The Valaisan controversy revisited: Multi-stage folding of a Mesozoic hyper-extended margin in the Petit St. Bernard pass area (Western Alps)

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The Valaisan controversy revisited: Multi-stage folding of a Mesozoic hyper-extended margin in the Petit St. Bernard pass area (Western Alps)

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Abstract

The Valaisan units, in the Alps, sample remnants of a Mesozoic basin located along the distal margin of the European plate. The extent and timing of crustal thinning and the presence/absence of rift-related magmatism in this basin have been investigated in the newly defined Punta Rossa unit, at the Petit St. Bernard pass (Western Alps). The Punta Rossa unit consists of laterally discontinuous slivers of Paleozoic basement, rare meta-pillow lavas and abundant metasedimentary breccias. These rock types are located along the multiply folded interface between serpentinized ultramafics and radiolaria-bearing garnet–chloritoid micaschists. Fault breccias pre-dating Alpine metamorphism are common at the top of the ultramafics and throughout the continental basement slivers, but they are absent in all other lithologies. These observations suggest that subcontinental mantle and Paleozoic basement were juxtaposed by brittle faulting before the overlying sediments were deposited. Rift-related thinning was probably accompanied by minor mafic magmatism, as indicated by pillow lavas directly in contact with garnet–chloritoid micaschists.

The Punta Rossa unit preserves evidence of a multi-stage Alpine evolution. Post-high pressure isoclinal folding (F_{ctd}) is associated with a pervasive axial planar cleavage (S_{ctd}), defined by chloritoid and white mica. Following re-heating to ~ 400 °C, S_{ctd} was statically overgrown by garnet and chloritoid, prior to large-scale recumbent folding at greenschist facies conditions (F_{rec}). Interference between F_{ctd} and F_{rec} is responsible for the regional occurrence of basement rocks resting upon Mesozoic metasediments. Following F_{rec}, shear zones with top-to-the-south kinematics dissected the tectonic pile, prior to the formation of upright folds with NNE–SSW trending fold axes.

Therefore, the Punta Rossa unit preserves evidence of complete crustal excision in the Valaisan basin, with exhumation of ultramafics and minor mafic magmatism. Multi-stage deformation and a laterally discontinuous pre-Alpine architecture, typical of hyper extended rifted margins, are responsible for the complex outcrop pattern observed in the field.

1. Introduction

Paleogeographic reconstructions of domains that underwent subduction and orogeny rely on the assessment of the pre-orogenic relationship between different rock types within specific tectonometamorphic units. In areas that underwent multiple stages of deformation and metamorphism, this task may be complicated by tectonic reworking of primary lithological contacts and pervasive recrystallization, masking the original rock textures. In these contexts, a multidisciplinary approach, involving lithostratigraphic observation combined with standard structural and metamorphic studies may be crucial to detect pre-orogenic lithostratigraphic associations (e.g. Beltrando et al., 2010 and Vitale Brovarone et al., 2011). In the study presented here, this approach is applied to the complexly deformed Valaisan units near the Petit St. Bernard pass (Western Alps), in order to constrain their controversial pre-Alpine crustal architecture and help unraveling the paleogeographic significance of the Valaisan basin.

Remnants of this basin are presently found from the Italian–French Western Alps to the Engadine window, in the Eastern Alps (Fig. 1). The Valaisan basin branched off the Piemonte–Liguria Ocean and separated the European plate *sensu stricto* from the Briançonnais micro-block (e.g. Haug, 1909 and Trümpy, 1980; Fig. 1b). Several key aspects of its evolution remain to be fully understood, with important implications for the overall evolution of rifting in the Western Tethys. The main controversies regarding the Valaisan basin concern (1) its lateral extent, (2) the age of crustal thinning and (3) whether or not extensional tectonics resulted in complete crustal excision and rift-related magmatism. These questions have been addressed by a large number of studies focused on the relatively few occurrences of serpentinized ultramafics and mafic igneous rocks within the Valaisan domain (Fig. 1a).

The opening of the Valaisan basin has been placed alternatively in the Middle Jurassic, at the same time as continental breakup was occurring in the more southerly located Piemonte–Liguria Ocean (Manatschal et al., 2006), or in the Aptian–Albian (Frisch, 1979 and Stampfli, 1993). In this latter scenario, crustal thinning would have been related to transtensional tectonics induced by the opening of the Bay of Biscay in the southern North Atlantic, triggering the eastward motion of Iberia (Frisch, 1979 and Stampfli, 1993). The Valaisan basin either tapered out laterally, in the southern part of the Western Alps (e.g. Trümpy, 1980) or extended more or less continuously from the Alpine domain to the southern North Atlantic (e.g. Stampfli et al., 2002).

The extent of crustal and lithospheric thinning that was achieved in the Valaisan basin is also debated. Oman-type ophiolites are missing, but mafic igneous rocks and serpentinized ultramafics are found in a few localities throughout the Western and Central Alps (Masson, 2002). The local presence of MORB-type mafic sills in several parts of the Valaisan domain (Fig. 1a), from the Misox Zone, in the Eastern Central Alps to the Versoyen complex, in the Petit St. Bernard area, has been repeatedly used to suggest that the Valaisan basin was, at least locally, floored by mafic crust. However, geochronological studies have repeatedly shown that a large part of the magmatic activity in the Versoyen complex took place in the Paleozoic (Beltrando et al., 2007, Masson et al., 2008 and Schärer et al., 2000). Jurassic crystallization ages are currently known only from the Misox Zone (161.0 ± 3.9 Ma; Liati et al., 2005), while Cretaceous crystallization ages have been estimated from the Chiavenna ophiolites, in the Central Alps (ca. 93 Ma; Liati et al., 2003) and the Balma Unit, in the Western Alps (93.4 ± 1.7 Ma; Liati and Froitzheim, 2006). Importantly, the latter two tectonometamorphic units, which have sometimes been attributed to the Valaisan basin, do not crop out in structural continuity with the Valaisan domain.

Serpentinized ultramafics are found exclusively in the Tasna unit (Engadine window), in the Visp mélange (south-western Switzerland) and at the Petit St. Bernard pass (French Italian border; Fig. 1a). The Tasna Unit, which largely escaped Alpine deformation and metamorphism, preserves clear evidence of mantle exhumation at the basin floor by the activity of low-angle detachment faults (Florineth and Froitzheim, 1994 and Manatschal et al., 2006). In this area, rift-related extensional tectonics resulted in the juxtaposition of slivers of continental basement directly above serpentinized ultramafics, prior to the deposition of Lower Cretaceous sediments (Florineth and Froitzheim, 1994 and Manatschal et al., 2006).

At the Petit St. Bernard pass, and in the Visp mélange, in south-western Switzerland, serpentinized ultramafics are also associated with mafic igneous rocks. In the latter example, which is interpreted as an orogeny-related flysch deposit (Masson, 2002), metabasalts and serpentinites crop out as blocks (up to 2.5 km wide) in a black micaschist matrix, together with various Triassic and Paleozoic rocks.

The study presented here addresses the crucial question of the crustal architecture of the Valaisan basin with a new detailed structural map of the Valaisan domain in the Petit St. Bernard pass area, at the French–Italian border. This area, which underwent multiple phases of deformation and high pressure metamorphism, provides the only opportunity within the Valaisan domain to assess the relationship between serpentinized ultramafics, mafic igneous rocks, continental basement and metasediments in a single locality. Our structural, lithostratigraphic and Raman spectroscopy study allows to distinguish several tectonostratigraphic units. The lithostratigraphic composition and Alpine deformation history of the two units preserving evidence of mafic magmatism is described in detail. Subsequently, our results are compared with the extensive body of pre-existing literature and the paleogeographic consequences are briefly explored.

2. Geological setting

The Valaisan domain, in the Western Alps, is bounded towards the NW by the Penninic Front and towards the SE by the Houiller Front (Fig. 1). The Penninc Front separates the Valaisan domain from the more external Helvetic–Dauphinois domain, consisting of Paleozoic basement overlain by a Late Permian to Lower Oligocene sedimentary cover sequence (Escher et al., 1997). The Houiller Front, instead, separates the Valaisan domain from the overlying Houiller zone, which consists of Carboniferous and Permian sandstone, breccia and shale of continental origin, with minor Early Triassic dolomite and shale, which underwent only limited metamorphism during the Alpine orogeny.

The Valaisan units, in the Petit St. Bernard pass area, at the French–Italian border, have been the subject of several recent studies, alternatively focused on its Alpine deformation (e.g. Cannic et al., 1995, Fügenschuh et al., 1999 and Loprieno et al., 2011), Alpine metamorphism (e.g. Bousquet et al., 2002), lithostratigraphy (Antoine, 1971, Elter and Elter, 1965 and Masson et al., 2008 and references therein) and magmatic history (e.g. Beltrando et al., 2007 and Mugnier et al., 2008 and references therein). The Breuil Valley, which extends in the NNW–SSE direction on the Italian side of the pass, has attracted most of the attention, due to the presence of serpentinized ultramafics alongside different types of meta-igneous rocks (Fig. 2). This unique lithological association lies at the base of the long-standing debate on whether (1) Mesozoic crustal thinning led to mantle exhumation at the sea-floor, (2) crustal thinning was associated with mafic magmatism and (3) the Versoyen complex preserves evidence of such magmatism.

2.1. Lithological composition

Considering the range of different tectonic subdivisions that have been proposed for this small area (which are summarized in the next section and in the discussion), the existing information on the different rock types is herein reported without reference to the tectonic units they have alternatively been attributed to by the different authors. The rock types characteristically found in the Breuil valley range from serpentinized ultramafics to several types of meta-igneous rocks and metasedimentary rocks, including metabreccias, micaschists and calcschist, with minor marble and dolostones.

2.1.1. Meta-igneous rocks

Different types of meta-igneous rocks can be distinguished in the area (Fig. 2): (1) mafic–ultramafic sills and laccoliths interbedded with black schists, normally referred to as ‘Versoyen complex’ *sensu stricto* (Elter and Elter, 1965), (2) meta-pillow lavas (Loubat, 1968 and Loubat and Antoine, 1965) and (3) peraluminous metagranitoids (Beltrando et al., 2007). Both the Versoyen complex and the pillow lavas have been repeatedly advocated as evidence for Mesozoic rift-related mafic magmatism in the Valaisan basin (e.g. Antoine, 1971, Loprieno et al., 2011 and Loubat, 1975).

The Versoyen complex consists of sills ranging in thickness from 0.5 to 40 m, locally showing internal zoning, with cumulate gabbros and ultramafics passing upward to dolerites (Cannic, 1996). Chilled margins and intrusion breccias (Beltrando et al., 2007) are common at the contact with the black schists. The cores of sills have flat REE patterns characteristic of N-MORB and T-MORB, while the geochemistry of the sill margins provides evidence for contamination caused by the intrusion of hot mafic magmas into unconsolidated sediments rich in water (Cannic, 1996 and Mugnier et al., 2008). As pointed out by Loubat (1975) and Kelts (1981), the Versoyen complex resembles sill–sediment complexes presently found in the Gulf of California, where they are related to high sedimentation rates during spreading within narrow oceanic pull-apart basins. The age of the Versoyen intrusions has been the subject of a long-standing debate. Stratigraphic arguments, based on the proposed relationship with the Mesozoic sediments cropping out in the area (see below), led to the commonly held view that mafic magmatism took place in the Cretaceous (Antoine, 1971 and Loprieno et al., 2011). However, several U–Pb geochronological studies have now contradicted this view, showing that mafic magmatism in the Versoyen complex was probably restricted to the Paleozoic. Carboniferous ages of ca. 337 ± 4.1 Ma have been estimated with high-resolution in-situ U–Pb dating on zircons from the Clapet gabbro (Masson et al., 2008), while younger ages have been obtained from a metaleucogabbro dyke intrusive into the Clapet gabbro (272 ± 2 Ma, high-resolution in-situ U–Pb dating on zircon; Beltrando et al., 2007) and another metaleucogabbro dyke intrusive into a thick mafic sill in the central part of the Versoyen complex (309 ± 6 Ma, Schärer et al., 2000).

Further evidence of multi-stage magmatic activity in the area include the Permian peraluminous granitoids characteristically found in the Punta Rossa area (267 ± 1 Ma, high-resolution in-situ U–Pb dating on zircon; Beltrando et al., 2007; Fig. 2), the local presence of felsic dykes intrusive into mafic sills of the Versoyen complex and the rare basaltic dykelets, now consisting largely of albite + chlorite, intrusive into the peraluminous meta-granitoids (Mugnier et al., 2008). The composition of the latter is significantly different from the metamafics of the Versoyen complex, showing higher LREE and lower HREE content (Mugnier et al., 2008), but no age data for their formation is available.

2.1.2. Metabreccias

Metabreccias are commonly found associated with the meta-igneous rocks described above (Fig. 2). Based on their lithological composition and geographic location they are generally subdivided into Collet des Rousses metabreccia (Schoeller, 1929), Punta Rossa metabreccia (Antoine, 1971) and Miravidì metabreccia (Antoine, 1971). The Collet des Rousses metabreccia, in its type locality, located at the Collet des Rousses, at the SW edge of the study area (Fig. 2), crops out at the interface between the Versoyen complex and a large mass of calcschists, normally referred to as ‘Petit St. Bernard calcschists’. It consists of matrix-supported breccias with clasts of gray marbles, black schists (Schoeller, 1929), greenstone (Elter and Elter, 1965) and dolostone (Masson et al., 2008) reaching 60 cm in size. Lens-shaped clast-rich layers are locally interbedded with layered meta-arkose of mafic composition and black schists (Loubat, 1968). The presence of belemnites in the metabreccia matrix is used as evidence for a Mesozoic deposition age. The Punta Rossa metabreccia (Antoine, 1971), is associated with the peraluminous metagranitoids described above. It consists of sub-angular granitoid clasts, variably associated with micaschist clasts, in a dark micaschist matrix. The Miravidì metabreccia, which crops out to the NW of the Punta Rossa col, is a clast-supported breccia with blocks of metamafic rocks and subordinate black schists in a matrix of black schists (Antoine, 1971).

2.1.3. Gray micaschists and 'Valaisan Trilogy'

A large part of the central and northern Breuil valley is then occupied by a thick sequence of finer-grained metasediments (Fig. 2). Gray micaschists are generally found in close proximity to the meta-igneous rocks (Antoine, 1971). The rest of the metasedimentary sequence of the Breuil Valley is generally considered the equivalent of the so-called 'Valaisan trilogy' (Burri, 1979 and Trümpy, 1951), despite its basal part displays some minor differences with respect to the typical sequence cropping out in the more external Valaisan units (Antoine, 1971). From the contact with the gray micaschists, these metasediments are grouped in 'Aroley marble', 'Marmontains quartzite' and 'St. Christophe calcschists'. The Aroley marble consists of impure marble and carbonate schists, with rare conglomeratic beds near the base. The 'Marmontains quartzite' is characterized by alternating beds of carbonate-free black schists and quartzarenites, while the 'St. Christophe calcschists' consist of calcareous–arenaceous strata and black marls and schists. The onset of the Valaisan Trilogy sedimentation is poorly constrained, due to the rarity of fossils, and it has been placed at different stages in the Cretaceous, either in the Barremian–Aptian (Elter, 1954 and Sodero, 1968) or in the Turonian–Santonian (Antoine, 1965 and Antoine, 1971; see Loprieno et al., 2011 for a discussion).

