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# Tectonic evolution of the Briançonnais units along a transect (ECORS-CROP) through the Italian-French Western Alps

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*Key words:* Western Alps, Briançonnais, ECORS-CROP, deformation, post-nappe folding, exhumation, nappe stacking

ABSTRACT

Based on new structural data from an area in the Italian-French Western Alps, situated between the Petit Saint Bernard pass and the Gran Paradiso massif, the large-scale geometry of the tectonic features is established for the tectonic units derived from the Briançonnais paleogeographic domain. Based on this, and other new data on the metamorphic evolution and geochronology of the area, a consistent model for the tectonic evolution for the Briançonnais domain is proposed. A nappe stack consisting of, from bottom to top, Zone Houillère unit, Ruitor unit, Internal unit and Piemont-Ligurian oceanic unit, was affected by three deformation phases. The third phase of deformation (35–31 Ma), referred to as post-nappe folding, is responsible for the formation of two large-scale folds: the Ruitor and Valsavaranche mega-folds. An overturned nappe stack, characterized by foreland-dipping foliations, is found between the axial planes of these two mega-folds. No evidence was found for back-thrusting, postulated by many previous authors. The individual thrusts between the tectonic units were active during a second phase of deformation (43–35 Ma), characterized by top-NW to -NNW shearing. This D2 is related to nappe stacking and accompanied by substantial exhumation. Thrusting becomes relatively younger towards the external parts of the study area. We emphasize that extension played no significant role in the exhumation of the high-pressure units of the Italian-French Alps. The contacts between the tectonic units were already active during the first phase of deformation (50–43 Ma), which is related to subduction and peak pressures.

ZUSAMMENFASSUNG

Anhand neuer strukturgeologischer Untersuchungen zwischen dem Col du Petit Saint Bernard und dem Gran Paradiso Massiv, entlang der Grenze zwischen Italien und Frankreich, werden die Grossstrukturen der vom Briançonnais Mikrokontinent abgeleiteten tektonischen Einheiten aufgezeigt. Zusätzliche, neue geochronologische sowie petrologische Daten führen zu einem neuen, konsistenten tektonischen Modell für die paleogeographische Domäne des Briançonnais. Der Deckenstapel im untersuchten Gebiet besteht, vom Liegenden zum Hangenden, aus Zone Houillère Unit, Ruitor Unit, Internal Unit und Piemont-Liguria oceanic Unit. Dieser Deckenstapel wurde von drei Deformationsphasen überprägt. Während der dritten Deformationsphase (31–35 Ma), welche durch die Verfaltung dieses Deckenstapels charakterisiert wird, entstehen zwei Grossfalten: Ruitor und Valsavaranche Mega-Falte. Zwischen den Achsenebenen dieser beiden Mega-Falten ist ein überkippter Deckenstapel mit zum Vorland einfallenden Foliationen zu beobachten. Für die von einigen früheren Autoren postulierten Rücküberschiebungen konnten keine Evidenzen gefunden werden. Die verschiedenen Überschiebungen zwischen den tektonischen Einheiten waren während der zweiten Deformationsphase (43–35 Ma) aktiv und zeigen eine top-NW bis top-NNW Kinematik. D2 steht im Zusammenhang mit der Deckenstapelung, welche gleichzeitig zu substantieller Exhumation der Hochdruckeinheiten führte. Die Überschiebungen werden zu den externen Teilen des Untersuchungsgebietes hin zunehmend jünger. Extension spielte während der Exhumation nur eine untergeordnete Rolle. Die Kontakte zwischen den verschiedenen tektonischen Einheiten waren schon während der ersten Deformationsphase (50–43 Ma), d.h. während der Subduktion und des Hochdrucks aktiv.

## Introduction

Two oceanic suture zones bound the tectonic units derived from the Briançonnais paleogeographical domain: the Valaisan suture and the more internal Piemont-Ligurian suture. Prior to Tertiary collision between the Apulian and the European plates, responsible for the forming of the Alps (e.g. Argand 1916, Schmid et al. 2004), the Briançonnais paleogeographic domain was part of a micro-continent, situated between the above-mentioned oceanic units (Trümpy 1955, Frisch 1979, Stampfli 1993, Froitzheim et al. 1996).

In the northern part of the Italian-French Western Alps, the ECORS-CROP seismic traverse (Nicolas et al. 1990, Roure et al. 1996) crosses the following four major tectonic units, derived from the Briançonnais domain (Fig. 1): Zone Houillère unit, Ruitor unit, Internal unit and Gran Paradiso

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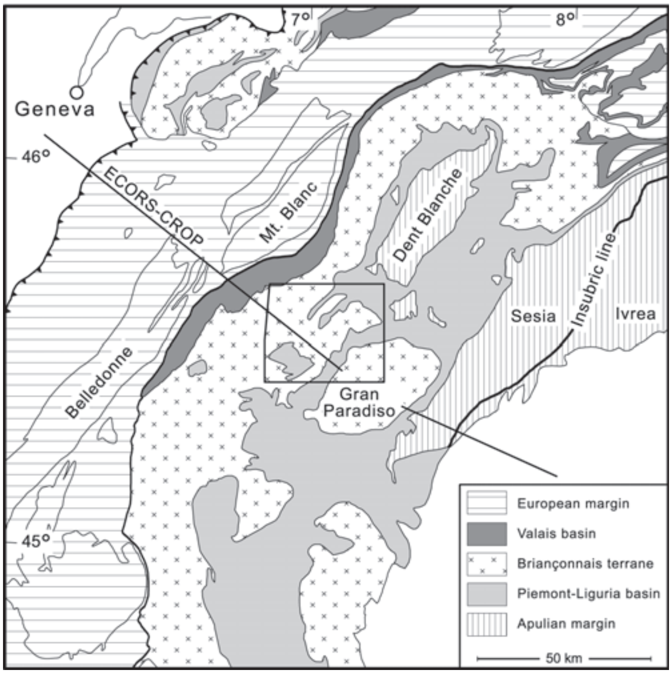



Fig. 1. Paleogeographic domains of the Western Alps, after Bucher et al. (2003). The rectangle shows the location of the study area.

massif (Fig. 2). Despite of the impressive works of many Alpine Geologists (Argand 1911, 1912, Ellenberger 1958, Elter 1960, Fabre 1961, Lemoine 1961, Dal Piaz 1965, Dal Piaz & Govi 1965, Elter & Elter 1965, Bertrand 1968, Caby 1968, Elter 1972, Marion 1984, Baudin 1987, Mercier & Beaudoin 1987, Cigolini 1995, Caby 1996) there still is no consistent picture regarding the large-scale structure, nor regarding the tectonic evolution of the Briançonnais units in the Italian-French Alps. During Alpine orogeny the Briançonnais units underwent a complex tectono-metamorphic evolution, resulting in a field metamorphic gradient that ranges from eclogitic conditions in the internal parts (Gran Paradiso; Chopin 1977, Dal Piaz & Lombardo 1986) to sub-greenschist facies conditions in the external parts of the Zone Houillère unit (Desmons et al. 1999). This gradual change points to a difference in the tectono-metamorphic evolution of the individual tectonic units of the Briançonnais. It also allows for investigating the processes responsible for such differences between the internal Penninic units and the more external Valais and European margin (Dauphinois) units. The Briançonnais is a key area in that it occupies an intermediate position, being situated between the most internal HP units and a second more external belt of high-pressure rocks (Valaisan; Goffé & Bousquet 1997, Bousquet et al. 2002), and/or the low-grade units of the European domain (Aprahamian 1988, Frey et al. 1999). These more external units are characterized by a different metamorphic evolution in terms of timing and P-T conditions.

In order to establish the structure and the tectonic evolution of the Briançonnais domain, the superposition of the different tectono-metamorphic events within the Briançonnais units and their kinematics during the Alpine cycle must be unraveled. Thereby the understanding of the geometry and the large-scale structures is of primary importance, as has been discussed since a long time (Milnes 1974, Müller 1983, Ring 1995, see also Bucher et al. 2003 and references therein). The retro-deformation of such large-scale structures, formed during the late stage deformation, is a prerequisite for unraveling the main stages of the tectonic and metamorphic evolution of an orogen (Dewey 1988, Platt et al. 1989, Escher et al. 1993).

The main schistosity along the ECORS-CROP profile changes from a SE-dip in the external part of the Briançonnais (Houiller Front) to a dominant NW-dip in the southeastern part (Gran Paradiso), a feature that is often referred to as "fan structure of the Briançonnais" (Fabre 1961, Lemoine 1961). It is classically explained by outward directed displacement, followed by inward directed back-thrusting (Butler & Freeman 1996). However, Caby (1996) already stated that the kinematics along the various tectonic contacts only show evidence for outward directed displacement.

It is the aim of this contribution to examine the large-scale structure of the Briançonnais domain in the Western Alps. The new structural data will be presented and used to constrain the present-day geometry, characterized by large-scale post-nappe folding, and to analyze the tectonic evolution of these dominant large-scale structures within the Briançonnais nappe stack. Based on this we will propose a new interpretation of the tectonic evolution of the internal part of the northern part of the Western Alps, and we will point out the geodynamic implications of the different deformation phases at the scale of the orogen.

## Geological setting

The investigated area, extending along the ECORS-CROP seismic line from the Pt. St. Bernard pass in the NW to the border of the Gran Paradiso massif in the SE (Fig. 2), traverses most of the Briançonnais units of the Italian-French Western Alps. In the NW the Zone Houillère unit, representing the most external part of the Briançonnais paleogeographic domain, is separated by the Houiller Front (Bertrand et al. 1996, Fügenschuh et al. 1999) from the Valaisan units (Antoine 1971, Loprieno 2001). The more internal Ruitor unit to the SE is classically separated into an external ("Ruitor externe") and an internal part ("Ruitor interne"), respectively (Caby 1996). The Internal unit, still further to the SE, is tectonically separated from the Piemont-Liguria (P-L) oceanic unit by a contact much discussed in the literature and referred to as the "Entrelor tectonic contact" (ETC) by Bucher et al. (2003). The P-L oceanic unit is the only tectonic unit of the investigated area that does not belong to the Briançonnais paleogeographic domain. The Gran Paradiso massif, outcropping to the SE of the P-L oceanic unit, again belongs to the Briançonnais domain and represents the internal basement massif situated in our study area (Brouwer et al. 2002). The "Internal Massifs" are interpreted to paleogeographically represent the most internal basement units, situated next to the P-L oceanic unit. Some authors therefore classify them as "External Piemont" and assign them to the "Piemontais" paleogeographical domain. The paleogeographic position, however, remains the same for either attribution.

### *Zone Houillère unit*

This unit is characterized by a Paleozoic sequence of continental deposits (Fabre 1961). The lower part of this sequence consists of black schists with anthracitic lenses and arkoses (Namurian to Stephanian in age; Feys 1963, Gréber 1965). The upper part is dominated by arkoses and conglomerates, probably of Stephano-Autunian age (Fabre 1961). The clasts mainly consist of polycrystalline quartz, micaschist and paragneiss. The latter display a polyphase metamorphic imprint (Desmons & Mercier 1993). A Permo-Triassic sequence discordantly overlies this Carboniferous sequence (Ellenberger 1958, Elter 1960). During the Alpine deformation the Zone Houillère unit was decoupled from its former basement, whose present-day position remains unknown, since it does not outcrop at the earth's surface (Desmons & Mercier 1993).

### *Ruitor unit*

The Ruitor unit dominantly consists of pre-Permian (450–480 Ma, Guillot et al. 2002) garnet micaschists and paragneisses with abundant intercalated metabasites (Baudin 1987). There is definitely an Alpine metamorphic overprint (Caby 1996), but some relicts of pre-Alpine metamorphism survived the Alpine cycle (Bocquet [Desmons] 1974). Its sedimentary cover is made up by a thin Permo-Triassic sequence, consisting of "Verrucano"-type conglomerates (Trümpy 1966) at the base, followed by lower Triassic meta-arkoses, which are stratigraphically overlain by quartz-phyllites and ankerite-bearing micaschists (Ulardic 2001). This sequence crops out all along Valgrisenche (Fig. 2).

The separation of the Ruitor unit into an external and an internal part is still a matter of debate since it is not marked by an unequivocal tectonic surface. Desmons & Mercier (1993) question this separation. Some authors made a separation based on the dominant mineral assemblage (Alpine vs. pre-Alpine; i.e. Caby in Debelmas et al. 1991a) while others used intensity of Alpine deformation as a criterion (i.e. Gouffon 1993) for defining such a boundary between two parts of the Ruitor unit. Further south, the Sapey gneiss occurs (Isère Valley) in the same tectonic position as the Ruitor unit (Fig. 2, Bertrand et al. 1998) and is interpreted to be the continuation of the latter. Bertrand et al. (1998) interpret the Sapey gneiss to be the basement of the Zone Houillère unit. This interpretation is debated since a long time and will be discussed later in this text.

### *Internal unit*

The Internal unit ("Zona Interna") of the Italian authors (Cigolini 1995 and references therein) corresponds to the "Briançonnais interne" of the French authors, found further south in the Vanoise-Mont Pourri area (i.e. Caby, 1996). Northwards the Internal unit was correlated with the Mont Fort unit (Gouffon 1993). The Internal unit is made up of a lower part, formed by paragneisses and micaschists with a polymetamorphic history (Bocquet 1974, Cigolini 1995), and of a monometamorphic upper part, consisting of lower Permian to Mesozoic formations. According to Amstuz (1955, 1962), the lower part is mainly of volcano-clastic origin. This succession is intruded by Paleozoic granitic and granodioritic bodies of variable size (i.e. the Cogne granodiorite, Bertrand et al. 2000).

Leucocratic gneisses define the base of the mono-metamorphic upper part. These are followed by a typical Permo-Triassic sequence consisting of conglomerates ("Verrucano"), quarzitic meta-sandstones, impure quarzites and ankerite-bearing micaschists. The younger Mesozoic cover is only preserved in the southern part of the study area. Multiple erosion events characterize the Mesozoic sequence, as is discussed by Jaillard (1989, 1990), Adatte et al. (1992) and Saadi (1992). For the purposes of this study, the data of the latter mentioned authors were completed with structural data.

