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Deformation mode switches in the Penninic units of the Urtier Valley (Western Alps): Evidence for a dynamic orogen

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Abstract

Multiple deformation mode switches from shortening to extension have been detected in the Penninic units of the Urtier Valley, to the north of the Gran Paradiso massif. An early shortening phase, whose traces are poorly preserved, led to the tectonic burial of rock units to high pressure conditions. Subsequent extensional shearing (SZ_{gr}^1) led to the formation of mylonitic fabrics. During this event the eclogitic Piemonte unit was exhumed to greenschist facies conditions ($P = 0.2-0.3$ GPa) in the footwall of the blueschist Piemonte unit. Exotic slices of continental basement and Mesozoic continental shelf carbonates are found along their contact, implying the existence of older thrust stacks dissected by the younger extensional shear zones. The extensional structures were later affected by upright folding (Fu), indicating yet another deformation mode switch, which led to re-burial to $P = 0.6-0.8$ GPa. Later multi-stage deformation culminated in an episode of extensional shearing with top-to-the-west kinematics (SZ_{gr}^2). Therefore, at least two shortening–extension cycles affected the Piemonte units of the Urtier Valley. Existing geochronological data allow less than 20 Myr for the complex deformation history discussed here. Shortening–extension cycles can be inferred also from published studies from other sections of the Western Alps. However, while the first shortening–extension cycle was widespread in the Penninic units, the lateral extent and relative timing of the second cycle in different areas are still unclear.

Keywords: Orogens; Alps; Shortening–extension cycles; Extensional shear zones; Upright folds

1. Introduction

Studies conducted in several mountain belts have shown that extensional deformation may play an important role in the evolution of orogens. Extensional shear zones have been reported from several orogenic belts located along convergent plate margins, including the Himalaya (Burg and Chen, 1984) and the European Alps (e.g. Mancktelow, 1985; Ballèvre et al., 1990; Ballèvre and Merle, 1993; Froitzheim et al., 1994; Wheeler and Butler, 1993; Nievergelt et al., 1996; Cartwright and Barnicoat, 2002; Avigad, 1996; Avigad et al., 2003; Reddy et al., 1999; Agard et al., 2002; Reddy et al., 2003; Forster et al., 2004). The significance of extensional deformation in the evolution of such mountain belts is a matter of controversy and extension is generally regarded as a local exception to an overall shortening regime, related to the internal dynamics of orogenic wedges (e.g. Mancktelow, 1992; Wheeler et al., 2001; Schmid et al., 1996; Beaumont et al., 2001) or as a late stage development in the evolution of orogens (Dewey, 1988; England and Houseman, 1989). However, recent studies from other stretches of the Alpine–Himalayan belt (Balanyá et al., 1997; Azañón and Crespo-Blanc, 2000; Rawling and Lister, 1999; Forster and Lister, 2005) and of other mountain belts (Collins, 2002; Dewey, 2005) have suggested that orogens may undergo multiple switches from shortening to extensional deformation and that such switches may be orogenic in scale. Although the driving forces for such switches are still unclear, shortening episodes appear to result in tectonic burial and high pressure metamorphism (Balanyá et al., 1997; Rawling and Lister, 1999; Beltrando et al., 2007), whilst

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extensional episodes culminate in exhumation of rock units and re-equilibration of the high pressure mineral assemblages at lower pressures (Azañón and Crespo-Blanc, 2000; Beltrando et al., 2007). Folding of the extensional structures (Rawling and Lister, 1999) or their overprint by thrusting (Balanyá et al., 1997; Collins, 2002) is considered the signature of renewed shortening deformation following an extensional episode.

Due to the widespread overprint that commonly affects older structures, the detection of such complex deformation histories cannot rely exclusively on geometric considerations, since re-orientation of older thrusts and extensional shear zones can mask their original nature (Wheeler and Butler, 1994). Techniques from structural geology must be used in combination with metamorphic petrology and geochronology. The resulting data can be expressed in ‘‘sequence diagrams’’ that contain a synthesis of the above information in a form somewhat similar to the methods generally adopted for structural analysis in the field (see below). In this contribution, we show how such diagrams provide a powerful tool for clearly presenting structural/metamorphic data and enhance correlations between different field areas.

The adoption of this approach in the study of the Penninic units in the Urtier Valley, in the Western Alps, allows the detection of two deformation mode switches in the 50–30 Ma interval.

2. Geological setting

The study area, which is located in the Urtier Valley, is part of the Penninic domain of the Western Alps. The Penninic domain is composed of the Piemonte oceanic units, the continental Internal Crystalline Massifs and Briançonnais domain and the Valaisan domain (Fig. 1). All the above units are believed to represent remnants of terranes that were originally located between the European plate and Adria, a promontory of northern Africa (e.g. Platt, 1986). Although the details of the palaeogeographic setting prior to the collision between the Adria micro-plate and the European plate are still a matter of controversy (see Froitzheim, 2001; Rosenbaum and Lister, 2005; Beltrando et al., in press for review), it is generally accepted that opening of the Piemonte ocean in the Jurassic culminated in the separation of the African and European plates. Later extensional tectonics and formation of the Valaisan basin in a more external position resulted in the isolation of the Briançonnais domain from the European plate *sensu stricto* (e.g. Trümpy, 1980; Stampfli et al., 2002). Opening of the southern Atlantic resulted in convergence between the African and the European plates from the Late Cretaceous (Rosenbaum et al., 2002). As a consequence, starting from the Eocene, the Penninic units were accreted to the Alpine orogen (e.g. Rubatto et al., 1998; Lapen et al., 2003). Following accretion, the Piemonte units experienced an episode of extensional deformation (e.g. Blake and Jayco, 1990; Ballèvre and Merle, 1993; Agard et al., 2002; Cartwright and Barnicoat, 2002; Reddy et al., 2003) that culminated in the exhumation of the eclogite facies Piemonte units from beneath the blueschist facies Piemonte units (Fig. 1b). This event resulted in the formation of shear zones and shear fabrics normally characterized by top-to-the-east kinematics that have been reported from the Piemonte units in several parts of the Western Alps (Ballèvre and Merle, 1993; Caby, 1996; Agard et al., 2001; Reddy et al., 2003). More complex kinematics, involving switches from SE- to NW-directed shearing, have been reported from sections of the Gressoney Shear Zone, which accommodated the exhumation of the eclogitic Piemonte unit in the Valtournenche valley (Reddy et al., 1999, 2003).

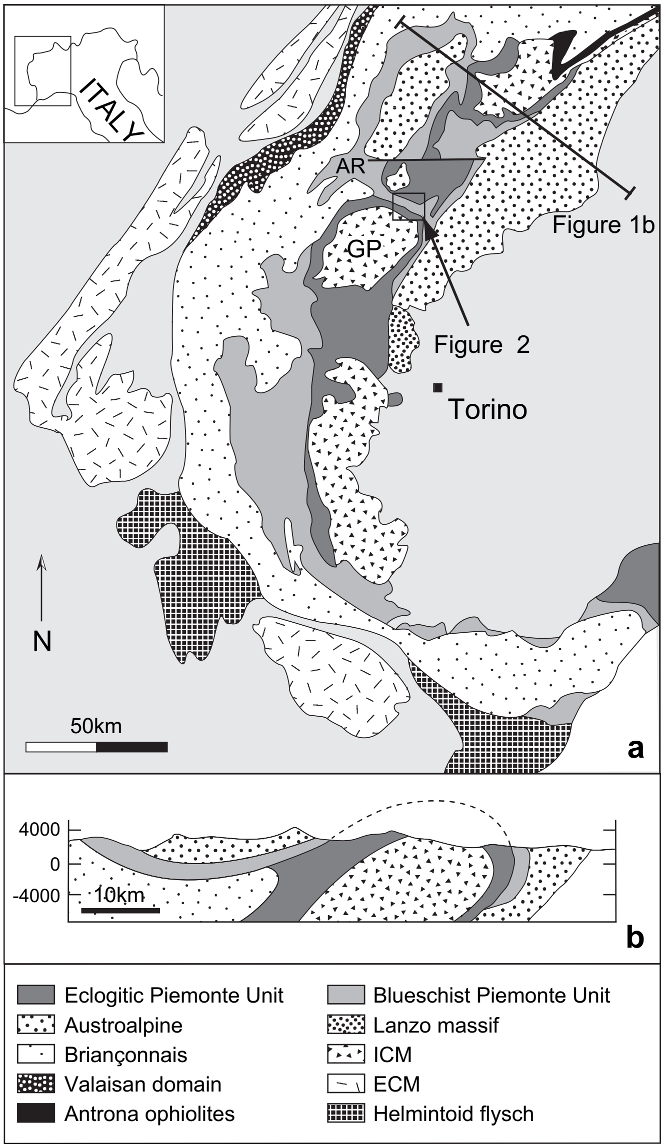


Fig. 1. Simplified tectonic map (a) of the Western Alps (modified from Schwartz et al., 2000) and cross section across the north-western Alps (after Reddy et al., 2003). The eclogitic Piemonte unit (dark grey) are overlain by the blueschist Piemonte unit (light grey).

A second phase of extensional deformation is also commonly recognized in the Piemonte units and in the more external Briançonnais domain. This deformation event is generally characterized by top-to-the-west kinematics, with west-dipping shear zones displacing the older extensional fabrics (e.g. Ballèvre et al., 1990; Caby, 1996; Agard et al., 2002), although top-to-the-east kinematics have also been reported (Reddy et al., 1999). This episode of deformation is normally interpreted to represent the continuation of the first extensional event (Agard et al., 2002; Ganne et al., 2005), before the onset of brittle extensional tectonics (Philippot, 1990; Rolland et al., 2000; Schwartz, 2002; Agard et al., 2003).

In its northern part, the contact between the eclogite and blueschist facies Piemonte units is characterized by the presence of numerous exotic units, without lithological equivalents in the ocean-derived Piemonte units. These slices have a very limited areal extent (from a few m^2 to 4–6 km^2) and generally display a tabular shape with the shortest side perpendicular to the contact. They range from continental basement rocks (Hermann, 1937; Ballèvre et al., 1986) to Mesozoic continental shelf sediments (Elter, 1972) to the Ultra-High-Pressure Lago di Cignana unit (Forster et al., 2004). The presence of the continental basement rocks, which display a close affinity with the more internal Sesia-Lanzo unit (Compagnoni et al., 1977), has been ascribed to thrusting (Stutz and Masson, 1938; Elter, 1960; Compagnoni et al., 1977; Froitzheim et al., 2006), reactivation of older thrusts in an extensional setting (Ballèvre and Merle, 1993; Wheeler et al., 2001; Forster et al., 2004) or palaeogeography (Dal Piaz, 1999; Dal Piaz et al., 2001).

3. The Urtier Valley area

In the following sections a description of the lithological characteristics and deformation history of the Urtier Valley area, which is located to south of the Aosta Valley, is provided. This relatively less-studied area was chosen to constrain the geometry and kinematics of the contact between the eclogitic and blueschist Piemonte unit, which has been studied in detail both further to the north (Ballèvre and Merle, 1993; Reddy et al., 1999, 2003; Forster et al., 2004; Pleuger et al., 2007) and to the south (Agard et al., 2001; Schwartz, 2002).

The study area is characterized by the presence of five tectonometamorphic units (Figs. 2 and 3): (1) the eclogitic Piemonte unit, which comprises remnants of oceanic crust that were metamorphosed under eclogite facies conditions during the Alpine orogenesis; (2) the blueschist facies Piemonte unit, mainly composed of marine sediments and olistoliths, normally interpreted as the transitional zone between the oceanic basin and the European margin s.l.; (3) a Mesozoic carbonaceous–dolomitic sedimentary sequence, named "Faisceau de Cogne" (Elter, 1972), that was deposited on a continental shelf (Fig. 4a, b); (4) slices of continental basement with Sesia-Lanzo affinity (Fig. 3a, c); and (5) the northern end of the continental Gran Paradiso Massif, mainly made of a metapelitic/metasedimentary basement intruded by late-Hercynian granitoids. A discontinuous layer of dolomitic limestones is found along the contact between the Gran Paradiso massif and the eclogitic Piemonte unit (Elter, 1972).

3.1. Eclogite facies Piemonte unit

The eclogite facies Piemonte unit crops out on both sides of the Urtier Valley and in a thin strip at the bottom of it (Fig. 2). Metamafic rocks preserving the eclogitic assemblage omphacite + garnet + rutile are only rarely preserved. The presence of rutile in place of titanite as the main Ti-bearing phase has been used as the criterion to differentiate between lithologies belonging to the eclogite or blueschist Piemonte unit in cases where all other traces of eclogite facies metamorphism have been obliterated by later retrogression. Since the transition between titanite and rutile, which is related to changes in pressure, is strongly influenced by rock composition, comparisons have been drawn between lithologies of similar bulk composition and analogous major mineral assemblages. For example, prasinites, which are widely found in the area (Fig. 2) and are generally characterized by the assemblage chlorite + albite + epidote + actinolitic amphibole, consistently preserve relict rutile in the southern and northern parts of the Urtier Valley, where eclogites *sensu stricto* are also found. In contrast, only titanite is observed in the prasinites from the central Urtier Valley, which therefore have been attributed to the blueschist Piemonte unit (Fig. 2). Similarly, micaschists characterized by the assemblage garnet + phengite (Si = 3.30 a.p.f.u.) + quartz + clorithoid contain rutile or titanite depending on whether they belong to the eclogitic or blueschist Piemonte unit, respectively.

Serpentinites, meta-gabbros, prasinites and calcschists/micaschists can be found in the eclogitic Piemonte unit. The relative abundance of different lithologies varies widely between the southern and the northern sides of the valley (Fig. 2).

Serpentinites constitute the majority of the eclogitic Piemonte unit in the southern part of the study area, where they often contain metamorphic olivine and titanian clinohumite. In the Acque Rosse (Eaux Rouges) Valley, pods of eclogites are commonly found within serpentinites. The abundance of porphyroblastic rutile and retrograde titanite suggests that these eclogites were derived from metamorphism of Fe–Ti gabbros. A primary origin for the contacts between gabbros and serpentinites is suggested by their gradational nature and widespread metasomatism. Abundant prasinites are found further to the south, closer to the Gran Paradiso massif. They are characterized by meter-scale compositional banding, related to variations in the relative abundance of albite and green amphibole. Calcschists and micaschists are characterized by compositional banding at the scale of tens of centimetres, related to variations of the relative abundance of the carbonatic and pelitic components. Centimetre-size aggregates of white micas and porphyroblastic garnet are commonly observed in the calcschists.

The lithological association found on the southern side of the Urtier Valley shares marked similarities with other parts of the eclogite Piemonte unit, such as the Zermatt-Saas Zone (Bearth, 1967), the Mont Avic Massif, the Unita‘ Inferiore (Perotto et al., 1983) and the Monviso massif (Lombardo et al., 1978). The association of serpentinites, meta-gabbros, prasinites, calcschists and micaschists suggests that the eclogitic Piemonte unit samples remnants of an oceanic crust.