2.1.4. Marbles, dolostones and Petit St. Bernard calcschists

Marbles and dolostones are found only on the NE slopes of the Breuil Valley, in the Laytire area (Fig. 2). These rocks are considered to derive from upper Triassic dolomitic schists and Lower Jurassic cherty marbles in stratigraphic contact with the overlying Petit St. Bernard calcschists (Elter and Elter, 1957). The latter consist of belemnite-bearing (Franchi, 1899) carbonate micaschists and graphitic marbles, interpreted as Early to Middle Jurassic in age (Elter and Elter, 1965). These lithologies are part of the Petit St. Bernard unit, which occupies the southern part of the area. Its lithological composition is extensively described by Elter and Elter (1957 and 1965), Debelmas et al. (1991) and Antoine et al. (1992). This unit has generally been considered as a distinctive Alpine tectonometamorphic unit (e.g. Antoine et al., 1992, Bousquet et al., 2002 and Elter and Elter, 1957; see Loprieno et al., 2011 and Masson et al., 2008 for alternative interpretations), separated from the mafics/ultramafics bearing units underneath by Alpine shear zones. Our study confirms this interpretation. Therefore, given that the Petit St. Bernard lithologies do not display pre-Alpine relationships with the mafic and ultramafic rocks of the area, their Alpine deformation history will not be considered hereafter.

2.2. Outstanding controversies

As mentioned above, despite the numerous studies that have been carried out in this domain and the geological maps already available (Antoine, 1971, Carraro et al., in press, Debelmas et al., 1991 and Loprieno et al., 2011), the relationships between meta-igneous rocks, ultramafics and the different types of metasediments are still controversial, with important implications for paleogeographic reconstructions. For example, Antoine (1971) and Loprieno et al. (2011) suggested that the Collet des Rousses metabreccia is the stratigraphic base of the Versoyen complex, thus constraining its mafic magmatism to the Mesozoic. This attribution has been questioned by several authors, who proposed that the Collet des Rousses metabreccia is either the stratigraphic base (Masson et al., 2008 and Schoeller, 1929) or top (Elter and Elter, 1965) of the Petit St. Bernard calcschists. Also the relationship between Versoyen complex and serpentinized ultramafics is controversial, the latter having been alternatively considered as hydrated cumulus peridotites formed during the Versoyen complex magmatism, in the Carboniferous (Mugnier et al., 2008), tectonic slivers located along Alpine thrusts (Antoine, 1971) or mantle exhumed in the Cretaceous at the bottom of the Valaisan basin (Loprieno et al., 2011). A further major point of debate concerns the polarity of the metasedimentary sequence in the central and northern Breuil Valley. This metasedimentary sequence is generally considered to be overturned and in stratigraphic continuity with the ultramafics and meta-igneous rocks of the area (Antoine, 1971 and Loprieno et al., 2011). Masson et al. (2008) proposed an alternative interpretation, suggesting that the 'Valaisan Trilogy', in the area, is not overturned and is separated from the continental basement by an Alpine thrust.

2.3. Tectonometamorphic evolution

Evidence of high pressure metamorphism are reported from most of the rock types cropping out in the area: jadeite is documented from the metagranitoids of the Punta Rossa area (Saliot 1979 in Bousquet et al., 2002), while carpholite is reported both from metasediments of the Petit St. Bernard unit and from the metasediments associated with continental basement rocks (Bousquet et al., 2002, Goffé and Bousquet, 1997 and Loprieno et al., 2011). Omphacite + garnet + glaucophane mineral assemblages in metamafics are reported from the Versoyen complex rocks from the Aiguille du Clapet area, in France (Cannic, 1996 and Schürch, 1987). Chloritoid + chlorite + phengite aggregates formed at the expense of former carpholite are generally considered to be related to re-heating and decompression from an early metamorphic stage at P = 1.7 GPa and T = 375 °C to a second stage at P = 1.5 and T = 450–500 °C (Bousquet et al., 2002 and Cannic et al., 1995). This heating event was contemporaneous with the formation of the earliest mineral fabric still visible in the area (S1 of Fügenschuh et al., 1999). Subsequent intense F2 folding was followed by thrusting and by a further fold generation, related to thrusting onto the more external Helvetic–Dauphinois domain (Loprieno et al., 2011).

3. Litostratigraphy

As a result of the lithostratigraphic and structural study presented below, the different Valaisan rock types of the Breuil Valley have been grouped into two different tectonostratigraphic units, labelled 'Punta Rossa' and 'Hermite' units. Their distinction is based on the different lithostratigraphic composition and on the fact that, in the study area, they are generally separated by a late-Alpine shear zone that is never affected by the earliest folding phase visible in the field (F_{ctd}, see description below). The Punta Rossa unit, which locally preserves pre-Alpine relationships between serpentinized ultramafics, Versoyen complex rocks, continental basement, meta-pillow lavas and metasediments has been the main subject of this study.

3.1. Punta Rossa Unit

The Punta Rossa Unit extends from the Torveraz valley in the south, where it is overlain by the Hermite unit, to the northern boundary of the study area (Fig. 2 and Fig. 3). This domain consists of serpentinized ultramafics, cataclastically deformed continental basement, including peraluminous meta-granitoids and Versoyen complex, meta-pillow lavas, polymictic breccias, micaschists and calcschists. Since the different lithologies are extensively described in the previous literature, this section will focus mainly on documenting the local preservation of pre-Alpine contacts and textures, which represents the main novelty of this study, allowing to reconstruct the pre-Alpine geometry of this domain.

3.1.1. Ultramafics

The two largest outcrops of serpentinized ultramafics are located on the ridge to the south-west of Punta Rossa and on the western side of Tormottaz Lake, while two relatively minor occurrences are found on the south-western slope of Punta Rossa and on the ridge line to the north of Miravidì, in the NW part of the study area (Fig. 2, Fig. 3 and Fig. 4; see also Masson et al., 2008). Serpentinite bodies display textural and mineralogical zoning, which are closely related to the distance from the surrounding polymictic breccias and continental basement rocks. At a distance in excess of 10 m, the texture of the pre-existing spinel lherzolite is generally preserved, with a weak foliation defined by the original spinel and cm-sized clinopyroxene, now completely replaced by aggregates of tremolite ± antigorite (Fig. 5a). No relicts of the original peridotitic mineral assemblage have been observed and both orthopyroxene and olivine are completely replaced by brucite and interlocking antigorite. Relicts of the peridotite texture disappear within a few meters from the contact with the polymictic breccia. In this setting, the massive serpentinite is locally replaced by a clast-supported tectonic breccia with variably sized angular clasts (Fig. 5b) largely consisting of antigorite, associated with tremolite + talc + rare carbonates. Different types of metasomatic rims, ranging in thickness from a few dm to over 2 m, are characteristically found along the contacts. They largely consist of tremolite, talc, carbonate, developed at the expense of the original peridotitic assemblage. Massive chloritites and ovardites are also characteristically found in this position.

3.1.2. Continental basement

In the Punta Rossa unit, laterally discontinuous slivers of crystalline basement rocks are commonly associated with ultramafics (Fig. 3 and Fig. 4b and c). The largest outcrops are located (1) on the Punta Rossa peak, (2) on the ridge to the south of the peak, (3) near Tormottaz Lake (Fig. 4b and c) and (4) near Bassa Serra col. Crystalline basement largely consists of leucocratic peraluminous metagranitoids, but relatively large masses of metamafic rocks, generally associated with black schists, are also found along the ridge to the south of Punta Rossa, at Tormottaz Lake (Fig. 4b and c) and to the north of Punta Rossa col.

Peraluminous granitoids locally preserve evidence of their pre-Alpine mineral paragenesis, which included pluri-mm sized white mica, quartz and K-feldspar, now largely replaced by aggregates of albite and fine grained white mica. As already noted in previous studies (Antoine, 1971 and Hermann, 1930), the granitoid was widely affected by cataclastic deformation, resulting in a blocky appearance at the outcrop scale. Domains devoided of this brittle overprint are relatively rare and restricted to the largest sliver of continental basement, preserved in the Punta Rossa area. The relative timing of brittle deformation with respect to Alpine metamorphism is best seen in the proximity of Tormottaz Lake. In this locality, angular polymineralic clasts ranging in size from a few millimeters to 3–4 cm, are wrapped around by a dark matrix, giving rise to a meso-scale texture typical of a fault breccia with mm-thick gauge layers (Fig. 5d). However, no evidence of brittle deformation is preserved at the microscopic scale, since the dark matrix hosts a chlorite + white mica fabric post-dating glaucophane and lawsonite porphyroclasts (now replaced by albite + chlorite aggregates and white + chlorite + epidote aggregates, respectively; Fig. 5e). These observations are interpreted as evidence that cataclastic deformation, which is responsible for the formation of angular clasts, pre-dated polyphase Alpine metamorphism.

As mentioned above, mafic rocks are also commonly found associated with the meta-granitoids. The most spectacular example is preserved in the Tormottaz Lake area (Fig. 4b, c), where a prasinite layer is locally interposed between ultramafics and leucocratic meta-granitoids. This rather homogenous metamafic layer, which largely consists of albite + chlorite + epidote + green amphibole, is in sharp contact with the metagranitoid. In two other circumstances, to the NW of the

Punta Rossa col and to the south of Bassa Serra col, meta-mafics, which are interlayered with black schists, giving rise to the typical Versoyen complex pair, preserve ophitic textures, evidence of their original intrusive protoliths. Near Bassa Serra col, metagranitoid dykes preserve intrusive relationships with the surrounding black micaschists typical of the Versoyen complex (Fig. 5c). Relatively large outcrops of meta-mafics and black schist are sometimes found within the gray micaschists. Typical occurrences are observed in the gray micaschist-dominated slope located directly to the north of the Punta Rossa peraluminous granitoid (Fig. 3).

3.1.3. Meta-pillow lavas

Meta-pillow lavas have been described from several localities within the field area. However, based on our observations, the only unambiguous evidence for basaltic lavas erupted at the seafloor is preserved near the Bassa Serra col (Fig. 2 and Fig. 5f and g; Loubat, 1968). In all other occurrences, including the outcrops to the NW of the Punta Rossa col and those to the W of Tormottaz Peak (Antoine, 1971), metamafics preserve evidence of ophitic textures, are interleaved with black schists and do not show any clear evidence of submarine flow, including lava tubes, pillows or varioles. As a result, in these localities the metamafic-black schist pair closely resembles the Versoyen complex, which is found throughout the Punta Rossa unit.

3.1.4. Metabreccia

The ultramafics and crystalline rocks described so far are invariably associated with metabreccias, which contain clasts of all the lithologies described above (Fig. 5h, i, j). Metabreccias are found directly in contact with ultramafics (ridge to the south of Punta Rossa; Fig. 4a), with leucocratic meta-granitoids (SE slope of Punta Rossa), with intrusive meta-mafics (to the NW of Punta Rossa col; Fig. 5j) and with meta-pillows (to the SE of Bassa Serra col). The lithological composition of this breccia is highly variable and is strongly controlled by the type of associated basement. Therefore, we opted for abandoning local denominations for the different meta-breccia outcrops, since our structural study (see Section 4) reveals that they were originally located along the same horizon. Therefore, this metasedimentary unit comprises the 'Punta Rossa conglomerate', the 'Miravidì breccia' and the pillow breccia. The thickness of the metabreccia is highly variable, probably as a combined effect of pre-Alpine geometry and Alpine deformation and ranges from a few meters, such as on the western side of Tormottaz Lake, where ultramafics and gray schists are separated by less than 5 m of polymictic breccia and meta-arkose, to about 20 m, on the ridge to the south-west of Punta Rossa.

A matrix-supported breccia, consisting of clasts of ultramafics ranging in size from 10 to over 40 cm in a serpentinite matrix crops out on the ridge to the SW of Punta Rossa (Fig. 5h).

In the Punta Rossa area, where continental basement is rather homogeneous, differentiating between cataclastically deformed basement and re-sedimented monogenic breccia is often very difficult, due to the extensive Alpine deformation and metamorphism. As a result, we opted for grouping together tectonic and sedimentary monogenic breccias in the map presented in Fig. 3 under the 'tectono-sedimentary breccia' label. In all circumstances, the first unambiguous occurrence of sedimentary breccias is marked by the presence of polygenic breccias with a black matrix.

Metabreccias often provide clear indications of stratigraphic polarity and preserve transitional contacts with the underlying crystalline rocks and the overlying gray micaschists. An excellent example is located to the NW of the Punta Rossa col, where overturned 'Versoyen complex' mafic layers and black schists are underlain by a 10 m thick breccia consisting of angular clasts, mostly of metamafics (Fig. 5j). This breccia is clast-supported in the proximity of the contact, but the matrix to clast ratio increases progressively while approaching the underlying gray micaschists.

3.1.5. Gray micaschists

Gray micaschists crop out continuously throughout the area, in contact with the metabreccia. Contacts with serpentinized ultramafics, such as at the base of the ridge to the SW of Punta Rossa (Fig. 3), are ascribed to the activity of Alpine shear zones (see below). A detailed description of the deformation/metamorphic evolution of this lithology is presented in Section 4. Gray micaschists consist largely of graphitic schists, which become progressively more carbonate-rich towards the overlying calcschists. Remarkably, microfossils, including radiolaria, are commonly found within this lithology (Fig. 5k), probably as a result of diagenetic pyritization, shielding them from subsequent deformation. Clasts of metagranitoids, metamafics and marbles are locally observed. Locally, such as to the north of Punta Rossa and to the east of Punta dei Ghiacciai, large outcrops of metamafics, which possibly originated as blocks, are also found within this lithology (Fig. 2 and Fig. 3). The contact between carbonate-rich micaschists and the overlying calcschists is either gradational or characterized by interlayered calcschists (Fig. 5l).

3.1.6. Calcschists

A large part of the central and northern part of the Breuil Valley is occupied by metasediments, which have normally been ascribed to the ‘Valaisan trilogy’ (Burri, 1979 and Trümpy, 1951; see Masson et al., 2008 for a different view on the significance of these metasediments). Discussions on the age of these metasediments and on their correlations with the ‘Valaisan Trilogy’ are beyond the scope of this study.

3.2. Hermite Unit

With ‘Hermite Unit’ we indicate the tectonostratigraphic unit generally separated from the underlying Punta Rossa Unit by a late-Alpine shear zone (Fig. 2 and Fig. 3), which is described in Section 4. The Hermite unit is separated from the overlying Petit St. Bernard unit by a late-Alpine shear zone marked by cargneules. The Hermite unit defined here corresponds to the northern part of the Versoyen–Petit St. Bernard unit of Masson et al. (2008) and to the southern part of the ‘Internal Valaisan Unit’ of Loprieno et al. (2011).

The Hermite Unit consists of Versoyen complex rocks (e.g. Loubat, 1968; Fig. 6a), Collet des Rousses metabreccias (Fig. 6b and c) and Arguerey calcschists (Antoine, 1971; Fig. 6d), which have already been extensively described in the literature. Due to Alpine metamorphism, the mafic layers of the Versoyen complex now consist of albite–chlorite–actinolite bearing metamicrogabbros, albite–chlorite–epidote bearing metadolerites and greenstones. In the Aiguilles de l'Hermite-Punta dei Ghiacciai area aegirine and glaucophane rims are observed around magmatic clinopyroxene. Crosscutting relationships between different dyke generations are preserved near Punta dei Ghiacciai (Fig. 6a).

The Collet des Rousses metabreccia is characterized by a laterally variable thickness and is locally absent at the Versoyen complex–Arguerey calcschist interface (Fig. 3).

The Arguerey calcschists represent the most common metasedimentary rock in the Hermite Unit. They consist of chlorite-white mica graphitic marble, phengitic micaschist, graphitic-carbonate paragreenstone, graphitic marble interlayered with chloritic marble and carbonate schist. Locally, the Arguerey calcschists contain rounded boulders of gray marble, which range in diameter from

30 cm to 1 m. Greenschist facies mineral assemblages, mainly consisting of chlorite + white mica are dominant, but pseudomorphs of white mica + epidote after former lawsonite and of albite + green amphibole after former blue amphibole are locally found.

