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From N-S collision to WNW-directed post-collisional thrusting and folding: Structural study of the Frontal Penninic Units in Savoie (Western Alps, France)

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Key words: Structural geology, nappe stacking, post-nappe refolding, Frontal Penninic Units, Western Alps

ABSTRACT

The Frontal Penninic Units (FPU) south of Moûtiers (Savoie), are an important geometrical link between the internal and highly metamorphic Penninic units and the external fold-and thrust-belt of the Dauphinois. They were subjected to large-scale poly-phase deformation, analysed in detail by this work. The deformation history of the FPU, after correlation with that of the more internal Penninic units and the external Dauphinois units, reveals three stages of the tectonic evolution, additionally constrained by recent metamorphic and fission track studies.

A first pre- to syn-collisional stage of subduction and nappe stacking during the Eocene led to detachment of the Houiller ("Zone Houillère") and Subbriançonnais units, followed by subsequent poly-phase (D1 and D2) isoclinal large-scale folding within an accretionary wedge that formed in front of the internal Briançonnais and above the previously subducted Valais ocean. In the frontal parts of this wedge, made up of the Cheval Noir flysch unit, sedimentation was contemporaneous with this deformation until final collision with Europe at the end of the Priabonian. Top-north thrusting in a sinistrally transpressive tectonic scenario is inferred from kinematic indicators. This oblique convergence indicates a lateral position of the Dauphinois during and before collision with the Subbriançonnais-Briançonnais ribbon continent and the Adria plate.

The onset of the second stage at around the Eocene-Oligocene boundary reveals an important change towards top-WNW thrusting, related to WNW-directed indentation of the Adria plate. During Oligocene to Early Miocene times the nappe stack of the FPU became re-folded by large-scale F3 folds, together with the more internal Penninic units. Simultaneously, the entire Penninic nappe stack was carried onto the Dauphinois unit along the WNW-directed Roselend Thrust. Hence, the French-Italian Western Alps, characterised by this west-directed thrusting, underwent a different tectonic evolution from that of the Swiss-Italian Alps, were top N-NW thrusting continued during this second stage. Decoupling occurred by dextral movements along the Insubric-Simplon-Rhone fault system.

After a period of quiescence within the FPU during the Late Miocene, associated with progressive foreland-propagation of post-collisional deformation into the external massifs of the European foreland deformation, deformation in the FPU resumed again during a third stage, which initiated about 5 Ma ago. This stage is presently still ongoing and characterized by normal faulting.

ZUSAMMENFASSUNG

Die frontalen penninischen Einheiten (FPU) südlich von Moûtiers stellen ein wichtiges geometrisches Bindeglied dar zwischen den internen hochmetamorphen Penninischen Einheiten einerseits und dem externen Falten- und Überschiebungsgürtel des Dauphinois andererseits. Ihre mehrphasige Deformation wird in diesem Beitrag im Detail analysiert. Die Verformungsgeschichte der FPU kann, nach Korrelation mit derjenigen der interneren penninischen Einheiten und des externeren Dauphinois, in drei Hauptstadien der tektonischen Entwicklung unterteilt werden. Diese Unterteilung wird durch neue Untersuchungen zur Metamorphosegeschichte und durch Spaltspurdatierungen zusätzlich unterstützt.

Ein erstes prä- bis syn-kollisionales Stadium der Subduktion und der Deckenstapelung während des Eocän führte zur Abscherung der sedimentären Einheiten der Zone Houillère und des Subbriançonnais, unmittelbar gefolgt von mehrphasiger und grossräumiger isoklinaler Verfaltung (D1 und D2) innerhalb eines Akkretionskeils, der sich vor dem internen Briançonnais und über dem vorgängig subduzierten Valaisan bildete. In den frontalen Teilen dieses Keils, in der zukünftigen Cheval Noir Flysch-Einheit, dauerte die Sedimentation aber noch an bis zur finalen Kollision der frontalen penninischen Einheiten mit dem europäischen Vorland am Ende des Priabon. Kinematische Indikatoren lassen auf nach Norden gerichtete Überschiebungen schliessen, die in einem sinistral transpressiven Szenario stattfanden. Diese schräge Konvergenz zeigt, dass das Dauphinois eine laterale Position einnahm während und vor seiner Kollision mit dem Subbriançonnais-Briançonnais-Mikrokontinent und der Adria-Platte.

Der Beginn des zweiten Stadiums der Verformung an der Wende des Eocän zum Oligocän ist mit einem wichtigen Wechsel hin zu nach WNW gerichteten Überschiebungen verbunden, im Kontext mit der Indentation der Adria-Platte nach WNW. Während dem Oligocän und frühen Miocän wurde der Deckenstapel der FPU um grossräumige F3-Falten wiederverfaltet, zusammen mit den interneren Penninischen Einheiten. Gleichzeitig wurde der gesamte penninische Deckenstapel an der Roselend-Überschiebung nach WNW über die Dauphinois-Einheit transportiert. Also zeigen die französisch-italienischen Alpen, durch nach Westen gerichtete Überschiebungen charakterisiert, während diesem Stadium eine andere Entwicklung als die schweizerisch-italienischen Alpen, in welchen gleichzeitig immer noch nach N bis NW gerichtete Überschiebungen stattfanden. Die dextralen Bewegungen an der Insubrischen und der Simplon-Rhone-Linie erlaubten eine Entkoppelung dieser beiden Teile der Alpen.

Nach einer Ruhephase innerhalb der FPU während des späten Miocän, als die Deformation sich progressiv in die externen Massive des europäischen Vorlands verlagerte, setzte die Verformung in den FPU wieder ein während eines dritten Stadiums, welches ungefähr vor 5 Ma begann. Dieses dauert heute noch an und ist durch Dehnungstektonik charakterisiert.

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1. Introduction

Eocene N-S-oriented convergence between the European lower plate and the Adriatic upper plate (Dewey et al. 1989) led to frontal collision in the Central Alps (Schmid & Kissling 2000). However, due to the promontory-type shape of the Adriatic indenter (Argand 1924), the Dauphinois domain in the foreland of the French-Italian Western Alps (Fig. 1) remained in a lateral position, leading to oblique Eocene convergence in that part of the Alps.

Numerous radiometric ages (e.g. Agard et al. 2002 and references cited therein) indicate that most of the metamorphism and deformation in the internal Penninic units of the French-Italian Western Alps occurred during the pre- to syn-collisional stages of Alpine orogeny in the Eocene. These Penninic units are derived from the Valaisan, Subbriançonnais-Briançonnais and Piemont-Liguria paleogeographical domains (Froitzheim et al. 1996, Schmid et al. 2004). A number of structural studies in the Penninic units evidenced the importance of Eocene north-directed thrusting and associated sinistral strike slip movements during N-S convergence (Ceriani et al. 2001; Choukroune et al. 1986; Fügenschuh et al. 1999; Ricou & Siddans 1986).

The Dauphinois units (Fig. 1), which are part of the European plate, however, did not get fully involved in Alpine orogeny before the end of the Eocene, i.e. after collision. Apart from local evidence for pre-Priabonian N-S compressional phases (Debelmas & Kerckhove 1980), most of the thrusting is post-Priabonian and W-directed (i.e. Beach 1981, Butler et al. 1986, Fry 1989).

The Frontal Penninic Units (FPU) represent a key-area for correlating deformation phases and kinematics in the internal and higher metamorphic Penninic units with those of the external Dauphinois fold-and thrust belt. They are the more external part of the Alpine accretionary wedge and belong to the frontal Penninic domains (Valaisan, Subbriançonnais and external Briançonnais). The present article focuses on the tectonic evolution of the FPU in an area south of Moûtiers (between Vallée de l'Isère and Vallée de l'Arc, see Fig. 1).

Previous research on the FPU south of Moûtiers provided a large amount of stratigraphical data (Antoine et al. 1980, Barbier 1948, Fabre 1961, Martinez et al. 1979, Serre et al. 1985). However, the tectono-metamorphic evolution of the FPU was relatively poorly studied up to now, although a complex poly-phase structural evolution of these units can be deduced from the pioneering work of Barbier (1948) and Fabre (1961). Some recent work confirmed this complexity (Aillères et al. 1995; Aillères 1996), while Spencer (1992) proposed a relatively simple deformation history, characterised by WNW-directed thrusting.

Ceriani (2001, unpublished PhD thesis) studied the polyphase deformation history of the FPU, which took place under low-grade metamorphic conditions, in great detail. The present article publishes and discusses the most important structural data, collected during three field summers, in a first step.

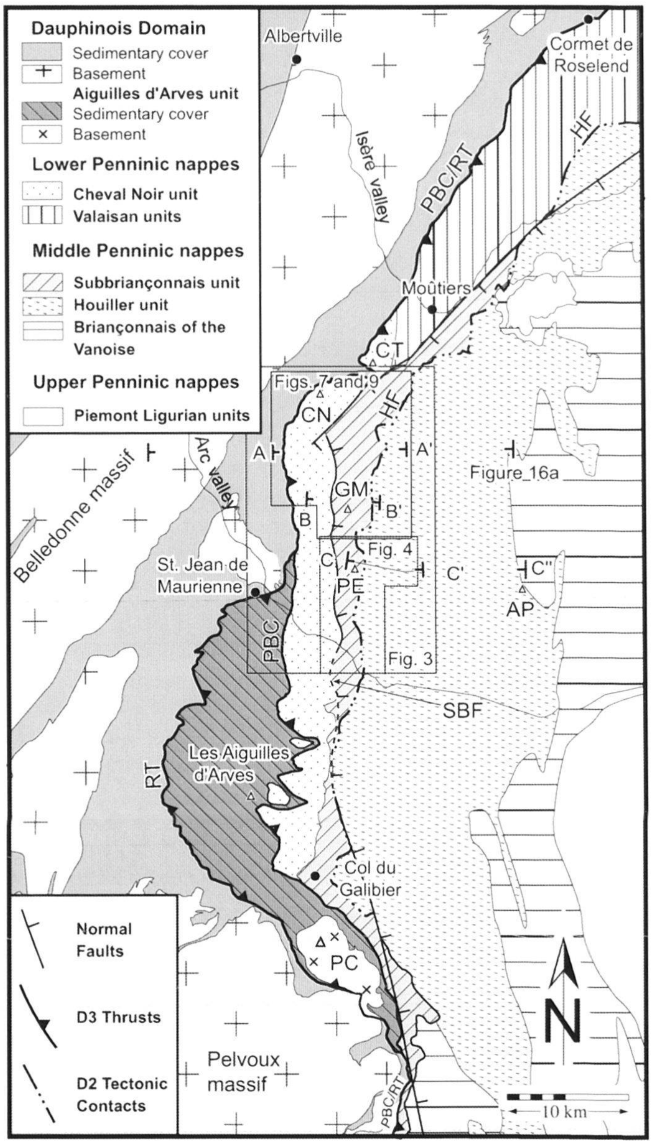

Fig. 1. Tectonic map of the Western Alps between Cormet de Roselend and Pelvoux Massif. Boxes indicate areas covered by Figs. 3, 4, 7 and 9. HF: Houiller frontal thrust; PBC: Penninic Basal contact; RT: Roselend thrust; SBF: Subbriançonnais front (mostly overprinted by normal faulting); AP: Aiguille de Péclet; GM: Aiguilles de la Grande Moendaz; PC: Pics de Combeynot; PE: Grand Perron des Encombres.