Towards the north, the eclogitic Piemonte unit crops out again in a narrow strip of calc-micaschists located in the middle of the Urtier Valley and then on the northern side of the

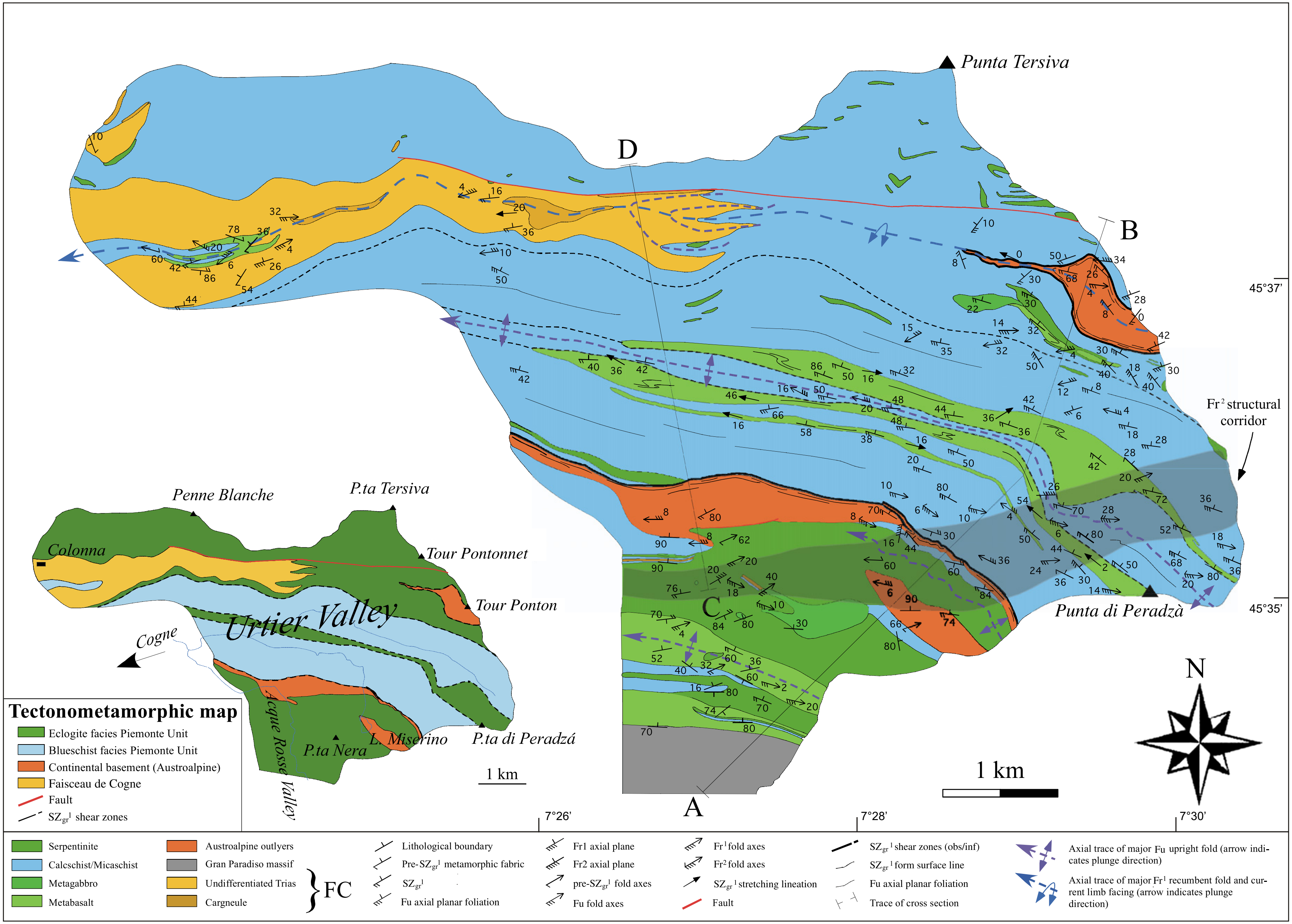


Fig. 2. Geologic map (a) of the upper Urtier Valley, to the south of the Aosta Valley. Locations of cross sections (Fig. 9) are indicated. Inset (b) shows a tectonometamorphic map of the same area, where the position of the exotic slices of continental Austroalpine basement and Mesozoic continental shelf sediments of the Faisceau de Cogne at the contact between the eclogitic and blueschist Piemonte units can be clearly visualised.

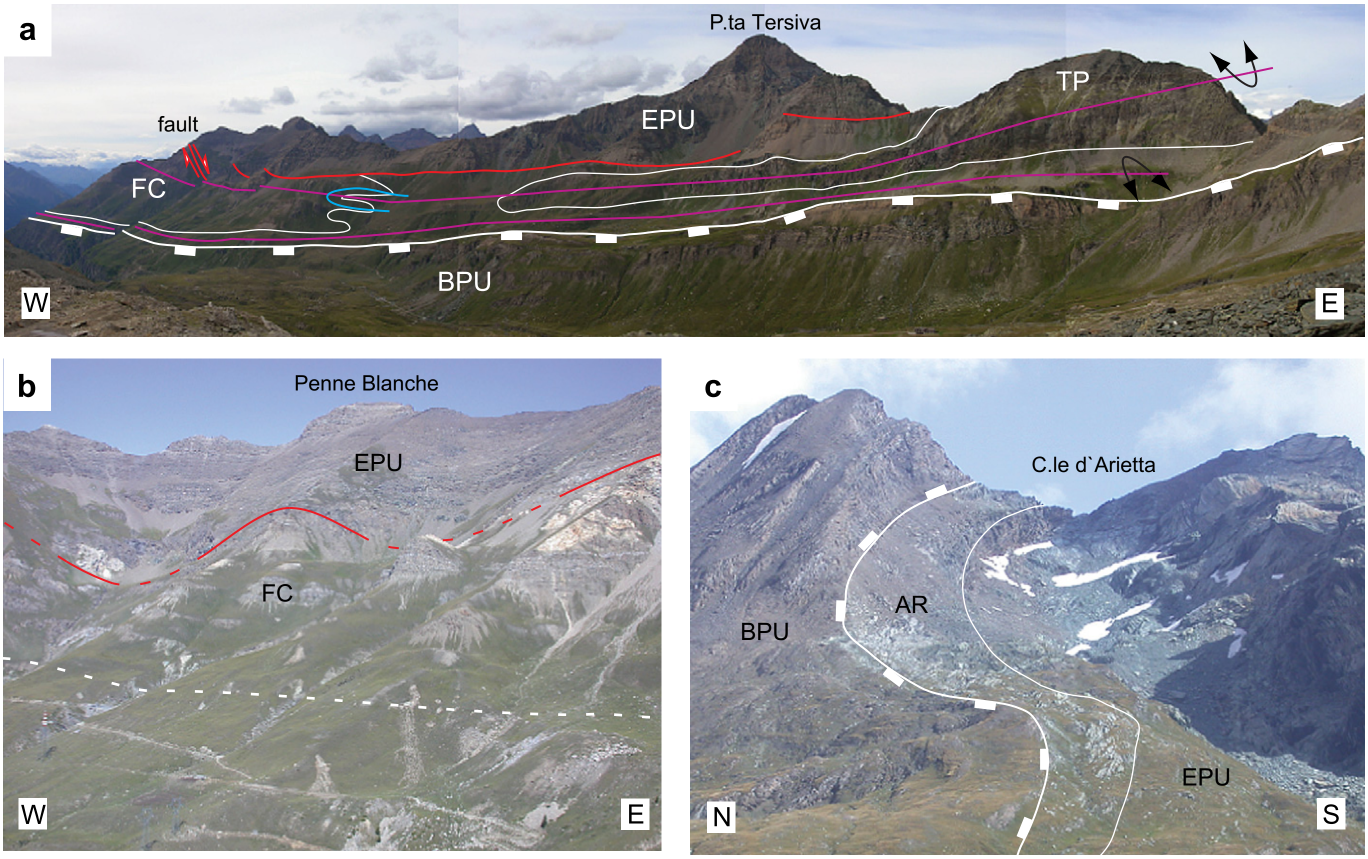


Fig. 3. Photographs showing the large scale structure of the eclogite-blueschist facies Piemonte unit contact in the Urtier Valley. (a) Continental basement of the Tour Ponton unit and Mesozoic sediments of the Faisceau de Cogne (thin white lines indicate the boundaries of individual slices) crop out in close proximity to the contact (thick white line), in the core of a recumbent fold (Fr^1) on the northern side of the valley; (b) In the western part of the study area, a normal fault (red line) is present at the contact between the Faisceau de Cogne and the eclogitic Piemonte unit; (c) the Acque Rosse slice of continental basement crops out along the contact between the eclogitic and blueschist facies Piemonte units, on the southern side of the Urtier Valley. EPU = eclogitic Piemonte unit; BPU = blueschist Piemonte unit; TP = Tour Ponton unit; FC = Faisceau de Cogne; AR = Acque Rosse unit.

valley (Fig. 3a, b). Retrogressed eclogites and flaser metagabbros can be found at the base at the Tour Ponton continental slice. Large masses of retrogressed eclogites have also been reported from the base of the Tour Ponton in the Champorcher Valley, just to the east of the study area (Nervo and Polino, 1976). Calcschists and micaschists are the most common lithologies in the eclogitic Piemonte unit to the north of the Tour Ponton and Faisceau de Cogne slices. Bands of serpentinites and mafic rocks are interleaved with the calcschists.

3.2. *Blueschist facies Piemonte unit*

The blueschist facies Piemonte unit crops out at the bottom of the Urtier Valley, between the northern and southern occurrences of the eclogitic Piemonte unit (Fig. 2). Lithologies have been assigned to this tectonometamorphic unit based on the complete absence of any trace of eclogite facies metamorphism and on the presence of titanite, instead of rutile, as the main Ti-bearing phase. However, the presence of phengite ($Si = 3.3$ a.p.f.u.) in micaschists still suggests relatively high pressures of crystallization of the peak pressure assemblage.

The lithological association found in the blueschist unit comprises a wide range of sedimentary rocks. Calcschists and micaschists with variable relative abundance of pelitic and carbonaceous components are common and a complete range from graphitic schists/phyllites and quartz micaschists to impure marbles is present. Three main layers of prasinites are found in the blueschist Piemonte unit. They range in thickness from 1 m to more than 500 m and they can be followed for several km along strike (Fig. 2). They are characterized by alternating plagioclase + epidote and green amphibole-rich layers at the millimetre-scale. Fuchsite-rich layers, probably products of ophiolitic detritism, can be observed a few meters to the north of the Acque Rosse continental slice. Small bodies of serpentinites are observed in the northern part of the blueschist Piemonte unit.

The lithological composition of the blueschist Piemonte unit in the study area make it very similar to the Combin unit (Bearth, 1967) further to the north and the Unita‘ Superiore (Perotto et al., 1983) and Queyras unit further to the south, which are considered to represent a sedimentary sequence deposited on the margin of the Piemonte ocean. A similar origin is likely for the blueschist Piemonte unit in the Urtier Valley.

3.3. Continental basement slices

Two distinct slices of continental basement, named the Acque Rosse unit (Paganelli et al., 1995) and the Tour Ponton unit (Nervo and Polino, 1976), crop out on both sides of the Urtier Valley (Figs. 2 and 3). Centimetre-sized garnet porphyroclasts that formed under amphibolite to granulite facies conditions during the Variscan orogeny (Nervo and Polino, 1976) are preserved in metapelites in the southern part of the Acque Rosse unit and in the Tour Ponton unit away from the contacts with the eclogitic Piemonte unit. The continental basement units underwent eclogite facies metamorphism during Alpine orogenesis (e.g. Nervo and Polino, 1976; Paganelli et al., 1995). Pervasive greenschist facies retrogression is observed proximal to the contacts with the surrounding tectonometamorphic units. Albite porphyroblasts are commonly observed in gneisses and metapelites located near the contacts between the Tour Ponton and the eclogitic Piemonte unit as well as in the northern branch of the Acque Rosse unit. Mafic layers are common and provide some of the best-preserved eclogites in the area.

These slices of continental basement, made of lower to middle crustal protoliths intruded by Permian granitoids and gabbros, display close lithological similarities with the Sesia-Lanzo Zone and more generally with the Austroalpine basement units, which are located in a more internal position in the Western Alps (Fig. 1).

3.4. Faisceau de Cogne

The so-called ‘‘Faisceau de Cogne’’ (Elter, 1972) is a lithological association of Mesozoic sediments that crop out on the north side of the Urtier Valley, in close proximity to the interface between the eclogite and blueschist facies Piemonte units (Figs. 2 and 3). It comprises Triassic quartzites and dolomites overlain by calcschists and marbles of proposed Liassic to Cretaceous age (Elter, 1971, 1972). Abundant cargneules, dolomitic breccias in carbonatic matrix, are also found. Analogous lithologies are reported from the Mesozoic cover of the Briançonnais domain, located in a more westerly position (Fig. 1; Elter, 1972). To the west, outside the study area, the Faisceau de Cogne can be traced almost continuously into a Mesozoic sequence that overlies the Briançonnais Ruitor Massif (Elter, 1987). Rutile is ubiquitously found as the Ti-bearing phase in all lithologies of the Faisceau de Cogne.

3.5. Gran Paradiso massif

The Gran Paradiso massif occupies the southernmost part of the study area and crops out underneath the eclogitic Piemonte unit (Figs. 2 and 3). The massif is composed of late-Variscan granitoids that intruded a basement mainly composed of metapelites. In the study area the Gran Paradiso Massif is composed of coarse grained orthogneisses characterized by K-feldspar porphyroclasts and a biotite-bearing mylonitic foliation.

4. Structural evolution

The deformation history of the study area has been reconstructed on the basis of observations of structural patterns, styles and overprinting relationships between different structures, fabrics and metamorphic mineral assemblages. Typically, only a few fabrics and structures are observed in each individual outcrop and commonly, during fieldwork, a sequence of events is constructed in each case, based on overprinting relationships. This sequence of events can be portrayed in a ‘‘deformation sequence diagram’’, where folding and shearing events are labelled F and SZ, respectively. Subsequent microstructural and petrographic observations can then be combined with the field-derived deformation sequences with the aim of providing a tool for concise and unambiguous communication of structural and metamorphic data.

The systematic creation of deformation sequence diagrams for key outcrops provides a tool for correlating deformation histories on the basis of common deformation patterns, key-deformation events or mineral parageneses that may be used as markers. Since different lithologies display systematic differences in their structural record, probably as a consequence of different mechanical behaviour, deformation sequence diagrams have been derived for the continental basement gneisses, the Piemonte unit metapelites and the metamafic rocks. Correlations across the different groups have subsequently been established in order to provide a deformation sequence diagram for the study area.

4.1. Continental basement gneisses

The gneisses belonging to the continental basement slices are generally characterized by a pervasive planar fabric containing a strong WNW–ESE trending mineral stretching lineation (Fig. 4a). This fabric is never found to be axial planar to folds. Mica fish (Fig. 4b) and aggregates of quartz grains displaying a strong lattice preferred orientation are observed in thin section. Furthermore, asymmetric boudinage of pre-existing epidote + chlorite + (relict) rutile + garnet + titanite beds is commonly observed. Such features suggest that the fabric formed as a result of non-coaxial deformation. Relicts of an earlier differentiated fabric containing phengite [$\mathrm{Si} = 3.36$ atoms per formula unit (a.p.f.u.)], rutile and rare garnet are occasionally preserved in microlithons bounded by shear planes (Fig. 4c), hinting at an earlier history in eclogite facies conditions.