New observations to the north of the Aiguilles de l'Hermite, possibly related to recent deglaciation, led to the recognition of a primary contact between the different lithologies of the Hermite unit (Fig. 6d). Versoyen complex rocks are in contact with a breccia consisting of blocks of mafics rocks in a dark micaschist matrix, attributed to the Collet des Rousses metabreccia. The metabreccia is in turn overlain by impure marbles, attributed to the Arguerey calcschists. Moving laterally along the top-basement surface, Arguerey calcschists are directly in contact with Versoyen complex rocks, suggesting an originally lenticular shape for the metabreccia.

In conclusion, these new observations on the Hermite unit indicate that the Collet des Rousses metabreccia was deposited above the Versoyen complex, prior to the deposition of the Arguerey calcschist. The laterally discontinuous distribution on the Collet des Rousses metabreccia is, at least in part, a pre-Alpine feature.

4. Deformation history

The deformation history of the study area has been reconstructed on the basis of observations of structural patterns, styles and overprinting relationships among different structures, fabrics and metamorphic mineral assemblages.

The observations have been portrayed in “deformation sequence diagrams” (Beltrando et al., 2008, Forster and Lister, 2008 and Viete et al., 2010), which integrate petrographic, micro- and meso-structural observations. The systematic creation of deformation sequence diagrams for key outcrops and different lithologies 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. The data is then presented in a concise form, where folding and shearing events are labelled F and SZ, respectively, static crystallization of metamorphic minerals is indicated as Δ and metamorphic fabrics axial planar to folds are indicated as S. Metamorphic conditions during deformation or characteristic minerals are indicated as sub-scripts.

In the study area, radiolaria-bearing micaschists of the Punta Rossa unit and black schists of the Versoyen complex preserve the most complete record of the petrographic and microstructural evolution, which in all other rock types has been largely obliterated by static recrystallization at greenschist facies conditions. Information provided by these lithologies has been integrated, when necessary, with observations from selected samples of different rock types. Correlations are discussed in the text and shown in the cumulative deformation sequence diagram presented at the end of this section. Due to the analogies of the deformation sequences between Punta Rossa and Hermite units, the deformation/metamorphic history is presented thoroughly for the Punta Rossa unit, which is the main subject of this study, and more succinctly for the Hermite unit. Our results for the Breuil Valley largely confirm the deformation history described for the Valaisan domain at large by Loprieno et al. (2011). However, the detailed account below is justified by the need to reconstruct the pre-Alpine architecture of the Punta Rossa unit.

4.1. Structural evolution of the Punta Rossa unit

The radiolaria-bearing gray micaschists, at the meso- and micro-scale, are characterized by a pervasive planar fabric, defined by white mica (Si = 3.3 a.p.f.u.) and chloritoid (S_{ctd}; Fig. 7a). Occasionally, the latter marks a mineral stretching lineation (L_{ctd}) oriented ca. NNE–SSW

(Fig. 10c). Locally, such as in the area located to the west of the Punta Rossa col (Fig. 7b), S_{ctd} is demonstrably axial planar to isoclinal folds that affect the entire lithostratigraphy (F_{ctd}). F_{ctd} axes are parallel to L_{ctd} (Fig. 10c). Relicts of an older deformation/ metamorphic history are rarely found at the outcrop scale, with older folds refolded by F_{ctd} (Fig. 7b). Mineral fabrics pre-dating S_{ctd} are often preserved in microlithons, where white mica with a high celadonite content (Si = 3.4–3.5 a.p.f.u.) defines a relict foliation. Further evidence of a pre-S_{ctd} evolution is indicated by former porphyroclasts that have been completely replaced by mineral aggregates, such as the rhomboidal aggregates of muscovitic white mica, paragonite and chlorite, possibly derived from earlier lawsonite porphyroblasts and the prismatic aggregates of chloritoid, quartz, white mica and chlorite, which may derive from former carpholite (Fig. 7a; Bousquet et al., 2002). The ubiquitous preservation of the original porphyroclast shape is interpreted as evidence that their re-quilibration post-dated the formation of S_{ctd}.

A second generation of chloritoid crystals is oriented at high angle with respect to S_{ctd}, often associated with small garnet porphyroblasts, with a diameter < 100 µm (Fig. 7a). These observations result in the following deformation sequence:

$$S_{lws-carph},\ S_{ctd},\ \Delta_{gt-ctd}$$

where and older foliation, defined by white mica, lawsonite and carpholite ($S_{lws-carph}$), is overprinted by a younger fabric (S_{ctd}), prior to the static growth of garnet and chloritoid (Δ_{gt-ctd}).

Folds associated with S_{ctd} are responsible for the frequent repetitions of the different lithologies of the Punta Rossa unit at the tens of meter scale, as observed in the area of the Punta Rossa col (Fig. 3 and Fig. 9a). Fold hinges are rare, but axial planes can be located based on parasitic fold asymmetry on the fold limbs and changes in polarity of the stratigraphic sequence. The most significant F_{ctd} fold in the area is responsible for the overturning of the entire lithostratigraphy of the Punta Rossa unit in the Breuil Valley (Fig. 9). The upper limb of this fold, which is restricted to the immediate proximity of the contact with the overlying Hermite unit (Fig. 7c and d), is characterized by a normal stratigraphic sequence, with ultramafics and continental basement overlain by tectonosedimentary breccia and radiolaria-bearing gray micaschists. The serpentinites on the ridge to the south-west of Punta Rossa (Fig. 7d) and the Punta Rossa metagranitoid crop out at the core of this F_{ctd} fold (Fig. 9). The lower limb of this large scale fold occupies the rest of the Breuil Valley, where, with a few exceptions described below, ultramafics and basement rocks consistently overlie metasediments. Overturned contacts are spectacularly exposed on the ridge to the south-west of Punta Rossa, where the tectonosedimentary breccia underlies the ultramafics (Fig. 7d), and on the southern slope of Punta Rossa, where hinges of parasitic F_{ctd} folds are responsible for the local exposure of polygenic breccia underneath Punta Rossa metagranitoids (Fig. 3 and Fig. 9b). Meta-igneous rocks crop out at the top of the lithostratigraphic pile also in the area to the north of the Punta Rossa col, where metamafic intrusives are underlain by the sedimentary breccia (Fig. 9), and in the northern part of the field area, near the Col di Bassa Serra, where metagranitoids, metamafics intrusive into black schists and meta-pillows overlie the Mesozoic metasediments (Fig. 5g).

Notably, in the southern part of the field area, to the south of the large-scale upright fold (F_{up}), which will be described below, metasediments crop out at the hinge of F_{ctd} antiforms, suggesting that the entire lithostratigraphy was already overturned prior to F_{ctd}.

Due to the rarity of F_{ctd} hinges observed in the field, the frequent changes in the stratigraphic polarity observed in the area could not be related in all circumstances to the existence of F_{ctd} axial planes. The presence of shear planes dissecting F_{ctd} folds is indeed considered likely at the base of the tectonosedimentary breccia underlying the large serpentinite body to the south-west of Punta Rossa (Figs. 7c and 9a). In this locality a serpentinite sliver less than 5 meters thick is immediately underlain by radiolarian micaschists, without the interposition of the tectonosedimentary breccia found immediately above. A similarly abrupt transition is observed immediately to the north, where small serpentinite slivers, which preserve a primary contact with the overlying metagranitoid and tectonosedimentary breccia, are underlain by a highly foliated tectonosedimentary breccia, without any evidence of a F_{ctd} hinge. The proposed post-F_{ctd} shearing could not be responsible for significant relative motion, given that it did not result in significant excision of rock types and is probably related to the motion along the Punta Rossa–Hermite units (SZ_{gr}) described below.

Locally, such as in the micaschist outcrops on the NW side of Tormottaz Lake, S_{ctd} is affected by meso-scale folds with rounded hinge, an interlimb angle of ca 80°, axial plane dipping to the West (270/40) and fold axis oriented NS (Fig. 10e and f). Such folding is associated with the formation of a new axial planar cleavage, with sub-mm to mm spacing, normally restricted to the hinge area (Fig. 7e). The new fabric is defined by white mica, chlorite, quartz and graphite and is labeled S_{rec} (where 'rec' indicates 'recumbent'). Folding is also responsible for deformation of the white mica aggregates developed at the expense of porphyroclastic lawsonite.

The relationships between the different fabrics and assemblages observed in this area can be summarized as follows:

$$S_{lws-carph}, S_{ctd}, \Delta_{wm}, S_{rec}.$$

As apparent from Fig. 10e and g, F_{rec} axial planes dip alternatively to the east and west at low to moderate angles, as a result of the later F_{up} folding (see below). The study area is characterized by two km-scale F_{rec}, spectacularly exposed on the eastern slope of the Tormottaz and Punta Rossa peaks (Figs. 7f and 9b) and to the north of the Aiguilles de l'Hermite, in the Hermite unit (Fig. 9a). The Tormottaz Lake serpentinite crops out in the hinge of a F_{rec} synform (Fig. 3 and Fig. 4b, c and 9b). Apart for this example, F_{rec} folds have a relatively limited impact on the scattering of older structural elements, since most of the field area is located in the interlimb area between the axial planes of the two large folds mentioned above. F_{rec} is responsible for the local presence of Versoyen complex rocks, which have been attributed to the Hermite unit, underneath the Punta Rossa unit at the bottom of the Breuil Valley (Fig. 3 and Fig. 9b), indicating that the two units were already juxtaposed prior to the folding event.

Significantly, except for this relatively small outcrop, the Punta Rossa and Hermite units are separated by a tectonic contact that postdates F_{rec}. This contact is slightly discordant with respect to the pre-existing lithological boundaries and to the axial planes of F_{ctd} and F_{rec} and largely nucleated in the metasediments overlying the Punta Rossa serpentinite and metagranitoid (Fig. 3 and Fig. 7c and d, 9). Asymmetric folding of the pre-existing planar surfaces, such as lithological contacts in the metasediments and S_{ctd} in the micaschists, is characteristically found within ca. 10 m from this contact and consistently indicates top-to-the-southeast shearing developed at the expense of an originally steeply-dipping layering (Fig. 7g). Microscopic observations (Fig. 8a) indicate that the SE dipping chlorite-rich shear planes (Fig. 10h), which are common within 2–4 m from the contact, cut across chlorite-rich pseudomorphs developed at the expense of former chloritoid (Δ_{gr}). These observations are taken to indicate that top-to-the-southeast shearing took place at greenschist facies conditions (SZ_{gr}). The sequence of deformation and metamorphic event that is commonly observed in the close proximity of the shear zone (Fig. 8a) can be summarized as follows:

$$S_{ctd},\Delta_{gr},SZ_{gr}$$

indicating that a pre-existing fabric characterized by chloritoid (S_{ctd}) is statically overprinted at greenschist facies conditions (Δ_{gr}) prior to shearing at greenschist facies conditions (SZ_{gr}).

Further evidence of shearing at greenschist facies conditions at the Punta Rossa–Hermite unit interface is preserved in the northern part of the area, to the west of the Lacs du Glacier d'Arguerey (Fig. 2 and Fig. 3), where unambiguous shear sense indicators have not been found either at the outcrop or microscope scale.

This SZ_{gr} contact is then affected by large-scale upright folds (F_{up}) characterized by steep axial planes and NNE–SSW to NE–SW striking fold axes (Figs. 8b, Fig. 9 and Fig. 10j and k). F_{up} folds are characterized by a box fold geometry and by relatively large along-axis strain gradient, resulting in significant variations in the fold amplitude. At the outcrop scale, F_{up} folds can locally be associated with a spaced axial planar cleavage restricted to a few outcrops to the north-west of the Tormottaz peak. More commonly, F_{up} results in re-orientation of pre-existing planar features at all scales. The relationship between the latter folding event and the metamorphic evolution undergone by the Punta Rossa unit is best seen in samples of the sedimentary metabreccia (Fig. 8c). In this lithology a mineral fabric defined by chlorite and white mica, which is axial planar to recumbent folds comparable to F_{rec} observed in the radiolaria-bearing micaschists, is affected by open folds with sub-vertical axial planes and NNE–SSW trending axes. These folds are statically overgrown by albite porphyroblasts. This sequence of deformation and metamorphic episodes (Fig. 8c) can be summarized as follows:

$$S_{rec},F_{up},\Delta_{ab}.$$

A spectacular example of this folding event can be observed to the NW of Punta Rossa, where a large-scale antiformal box fold affects the S_{ctd}-dominated sequence (Fig. 9). As result, the originally SE-dipping S_{ctd} mineral fabrics, which are characteristic of the Punta Rossa area, become horizontal in the wide F_{up} hinge area, prior to becoming WNW-dipping towards the Tormottaz Lake (Fig. 9).

The Punta Rossa unit is also affected by large scale faulting, which post-dates all the deformation events described above. Steep, SE-dipping normal faults are observed in the serpentinite-rich ridge to the south of Punta Rossa. Brittle deformation is associated with fracturing of the original antigorite serpentinite and crystallization of chrysotile. Movement along these faults is probably responsible for the local rotation of F_{up} axes observed along this ridge (Fig. 3 and Fig. 10j and k). Normal faults also rework the northern boundary of the Punta Rossa body. Although they can only be directly observed in the NE-most part of this domain, close to the Doire de Verney stream bed, the presence of a normal fault buried underneath the rock debris to the north of Punta Rossa is also proposed.

Another major fault overprints the contact between the Punta Rossa and Hermite units between Tormottaz Lake and the Collet des Rousses. This high-angle, NS trending structure is defined by the alignment of cargneule outcrops and by the widespread evidence of cataclastic deformation and chlorite–albite filled veins in the metamafics and tectonosedimetary breccia.

The cumulative deformation sequence diagram of the Punta Rossa unit, obtained by correlating observations performed on single outcrops/samples, is shown in Table 1.

4.2. Hermite unit

The deformation/metamorphic record preserved in the Arguerey calcschists and in the Versoyen black schists of the Hermite unit is comparable to the one observed in the Punta Rossa micaschists. Detailed structural observations in the Hermite unit are generally hampered by the steep slopes and glaciers and are largely restricted to the Torveraz Valley (Fig. 3). This domain is characterized by an ENE–WSW trending band of metasediments, largely consisting of Arguerey calcschists and minor Collet del Rousses metabreccias, bounded to the north and south by Versoyen complex rocks (Fig. 3). The metasediments are characterized by a pervasive foliation that, in the western part of the area, is demonstrably axial planar to a tight antiform with axis 252/12 (Figs. 9a, 10m and 11a). The axial planar fabric (S_{ctd}), which is characterized by chloritoid (now completely replaced by chlorite + white mica + quartz + titanite), is then affected by tight folds (F_{rec}) with axis oriented NNE–SSW (Figs. 10n and o). F_{rec} is locally associated with a spaced crenulation cleavage in the black schists and Arguerey calcschists, while no axial planar foliation is observed in the other rock types. F_{rec} pre-dated the pervasive re-equilibration of the chloritoid porphyroclasts in greenschist facies conditions, as suggested by the preservation of the original chloritoid sites despite pervasive folding. F_{rec} folds are spectacularly exposed on the slopes of the Aiguilles de l'Hermite (Figs. 9a and 11b), where Versoyen complex, Collet des Rousses meta-breccias and Arguerey calcschists are affected by a large recumbent fold with NS trending axis and axial plane alternatively dipping to the north and to the south, due to later folding by F_{up} (see below). As a result of F_{rec}, Collet des Rousses metabreccia and Arguerey calcschists crop out alternatively above and below the Versoyen complex. As already mentioned in the previous section, Versoyen complex rocks are also found at the bottom of the Breuil Valley, near the Barmettes (lower right part of Fig. 3). In this location, the main mineral fabric in the associated black schists (S_{ctd}) dips below the overlying Punta Rossa unit lithologies (Fig. 9b). This single occurrence of Hermite unit geometrically below the Punta Rossa unit is ascribed to the large-scale axial plane of F_{rec} exposed in the Punta Rossa unit, a few tens of meters to the south. It should be noted that the attribution of this small outcrop to the Hermite unit, rather than to the Punta Rossa unit, which also hosts Versoyen complex rocks, is based on (1) the lack of evidence of cataclastic deformation, which is common in the neighboring meta-peraluminous granitoid and (2) the lack of intrusive relationships between peraluminous granitoid and Versoyen complex, which are observed elsewhere (Fig. 5c).

