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Structural evolution of different tectonic units across the Austroalpine-Penninic boundary in the middle Orco Valley (Western Italian Alps)

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Abstract. A structural study along the Orco Valley, which represents a geological section through the Alpine belt (western Italy), is reported. A Lower Tectonic Element, composed of units with eclogite facies relics (Gran Paradiso and Zermatt-Saas-like Unit) and an Upper Tectonic Element, made of greenschist facies units (Combin-like Unit and Gneiss Minuti Complex of the Sesia-Lanzo Zone) have been distinguished. These two elements show a different main Alpine tectono-metamorphic event (D_1) and are separated by a mylonitic contact (D_2 ~~event~~) developed under greenschist facies conditions (Orco Shear Zone). This regional scale shear zone was responsible for the exhumation of the deeper eclogitic units, and has been inferred as the continuation of the Combin Fault south of the Aosta Valley. From D_3 ~~event~~ onward, the same tectono-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.

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

1. Introduction

The axial portion of the Western Italian Alps (Austroalpine and Pennidic Domains) represents a fossil subduction complex developed during the Alpine orogenic cycle. In the last twenty years, many geological transects (e.g. Pognante et al. 1987; Inger and Ramsbotham, 1997; Bucher et al., 2004) have improved our knowledge of the structural and metamorphic framework of the Western Alps. This has ~~subsequently~~ brought to a better insight ~~on~~ the geodynamic evolution of the Alpine mountain belt and has lead many workers to suggest different exhumation mechanisms for HP rocks (Platt, 1993; Ballèvre & Merle, 1993; Reddy et al., 1999). However, some questions about the timing of tectonic coupling between oceanic and continental units still remain~~s~~ controversial. ~~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 Zermatt-Saas Unit ~~have been~~ coupled during eclogite-facies tectono-metamorphic stage and have been exhumed together by a buoyancy-driven process. Instead Kassem & Ring (2004) proposed that the Gran Paradiso has been coupled to the Zermatt-Saas Unit early during subduction under brittle conditions. Finally Pleuger et al. (2005) suggested tectonic coupling of the Monte Rosa Massif and the Zermatt-Saas Unit before the 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.

This work is based on structural analysis of an area of 35 km^2 and take into consideration three tectonic units differing ~~for~~ paleogeographic position and Alpine metamorphic evolution. From W to E and in ascending structural order, they are: the continental crust of the Gran Paradiso Unit generally attributed to the European paleo-margin, the Piedmont Zone that represents the remnants of the Tethys Ocean and the 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 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 and continental crust units and of eclogite versus greenschist facies units has been established.

2. Geological background

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).

FIG. 1

The metasedimentary rocks have been reworked by Alpine orogeny that transforms them into a polymetamorphic complex, made of paragneisses and micaschists with lenses of eclogites, interpreted as pre-Alpine amphibolites (Compagnoni and Lombardo, 1974) or Variscan gabbros (Biino and Pognante, 1989). Eclogitic assemblages in the metabasites have been used to estimate minimum PT conditions for the eclogitic event at P > 12–14 kbar and T of 500–550 °C (Ballèvre, 1988; Brouwer et al., 2002). Within orthogneisses, layers of whiteschists that developed in metasomatic shear zone during eclogitic event also occur (Compagnoni and Lombardo, 1974). For these rocks PT conditions of 21–23 kbar and 540–570 °C have been reported by Wei and Powell (2003, 2004) and Meffan-Main et al (2004). Conditions of 18-20 kbar and 490° C are reported for the Gneiss Minuti Complex (Le Bayon et al., 2006). The high-P event is followed by a late stage of re-equilibration at 4–6 kbar and 500–550 °C, interpreted as a re-heating stage ~~occurred~~ after an initial cooling during decompression (Borghi et al., 1996; 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 (20-24 Ma at 100 ± 20 °C) (Hurford and Hunziker, 1989).

2.2. The Piedmont Zone

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

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

PT conditions for different tectonic slivers belonging to Zermatt-Saas decrease from 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 for the Cignana Unit, in Valtournenche, indicating P of 26-28 kbar and T of 600°C (Reinecke, 1991, 1998). Messiga et al. (1999) reported conditions of 24 kbar at 600 ± 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 (Barnicoat et al., 1995; Cartwright and Barnicoat, 2002). The high-P event is dated at 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 ^{40}Ar-^{39}Ar white mica, Dal Piaz et al., 2001; Rb-Sr white mica, Cartwright and Barnicoat, 2002) while greenschist re-equilibration spread from 36 to 42 Ma (Rb-Sr whole rock-white mica, Amato et al., 1999; Cartwright and Barnicoat, 2002).

In the Combin Unit the high-P event developed under blueschist facies conditions (12-13 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, 1997).

2.3. The Sesia-Lanzo Zone (SL)

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).

The EMC reached conditions of 15-18 kbar and 550-620 °C (Pognante et al., 1980, 1987; Lardeaux et al., 1982; Pognante, 1989; Lardeaux and Spalla, 1991) dated 65-80 Ma (Rb-Sr white mica, Inger et al., 1996; Duchêne et al., 1997; Rubatto et al., 1999). The GMC, instead, has been pervasively equilibrated at P < 13 kbar and 450-500°C (Williams and Compagnoni, 1983; Pognante et al., 1987; Pognante, 1989; Spalla et al., 1996) at about 37-39 Ma (Hunziker et al., 1993; Inger et al., 1996).

3. Tectono-stratigraphic setting

According to their different structural and metamorphic evolution, the tectonic units outcropping in the study area (Fig. 2) have been grouped in two main Tectonic Elements. From NW to SE they are: I) a Lower Tectonic Element (LTE) preserving relics of eclogite facies metamorphism and consisting of the Gran Paradiso Unit and oceanic tectonic slices referred to the Zermatt-Saas Unit according to lithostratigraphic and metamorphic affinities; II) an Upper Tectonic Element (UTE) made of greenschist facies units devoid of eclogitic relics consisting of a Combin-like unit and the Gneiss Minuti Complex of the Sesia-Lanzo Zone. These two Tectonic Elements are separated by a tectonic contact of regional importance. A detailed summary of the metamorphic assemblages and the tectono-metamorphic relationships of the different studied units are respectively reported in Tables 1 and 2.

FIG. 2

TABLE 1

TABLE 2

3.2. Lower Tectonic Element (LTE)

In the Lower Tectonic Element the GP continental crust represents the deepest tectonic unit of the study area, thrusted by a tectonic mélange of oceanic affinity referred to the Zermatt-Saas Unit.

The Gran Paradiso Unit consists of orthogneisses, a polymetamorphic basement and rare Mesozoic covers (quartzites and dolomitic marbles) preserved near the tectonic contact with oceanic units. The orthogneisses are heterogeneously deformed ranging from isotropic rocks with magmatic structures perfectly preserved, to augen-gneisses and flaser-gneisses. Locally thin layers of whiteschists which grade to augen-gneisses are present. The polymetamorphic basement is mainly composed of micaschists hosting metabasites bodies. They consist of up to 1 metre-sized lenses or layers of fine grained and felsic eclogites, and up to 100-150 m thick fine to medium-grained foliated metagabbros, that locally preserve the eclogite facies assemblage. A late metamorphic greenschist facies overprinting developed under static conditions in both micaschists 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 spinel-lherzolites, 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.

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

3.3. Upper Tectonic Element (UTE)

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 rare quartzites and of calcschists interlayered with thin meta-carbonatic and meta-pelitic levels.

3.4. Mylonitic rocks along tectonic contacts

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.