In micaschist from the Tour Ponton unit, garnet porphyroclasts are wrapped around by the mylonitic foliation and chl + ab + qtz are observed to crystallize in the pressure shadows. The presence of chlorite, albite, epidote and white mica of muscovitic composition ($\mathrm{Si} = 3.01–3.15$ a.p.f.u.; Table 3) defining the foliation planes in orthogneisses indicates that shearing took place under greenschist facies conditions. C-type shear bands (Passchier and Trouw, 1998) are mainly preserved at the contacts between the Austroalpine slices and the Piemonte units and are oriented parallel to them. C planes commonly dip towards the NE at medium to high

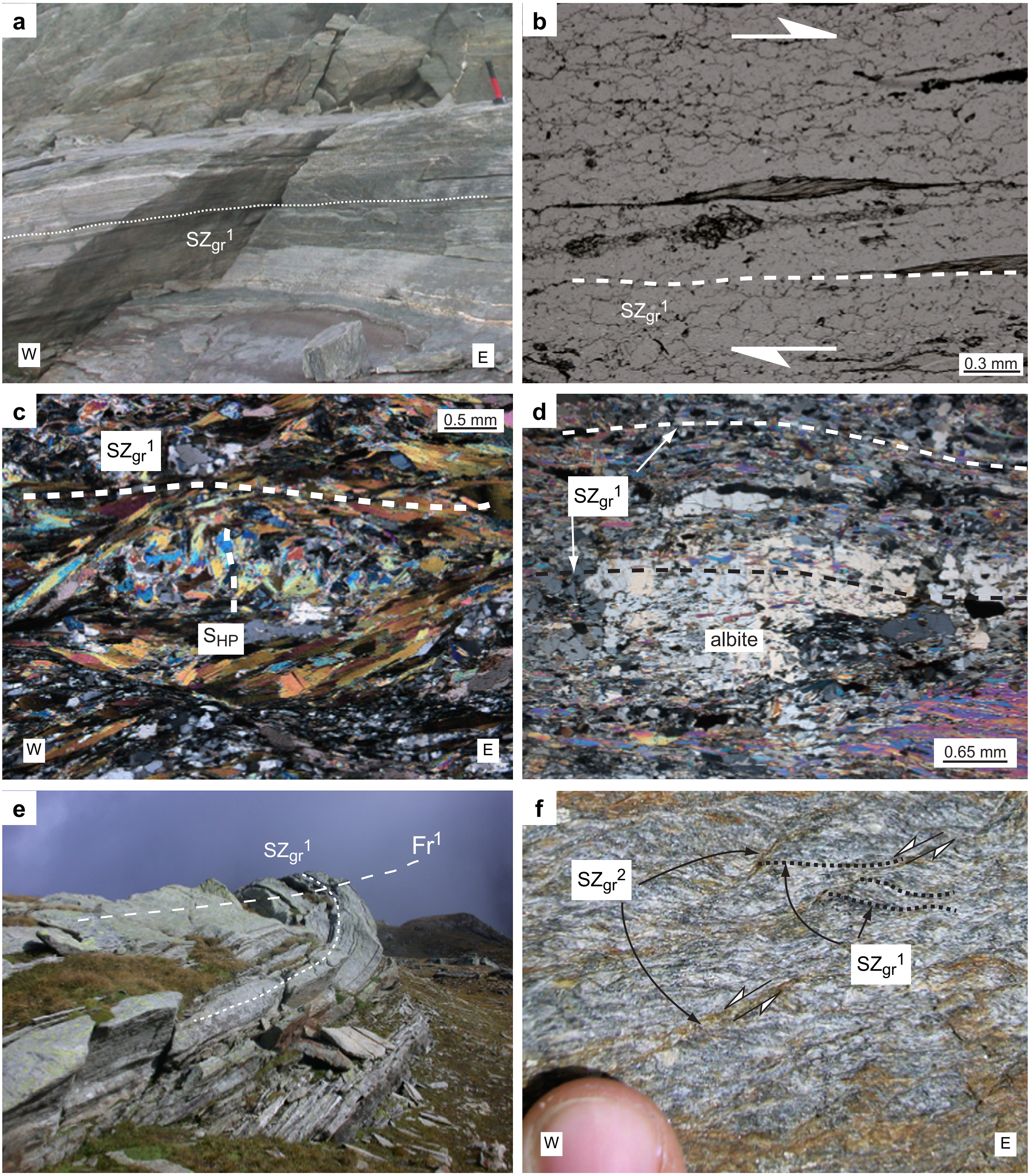


Fig. 4. Structural elements of the continental basement units of the Urtier Valley. The Tour Ponton unit (a, b, c and d), near the contacts with the eclogitic Piemonte unit, is characterized by a pervasive fabric (SZ^1_{gr}) with a marked stretching lineation and mica fish (b). Traces of an older high pressure fabric defined by phengite and rutile (S_{HP}) are preserved in microlithons (c). The shear fabric is statically overgrown by albite porphyroblasts (d). The shear fabric is also affected by upright folding (see Fig. 5) and by two generations of recumbent folds (Fr^1 in Fig. 4e and Fr^2 in Fig. 5). Late west-dipping shear planes (SZ^2_{gr}) accommodate top-to-the-west shearing (f).

angles (Fig. 6), although later folding (see below) has also resulted in SW dipping shear planes at some localities.

The overprinting relationships between the shear fabric and the pre-existing foliation can be portrayed, together with the information on metamorphic conditions, in the following deformation sequence diagram:

$$S_{HP}, SZ^1_{gr}$$

where S refers to a fabric whose origin cannot be associated either to folding or shearing on the basis of our observations, while SZ indicates a mylonitic fabric. The subscript refers to the pressure–temperature conditions of deformation, with HP and gr indicating high pressure and greenschist facies conditions, respectively. The superscript is used to distinguish this early SZ_{gr} episode from a later one (see below).

Microstructural observations (Fig. 4d) reveal that the shear fabric SZ^1_{gr} is overgrown statically by albite porphyroblasts in the common deformation sequence:

$$SZ^1_{gr}, \Delta_{gr}$$

with Δ indicating that the growth event occurred under static conditions.

In key outcrops, the shear fabric is folded around tight upright folds with E–W trending axes and no associated axial planar foliation (Fig. 5), giving rise to the commonly observed deformation sequence:

$$S_{HP}, SZ^1_{gr}, Fu$$

where Fu stands for the upright folding event.

These upright folds are then affected by two kinds of recumbent folds with ENE–WSW trending fold axes (Figs. 4e and 5), which can be distinguished on the basis of style and orientation. Recumbent folds characterized by close fold hinges and north-dipping axial planes (Fr^1) are found throughout the study area (Fig. 4e), whilst recumbent folds with open hinges and shallow south-dipping axial planes (Fr^2, Fig. 5) are limited to a W/NW–E/SE-trending band found in the central-southern part of the study area (Fig. 2). Commonly observed deformation sequences are:

$$SZ^1_{gr}, Fu, Fr^1$$

$$SZ^1_{gr}, Fu, Fr^2$$

where Fr^1 and Fr^2 stand for the two generations of recumbent folds. No overprinting relationship between the two different fold generations was found in outcrop, possibly as a consequence of the limited occurrence of Fr^2 only in a narrow corridor in the central-southern part of the study area (Fig. 2). The presence of both kinds of recumbent folds in neighbouring outcrops in the northern part of the Acque Rosse unit allows to rule out the possibility that they were derived from a single fold generation that underwent rotation locally. The lack of observed overprinting relationships between the two fold styles, however, does not allow to establish a relative chronology and the possibility that they formed contemporaneously cannot be ruled out. The ambiguous timing relationship between Fr^1 and Fr^2 can be expressed in a deformation sequence diagram by writing the two structures in column, with arrows pointing both ways to indicate that Fr^1 could either be older, or younger or of the same age as Fr^2 (Table 2). This approach allows to take into account the ambiguities involved in establishing a deformation sequence when some overprinting relationships are missing, either because they simply have not been observed for lack of appropriate outcrops or because the two structures formed coevally (Potts and Reddy, 1999).

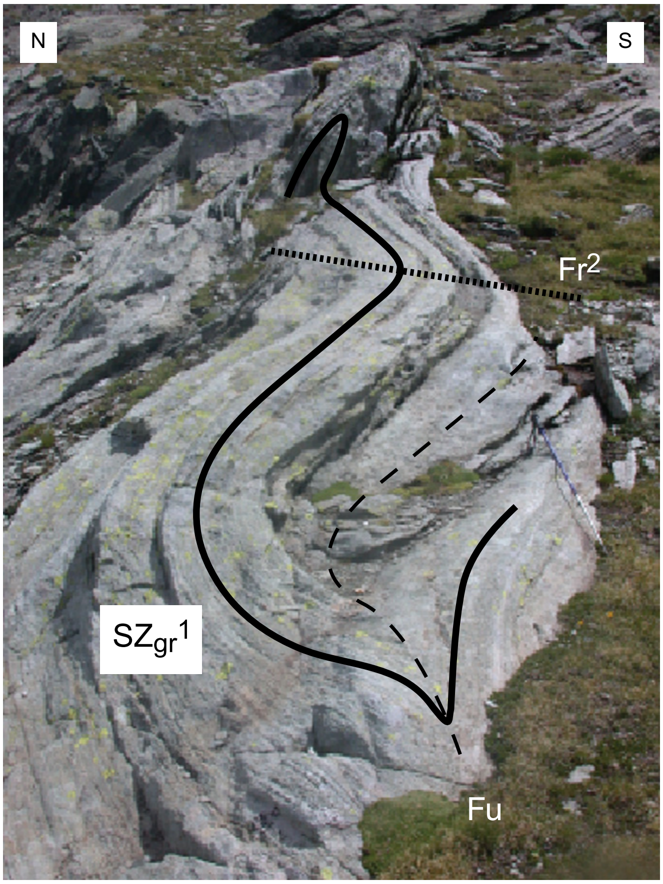


Fig. 5. Continental basement rocks of the Acque Rosse unit containing a shear fabric (SZ^1_{gr}) affected by upright (Fu) and recumbent (Fr^2) folding.

NW-dipping shear planes that accommodated top-to-the-west shearing are commonly observed to dissect and displace all older fabrics and mesoscopic folds (Fig. 4f). Individual shear planes tend to be several centimetres in length and the spacing between them is normally in the order of a few centimetres (Fig. 4f). Chlorite, white mica, quartz and albite define these shear planes, suggesting greenschist facies conditions for their formation. Outcrops containing these late shear planes are normally characterized by the following deformation sequences:

$$SZ^1_{gr}, Fu, SZ^2_{gr}$$

$$SZ^1_{gr}, Fr^1, SZ^2_{gr}$$

Later faults are the last fabric element that can be found in the study area.

Table 1
Representative analyses of mineral compositions from the white micas in Urtier Valley lithologies

Fabric sample # lithology unit	S_{HP} MB0517 micaschist EPU	S_{HP} MB0556 micaschist EPU	S_{HP} ALP0434 gneiss Tour Ponton	SZ^1_{gr} ALP0434 gneiss Tour Ponton	SZ^1_{gr} MB0520 gneiss Tour Ponton	SZ^1_{gr} MB0520 gneiss Tour Ponton	Fu MB0556 micaschist EPU	Fu ALP0442 micaschist BPU
SiO_2	51.63	51.32	50.80	45.98	48.54	47.59	47.73	48.47
TiO_2	0.17	0.10	0.20	0.15	0.16	0.09	0.27	0.31
Al_2O_3	27.42	29.81	27.63	37.23	32.50	33.71	34.86	32.46
FeO	2.23	3.01	3.84	1.05	2.13	2.25	1.30	2.53
MnO	0.04	0.00	0.00	0.01	0.03	0.02	0.14	0.02
MgO	3.13	3.11	3.57	1.45	1.54	1.29	1.75	1.51
CaO	0.01	0.01	0.00	0.01	0.03	0.02	0.01	0.00
Na_2O	0.76	0.33	0.03	0.62	0.45	0.60	0.89	0.69
K_2O	10.29	10.34	10.36	9.37	10.04	10.06	8.65	9.74
Total	95.68	95.85	96.43	95.86	95.40	95.63	95.60	95.74
Si	3.42	3.32	3.36	3.01	3.22	3.15	3.13	3.20
Ti	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.02
Al	2.14	2.27	2.15	2.88	2.54	2.63	2.69	2.53
Fe^{2+}	0.12	0.16	0.21	0.06	0.12	0.12	0.07	0.14
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Mg	0.31	0.30	0.35	0.14	0.15	0.13	0.17	0.15
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.10	0.04	0.00	0.08	0.06	0.08	0.11	0.09
K	0.87	0.85	0.87	0.78	0.85	0.85	0.72	0.82
Sum cations	6.97	6.96	6.96	6.96	6.94	6.97	6.92	6.95

ALP0442, MB0517 and MB0556 are micaschists from the eclogitic Piemonte unit, while MB0520 and ALP0434 is a gneiss from the Tour Ponton unit. Mineral compositions were determined with an electron microprobe CAMECA SX100 at the Research School of Earth Sciences, Australian National University, Canberra. Operating voltages of 15 kV and currents of 20 nA have been chosen for the analysis. The spot size of 5 μm was used in order to avoid alkali migration and K and Na were fixed as the first two elements to be measured. Analyses were normalized to 11 oxygens.

The deformation sequence diagram for the continental basement units can then be constructed by correlating the sequence diagrams produced for the key outcrops. Correlations across different outcrops can be established using key-deformation events that are widely observed in the continental basement units (in our case the two shearing episodes). The other deformation episodes can be placed in the deformation sequence diagram based on overprinting relationships with the two SZ_{gr} fabrics and with one another (Table 2).

4.2. Piemonte unit micaschists

The micaschists of the Piemonte units, which cover more than half of the study area (Fig. 2), are characterized by a pervasive fabric defined by muscovite (Si = 3.05–3.20 a.p.f.u.; Table 1), chlorite, quartz, calcite and albite (Fig. 7c). This fabric is axial planar to tight upright folds with E–W trending axes and transposes older fabrics (Fig. 7c). The fabric that is most commonly found in the microlithons is defined by

Table 2
Deformation sequence diagram for the continental basement units

S_{HP}	$SZ_{gr}{}^1$							DEFORMATION SEQUENCES TYPICALLY OBSERVED IN THE CONTINENTAL BASEMENT UNITS
	$SZ_{gr}{}^1$	Δ_{gr}						
S_{HP}	$SZ_{gr}{}^1$		Fu					
	$SZ_{gr}{}^1$		Fu	Fr^1				
	$SZ_{gr}{}^1$		Fu		Fr^2	$SZ_{gr}{}^2$		
S_{HP}	$SZ_{gr}{}^1$					$SZ_{gr}{}^2$	flt	
	$SZ_{gr}{}^1$		Fu			$SZ_{gr}{}^2$		
	$SZ_{gr}{}^1$			Fr^1		$SZ_{gr}{}^2$	flt	
S_{HP}	$SZ_{gr}{}^1$	Δ_{gr}	Fu	← Fr^1 → ← Fr^2 →		$SZ_{gr}{}^2$	flt	combined deformation sequence diagram

The representation ‘flt’ is used to indicate the late episode of brittle folding.