In the Torveraz Valley, F_{ctd} and F_{rec} axial planes are dissected by the contact between the Hermite and Punta Rossa units, providing further evidence that the present-day interface was largely established as a result of post-F_{rec} shearing (Fig. 3).

All the above structural elements are affected by F_{up} folds (Fig. 10q). An F_{up} synform is spectacularly exposed on the NE slope of Aiguille de l'Hermite, where it refolds the F_{rec} (Fig. 9 and Fig. 11b). Further F_{up} folds are responsible for the large amplitude re-orientation of the Versoyen complex in the eastern slope of the Punta dei Ghiacciai.

S_{ctd} in Arguerey calcschists and Versoyen black schists is often dissected by an extensional crenulation cleavage steeply dipping to the SE (SZ_{SE}; Figs. 10p and 11c). These shear planes, which are characterized by a spacing of several millimeters, are especially well developed towards the contact with the overlying Petit St. Bernard (PSB) unit. This contact is never exposed and the interface between Hermite and PSB unit is mapped following a sequence of cargneule outcrops found throughout the area. On the ridge to the south of the Collet des Rousses, the sharp contact between Hermite and PSB units cuts at a high angle the lithological layering of the Collet des

Rousses metabreccia, which is transposed by F_{rec} (Fig. 11d). This observation indicates that shearing along the Hermite-PSB interface post-dated F_{rec}. The relative timing of SZ_{SE} and F_{up} could not be established, due to the lack of F_{up} folds in the southern part of the area.

5. Raman Spectroscopy on Carbonaceous Material (RSCM)

The Raman Spectroscopy of Carbonaceous Material (RSCM) technique is based on the observation that sedimentary carbonaceous material is progressively transformed to graphite with increasing metamorphism. Beyssac et al. (2002) found a linear relationship between temperature and the structural state of CM quantified by Raman microspectroscopy. Because of the irreversible character of graphitization, CM structure is not sensitive to the retrograde path during exhumation of rocks but preserves the structure acquired at maximum *T* during metamorphism (Beyssac et al., 2002). For this reason, the RSCM method represents a powerful tool for characterizing metasedimentary sequences lacking diagnostic mineral assemblages. Temperature can be determined in the range 330–650 °C, with a precision of ± 50 °C due to uncertainties of petrologic data used for calibration. Relative uncertainties on *T* are, however, much smaller (~ 10–15 °C: Beyssac et al., 2004).

Nine representative samples have been selected for RSCM analyses from the Punta Rossa, Hermite and Petit St. Bernard units (Table 2; see Fig. 2 for sample location). With the exception of two Versoyen-type black schists from the Hermite unit (VA 27 and 28) all other samples were selected from Mesozoic metasediments. In the Punta Rossa unit, two samples were taken from the radiolaria-bearing micaschists directly in contact with the meta-pillow lavas near the Bassa Serra col (VA63; Fig. 5g) and close to the ultramafics to the north of Miravidì peak (VA 13; Fig. 2). A further sample (VA 15) was taken from Marmontains quartzite, a few tens of meters (stratigraphically) upsection with respect to VA 13.

Samples of the Hermite unit were collected both from the Versoyen black schists, within an albititic layer less than 2 m from a meta-dolerite sill (VA27) and further from any mafic layer (VA28), and in the overlying Arguerey calcschists (VA 21).

All samples from the Petit St. Bernard unit were collected from the Petit St. Bernard calcschists in different parts of the area. VA57 was taken within a few tens of meters from the Houiller Front, VA 61 from the middle of the PSB calcschists and VA70 from the cherty marble stratigraphically overlying the Upper Triassic to Lower Jurassic metasediments in the eastern part of the study area.

The selected samples do not show evidence of pre-Alpine metamorphism or pre-Alpine detrital mineral relicts. Results are reported in Table 2 and Fig. 2. The obtained *T* ranges from 391 to 467 °C. The samples from the Petit St. Bernard unit yield estimates in the 459–467 °C range. Temperatures estimated from three samples from the Hermite unit show a rather wide scatter, from 400 °C to 412 °C and 426 °C. Slightly lower temperatures are observed in the Punta Rossa unit, where *T* ranges from 391 to 400 °C.

These results indicate that the Petit St. Bernard unit experienced significantly higher Alpine temperatures than the underlying Punta Rossa and Hermite units. Therefore the Petit San Bernard unit can be interpreted as an independent metamorphic (i.e. thermometric) unit. On the other hand, the temperature ranges estimated for the Hermite and Punta Rossa units partly overlap. Therefore, the two units cannot be distinguished from a thermometric point of view. Significantly, sample VA27, collected close to a metamafic dyke, does not show thermal perturbations due to magma intrusion, indicating that contact metamorphic temperatures did not exceed Alpine temperatures.

6. Discussion

6.1. Alpine tectonometamorphic evolution

In this study, the mafic and ultramafic rocks and associated metasediments of the Valaisan domain in the Breuil Valley have been subdivided in three sub-units (Fig. 2 and Fig. 3). This subdivision, as argued below, is based on lithostratigraphic and structural criteria, which have been integrated with a thermometric study by Raman spectroscopy on carbonaceous material.

The Petit St. Bernard unit, which has been dealt with only marginally in this contribution, has generally been considered as an independent tectonometamorphic unit, on the basis of structural (e.g. Loprieno et al., 2011) and lithostratigraphic studies (Antoine, 1971 and Elter and Elter, 1957; see Masson et al., 2008 for an alternative interpretation). Our study confirms this commonly held view, showing that the PSB calcschists experienced Alpine temperatures in the 450–470 °C range, distinctively higher than the underlying units. Furthermore, structural mapping (Fig. 3) shows that the PSB calcschists are separated from the underlying units by a tectonic contact that accommodated top-to-the-SE shearing, leading to the widespread formation of shear bands (SZ_{SE}), especially in the Arguerey calcschists (Fig. 11c). This contact is clearly discordant with respect to the trace of the axial planes of two oldest fold generations that can be followed across the area (F_{ctd} and F_{rec}; Fig. 3). The relationship between shearing and the youngest folding generation (F_{up}) could not be determined due to the lack of F_{up} folds in the southern part of the study area. It is unclear whether extensional deformation along the Hermite–PSB unit interface was contemporaneous with top-to-the-SE shearing along the contact between Hermite and Punta Rossa units, which also post-dates F_{rec}. The two shear zones converge towards the bottom of the Breuil valley (Fig. 3 and Fig. 9b), where exposure is relatively poor, preventing observations of cross-cutting relationships.

The maximum timing of juxtaposition between the Petit St. Bernard unit and the underlying Hermite unit is best constrained in the Aiguille de Clapet area, on the French side of the pass (Loprieno et al., 2011). In this area the contact between the two units, which was established by pre-F_{rec} thrusting, is deformed by F_{rec} (labeled F2 by Loprieno et al., 2011). Therefore, in the Breuil Valley, this contact is reactivated by younger deformation events.

In this study, the serpentinite, metamafics and metasediments that crop out underneath the Petit St. Bernard unit have been grouped in two distinct tectonostratigraphic units, named Punta Rossa and Hermite units. This subdivision is in contrast with earlier studies, where the two units are generally grouped under the common label of Internal Valaisan Domain (Fügenschuh et al., 1999) or Versoyen Unit (Loprieno et al., 2011). Our approach is based on a range of observations on the present-day architecture of the area and on the lithological composition of the two units. In the Breuil valley, the Hermite and Punta Rossa units are persistently separated by a greenschist facies shear zone (SZ_{gr}), which has also been observed to continue to the west of the study area (Masson et al., 2008). Importantly, this tectonic contact dissects the two oldest fold generations that characterize both the Hermite and Punta Rossa units (F_{ctd} and F_{rec}). In the eastern part of the study area, near the Doire de Verney river bed (Fig. 3), in the footwall of the SZ_{gr} shear zone, Versoyen metagabbros attributed to the Hermite unit are locally folded together with the Punta Rossa unit by F_{rec}, thus indicating that their juxtaposition pre-dated large-scale recumbent folding. The rarely preserved pre-F_{rec} contact and the SZ_{gr} shear zone separate two domains with significantly different lithostratigraphic associations. The Hermite unit, as described above, largely consists of meta-mafics intrusive into black schists (Versoyen complex), locally overlain by a polymictic metabreccia and meta-arkose sequence (Collet des Rousses metabreccia), followed upward by the Arguerey calcschists. The Punta Rossa unit, instead, consists of large slivers of serpentinized ultramafics, slivers of peraluminous metagranitoids, minor metamafics intrusive into black schists (Versoyen complex), meta-pillows, abundant metabreccias, radiolaria-bearing gray micaschists and a thick sequence of largely carbonatic meta-sediments. Significantly, the thus defined lithostratigraphic units are never found folded together by the oldest fold generation visible in the field (F_{ctd}).

On the other hand, our microstructural and Raman spectroscopy study shows that the two units display a similar tectonometamorphic evolution, with high-pressure metamorphism followed in both units by F_{ctd}. Temperature maxima, in the 390–420 °C range, were probably reached during the formation of S_{ctd} or immediately afterwards and were accompanied by the destabilization of carpholite and lawsonite, as also shown by Bousquet et al. (2002). RSCM *T* of the Punta Rossa and Hermite units (~ 400 °C) are lower than those estimated for the same rocks by Bousquet et al. (2002; 450–500 °C) by means of the chlorite-chloritoid thermometer. The observations listed above support the conclusion that the juxtaposition between the two units can only be demonstrably constrained between pre-F_{rec} and post-F_{ctd} times. However, our conclusion does not rule out the possibility that the two units were already juxtaposed before F_{ctd}, but that such structural evidence, in the Breuil valley, has been erased by subsequent deformation.

6.2. Detection of rift-related stratigraphic relationships in poly-deformed Alpine-type terrains

The understanding of the pre-orogenic relationship between different rock types relies on the detection of primary stratigraphic contacts. This task, in polydeformed and metamorphosed terrains, may be significantly hampered by reactivation of lithological contacts and by pervasive recrystallization. Despite these potential difficulties, several key observations from the Hermite and Punta Rossa unit indicate that pre-Alpine relationships between the different lithologies are preserved, at least locally. In this brief discussion we wish to point out the key observations that allow to reconstruct the rift-related lithostratigraphy of the Valaisan basin.

6.2.1. Mantle exhumation in the Punta Rossa unit

As shown in the previous sections, the Punta Rossa unit consists of serpentinized ultramafics that are alternatively in contact with polymictic breccias, crystalline rocks of mafic composition and peraluminous meta-granitoids. Exhumation of the ultramafics at the basin floor is indicated by the local occurrence of a matrix-supported ultramafic breccia directly in contact with the large serpentinite body to the south-west of Punta Rossa (Fig. 5h). Other potentially primary contacts are preserved at the southern end of this ridge, where a clast-supported ultramafic breccia, with angular clasts, interpreted of tectonic origin, is directly overlain by a polymictic sedimentary breccia with clasts of micaschists and granitoids (Fig. 4a). In this context the fault breccia may still mark the original fault plane responsible for the exhumation of the ultramafics at the basin floor. Importantly, polymictic breccias are also found directly in contact with monogenic breccias with clasts of granitoid composition, which grade into the Paleozoic peraluminous granitoids. This observation, indicating that sedimentary breccias were deposited both above exhumed ultramafics and continental basement, provides indirect evidence of their juxtaposition prior to sediment deposition. Furthermore, similarly to the ultramafics, the peraluminous metagranitoids preserve widespread evidence of cataclastic deformation pre-dating Alpine metamorphism (Fig. 5d, e), while no evidence of cataclastic deformation is found in the metasediments.

Primary relationships between continental basement and metabreccias are often observed, with continental basement grading upward to a clast-supported monogenic breccia (Fig. 5j), with clast composition strongly controlled by the neighboring lithologies. The clast to matrix ratio decreases progressively until clasts disappear and the dominant rock type consists of a gray micaschists, which in thin section preserves evidence of radiolaria and other microfossils. This is the first lithology that can be traced continuously throughout the Punta Rossa unit, as opposed to the markedly discontinuous rock types described so far (Fig. 3 and Fig. 9). At outcrop and valley scale, the micaschists appear to seal the ultramafics/continental basement/metabreccia association.

The presence of this continuous micaschist layer is also at the base of the correlation between the slivers of continental basement and meta-pillows located near the Bassa Serra col and the metamorphic basement located further south, in the Punta Rossa and Tormottaz area. Indeed, the Bassa Serra Col area is characterized by relatively poor outcrop conditions, which require some care when correlating with the better exposed Punta Rossa area. However, the finding of overturned meta-pillows grading downward to meta-pillow breccias with a dark micaschist matrix, then replaced by the gray micaschists identical to those found further to the south is interpreted as evidence that the pillows, prior to the depositions of the radiolaria-bearing shale, laid at the same structural level as the slivers of Paleozoic basement.

The radiolaria-bearing gray micaschists locally host large blocks of the different types of basement rocks found in the Punta Rossa unit, with a predominance of Versoyen-type slivers. We suggest that they may represent olistoliths re-sedimented from neighboring basement highs. However, we cannot exclude that, at least locally, they may represent hinges of F_{ctd} or older fold generations.

As already noted by Antoine (1971), the micaschists become progressively richer in carbonates away from the continental basement and breccia. Towards their stratigraphic top, they are locally interlayered with calcschists, prior to the onset of widespread carbonate sedimentation. The latter is characteristic of the ‘Valaisan Trilogy’ metasediments, which are exposed in the lower part of the Breuil Valley.

The resulting pre-Alpine crustal architecture of the Punta Rossa unit (Fig. 12) consists of serpentinized ultramafics locally exhumed at the basin floor and overlain by laterally discontinuous slivers of Paleozoic continental basement. The latter consists of Versoyen complex rocks intruded by peraluminous granitoids. Exhumation was accomplished through motion along faults, whose activity ultimately resulted in the juxtaposition of mantle rocks and continental basement that presumably originated from upper crustal levels. Extensional tectonics were probably accompanied or immediately followed by minor mafic magmatism, leading to submarine lava flows, well preserved only in one locality. The rare mafic dykes intrusive into the Punta Rossa granitoids may also be related to this minor magmatic activity. The thus established lithostratigraphic association provided the source for abundant clastic sedimentation. The clast size, combined with the observation that, at least initially, the clast composition mirrors closely the type of underlying basement rocks, suggest limited transport, potentially related to local infill of topographic lows. This stage was followed by widespread pelagic sedimentation, probably largely draping the existing basement topography, putting an end to re-sedimentation of basement clasts, with the exception of occasional olistoliths.

Therefore, the lithological composition and pre-Alpine architecture of the Punta Rossa unit displays several similarities with hyper-extended margins and Ocean–Continent transition zones from present-day and fossil magma-poor rifted margins (e.g. Florineth and Froitzheim, 1994, Manatschal, 2004 and Péron-Pinvidic and Manatschal, 2009). In these domains, subcontinental mantle is exhumed at the footwall of low-angle detachment faults. Motion along such faults results in tectonic erosion of slivers of continental basement from the hanging wall block, which remain as isolated slivers resting upon ultramafics (continental allochthons of Manatschal, 2004).