The tectonic contact between the Gran Paradiso and the Zermatt-Saas-like Unit is characterized by the presence of sheared Mesozoic cover~~s~~ belonging to both units. Where metasediments are absent serpentinites become mylonitic (Srp + Mg-Chl + Ol + Di; mineral abbreviations according to Kretz, 1983), eclogites are re-equilibrated under 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 Orco Valley, a mylonitic foliation that envelops eclogite~~s~~ boudins has been observed. This foliation is made of Act-Chl-Wm-schists and preserves portions of an older foliation defined by blue Am + Chl + Wm which suggests that the tectonic contact developed under blueschist facies conditions and was reworked during later decreasing P. The thickness of the deformation zone varies between 1-5 m~~eters~~ where competent rocks are in contact, to 10-50 m~~etres~~ where Mesozoic cover~~s~~ ~~are~~ present.

Tectonic contact between the Gneiss Minuti Complex of the Sesia-Lanzo Zone and the 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.

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

4. Structural and metamorphic evolution

Three different Alpine tectono-metamorphic events at the regional scale (D_1, D_2, D_3), followed by two ductile to brittle events (D_4, D_5) have been distinguished. The study area is marked by a regional transposed foliation concordant with the lithological 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 main tectonic elements. In the following sections, we will refer to S_1 as the main regional foliation of each tectonic element, which is not synchronous across the whole area. The mineral assemblages related to the different deformation events are summarized in Table 1 for the main rock types.

4.1. D_1 structures and metamorphism in the Lower Tectonic Element

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

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.

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 events. Folds are isoclinal in eclogites and rootless in serpentinites (Fig. 5c) and metasediments. The mineral lineations are defined by Ca-Na amphibole + zoisite in metagabbros and in re-equilibrated eclogites and by magnetite aggregates in serpentinites. Both fold-axes and stretching lineations plunge to E and show a substantial parallelism ~~like~~ in the Gran Paradiso Unit (Fig. 3b). Locally a well-preserved pre-S_1 eclogitic foliation occurs in metabasites and metagabbros. In meta-peridotites a relic foliation defined by olivine + chlorite + amphibole + magnetite is preserved. The following D_1 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.

FIG. 6

4.2. D_1 structures and metamorphism in the Upper Tectonic Element

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. D_1 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.

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

Pre-S_1 relic foliations are preserved both in the Sesia-Lanzo gneisses and in the Combin calcschists and are defined by greenschist facies assemblages too.

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

4.3. D_2 structures and metamorphism

D_2 event deforms D_1 structures in all tectonic units, but its structural imprinting affected differently LTE and UTE. Indeed, in the former, D_2 structures are developed only at the mesoscale while, in the latter, macroscale folds are also present and D_2 structures are very common. D_2 develops polyharmonic and asymmetric folds that show close to isoclinal profile, but rarely an axial plane foliation occurs at the mesoscale (Fig. 4d, e). Axial planes dip 30-60° towards E to SE while the axes are scattered on the average maximum circle of the foliation planes (Fig. 3g, h) showing the presence of non-cylindrical structures developed during non-coaxial deformation. Therefore, A_2 axes show a variable angle respect to the stretching lineations L_2 which plunge concordantly towards E. The asymmetric Z folds (looking to N) present on the long limbs have an enveloping surface dipping to the E more than S_2 surfaces. These features of the meso to macroscale D_2 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.

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

4.4. D_3 structures and metamorphism

D_3 phase develops box folds with open to close profiles which indicate a prevalent top to SE asymmetry. Axial planes dip mainly NW by a range of inclination from 30° to sub-vertical with some data in the opposite quadrant, indicating polyclinal profile typical of box folds (Figs. 3i and 4f). Rarely C'-type conjugate shear bands, with reverse-slip movement is developed at the mesoscale in calcschists (Fig. 4f), serpentinites and subordinately in the Sesia-Lanzo gneisses, with a stretching lineations L_3 defined by quartz and calcite fibres and by striations. L_3 on C'-type surfaces and shear bands geometry indicate both top to NW and top to SE sense of shear pointing to a NW-SE directed compression. Axes plunge equally 10-30° towards NE and SW while the scattering of at least 60° is due to D_5 deformation phase.

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

FIG. 7

FIG. 8

4.5. D_4 Extensional Crenulation Cleavage (ECC)

Extensional Crenulation Cleavage (as defined by Platt & Vissers, 1980) is well developed in calcschists and locally in serpentinites at the mesoscale (Fig. 4g). It is underlined by centimetric to millimetric spaced surfaces which mostly occur along a NE-SW belt less than one kilometre thick within the calcschists and subordinately in the Sesia-Lanzo gneisses of the UTE. S_4 surfaces dip mainly to SE by 60° to sub-vertical 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. 3l). Locally at the contact between calcschists and gneisses, ECC steps gradually into frictional structures in the latter lithologies, suggesting that this deformation event took place under the brittle-ductile transition regime. ECC shows a significant grain-size reduction (Fig. 5e,g,h) suggesting high strain-rate and is defined by low-grade 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.

4.6. D_5 structures and frictional deformation regime

D_5 event is only detected at the macroscale analyzing variation in orientation of previous structures. It is responsible for undulations of S_1 with 10 to 100-200 meter 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.

5. Discussion

5.1 Coupling of the Gran Paradiso versus the Zermatt-Saas

In the Gran Paradiso Unit the development of the S_1 at the expense of garnet + omphacite + glaucophane assemblages in metabasites, indicates that main foliation occurred during exhumation under medium PT conditions (Table 1). Eclogitic-peak pre-D_1 event in orthogneisses was recorded only along thin shear bands where whiteschists developed, while surrounding rocks remain in metastable conditions probably because of H_2O deficiency that prevents the activation of metamorphic reactions and recrystallization into denser rocks (Austrheim et al., 1997; Proyer, 2003). On the base of bibliographic data, a maximum age of 43 ± 0.5 Ma (Meffan-Main et al., 2004) at 21–23 kbar and 540–570 °C (Wei and Powell, 2003, 2004) can be assigned to the eclogite facies pre-D_1 event for the Gran Paradiso Unit.

In the Zermatt-Saas-like Unit an eclogitic pre-S_1 foliation is locally well preserved while metagabbros and most metabasites are extensively re-equilibrated during D_1 event, which is characterised by medium PT conditions.

The tectonic contact between the Gran Paradiso and the Zermatt-Saas-like units is deformed by D_1 event (Figs. 8, 9 and 10a,b) and is defined by blueschist assemblages (see § 3.5). This tectonic contact is deformed by a macro-scale fold showing an anvil-shaped section (Mies, 1993) as reported in structural map of Fig. 7. This geometry, linked to the parallelism between L_1 and A_1 (Fig. 3a-c), is referred to the development of sheath folds whose structure is sketched in Fig. 9. The structural evidence that eclogite facies pre-S_1 foliation of the Zermatt-Saas metabasites is truncated by the tectonic contact and is folded by D_1 event (Fig. 6) implies that the coupling between the Gran Paradiso and the Zermatt-Saas-like units developed after pre-S_1 eclogite facies event but before D_1 event, suggesting nappes emplacement during exhumation.

FIG. 9

D_1 event developed during top to W compressional regime (Figs. 4c and 8) and could be related to the top to NW shearing event of Inger and Ramsbotham (1997), dated at 38-40 Ma, within Gran Paradiso Unit W of Locana. On the base of structural and petrographic features, the main foliation S_1 of the Gran Paradiso Unit can be related to the regional fabric decribed by Brouwer et al. (2002) west of the study area, for which they suggest metamorphic conditions of 10-12 kbar and 500-550°C.