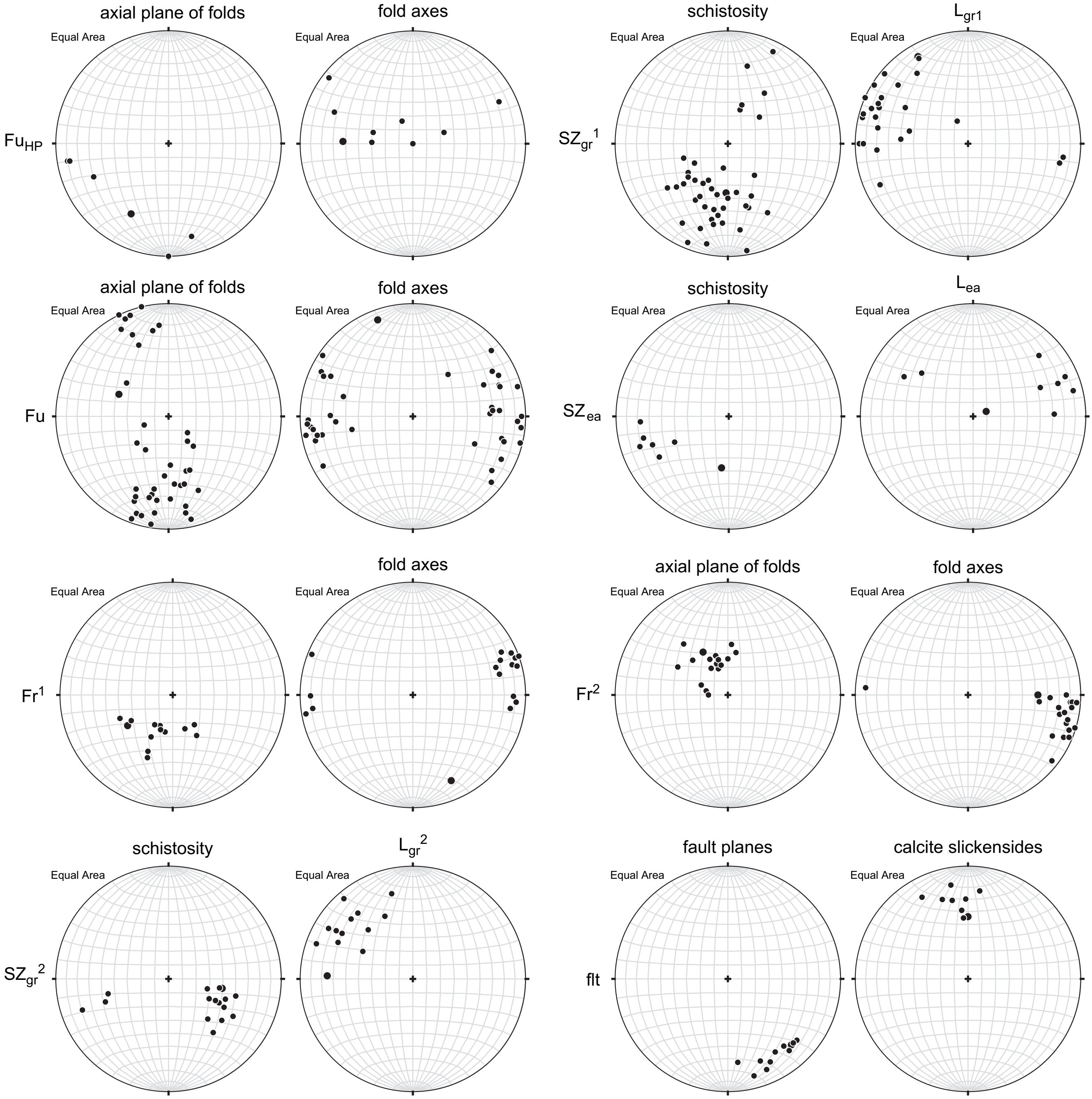


Fig. 6. Lower hemisphere Schmidt projection plots of structural elements in the study area. The orientation of axial planes for each fold generation has been plotted also for the folding events that did not develop an axial planar foliation.

phengitic micas with decussate structures, garnet and chloritoid, and is oriented at an angle with the axial planar foliation. This commonly observed overprinting relationship can be portrayed in a deformation sequence diagram of the kind:

S_{HP}, Fu_{gr}

Hints of an early history in eclogite facies conditions are also given by rare isoclinal folds with almost vertical axial planes and E-plunging steeply dipping fold axes observed in the micaschists of the eclogitic Piemonte unit (Fig. 7a). In one case (Fig. 7a) these folds affect a foliation that is defined by rutile and phengitic mica (Si = 3.35–3.45 a.p.f.u.; Table 1). This foliation has undergone recrystallization, resulting in formation of decussate structures, indicating that high pressure conditions were present during and after folding. For this particular case, the deformation sequence diagram is:

$S_{HP}, F_{HP}, \Delta_{HP}$

The above deformation sequence indicates that an earlier foliation that formed under eclogite facies conditions was

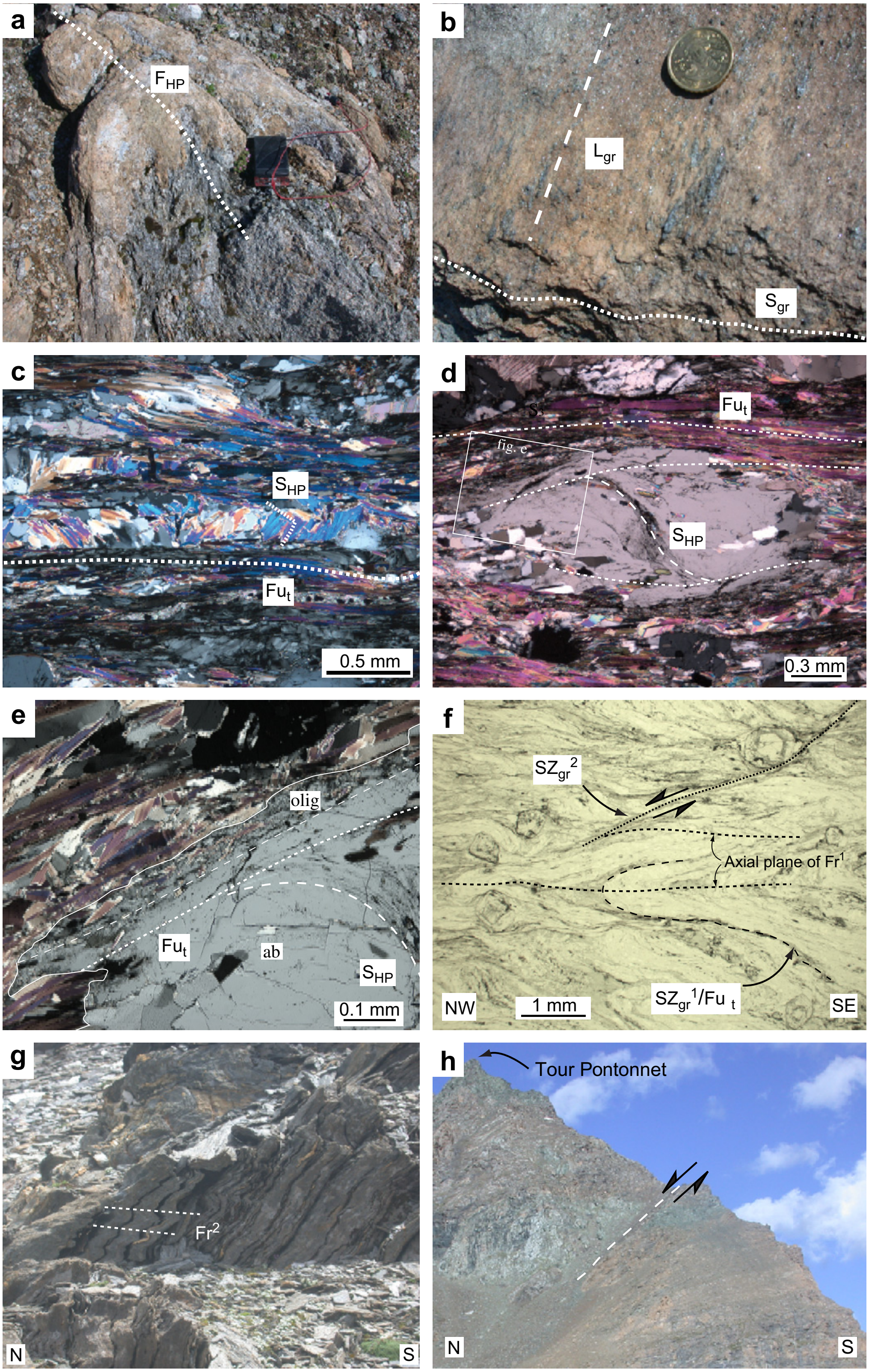


Fig. 7. Structural elements in the micaschists of the Piemonte units. Rare upright folds (F_{HP}) in the calcschists of the eclogitic Piemonte unit near the Miserino Lake, to the south of the Acque Rosse unit record the oldest stages of the deformation history (a); (b) a pervasive foliation that developed in greenschist facies conditions (S_{gr}), containing a marked mineral stretching lineation (L_{gr}) is sometimes observed; (c) relicts of a foliation that developed in high pressure conditions (S_{HP}) are often observed in microlithons between the planes defined by the axial planar foliation of the upright folds (Fu); (d) relict S_{HP} is also preserved in the cores of albite porphyroblasts and progressively deflected into parallelism with Fu; (e) fabric tightening, probably related to the last stages of Fu, was followed by the formation of oligoclase rims around albite, overgrowing the matrix foliation; (f) recumbent folds (Fr^1) affect an older composite foliation and are themselves displaced by west-dipping extensional shear planes (SZ^2_{gr}); (g) recumbent folds with south-dipping axial planes (Fr^2) are found in a narrow strip in the southern part of the field area; (h) north-dipping normal fault.

Table 3
Deformation sequence diagram for the Piemonte unit micaschists

S_{HP}				Fu_{gr}								DEFORMATION SEQUENCES TYPICALLY OBSERVED IN THE PIEMONTE UNIT MICASCHISTS
S_{HP}	F_{HP}	Δ_{HP}										
			S_{gr}	Fu_{gr}								
S_{HP}				Fu_{gr}	$\Delta_{gr/ea}$	Fu-t	Δ_{am}					
S_{HP}				Fu_{gr}				Fr_{gr}^1		SZ_{gr}^2	flt	
S_{HP}				Fu_{gr}					Fr^2	SZ_{gr}^2		
											flt	
S_{HP}	F_{HP}	Δ_{HP}	S_{gr}	Fu_{gr}	$\Delta_{gr/ea}$	Fu-t	Δ_{am}	← Fr_{gr}^1 → ← Fr^2 →		SZ_{gr}^2	flt	combined deformation sequence diagram

folded and then statically recrystallized under high pressure conditions.

More rarely, especially in the micaschist on the northern side of the Urtier Valley, the upright folds (Fu_{gr}) overprint a pervasive foliation defined by greenschist facies minerals and containing an E–W mineral stretching lineation marked by actinolitic amphibole (Fig. 7b). This overprinting relationship can be portrayed in the deformation sequence diagram:

S_{gr}, Fu_{gr}

As already stated above, a fabric that is axial planar to the upright folds is the most commonly observed structure at the outcrop scale in the metapelites. Microstructural observations reveal the presence of decussate structures in the microlithons between the foliation planes (Fig. 7c). Relict of the older foliation are also preserved in albite porphyroblasts characterized by an internal foliation oriented at a high angle to the matrix foliation and progressively curved into parallelism with it towards the margins of the crystals (Fig. 7d). A second phase of plagioclase growth resulted in the crystallization of oligoclase rims around the albite cores overgrowing the matrix foliation (Fig. 7e). The lower degree of obliteration of the older fabric inside the albite porphyroblasts may be related to an armouring effect that protected the internal foliation from the progressive fabric tightening observed in the matrix. This indicates that the albite porphyroblasts grew during the early stages of Fu_{gr}. Continuing deformation resulted in fabric tightening, followed by the formation of oligoclase (Fig. 7e). The above observations can be summarized in the following deformation sequence:

$S_{HP}, Fu_{gr}, \Delta_{gr/ea}, \text{Fu-t}, \Delta_{am}$

where Fu-t refers to the tightening of Fu structures and $\Delta_{gr/ea}$ and Δ_{am} refer to the two stages of plagioclase growth. Greenschist or epidote–amphibolite facies conditions for the formation of albite are suggested by its association with chlorite, epidote and white mica. Lower amphibolite facies conditions would have been characteristic of the formation of the oligoclase rims.

The upright folds are then affected by two styles of recumbent folds for which overprinting has never been observed, as already discussed for the continental basement gneisses (Fig. 7f, g). The rare presence of a weak axial planar foliation to Fr^1 folds defined by chlorite allows to postulate greenschist facies conditions for their formation. W/NW-dipping shear planes accommodating top-to-the-west shearing oriented at high angles to the older fabrics are found to displace all the structures described above (Fig. 7f). Chlorite, white mica, quartz and albite are commonly found along these shear planes, suggesting greenschist facies conditions for their formation. Therefore:

$S_{HP}, Fu_{gr}, Fr_{gr}^1, SZ_{gr}^2$

$S_{HP}, Fu_{gr}, Fr^2, SZ_{gr}^2$

are commonly observed deformation sequences.

N-dipping brittle faults that accommodated normal-sense movement represent the last structures that formed in the study area (Fig. 7h).

The deformation sequence diagrams determined for the individual outcrops can be combined in a sequence diagram for the micaschists of the Piemonte units, using the Fu_{gr} and SZ_{gr}^2 structures as main markers for the correlation (Table 3). It is important to notice that the lack of observed relationships between Δ_{am} and the episodes of recumbent folding leaves the relative timing of the two event unresolved. However, based on the observation that the study area underwent exhumation after the episode of upright folding, it is considered more likely that Δ_{am} preceded the episodes of recumbent folding, which probably took place in greenschist facies conditions, at lower temperature and (probably) lower pressures.

