped Kfs porphyroclasts in orthogneisses of the the Gran Paradiso 815 Unit showing top to W sense of shear; b) S_1 surface in the Gran Paradiso paragneisses 816 with a curved A_1 intersection lineation, indicating a non-cylindrical folding; c) D_1 isoclinal folds in the Sesia-Lanzo gneisses transposing leuco-gneisses layers; d) D₂ fold 817 818 in the Sesia-Lanzo gneisses folding a D_1 isoclinal fold; e) D_3 open folds in the Gran 819 Paradiso paragneisses folding a tight to isoclinal D_2 fold; f) D_3 box fold in the Combin-820 like calcschists with S₃ surfaces defined by a spaced and discontinuous reverse-slip C' 821 types shear bands; g); discontinuous Extensional Crenulation Cleavage (S-C' types 822 shear bands) in the Zermatt-Saas-like serpentinites; h) S-C type shear bands showing 823 top to E sense of shear in mylonitic calcschists along the tectonic contact between the 824 Upper Tectonic Element and the Lower one.

825

Fig. 5. Microstructures representing the four deformation phases distinguished in the study area: a) D_1 rootless fold in the Gran Paradiso whiteschists with a well preserved pre-S₁ foliation; b) D_2 asymmetric fold in the Gran Paradiso paragneisses originating an S₂ foliation; c) D_1 rootless fold in the Zermatt-Saas serpentinites defined by a Mag layer deformed by a D_2 closed fold; d) D_2 discrete crenulation cleavage in the Combin calcschists; e) D_4 spaced Extensional Crenulation Cleavage (ECC) in the Combin-like calcschists showing millimetric displacement; f) rootless D_1 isoclinal folds in the Sesia-Lanzo gneisses preserving a pre-S₁ foliation; g) D_1 rootless fold preserving a pre-S₁ foliation in the Sesia-Lanzo micaschists, S₁ is cut by D_4 ECC; h) mylonitic foliation in the Sesia-Lanzo gneisses along the tectonic contact between LTE and UTE cut by D_4 ECC.

837

Fig. 6. Structural and metamorphic relationship between the Gran Paradiso orthogneisses and the Zermatt-Saas eclogites: a) orthogneisses show a well-developed S_1 foliation while metabasites preserve a pre-S₁ foliation; b) eclogite facies pre-S₁ foliation is preserved in metabasites and is cut by mylonites.

842

Fig. 7. Simplified structural map of the study area with some structural features of the D_1 event. Only the different paleo-geographic units are distinguished to show their structural relationship (geochronological data from Inger et al., 1996; Inger and Ramsbotham, 1997; Meffan-Main et al., 2004).

847

Fig. 8. Cross sections representing structural relationship between the different tectonic
units (see text for explanation). GP: Gran Paradiso Unit; ZS: Zermatt-Saas Unit; CO:
Combin Unit; SL: Sesia-Lanzo Gneiss Minuti Complex; OSZ: Orco Shear Zone.
Legend as in Fig. 7.

852

Fig. 9. Three dimension sketch of the structural relationship between the Gran Paradiso and the Zermatt-Saas Unit showing a D_1 non-cylindrical synform-antiform pair deforming their tectonic contact. Axial plane Pa_1 and mean direction of L_1 stretching lineation are indicated. The structure outcrops north of Schiaroglio (see fig. 7). Sketch not in scale.

858

859 Fig. 10. W-E cross-sections representing the structural history of the Orco Valley 860 geological transect related to the its possible geodynamic evolution. OSZ: Orco Shear 861 Zone; EMC-SL: Eclogitic Micaschists Complex, Sesia-Lanzo; GMC-SL: Gneiss Minuti 862 Complex, Sesia-Lanzo; CO: Combin Unit; ZS: Zermatt-Saas Unit; GP: Gran Paradiso 863 Unit. LTE: Lower Tectonic Element; UTE: Upper Tectonic Element. a) pre-D₁ stage 864 and HP metamorphism in LTE. The position of the OSZ is indicated and probably 865 accomodated reverse-slip movement. b) D_1 stage represents the main folding event 866 resulting in a well-developed regional foliation in both UTE and LTE. c) D_2 stage is 867 linked to minor folding (not shown) and to the exhumation of the LTE along the OSZ 868 that cuts D_1 structures. d) D_3 stage folded the OSZ and caused the doming of the Gran 869 Paradiso Unit. e) D₄ stage is associated to Extensional Crenulation Cleavage (ECC) on 870 both side of the LTE and probably represents the onset of gravitational collapse.