FIG. 10

5.2 Coupling of the Sesia-Lanzo GMC and the Combin Unit

Both the greenschist facies units are pervasively deformed during D_1 event that developed the main regional foliation under greenschist facies conditions (Figs. 7 and 10b). The presence of rare pre-D_1, zoisite + rutile assemblages, in little deformed lithons within Sesia-Lanzo orthogneisses indicates an older metamorphic event, but evidences of eclogitic or blueschist facies assemblages lack. Inger et al. (1996) reported an age of

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

5.3 Coupling of LTE vs UTE: the Orco Shear Zone

~~Time constraining~~ of the tectonic contact between Upper and Lower Tectonic Element (Orco Shear Zone) is not simple. The geometric and structural relationships show that this tectonic contact cut D_1 structures both in LTE (HP units) and UTE (LP units) and is folded by D_3 event (see Figs. 2, 7 and 8). The evidence of a top to E sense of shear (Fig. 4h) in the mylonitic foliation along the contact between LTE and UTE is in agreement with D_2 tectonic transport. ~~Particularly,~~ D_2 structures are slightly different in LTE and UTE: the main axial plane surface differs by at least 25° ~~of orientation~~ (Fig. 3g, h) and moreover D_2 structures are better developed in the UTE, suggesting that the contact can be related to late-D_2 event (Fig. 10c). Therefore, the Orco Shear Zone represents a metamorphic gap between the two Tectonic Elements accommodating exhumation of the Lower one, and stopped working before the onset of D_3 event (see Figs. 2, 7 and 8). This regional scale structure is responsible for the disappearing of Zermatt-Saas-like oceanic units towards N, in Soana Valley (see Fig. 8 of Inger & Ramsbotham, 1997) where GP orthogneisses are directly in contact with the calcschists of the Combin-like Unit. The disappearing of the oceanic crust can be attributed to a delamination process during exhumation along this tectonic contact, for which Inger and Ramsbotham (1997) suggest an age of 34-39 Ma.

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

5.4 Late structural and metamorphic evolution

After D_2 event a metamorphic stage under static conditions was recorded in all the studied units. It is characterized by albite + biotite in Gran Paradiso paragneisses and Sesia-Lanzo gneisses and by albite + green amphibole + epidote ± biotite in Gran 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.

The following ECC caused a further differentiated exhumation between the Lower Tectonic Element (the footwall) and the Upper one (the hangingwall) (Fig. 10e). ECC developed in ductile conditions in phillosilicates-rich rocks while in quartz-feldspatic ~~ones~~ is defined by fractures and faults indicating a plastic-frictional transition regime in agreement with deformation at a shallow crustal level. The presence of ECC at the western border of the Gran Paradiso Unit (this work; Rolland et al., 2000; Bucher et al., 2003) can be related to an axial culmination of the Alpine mountain belt in this area, corresponding to the outcropping of the deepest eclogitic units of the Western Alps. D_4 probably represents the onset of the gravitational collapse of the Alpine-orogen linked to further exhumation of the Lower Tectonic Element.

6. Conclusions

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 key-area in the Western Italian Alps. ~~At first two~~ main Tectonic Elements have been distinguished (Fig. 7): the Lower one composed of eclogite facies units (Gran Paradiso

Unit and Zermatt-Saas-like oceanic units) the Upper one made of greenschist facies units (the Combin-like Unit and the Gneiss Minuti Complex of the Sesia-Lanzo Zone). In both Tectonic Elements, the units were independently coupled before the occurrence of the regional schistosity (S_1) which developed under different metamorphic conditions and probably in different time across the two Tectonic Elements.

In the Lower Tectonic Element (LTE), Gran Paradiso and Zermatt-Saas-like units were coupled during exhumation after pre-D_1 eclogite facies conditions and then were folded together by D_1 event under medium PT conditions (upper-greenschist to epidote-albite amphibolite facies). Pre-D_1 structural and mineralogical HP relicts are still present at every scale, particularly in the Zermatt-Saas-like Unit where mesoscale eclogitic foliations and macroscale structures are preserved. Additionally this unit consists of different tectonic slices in agreement with the structural setting proposed by Battiston et al. (1984) towards N in Val Soana. Instead, in the Gran Paradiso orthogneisses eclogite facies assemblages occur only along discrete shear zones where whiteschists developed.

In the Upper Tectonic Element (UTE), structural and mineralogical evidences of a pre-D_1 evolution are preserved, too. However, in these units, both the pre-D_1 metamorphic assemblages and the regional foliation (D_1) developed under greenschist facies conditions.

LTE and UTE are separated by a normal-slip tectonic contact represented by a thin mylonitic top to E shear zone that occurred during late-D_2 event. This first order structure (Orco Shear Zone) led to the exhumation of the HP units (LTE) and coupled them with LP ones (UTE). This contact defines the boundary between the Zermatt-Saas-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.

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

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Figures Captions

Fig. 1. a) Tectonic map of the Western Alps (modified after Schmid et al., 2004). b) Simplified geological map of the Gran Paradiso Massif and surrounding units (modified after Compagnoni and Lombardo, 1974).

Fig. 2. Simplified geological map of the study area located at the western border of the Gran Paradiso Unit.

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.

Fig. 4. Meso-scale structures representing the four deformation phases distinguished in the study area: a) σ-shaped Kfs porphyroclasts in orthogneisses of the the Gran Paradiso Unit showing top to W sense of shear; b) S_1 surface in the Gran Paradiso paragneisses 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) D_2 fold in the Sesia-Lanzo gneisses folding a D_1 isoclinal fold; e) D_3 open folds in the Gran Paradiso paragneisses folding a tight to isoclinal D_2 fold; f) D_3 box fold in the Combin-like calcschists with S_3 surfaces defined by a spaced and discontinuous reverse-slip C' types shear bands; g); discontinuous Extensional Crenulation Cleavage (S-C' types shear bands) in the Zermatt-Saas-like serpentinites; h) S-C type shear bands showing top to E sense of shear in mylonitic calcschists along the tectonic contact between the Upper Tectonic Element and the Lower one.

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-S_1 foliation; b) D_2 asymmetric fold in the Gran Paradiso paragneisses originating an S_2 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-S_1 foliation; g) D_1 rootless fold preserving a pre-S_1 foliation in the Sesia-Lanzo micaschists, S_1 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.

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-S_1 foliation; b) eclogite facies pre-S_1 foliation is preserved in metabasites and is cut by mylonites.

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).

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.

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.

Fig. 10. W-E cross-sections representing the structural history of the Orco Valley geological transect related to the its possible geodynamic evolution. OSZ: Orco Shear Zone; EMC-SL: Eclogitic Micaschists Complex, Sesia-Lanzo; GMC-SL: Gneiss Minuti Complex, Sesia-Lanzo; CO: Combin Unit; ZS: Zermatt-Saas Unit; GP: Gran Paradiso Unit. LTE: Lower Tectonic Element; UTE: Upper Tectonic Element. a) pre-D_1 stage and HP metamorphism in LTE. The position of the OSZ is indicated and probably accomodated reverse-slip movement. b) D_1 stage represents the main folding event resulting in a well-developed regional foliation in both UTE and LTE. c) D_2 stage is linked to minor folding (not shown) and to the exhumation of the LTE along the OSZ that cuts D_1 structures. d) D_3 stage folded the OSZ and caused the doming of the Gran Paradiso Unit. e) D_4 stage is associated to Extensional Crenulation Cleavage (ECC) on both side of the LTE and probably represents the onset of gravitational collapse.

Table 1. Evolution of the mineral assemblages respect to the structural and metamorphic setting in the main lithologies occurring in the different tectonic units.