### *Piemont-Liguria oceanic unit*

The P-L oceanic unit predominantly consists of calcschists. These are interlayered with different amounts of metabasites (Elter 1972, Cigolini 1995). Two types of metabasites do occur: mostly retrogressed eclogites and prasinites. While some authors proposed a subdivision of the Piemont-Liguria oceanic unit within our working area into an eclogitic ("Zermatt–Saas Fee") and a non-eclogitic ("Combin") part (Droop et al. 1990, Ballèvre and Merle 1993, Dal Piaz 1999), our observations indicate a mélange consisting of eclogitic and blueschist mafic boudins, embedded in a matrix of HP metasediments (Bucher et al. 2003).

### *Gran Paradiso massif*

The Gran Paradiso massif comprises mainly Hercynian granitoids with an intrusion age of 350–270 Ma (Bertrand et al. 2000). These intruded meta-sedimentary rocks (Gneiss Minuti) that contain eclogite pods metamorphosed during the Alpine cycle (Compagnoni and Lombardo 1974, Ballèvre 1990, Borghi et al. 1996). Evidence for HP metamorphic conditions is also found within the orthogneisses (Brouwer et al. 2002). Paleogeographically the Gran Paradiso massif represents the most internal unit of the Briançonnais domain, adjacent to the Piemont-Liguria Ocean.

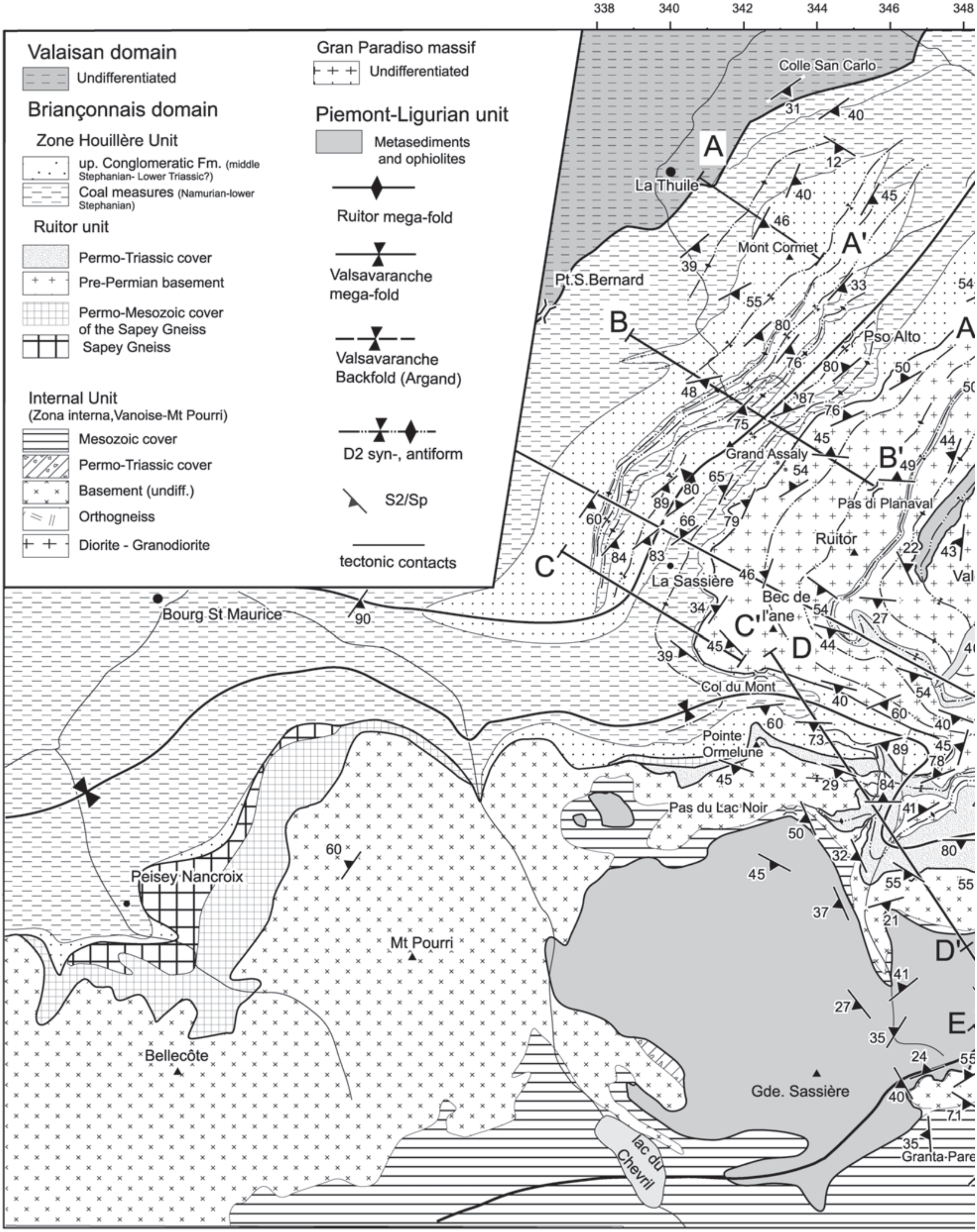
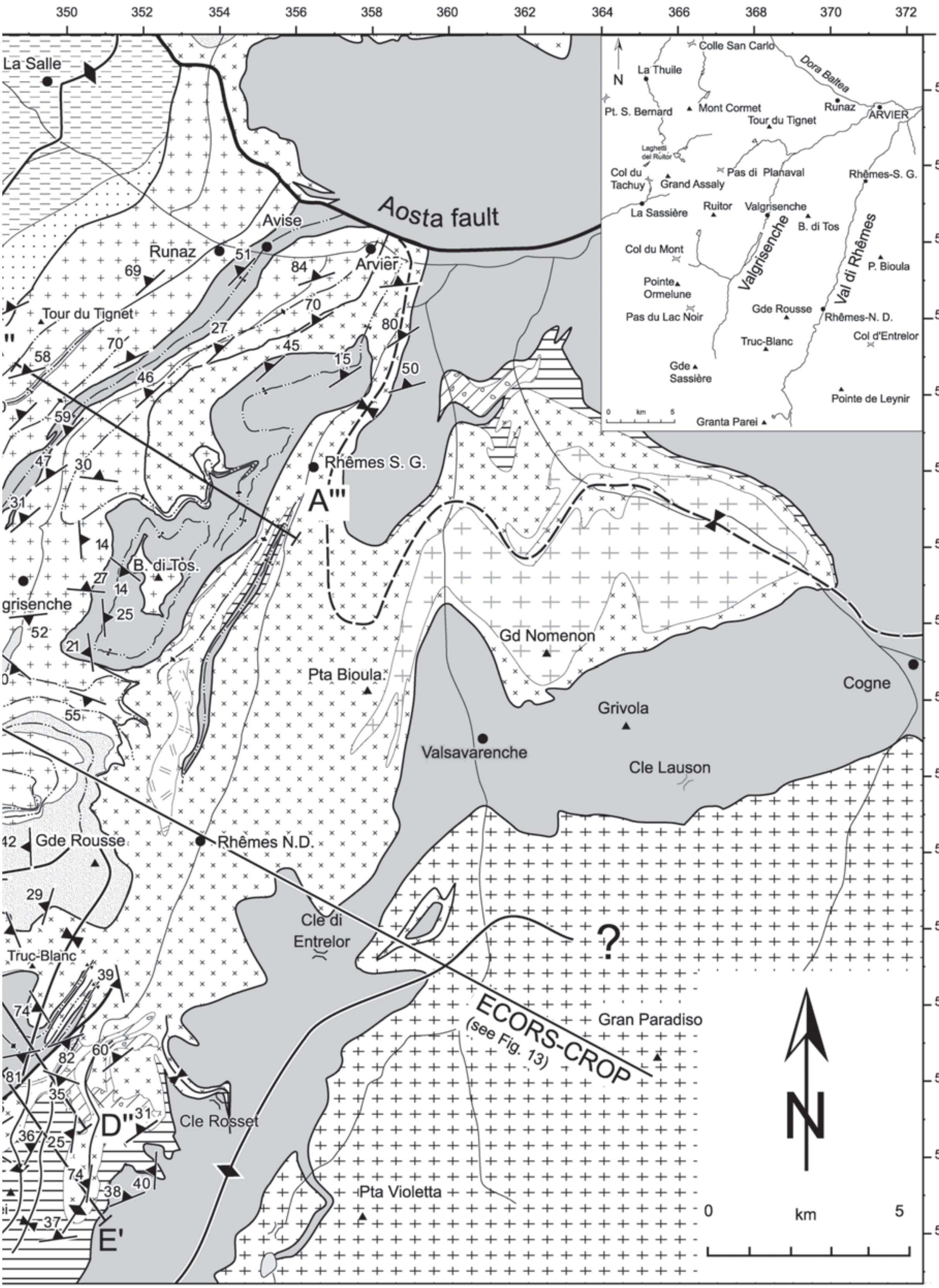



Fig. 2. Geological and structural map of the study area. Letters A-A' to E-E' mark the traces of the detailed cross sections shown in Figure 12.


Aosta fault
La Salle
Avise
Runaz
Arvier
Tour du Tignet
Rhêmes S. G.
A'''
B. di Tos.
Pta Bioula
Gd Nomenon
Grivola
Cogne
Valsavarenche
Cle Lauson
Gde Rousse
Rhêmes N.D.
Truc-Blanc
Cle di Entrelor
?
ECORS-CROP
(see Fig. 13)
Gran Paradiso
D''
Cle Rosset
E'
Pta Violetta
0 km 5
N
Colle San Carlo
La Thuile
Dora Baltea
Pt. S. Bernard
Mont Cormet
Runaz
ARVIER
Tour du Tignet
Laghetti del Ruitor
Col du Tachuy
Grand Assaly
Pas di Planaval
Rhêmes-S. G.
La Sassière
Ruitor
Valgrisenche
B. di Tos
Col du Mont
Val di Rhêmes
P. Bioula
Pointe Ormelune
Pas du Lac Noir
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Col d'Entrelor
Truc-Blanc
Gde Sassière
Pointe de Leynir
Granta Parei

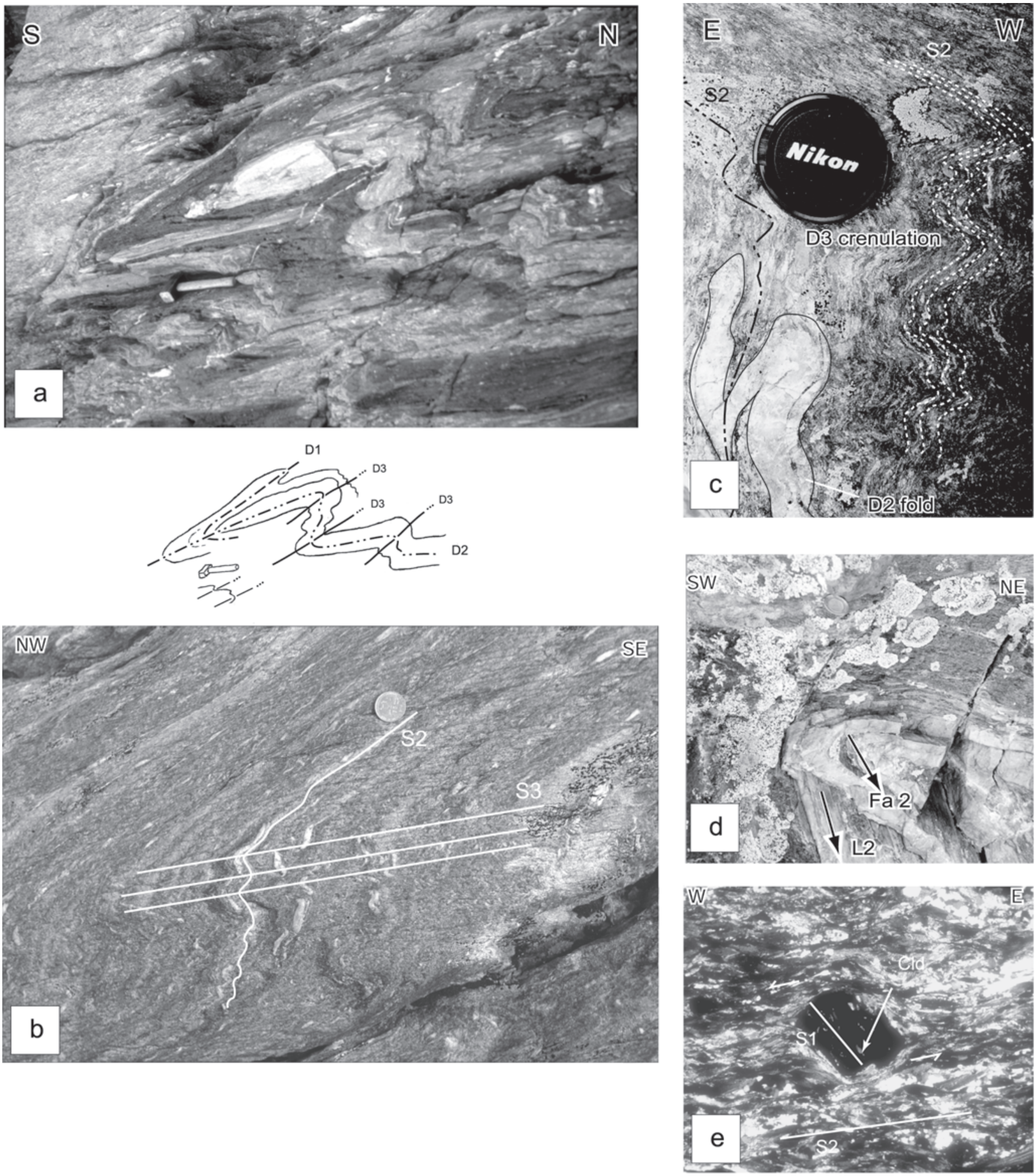



Fig. 3. Meso- and microscopic structures. a) Superposed D1-, D2 and D3-folds in the P-L oceanic sediments from the Valgrisenche; b) asymmetric D3 folds in the Upper Conglomeratic Formation of the Houiller unit from the upper limb of the Ruitor mega-fold; c) D2 fold, overprinted by open D3 folds with a subhorizontal axial plane, in the Permo-Triassic cover from the uppermost Valgrisenche; d) characteristic D2 fold in the Permo-Triassic cover of the Internal unit, showing parallelism between F2 fold axis and stretching lineation, from the uppermost Val di Rhêmes; e) Garnet porphyroclast, preserving a relict internal S1 foliation, defined by chloritoid and phengite, embedded in the S2 foliation; thin section from the Cogne area (micrograph with crossed polarizers).