Then it integrates them on the scale of larger scale cross sections. Finally, it attempts to kinematically retro-deform the main stages of deformation. Thereby new data on the FPU published elsewhere, regarding metamorphic evolution (Ceriani et al. 2003) and fission track data (Fügenschuh & Schmid 2003), provide timing constraints.

The tectono-metamorphic evolution in the investigated area started with the pre- to syn-collisional stage, i.e. with subduction and exhumation of the Valaisan units (Fügenschuh et al. 1999). It continued with post-collisional thrusting that carried the FPU on top of the Dauphinois (Ceriani et al. 2001; Fügenschuh et al. 1999). The data on the FPU presented in this study are also closely related to recent work on the tectono-metamorphic evolution of the more internal Penninic units (Bucher et al. 2003). Furthermore, they support and complement recent larger scale discussions on the tectonic evolution of the Western Alps by the Basel research team (Ceriani et al. 2001; Fügenschuh et al., 1999; Schmid & Kissling 2000).

2. Geological setting

The Penninic Basal Contact (PBC) delimits the FPU from the western and external Dauphinois (or "Helvetic") domain consisting of basement (external crystalline massifs) and autochthonous to para-autochthonous cover series (Fig. 1; Ceriani et al. 2001). The term PBC, having no kinematic implication, simply denotes the base of the Penninic units (Ceriani et al. 2001). However, it coincides with a WNW-directed thrust, i.e. the Roselend Thrust, in the northern part of the working area. This post-collisional thrust can be followed around the entire Western Alps (Fig. 1 and Ceriani et al. 2001).

The FPU consist, from west to east, of the Cheval Noir, Subbriançonnais, and Houiller (="Zone Houillère") units (Fig. 1). The most external Cheval Noir unit (CNU) is situated directly above the PBC. The CNU, defined by Serre et al. (1985), was previously considered as part of the "Ultradauphinois" domain (Barbier, 1948). However, the CNU consists of a thick series of Tertiary (mainly Priabonian) sediments (wildflysch, breccias and flysch), which directly rest, in stratigraphical contact, on a Briançonnais-type substratum (Serre et al. 1985; Ceriani et al. 2001). This substratum mainly consists of Permian (Verrucano-type) conglomerates and pelites, overlain by a condensed series of Jurassic and Cretaceous sediments. Hence this CNU has to be considered "Penninic" (Ceriani et al. 2001). The "Niélard", "Valbuche" and "Crève Tête" units, part of the "Nappe des Brèches de Tarentaise" of Barbier (1948), are also considered as part of the Penninic CNU (Ceriani et al. 2001). North of Moûtiers, however, the CNU wedges out and is "replaced" by the Valaisan units in map view (Fig. 1). Towards the south the CNU ends in the Col du Galibier area (Fig. 1), while the two more internal FPU described below (Subbriançonnais and Houiller units) can be traced all around the arc of the Western Alps.

The Subbriançonnais Front (SBF) separates the Subbriançonnais unit (SBU), also referred to as „Nappe du Pas-du-Roc" (Barbier 1948), from the more external CNU (Fig. 1). The SBU is made up of marine Mesozoic dolomites, pelites, shales and limestones of Late Triassic to Cretaceous age. Two sub-units, i.e. Grande Moendaz and Perron des Encombres units (Barbier 1948), were defined on the basis of sedimentological and facies arguments, and interpreted to be separated by a tectonic contact. Peres Postigo (1988) further divided the Perron des Encombres unit into two different tectonic units, separated by yet another tectonic contact, i.e. the "Cicatrice of Varlossière". However, according to our observations, all these sub-units are not separated by tectonic contacts everywhere. Hence, we use the term "Subbriançonnais unit" to denote the entire tectonic unit made up of a sedimentary sequence in typical Subbriançonnais facies.

The Houiller unit (HU) is situated east of another thrust, the Houiller Front (HF). Classically, this Carboniferous to lower Triassic sequence is interpreted to belong to the "Briançonnais" domain, although it could also represent the older stratigraphic substratum of the SBU. It largely consists of continental detrital sediments of Carboniferous and Permian age, i.e. coarse-grained sandstones and breccias interbedded with pelitic layers. To the east a very thin basement unit (Gneiss du Sapey) separates the HU from more internal Penninic units (Briançonnais of the Vanoise, and the easterly adjacent Piemont-Liguria paleogeographical domain).

3. Structural data

During field work it soon became apparent that not all units of the area underwent the same tectono-metamorphic evolution, since deformation progressed towards the foreland. During the following descriptions of poly-phase deformation the reader is referred to Table 1, summarising the correlation of poly-phase deformation across tectonic units (note that D1 and D2 do not affect all the units). The data supporting this correlation will be described in due course.

Structural data will be presented for each of the tectonic units and the major tectonic contacts bordering them, respectively, progressing from internal (eastern) to external (western) units. All data were attributed to 13 sub-areas (SA) or domains of structural homogeneity, whose location is given in Fig. 3. The data are also summarised in a structural map covering the entire working area between Isère and Arc rivers (Fig. 3), photographs (see Figs. 2, 5, 6 and 8), and three detailed geological maps (see Figs. 4, 7 and 9), whose areas are indicated in Fig. 1.

3.1 Houiller unit (HU)

Three major ductile deformation phases (Table 1) were observed in the frontal part of the HU (Fig. 4). Intensity of deformation and orientation of structures vary through the unit (see sub-areas 1, 2 and 3 indicated in Fig. 3).

D1, associated with isoclinal F1 folds and an intense and penetrative schistosity S1, is well developed in all lithologies (i.e. conglomerates, sandstones and pelites). Generally, S1 is parallel to bedding S0 (Figs. 2a and b), but stretching lineations (Fig. 3) are only rarely observed in S1. Strain intensity during D1 appears to increase eastwards, in sub-areas 2 and 3, where S1 is very penetrative (Figs. 2a and b) and where large F1 folds are observed.

Deformation phase D2 produced a second schistosity S2, well developed in all lithologies. It is spaced or slaty to penetrative in competent and incompetent lithologies, respectively. S2 is axial planar to large tight to isoclinal F2 folds, with a max-

Table 1. Correlation and timing of the main deformation phases. ECM: External crystalline massifs; HF: Houiller Front; RT: Roselend Thrust; SBF: Subbriançonnais Front. Grey cells: no deformations observed in the working area (Modified after Ceriani et al. 2001).

	External Dauphinois	Internal Dauphinois	RT	Cheval Noir unit	SBF	Subbriançonnais unit	HF	Houiller unit	Age
D_4					normal faulting				<5Ma
	Foreland migration Top WNW thrustng - Thrusting ECM								
D_3		Main cleavage & related folds ***Peak of metamorphism***	**Top WNW thrusting**	Open folds with a poorly developed axial plane cleavage	Folded	Open folds with a poorly developed axial plane cleavage	Folded	Open folds with a poorly developed axial plane cleavage	Early Oligocene to Early Miocene
D_2				Main cleavage Isoclinal folds ***Peak of metamorphism***	**Top N thrusting**	Isoclinal folding with a strong axial plane cleavage ***Peak of metamorphism***	**Top NNW thrusting**	Isoclinal folding with a strong axial plane cleavage	Priabonian
D_1					?	Main cleavage Isoclinal folds N-S stretching lineation	?	Main cleavage Isoclinal folds ***Peak of metamorphism***	Pre-Priabonian (Eocene)

imal wavelength of a few hundreds of meters. With exception of the hinge zone of the F2 folds the S1 schistosity is often transposed into parallelism with the S2 schistosity forming a composed S1/S2 schistosity. Sub-horizontal F2 folds axes roughly trend N-S (Figs. 3a, 4c, d and e). In sub-area 1, in the vicinity of the frontal thrust of the HU (the syn-D2 HF, see below), intensity of D2-deformation is increasing and F2 isoclinal folds have a very constant orientation. The penetrative axial planar schistosity (S2) dips steeply east, and fold axes (F2) are NNE-SSW oriented (Fig. 4c). L2 stretching lineations strike N-S (Fig. 3c). This contrasts with the domains further east (i.e. SA-2 and SA-3), where the orientation of D2 structures varies (Figs. 4d and e) due to F3 folding.

The third deformation phase D3 is characterized by a steeply inclined spaced cleavage S3 (Fig. 4f), well developed within incompetent lithologies, and by chevron-type to open NNE-SSW-striking F3 folds (Fig. 4). In the external part of the HU (SA-2 and SA-3) the steeply east and west-dipping S3 cleavages (Figs. 4f and g) define fans related to the open shapes of F3 folds. F3 wavelength varies from some tenths to some hundreds of meters. In the Aiguille du Péclet area (eastern termination of the HU, Fig. 1), however, S3 schistosity is more gently dipping, (40 - 45° dip to NW), while fold axes plunge to the SW in this area.

3.2 Houiller Front (HF)

The HF, a thrust separating HU from SBU, is marked by a continuous thick band of evaporites that host lenses of Jurassic and Cretaceous sediments, neither characteristic for the adjacent HU nor for the SBU. Schistosity within the evaporites of the HF generally dips E to ESE while stretching lineations scatter around a N-S orientation (Fig. 3l). North and immediately west of the locality "Gittamelon" in the Vallée des Encombres (see Figs. 3a) sigma clasts formed by dolomite blocks, embedded in gypsum and anhydrite of the HF, indicate top-north thrusting of the HU onto the SBU along this thrust (Figs. 5a and b, see also Fig. 4 in Fügenschuh et al. 1999).

In the parts of the HU and SBU immediately adjacent to the HF (SA-1 and SA-5), S2 schistosities (Figs. 4c and 7d) and S-plunging L2 lineations (Fig. 3a) are observed to be very intense and parallel to schistosity and stretching lineations observed within the evaporites of the HF, respectively (compare Figs. 3c, e and l). Hence this top-north HF thrust is interpreted to have been active during D2. Since the evaporites associated with the HF were subsequently folded by open or chevron-type F3 folds, the HF obviously predates D3. Large-scale F3 folds, whose orientation is given in Fig. 7m, spectacularly refold the HF in the study area (Figs. 6 and 7).

3.3 Subbriançonnais Unit (SBU)

The SBU, subdivided into the six subareas 4, 5, 6, 7, 8 and 9 (Fig.3) is also characterized by the three major ductile deformation phases D1 to D3. However, its frontal parts near the SBF were additionally affected by subsequent normal faulting (D4, Table 1).

The oldest deformation (D1) produced a pervasive schistosity (S1, Figs. 2c and d), often parallel to S0, whose orientation strongly varies due to later deformations. Associated parasitic F1 folds are extremely tight and only occasionally visible in outcrop scale (Figs. 2c, e and f). Major F1 folds of kilometric scale are only occasionally visible (see Fig. 11b discussed later). Mostly they are inferred from inversions of stratigraphical younging (Ceriani 2001). The axial traces of such major F1 folds are mapped in Figs. 4 and 7.