6.2.2. Hermite Unit

This newly defined tectonostratigraphic unit comprises basement rocks and metasediments that are generally separated from the underlying Punta Rossa unit and the overlying Petit St. Bernard unit by late-stage tectonic contacts that dissect the two generations of folds (F_{ctd} and F_{rec}) that post-dated high-pressure metamorphism in the Hermite and Punta Rossa units. It should be noted again that this new subdivision is based on present-day structural relationships as well as on lithostratigraphic considerations. As shown in the previous sections, younging directions in the Hermite unit are locally indicated by cross-cutting relationships between the Versoyen complex and the Collet des Rousses metabreccias, which rework Versoyen-type lithologies. Similarly to the tectonosedimentary breccia of the underlying Punta Rossa unit, the Collet des Rousses metabreccias are laterally heterogeneous and taper out locally. This geometry, in specific circumstances, such as to the NE of Aiguilles de l'Hermite, is demonstrably unrelated to Alpine deformation, suggesting that the metabreccias were probably deposited preferentially in topographic lows. Significantly, the composition of the clasts is more varied than for the Punta Rossa unit, displaying abundant gray marbles alongside the Versoyen-type rocks, suggesting that they originated from a different source area with respect to the metabreccia of the Punta Rossa unit. The Collet des Rousses metabreccia grades upward into the Arguerey calcschists, which display several similarities with the more carbonate-rich part of the radiolaria-bearing garnet–chloritoid micaschists of the Punta Rossa unit.

As already discussed above, the two units were probably already juxtaposed in the early phases of their exhumation history, when early high pressure-low temperature mineral assemblages re-equilibrated at T = 390–420 °C. However, the relative position of Punta Rossa and Hermite units prior to Alpine deformation cannot be constrained unambiguously in the Breuil Valley. An origin from different parts of the margin is favored based on the lack of evidence of pre-Alpine brittle deformation in the Versoyen complex of the Hermite unit and on the abundance of gray marble clasts, possibly derived from erosion of a shallow water carbonate platform located further inland.

6.3. Comparison with previous studies: timing of mafic magmatism

The study presented here suggests a new subdivision of the lithostratigraphic units of the Valaisan domain in the Petit St. Bernard area and provides new key observations on the polarity of the different lithostratigraphic units, as well as some insights on the timing of magmatism in the area.

The relationship between Versoyen complex, Petit St. Bernard unit and Collet des Rousses metabreccia represents one of the most controversial points among pre-existing studies, since it lays at the base of the attribution of the Versoyen complex magmatism to the Cretaceous. The Collet des Rousses metabreccia has been alternatively considered as the stratigraphic base (Masson et al., 2008 and Schoeller, 1929) or top (Elter and Elter, 1965) of the Petit St. Bernard calcschists. On the other hand, Antoine (1971) and Loprieno et al. (2011) suggested that it may represent the stratigraphic base of the Versoyen complex, thus constraining its mafic magmatism to the Mesozoic. However, as shown here (Fig. 6d), the Collet des Rousses metabreccia was deposited above Versoyen complex rocks, which are also reworked in the overlying breccia (Fig. 6c and d). Indeed, direct dating of the mafic sills characteristic of the Versoyen complex is still lacking, despite several attempts (Masson, pers. comm.). However, mafic rocks associated with the sills have already been dated to the Paleozoic, with a Carboniferous magmatic phase (Masson et al., 2008) followed by intrusion of leucogabbros in the Permian (Beltrando et al., 2007). Furthermore, interlayered mafic sills and black schists identical to the Versoyen complex are intruded by granitoid dykes (Fig. 5c; Mugnier et al., 2008), which in the area have also been dated to the Permian (267 ± 1 Ma; Beltrando et al., 2007). Also, the trace element composition of the Versoyen-type metamafics is markedly different from the mafic dykes intrusive in the Punta Rossa granitoids

(Mugnier et al., 2008). These dykes, together with the meta-pillows, are the only mafic rocks demonstrably younger than 267 ± 1 Ma in the area. Therefore, despite the lack of radiometric age determinations, several lines of evidence seem to indicate that the Versoyen complex was part of the Paleozoic basement of the distal European margin. As a result of crustal stretching along the distal European margin, Versoyen complex rocks were directly exposed at the floor of the Valaisan basin and were overlain by Collet des Rousses breccia and Arguerey calcschists, now preserved in the Hermite unit. In the more distal parts of the margin, complete crustal excision resulted in the local sampling of Versoyen-type basement alongside windows of exhumed mantle, as preserved in the Punta Rossa unit.

Our structural study confirms the commonly held views on the overturned polarity of the fine-grained metasedimentary sequence of the northern part of the Breuil valley, which, as shown in the previous sections is in stratigraphic continuity with the Punta Rossa basement rocks. Masson et al. (2008) proposed an alternative interpretation, suggesting that the 'Valaisan Trilogy' is not overturned and is capped by a gray micaschist with large blocks of Versoyen complex, representing a syn-orogenic flysch deposit (Merchandeur wyldflysh). Furthermore, Masson et al. (2008) proposed that the wildflysch is separated from the overlying Versoyen complex by an Alpine thrust, especially evident to the north of Miravidì peak. Our observations support the existence of this Alpine shear zone, which separates the Hermite unit from the underlying Punta Rossa unit (Fig. 3 and Fig. 9a). However, we wish to highlight that, in the Breuil Valley, the micaschists with Versoyen blocks can be traced laterally in the radiolaria-bearing gray micaschists that are directly in contact with the Paleozoic basement and the tectonosedimentary breccia of the Punta Rossa unit (Fig. 3). This observation indicates that their deposition pre-dated the sedimentation of the Valaisan Trilogy. However, we cannot exclude that some of the Versoyen-type slices in the immediate footwall of the tectonic contact between the Hermite unit and Punta Rossa units, to the east of Punta dei Ghiacciai, may be related to motion along slightly discordant shear zones associated with this interface.

6.4. Paleogeographic implications

The study presented here displays evidence for mantle exhumation and limited submarine magmatic activity within the Valaisan basin. Therefore, complete crustal excision was locally achieved within this domain, whose lithostratigraphic association displays several similarities with the transitional areas between typical continental and oceanic crustal domains in present-day magma-poor rifted margins. There is now a growing body of evidence that similar lithostratigraphic domains, originated from the more southerly located Piemonte–Liguria basin (Fig. 1), have been involved in the Alpine orogeny throughout the Western Tethyan realm. Early findings in relatively poorly deformed and metamorphosed sections of the peri-Mediterranean orogens (e.g. Cello and Mazzoli, 1999, Froitzheim et al., 1994, Marroni and Pandolfi, 2007 and Molli, 1996) have been recently confirmed in highly metamorphosed and deformed areas of the Western Alps (Beltrando et al., 2010 and Dal Piaz, 1999) and Corsica (Vitale Brovarone et al., 2011).

A similar lithostratigraphic association within the Valaisan domain has so far been reported only from the Tasna unit, in the Engadine window (Florineth and Froitzheim, 1994 and Manatschal et al., 2006). The overall pre-Alpine architecture of the Valaisan domain at the Petit St. Bernard pass displays some similarities and important differences with respect to Tasna. In contrast to Tasna, in the Punta Rossa unit mantle exhumation was followed/accompanied by minor mafic magmatism. Evidence of significant sedimentation post-dating magma extrusion and pre-dating the onset of sedimentation of the Valaisan trilogy, probably in the Cretaceous, may suggest a pre-Cretaceous age for crustal thinning in this part of the Valaisan Domain. Indeed, Jurassic magmatism has been reported from the Misox Zone, which belongs to the Valaisan units of the Swiss Alps (Liati et al., 2005).

Another important difference with respect to Tasna is related to the large amount of reworking of the ultramafics and continental basement rocks, which in Tasna is restricted to the first few centimeters overlying the top-basement detachment faults (Florineth and Froitzheim, 1994). In the Petit St. Bernard area, instead, the mantle exhumation surface is invariably sealed by thick, coarse clastic deposits. This observation may be indicative of significant topography and/or of the presence of abundant source rocks nearby. This conclusion is supported by the similar breccia that overlies the Paleozoic basement of the Hermite unit.

Therefore, we conclude that the Valaisan domain was floored by highly thinned continental crust and, at least locally, by mantle windows and lava flows. Indirect evidence indicates a pre-Cretaceous age for mantle exhumation, suggesting that crustal thinning in the Valaisan basin may have been kinematically linked with opening of the Western Tethys. Importantly, the detection of exhumed mantle lithosphere and limited mafic magmatism in the Punta Rossa unit should not be taken as an indication of the existence of an Oman-type oceanic crust in the parts of the Valaisan basin originally located further outboard. At present, there is no evidence that this type of mafic oceanic crust ever formed in the Valaisan domain.

6.5. Conclusion

This study of the Valaisan units at the Petit St. Bernard pass, at the French–Italian border, shows that rift-related crustal thinning in the Mesozoic led to local exhumation of subcontinental mantle to the sea floor. Evidence of complete crustal excision is presently preserved only in the Punta Rossa tectonostratigraphic unit, where exhumed mantle is directly overlain by laterally discontinuous slivers of Paleozoic basement and occasional meta-pillow lavas. Paleozoic basement alternatively consists of peraluminous metagranitoids and interlayered metagabbros and metadolerites intrusive into black schists. Ultramafics and Paleozoic basement are overlain by sedimentary breccias, which grade upward into radiolaria-bearing gray micaschists and into the largely carbonatic sediments of the Valaisan trilogy. The lithostratigraphic association described above is generally overturned, as a result of a multi-stage deformation history. This multistage deformation history, combined with a rift-related architecture characterized by discontinuous slivers of continental basement and metabreccias, is responsible for the complex outcrop pattern observed in the field.

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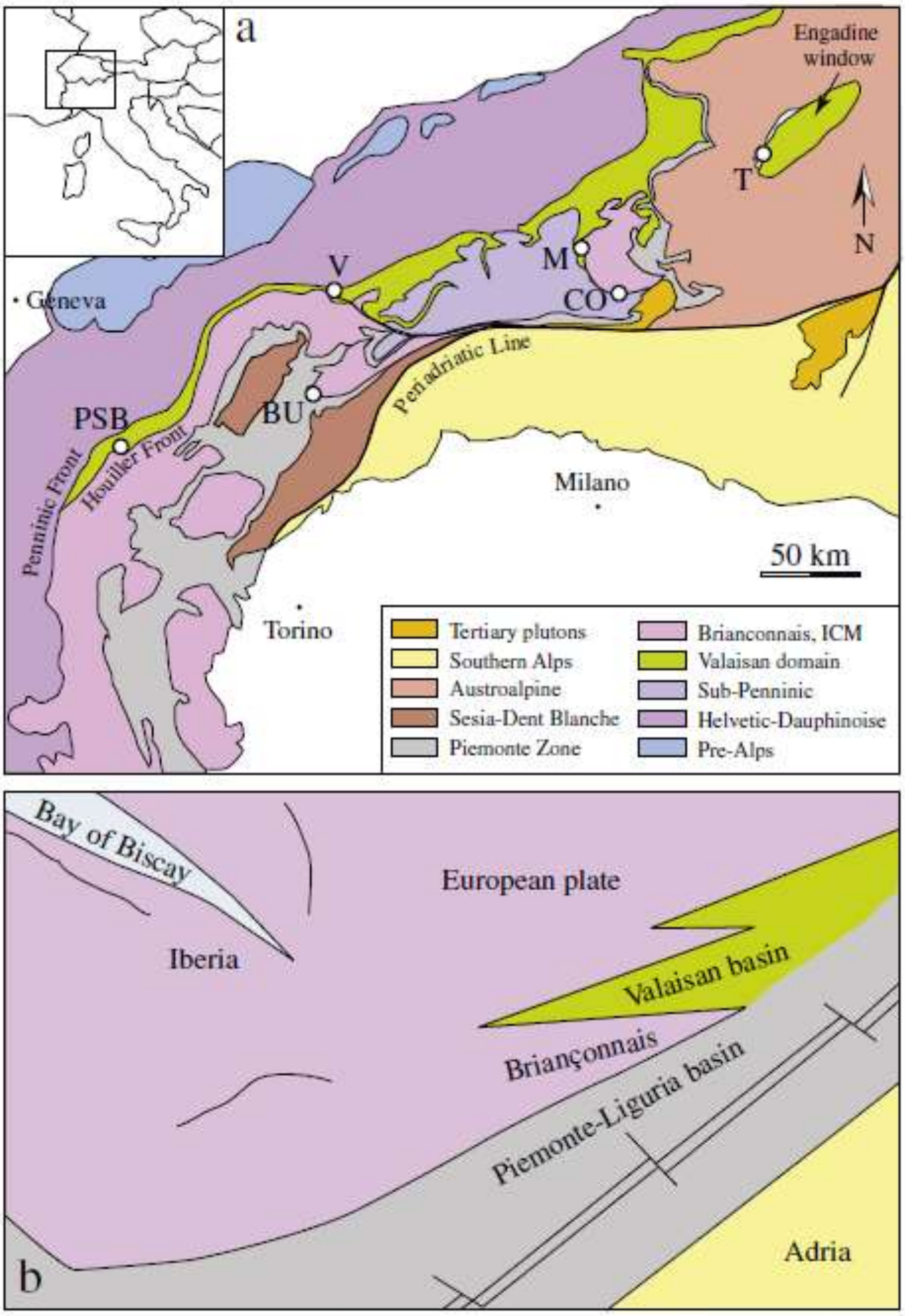


Fig. 1. (a) Simplified tectonic map of the Western and Central Alps. The Valaisan units with serpentinized ultramafics and/or Mesozoic mafic rocks are indicated. BU = Balma unit; CO = Chiavenna ophiolite; M = Misox Zone; PSB = Petit St. Bernard pass; T = Tasna unit; V = Visp mélange. ICM = Internal Crystalline Massifs. (b) Simplified paleogeographic reconstruction of the Western Tethys in the Cretaceous (modified from Manatschal et al., 2006).

Fig. 2.

Simplified geological map of the Valaisan units in the Breuil Valley. Red dots indicate sampling localities for Raman analyses on carbonaceous material. Inset shows the different tectonostratigraphic units detected in the area.