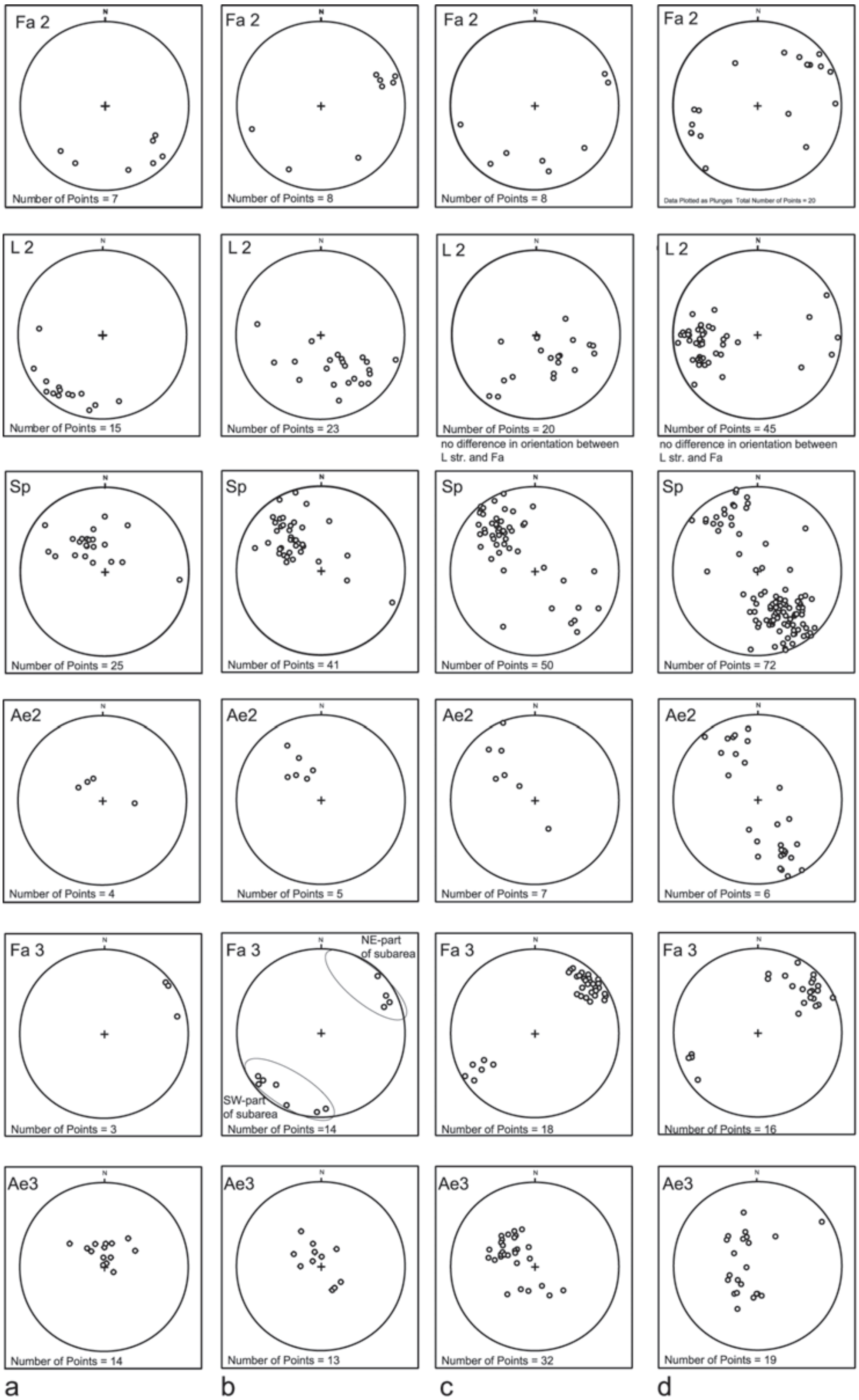



Fig. 4. Structural data from Area I, i.e. the external part of the Zone Houillère unit. Stereoplots (equal area, lower hemisphere) in columns a, b, c and d show data from sub-areas a to d within Area I, as defined in Fig. 5. Abbreviations are: Fa2: fold axis of D2; L2: stretching lineation of D2; Sp: composite foliation S0/S1/S2; Ae2: axial plane of D2 folds; Fa3: fold axis of D3; Ae3: axial plane of D3 folds.

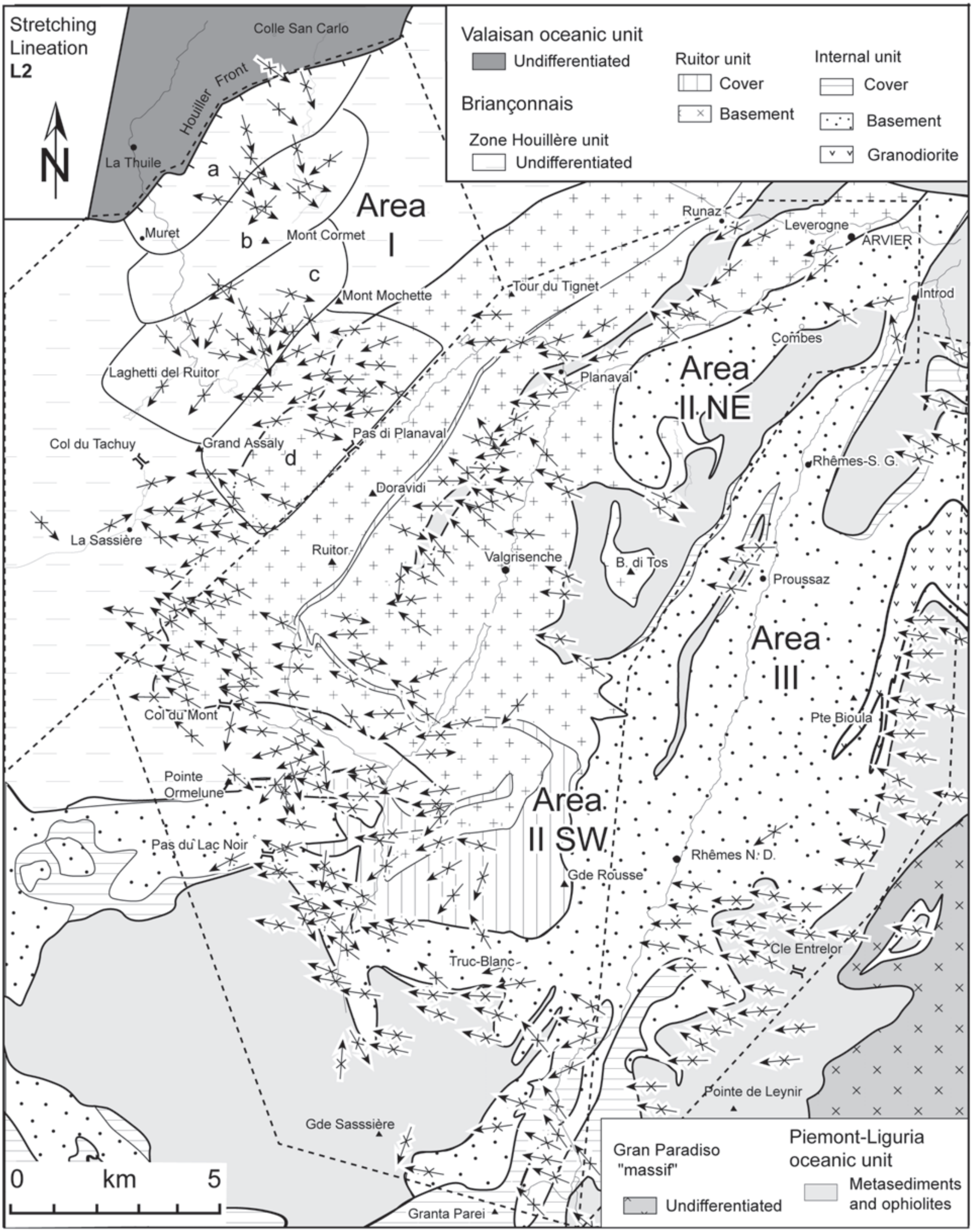



Fig. 5. Map of L2 stretching lineations. Dashed lines indicate the outlines of the Areas I to III and their sub-areas, respectively, from which the structural data shown in Figs. 4 and 6 have been collected.

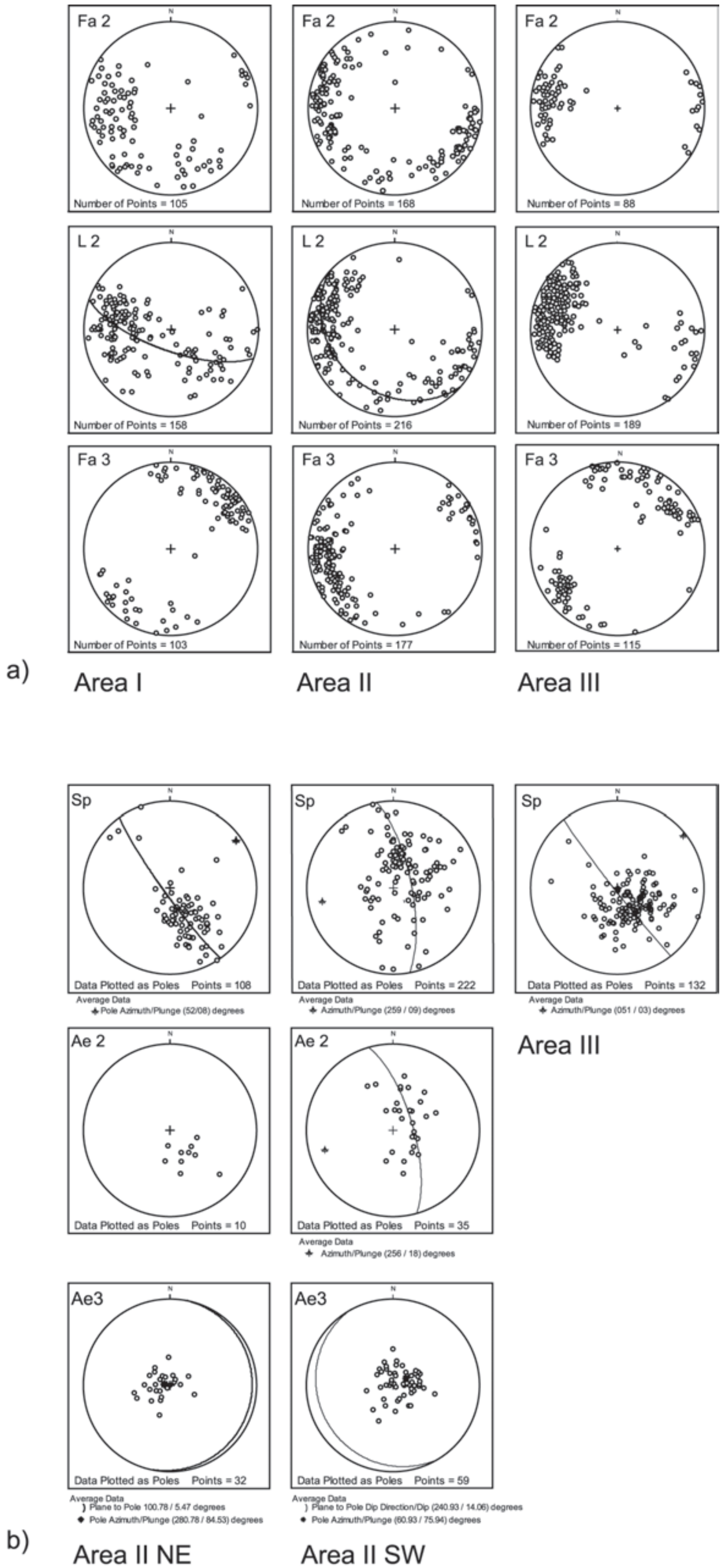



Fig. 6. Structural data from the study area, grouped in three areas. Area I: external part; Area II: central part; Area III: internal part; for locations see Fig. 5. a) Linear features Fa2, L2 and FA3; b) planar features Sp, Ae2 and Ae3; see Fig. 4 for abbreviations. Areas I, II and III, as well as the NW and SE part of Area II, are outlined in Fig. 5. Note that all the planar features from Area I are shown separately in Figure 4.