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

Figure 1
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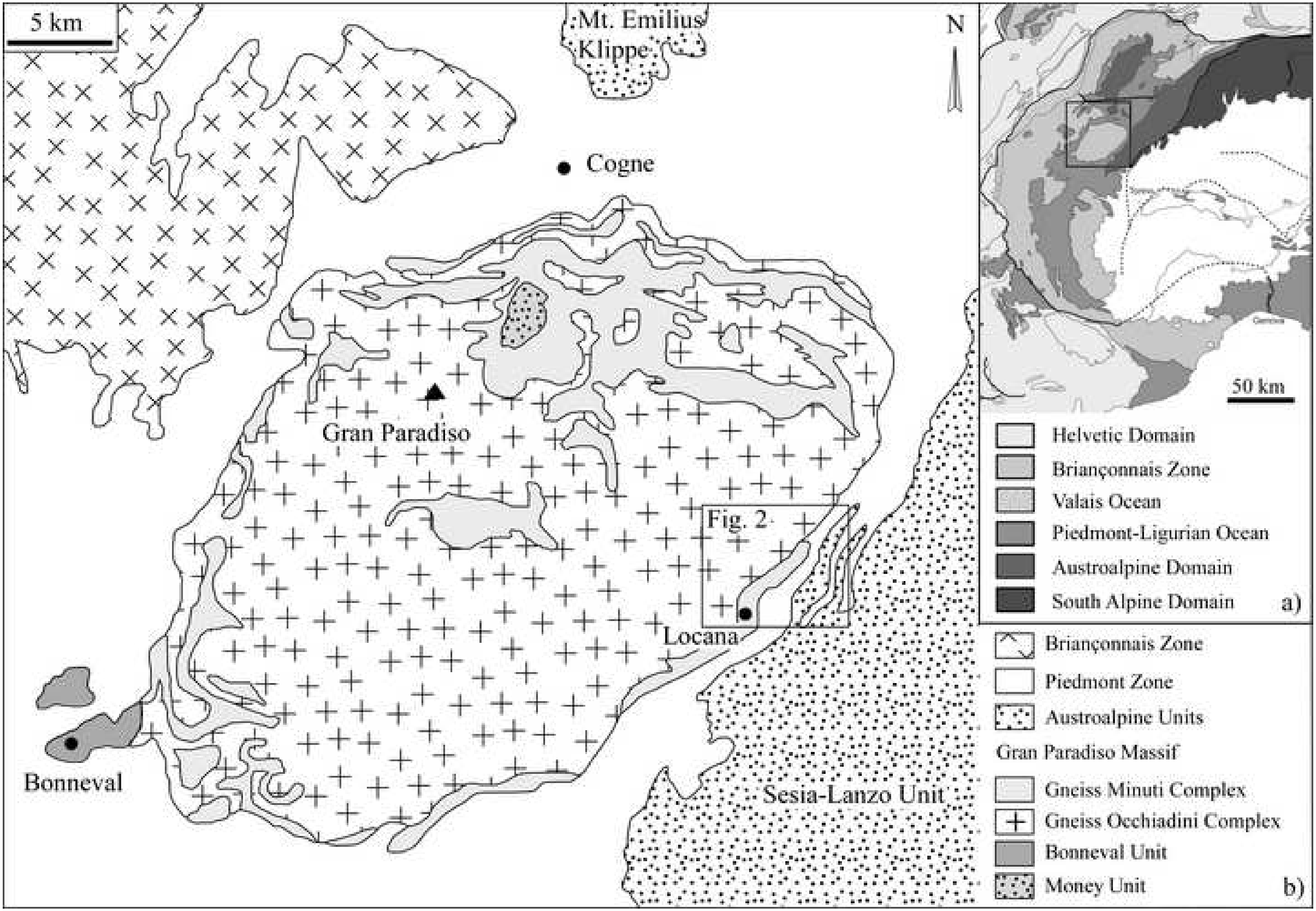

Figure 2

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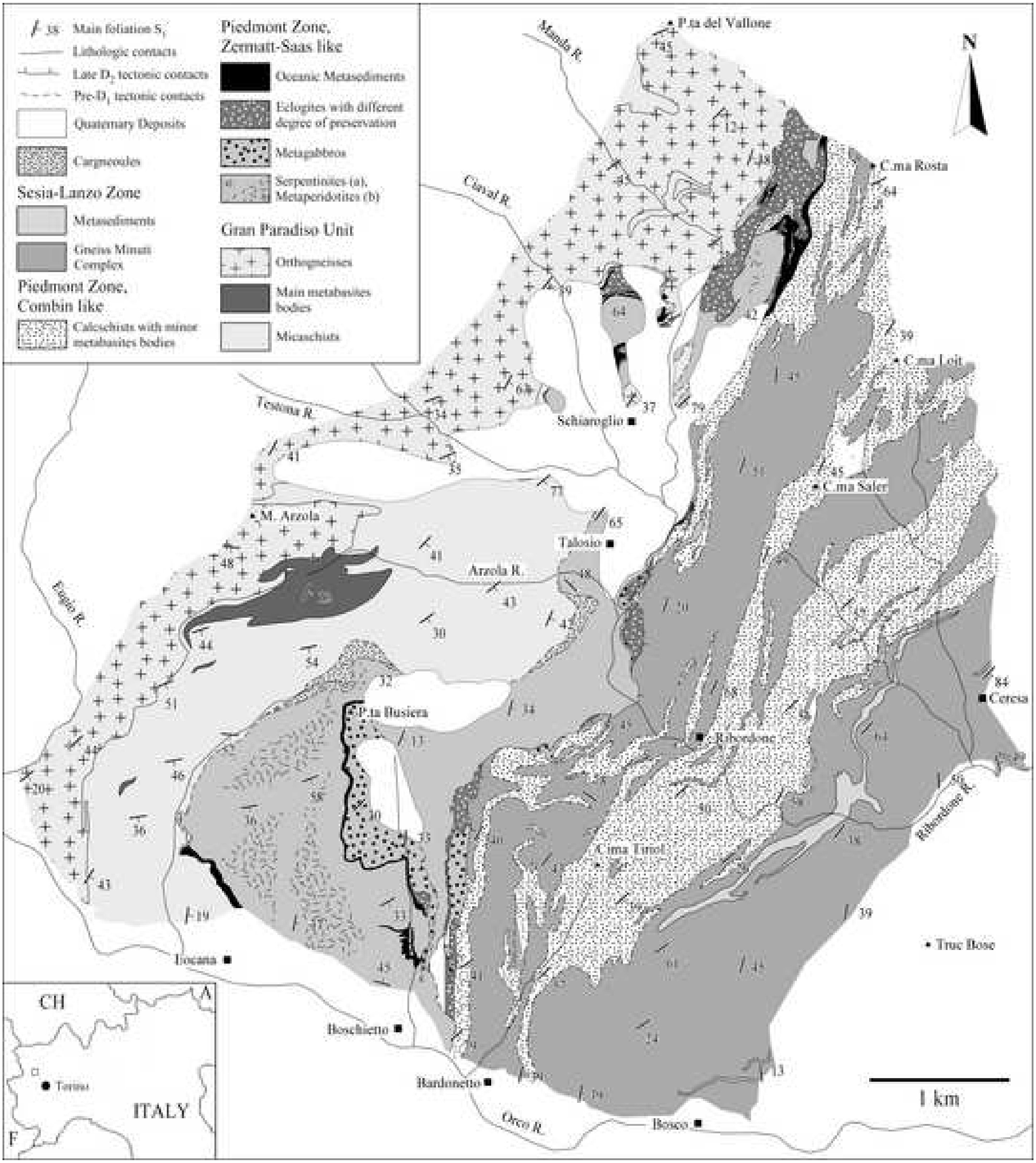