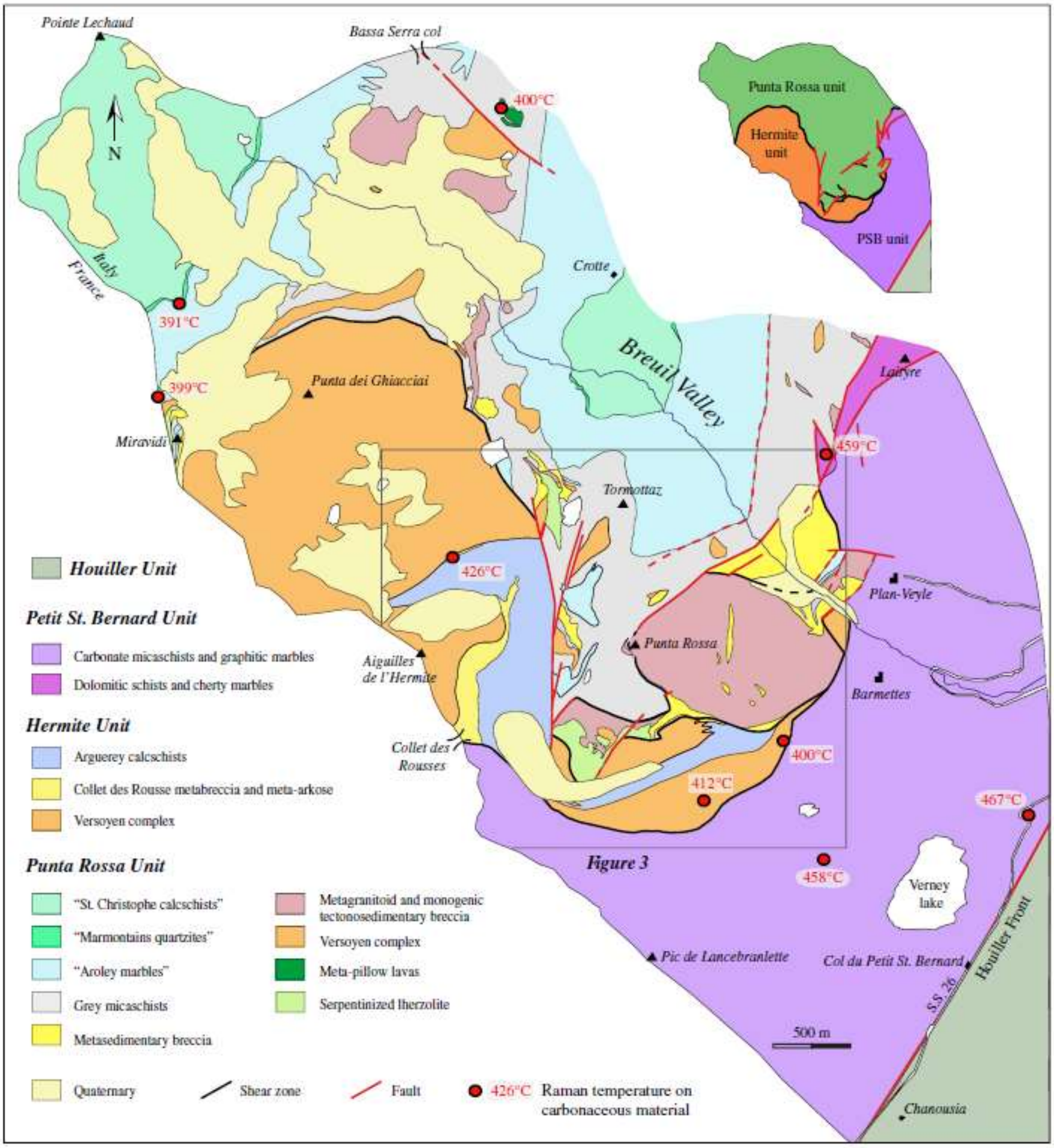
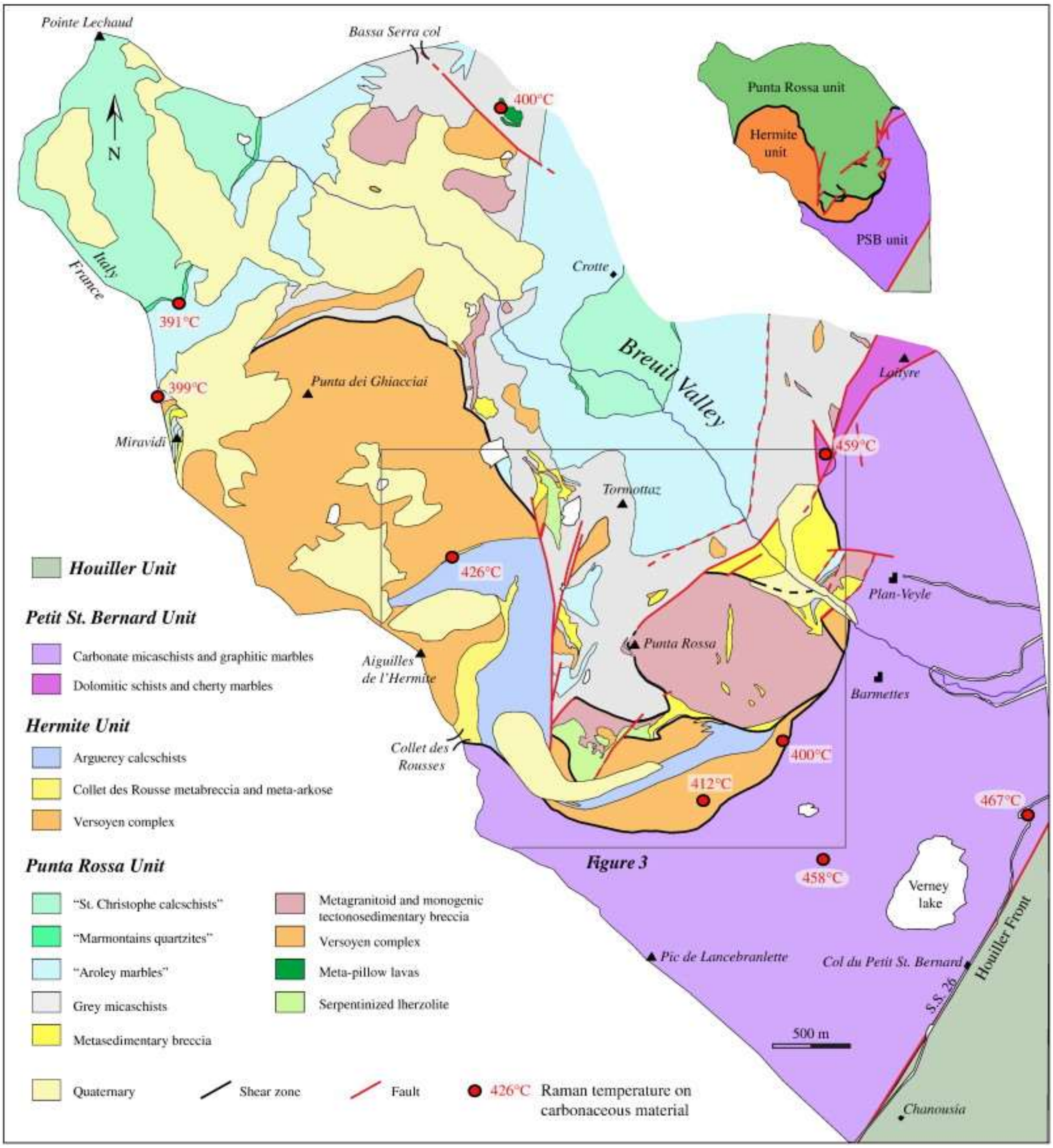


Fig. 3.

Geological map of the area surrounding the Punta Rossa peak, with structural elements classified based on field relationships and microstructural observations (see text for details).



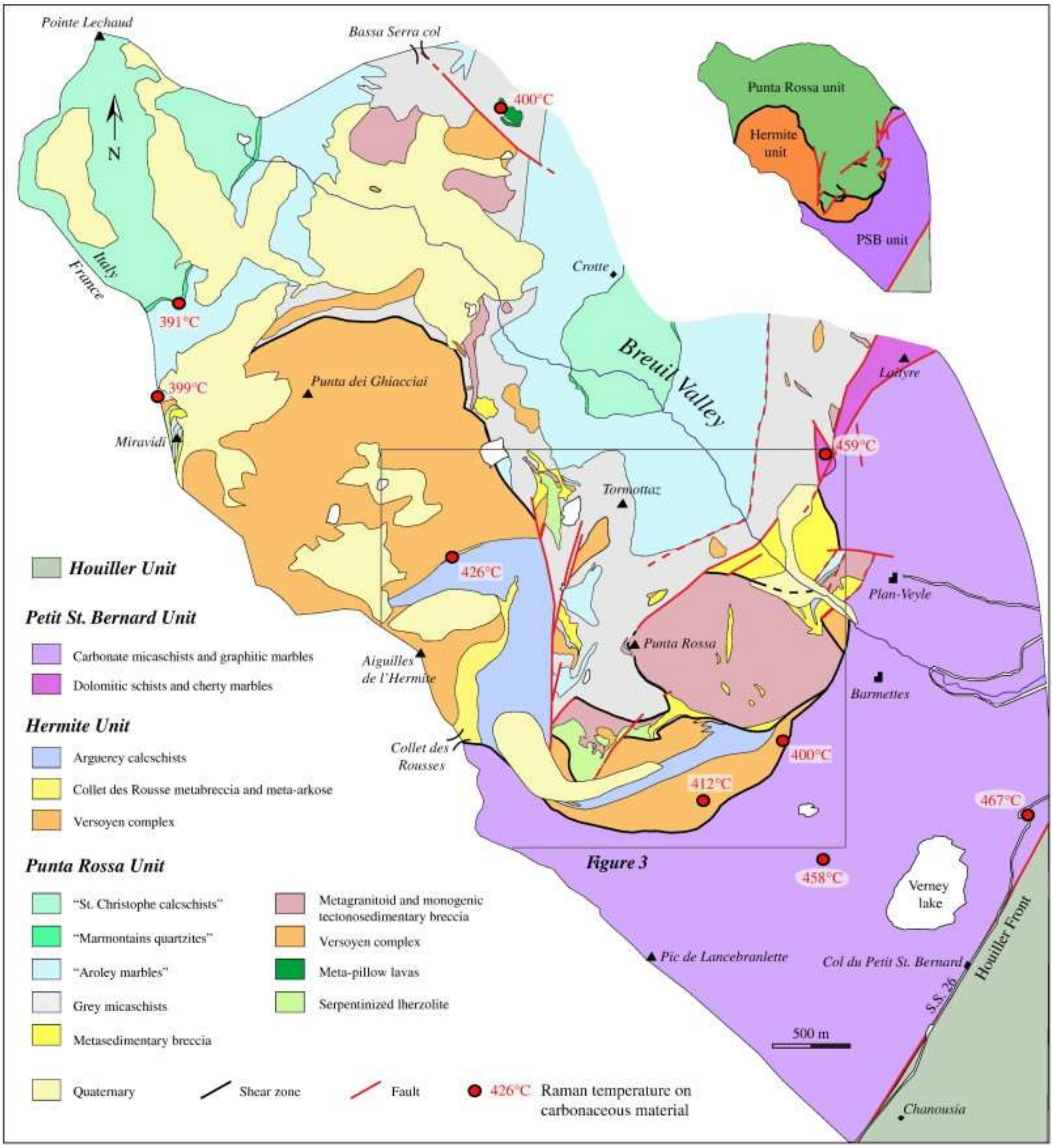


Fig. 4.

Relationship between serpentinized ultramafics, Paleozoic basement and Mesozoic metasediments in the Punta Rossa unit. On the ridge to the SW of Punta Rossa, serpentinized ultramafics are locally overlain by polymictic breccias of sedimentary origin (a). Note that the tremolite-rich fabric in the ultramafics in the center of the picture is truncated by the lithological contact with the breccia, suggesting minor reactivation. Star marks the location of the outcrop shown in Fig. 5i. In the Tormottaz lake area (b) ultramafics crop out in the core of a F_{rec} synform (see Section 4 for explanation) and are directly in contacts with slivers of cataclastically deformed peraluminous metagranitoids and metamafics. All the above lithologies are overlain by a polymictic breccia and by radiolaria-bearing gray micaschists. Star marks the location of the metamorphic fault breccia shown in Fig. 5d and e.

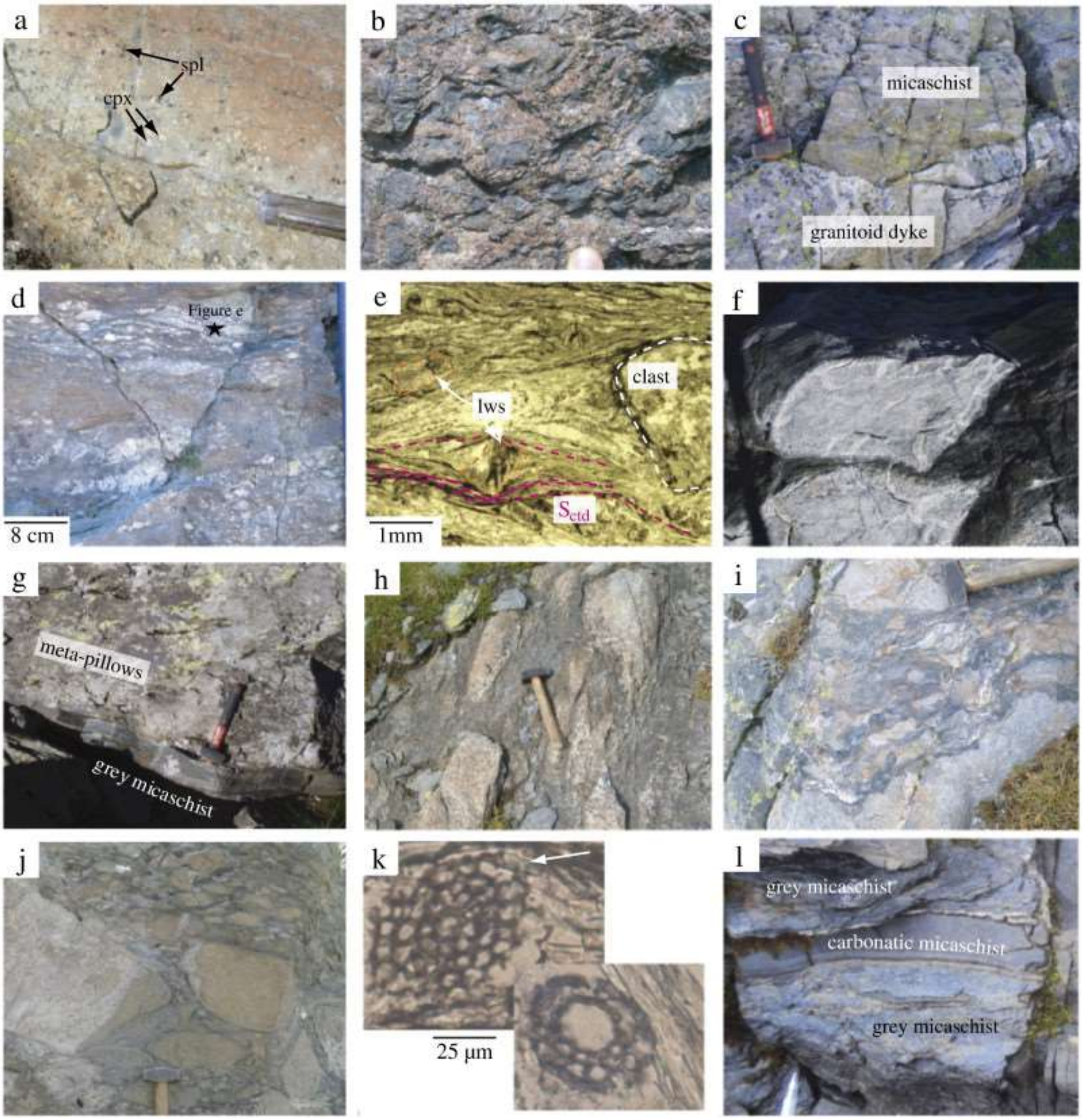


Fig. 5.

Lithostratigraphic composition of the Punta Rossa unit: (a) serpentinized ultramafics with textural relicts of the peridotite clinopyroxene and spinel; (b) clast-supported ultramafic breccia at the contact with metamorphic polygenic breccia; (c) metagranitoid dyke intrusive into black micaschists in Paleozoic basement; (d) metamorphic fault breccia developed at the expense of a Paleozoic granitoid; (e) polymineralic clasts are wrapped around by a chlorite + white mica metamorphic fabric, which post-dates crystallization of lawsonite, now replaced by white mica and epidote. These observations indicate that Alpine metamorphism post-dated brittle fracturing; (f) meta-pillow; (g) overturned contact between meta-pillows and gray micaschists; (h, i, j) different types of sedimentary breccia, with ultramafic clasts (h), metagrabbro, micaschist and granitoids clasts (i) and with clasts of metagabbros with ophitic texture (j); (k) microfossils preserved in the gray micaschists. Arrow indicates a chloritoid crystal; (l) transition between micaschist and carbonate micaschist.