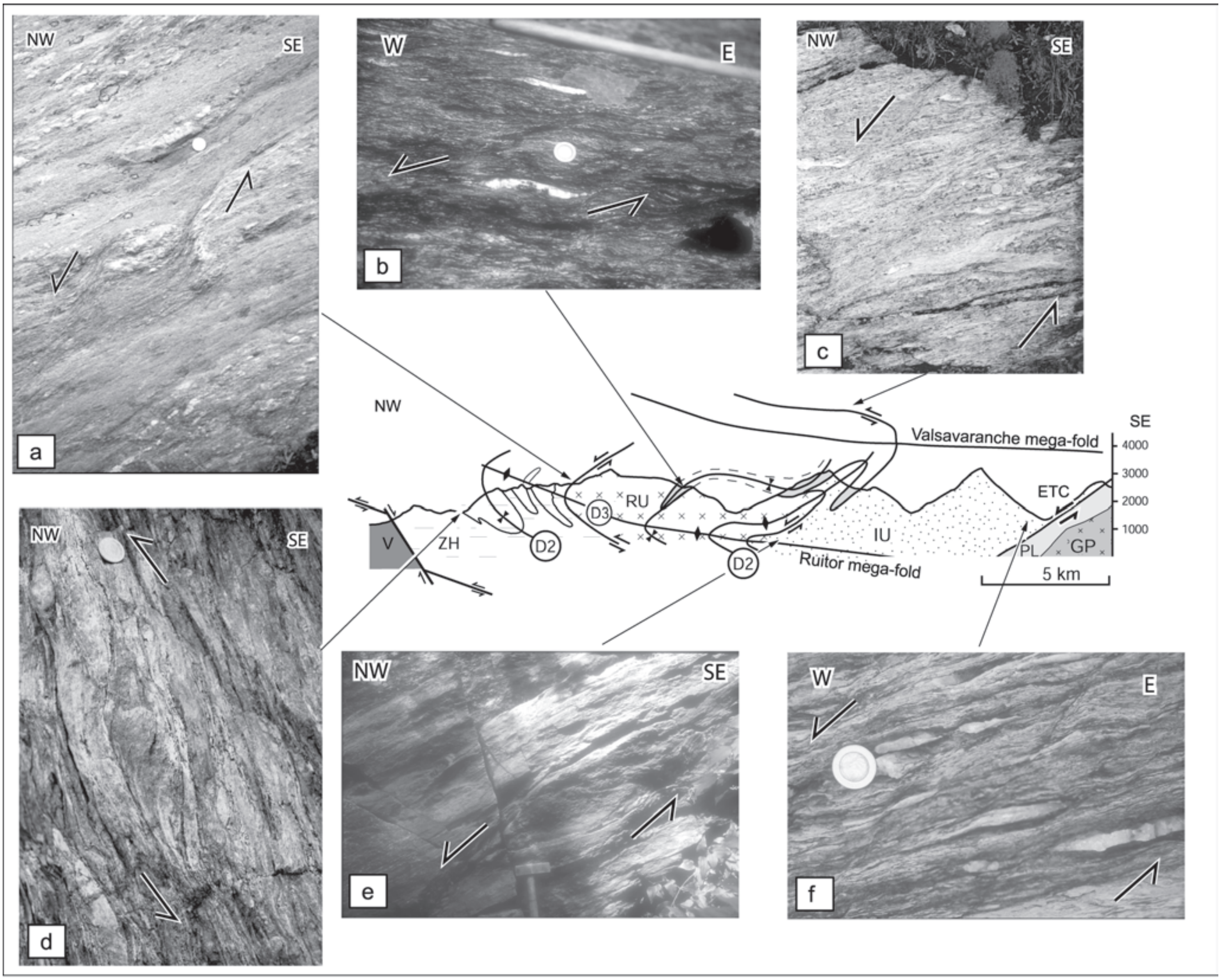



Fig. 7. Photographs illustrating kinematic indicators from different tectonic contacts: a) Top-W sense of shear in the Zone Houillère unit, at the contact with the Ruitor unit (Glacier de l'Invernet); b) top-W sense of shear at the tectonic contact between the Piemont-Liguria Schistes Lustrés and the Ruitor unit in the Avise synform; c) top-W sense of shear in the uppermost Valgrisenche (Permo-Triassic cover of the Internal unit); d) top-W sense of shear in the Zone Houillère unit; note that the foliation is SE-dipping and hence schistosity and related senses of shear remained in their original orientation; e) tectonic contact between Ruitor unit and Internal unit, also showing top-NW sense of shear (in the Ruitor unit above Arvier); f) shear bands within the Internal unit in the Val di Rhêmes, near the Rifugio Benevolo (Permo-Triassic cover). Center: Cross section, modified after Bucher et al. (2003); V: Valaisan domain; ZH: Zone Houillère unit; RU: Ruitor unit; IU: Internal unit; PL: Piemont-Liguria unit; GP: Gran Paradiso unit; ETC: Entrelor tectonic contact. See Bucher et al. 2003 for photographs of top-W sense of shear indicators from the ETC.

## Deformation history

Overprinting patterns observed on the macroscopic (large-scale), mesoscopic (outcrop scale) and microscopic scales (Fig. 3) indicate the existence of three major ductile deformation phases (D1 to D3). All three deformation phases are present in all investigated tectonic units. First order large-scale structures were mapped by using second order fold asymmetries of parasitic folds, and additionally, bedding-cleavage relationships. Transport directions were inferred from mesoscopic or microscopic sense of shear criteria (Simpson & Schmid 1983).

While the separation into three mesoscopically and microscopically visible deformation phases is generally in agreement with the observations of other workers, who carried out detailed investigations on parts of the study area (Caby 1968, Baudin 1987, Cigolini 1995, Caby 1996), the significance of these different deformation phases on a macroscopic scale remains disputed. Hence the present-day overall geometry of the nappe stack is still in discussion (Bucher et al. 2003). Local variations in the orientation of these structures and changes in the strain magnitude associated with the various deformation phases will be discussed later.

### *Pre-Alpine structures*

The strong Alpine blueschist, and especially, a subsequent greenschist overprint (Baudin 1987), transposed most of the pre-Alpine planar features. Despite of this, two or three pre-Alpine amphibolite facies metamorphic events have so far been recognized within relict fold hinges found in the Ruitor unit (Desmons et al. 1999). While most other pre-Alpine minerals were destroyed during Alpine deformation, pre-Alpine garnet is often preserved, especially in the western and central parts of the Ruitor unit. Based on this observation it appears that Alpine deformation is weaker in the western and central parts of the Ruitor unit. Relics of a pre-Alpine metamorphic event were also preserved in the Internal unit (Cigolini 1981, 1995).

### *D1 structures*

D1, the first Alpine deformation feature present in all the studied tectonic units, has largely been overprinted by subsequent deformations. On a mesoscopic scale the first foliation S1 is only preserved in F2 fold hinges (Fig. 3a). In thin section S1 is either defined by a relict foliation formed by chloritoid, phengite and garnet, preserved within D2 microlithons, or, as an internal foliation within garnet formed by phengite or chloritoid (Fig. 3e). This D1 mineral assemblage is associated with peak pressure conditions. Pressures range from 10–14 kbar (at temperatures around 400–450°C), as found in the Internal unit and the Ruitor unit, down to 5 kbar (at around 350–400°C), as described for the Zone Houillère unit (Bucher et al. 2003). However, no major D1 fold structures were observed at the large-scale in the study area.

### *D2 structures*

D2 represents the major phase of deformation observed within the study area. The very penetrative D2 structures are characterized by tight to isoclinal folds, observable at all scales (Fig. 3a, c). While an older schistosity S1 is sometimes recognizable in D2-fold hinges, S1 becomes sub-parallel to the strong axial plane cleavage S2 in the F2 fold limbs (Fig. 3c). Hence, the main foliation in the area is a composite between S1 and S2 (Figs. 2, 4, 6). In the Internal unit the mineral assemblage garnet, phengite, epidote, chlorite and plagioclase is stable in the second schistosity, replacing the peak-pressure mineral assemblage. P-T estimates indicate that D2 is contemporaneous with decompression from 14 to 5 kbar at temperatures around 450°–500°C (Bucher et al. 2003).

Plunging angle and azimuth of F2 fold axes are variable. A plunge from E-SE to W-NW is observed between the Houiller Front and the Valgrisenche, while F2 predominantly plunges to the W-NW in rest of the study area (Figs. 4, 5, 6). A strong

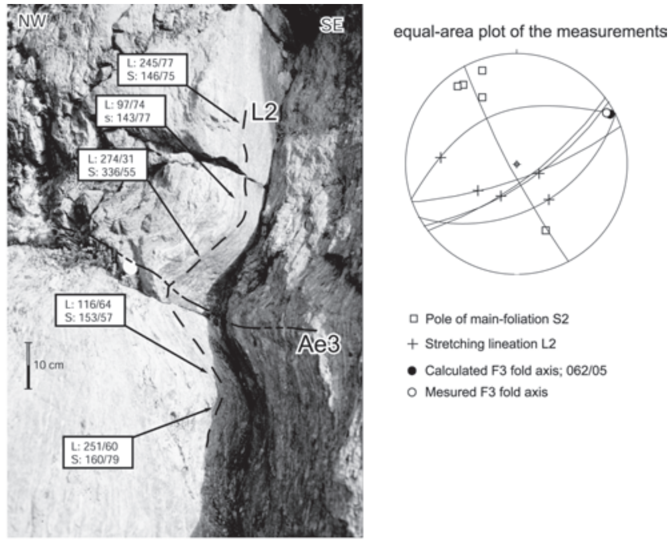



Fig. 8. D2 stretching lineation, refolded by M-type parasitic D3 folds, from the hinge of the Ruitor mega-fold in the Upper Conglomeratic Formation of the Houiller unit. Photograph and stereoplot illustrate the variability of the plunge of L2 (between a SE- and a W-plunge, respectively), due to the overprinting by D3.

stretching lineation, defined by quartz and mica, is often observed to be oriented parallel to these fold axes (Fig. 3d). The transport direction, including that observed along the contact referred to as "Entrelor tectonic contact" (Bucher et al. 2003) or "Entrelor shear zone" (Butler & Freeman 1996), is consistently top-W-NW, as is indicated by shear bands and asymmetric porphyroclasts (Fig. 7a–f). The observed parallelism between fold axes and stretching lineations (Fa2 and L2 depicted in Fig. 3d, see also orientation data from Areas I to III in Fig. 6) indicates pervasive top-W-NW shearing during D2. Where fold axes and stretching lineations related to D2 are parallel, no inversion of the sense of shear occurs across D2 folds. Figure 4 shows the progressive change in orientation of the composite main foliation (Sp) form a SE-dip (sub-area a) to a predominate dip to the NW (sub-area d). This, together with the data given in Figure 6b, particularly the best fit great circle of the folded composite foliation (Sp), as well as the folding of axial planes of D2 (Ae2), points to overprinting during D3 folding around a NE-SW striking D3 fold axis (see also data on Fa3 given in Figure 6a). This is a clear indication that D3 folding strongly overprints the D2 structures.

The wide range in the orientation of L2 and F2 resulted from this overprinting by the third phase of deformation. The overprint manifests itself by the observation that L2 stretching lineations often plot on a great circle (Fig. 6a, Areas I and II). Direct observations, such as those pictured in Figure 8, show that the variation of the L2 stretching lineation within the hinge zone of a D3 fold is indeed due to D3 overprinting. Locally the variations in the orientation of Fa2 and L2 can be large (Figs. 4, 6), but a systematic variation is superimposed at a larger scale, as will be discussed later.

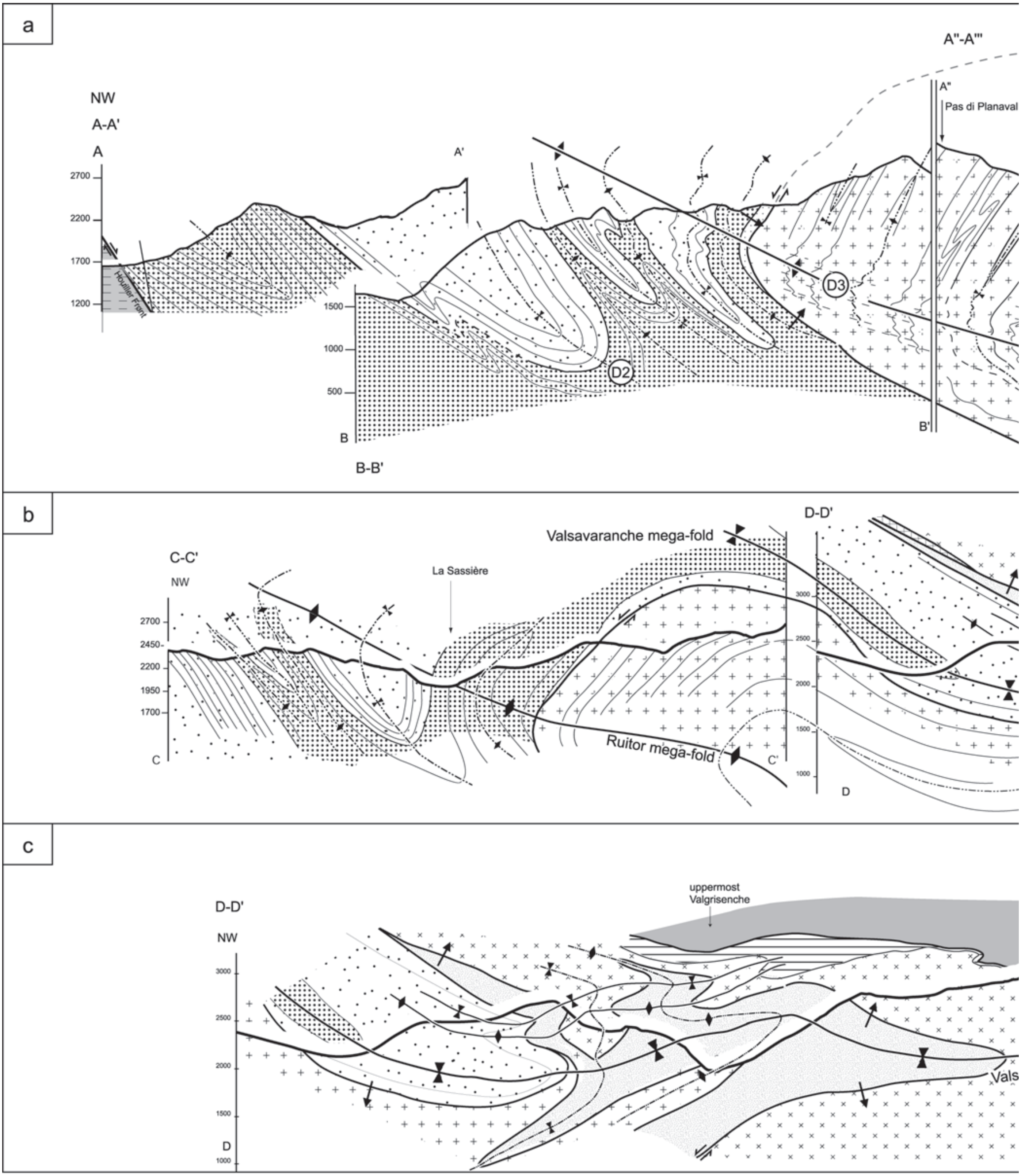
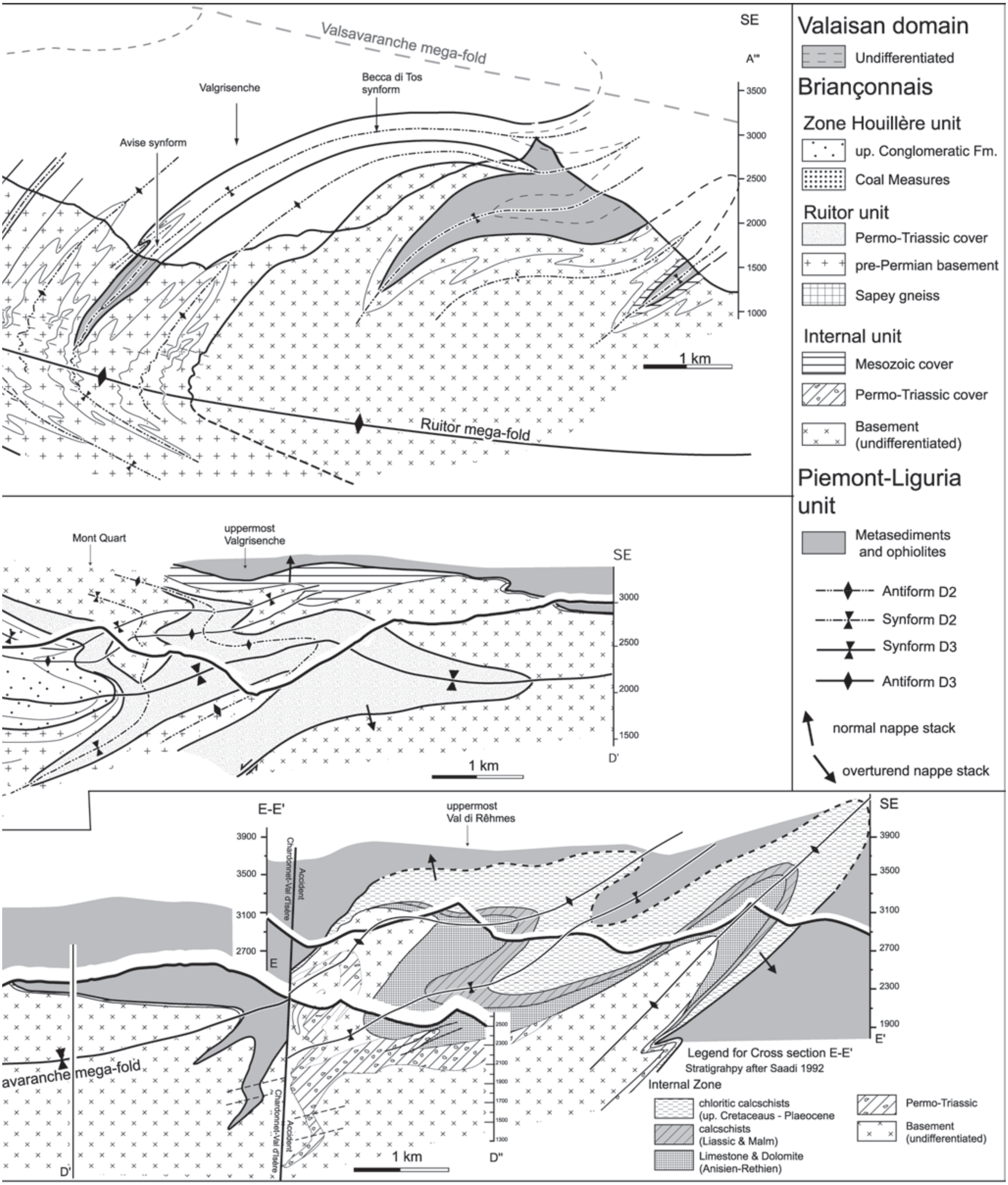