4.3. Metamafic rocks

The same method of structural analysis can be applied to the metamafic rocks. Metamafic rocks from the eclogitic Piemonte unit, blueschist Piemonte unit and continental basement units are described together, given that their deformation

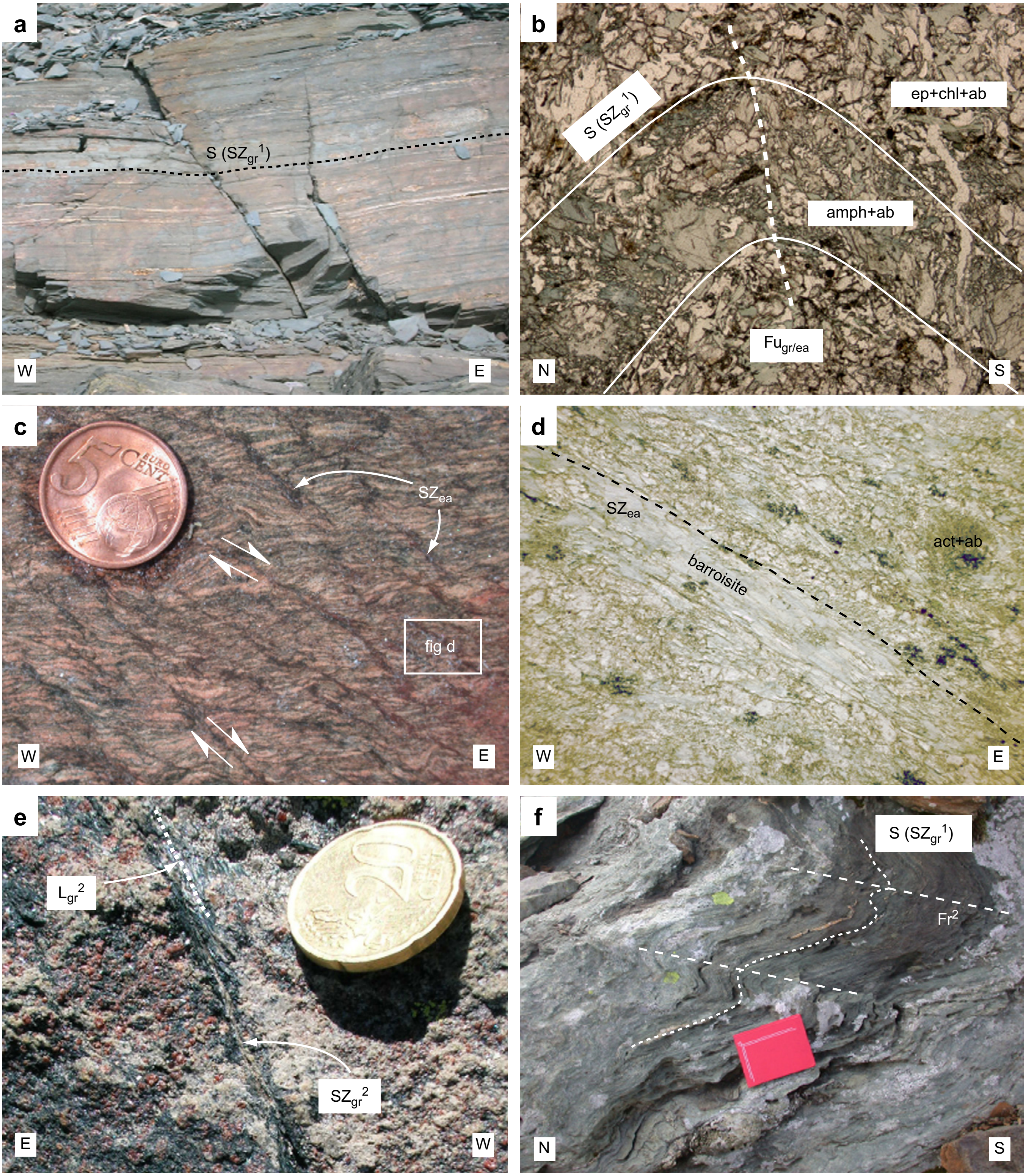


Fig. 8. Structural elements in the metamafic rocks of the Urtier Valley. A pervasive compositional layering (a) is statically overprinted by greenschist facies minerals and folded around upright folds (b); (c) east-dipping shear planes containing barroisitic amphibole (SZ_{ea}) and epidote transpose a pre-existing fabric. Microscope observations (d) reveal that the pre-existing fabric had been statically overprinted by the assemblage act + ab + chl + ep before the formation of the shear planes; (e) west-dipping shear planes (SZ_{gr}^{2}) containing a marked lineation defined by green amphibole (L_{gr}^{2}) dissect a former eclogite; later recumbent folds (Fr^{2}) are also observed (f).

histories could not be differentiated (see below). As already discussed, the only difference between the units is represented by the presence of relict eclogite facies mineral assemblages in the eclogitic Piemonte unit and continental basement units, while no traces of an early high pressure event in eclogite facies are preserved in the blueschist Piemonte unit.

The prasinites that lay at the bottom of the Urtier Valley are characterized by a millimetre-scale compositional layering with epidote-rich and green amphibole-rich layers (Fig. 8a). Microscope investigation reveals that greenschist facies minerals grew statically over a pre-existing differentiated fabric (Fig. 8b). Upright folding followed this episode of static growth (Fig. 8b). Barroisitic amphibole, indicative of metamorphic conditions characteristic of epidote–amphibolite facies (see below and Beltrando et al., 2007), grows at the expense of the green actinolitic amphibole in the hinge zones of the upright folds (Fig. 8b). These observations result in the commonly observed deformation sequence:

$$\mathrm{S}, \Delta_{\mathrm{gr}}, \mathrm{Fu}_{\mathrm{ea}}$$

with S indicating that a differentiated fabric, whose origin could not be related either to shearing or to folding, was present prior to the episode of static mineral growth in greenschist facies conditions.

Rare E/NE-dipping shear planes that accommodated top-to-the-east shearing (Fig. 8c, d) are observed to overprint the greenschist facies assemblage made of actinolitic amphibole + epidote + chlorite + albite + titanite (Fig. 8d). Barroisitic amphibole, epidote and titanite defining a strong stretching lineation crystallize along the E/NE-dipping shear planes (Fig. 8d). This sequence of events can be expressed by the following deformation sequence diagram:

$$\mathrm{S}, \Delta_{\mathrm{gr}}, \mathrm{SZ}_{\mathrm{ea}}$$

with the subscript "ea" referring to the epidote–amphibolite facies metamorphic conditions at which the shear fabric formed.

A similar sequence of events is observed in a metamorphic Fe–Ti gabbro belonging to the Acque Rosse unit. In this rock, the assemblage garnet + omphacite + rutile, indicative of eclogite facies conditions, is overprinted by actinolitic amphibole + epidote + chlorite + albite + titanite, before the formation of east-dipping shear planes containing barroisitic amphibole, epidote and titanite. The barroisite-bearing shear planes are then themselves displaced by the common W/NW-dipping shear planes accommodating top-to-the-west shearing. Green actinolitic amphibole and traces of epidote (Fig. 8e) defining a marked E–W trending stretching lineation are found along these late shear planes. Therefore, the following sequence diagram:

$$\Delta_{\mathrm{HP}}, \Delta_{\mathrm{gr}}, \mathrm{SZ}_{\mathrm{ea}}, \mathrm{SZ}_{\mathrm{gr}}^{2}$$

can be constructed for this particular outcrop.

Two episodes of recumbent folding are observed to affect the upright folds in the metamafic rocks of the Piemonte unit (Fig. 8f). However, due to the scarcity of metamafic rocks in the relatively narrow E/NE–W/SW-trending band where the open recumbent folds with south-dipping axial plane are found, no overprinting has been observed between them. As for all other lithologies in the Urtier Valley, W/NW-dipping shear planes accommodating top-to-the-west shearing offset all previous structures. Therefore, the deformation sequence diagrams:

$$\mathrm{S}, \Delta_{\mathrm{gr}}, \mathrm{Fu}_{\mathrm{ea}}, \mathrm{Fr}^{1}, \mathrm{SZ}_{\mathrm{gr}}^{2}$$

$$\mathrm{S}, \Delta_{\mathrm{gr}}, \mathrm{Fu}_{\mathrm{ea}}, \mathrm{Fr}^{2}, \mathrm{SZ}_{\mathrm{gr}}^{2}$$

can be constructed for selected outcrops.

Late N-dipping brittle faults are observed at the outcrop scale on the northern slopes of the Urtier Valley.

The rarity of the east-dipping, barroisite-bearing shear planes in the metamafic rocks did not allow to observe overprinting relationships with the folding episodes. Therefore, their timing with respect to the folding episodes could be postulated exclusively on the basis of mineral parageneses. The presence of barroisitic amphibole particularly in the hinge zones of $\mathrm{Fu}_{\mathrm{ea}}$ and in the $\mathrm{SZ}_{\mathrm{ea}}$ shear planes is taken as an indication that the two structures formed in close sequence or simultaneously, prior to Fr^{1}. The formation of $\mathrm{SZ}_{\mathrm{ea}}$ may be related to shearing on a fold limb due to flexural slip associated with Fu. Alternatively, its origin could be related to an episode of deformation characterized by non-coaxial flow, such as the activity of a thrust or an extensional shear zone. This latter hypothesis may be supported by the finding of east-directed thrusting overprinting the upright folds just to the east of our

Table 4
Deformation sequence diagram for the Piemonte unit metamafic rocks

	S	Δ_{gr}	Fu_{ea}					DEFORMATION SEQUENCES TYPICALLY OBSERVED IN THE PIEMONTE UNIT METAMAFIC ROCKS
	S	Δ_{gr}				SZ_{gr}^{2}		
Δ_{HP}		Δ_{gr}	SZ_{ea}			SZ_{gr}^{2}		
	S	Δ_{gr}	Fuea	Fr^{1}		SZ_{gr}^{2}		
	S	Δ_{gr}	Fuea		Fr^{2}		flt	
Δ_{HP}	S	Δ_{gr}	$\leftarrow Fu_{ea} \rightarrow$ $\leftarrow SZ_{ea} \rightarrow$	$\leftarrow Fr^{1} \rightarrow$ $\leftarrow Fr^{2} \rightarrow$		SZ_{gr}^{2}	flt	combined deformation sequence diagram

study area (Vearncombe, 1985). However, due to the limited occurrence of SZ_{ea} neither of the two hypothesis can be proved/disproved.

The episode of static growth of greenschist facies minerals and the SZ^2_{gr} events, which are the most commonly observed deformation/metamorphic events in the metamafics of the Urtier Valley, have been used as marker events to produce the deformation sequence diagram in Table 4.

4.4. Correlations

Once deformation sequences have been determined for individual lithologies and the ambiguities related to missing relationships have been adequately portrayed (Potts and Reddy, 1999), correlations between different lithologies can be established.

As illustrated above, in the Urtier Valley different lithologies responded differently to the deformation history of the study area and slight differences in the structural record are observed. Notably, the dominant fabrics at the outcrop scale differ from lithology to lithology.

A shear fabric oriented parallel to the contacts between the different units is the most pervasive fabric in the continental basement units (SZ^1_{gr}, Fig. 4a–c). This fabric is folded around upright folds with E–W trending fold axes (Fu, Fig. 5). This folding episode results in the formation of a pervasive axial planar foliation in the micaschists of the Piemonte units (Fig. 7c, d), which is the predominant fabric observed at the outcrop scale for this lithology. Traces of a greenschist facies fabric characterized by a strong mineral stretching lineation (Fig. 7b), possibly analogous to the one found in the continental basement units, are locally preserved in the micaschists. The metamafic rocks, instead, are characterized by a pervasive fabric oriented parallel to the lithological contacts and folded around the upright folds (Fig. 8a, b). Complete static overprint of this fabric under greenschist facies conditions did not allow to assess whether it was originally equivalent to the shear fabric found in the continental basement slices.

Correlations among the deformation sequence diagrams obtained for the three main lithologies of the area can be performed using widespread structures/fabrics that are found in all lithologies. In the Urtier Valley, such markers include:

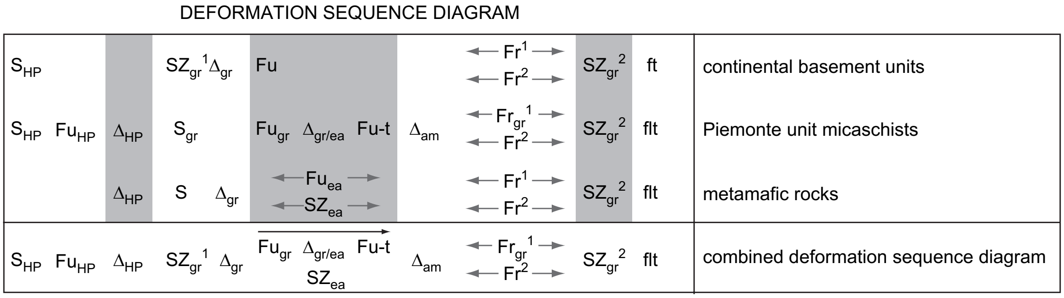
(a) an early foliation that formed under high pressure conditions;
(b) upright folding under greenschist to epidote–amphibolite facies conditions; and
(c) late W/NW-dipping shear planes that display a consistent top-to-the-west sense of shear throughout the entire area.

Combining the deformation sequence diagrams illustrated in Tables 2, 3 and 4 results in the deformation sequence diagram for the entire area illustrated in Table 5. It is immediately apparent that while in most circumstances correlations are unambiguous, since specific deformation events produced a similar structural/metamorphic record in all lithologies, ambiguities may arise when: (1) structural/metamorphic features were developed exclusively in some lithologies; and (2) structural/metamorphic features have been partly or completely obliterated in some lithologies.

The pre-upright folding history provides an example of this latter case: the pervasive fabric in the metamafic rocks that is completely obliterated in greenschist facies conditions (S) and the rarely preserved greenschist facies foliation that contains a strong mineral stretching lineation in metapelites (S_{gr}) are considered likely to be the equivalent of the shear fabric that is predominant in the continental basement gneisses (SZ_{gr}). This correlation, which for the micaschists–continental gneiss pair is based on deformation styles, orientation of structures and metamorphic grades, is somewhat more speculative for the metamafic rocks–continental gneiss pair, due to the pervasive overprint of the differentiated fabric in the metamafic rocks. It cannot be excluded that the differentiated fabric observed in the metamafic rocks formed prior to SZ^1_{gr}. The advantage of representing the data with the ''deformation sequence diagram'' of Table 5 is that these ambiguities, which are routinely encountered by structural geologists, are clearly represented and their impact on the final interpretation can be independently evaluated by the reader. This way of presenting data is comparable to the ''deformation network'' approach (Occhipinti and Reddy, 2004).

Therefore, deformation sequence diagrams provide a transparent method for correlating deformation histories determined from different outcrops and lithologies. The procedure used for their construction is routinely adopted when undertaking

Table 5
Deformation sequence diagram correlating the deformation histories obtained from the continental basement units and the Piemonte unit micaschists and metamafic rocks



DEFORMATION SEQUENCE DIAGRAM

S_{HP}			SZ_{gr}^{1}	Δ_{gr}	Fu				← Fr^1 → ← Fr^2 →	SZ_{gr}^{2}	ft	continental basement units
S_{HP}	Fu_{HP}	Δ_{HP}	S_{gr}		Fu_{gr}	$\Delta_{gr/ea}$	Fu-t	Δ_{am}	← Fr_{gr}^{1} → ← Fr^2 →	SZ_{gr}^{2}	flt	Piemonte unit micaschists
		Δ_{HP}	S	Δ_{gr}	← Fu_{ea} → ← SZ_{ea} →				← Fr^1 → ← Fr^2 →	SZ_{gr}^{2}	flt	metamafic rocks
S_{HP}	Fu_{HP}	Δ_{HP}	SZ_{gr}^{1}	Δ_{gr}	Fu_{gr} SZ_{ea}	$\Delta_{gr/ea}$	Fu-t	Δ_{am}	← Fr_{gr}^{1} → ← Fr^2 →	SZ_{gr}^{2}	flt	combined deformation sequence diagram

structural mapping. Often, however, the thus determined deformation sequence is then converted in a D_1, D_2, etc., sequence upon publication. This approach locks the observations into a progressive numbering scheme and prevents readers to independently assess the quality of the structural analyses and the soundness of the correlations.

Deformation sequence diagrams present several advantages over the commonly used technique of progressive numbering of deformation events (D_1, D_2, etc.) in that: (1) they are easily modified in the case of new information becoming available, without disruption of the previously determined sequence; (2) they facilitate correlations with other areas; and (3) they are more descriptive than a D_1, D_2, etc., scheme and can be extended to include observations of metamorphism. Furthermore, the deformation sequence diagram method is more transparent in that it avoids the common practice of grouping shearing and folding events under a common deformation episode. Although contemporaneous shearing and folding can certainly occur during the same deformation event, overprinting relationships are often observed but do not find expression in the D_1, D_2, etc., sequence. This may conceal complexities in the deformation history.

4.5. Large scale structures

The large scale structure of the study area is dominated by upright folds with E–W fold axes associated with Fu (Fig. 9). In particular, these folds affect the contact between the eclogitic and blueschist Piemonte units and are responsible for the repetition of the eclogitic Piemonte unit on both sides of the Urtier Valley (Figs. 2 and 9) and for the presence of a thin strip of micaschists belonging to the eclogitic Piemonte unit in the middle of the valley. Also, the southern and northern branches of the Acque Rosse unit are located on the two limbs of an Fu antiform with serpentinites in the core (Fig. 9). The Fu upright folds represent the oldest structures that can be unambiguously correlated across the various tectonometamorphic units found in the Urtier Valley. Therefore, the juxtaposition of the eclogitic and blueschist Piemonte units must pre-date Fu but post-date the formation of S_{HP}, for which different pressures can be estimated in the two units (see discussion below).