The stretching lineation (L1), contained within the S1 schistosity, is defined by the long axes of stretched clasts, boudinage of competent layers, stretched belemnites (Fig. 2d) and pressure fringes on pyrites. In general, the orientation of L1 stretching lineations varies due to refolding during subse-

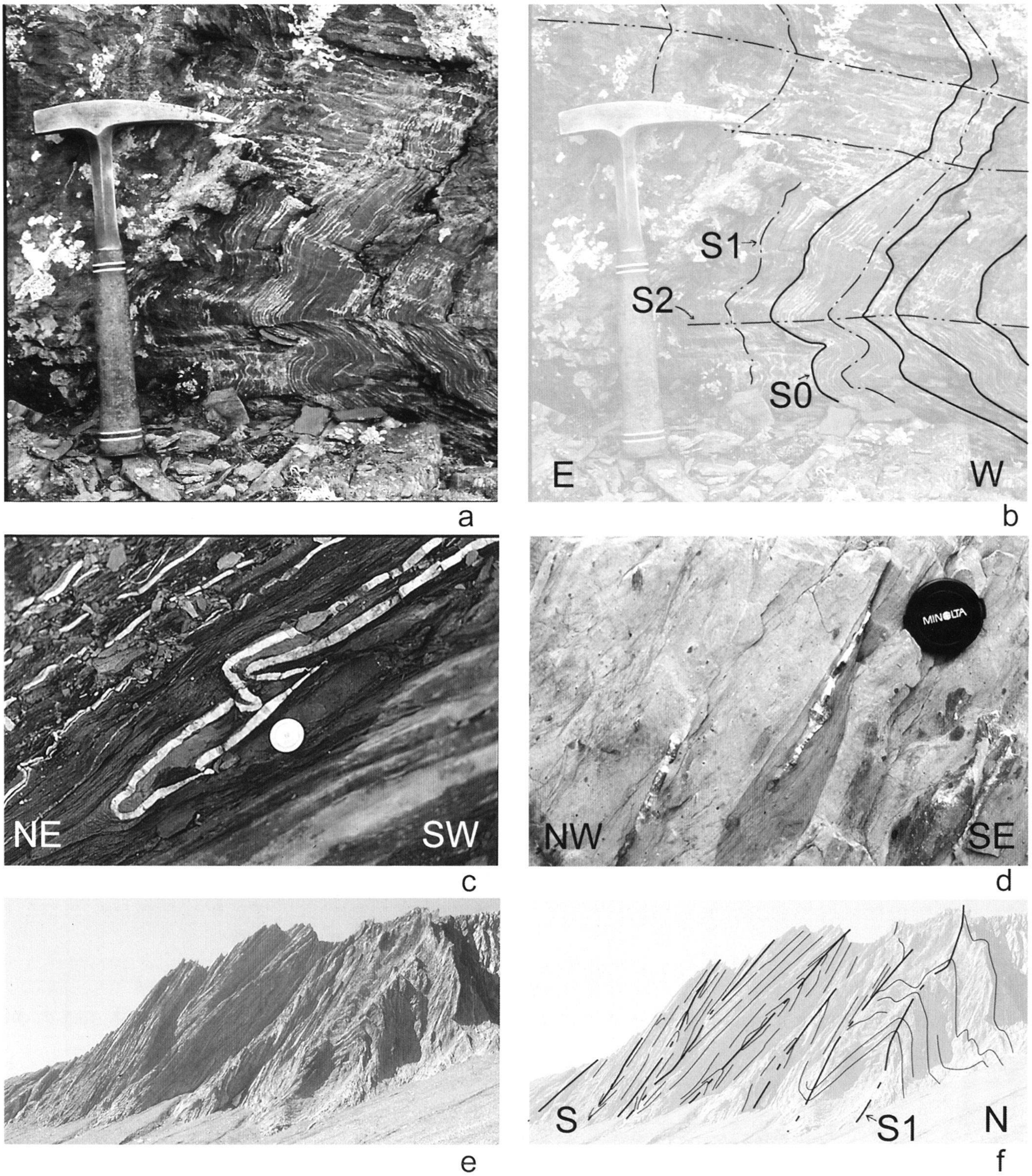

Fig. 2. Field photographs illustrating poly-phase deformation.
a) & b) Penetrative S1, parallel to bedding S0, preserved in the hinge zone of an F2 fold, characterised by a gently west-dipping spaced crenulation cleavage; Carboniferous sediments of the HU.
c) Isoclinal F1 fold in Middle Liassic marl and limestone near transition into Aalenian black shales (SBU). F1 fold is refolded by F2.
d) Stretched belemnites and pressure fringes on pyrite, marking stretching direction L1 in S1 schistosity; Cancellophycus Formation (SBU).
e) & f) Eastern wall of Grande Moendaz, exposing large isoclinal F1 folds in the Cancellophycus Formation (SBU).

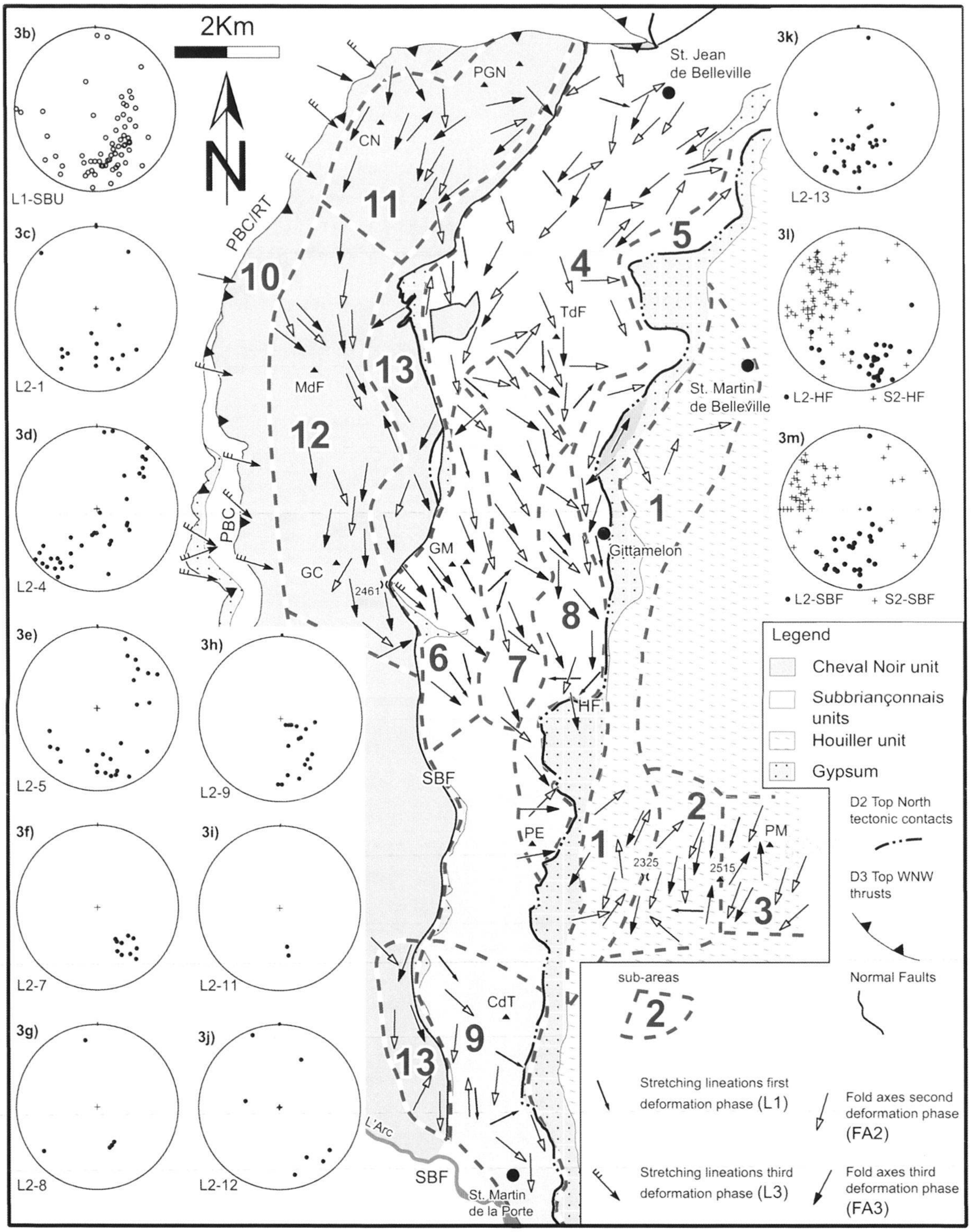

Fig. 3.

a) Tectonic map of the Frontal Penninic Units (FPU) south of Moûtiers (see Fig. 1 for location) indicating orientations of fold axes and stretching lineations of the first (L1), second (FA2) and third (FA3 and L3) deformation phases, respectively. HF: Houiller Front; SBF: Subbriançonnais Front; PBC: Penninic Basal Contact; RT: Roselend Thrust; CdT: Croix des Têtes; GC: Grand Coin; GM: Grande Moendaz; MdF: Pointe du Mont du Fût; PE: Grand Perron des Encombres; PGN: Pointe du Grand Niélard; PM: Pointe de la Masse.

b) to m) Equal area, lower hemisphere stereoplots. The first symbol beside the stereoplots indicates lineations or schistosities belonging to the different deformation phases (e.g. L1, L2, S2), the second symbol (e.g. SBU in Fig. 3b) indicates the geographical origin of the data, i.e. a tectonic unit (e.g. CNU, HU, SBU), a tectonic contact (e.g. HF, SBF, RT) or one of the sub-areas outlined in Fig. 3a (e.g. 1, 2 etc.).

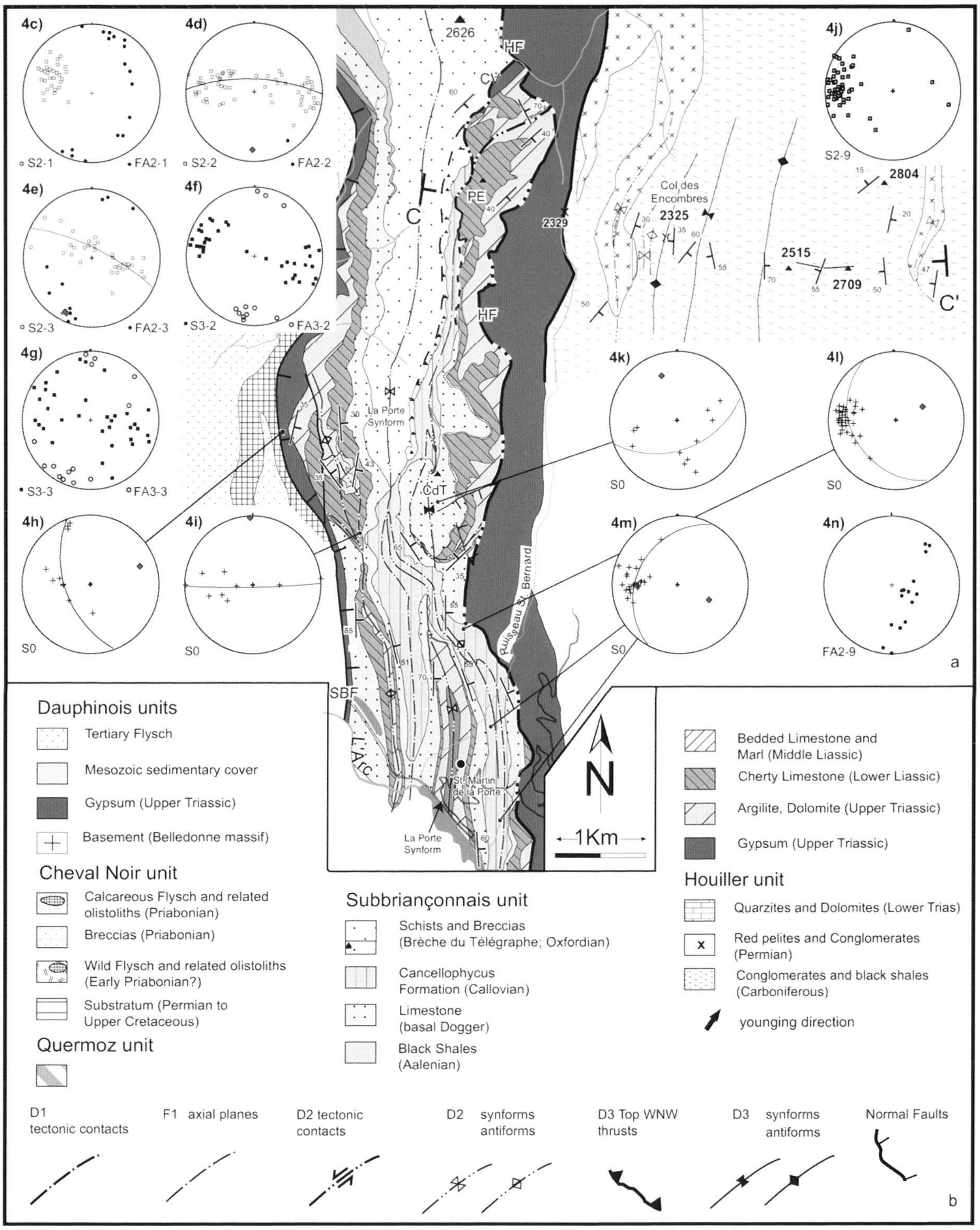

Fig. 4.