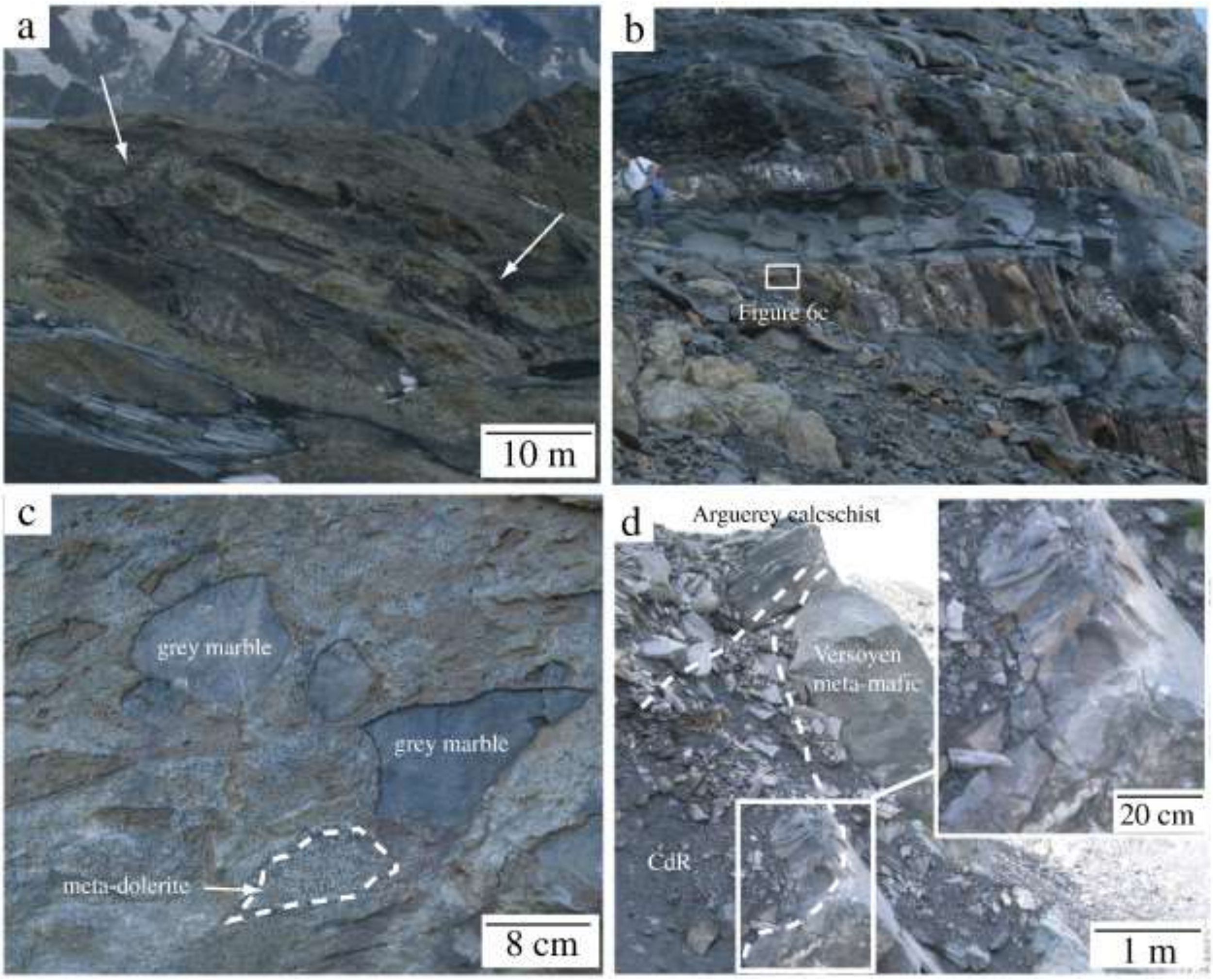


Fig. 6.

Lithostratigraphy of the Hermite unit: (a) multiple generations of cross cutting metamafic layers in the Versoyen complex. Arrows indicate the youngest dykes. (b) Outcrop of Collet des Rousses metabreccia, with darker layers consisting mainly of prasinitic meta-arkose and green-brownish layers consisting of polymictic breccia with clasts of gray marble and metamafics analogous to the Versoyen complex (c); (d) contact between Versoyen complex metamafics, Collet des Rousses metabreccia and Arguerey calcschists. Inset shows clasts in Collet des Rousses metabreccia. Outcrop location is indicated in Fig. 11b.

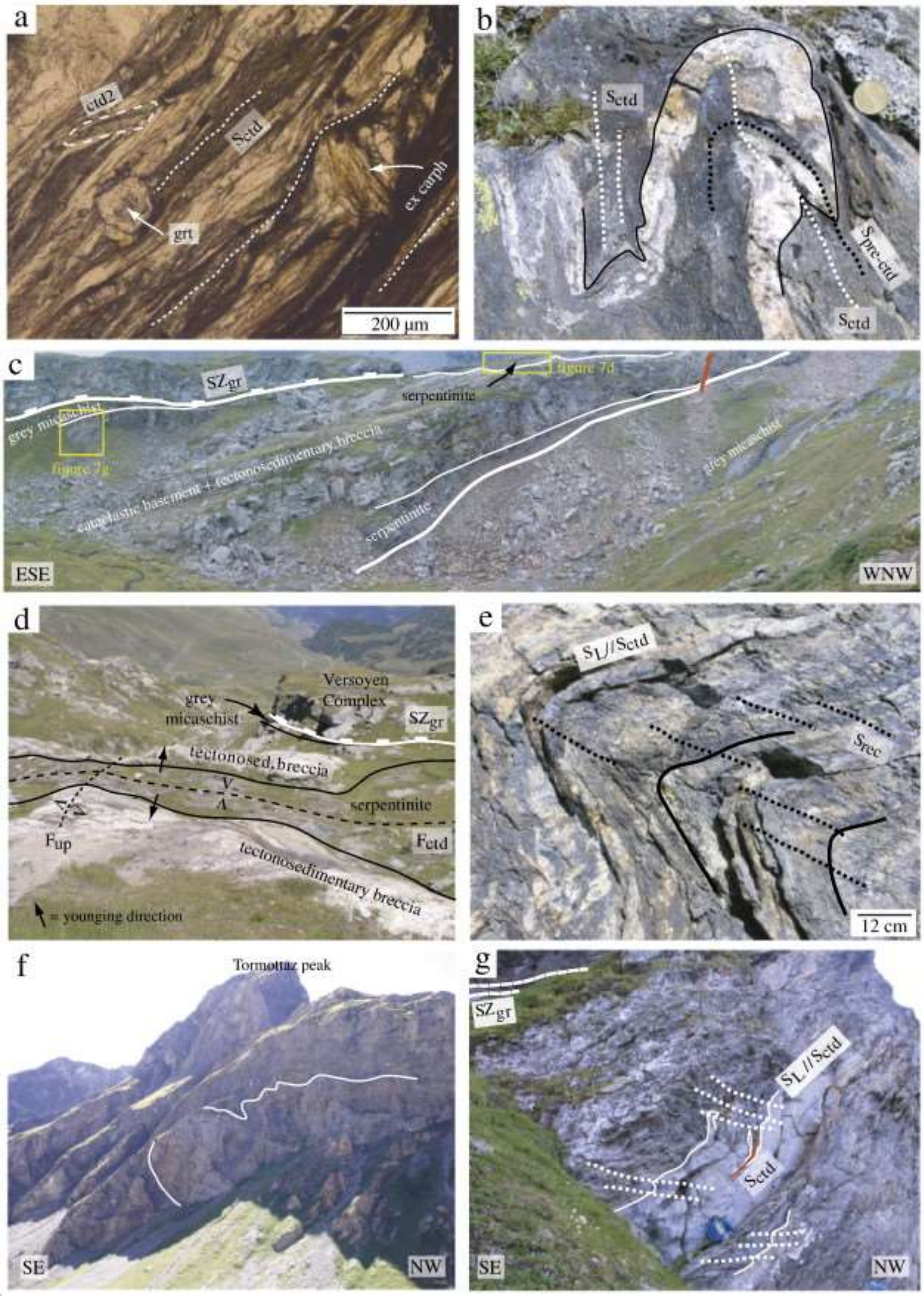


Fig. 7.

Structural elements of the Punta Rossa unit. The oldest folds commonly recognizable in the field (F_{ctd}) develop a tightly spaced axial planar cleavage (a; S_{ctd}) and locally deform pre-existing folds (b; $F_{pre\text{-}Sctd}$). Pre-S_{ctd} metamorphism is indicated by former carpholite porphyroclasts, now replaced by chlorite + white mica. Note that S_{ctd} is not deflected around garnet and chloritoid 2 porphyroblasts, indicating that their crystallization post-dated F_{ctd}. (c, d) Ultramafics and metagranitoids to the south of Punta Rossa crop out in the core of F_{ctd} synforms, with the upper limb preserving a normal stratigraphic polarity, with tectonosedimentary breccias and gray micaschist overlying serpentinites and Paleozoic basement. (e) Hinge area of a F_{rec} fold, with the characteristic spaced axial planar cleavage; (f) large scale F_{rec} fold on the NE side of Tormottaz peak. Note the contact between gray micaschists and calcschists steepening up in the proximity of the mountain top as a result of F_{up}. (g) The Punta Rossa unit is bounded upward by an extensional shear zone (SZ_{gr}). Top-to-the-SE sense of shear is defined based on the asymmetry of folds affecting F_{ctd} in the immediate footwall of the contact (f). Note that shear zones related to SZ_{gr} also run at the bottom of the cliff in the foreground in (c), where ultramafics are directly underlain by gray micaschists without the presence of tectonosedimentary breccia.

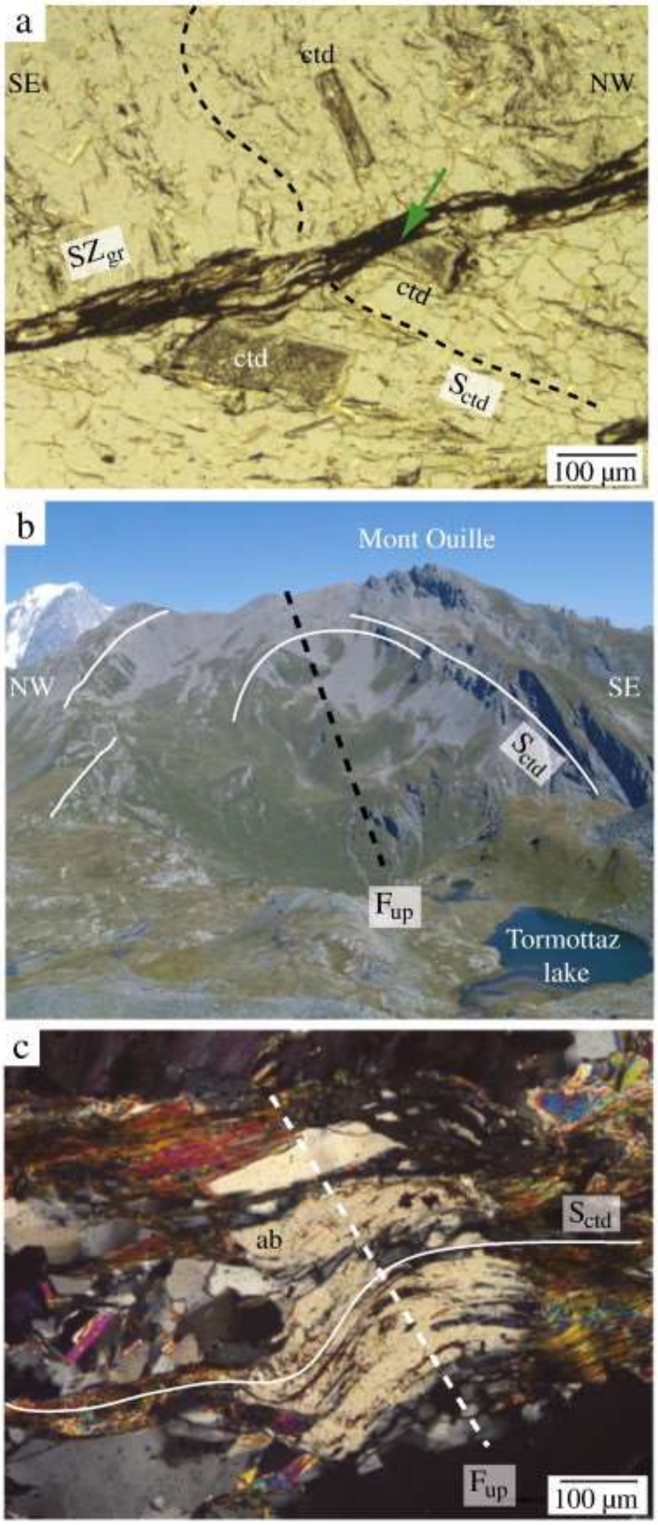


Fig. 8.

Structural elements of the Punta Rossa unit. (a) Metamorphic fabrics related to SZ_{gr} dissect and dismember chlorite + white mica aggregates developed at the expense of former chloritoid elongated along S_{ctd} (green arrow). This observation indicates that shearing post-dated retrogression of ctd under greenschist facies conditions; (b) large scale upright fold (F_{up}) on the north-eastern side of the Breuil Valley; (c) F_{up} fold hinges are statically overgrown by albite porphyroblasts.

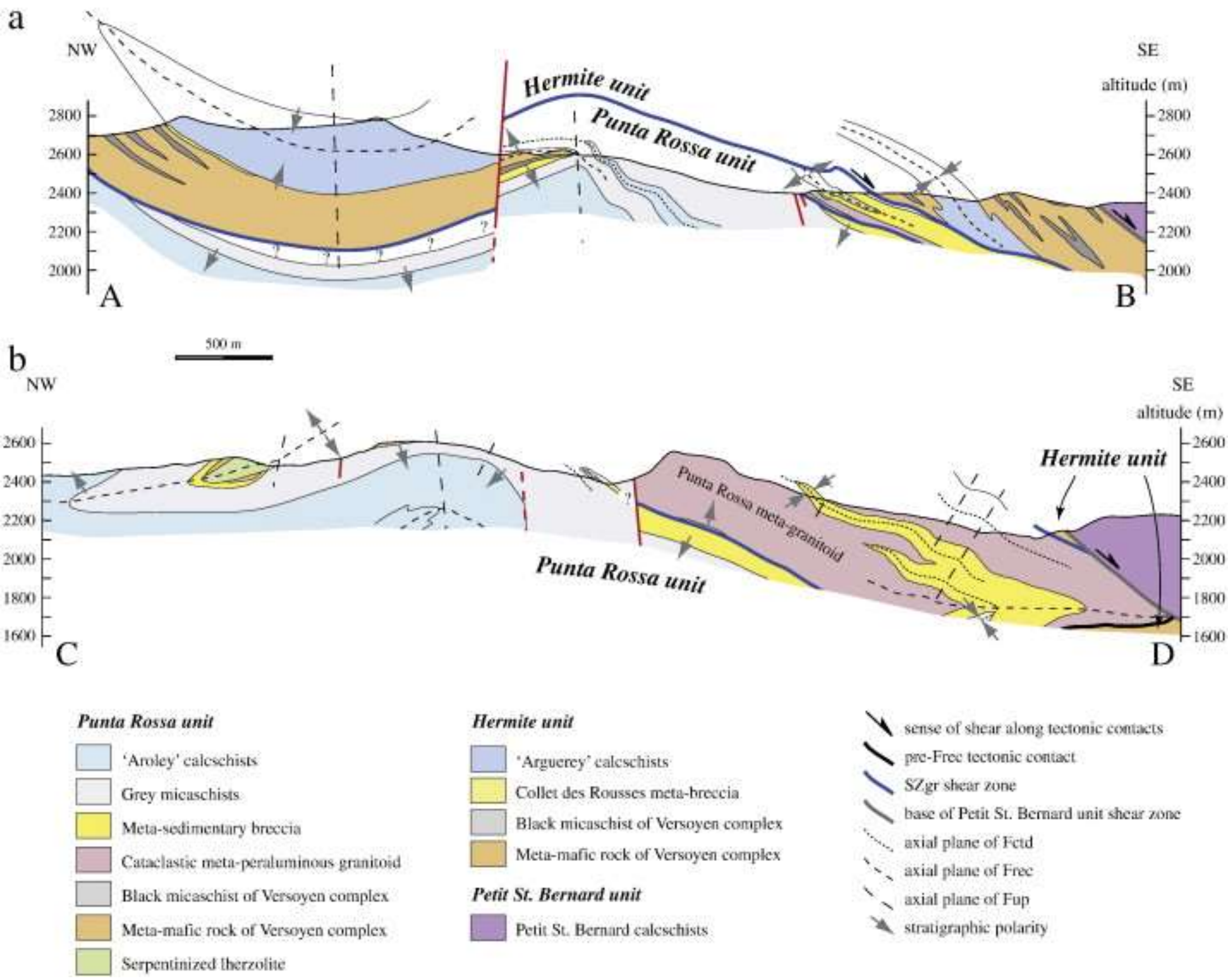


Fig. 9.