Fig. 9. Detailed cross sections (see Fig. 2 for traces of profiles). The detailed profiles were projected into a joint vertical plane, oriented perpendicular to the mean azimuth of the F3 fold axis (030, 055 respectively) and using an angle of projection given by the plunge of the F3 fold axes. Note that the post-D3 doming is taken into account by contouring the plunge of the F3 fold axes. All the individual cross sections were constructed by using the same procedure. The difference in the




orientation between the cross section A-A' to C-C' and D-D'' to E-E' is due to the changing orientation of the D3 fold axes. a) Cross section A-A', A''-A''' and B-B'; b) cross section C-C' and D-D'; c) cross section D-D', D-D'' and E-E'.

*D3 structures*

D3 is characterized by open parasitic folds that refold the composite S1/S2 main foliation (Fig. 3b–c). The fold axes related to D3 (Fa3) are generally NE-SW oriented and plunge moderately either to the NE or to the SW (Fig. 6a, Fig. 10). In general, the D3 axial planes gently dip to the SE with 5 to 20°, but dips to the SW or NE are also observed locally (Ae3 in Figs. 4, 6). An axial plane pressure solution cleavage is only locally established. Towards tectonically higher positions D3 folds become progressively tighter. The transport direction associated with D3 will be discussed later.

## Discussion of the regional variability regarding orientation and strain intensity of D2 and D3 structures

In order to visualize the regional variation in the orientation of L2, Fa2 and Fa3, the study area was subdivided into the sub-areas indicated in Fig. 5.

Area I exhibits the largest variation in the orientation of L2 (Fig. 5). Note, however, that the external parts of Area I (see areas labeled a, b and c in Fig. 5) differ from the rest of the study area in that a large angle between the orientations of L2 stretching lineations and F2 fold axes (Fa2), respectively, is observed. While L2 and Fa2 are parallel in Areas II and III (see Fig. 6), they are often nearly perpendicular to each other in Area I (Fig. 4), particularly in the external parts (Zone Houillère near the Houiller Front. This difference is interpreted to be due to increasing D2-straining toward the SE. In fact, D2-folds become much tighter in this same direction (see cross section depicted in Fig. 9a). It is suggested that the amount of strain during D2 was not sufficient to parallelize F2 fold axes and L2 stretching lineations in the very external parts of the study area.

Apart from the variation regarding non-parallelism vs. parallelism between L2 and Fa2 discussed above, a systematic variation is observable over the entire study area regarding the orientations of L2 stretching lineations and F3 fold axes (Figs. 5 & 10). In the external part of the Zone Houillère unit, where the main foliation dips to the SE (Figs. 2, sub-areas a and b in Fig. 4), L2 stretching lineations scatter and mostly plunge to the SW or to the SE (Fig. 4, 5). In the internal part of the Zone Houillère unit, in the Ruitor unit and the Internal unit of the Valgrisenche, the main foliation generally dips to the NW (sub-area d in Fig. 4, Fig. 6). The L2 stretching lineations, which are here parallel to Fa2, change to a predominant plunge to the WNW (Fig. 5). Nevertheless, local variations interpreted to be due to the effects of D3 straining, are still observed as is seen from the stereoplot in Fig. 6a (Area II), which indicates a spread of L2 within a great circle. Closer to the Gran Paradiso massif, however, where the main foliation still dips to the NW, L2 is very predominantly ENE-WSW oriented (Fig. 6a, Area III), hence the great circle distribution disappears. This systematic variation is interpreted to be due to the fact that strain intensity associated with the third phase of deformation, increases towards higher tectonic levels, i.e. towards the SE. Hence, increasing D3-strain led to an increasing amount of reorientation of L2 and F2 towards the ESE.

D3 fold axes (Fa3) either plunge to the NE or to the SW (Fig. 6a, Areas I to III; Fig. 10). This variation occurs along strike, rather than across strike, as was observed for D2 structures. In the northeastern part of the study area F3 fold axes plunge to the NE, while they plunge to the SW in the southwest (Fig. 10). A central region, within which D3 fold axes are sub-horizontal, separates these areas. This reflects late-stage (post-D3) doming on a kilometric scale, the Ruitor area forming an axial culmination. Doming can also be inferred from the variability of the D3 axial planes (Ae3), as is shown in Fig. 6b.

## Sense of movement inferred for individual tectonic contacts during D1 and D2

The kinematics of movement along the tectonic contacts and the attribution of theses kinematics to a specific deformation phase are crucial for understanding the evolution of the study area. Concerning the attribution to particular phases of deformation, field evidence clearly shows that all tectonic contacts outcropping in the study area were overprinted by the third deformation phase after their formation; hence they are either syn-D1 or syn-D2. The tectonic contacts analyzed in terms of kinematics are, from external to internal: contact between Zone Houillère unit and external Ruitor unit, contact between Ruitor unit and Internal unit, and the contacts between Piemont-Liguria oceanic unit and Ruitor or Internal unit, respectively (Fig. 2).

Mesoscopic shear sense indicators are well preserved where overprinting by D3 folds is not too intense. Shear bands and rotated clasts consistently show top-WNW to top-NW kinematics (Fig. 7a–f). In such cases the senses of shear associated to the L2 stretching lineations characterize the kinematics of movement during D2. In case of the mylonites formed at tectonic contacts their foliation is parallel to the main foliation S2, and the stretching lineations define the kinematics of movement. Hence the kinematics of the tectonic contacts, indicating a top-NW sense of shear, can unequivocally be attributed to the second phase of deformation. Also note that D2 folding and shearing sub-parallel to L2 is contemporaneous, hence this D2 folding could not re-orient the sense of shear.

While all tectonic contacts in the study area were active during D2, relict D1 senses of shear were, however, identified at the tectonic contact between Ruitor unit and Internal unit. Microfabric analysis of preferred quartz c-axis orientation revealed different senses of shear for different layers within one and the same thin section (Fig. 11a shows a relict top-E shear sense). Top-WNW sense of shear, also deduced by quartz c-axis analysis, could be correlated with other criteria such as shear bands and sigma clasts, that are microscopically (Figure 11b) as well as mesoscopically visible and easily attributed to D2. Note that there is an independent observation indicating a pre- or early-D2 activity along the same tectonic

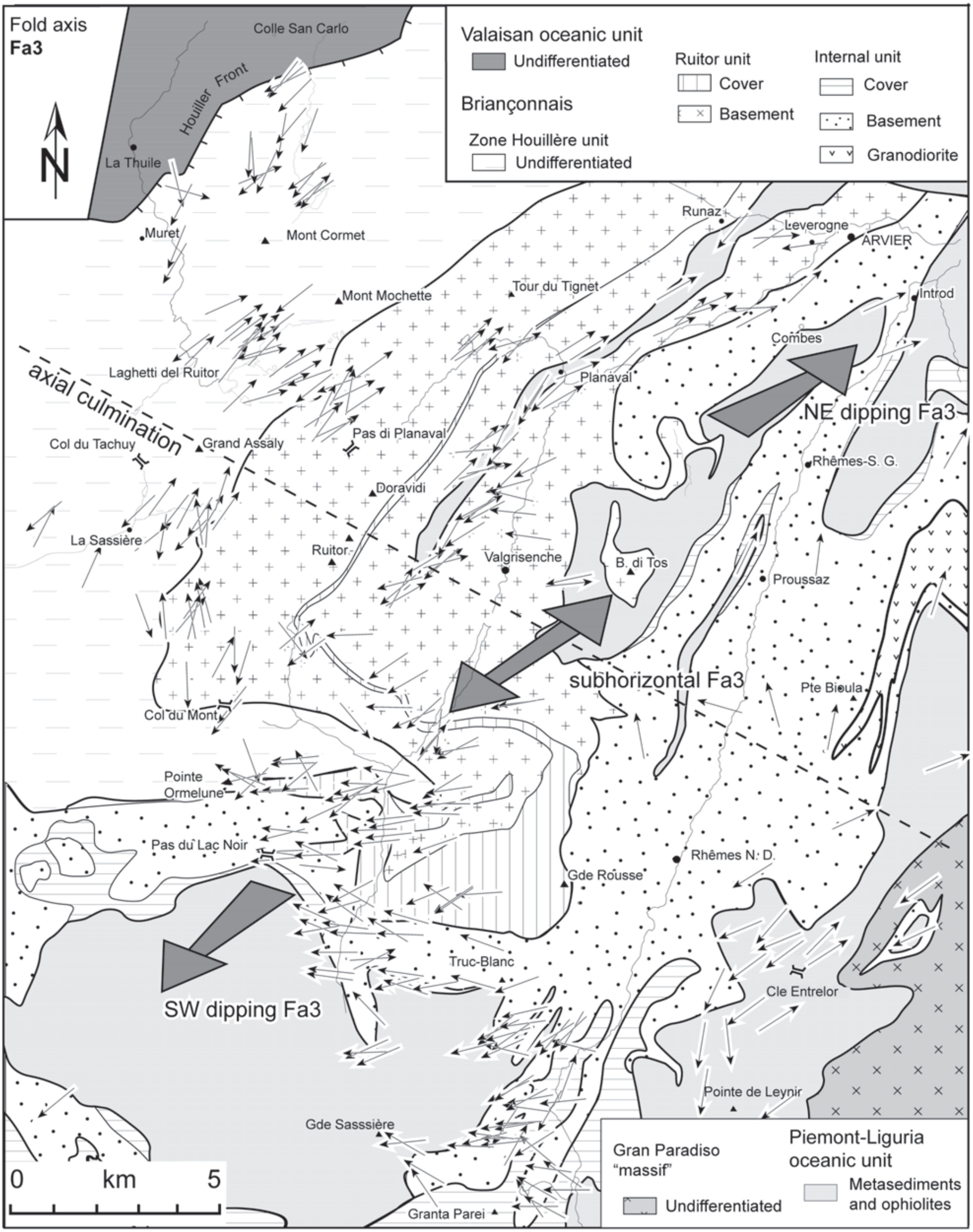



Fig. 10. Map of F3 fold axis. Grey arrows display the geographic distribution of the dominant orientation of the F3 fold axes, evidencing late doming (D4).