a) Geological Map of southern part of the Subbriançonnais and of the Houiller units in the area between Grand Perron des Encombres, Pointe de la Masse (north) and the Croix des Têtes (south). See Fig. 1 for location. CV: Cicatrice de Varlossière; HF: For the other abbreviations see Fig. 1.

b) Legend of the patterns, also valid for Figs. 7, 9, 10, 11 and 14, and, of the structural symbols, also valid for Figs. 6, 7, 8 and 9.

c) to n) Equal area, lower hemisphere stereoplots. The first symbol besides the stereoplots indicates lineations, schistosities or fold axes of the different deformation phases (e.g. L1, L2, S0, S2, FA2). The second symbol (e.g. 1 in Fig. 4c) denotes the sub-area, where the data are from. See Fig. 3 for location of the sub-areas. Stereoplots d) and e) display best-fit poles for FA3, determined from folded S2 cleavages. Stereoplots h), i), k), l) & m) provide best-fit poles for FA2, determined from folded S0 cleavages.

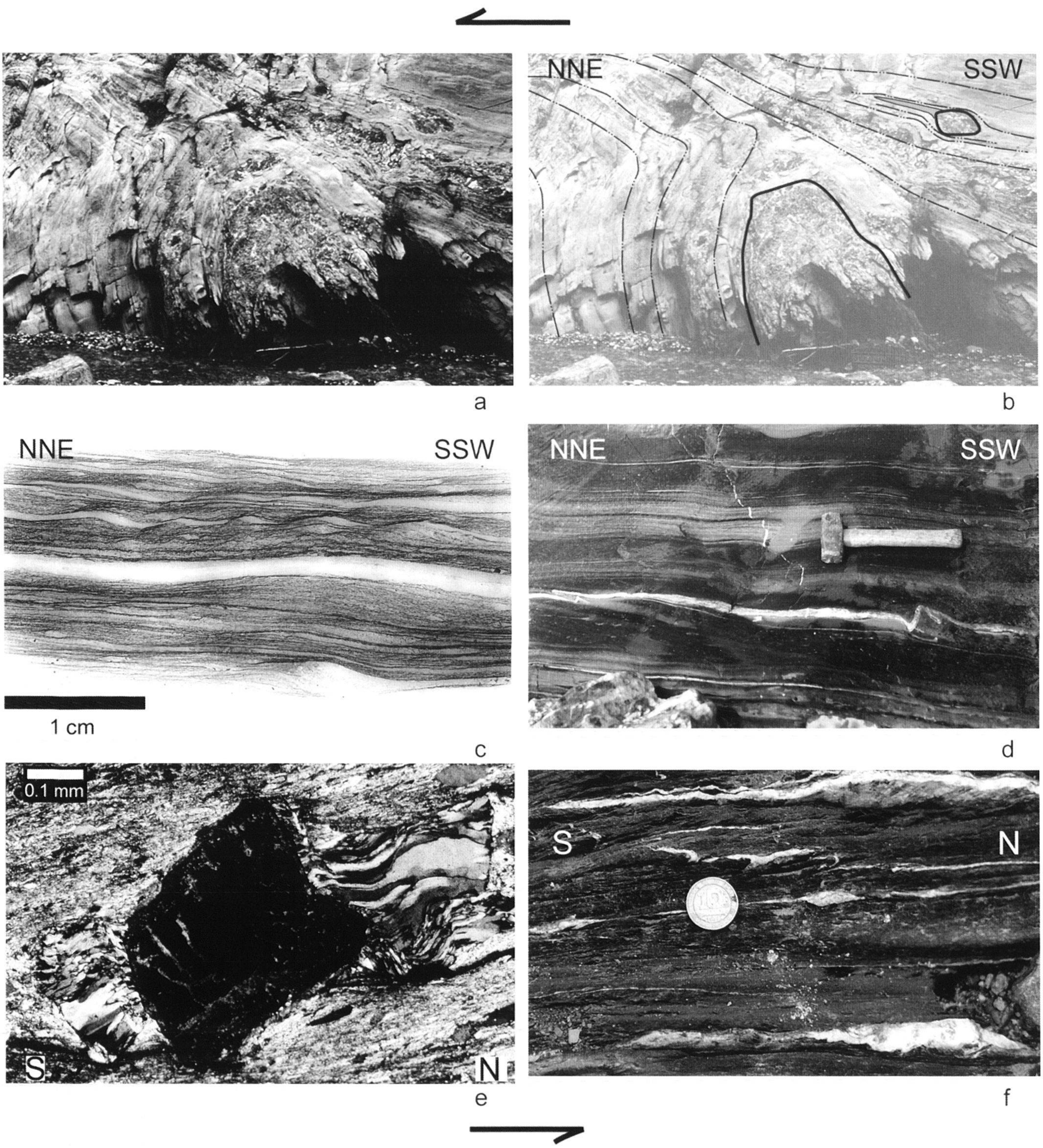

Fig. 5. Photographs of mesoscopic and microscopic sense of shear indicators (senses consistently sinistral in respect to photograph):
a) & b) D2 Top-north shear sense in evaporites from the HF thrust, Gorges de Planlebon (see Fig. 7)
c) Micrograph with shear bands and sigma clasts (bottom) in mylonitic Aalenian black shale (SBU), indicating top-NNE shear sense during D2 along the La Combe shear zone.
d) Sheared veins in Aalenian black shales (SBU), indicating top-NNE shear sense during D2 along the Nant Brun shear zone.
e) & f) top-N shear senses from syn-D2 SBF (preserved from D4 normal faulting in the Valbuche area); e) asymmetric fibrous growth in pyrite pressure fringes in silica-rich wild-flysch of the CNU: f) sheared veins and sigma clasts in Aalenian black shales of the SBU.

quent deformations (Figs. 3a and b). In the Grande Moendaz area (sub-area 6), however, L1 stretching lineations predominantly plunge SSE and are parallel to F1 fold axes (Fig. 7g). This orientation is interpreted to reflect the primary top-NNW transport direction during D1, because in this area (1) the original orientation is preserved due to the absence of F2 folds and (2) L1 and FA3 are sub-parallel to each other (compare Figs. 7g and h).

Some tectonic contacts observed within the SBU are attributed to the first deformation phase. The most important D1 tectonic contact is the "Cicatrice of Varlossière" ("CV" in Figs. 4 and 7), locally marked by the presence of evaporites. This contact predates D2 since it is clearly truncated by the syn-D2 HF (Figs. 4, 6 and 7). However, towards south it becomes less important and completely disappears in the Croix des Têtes area (Fig. 4).

The second deformation phase (D2) is characterized by a second set of large-scale tight to isoclinal folds with wavelengths in the range of 200 to 300m (Fig. 8). The associated strong axial planar cleavage (S2) is often spaced on the scale of some millimetres. In the northern sub-areas (i.e. SA-4 and SA-5), S2 generally steeply dips to the SE (Figs. 7b and d). However, S2 dips to the E to ESE in SA-6 and SA-7 (Figs. 7f and j) and SA-9 (Fig. 4j). In sub-area 8 S2 is strongly folded by F3, together with the HF (Fig. 7l). In sub-area 4 FA2 fold axes generally dip towards NE (Fig. 7b), but towards SE to S in the remainder of the SBU (Figs. 3a, 4n and 7j).

This variation in the orientation of the F2 fold axes is interpreted to be largely due to strong competence contrasts between the Liassic limestone, which forms the Tête de Fer, and the surrounding weaker lithologies (Ceriani 2001). This is also the case in sub-area 9 (Figs. 3a and 4). There, F2 fold axes are extremely variable in orientation (Fig. 4n), despite of the constant orientation of S2 (Fig. 4j). A closer inspection of D2 structures (Figs. 4h, i, k, l and m) shows that the orientation of F2 fold axes abruptly changes along the same fold axial trace by passing from one lithology to another, i.e. from very competent Oxfordian breccia, basal Dogger strata and Liassic Limestone to incompetent beds such as the Cancellophycus Formation.

L2 stretching lineations are often marked by stretched belemnites and/or pressure fringes on pyrites (Ceriani 2001). L2 strikes N-S to NE-SW (Figs. 3a, d and e) in sub-areas 4 and 5, but NNW-SSE to NW-SE in the central and southern domains (i.e. SA-7, SA-8 and SA-9; Figs. 3f, g and h).

In sub-area 4 syn-D2 shearing is very intense, as is evident from the "Nant Brun" and "La Combe" shear zones mapped in Fig. 7. The change in deformation style from folding in the south (SA-6, SA-7 and SA-8) to pervasive shearing in the north (SA-4) is probably related to the abundance of more incompetent lithologies, such as the Aalenian shales, in sub-area 4. The two major syn-D2 shear zones, developed within Aalenian black shales, are characterised by a steeply SE-dipping S2 schistosity and gently SSW- to SW-plunging stretching lineations (Fig. 7e). Shear sense criteria indicate top-north transport across these shear zones (Figs. 5c and d). The "La Combe shear zone" diminishes in importance towards the south and completely disappears south of the Tête de Fer (Fig. 7). The Nant Brun shear zone (Fig. 7), however, is cut in the south by a D4 normal fault situated at the SBF.