The presence of two thin slices of continental gneisses belonging to the Acque Rosse unit inside the eclogitic Piemonte unit in the Acque Rosse Valley (Fig. 2) may indicate that the two units underwent a common deformation history even prior to SZ^1_{gr}.

The recumbent folds with axial planes dipping shallowly to the north also exert a major control on the geometry of the study area and are responsible for the observed dispersion of the axial planes of the Fu folds along a north–south girdle (Fig. 6). The most spectacular example of Fr^1 is represented by the synform that contains the Tour Ponton slice in its core (Fig. 9). This fold represents the eastern continuation of the "Ruitor megafold" (Bucher et al., 2004). Interference between this fold and Fu folds is responsible for the presence of calcschists and prasinites belonging to the blueschist Piemonte unit interleaved with the Faisceau de Cogne in the northwestern part of the study area (Figs. 2 and 9).

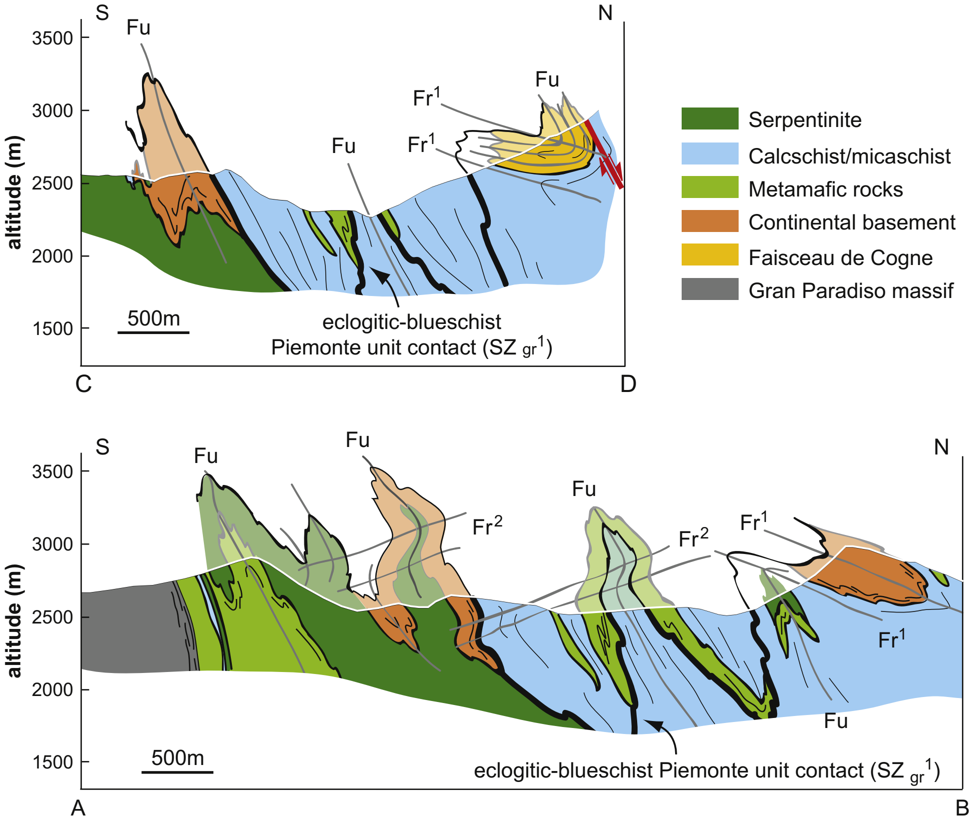


Fig. 9. Schematic cross sections of the upper Urtier Valley. Thicker line indicates the contact between eclogite and blueschist facies Piemonte rocks.

The recumbent folds with axial planes shallowly dipping to the north are exclusively found in an ENE–WSW trending band extending from the Col de Peradza‘ to the Acque Rosse Valley (Fig. 2). Spectacular examples of such folds refolding Fu are observed in the serpentinitic ridge east of Miserino Lake and in the blueschist Piemonte unit near the contact with the Acque Rosse unit (Fig. 10).

A steep, north-dipping normal fault can be followed for several kilometres along the northern part of the study area, on the northern slopes of the Urtier Valley (Figs. 2, 3a, b and 9). Drag folds, calcite slickenfibres and outcrop scale subsidiary faults all indicate that this major structure accommodated normal-sense movement. The fault is responsible for the north-eastern termination of the Faisceau de Cogne. Its presence also accounts for the abrupt lithological change in the southern slopes of the Tour Pontonnet and Punta Tersiva from a calcschist dominated sequence in the footwall to a calcschist + serpentinite + prasinite association in the hangingwall (Fig. 7h). This change had been erroneously related by Butler and Freeman (1996) to the presence of the Entrelor shear zone.

4.6. Correlation of structures and pressure–temperature evolution

The pressure–temperature (PT) evolution of the Piemonte units in the Urtier Valley has been described in detail in Beltrando et al. (2007) and is characterized by two pressure cycles (Fig. 11). A high pressure event in the eclogitic Piemonte unit and continental basement slices at ca. 1.5 GPa was followed by exhumation to $P = 0.20–0.35$ GPa, as indicated by the overprint of HP minerals by a symplectite of actinolitic amphibole and albite associated with chlorite and epidote. A second

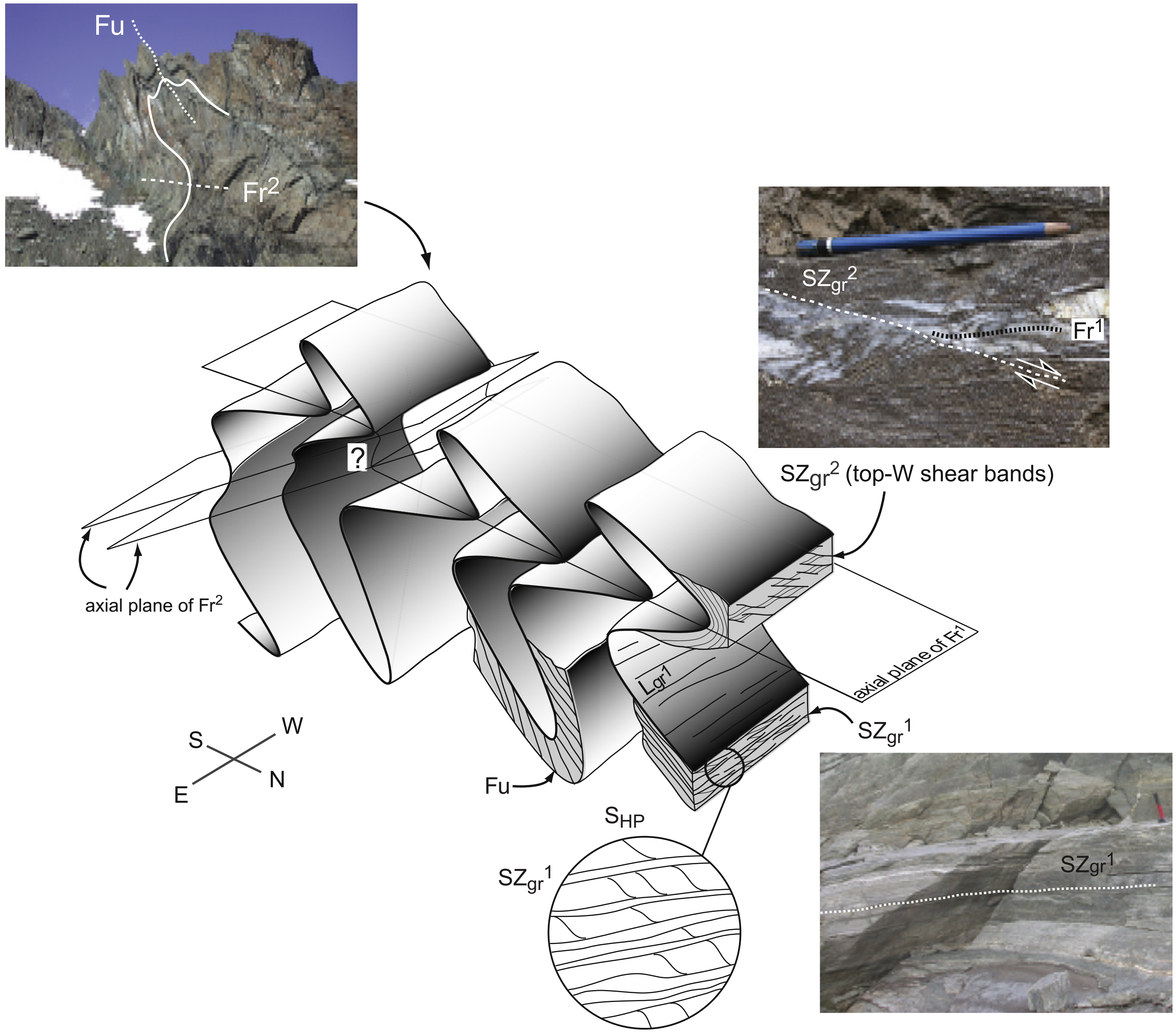


Fig. 10. 3D diagram illustrating the idealized structure of the study area and the overprinting relationships between all deformation events. Question mark refers to the unknown relationship between Fr^1 and Fr^2.

burial event brought the studied rocks to $P = 0.65–0.80$ GPa, as indicated by the crystallization of amphibole of barroisitic composition at the expenses of the actinolite, before final exhumation to the surface took place (Fig. 11).

Microstructural and petrographic observations allow to match the deformation sequence obtained in the present study with the PT history outlined in Beltrando et al. (2007). Eclogite facies conditions were characteristic of the early deformation history of the eclogitic Piemonte unit and continental basement units, as indicated by the presence of phengite and rutile along relict S_{HP} fabrics. Pre-SZ^1_{gr} fabrics in the blueschist Piemonte unit, instead, lack evidence of metamorphism in eclogite facies conditions. The presence of chloritoid, garnet, titanite and white mica in relict S_{HP} in micaschists suggests PT conditions in the blueschist facies field.

Lower pressure conditions are recorded by fabrics associated with the younger deformation events (Fig. 11). The presence of muscovite, epidote, chlorite, albite, actinolitic amphibole and titanite along SZ^1_{gr} indicates greenschist facies conditions during shearing. The sharp decrease in Si content of micas observed from S_{HP} to SZ^1_{gr} in orthogneisses of the continental basement slices also indicates a decrease in pressure between the two deformation events (see sample ALP0434 in Table 1, Fig. 11; Massonne and Schreyer, 1987). Metamorphic conditions evolved from greenschist to epidote–amphibolite facies during Fu, as indicated by the presence of barroisitic amphibole replacing actinolite in the hinge zones of Fu.

Rare chlorite in the weakly developed axial planar foliation to the recumbent folds and in the SZ^2_{gr} shear planes indicates a return to greenschist facies conditions (Fig. 11). The transition from epidote–amphibolite to greenschist facies may have been characterized by a short-lived residence in amphibolite facies conditions, as suggested by the presence of oligoclase rims around albite porphyroclasts.

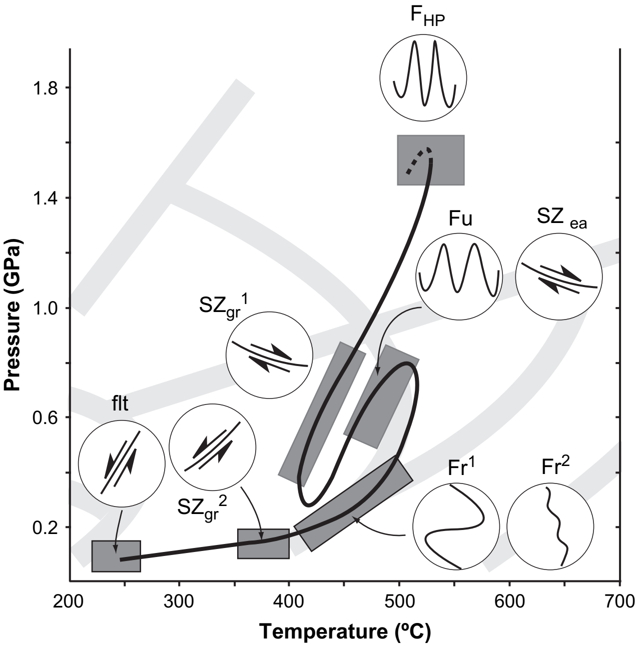


Fig. 11. Position of the deformation events in the Pressure–Temperature history recorded by the mafic rocks in the study area (from Beltrando et al., 2007). Burial events appear to be related to episodes of shortening deformation, whilst episodes of extensional deformation culminate in exhumation of the studied rocks.

Therefore, the multi-stage deformation history observed in the Urtier Valley is associated with a complex pressure–temperature evolution: a high pressure metamorphic event, which reached eclogitic conditions in the eclogite Piemonte unit and continental basement units and blueschist conditions in the blueschist Piemonte unit, was followed by exhumation to greenschist facies conditions (SZ^1_{gr}), before renewed burial to epidote–amphibolite conditions (Fu). The latter event was followed by renewed greenschist facies metamorphism (recumbent folds and SZ^2_{gr}).

5. Discussion

5.1. Interpretation of the deformation history

Several generations of structures have been recognized in the study area, which is part of the Piemonte units of the Western Alps. A chronological sequence has been established on the basis of overprinting relationships between fabrics and mineral assemblages. As a result, a deformation sequence has been defined (Table 5), containing deformation events predominantly characterized either by folding (Fu and the recumbent folding) or by pervasive shearing (SZ^1_{gr} and SZ^2_{gr}). Apart from some very limited occurrences of pre-SZ^1_{gr} folds, we have been unable to correlate pre-SZ^1_{gr} fabrics to specific structures. Therefore, the S_{HP} fabrics may have formed in response to folding or shearing, or a combination of both.

In the following sections we will demonstrate that the deformation and metamorphic history described in this study was characterized by two deformation mode switches from shortening to extension. Integration of our results with published data will also allow to assess the extent and significance of such deformation mode switches in the context of the evolution of the Western Alps.

5.1.1. First deformation mode switch (D_{HP}, SZ^1_{gr})

The contact between the eclogitic and blueschist Piemonte units can be followed for the entire length of the Western Alps (Fig. 1) and has been the subject of extensive studies, especially in the northern side of the Aosta Valley. Here, Bearth (1967) first drew the distinction between the blueschist facies Combin zone and the eclogitic Zermatt-Saas zone on lithological grounds. Metamorphic, structural and geochronological studies have generally been interpreted to indicate that the contact had been active as an extensional shear zone at 45–36 Ma (Ballèvre and Merle, 1993; Cartwright and Barnicoat, 2002; Reddy et al., 1999, 2003), although the complex kinematics reported from the area hint to a more complicated history (see discussion below; Reddy et al., 1999; Pleuger et al., 2007). In the Urtier Valley, SZ^1_{gr} shear fabrics are found at the contacts between eclogitic Piemonte unit, blueschist Piemonte unit, Austroalpine slices and Faisceau de Cogne. Such fabrics are especially well preserved in the slices of continental basement of Austroalpine affinity, where they are oriented parallel to the contacts with the Piemonte units. In the prasinitic layers of the blueschist Piemonte unit, they are often preserved as ‘ghosts’ of highly sheared minerals that were subsequently statically overprinted by greenschist facies mineral assemblages. The presence of SZ^1_{gr} shear fabrics in all units and particularly along their contacts suggests that the juxtaposition of eclogitic Piemonte unit, blueschist Piemonte unit, Austroalpine slices and Faisceau de Cogne occurred as a result of non-coaxial deformation during SZ^1_{gr}. Purely geometrical considerations would not allow to determine whether SZ^1_{gr} accommodated thrusting or extension, due to later pervasive deformation. However, petrographic and microprobe investigations of samples from the eclogitic Piemonte unit and Austroalpine slices revealed that older transposed fabrics (S_{HP}) are defined by phengite, whilst muscovite is found along SZ^1_{gr}, indicating the latter formed at lower pressure (Table 1). Therefore, a considerable amount of exhumation had to occur between D_{HP} and SZ^1_{gr}, possibly as a result of SZ^1_{gr} simple shearing. Such deformation event would have resulted in the juxtaposition of the eclogitic and blueschist Piemonte units, which experienced different metamorphic conditions prior to it. However, it is unclear whether SZ^1_{gr} is responsible for the exhumation of the eclogitic Piemonte unit from depths in excess of 40 km or whether it can account only for the last stages of this exhumation event.