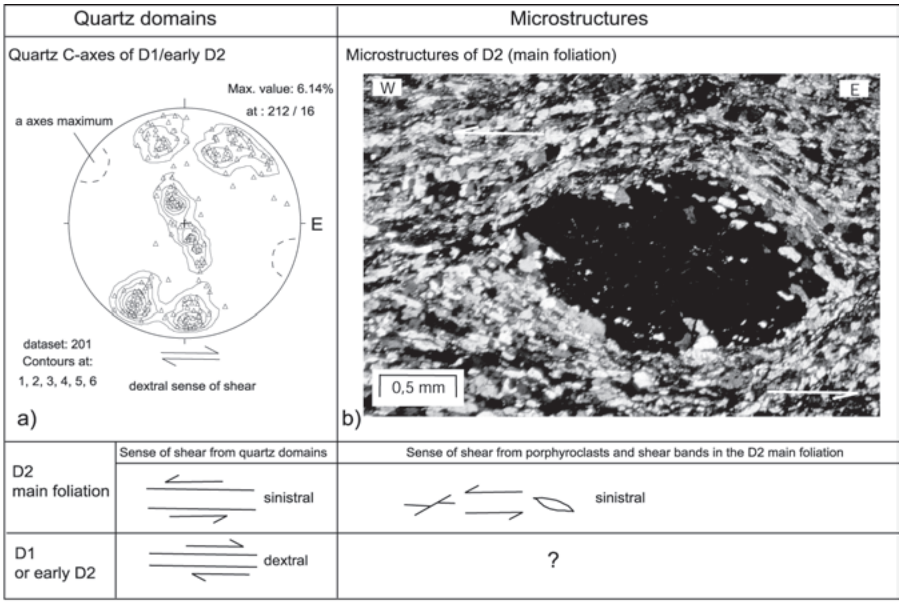



Fig. 11. a) Quartz C-axis preferred orientation, showing a relict D1 top-E sense of shear; b) sigma clast showing D2 top-NW transport direction along the tectonic contact between Ruitor unit and Internal unit (garnet-micaschists of the Ruitor unit from uppermost Valgrisenche).

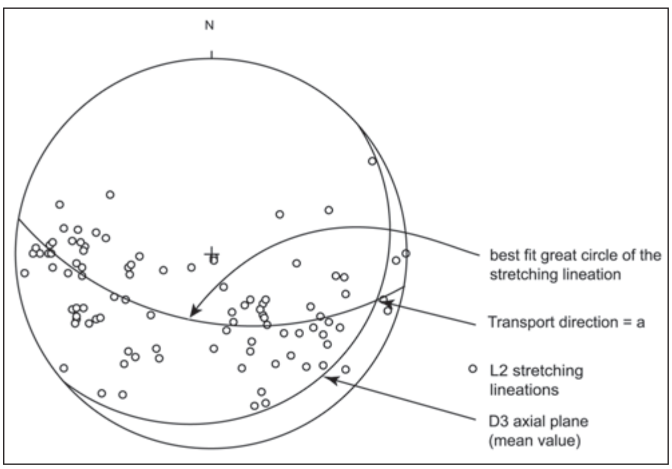



Fig. 12. Construction of transport direction for D3 using a fold in the Upper Conglomeratic Formation of the Houiller unit (after Ramsay & Huber 1987, their Fig. 22.7). Data cover the northeastern part of Area I shown in figure 5.

contacts: D2 folds, except for the contact between Ruitor unit and Zone Houillère unit, locally refold all of them.

In summary, the studied tectonic contacts could have been already active during D1, or alternatively, during an early stage of D2. Since no L1 stretching lineations are preserved no conclusions can be made regarding the kinematics during D1. With respect to D2, the kinematics of movement is presently found to be top-WNW to top-NW. However, since L2 was reoriented by D3 straining, as described earlier, the related syn-D2 kinematics must also have been systematically reoriented. The observed progressive reorientation towards the WNW, with increasing amounts of D3-strain, suggests original top-NW, or even top-NNW, shearing during D2.

*Transport directions associated with D3*

Since no stretching lineation did form during D3, the transport direction cannot be directly inferred. The simple assumption, that the transport direction is perpendicular to the fold axis is not justified, because D3 folds are shear folds, as is indicated by the observation that L2 lineations plot on a great circle (Fig. 12). However, construction of the slip vector "a" active during D3 folding (Ramsay & Huber 1987; their Fig. 22.7) suggests that the transport direction strikes E-W to ESE-WNW (Fig. 12). Note that the polarity of shearing cannot be deduced by this method. Hence this direction could be compatible with the classical postulate of back-thrusting towards the ESE, (i.e. Butler & Freeman 1996). However no stretching lineations or shear zones connected to D3 where observed and large-scale observations, discussed below, do in fact indicate top-WNW transport during D3.

## Cross sections and regional structures

Six detailed cross sections (see Fig. 2 for location) were projected into the three combined cross sections depicted in Fig. 9. These combined cross sections will now be discussed in order to examine the large-scale structure of the Briançonnais in the Italian-French Western Alps.

*Combined cross sections A-A', A''-A''' and B-B' (Fig. 9a)*

This first set of cross sections (Fig. 9a) runs NW-SE, from the Houiller Front in the area of the Petit Saint Bernard pass to the Val di Rhêmes (Fig. 2). Near the Houiller Front, the main foliation (S2) dips to the SE (Fig. 2, sub-areas a and b in Fig. 4). At the earth's surface S2 gradually gets steeper and finally sub-vertical by going towards the tectonic contact with the Ruitor unit (Fig. 2, sub-areas c and d in Fig. 4). In the northwestern part of section B-B' (Fig. 9a) D3 fold vergency indicates a large scale, northwestward closing antiform situated further to the SE. Where the main foliation is found in a sub-vertical orientation, M-type D3 folds within the Zone Houillère unit indicate the major hinge of a D3 fold. Still within the Zone Houillère, but close to the contact with the Ruitor massif (southeastern part of the cross section B-B' in Fig. 9a) the main foliation changes into a predominant dip to the NW (Figs. 2, 6b) and D3 fold vergency also changes (Fig. 3b). This change in fold vergency is associated with a mega-fold situated within the Ruitor unit (Fig. 9a, southeastern part of section B-B'): the D3 Ruitor mega-fold. The M-type D3 folds mentioned above represent the hinge zone of this Ruitor mega-fold. It is the gradual change in dip of the S2 foliation from a SE dip towards the internal zone that is referred to as "fan-structure" in the literature. However, this "fan-structure" is simply a geometric effect caused by the large-scale D3 Ruitor mega-fold with its flat-lying, gently SE-dipping axial plane.

Along this profile and within the Zone Houillère unit, several large-scale F2 folds are evidenced (Fig. 9a, profiles A-A', B-B'). The axial plane of the easternmost F2 fold is cut by the contact between the Zone Houillère unit and the Ruitor unit. This indicates that this contact is a tectonic one, and that it was still active after D2 folding, i.e. during a late stage of D2. This tectonic contact is, however, refolded by the D3 Ruitor mega-fold. Sedimentological younging criteria indicating younging of the Zone Houillère unit towards the Ruitor unit (Mercier pers. comm. and own observations) indicate that the internal parts of the Zone Houillère unit are in an overturned position. Hence the tectonic contact on top of the Zone Houillère unit, situated in the lower limb of the Ruitor mega-fold, must represent the late-D2 basal thrust of the Ruitor unit onto the Zone Houllière unit.

The Ruitor unit is characterized by a dominant dip of the main foliation (S2) to the NW at the earth's surface. While the D2 antiform situated immediately NW of the Pas di Planaval (Fig. 9a) was already evidenced by Baudin (1987), the first D2 synform found SE of the Pas di Planaval was recognized as a band of Permo-Triassic cover, pinched within the basement of the Ruitor unit, by Caby (1996) (see Fig. 9a, profile A''-A''').

The sediments in this synform play an important role for understanding the large-scale structure of the area. Firstly they independently indicate, besides the evidence described earlier and derived from the facing of the D2 folds from the Zone Houillère, that the Ruitor unit is not the basement of the Zone Houillère. It is this Permo-Triassic cover, lacking Carboniferous deposits and found within a narrow syncline, that represents the cover of the Ruitor basement. Secondly, while different authors (Gouffon 1993, Caby 1996) interpreted the footwall of this Permo-Triassic cover to represent a tectonic contact between "external" and "internal" Ruitor units, the two are simply separated by a narrow D2 upward- and SW-facing syncline, reoriented in the upper limb of the Ruitor mega-fold by D3. This interpretation was recently confirmed by Ulardic (2001), who mapped a synform along the southern continuation of the same cover sequence in the upper Valgrisenche, based on the litho-stratigraphy of the Permo-Triassic sediments. In summary, external and internal Ruitor unit represent the same tectono-metamorphic unit, refolded by F2. This confirms the view of Desmons & Mercier (1993), who pointed out the important role of the intensity of the D2 retrogression, increasing towards the SE. Note that the cross section confirms the increasing intensity of the deformation during D2, expressed by the tightening of the D2 folds towards the SE (Fig. 9a, B-B').

The structures analyzed further to the SE are those which were previously described by Cigolini (1995) and Caby (1996). The synform formed by a D1-thrust at the base of the P-L oceanic unit, that appears pinched within the Ruitor unit (immediately NW of Valgrisenche in profile of Fig. 9a), corresponds to the D2 "Avise synform" described by Caby (1996). This D2-structure refolds the D1 thrust of the P-L oceanic unit onto the Briançonnais domain and finds its south-eastern continuation within the flat lying P-L sediments below the klippe of the Becca di Tos (Dal Piaz 1965) at the SE end of the profile of Figure 9a.

The change from steeply NW-dipping main (S2) foliations in the profile of Figure 9a to flat-laying foliations further to the SE is an effect of large-scale folding during the third phase of deformation. D3 large-scale folding is responsible for the right-way up and SE-dipping nappe stack observed in the external part of the cross section. The area with the sub-vertical dip of the S2 main foliation, observed further to the SE, represents the hinge zone of the D3 Ruitor mega-fold. The internal part of this cross section, characterized by a NW-dip of the main foliation, exhibits an overturned nappe stack. In summary, the overturning of the nappe stack is due to the formation of the Ruitor mega-fold during D3.

Note that the Ruitor mega-fold is a backfold with a flat lying axial plane, comparable to the Mischabel backfold (Müller 1983) of the Zermatt area, and analogous to what is observed around the Niemet-Beverin fold of the Briançonnais-type Schams nappes of eastern Switzerland (Schmid et al. 1990, Schreurs 1993). It is, however, not a backfold that is necessarily kinematically linked to backthrusting, such as the Vanzone antiform of western Switzerland that formed later in respect to the Mischabel backfold (Kramer 2002). Furthermore the hinterland-dipping axial plane is not compatible with a classical model of backfolding associated by backthrusting.

### *Combined cross sections C-C' and D-D' (Fig. 9b)*

This combined cross section is situated further to the SW (Fig. 2). Due to an axial plunge to the SW (Area II SW in Fig. 6b), associated with post-D3 doming, the structurally highest levels of the study area are exposed along its trace. The profile, running through the uppermost Valgrisenche (Fig. 2), features a second and structurally higher large-scale D3 fold, the Valsavaranche mega-fold closing to the SE. Note that the "type locality" of this "Valsavaranche mega-fold" occurs much further to the NE, i.e. in the lowermost Valsavaranche (Fig. 2), as will be discussed later.

The northwestern part of this cross section (C-C' in Fig. 9b) displays structures similar to those discussed in the section of Fig. 9a. In part D-D' of this section, however, the axial trace of the Valsavaranche mega-fold enters the profile, as is evidenced by a synform with the Zone Houillère unit in its core, surrounded by basement and cover of the Ruitor unit (Figs. 2 & 9b).

Note that the Permo-Triassic cover sequence, which crosses the uppermost Valgrisenche, and which is attributed to the Ruitor unit in this study (Figs. 2 & 9b), was classified as the Permo-Triassic cover of the Internal unit in the map by Debelmas et al. (1991b). We did not follow this interpretation since the Internal unit (Vanoise-Mont Pourri unit as defined by French authors) has its own sedimentary cover, including a Permo-Triassic sequence at the base. This cover is however outcropping at a higher structural level in this section (Fig. 9b), i.e. directly below the northern end of the klippe formed by the Piemont-Liguria unit at the Gde Sassière (Fig. 2). Note also that Debelmas et al. (1991b) interpret the Sapey gneiss outcropping to the west of the Pointe Ormelune (Fig. 2) to continue eastwards and into the profile trace of section D-D' (Fig. 9c). Own field observations, however, clearly indicate that leucocratic rocks interpreted as Sapey gneiss are in fact part of the upper Conglomeratic Formation of the Zone Houillère unit (Fig. 2).

Further to the SE along the same profile (SE of uppermost Valgrisenche, Fig. 9b) the large-scale D3 Valsavaranche mega-fold is seen to fold the contact between the Permo-Triassic cover of the Ruitor unit (in agreement with all authors) and the basement of the Internal unit. Between Mont Quart and uppermost Valgrisenche this same tectonic contact between Ruitor unit and Internal unit is also folded by D2 large-scale folds.

Near the southeastern termination of profile D-D' in Figure 9 the Permo-Mesozoic cover of the Internal unit is again overlain by the P-L oceanic unit of the Grande Sassière klippe. This is clear evidence that the nappe stack is right-way-up in the upper limb of the D3 Valsavaranche megafold. The complete nappe pile formed during D1 and D2 consisted of, from base to top, Zone Houillère unit, Ruitor unit, Internal unit and P-L oceanic unit. It is preserved in this profile in its original orientation in the "normal" upper limb of the Valsavaranche mega-fold only.

*Combined cross sections D-D'' and E-E' (Fig. 9c)*

At the south-eastern end of cross section D-D'' (Fig. 9c) the axial trace of the Valsavaranche mega-fold is seen to run into the P-L oceanic unit. Immediately further to the SE, however, it is cut by a young vertical tectonic contact already described by Marion (1984). Unfortunately the kinematics of this brittle fault, largely sealed by Quaternary cover, remains unknown.

To the SE of this fault, as shown in cross section E-E' (Fig. 9c), lithologies and structures are changing. Instead of the relatively thin Permo-Mesozoic cover sequence of the Internal unit found NW of this fault, a thicker Mesozoic sequence is present here, characterized by a well-defined stratigraphy comprising Triassic to Paleocene sediments (Jaillard 1989 & 1990, Saadi 1992). On a larger scale this sedimentary sequence belongs to the "série Val d'Isère – Ambin" defined by Ellenberger (1958).