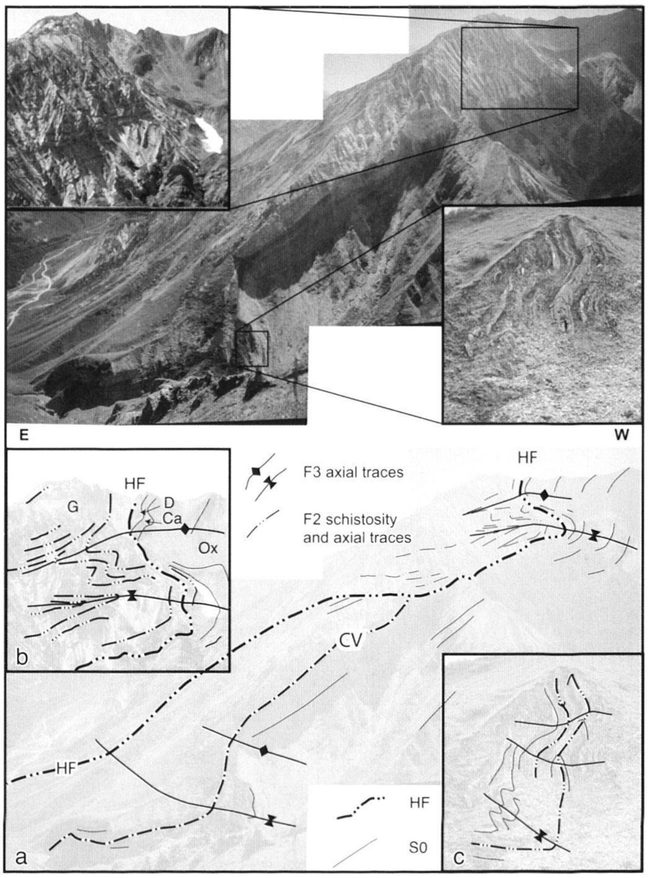

Fig. 6.
a) Panoramic view of the D2 Houiller Frontal (HF) thrust and the D1 Cicatrice of Varlossière (CV) east of Cime Noire (Point 2626, bottom of Fig. 7), folded by F3 open folds with gently SW-dipping axial planes.
b) F3 folds in gypsum, defining the position of the HF (light rock resting above the line marking the HF in the picture).
c) F3 folds in Oxfordian sediments of the SBU below the HF.
Ox: Oxfordian schists and breccias Ca: Cancellophycus Formation, D: basal Dogger, G: gypsum. For the explanation of tectonic letter symbols see Fig. 1.

The third deformation phase is less intense, compared to D1 and D2, and characterized by open to chevron-type folds (Fig. 6). F3 folds are associated with a spaced axial planar cleavage, which is only occasionally well developed. The orientation of associated axial planes S3 varies through the SBU. In the north (SA-4) a spaced crenulation cleavage S3 steeply dips to the W to SW and is rarely associated with minor open to chevron type folds, whose axes gently plunge to the SW (Fig. 7c).

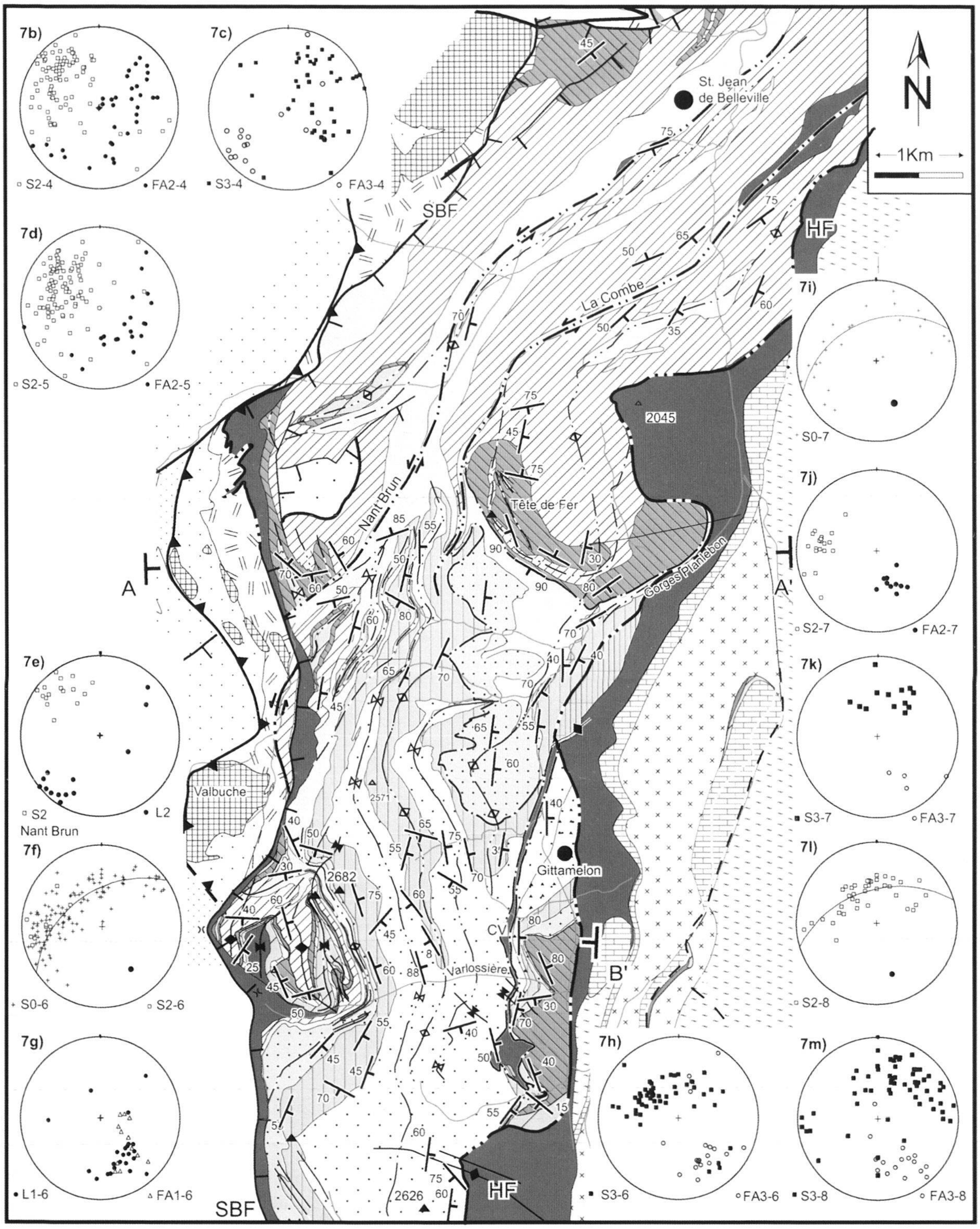

Fig. 7.

a) Geological Map of the northern and central part of the Subbriançonnais Unit (SBU) (see Fig. 1 for location). CV: Cicatrice de Varlossière; HF: Houiller Front; SBF: Subbriançonnais Front. For patterns and symbols see legend in Fig. 4b.

b) to m): Equal area, lower hemisphere stereoplots. The first symbol besides the stereoplots (e.g. S2 in Fig. 7b) indicates: S0 (=bedding); S2 and S3 schistosities; L1 and L2 stretching lineations; FA2 and FA3 fold axes. The second symbol (e.g. 4 in Fig. 7b) indicates tectonic contacts (Nant Brun) or sub-areas (1, 2 etc.) where the data are from. See Fig. 3 for location of sub-areas. f), i) and l): best fit poles for FA3, determined from folded S0 beddings (f & i) and from folded S2 schistosities (l).

In the central part of the SBU the F3 folds are more common than further north or south. Here F3 axial planes and S3 schistosities display a kind of fan. In the west (SA-6) they dip SE, F3 fold axes plunging SE to SSE (Figs. 7f and h). Moving further east S3 first steeply dips to the south in SA-7 (Fig. 7k) and finally to the SW in the eastern part of the SBU (SA-8; Fig. 7m). In sub-areas 6 to 8 FA3 fold axes constantly plunge SSE (Figs. 7f, h, i, k, l and m). The variations in orientation of FA3 fold axes from SA-4 to SA-6, SA-7 and SA-8 are due to lithological contrasts, and/or pre-existing D2 structures.

Some rare ESE-dipping stretching lineations, attributed to D3, were observed in SA-6 (Fig. 3). They developed within Triassic pelites, where the S3 schistosity is more pervasive compared to other areas.

3.4 Subbriançonnais Front (SBF)

The Subbriançonnais Front (SBF), a complex tectonic contact, borders the SBU to the west. A former basal thrust of the SBU, formed during D2, is overprinted by a major D4 normal fault along the SBF (Figs. 1, 4 and 7). Since this normal fault does not reactivate the former syn-D2 thrust everywhere, a small portion of it is preserved in the Valbuche area. There the Middle Liassic sediments of the Subbriançonnais unit are thrust over wild-flysch of the Cheval Noir unit (Fig. 7). The associated S2 schistosity steeply deeps to the E and carries a N-S oriented stretching lineation (Fig. 3m). Kinematic indicators (Figs. 5e and f) indicate top-N thrusting along the SBF. This schistosity observed along the SBF (Fig. 3m) and within immediately adjacent rocks (Fig. 9i) corresponds to the first one detected in the Cheval Noir unit, but to the second one observed in the Subbriançonnais unit (i.e. it corresponds to the regional "S2", see Table 1). This clearly indicates that the SBF was active as a top north sinistral transpressive thrust during the regional D2, as was the case for the HF.

Normal fault reactivation of large parts of the syn-D2 SBF-thrust occurred during a fourth deformation phase (table 1), also observed outside the working area. Two major faults intersect each other south of Moûtiers (Fig. 1; Fügenschuh et al. 1999; Ceriani et al. 2001). A northern one strikes NE-SW and largely follows the border between Subbriançonnais and Valaisan units, finding its SW termination south of Moûtiers (Fig. 1 and NW corner of Fig. 7), where it overprints the SBF. A second N-S-striking major fault appears south of the Cheval Noir peak, following and reactivating the SBF (Figs. 1 and 7).

3.5 Cheval Noir unit (CNU)

This most external unit amongst the FPU (Fig. 1) is deformed by only two major ductile deformation phases. These correspond to the regional D2 and D3 (Table 1) and are overprinted by brittle D4 normal faulting. Four sub-areas of structural homogeneity, whose borders strike mainly N-S, i.e. parallel to the adjacent tectonic contacts (SBF and the RT), were individuated within the CNU (Fig. 3).

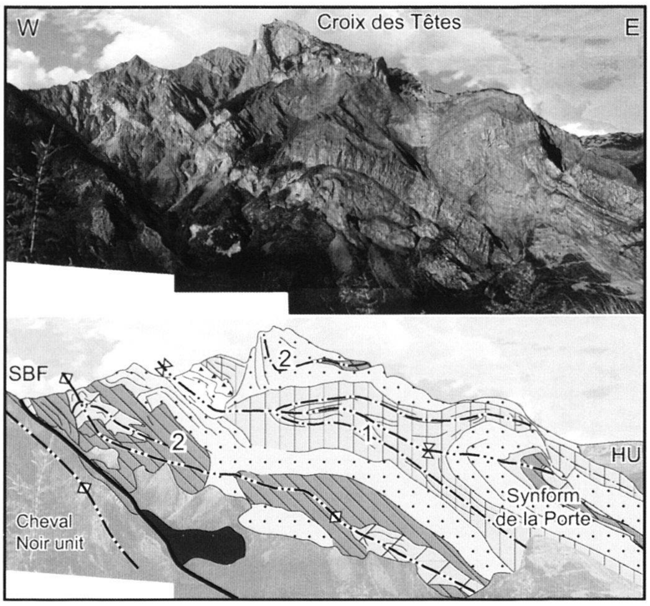

Fig. 8. Panorama of the southern part of the Subbriançonnais Unit (SBU) in the Croix de Têtes area. For patterns and symbols see legend enclosed in Fig. 4b. Note that the "Synforme de la Porte" looks like an antiform when seen from the Arc valley. This is due to intersection effects with the topography of its axial plane, dipping to the E, and of its fold axis, steeply plunging to the SE in the area of the photograph.