Several lines of evidence suggest that the SZ^1_{gr} observed in the Urtier Valley can be correlated with the episode of extensional deformation that accommodated the exhumation of the eclogitic Piemonte unit further to the north of our study area (Ballèvre and Merle, 1993; Cartwright and Barnicoat, 2002; Reddy et al., 2003). These are: (1) the similarities in tectonometamorphic stratigraphy between the study area and the Valtournenche, both characterized by the eclogitic and blueschist Piemonte units and by the presence of slices of exotic material of Austoalpine and Briançonnais affinity along or near the contact; (2) the observation that the shearing event culminated in exhumation to greenschist facies conditions and in the juxtaposition of the eclogitic and blueschist Piemonte units; and (3) $^{40}Ar/^{39}Ar$ geochronology, indicating an age of ca. 42 Ma for the formation of SZ^1_{gr} in the Urtier Valley (Beltrando et al., submitted for publication).

The deformation regime that was active in the area prior to this major extensional episode is more difficult to constrain exclusively based on structural observations, due to pervasive obliteration of fabrics and mineral assemblages that formed prior to SZ^1_{gr}. However, the fact that rock units that were originally located at the surface were brought to high pressure conditions necessitates tectonic burial and crustal (or lithospheric) thickening (Fig. 12). Such thickening could be achieved only as a result of shortening deformation. As described in the previous sections, traces of pre-SZ^1_{gr} deformation events have been found in the study area and are especially preserved at the sub-millimetric scale. Microscopic investigation of several samples reveals the presence of microlithons containing fabrics oriented at high angles to the extensional shear fabrics. Obliquity between two fabrics is a feature commonly observed during switches from compression to shortening deformation, when a vertical axial planar foliation associated with upright folds is overprinted by flat-lying fabrics related to the activity of extensional shear zones (e.g. Vissers, 1992). Therefore, the obliquity between eclogite facies fabrics (S_{HP}) and the extensional fabrics (SZ^1_{gr}) could be related to the overprint of older upright folds generated in a shortening regime under eclogitic conditions by the extensional shear fabrics. This hypothesis is supported by the fact that D_{HP} folds are indeed observed. However, the majority of the S_{HP} fabrics commonly observed in metapelites and continental basement gneisses could not be unambiguously related to pre-SZ^1_{gr} folds. It is possible, and indeed quite likely, that the high pressure fabrics found in the microlithons in the metapelites and in the continental basement gneisses formed during more than one deformation event. Furthermore, it cannot be excluded that some of the high pressure fabrics may have formed during the early stages of exhumation from eclogitic conditions and they represent precursors to SZ^1_{gr}. However, the detection of such multiple events and their correlation across lithologies lies beyond the resolution of the methods used in this study. Therefore, more studies in areas or lithologies that experienced a smaller degree of deformation/recrystallization following the high pressure event may be needed to constrain the pre-SZ^1_{gr} deformation regime. Disregarding these limitations, pre-SZ^1_{gr} shortening is required for the tectonic burial of the Piemonte units (Fig. 12a).

Therefore, we propose that the transition from D_{HP} to SZ^1_{gr} was characterized by a switch from shortening to extensional deformation in a similar way to what has already been proposed for the evolution of the Piemonte units further to the north (e.g. Ballèvre and Merle, 1993; Reddy et al., 2003). The switch from shortening to extensional deformation resulted in the exhumation of high pressure rocks and in the widespread preservation of mineral assemblages characteristic of eclogite facies conditions (Fig. 12b). This kind of short-lived episodes of extensional deformation has been indicated as important factors for the rapid exhumation and preservation of eclogitic units in convergent orogens (e.g. Platt, 1993; Ring et al., 1999).

This episode of widespread extension has been indicated as responsible for the presence of slices of exotic rocks along the interface between the eclogitic and blueschist Piemonte unit that are found from the Susa Valley to Valtournenche (Hermann, 1937). It has been proposed that the incomplete overlap between the extensional shear zones and pre-existent thrusts resulted in local sampling of rock units that, due to continuing movements, ended up completely isolated from their source (Ballèvre and Merle, 1993; Lister et al., 2001). The final geometry could have been achieved through the activity of a complex network of anastomosing shear zones (Fig. 12b, c). This interpretation seems viable in the light of the fact that exotic rock units are found at slightly different structural heights in the Lago di Cignana area (Forster et al., 2004) and in the Graian Alps, further to the south (Perotto et al., 1983; Pognante, 1983), indicating that crustal thinning was achieved through the activity of several extensional shear zones, that probably spanned from the Gneiss Minuti in the Sesia Zone

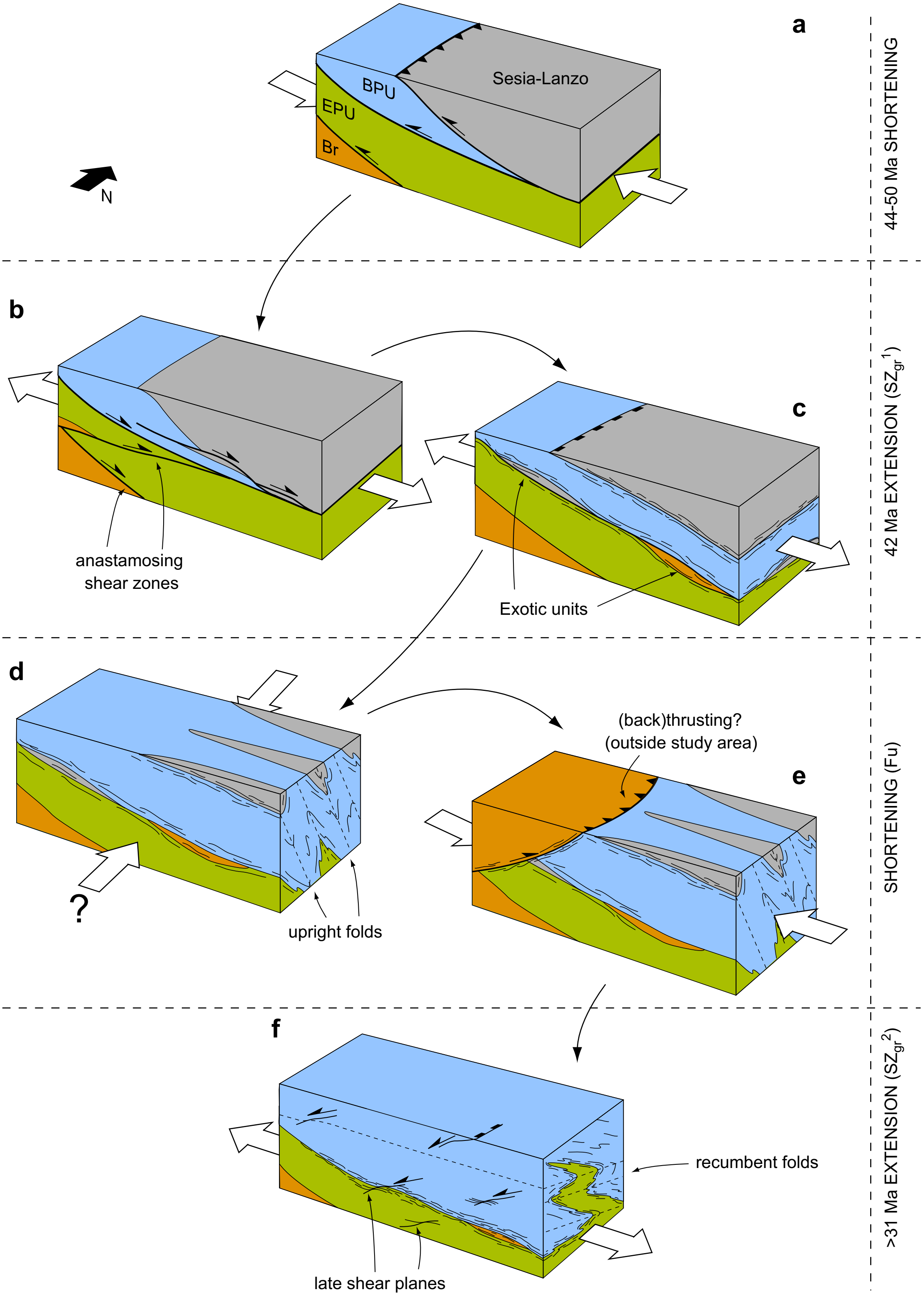


Fig. 12. Block diagrams illustrating the evolution of the Piemonte, Briançonnais and Austroalpine units of the Urtier Valley in the 50–30 Ma interval. (a) Shortening deformation at 50–44 Ma (age from Dal Piaz et al., 2001) culminated in high pressure metamorphism of the eclogitic Piemonte unit, blueschist Piemonte unit and Briançonnais domain (starting geometry similar to Ballèvre and Merle, 1993). (b) At ca. 42 Ma the thrust stack is dissected by an array of extensional shear zones partially overlapping with the older thrusts. Extension results in exhumation of all units and in the sampling of slices of Briançonnais and Austroalpine units that at the end of the deformation episode are located at the contact between the eclogitic and blueschist Piemonte units (c). (d) Renewed shortening culminates in upright folding of the post-extensional tectonometamorphic stratigraphy, possibly immediately followed by thrusting (e). After recumbent folding, renewed extension results in the formation of west-dipping shear planes (f). A minimum age for this episode of ductile deformation is provided by the zircon fission track ages estimated in the Gran Paradiso massif (Malusà et al., 2005).

to the Vanoise area in the Briançonnais Domain (see discussion below; Ganne et al., 2006).

5.1.2. Second deformation mode switch (Fu, SZ_{gr}^2)

Several folding events are observed to affect the extensional shear fabrics and the contact between the eclogitic and blueschist Piemonte unit that formed during extensional shearing. The presence of Fu upright folds affecting the contact between the eclogitic and blueschist Piemonte units is interpreted to indicate that renewed shortening followed the SZ_{gr}^1 extension (Fig. 12d). The recorded increase in pressure during Fu (Beltrando et al., 2007), implying a second episode of tectonic burial, supports this interpretation. It is interesting to notice that the orientation of the upright folds in the study area seems to imply north–south (i.e. orogen parallel) shortening for their formation (Fig. 12d). A similar origin has been suggested for the E–W oriented upright folds found in the Piemonte units further to the south (Tricart and Schwartz, 2006). However, the upright folds of the Urtier Valley can be followed to the east of the study area, where they progressively acquire a north–south orientation (Vearncombe, 1985), which is consistent with the general orientation found also further to the north (see below). These observations seem to indicate that the upright folds in the Urtier Valley may have been partially re-oriented after their formation, still maintaining their original sub-vertical axial plane. Therefore, their formation may have been related to orogen-perpendicular shortening, similarly to the thrusts that formed immediately after folding (Fig. 12e; Vearncombe, 1985) and their re-orientation may be related to partial transposition during subsequent deformation (Williams and Jiang, 2005).

Following Fu, two families of recumbent folds formed in the Piemonte units of the Urtier Valley. Recumbent folds are believed to result either from vertical shortening (i.e. crustal stretching; e.g. Sandiford, 1989; Froitzheim, 1992) or from large scale horizontal transport of rock masses, related to crustal thickening (e.g. Argand, 1924). The presence of chlorite along the axial planes of Fr^1 folds indicates that the study area had been exhumed from epidote–amphibolite to greenschist facies conditions prior to (or as a result of) recumbent folding. Therefore, it is possible that recumbent folding occurred in response to vertical shortening and crustal thinning, although the alternative possibility of it being related to the activity of thrust faults located outside the study area cannot be completely discarded.

Extensional deformation certainly occurred during SZ_{gr}^2. Shear bands, which are characterized by steep W-oriented dips and stretching lineations consistent with top-to-the-west movement, are interpreted to have developed during a period of E–W directed extension (Fig. 12f). This interpretation, which is based on geometric considerations, is reasonable due to the very limited amount of post-SZ_{gr}^2 deformation and is confirmed by correlations with other areas of the Western Alps (see next section).

Therefore, a second switch from shortening to extensional deformation took place between Fu and SZ_{gr}^2 (Fig. 12). Whilst Fu and SZ_{gr}^2 can be unambiguously related to shortening and extensional deformation, respectively, constraining the broader deformation regime responsible for the formation of recumbent folds has proved a difficult task. Therefore, the possibility that our interpretation of the Fu–SZ_{gr}^2 sequence may be an oversimplification of the actual evolution undergone by the Piemonte units in the Urtier Valley must be taken into account.

5.2. Regional significance of the observed deformation sequence

Two cycles of shortening–extensional deformation have been found in the Piemonte units of the Urtier Valley (Fig. 12). An early history of deformation under high pressure conditions (D_{HP}), which ended with a folding phase that has been tentatively interpreted to record shortening, was followed by the formation of extensional shear zones (SZ_{gr}^1), which were subsequently affected by upright folding (Fu), before renewed extension (SZ_{gr}^2) took place. The aforementioned deformation mode switches were associated with multiple burial-exhumation cycles of the study area. In particular, shortening deformation was responsible for tectonic burial, whilst extension culminated in tectonic exhumation. While the complex pressure–temperature evolution of the study area (Beltrando et al., 2007) has not been reported from other parts of the Western Alps, yet, similarly complex deformation histories have been detected in other parts of the Penninic domain (e.g. Ballèvre and Merle, 1993; Reddy et al., 2003). Correlations with the deformation sequences found in other areas of the Western Alps are fundamental in order to understand the significance of the deformation history found in the Urtier Valley for the evolution of the orogen. In particular, it is important to assess whether shortening–extension cycles occur only locally or are widespread and, in this latter case, whether they are contemporaneous or diachronous across the orogen. Ideally, sound correlations should be based on analogous structural, metamorphic and geochronological evolutions of the areas that are being compared. Unfortunately, only a handful of studies from the Western Alps provide all three sets of information (Reddy et al., 1999; Agard et al., 2001, 2002; Ganne, 2003; Reddy et al., 2003; Ganne et al., 2003, 2005). Their results are compared with the results from the Urtier Valley on the left hand side of Fig. 13. Numerous other studies provide either good structural (e.g. Perotto et al., 1983; Steck, 1989; Ballèvre and Merle, 1993; Schwartz, 2002; Bucher et al., 2004) or geochronological and petrological constraints (e.g. Inger et al., 1996; Cartwright and Barnicoat, 2002; Federico et al., 2005). However, since they do not provide a complete PT-t-deformation history, any attempted correlation is deemed to be somewhat ambiguous. Nevertheless, the studies by Schwartz (2002) and Ballèvre and Merle (1993) are included on the right hand side of Fig. 13, with the only aim of showing how the deformation history recognized in the Urtier Valley appears to be widespread in the Western Alps.