Laterally and towards the SE this rather complete Triassic to Cretaceous sequence is wedging out, except for the upper Cretaceous-Paleocene sequence that is found to still mark the contact of the basement of the Internal unit with the P-L oceanic unit at the south-eastern end of profile E-E' (Fig. 9c). This reflects a lateral facies change which is well known in the Briançonnais and due to multiple erosion events (Jaillard 1989, 1990) that characterize this paleogeographic domain. The structural map (Fig. 2) is partly based on detailed studies carried out in this particular region by Adatte et al. (1992) and Saadi (1992).

In profile E-E', i.e. SE of the subvertical fault mentioned above, the Valsavaranche mega-fold is defined by an M-shaped fold triple. The pair of antiforms with a synform in the middle indicates that the axial trace of the D3 Valsavaranche mega-fold dips to the NW at the south-eastern end of this cross section. The lower limb of this backfold with a foreland dipping axial plane is formed by the P-L oceanic unit that underlies the Internal unit and hence indicates an overturned nappe stack observable at the south-eastern end of profile E-E'. The overturned cover sequence of the Internal Zone (Fig. 9c) confirms this observation. This overturned D2-thrust of the P-L oceanic unit over the Internal zone ("Entrelor tectonic contact"; Bucher et al. 2003) can be followed along strike to the NW and into the area around the Col d' Entrelor. As discussed in Bucher et al. (2003) the observed top-W-NW sense of shear along this overturned thrust excludes back-thrusting along this contact, referred to as "Entrelor shear zone" by Butler & Freeman (1996) and interpreted as a backthrust by these same authors, in spite of clear evidence for top-W-shearing (Caby 1996).

The Valsavaranche mega-fold found near the south-eastern termination is responsible for the existence of a klippe of P-L oceanic unit in the Grande Sassière area (Fig. 2). This klippe is connected with the rest of the P-L oceanic unit that underlies the Internal unit around the M-shaped hinge-zone of this backfold (Fig. 9c). The D3 folds, which define the Valsavaranche mega-fold, can be followed southward and are correlated with folds described by Marion (1984) in the Val d'Isère.

**Summary and interpretation of the large-scale structures**

The cross sections of Figure 9 indicate large-scale refolding of the original D1/D2 nappe stack by two D3 mega-folds. This nappe stack is overturned in an area between the axial planes of these two mega-folds.

The structurally lower of the two mega-folds is the west-closing Ruitor mega-fold, found in the external part of the investigated area, where it affects the composite S1/S2 main foliation. The gradual change in dip of the S1/S2 main schistosity defines a "fan structure" which is only apparent since it is due to the large-scale D3 Ruitor mega-fold. This fold, characterized by a flat-lying axial plane, overturns the entire nappe stack in its upper limb (Fig. 9a).

We localized a second and structurally higher major D3 mega-fold in the uppermost parts of Valgrisenche and Val di Rhêmes (Fig. 9b, Fig. 2). This second mega-fold closes towards the east and brings the entire nappe stack back into an upright position, such as observed in the uppermost part of the Valgrisenche (i.e. in the Grande Sassière area). This hitherto undetected D3 mega-fold (Fig. 9b–c) is laterally correlated with the well-known Valsavaranche "backfold" described by Argand (1911), which also is an eastward closing fold, whose axial trace was mapped in the lower Valsavaranche and in the Val di Cogne (Fig. 2). Although the Valsavaranche mega-fold is a backfold in the sense that it locally exhibits a foreland-dipping axial plane, it is by no means kinematically linked to backthrusting. Basically, it just represents the structurally higher of a pair of flat-lying folds. This fold pair exhibits an asymmetry in the sense of mega-scale vergency. However, fold vergency does not indicate the overall sense of shearing (Ramsay & Huber 1987) and thus top-SE shearing cannot be directly deduced from the observed fold geometry (see later discussion). The dip to the foreland of the axial plane is only pronounced at the SE end of the profile of Fig. 9c and due to the late-stage culmination of the Gran Paradiso massif (D4).

The Valsavaranche mega-fold, evidenced by this study in the profile of Fig. 9c, and the Valsavaranche backfold of Argand (1911) occupy identical structural tectonic positions. This can be seen from the fact that the axial trace of the same east-closing mega-fold visible in the profile of Fig. 9c projects immediately above topography at the SE end of the profile of Fig. 9a (compare also Fig. 2). However, due to post-D3 doming (D4), culminating in the Ruitor-area, the trace of the axial plane of this mega-fold is not continuous along strike (Fig. 2). This is in line with the plunge of the fold axes of the third phase of deformation, as can be inferred from Fig. 10. Because of its position NE of the axial culmination, the axial plane of the Valsavaranche mega-fold of the northern and lower parts of the Val di Rhêmes and Valgrisenche dips to the NE (Fig. 2). The lower parts of these two valleys expose the upper limb of the Valsavaranche mega-fold and therefore a right-way-up nappe stack. This same normal nappe stack, structurally situated above the axial trace of the Valsavaranche mega-fold, is also found north of the Aosta fault, which cuts the axial trace of this mega-fold (Fig. 2 and Gouffon 1993). The change of dip of the axial trace of the Valsavaranche mega-fold into the SW-dip observed SW of the Ruitor axial culmination causes the axial plane of the Valsavaranche mega-fold to crop out again in the uppermost parts of the Val di Rhêmes and Valgrisenche (Fig. 2, Fig. 9c). There, i.e. in the Grande Sassière area, an upright nappe stack is exposed in the upper limb of this same D3 fold.

All tectonic contacts between the constituents of the D1/D2 nappe stack consisting of, from bottom to top, Zone Houillère unit, Ruitor unit, Internal unit and P-L oceanic unit, are former thrusts, and none of them are back-thrusts. These thrusts were refolded by a pair of D3 mega-folds. The refolding around a NE-SW-oriented axis, approximately perpendicular to L2, that is associated with top-NW senses of shearing, led to the preservation of the thrust-related kinematic indicators, even where former nappe contacts are overturned.

Occasionally, large-scale folding of the nappe contacts is also observed during D2 (i.e. central part of profile in Fig. 9b). While this D2-folding is pervasive and synchronous with the top-NW kinematics deduced for all D2 tectonic contacts, the kinematics of movement during D1, when these tectonic units constituting the nappe stack were first juxtaposed, remains unknown.

**Discussion**

Despite numerous previous studies, no consistent picture of the large-scale tectonic structure of the Italian-French Alps was available so far, although the successive deformation phases were recognized and described on a meso- and microscopical scale by most previous workers. Many of these studies only addressed individual tectono-metamorphic units. The structural data presented by this study, however, cover a significant portion of the tectonic units attributed to the Briançonnais domain along a major geological-geophysical transect through the Western Alps: the ECORS-CROP profile (Nicolas et al. 1990, Roure et al. 1996, Schmid & Kissling 2000). Furthermore the individual deformation phases can now be better tied to the metamorphic evolution (Bucher et al. 2003).

The finding that external Ruitor and internal Ruitor (or Zone de Leverogne after Gouffon 1993) are part of the same tectono-metamorphic unit is in agreement with Desmons & Mercier (1993), but contrasts with the interpretation of Gouffon (1993). However, the latter author makes a question mark regarding the attribution of the internal Ruitor (Zone de Leverone) to the Siviez-Mischabel nappe (Thélin et al. 1993). Furthermore the internal Ruitor has no continuation north of the Aosta fault (Fig. 1 of Gouffon 1993). Hence we suggest that there is only one Ruitor unit, and that this unit represents the southern continuation of the Pontis nappe of Western Switzerland (Gouffon & Burri 1997) to the south.

Many aspects of the large-scale geometry of D3 nappe refolding (Ruitor mega-fold and Valsavaranche mega-fold) remained undetected, except for parts of the Valsavaranche backfold, already described by Argand (1911), and parts of the Ruitor fold, described by Baudin (1987). On the other hand, we found no evidence for back-thrusting, claimed to be of major importance for the large-scale structure of the Western Alps by many authors (i.e. Butler & Freeman 1996). Hence, nappe refolding (D3) is the dominant mode of late stage deformation in the Western Alps (Bucher et al. 2003). The significance and origin of nappe refolding and related geodynamics depend on the relation between backthrusting, backmovement and backfolding. Classically, two phases of backfolding are known from the Penninic units of Western

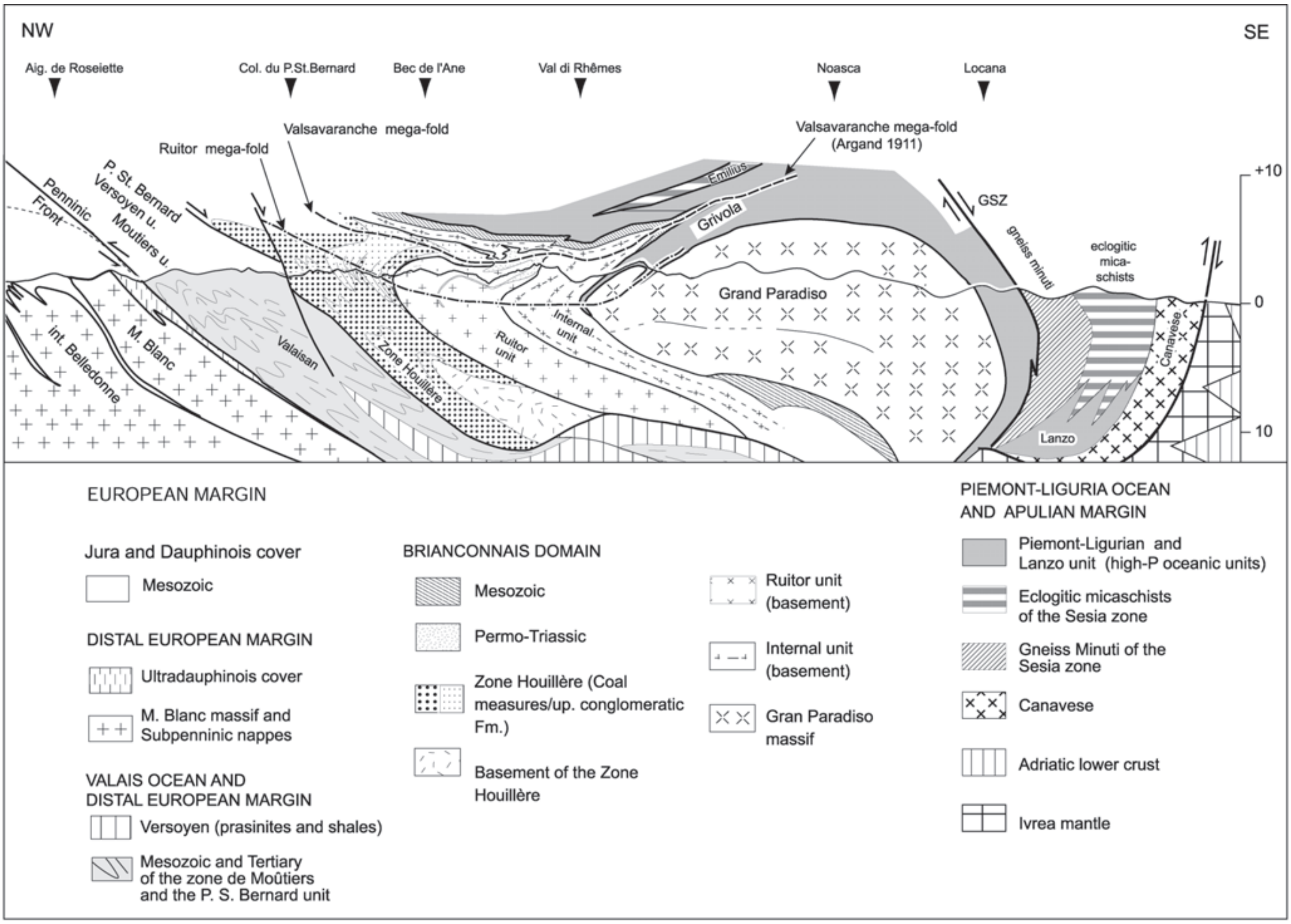



Fig. 13. Cross section along the ECORS-CROP seismic line (profile trace indicated in Figs. 1 & 2), modified after Schmid & Kissling (2000), depicting two large-scale post-nappe folds at the scale of the orogen. GSZ: Gressonney shear zone.

Switzerland and adjacent Aosta valley (e.g. Milnes et al. 1981). During a first phase of backfolding (D3) the Mischabel backfold, characterized by a flat-lying axial plane, develops. The associated sense of shear of D3 structures varies between top-SE and top-SW and parts of this shearing are associated with orogen parallel extension (Keller & Schmid 2001). This is in contrast to the second phase of backfolding, the Vanzone phase (D4), characterized by a steeply foreland-dipping axial plane and directly associated to backthrusting "s. str." along the Insubric line (Schmid et al. 1987, Kramer 2002). As shown by various authors the first (D3) backfolding phase is not necessarily kinematically linked to back-thrusting or back-movement (Pfiffner et al. 2000, Escher and Beaumont 1997, Ring 1995). However, the question if D3 led to overall backmovement along the ECORS-CROP seismic line still remains. It is argued, that such backmovement is only locally observed. Instead the large scale nappe refolding is interpreted to be due to NW-wards extrusion of the Gran Paradiso in profile view. This extrusion leads to vertical shortening and results in the relative movement of the overlying units, i.e. the internal Briançonnais, towards the hinterland. The consequences of this relative backmovement are D3 megafolds with flat-lying axial planes. These D3 megafolds are best explained by extrusion induced backfolding in an overall compressional regime. Therefore, although a relative movement towards the hinterland results, the D3 megafolds are not interpreted to have formed in the same geodynamic context as the younger Vanzone phase back-folding and back-thrusting. The latter indicates an overall hinterland directed transport direction of the entire nappe stack.