The first deformation phase present in the CNU (regional D2) develops a schistosity, whose intensity increases from west to east.

In the western part of the CNU (SA-10) this S2 schistosity is only developed within incompetent lithologies. In the central part of the CNU (SA-11 and SA-12) the S2 schistosity, mostly parallel to bedding S0, is always well developed and locally associated with major isoclinal F2 folds (see cross-section A-A', Fig. 10, discussed later). Here the orientation of S2 is strongly influenced by the effects of the third deformation phase (Figs. 9d and g). F2 fold axes generally trend N-S, but are also strongly dispersed (Figs. 9d and g).

In the eastern part of the Cheval Noir unit (SA-13) the S2 schistosity is well developed also in the more competent lithologies and the effects of D2 become predominant. S2 steeply dips to the east and carries a N-S oriented stretching lineations (Fig. 3k) related to the adjacent syn-D2 SBF-thrust (Fig. 3m). In the northern part of SA-13 (east of the Niélard peaks, Figs. 3a and 9) S2 dips to the SE and L2 stretching lineations trend NNE-SSW, as is also observed in the adjacent northern part of the Subbriançonnais unit. The high strain intensity associated with S2 (i.e. the first deformation event in the CNU) in sub-area 13 is another important argument for inferring a syn-D2 relative age for the SBF-thrust, supporting the correlations given in Table 1.

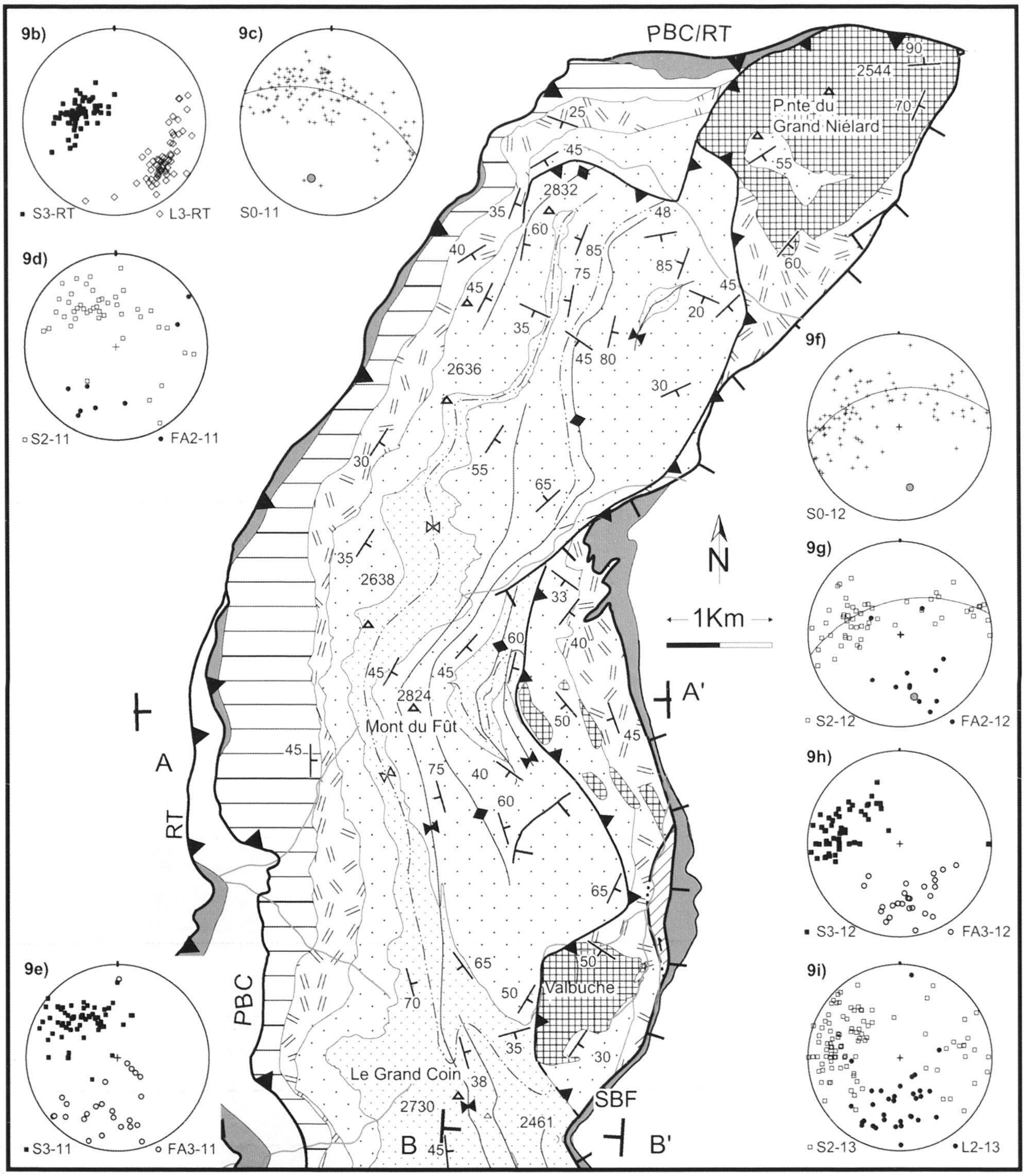

Fig. 9. Geological Map of the Cheval Noir Unit (CNU) between Niélard (north) and Le Grand Coin (south), see Fig. 1 for location, and for tectonic letter symbols. See legend given in Fig. 4b.
b) to h): Equal area, lower hemisphere stereoplots. The first symbol besides the stereoplots (e.g. S3 and L3 in Fig. 9b) indicates S0 (=bedding); S2 and S3 schistosities; L2 and L3 stretching lineations; FA2 and FA3 fold axes. The second symbol (e.g. RT in Fig. 9b) gives tectonic contact (e.g. RT) or sub-areas (1, 2 etc.) where the data are from. See Fig. 3 for the location of the sub-areas. c), e), f): best fit poles for FA3, determined from folded S0 (c, e) and from folded S2 schistosities (f).

The second deformation phase observed in the Cheval Noir unit (i.e. the regional D3) is characterized by chevron type folds with a wavelength of some hundreds of meters, and by thrusting along the Roselend thrust. F3 folds are typically associated with a spaced crenulation S3 cleavage (Ceriani 2001). In the north (SA-11), S3 cleavage dips with 30 to 60° to the SE (Fig. 9e) and fold axes plunge to the SSW (Figs. 9c and e). In sub-areas 12 and 13 axial planes of F3 steeply dip E to ESE (Fig. 9h), while FA3 fold axes predominantly plunge to the SSE (Figs. 3a, 9f, g and h).

The S3 schistosity, only well developed in incompetent lithologies, rapidly becomes very pervasive in the more external parts of the unit (SA-10), i.e. in the immediate vicinity of the thrust onto the Dauphinois domain described below (RT of Fig. 9). A secondary D3 thrust is also present within the Cheval Noir unit. It defines the base of the Niélard massif in the north, as well as the base of the Valbuche massif in the south (Fig. 9).

3.6 Penninic Basal Contact and Roselend Thrust

During collision with the foreland the Penninic Cheval Noir unit was thrusted onto the Dauphinois along the Penninic Basal Contact (PBC). This older thrust is reworked by a major post-collisional syn-D3 WNW-directed thrust, the Roselend Thrust (RT; Ceriani et al. 2001).

The RT is associated with a gently SE-dipping schistosity (Fig. 9b), corresponding to the second locally observed schistosity, i.e. to the regional D3 (Table 1). Stretching lineations measured along the RT indicate top-WNW transport directions (Figs. 3a and 9b). In the immediate vicinity of the RT, F3 folds axes turn into parallelism with the top-WNW transport direction (Fig. 3a). The RT is not overprinted by later normal faulting, as is clearly visible in a half window situated between Niélard and Crève Tête (Fig. 1, Ceriani et al. 2001).

In the north the Roselend Thrust coincides with the base of the CNU (Figs. 1 and 9). But it cuts into the Dauphinois and runs immediately below the PBC (Fig. 9) further south, where PBC and RT are very close to each other, forming a thick strongly deformed zone. South of the Arc valley RT and PBC become clearly separated, in order to rejoin each other again in the Pelvoux area (Fig. 1 & Ceriani et al. 2001).

4 Integration of structural data into cross-sections

This section presents three cross sections through the FPU (A-A', B-B' and C-C' of Fig. 10).

4.1 Cross Section A-A' through the northern part of the working area

At the eastern margin of this profile (Figs. 7 and 10a) an overturned stratigraphical series of the frontal HU ends with Lower Triassic dolomites. This series thrusts Triassic evaporites found all along the HF, and the Aalenian black shales of the SBU below.

The Aalenian shales are also in tectonic contact with the underlying Lower Liassic limestones. This D1 contact, interpreted as the northern continuation of the "Cicatrice de Varlossière" ("CV" in Fig. 7), was then cut by the syn-D2 HF and folded around a major F2 antiform centred around the Tête de Fer (Figs. 7 and 10a). This F2 antiform also refolds tight F1 folds (Fig. 10a; see Ceriani 2001 for details). At the western limb of the Tête de Fer antiform the CV is finally cut by the syn-D2 "La Combe" shear zone (Fig. 10a).

Immediately west of the "La Combe" D2 shear zone, isoclinal F2 folds refold a normal stratigraphical series. The major F2 synform with Oxfordian shales in the core represents the northern termination of the "Synforme de la Porte" (Figs. 4 and 7). West of this synform, however, the F2 folds refold series that are mostly overturned at the earth's surface. This change in facing of the F2 folds is due to the existence of a major F1 fold, whose axial trace is above the earth's surface in the area of the "Synforme de la Porte". The axial trace of this F1 fold repeatedly intersects topography west of the "Synforme de la Porte", running within Cancellophycus strata and Aalenian shales in cross section A-A' (Fig. 10a). This F1 megafold is interpreted to represent the northern continuation of the "Grande Moendaz F1 fold", better exposed in the Grande Moendaz area (see cross section B-B' of Fig. 10b).

West of the D2 top-north transpressive "Nant Brun" shear zone the F2 folds affect the overturned stratigraphical series (Figs. 7 and 10a), representing the inverse limb of the Grande Moendaz F1 fold, whose axial plane is interpreted, in this area, to be located at more than a kilometre below the earth's surface (Fig. 10a). The SBU finally terminates along a late stage normal fault that overprints a former syn-D2 SBF-thrust.

The wild-flysch of the CNU immediately adjacent to the SBF is right-way-up (Figs. 9 and 10). Bedding (sub-parallel to S2) dips to the W. In the west, this stratigraphical series is topped by a series of olistoliths, embedded in Priabonian Breccias, which abut against a D3 thrust. F3 folds found further west and in the immediate footwall of the D3 thrust, refold a previously overturned stratigraphical series of Priabonian breccias and younger calcareous flysch. These F3 folds are parasitic to a larger F3 synform, whose axial plane runs within Priabonian breccias and intersects the surface west of the Mont du Fût (Figs. 9 and 10a).