Figure 3

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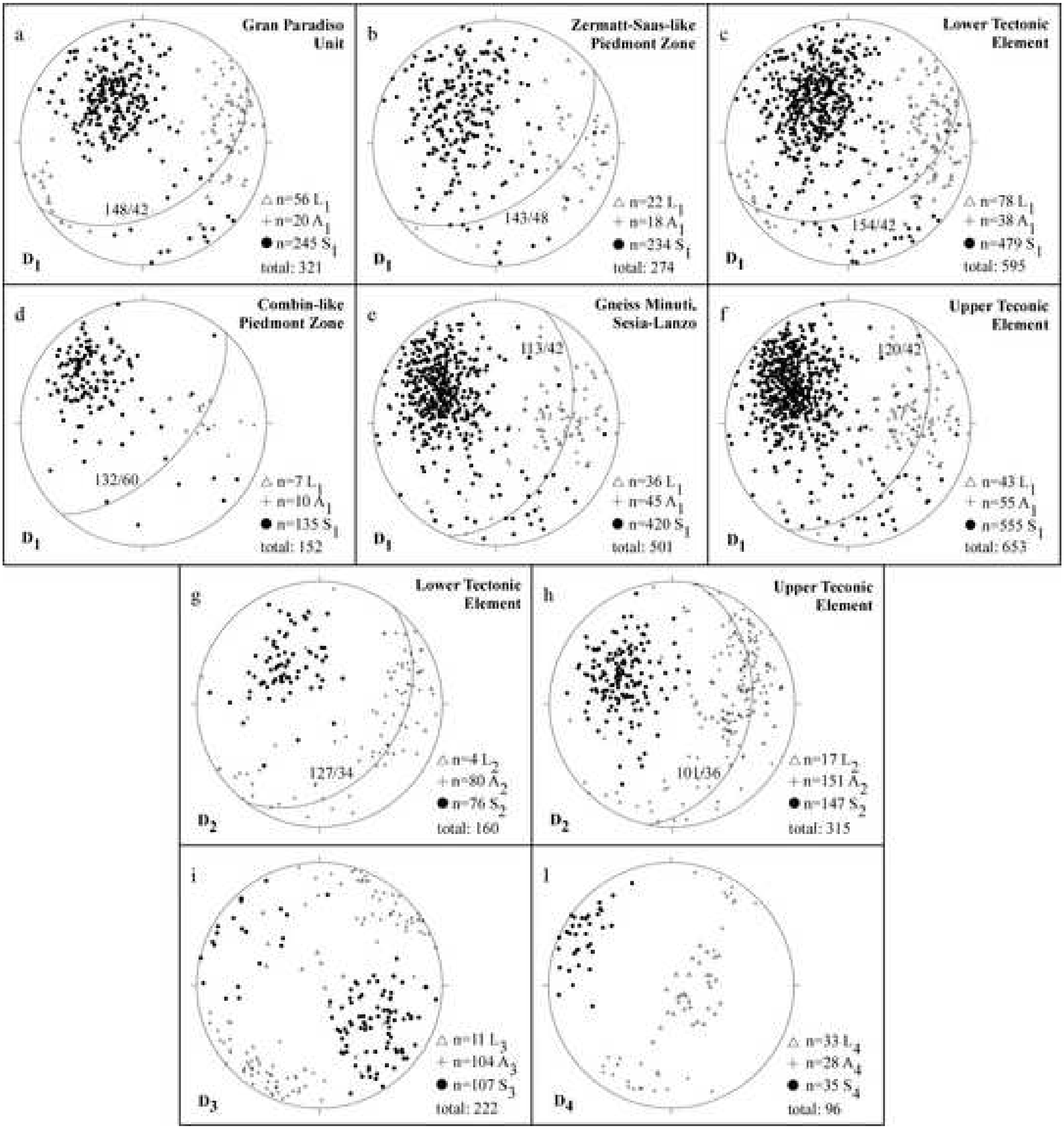

Figure 4

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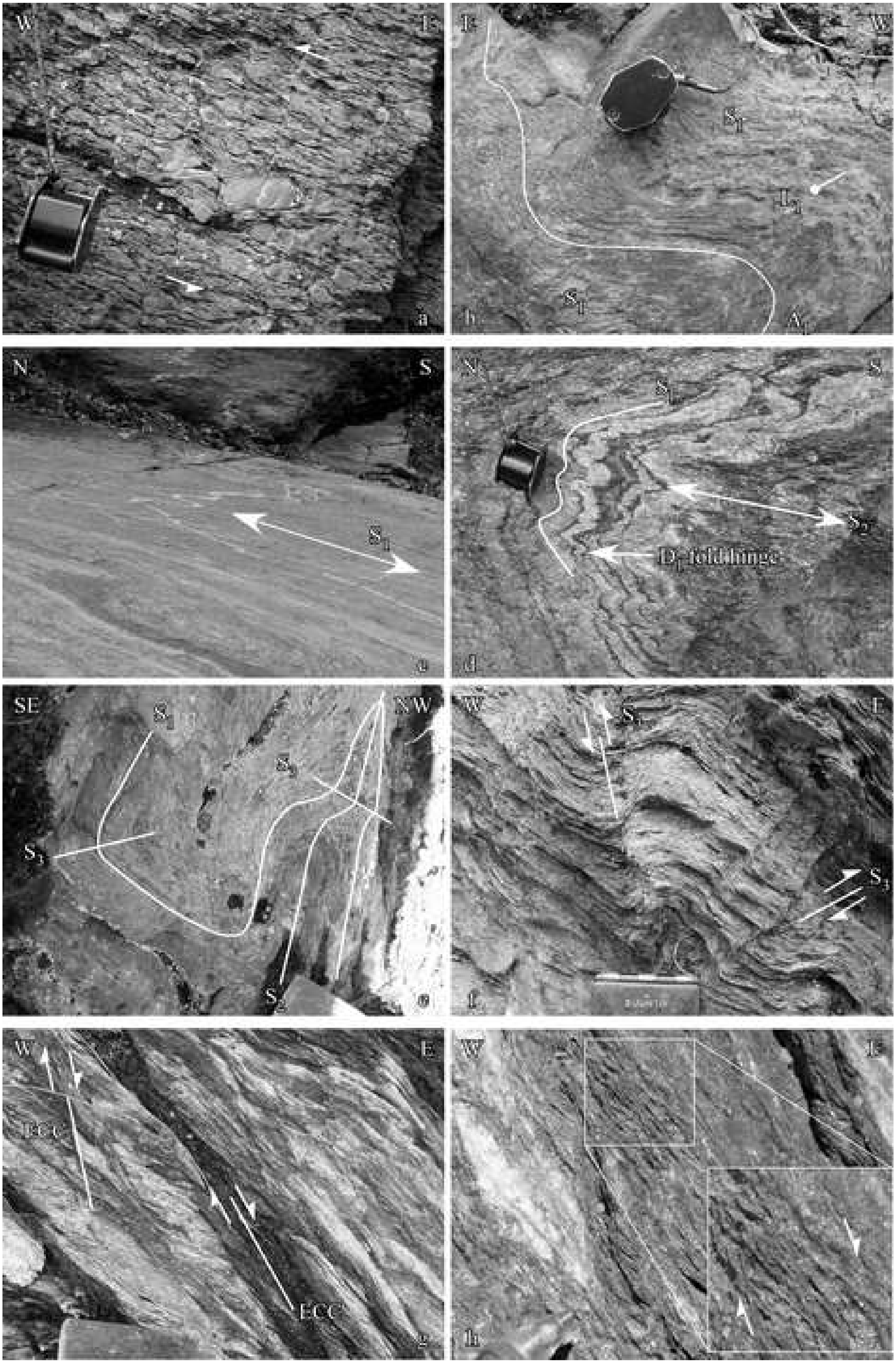