In conclusion we suggest that the geodynamic context of the two classical backfolding phases is different. The first backfolding phase (D3 mega-folds) develops during the north-(west)ward extrusion of the internal crystalline massifs, which is linked to local, hinterland directed back-movement and vertical shortening. In contrary, the second backfolding phase (Vanzone) results from overall hinterland directed kinematics, directly associated with backthrusting. Similar models are

Tab. 1. Table showing correlation of deformation phases and timing constraints. Strain gradients and inferred geodynamic processes are also shown.

| **Geodynamic process** | | **Zone Houillère unit** | **Tectonic contact** | **Ruitor unit** | **Tectonic contact** | **Internal unit** | **Tectonic contact** | **P-L oceanic unit** | **Age** (after Bucher et al., sub.) |
|---|---|---|---|---|---|---|---|---|---|
| **Late doming** | **D4** | Open folds without axial plane cleavage, subvertical axial plane | | Only evidenced by the changing D3 features (F3, S3) on kilometric scale | | Only evidenced by the changing D3 features (F3, S3) on kilometric scale | | Only evidenced by the changing D3 features (F3, S3) on kilometric scale | ? (< 31 Ma, FT from Hurford & Hunziker, 1989) |
| Strain gradient | | | | Increasing strain towards the SE | | | | | |
| Large scale **nappe refolding** | **D3** | Open folds with a poorly developed, gently dipping (< 25°) axial plane cleavage | folded | Open folds with a poorly developed, gently dipping (< 25°) axial plane cleavage | folded | Open folds with a poorly developed, gently dipping (< 25°) axial plane cleavage | folded | Open folds with a poorly developed, gently dipping (< 25°) axial plane cleavage | 35-31Ma |
| Strain gradient | | tightening of D2 fold | | - | | - | | - | |
| **Exhumation** to greenschist facies | **D2** | Main schistosity = S1/S2 composite foliation; isoclinal folds | **late D2** top W-NW thrusting | Main schistosity = S1/S2 composite foliation; isoclinal folds | **early D2** top W-NW thrusting | Main schistosity = S1/S2 composite foliation; isoclinal folds | **early D2** top W-NW thrusting | Main schistosity = S1/S2 composite foliation; isoclinal folds | 43-35 Ma |
| Suduction & **peak pressure** | **D1** | S1schistosity; isoclinal folds | - | S1schistosity; isoclinal folds | relics | S1schistosity; isoclinal folds | ? | S1schistosity; isoclinal folds | 50-43 Ma |

available for the Monte Rosa area (Ring 1995) and supported by the modeling of Merle & Guillier (1989).

The new findings described in this contribution ask for a modification of the ECORS-CROP profile published by Schmid & Kissling (2000). Figure 13 shows the modified version of this section, based on the data presented in the cross sections of Fig. 9. It exhibits three main features.

Firstly, this section clearly depicts the correlation of the Valsavaranche mega-fold described for our working area with the Valsavaranche backfold of Argand (1911). Note, that the trace of this mega-fold can be followed along the profile by some 30 km (Fig. 13). Hence it represents a major feature at the scale of the orogen.

Secondly, the profile shows that the original nappe stack was overturned over the same distance of about 30 km across strike, but only between the axial traces of the two mega-folds. Note that the area between these axial planes is characterized by foreland-dipping foliations and tectonic contacts. This nappe stack is bent back into a right-way-up position around the Valsavaranche mega-fold. This implies that no late stage thrusting (such as proposed by Butler & Freeman 1996 and Caby 1996) is needed to explain presence of a normal nappe stack in frontal and structurally highest parts of the internal Western Alps, such as preserved in form of the Grande Sassière klippe, or in form of the outcrops of the P-L oceanic unit found north of the Aosta valley (Fig. 2).

Thirdly, the modified cross section suggests that the Ruitor mega-fold may be continued subsurface to the SE for some considerable distance, before it reaches the earth's surface again within the frontal parts of the Gran Paradiso massif. This is due to the changing dip of the axial plane, caused by the late doming of the Gran Paradiso massif. The axial plane of the Ruitor mega-fold runs into the Gran Paradiso unit across an earlier formed (D2?) synform, made up of the P-L oceanic sediments of the Grivola (Fig. 13). This deduction, together with the structural data of Vearncombe (1985), suggests the existence of a normal nappe stack on top of the Gran Paradiso unit, and it also confirms that the Gran Paradiso unit is part of the Briançonnais paleogeographic domain.

Large portions of overturned nappe stacks, linked to large-scale nappe refolding, are described along the entire Alpine arc. Similar large-scale nappe refolding and refolded tectonic contacts have been described for the southern Western Alps (Tricart 1984, Philippot 1990, Henry et al. 1993). The Mischabel and related late stage folds of the western Swiss Alps (Müller 1983, Keller & Schmid 2001, Kramer 2002) and the Niemet-Beverin fold of the Schams nappes in the central Swiss Alps (Schmid et al. 1990, Schreurs 1993) are other examples. Hence, this large-scale nappe refolding is an important and common late-stage tectonic feature of the post-collisional evolution of the Alps. Evidently, this feature goes along with vertical shortening, given the flat-lying axial planes of the late-stage mega-folds mentioned above. Note that the flat-lying axial planes of all these folds are in contrast with the steeply dipping axial planes of the classical backfolds, that are related to backthrusting along the Insubric line (Schmid et al. 1987), such as the Vanzone antiform, formed later in respect to the Mischabel backfold (Milnes et al. 1981). Furthermore, note

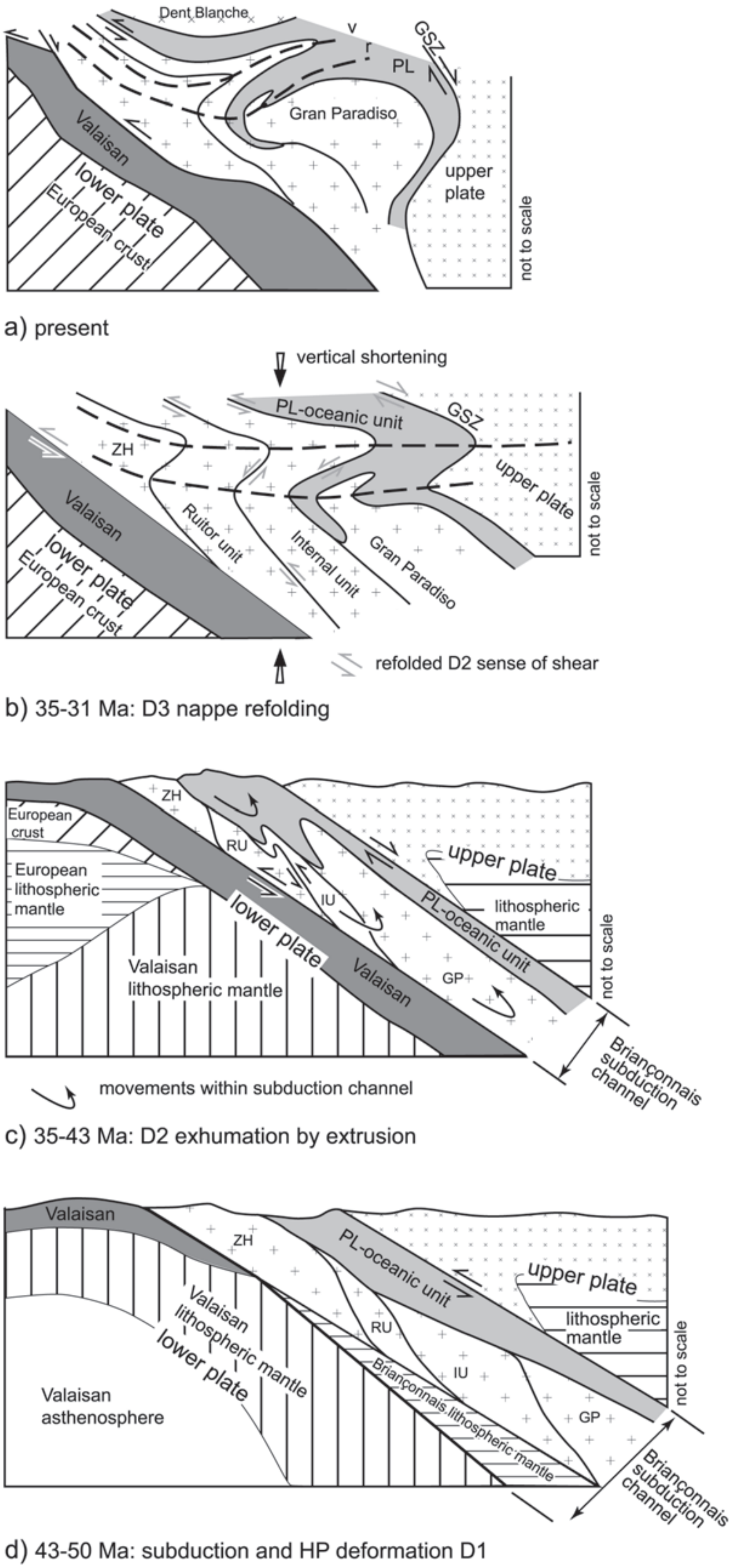



Fig. 14. Sketch of the tectonic evolution, modified after Bucher et al. (2003): a) Present situation; b) Evolution of D3 large-scale nappe refolding; note refolding of the nappe contacts without inversion of the sense of shear; similar structures are shown in the models of Pfiffner et al. (2000). c) Exhumation by extrusion within and parallel to the subduction channel (D2); note that exhumation takes place during the final stages of nappe stacking; also note that the sense of shear on top of the subduction channel is inverted in respect to the situation during the subduction; displacement vectors within the subduction channel derive from the models of Burov et al. (2001). d) Subduction and deformation under peak metamorphic conditions. Abbreviations are: r: Ruitor mega-fold; v: Valsavaranche mega-fold; GP: Gran Paradiso massif; DB: Dent Blanche unit; PL: Piemont-Ligurian oceanic unit; ZH: Zone Houillère unit; RU: Ruitor unit; IU: Internal unit; GSZ: Gressonney shear zone.

that no evidence for back-thrusting or normal faulting was found anywhere in the working area.

While the interpretation of the present geometry can largely be explained by D3 nappe refolding, differences in P-T conditions found amongst the different tectonic units of the working area (Bucher et al. 2003) are unrelated to this folding. These differences ask for a careful examination of the kinematics and the timing during the pre-D3 formation of the tectonic contacts between the different Briançonnais units. The tectonic contacts between Gran Paradiso unit, P-L oceanic unit, Internal unit and Ruitor unit are all clearly refolded by D2 folds. Hence they must have previously formed, namely at the end of D1, or alternatively, during early stages of D2 (Table 1). Note, however, that top-NW shearing was still active during D2 folding, particularly in the external part of the study area, e.g. at the tectonic contact between the Ruitor- and Zone Houillère unit, where top-NW shearing is still active during the final stages of nappe stacking (D2).

In contrast, the contact between Ruitor unit and Zone Houillère unit is not refolded by D2, and the axial planes of the D2 folds are cut by this tectonic contact. This indicates that this thrust of the Ruitor unit over the Zone Houillère unit formed late during D2 (Table 1). P-T estimates (Bucher et al. 2003) display a major gap in pressures (about 7 kbar) between these two units. This was interpreted in terms of late-D2 thrusting that emplaced higher metamorphic units (in terms of P and T) over less metamorphic units (Bucher et al. 2003). This inverse field metamorphic gradient, together with decompression documented during D2, suggests that the blueschist and eclogite facies units (Ruitor and more internal units) came to lie over the LP units (Zone Houillère and more external units) during exhumation, i.e. during the final stages of top-W to top-N nappe stacking (D2).

While D2 is related to exhumation within the entire working area, the differences in peak pressures and temperatures found within the individual tectonic units of the working area were established during D1. Peak pressures range from 10–14 kbar (at temperatures of about 450° C) in the Internal unit to 5 kbar (at around 400°C) in the Zone Houillère unit (Bucher et al. 2003).

**Conclusions and summary of the tectonic evolution**

The work presented here, together with the P-T estimates of Bucher et al. (2003) and new geochronological data (Agard et al. 2002, Bucher 2003) suggest the following tectonic evolution of the tectonic units of the Briançonnais domain (Figure 14, Table 1):

During D1 (50–43 Ma) all units reached peak pressure conditions resulting from southward subduction (Fig. 14d). Clear relationships between original paleogeographic position and depth are observable, more internal units having been subducted deeper than more external units. The external parts of the Zone Houillère unit remained within sub-greenschist facies conditions.

Exhumation and nappe stacking took place during D2 (43–35 Ma, Fig. 14c). We emphasize that, contrary to common belief (Ballèvre et al. 1990, Rolland et al. 2000), extension played no significant role during the exhumation from HP to greenschist facies conditions of the high-pressure units of the Western Alps. Instead, we propose ascent by extrusion within and parallel to a subduction channel, as discussed in Bucher et al. (2003). D2 nappe stacking started with the thrusting of the PL-oceanic units over the Briançonnais. Progressively, thrusting migrated across the Briançonnais domain. Ongoing deformation refolded these contacts during the late stages of D2 deformation, while top-NW to -NNW shearing was still going on (Fig. 14c). Finally, the Ruitor unit was thrust onto the Zone Houillère unit at a latest stage during D2.

Large-scale nappe refolding (D3; 35–31 Ma) post-dated early exhumation of the tectono-metamorphic units (Fig. 14b). The subhorizontal Ruitor and Valsavaranche axial planes indicate vertical shortening of a part of the former nappe pile in front of a very thick Gran Paradiso unit and below the Dent Blanche Austroalpine klippe (Fig. 13). D3 folding formed by a combination of inhomogeneous simple shearing (Merle & Guillier 1989, Bucher et al. 2003) and vertical shortening during the differential WNW-directed movement of the Gran Paradiso unit. Later, this geometry produced during D3 was only slightly modified by D4 doming (Ruitor area, Gran Paradiso area, Fig. 14a).

According to the data of Ceriani et al. (2001) and the age constraints of Fügenschuh & Schmid (2003), our D1 and D2 deformation phases, as well as most of the D3 deformation, predate top-W thrusting along the Roselend thrust, initiating at about 32 Ma ago. During this post-32 Ma deformation in the external Western Alps, following the closure of the Valais ocean, the internal units of the study area were only passively transported to the west. This passive top-W thrusting led to final exhumation of the study area by erosion at around 30 Ma, as indicated by fission track data (Hurford & Hunziker 1989, Fügenschuh & Schmid 2003).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