Further west, the overturned series outcropping at the Mont du Fût are seen to overly the calcareous flysch that outcrops in the core of a major west-facing D2 syncline (Figs. 9 and 10a; see Ceriani 2001 for detailed structural evidence). Further west, i.e. below the axial plane of this F2 syncline, the stratigraphical series are normal again. Above the PBC (Figs. 9 and 10a) the wild-flysch stratigraphically overlies a pre-Tertiary Briançonnais-type "substratum" (Serre et al. 1985)

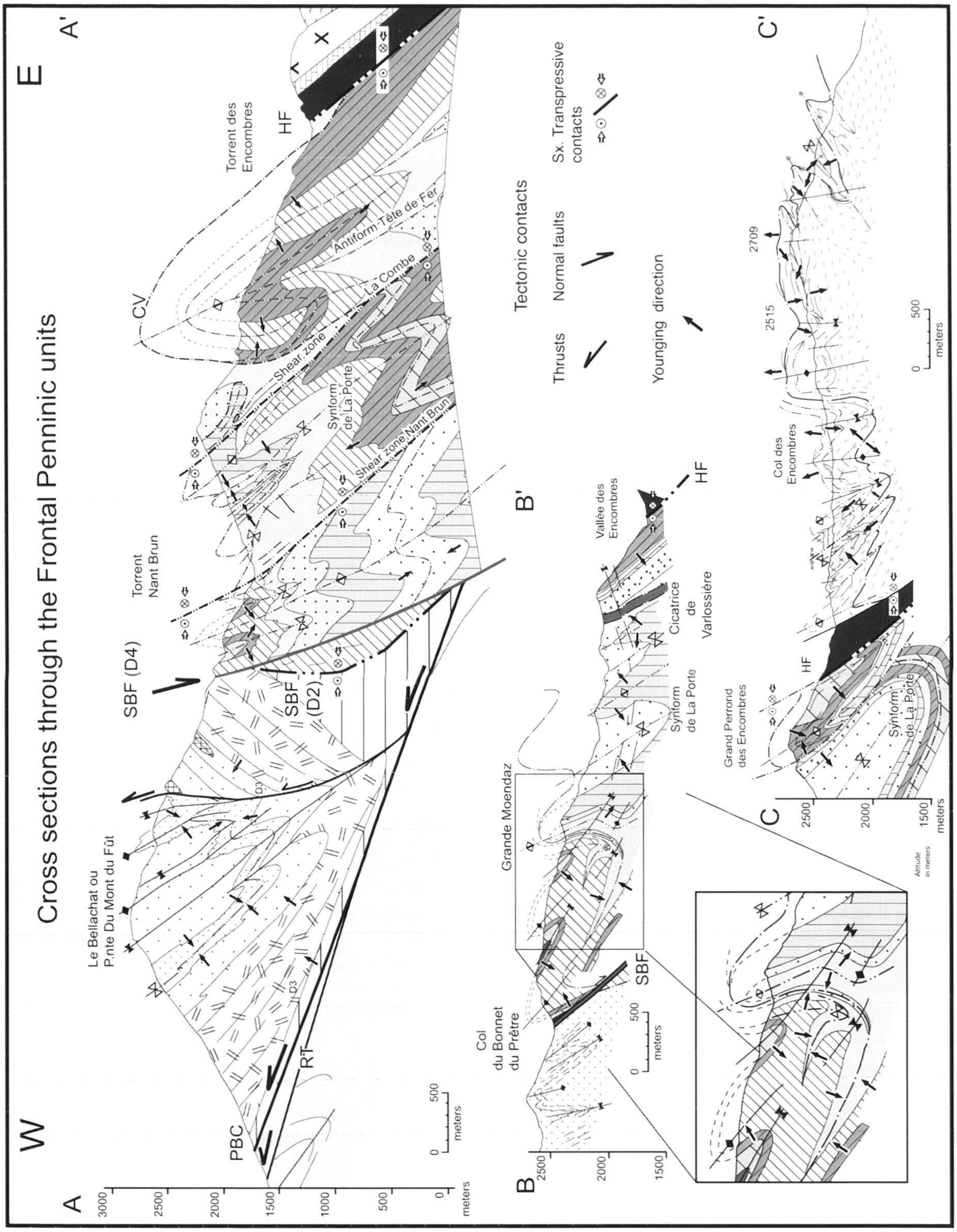

Fig. 10. Cross sections through the Frontal Penninic Unit (FPU). Symbols and patterns are given in Fig. 4b. For location see Figs. 1, 4, 7 and 9. Note that cross section B-B' illustrates the effect of the first deformation phase particularly well (see enlargement of the Grande Moendaz area). HF: Houiller Front; SBF: Subbriançonnais Front; PBC: Penninic Basal Contact; RT: Roselend Thrust.

a) Section A-A' through HU, SBU and CNU at the latitude of St. Martin de Belleville.

b) Section B-B' through CNU and SBU at the latitude of the Aiguilles de la Grande Moendaz.

c) Section C-C' through SBU and HU at the latitude of the Grand Perron des Encombres.

4.2 Cross Section B-B' through the Subbriançonnais unit in the central part of the working area

The calcareous flysch of the Cheval Noir unit at the western end of the profile (Fig. 10b), to be parallelised with the series found at the western end of profile A-A' (Figs. 9 and 10a), is right-way up and folded during D3. At the Col du Bonnet du Prêtre (qt. 2461 in Fig. 9) it is cut by the late stage normal fault (D4) at the SBF.

In the SBU spectacular large-scale fold interference structures are exposed (see panoramas depicted in Fig. 11). In the west two pairs of F3 large-scale antiformal synclines and synformal anticlines refold previously overturned stratigraphical series.

East of the second F3 synformal anticline (peak "a" in Fig. 11), the stratigraphical series young towards the east into Aalenian black shales (topographical depression between peaks a & b in Fig. 11) and finally into sandy limestone attributed to the basal Dogger formation (peak b in Fig. 11). Eastwards, however, this limestone is again followed by Aalenian shales (topographical depression between peaks b and c in Fig. 11). Hence the series suddenly young towards the west, indicating the presence of an extremely tight hinge of an F1 fold, made up by the basal Dogger formation. Barbier (1948, p. 50) interpreted the western occurrence of black shales and the basal Dogger limestone as a local anomaly in the stratigraphy of the Middle Liassic, normally made of banded limestones and marls, and he only accepted the second level of black shales as representing the Aalenian. However, structural mapping clearly indicates that the two levels of black shale and the calcareous band between them form the hinge of an extremely isoclinal fold, the Grande Moendaz F1 fold. In the northern wall of the Grande Moendaz the hinge formed by the basal Dogger limestone is seen to close towards the west, being refolded by F3 (Figs. 11a and b; profile B-B' in Fig. 10b). Hence, all the overturned stratigraphic series situated between Col du Bonnet du Prêtre and Grande Moendaz rest above the axial plane of the Grande Moendaz F1 mega-fold. Only a few outcrops at the base of the Grande Moendaz north wall expose a normal stratigraphical sequence, resting below the axial plane of this F1 fold (Fig. 11a).

East of peak b (Fig. 11), where the axial plane of the Grande Moendaz F1 fold is exposed, the Aalenian black shales outcrop followed eastwards by a second ridge (peak c in Fig. 11), again formed by basal Dogger limestone. This second repetition in the stratigraphical series, however, was mapped as a major F2 anticline with Aalenian black shales in its core (Fig. 11, see Ceriani 2001 for more details).

East of the peak c the younger and upright stratigraphical formations, situated below the axial trace of the F1- Grande Moendaz mega-fold (Cancellophycus formation and the Oxfordian shales), are folded by a series of upward facing F2 folds (Figs. 7 and 10b). Here, open F3 folds are of very minor importance.

Earlier studies in this area postulated a tectonic contact, separating the Grande Moendaz unit from the Perron des En-

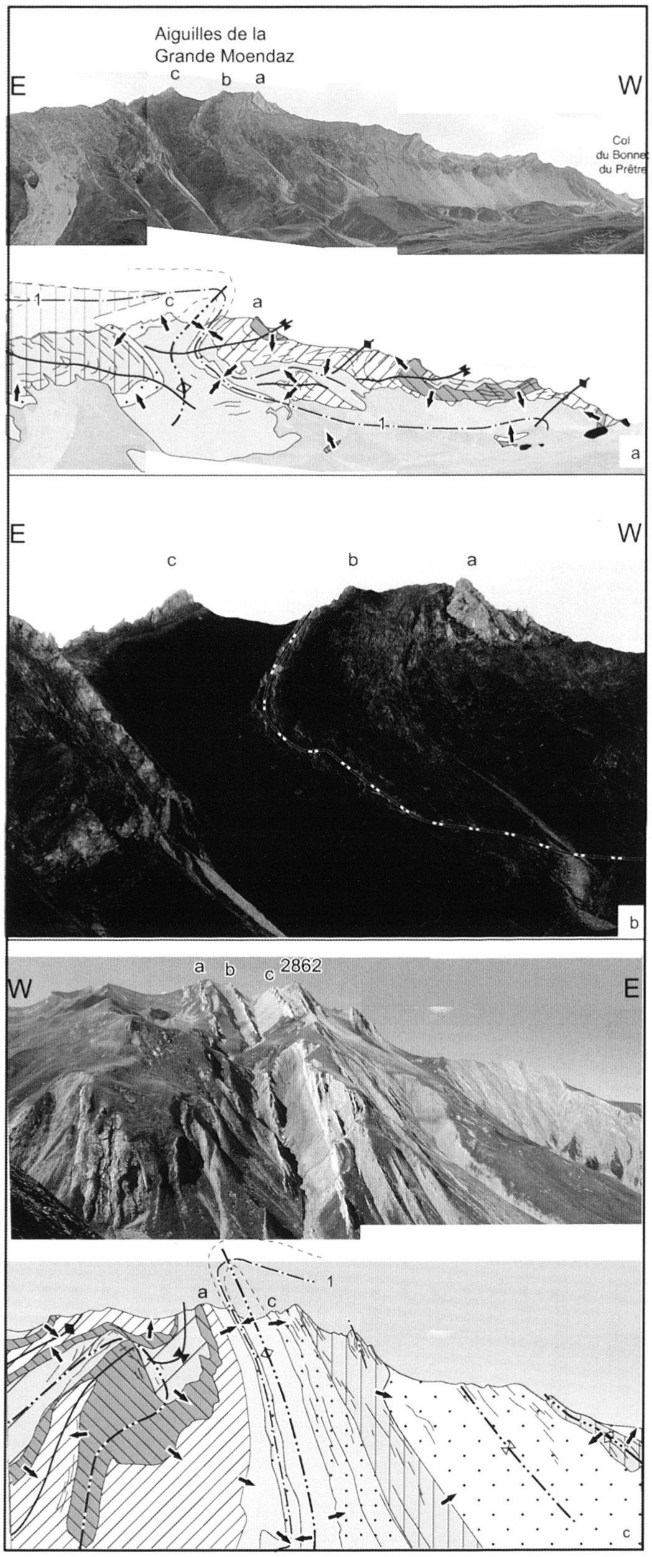

Fig. 11. Panoramic views of (a & b) northern and (c) southern wall of the Grande Moendaz (compare with Fig. 7 & profile B-B' of Fig.10b). For patterns and symbols see legend given in Fig. 4b.