Figure 5

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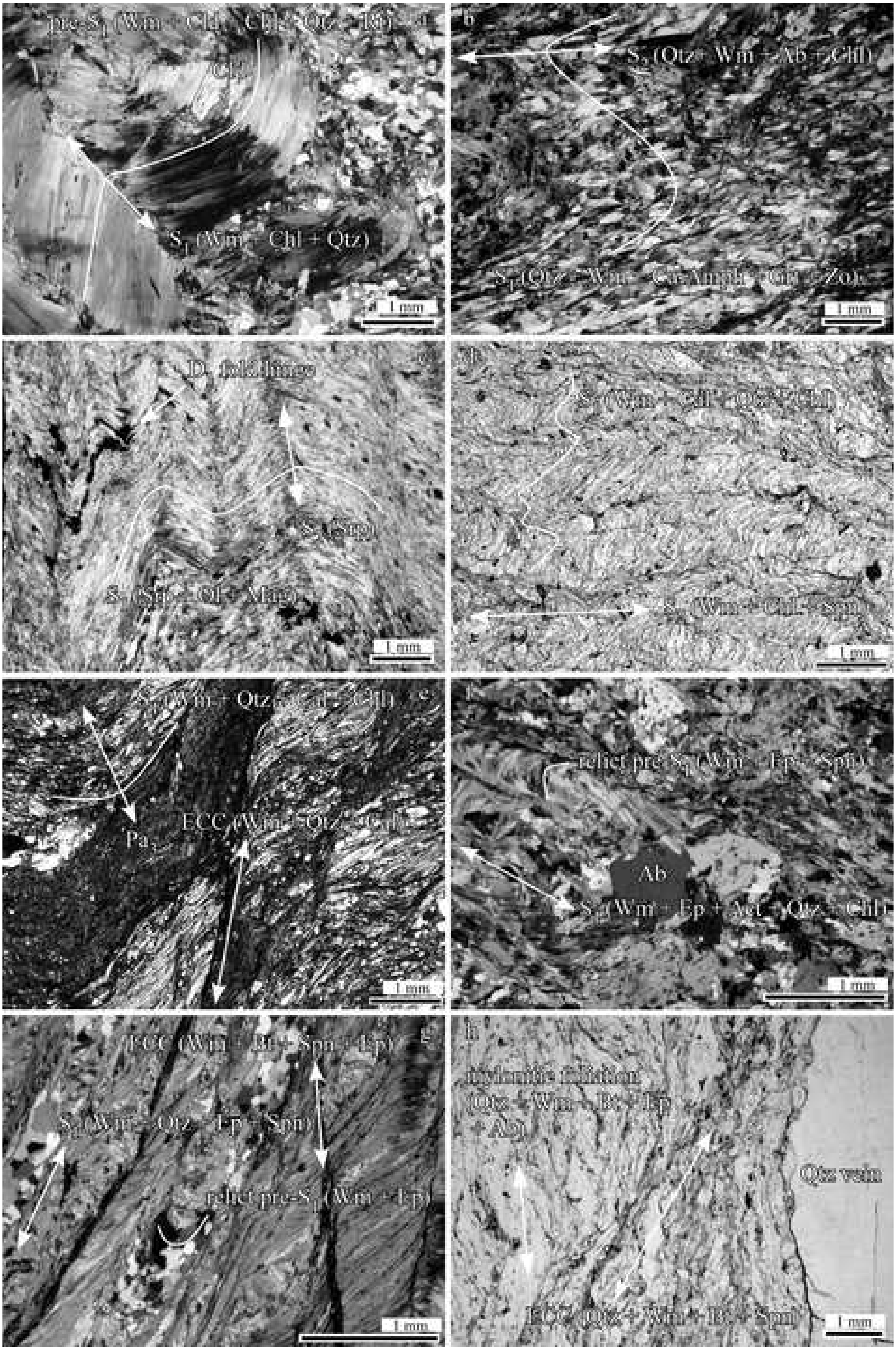

Figure 6
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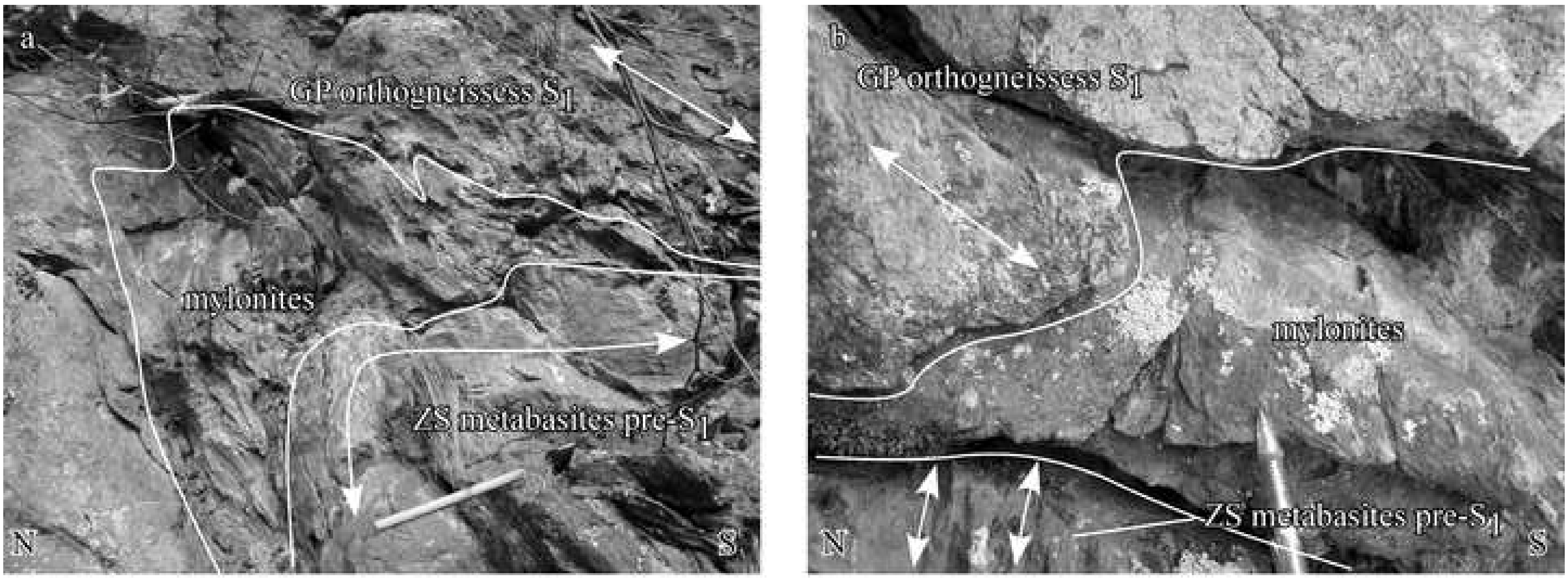

Figure 7
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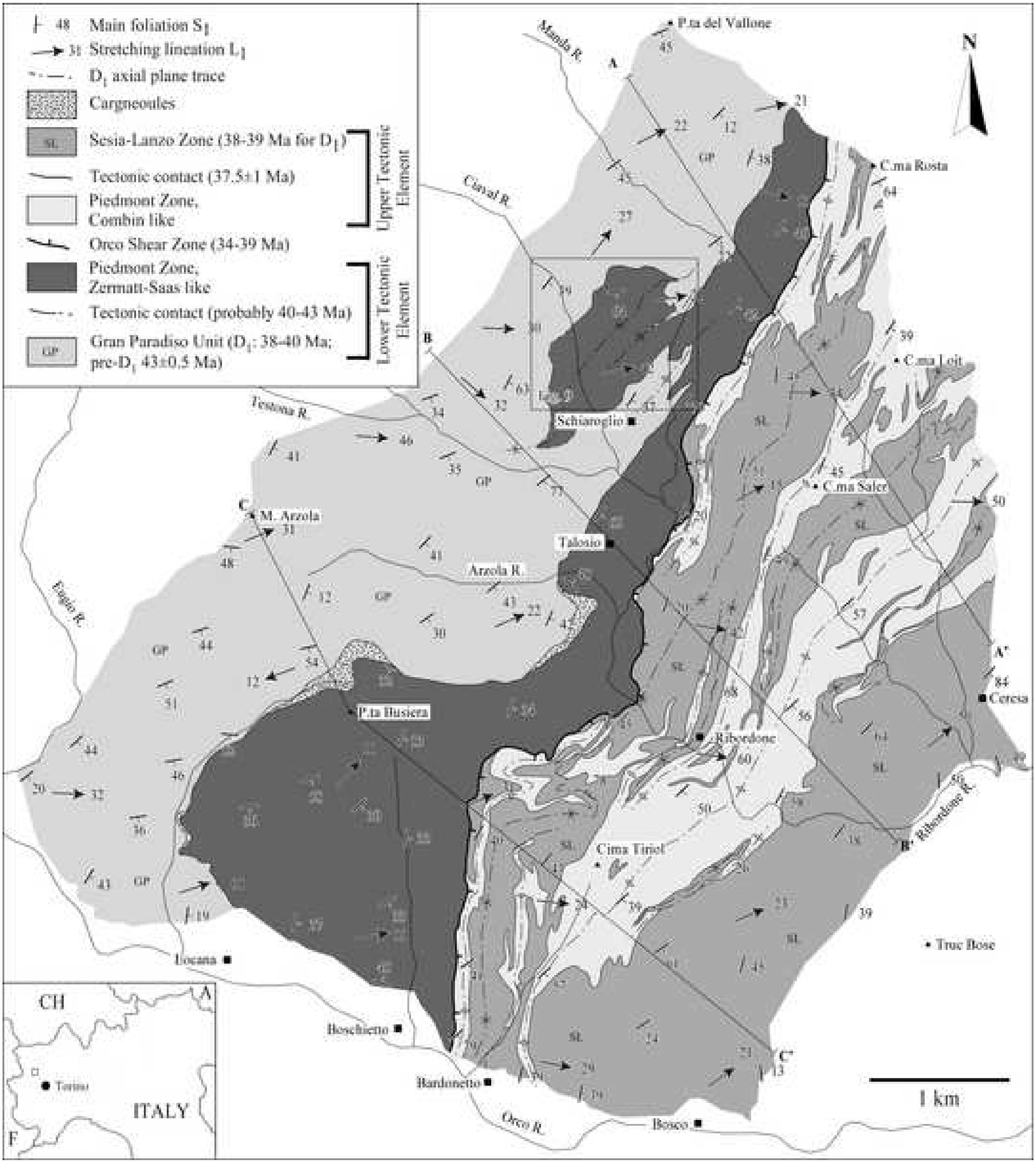