Cross sections of the study area. Note that in the NW part of the AB section the lithological composition of the Punta Rossa unit directly underneath the Hermite unit has been omitted. This approach is justified by uncertainties in projecting ultramafics, Paleozoic basement and meta-breccia, due to the marked pre-Alpine lateral heterogeneities.

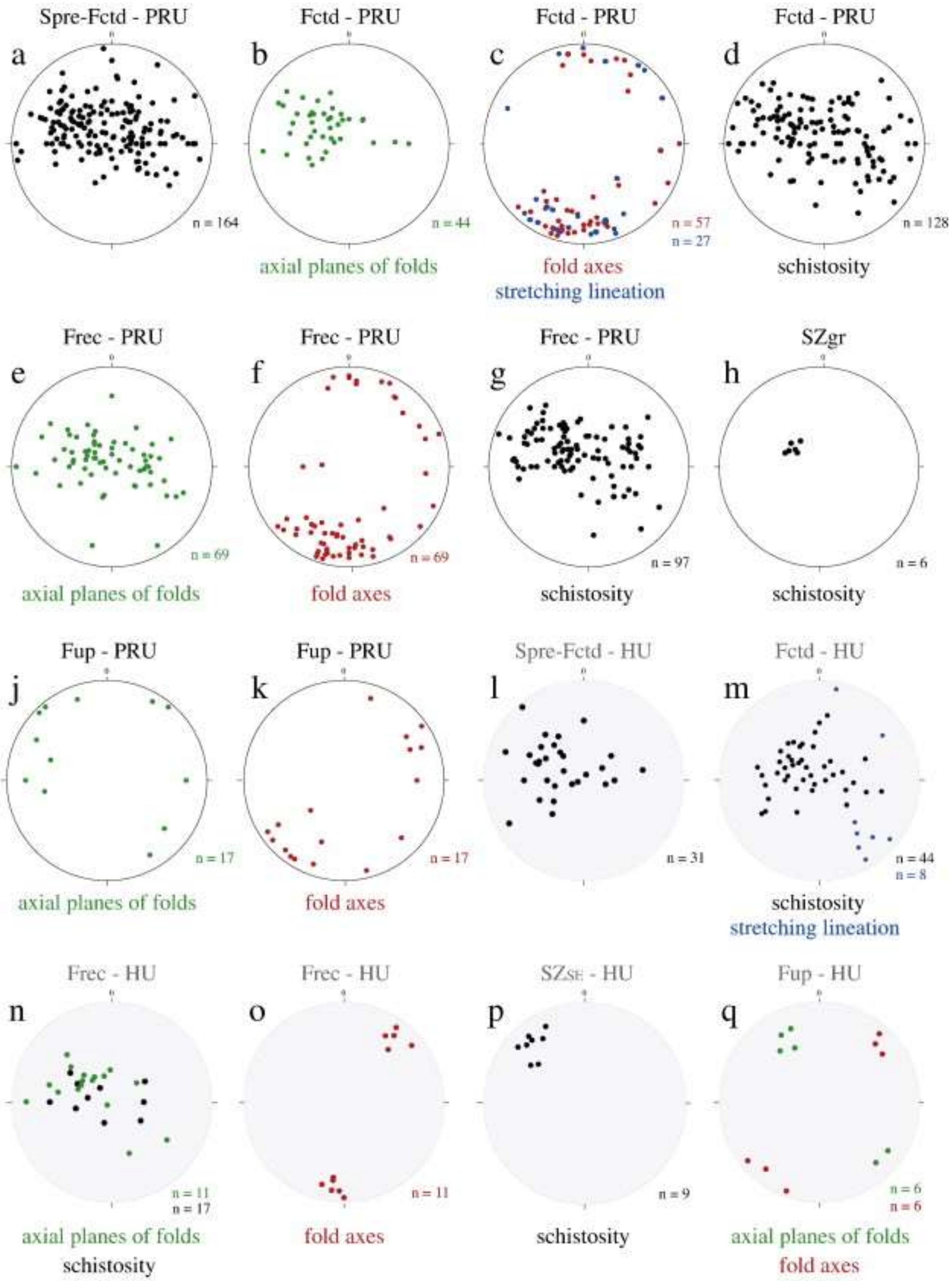


Fig. 10.

Lower hemisphere Schmidt projection plots of structural elements in the study area (see explanation in the text). PRU = Punta Rossa Unit; HU = Hermite Unit.

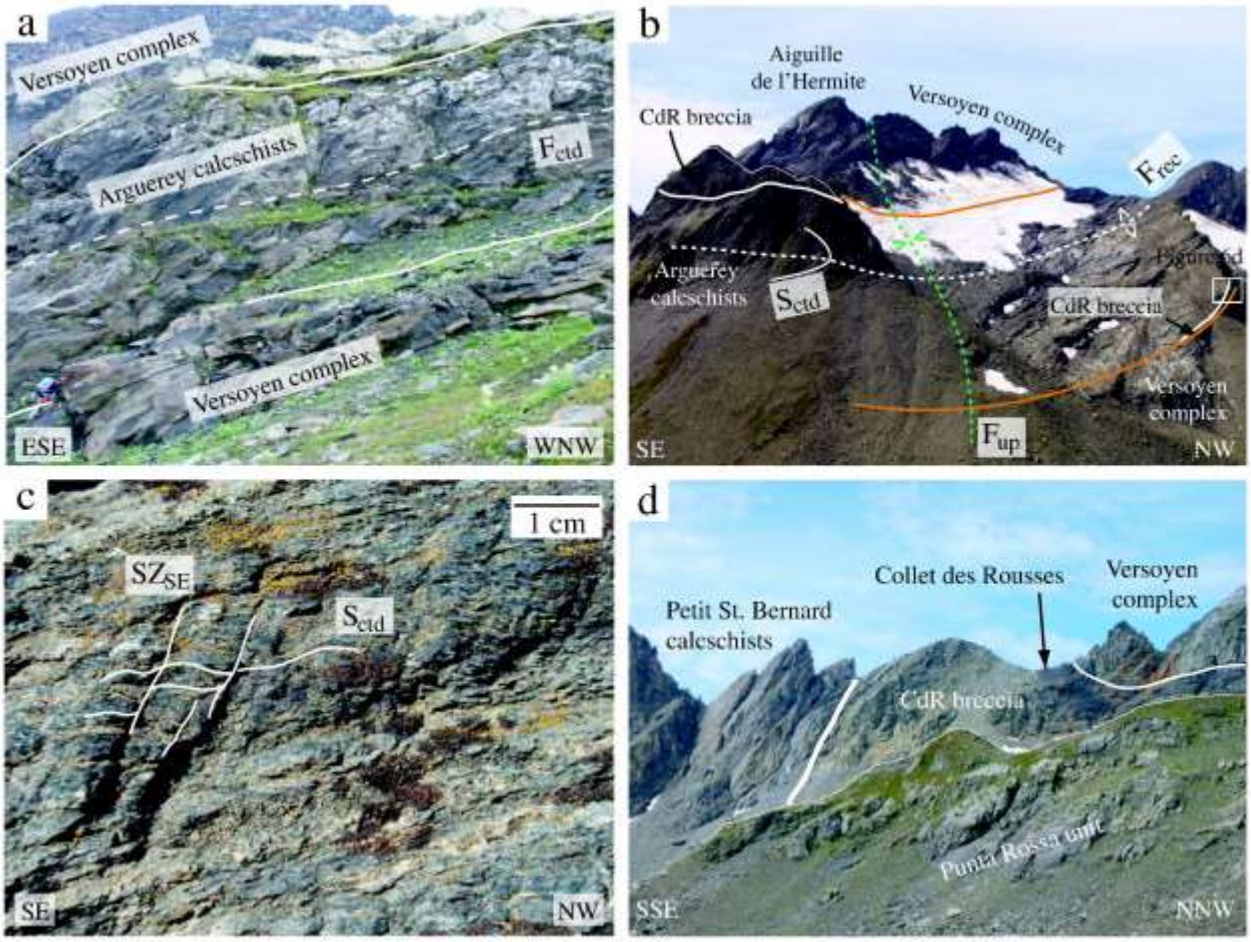


Fig. 11.

Structural elements of the Hermite unit. In the SW part of the study area (a), the contact between Versoyen complex and Arguerey calcschists is deformed by an isoclinal antiform with calcschists at the core (F_{ctd}). On the NE slope of Aiguilles de l'Hermite (b), a large scale recumbent fold (F_{rec}) deforms S_{ctd} and the lithological contacts between Versoyen complex, Collet des Rousses (CdR) metabreccia and Arguerey clacschists. Orange line indicates the stratigraphic top of the Versoyen complex, while white line indicates the stratigraphic top of Collet des Rousses meta-breccia. F_{rec} is then re-folded by a large amplitude synform with subvertical axial plane (F_{up}). The location of the outcrop shown in Fig. 6d is also indicated. In the Torveraz valley, S_{ctd} in the Arguerey calcschists is dislocated along shear bands dipping steeply to the SE, which accommodated top-SE extension (SZ_{SE}), interpreted as related to the juxtaposition of the Hermite and Petit St. Bernard units (c). This contact is best exposed to the south of Collet des Rousses (d), in the western part of the study area, where it truncates at high angle the transposed lithological banding of the Collet des Rousses metabreccia.

Fig. 12.
Reconstruction of the pre-Alpine architecture of the Punta Rossa unit, showing windows of exhumed mantle between Paleozoic basement allochthons. Submarine lava flows are rare. The areas where the depicted lithostratigraphic associations can be observed are indicated.

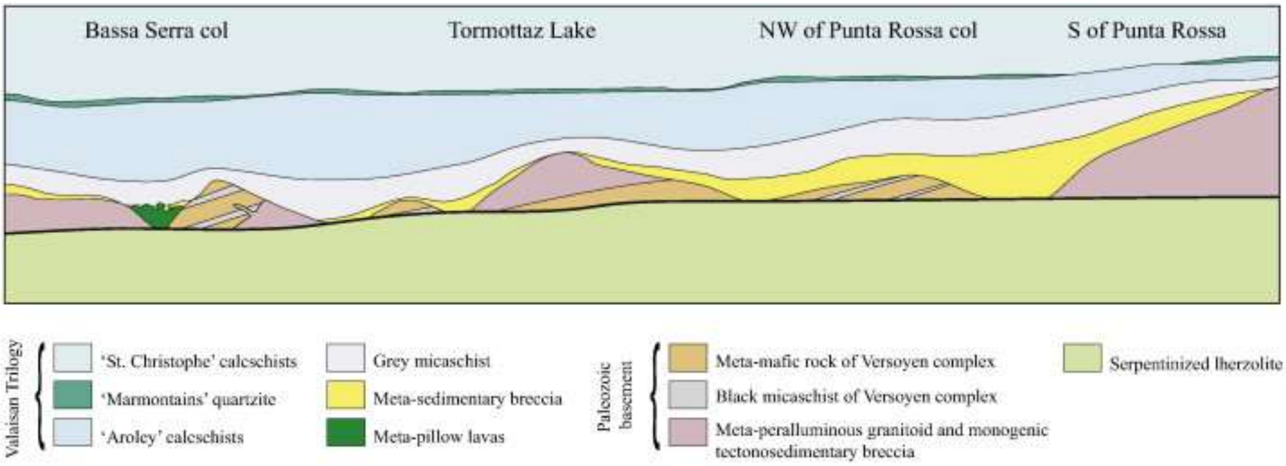


Table 1

Deformation sequence diagram for the Punta Rossa unit. Gray columns indicate the most common fabrics and structures in the field area. Horizontal arrows indicate uncertainties in the relative timing of 2 deformation/re-crystallization events. The representation 'Flt' is used to indicate the late episodes of brittle faulting.

S_{carph}	S_{ctd}	Δ_{gt-ctd}								
S_{lws}	S_{ctd}	Δ_{wm}		S_{rec}						
	S_{ctd}		Δ_{gr}		SZ_{gr}					
	F_{ctd}				SZ_{gr}					Deformation sequences typically observed in the Punta Rossa unit
				F_{rec}	SZ_{gr}					
	S_{ctd}					F_{up}				
					SZ_{gr}	F_{up}		Flt_{NW-SE}	Flt_{N-S}	
				S_{rec}		F_{up}	Δ_{ab}			
S_{HP}	S_{ctd}	$\Delta_{gt-ctd-wm}$		← S_{rec} → ← Δ_{gr} →	SZ_{gr}	F_{up}	Δ_{ab}	Flt_{NW-SE}	Flt_{N-S}	***Combined deforming sequence diagram***

Table 2

Results of RSCM analyses with R2 values, standard deviation (SD) and standard error (SE). See Beyssac et al. (2002) for details. Raman spectra were obtained using a Renishaw InVIA Reflex microspectrometer (IMPMC Paris). We used a 514 nm Laser Physics argon laser in circular polarization. The laser was focused on the sample by a DMLM Leica microscope with a 100× objective (NA = 0.85), and the laser power at the sample surface was set around 1 mW. The Rayleigh diffusion was eliminated by edge filters, and to achieve nearly confocal configuration the entrance slit was closed down to 15 µm. The signal was finally dispersed using a 1800 gr/mm grating and analyzed by a Peltier cooled RENCAM CCD detector. Because Raman spectroscopy of CM can be affected by several analytical mismatches, the analytical and fitting procedures described by Beyssac et al. (2002; 2003) were followed. 10–20 spectra were recorded for each sample in the extended scanning mode (1000–2000 cm^{-1}) with acquisition times from 30 to 60 s. Spectra were then processed using the software Peakfit (Beyssac et al., 2003).

Rock type	R^2	SD	T°C	n. spectra	SE	GPS coordinates (lat, long)	
Chloritic micaschist ("gray schist")	0.54	0.05	***399***	19	5	330,416	5,064,521
Albite bearing carbonatic quartzite ("Marmontains quartzite")	0.56	0.02	***391***	14	2	330,513	5,065,323
Ab-Chl carbonatic micaschist ("gray schist")	0.54	0.02	***400***	13	3	332,562	5,066,589
Ab-Chl graphitic micaschist ("black schist")	0.54	0.02	***400***	13	2	334,364	5,062,675
Ab-Chl-Ep graphitic schist ("black schist")	0.51	0.03	***412***	14	3	333,827	5,062,258
Chl-Wm grafitic marble ("Arguerey calcschist")	0.47	0.06	***426***	20	4	332,153	5,063,780
Graphitic-carbonatic micaschist ("Petit Saint Bernard calcschist")	0.39	0.03	***467***	14	3	335,787	5,062,061
Graphitic-carbonatic schist ("Petit Saint Bernard calcschist")	0.41	0.02	***458***	14	3	334,640	5,061,950
Graphitic-carbonatic schist ("Petit Saint Bernard calcschist")	0.41	0.06	***459***	12	8	334,572	5,064,522