871

Table 1. Evolution of the mineral assemblages respect to the structural and metamorphic

873 setting in the main lithologies occurring in the different tectonic units.

874

Table 2. Sketch of the tectono-metamorphic evolution of the studied units.



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		Lower Tectonic Element (eclogite facies relics)				i i i		Upper Tectonic Element (only greenschist facies assemblages)			
			Gran Paradiso Uni	9	1	Sedmont Zone			Piedman	d Zone	Sesia-Lanzo Zone
		G		ar sea a la	- 74	router-Sain Unit	2 2		Comhu	a Unit	Ginelia Monuti Complex
structural evolution	metamorphic conditions	micaschists	metabasines	onhogneisses (whiteschistii)	serpentinites (mitaperidotites)	metagabbros	metabasites	metamorphic conditions	calciclists	premiones	gneisses (metagranitoids)
pre-Alpine		ericlaves in orthogenisses	magmatic structures	K6, Q0, BI, PI	(Ol, Cyx, Ops, Spl) (Ol, Chl, Am, Mag)	magnustic structures	- 2 2		(+)	- 2 2	magmatic structores
pre-S ₁	eclogite facies	Get,Gin,Wm, Quz, Br	Omp, Gri, Gla, Zo, Wm, Ri	(Wes, Qtz, Chl, Cid, Ky, Tic, Grt)		Ome, Gin, Gri	Omp, Grt, Gln, Wm, ZovEp, Rt	greenchist facies	Wes, Cal, Qtz Chi	- 35	Wm, Qtz, Chl, Ep, Act; (Zo, Rt)
5,	middel-P greenchist to epidote-albite amphiholite facies	Wm, Qtz, Hbi Ab, Grt, Zo, Ri	Ca-Na Am, Zo, Woi, Chi, Ab, Ri	Win, Qiz, Ab, Ep, Spn (Qiz, Win, Chl)	Sey, Chi, OL Di	Any, Zo, Wm, Chl. Rt.	Ca-Na Am, Zo, Wm, Chi, Ri,	greenchist facies	Wm, Qtz, Cal, Spn, Chl	Act, Ab, Ep, Chl, Spi	Wm, Qtz, Ab, Ep/Czo, Chi, Act, Spn
\$,	greeuchist facies	Quz, Wm, Chl. Ab, Spn	3	59	Srp	100	59		Wm, Chl. Qtz, Sps	1	Wm, Chi, Act
s,	low-grade metamorphic conditions	+	8	÷.	Srp	12	+		Wm, Cal. Qtz	14	64
S, (ECC)	ductile to brittle	Qtz, Wm, Bt			Sep	+	+		Win, Cal, Qtz	(+).	Qiz, Wm, Bt, Spit

	Lower Tecto (eclogite fa	onic Element cies relics)	Upper Tectonic Element (only greenschist facies assemblages)				
pre-D ₁	Gran Paradiso Unit Zermatt-Sad pre-D ₁ eclogite eclogit facies facies facies		Combin Unit greenchist facies	Sesia-Lanzo GMC greenchist facies			
old tectonic contacts	blueschi	st facies	greenchist facies				
D	middel-P g to epidote-albite a	greenchist mphibolite facies	greer	ichist facies			
D ₂	greenchi	st facies	greenchist facies				
OSZ late-D ₂		greenchist facies					
D ₃	low-grade metamorphic conditions						
D ₄ (ECC)	ductile (low-grade metamorphic conditions) to brittle						