Figure 8

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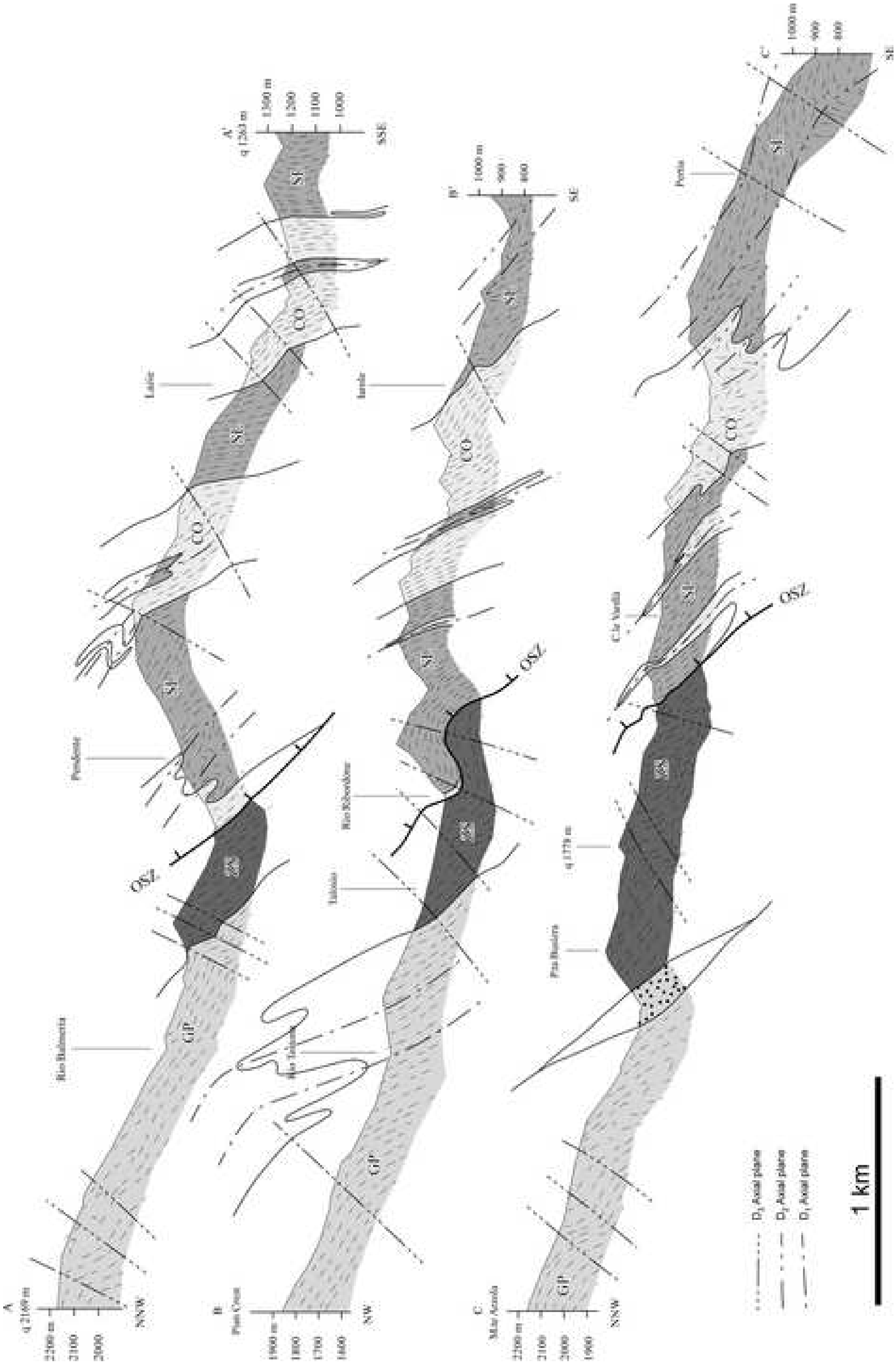

Figure 9

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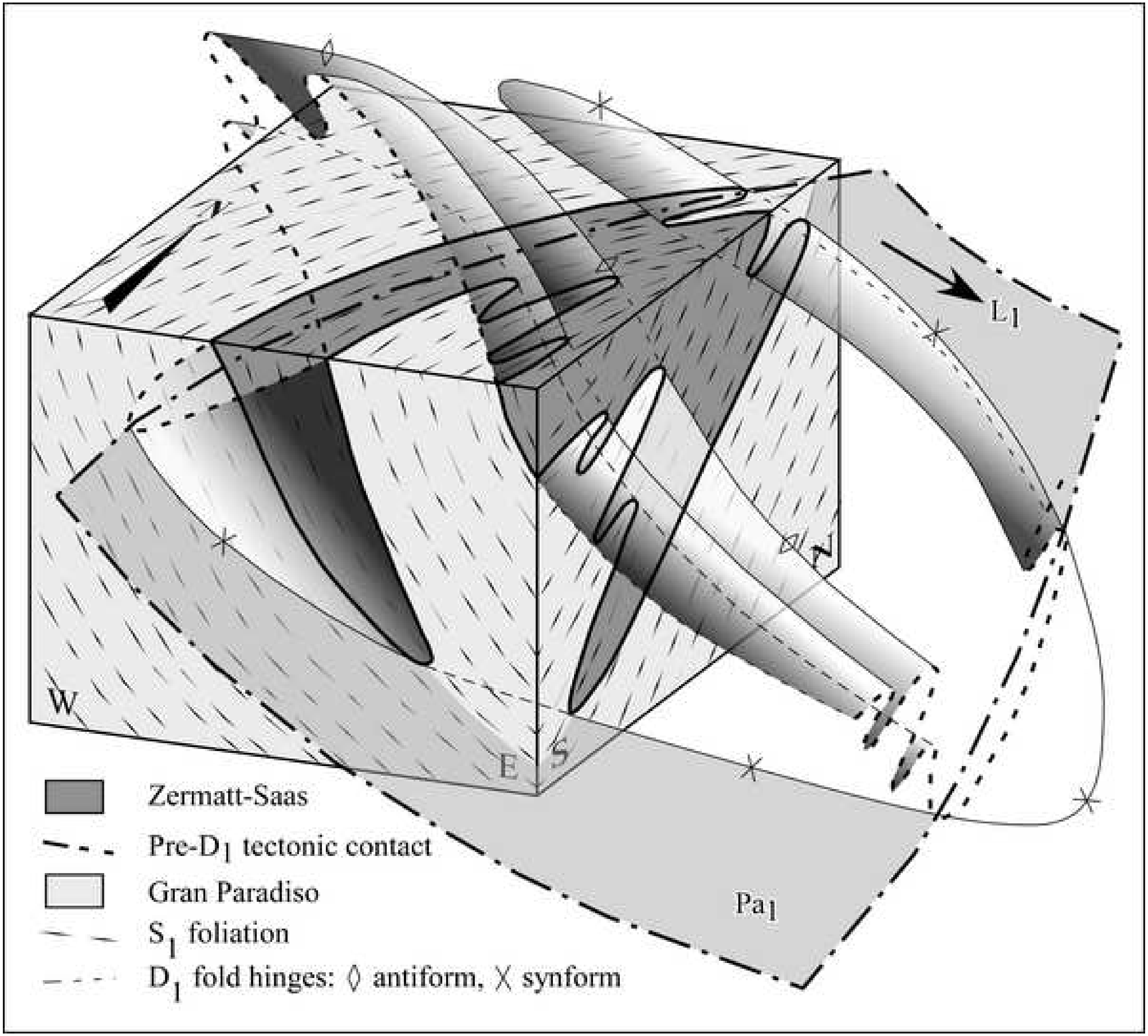