We are aware that the data set presented in Fig. 13 does not cover the entire extent of the Penninic units of the Western Alps and some areas are not included, but here we simply wish to provide a state-of-the-art overview on the similarities/differences between some well-studied areas, with the aim of constituting a possible starting point for future research and discussion. The deformation sequences provided in the cited papers have been "converted" into a sequence diagram format, in order to overcome the problems related to progressive numbering of deformation event in each individual area. Question marks have been associated to deformation events whose descriptions in the original papers were deemed to contain ambiguities. Correlations were established on the basis of structural patterns, style, metamorphic conditions (when provided) and, when available, geochronological data. When establishing correlations across different areas, the possibility that old structures may have been re-oriented through later deformation should be taken into consideration (e.g. Krabbendam et al., 1997). Therefore, caution should be used when establishing correlations based exclusively on the style and orientation of folds.

An early episode of shortening deformation related to thrusting and/or folding has been reported from several parts of the Piemonte units (Fig. 13; Agard et al., 2002; Reddy et al., 2003) and is associated with east–west striking stretching lineations that formed under high pressure conditions in the north-western (Steck, 1989) and south-western (Philippot, 1990) Alps. It is generally accepted that this episode culminated in high pressure metamorphism of the eclogitic Piemonte units at ca. 50–44 Ma (e.g. Duchêne et al., 1997; Rubatto et al., 1998; Lapen et al., 2003). However, ^{40}Ar/^{39}Ar geochronology on phengite from the Schistes Lustrés, in the Cottian Alps, yielded significantly older ages of 55–62 Ma, which have been interpreted as the age of high pressure metamorphism (e.g. Agard et al., 2002). Although the debate as to the significance of those ages lies beyond the scope of this paper, we simply wish to highlight the fact that ages of 44–50 Ma have been estimated from Piemonte unit rocks located both to the north and to the south of the Cottian Alps, with several methods, including ^{40}Ar/^{39}Ar on phengite (Dal Piaz et al., 2001; Federico et al., 2005; Gouzu et al., 2006). Therefore, the possibility that some estimates from the

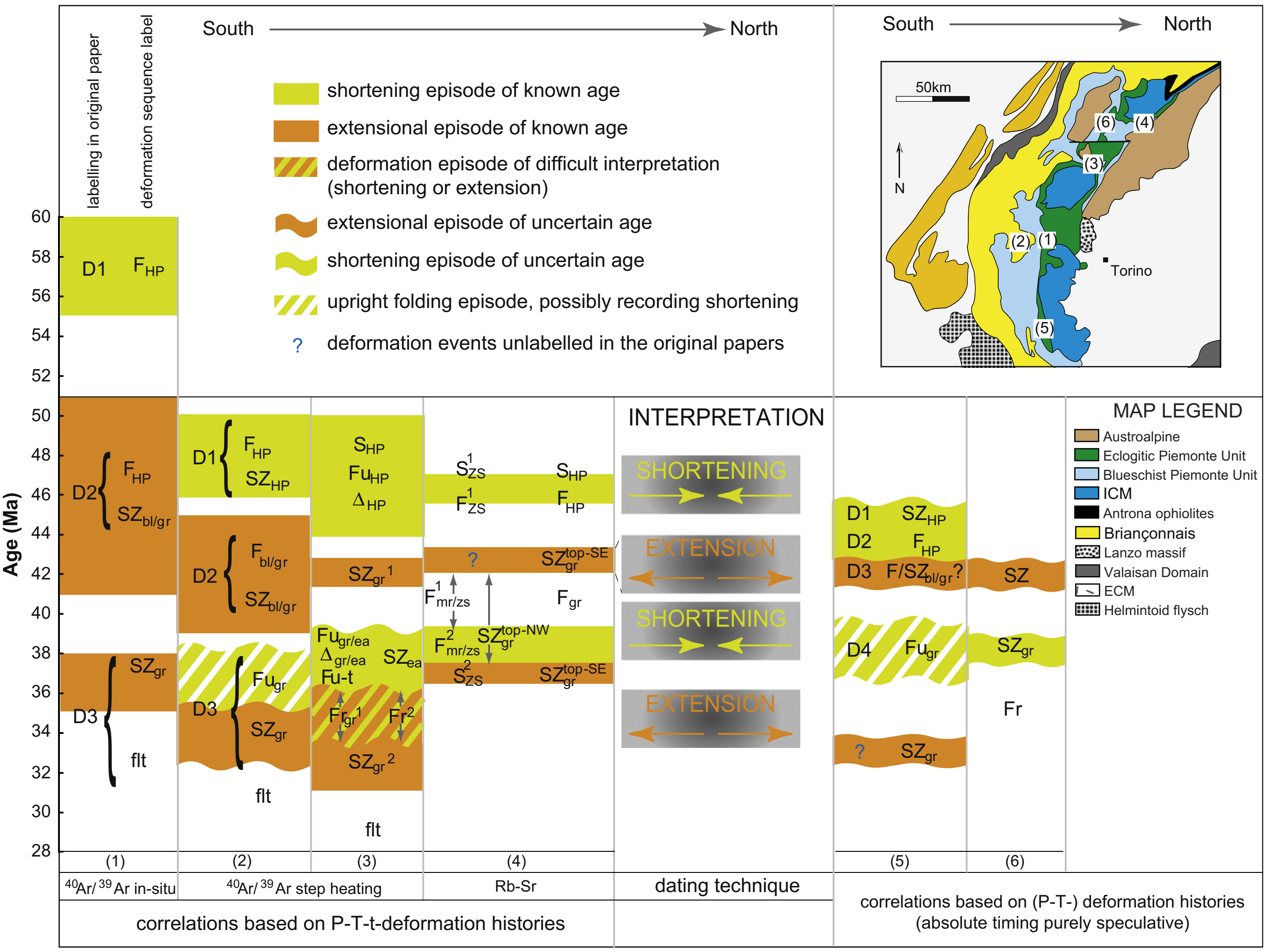


Fig. 13. Compilation of the deformation histories published from the Penninic units of the Western Alps. The deformation histories have been converted in deformation sequence diagrams to facilitate correlations. Two episodes of shearing in greenschist facies conditions represent the deformation events that can be more easily correlated across the entire Western Alps. 1 = Agard et al., 2001, 2002; 2 = Ganne, 2003; Ganne et al., 2005; 3 = this study and Beltrando et al., 2007 (age of the high pressure deformation from the Urtier Valley is taken from Dal Piaz et al., 2001); 4 = Reddy et al., 1999; 5 = Schwartz, 2002; 6 = Ballèvre and Merle, 1993.

Cottian Alps may have been affected from externally derived ^{40}Ar, whose possible presence in phengite is well documented (e.g. Arnaud and Kelley, 1995), should be taken into account.

The reach of peak pressure conditions was ubiquitously followed by an episode of extensional deformation in the course of which the eclogitic Piemonte units underwent a significant amount of exhumation to blueschist (Agard et al., 2002) or greenschist (Cartwright and Barnicoat, 2002; Reddy et al., 2003) conditions (Fig. 12). This episode was characterized by top-to-the-east kinematics on east-dipping shear planes in the Cottian Alps (Agard et al., 2001), where mineral lineations are defined by phengite flakes and oriented mica–chlorite associations replacing carpholite. A more complex kinematic evolution in greenschist facies conditions, which deserves particular attention, has been described from the Piemonte units in the north-western Alps (Reddy et al., 1999, 2003; Pleuger et al., 2007). There, predominant top-to-the-SE extensional shearing is reported from the eclogitic and blueschist Piemonte units. However, a distinct episode of shearing characterized by top-to-the-NW kinematics is observed between the earlier top-to-the-SE extension and the formation of the contact between the eclogitic and blueschist Piemonte unit, which took place during a second event of SE-directed shear. The geometric overprinting relationships observed in the field have been confirmed through Rb–Sr dating, which yielded ages of 42.3–41.2 Ma for the early top-to-the-SE deformation, while 39.2–37.2 Ma and 37.5–36.5 Ma have been estimated for the top-to-the-NW and late top-to-the-SE deformation, respectively (Reddy et al., 1999). The significance of the NW-directed shear is controversial, as it has been alternatively related to renewed shortening deformation (Pleuger et al., 2007) following earlier extension (Ballèvre and Merle, 1993), or to a pure shear component of deformation during the activity of the Gressoney shear zone, predominantly characterized by SE-directed shear (Reddy et al., 1999). Renewed shortening deformation following early extension and preceding a second extensional episode would imply that the deformation mode switches found in the Urtier Valley may also be present further to the north. Indeed, post-shearing folds are not restricted to the Urtier Valley, but can also be seen further to the north, near the village of Verres, in the Aosta Valley, or in the Täsch Valley, in Switzerland (Sartori, 1987), and further to the south, on the southern slopes of the Rocciamelone mountain (Perotto et al., 1983; Fudral, 1998). Therefore, these preliminary correlations suggest that the deformation mode switch from shortening to extension and back to shortening found in the Urtier Valley may represent a much more common feature than hitherto recognized.

As reported above, ages >41 Ma have been estimated for the early top-to-the-east shearing event in the Valtournenche (Reddy et al., 1999, 2003). These estimates are in accordance with the age of ca. 42 Ma obtained from muscovite separated from the greenschist facies mylonites at the contact between the eclogitic and blueschist Piemonte units in the Urtier Valley (Beltrando et al., submitted for publication). Correlations with the Cottian Alps, from which ^{40}Ar/^{39}Ar in-situ laser probe analyses from the extensional shear zones yielded ages ranging between 51 and 40 Ma (Agard et al., 2002), are more problematic. Interestingly, younger ages were obtained from samples pervasively recrystallized during the shearing episode, whilst samples characterized by a weaker overprint yielded slightly older ages (cfr. samples 12 and 12* in Agard et al., 2002). Therefore, the possibility that the large age spread reported in Agard et al. (2002) may also be the result of mixing between older micas related to the pressure peak and younger micas that actually crystallized during the shearing event should be considered. This consideration seems to be supported by the ^{40}Ar/^{39}Ar ages of 45–39 Ma estimated for the blueschist facies extensional shear zones with top-to-the-east kinematics in the Vanoise massif (Ganne, 2003), located only a few km to the north–west of the area studied by Agard et al. (2001, 2002).

Therefore, comparison of our results with published literature indicates that the Penninic units of the Western Alps were affected by early shortening deformation (probably at 50–44 Ma), immediately followed by extensional shearing. This extensional event, which probably ceased at ca. 39 Ma, was followed, at least to the north of the Gran Paradiso massif, by shortening deformation. Existing geochronological data are too scarce to determine whether this switch from extensional to shortening deformation was contemporaneous or diachronous in the different areas.

As already discussed above, a second episode of extensional deformation is generally observed in the Piemonte units. West-dipping extensional shear planes accommodating E–W extension under greenschist facies conditions, equivalent to our SZ_{gr}^{2}, have been observed in the Piemonte units throughout the Western Alps (Ballèvre et al., 1990; Caby, 1996; Rolland et al., 2000; Agard et al., 2002; Schwartz, 2002), where they invariably represent the last episode of ductile deformation (Figs. 12f and 13). The formation of these shear bands in the Gran Paradiso massif (Freeman et al., 1997; Brouwer et al., 2002) and in the Briançonnais domain (Fig. 12; Caby, 1996; Bucher et al., 2004; Ganne et al., 2005), has been related to the late stages of extensional exhumation of the Gran Paradiso massif, which crops out at the southern end of area presented in this study. This deformation event has been tentatively placed at 35–30 Ma (Rolland et al., 2000), although an older age of 38–35 Ma has also been proposed (Agard et al., 2002). The late, SE-directed extensional phase responsible for the reactivation of the eclogitic-blueschist Piemonte unit contact in the north-western Alps at ca. 37.5–36.5 Ma (Reddy et al., 1999) could be the kinematic equivalent of the top-to-the-west extension that dominates to the south of the Aosta–Ranzola fault (Reddy, personal communication).

It has been proposed (Agard et al., 2002; Ganne et al., 2005) that this late episode of extensional deformation represents the continuation of the earlier SZ_{gr}^{1} extension. While this suggestion may hold true for some areas, we have shown that shortening deformation is interposed between the two extensional events in our study area and possibly in several other parts of the Western Alps (Figs. 12d, e and 13).

SZ_{gr}^{2} is followed by N–S directed extension accommodated by N-dipping faults. The orientation and dip of the major extensional fault found in the northern part of the study area are analogous to those of the Aosta-Ranzola fault, which crops out further to the north (Bistacchi et al., 2001). Ages of 30–28 Ma have been provided for the activity of this fault. Evidence of post-30 Ma N–S brittle extension is commonly found in the Western Alps. The switch from dominantly E–W extension during SZ_{gr}^{2} to N–S extension as exhumation progressed in the brittle regime has been observed in other parts of the Western Alps (e.g. Agard et al., 2003) and has been attributed to the creation of a new free boundary by the opening of the Gulf of Leon starting at ca. 30 Ma or to the anticlockwise rotation of the Adria indenter (e.g. Collombet et al., 2002).

Therefore, although variability is observed and further tests are needed, a general pattern seems to emerge from the deformation history recorded in different parts of the Piemonte units in the Western Alps (Figs. 12 and 13). Shortening deformation is generally observed in the early stages of the deformation history under high pressure conditions. This phase is followed by a widespread episode of extensional shearing. Renewed shortening is observed at least locally, before a widespread younger phase of extensional deformation. The two extensional events appear to be particularly well expressed in the structural record and may be used as "markers" to establish correlations among different areas, provided that their contemporaneity is proved (Fig. 12).

Further studies are needed to address the lateral extent and relative timing of the above mentioned deformation events. The results will help understanding whether different parts of the Western Alps behaved relatively independently through time and shortening–extension cycles are localized (and perhaps related to the internal dynamics of orogenic wedges) or whether the shortening–extension cycles are orogenic in scale, as already proposed for other mountain belts (Balanyá et al., 1997; Azañón and Crespo-Blanc, 2000; Rawling and Lister, 1999; Collins, 2002; Dewey, 2005; Forster and Lister, 2005).

It is important to note that the shortening–extension cycles described here do not necessarily lead to cycles of crustal thickening and thinning. Extensional shear zones may accommodate the exhumation of high pressure rocks without thinning the crust, as proposed for the extrusion of wedges of crustal material bounded by a thrust at the sole and an extensional shear zone at the roof (e.g. Wheeler et al., 2001). Crustal thickening and thinning can be distinguished only considering the large scale geodynamic context and also other data sets, including reconstructions of plate kinematics and the sedimentological evolution of peripheral basins.

6. Conclusion

The Penninic units in the area located between the Gran Paradiso massif and the Aosta Valley underwent a complex deformation history characterized by multiple switches from shortening to extension. An early shortening event, probably coeval with the reach of high pressure metamorphic conditions, was followed by an extensional episode that resulted in the exhumation of the eclogitic Piemonte unit from beneath the blueschist Piemonte unit. Renewed shortening is indicated by pervasive folding of the extension-related fabrics and of the contact between the eclogitic and blueschist Piemonte units. A later, low-strain extensional episode affected the thus formed tectonometamorphic pile. Brittle extensional faulting represents the latest deformation stage recognizable in the area.

Such complex deformation history took place in less than 20 Ma. An attempt to correlate these results with published studies from other parts of the Western Alps suggests that shortening–extension cycles may be more widespread that hitherto recognized.

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