Figure 10
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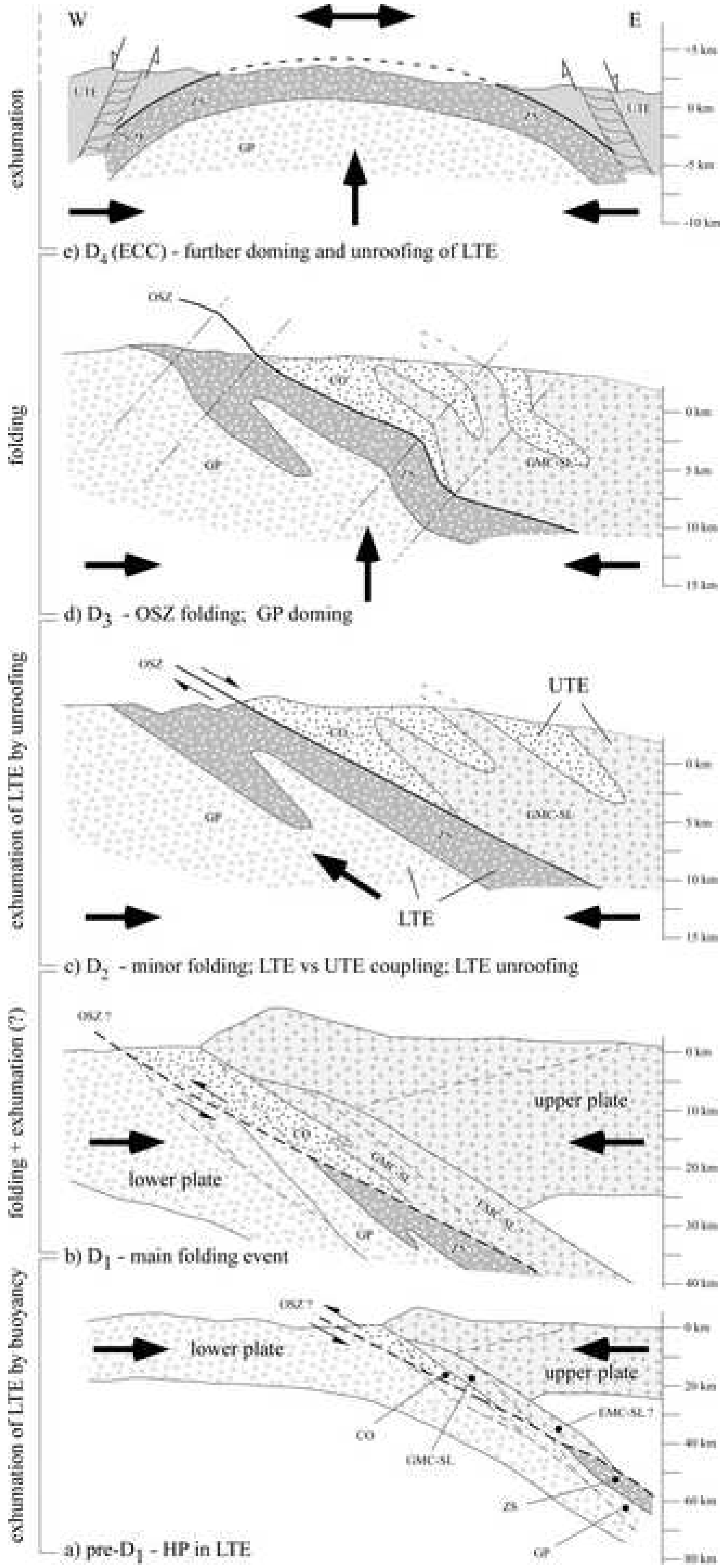

Table 1

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		Lower Tectonic Element (eclogite facies relics)							Upper Tectonic Element (only greenschist facies assemblages)		
		Gran Paradiso Unit			*Piedmont Zone*				*Piedmont Zone*		*Sesia-Lanzo Zone*
					Zermatt-Saas Unit				*Combin Unit*		*Gneiss Minuti Complex*
structural evolution	**metamorphic conditions**	micaschists	metabasites	orthogneisses (whiteschists)	serpentinites (metaperidotites)	metagabbros	metabasites	**metamorphic conditions**	calcschists	greenstones	gneisses (metagranitoids)
pre-Alpine		enclaves in orthogneisses	magmatic structures	Kfs, Qtz, Bt, Pl	(Ol, Cpx, Opx, Spl) (Ol, Chl, Am, Mag)	magmatic structures	-		-	-	magmatic structures
pre-S_1	**eclogite facies**	Grt,Gln,Wm, Qtz, Rt	Omp, Grt, Gln, Zo, Wm, Rt	(Wm, Qtz, Chl, Cld, Ky, Tlc, Grt)	-	Omp, Gln, Grt	Omp, Grt, Gln, Wm, Zo/Ep, Rt	**greenschist facies**	Wm, Cal, Qtz Chl	-	Wm, Qtz, Chl, Ep, Act; (Zo, Rt)
S_1	**middel-P greenschist to epidote-albite amphibolite facies**	Wm, Qtz, Hbl Ab, Grt, Zo, Rt	Ca-Na Am, Zo, Wm, Chl, Ab, Rt	Wm, Qtz, Ab, Ep, Spn (Qtz, Wm, Chl)	Srp, Chl, Ol, Di	Am, Zo, Wm, Chl, Rt;	Ca-Na Am, Zo, Wm, Chl, Rt,	**greenschist facies**	Wm, Qtz, Cal, Spn, Chl	Act, Ab, Ep, Chl, Spn	Wm, Qtz, Ab, Ep/Czo, Chl, Act, Spn
S_2	**greenschist facies**	Qtz, Wm, Chl, Ab, Spn	-	-	Srp	-	-		Wm, Chl, Qtz, Spn	-	Wm, Chl, Act
S_3	**low-grade metamorphic conditions**	-	-	-	Srp	-	-		Wm, Cal, Qtz	-	-
S_4 (ECC)	**ductile to brittle**	Qtz, Wm, Bt	-	-	Srp	-	-		Wm, Cal, Qtz	-	Qtz, Wm, Bt, Spn

Table 2

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	Lower Tectonic Element (eclogite facies relics)		Upper Tectonic Element (only greenschist facies assemblages)	
	Gran Paradiso Unit	*Zermatt-Saas Unit*	*Combin Unit*	*Sesia-Lanzo GMC*
pre-D_1	eclogite facies	eclogite facies	greenchist facies	greenchist facies
old tectonic contacts	blueschist facies		greenchist facies	
D_1	middel-P greenchist to epidote-albite amphibolite facies		greenchist facies	
D_2	greenchist 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			