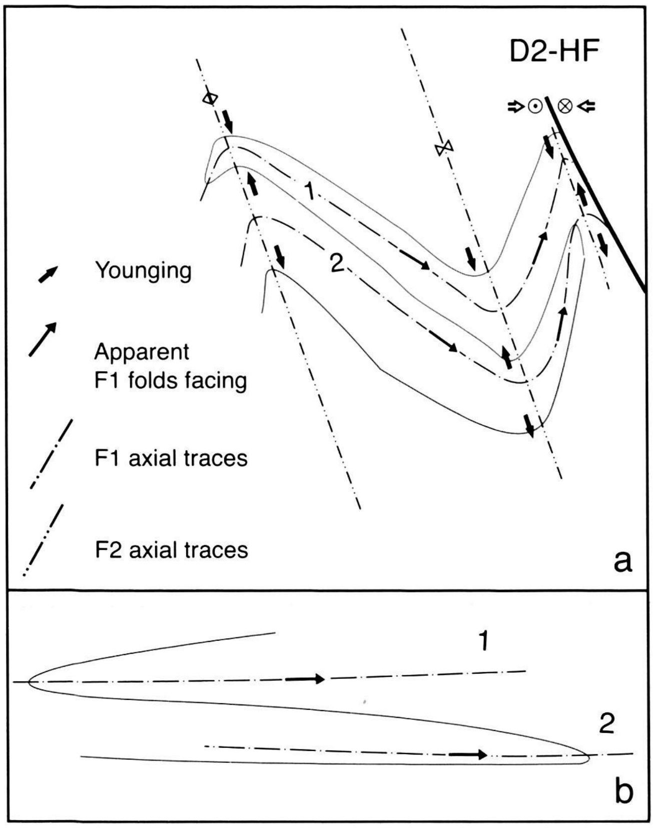

Fig. 12. Simplified sketch, illustrating retro-deformation of the effects of D2 in the SBU. HF: Houiller Front.

combres unit (Barbier 1948), or from the "Unité de la Croix des Têtes" (Perez- Postigo 1988), respectively. However, this study could not confirm the presence of this tectonic contact.

However, a clear tectonic contact, the "Cicatrice de Varlossière", was found near the eastern end of profile B-B' (Fig. 10b). East of this contact, marked by evaporites, the facies, which is typical for the Perron des Encombres unit, i.e. the Brêche du Telegraphe (Barbier 1948), is exposed (Fig. 10b). This overturned series ends with Lower Liassic Limestone against the HF in the Vallée des Encombres.

4.3 Cross Section C-C' through the eastern part of the Subbriançonnais unit and the western part of the Houiller unit in the southern part of the working area

The SBU at the western margin of profile C-C' (Fig. 10c) exposes Oxfordian schists defining the core of F2 "Synforme de la Porte". The overturned Cancellophycus formation in the eastern limb of this synform is in tectonic contact with Lower Liassic limestone forming the Grand Perron des Encombres peak (Figs. 4 and 10c). This tectonic contact was reworked by a D2 thrust, which truncates the D1 "Cicatrice de Varlossière" just north of this profile (see Fig. 4). Note that the D2 folds affect previously overturned stratigraphic series east of this important tectonic contact. This again clearly indicates the existence of an earlier (D1) phase of folding. A downward-facing D2 antiform-synform pair is found in the footwall of the syn-D2 Houiller Front.

Within the Houiller unit, however, large-scale D2 folds refold a normal stratigraphical series again. West of the Col des Encombres F2 folds display a constant orientation (SA-1; Figs. 4 and 10c) while more to the east (sub-area 2 between the Col des Encombres and the point quoted 2515 m (Fig. 10c) F2 folds are seen to be refolded by F3 folds with very steeply E-dipping axial planes. In spite of this complication the axial traces of these F2 folds could be traced further to the east by using S0/S2 relationships and younging criteria (Fig. 10c). Two pairs of tight F3 synforms and broader antiforms were mapped. The symmetrical shape of these F3 folds indicates that they are M-shaped parasitic folds marking the hinge zone of a larger scale F3 antiform. Aillères (1996) postulated a tectonic contact between their "Unité des Encombres" and their "Unité de la Masse" in this area that could, however, not be confirmed by this study.

East of this F3 antiformal hinge zone (SA-3), and all the way to the eastern termination of profile C-C' (Fig. 10c), F2 axial planes gently dip west. Hence they have the appearance of "backfolds" (Fig. 2a) and they are only locally disturbed by the presence of rare and asymmetric F3 folds. The vergence of these minor F3 folds indicates the presence of a second F3 antiform further to the east. In this eastern part of the profile the S1 schistosity is sometimes very pervasive (Fig. 2a) and major isoclinal F1 folds are visible here. The trace of a major F1 fold outcrops east of Col des Encombres (Fig. 10c). The trace of this F1 fold was mapped by carefully analysing S0/S1 and S1/S2 relationships, as well as facing directions of the F2 folds, which change across the F1 axial plane.

5. Summary and large scale correlations within the working area

5.1 Cheval Noir unit (CNU)

Large-scale fold interference patterns found in the CNU are exclusively due to D2-D3 interferences since D1 is not recorded in this unit. The first phase of deformation locally observed in the CNU is correlated with the SBF thrust, which represents the second deformation phase observed within the SBU (Table 1). Hence it is concluded that deformation did not yet propagate into the CNU during the regional D1, only recorded within the easternmost FPU (SBU and HU).

5.2 Subbriançonnais unit (SBU)

The main structures within the SBU, as found along the three cross sections A-A', B-B' and C-C' described above, can be correlated throughout the SBU (for further details, see profiles

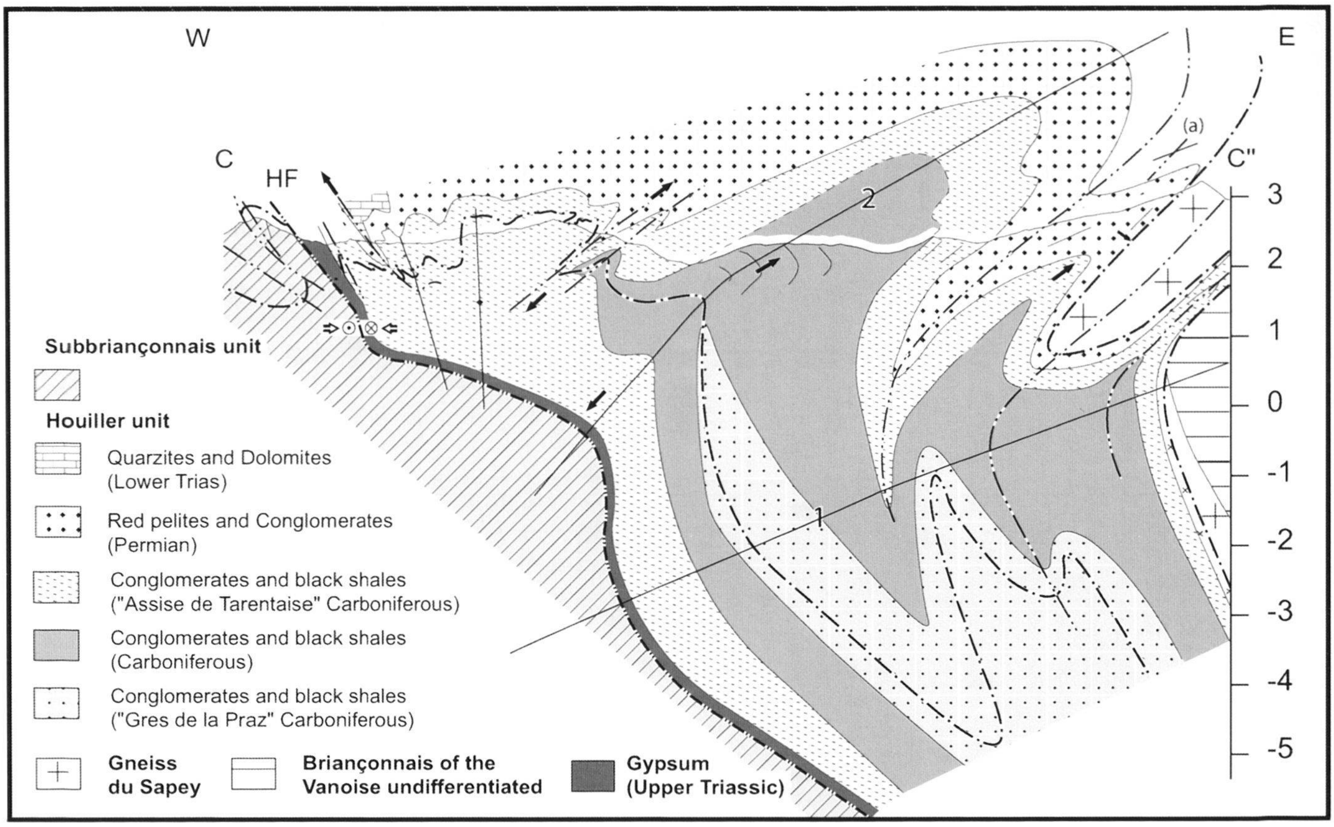

Fig. 13. Schematic cross section C-C" through the entire Houiller unit, based on section C-C' (Fig. 10c), the 1: 50'000 sheet Modane (Debelmas 1989) and the works of Fabre (1961) and Aillères (1996). Trace of profile indicated in Fig. 1.

through the southernmost part of the SBU in Ceriani, 2001). Mapping of axial traces (Figs. 4 and 7), together with the comparison of profiles (Fig. 10), shows that the syn-F2 "Synforme de la Porte" represents the most important D2 structure found within the SBU.

In the southern part of the SBU (Figs. 4 and 8) an F2 antiform ("Antiforme de la Serpolière" of Barbier 1948) outcrops further west and finds a possible continuation further north and in cross sections AA' and BB' (Fig. 10). However, this D2 antiform is not present at the latitude of cross section CC', probably due to omission by D4 normal faulting at the SBF (Fig. 4). A second large F2 antiform is present east of the "Synforme de la Porte" (Tête de Fer antiform in Fig. 10a) whose amplitude diminishes going towards the south, until it disappears (Fig. 7). Further south (Figs. 4 and 10c) another F2 antiform, which cannot be directly correlated to the Tête de Fer Antiform, is present in the same tectonic position.

Fig. 12a provides a schematic reconstruction of the structure of the SBU formed by the end of D2, i.e., after overthrusting along the HF and SBU thrusts. The F2 folds are seen to overprint former isoclinal D1 mega-folds (Fig. 12 b).

It is the changing facing of the major F2 folds that indicates the presence of two major F1 folds in the SBU whose axial traces can be followed through the entire SBU (see Ceriani 2001). The structurally higher of these F1 folds (the Grande Moendaz fold labelled "1" in Figs. 8, 11 and 12) has Oxfordian schists in its core (profile B-B'). This same F1 fold is also found further north (see description of profile AA'), and south (see Figs. 4 and 8). The structurally lower major F1 fold ("2" in Figs. 8 and 12b), with Upper Triassic dolomites in its core, is well exposed in the Croix des Têtes area (Figs. 4 and 8) and in the limb of the "Synforme de la Porte" (Fig. 8, see profile E-E' in Ceriani 2001), and in the core of an F2 antiform (Fig. 8, see profile D-D' in Ceriani 2001). The syn-D1 "Cicatrice de Varlossière" occupies the same structural position as this structurally lower F1 fold and is therefore interpreted as its northern continuation.

After simple 2D retro-deformation of the effects of D2 folding (Fig. 12b) the D1 folds would exhibit an apparent facing to the east. However, this facing is only apparent since F1 folds rotated into parallelism with the direction of transport of the first deformation phase, inferred to be top-north, i.e. perpendicular to the 2D cross section considered here (see Ceriani 2001 for further discussion).

In summary, the SBU is multiply folded by spectacular large-scale D1 and D2 folds. The dominating D1 and D2 struc-

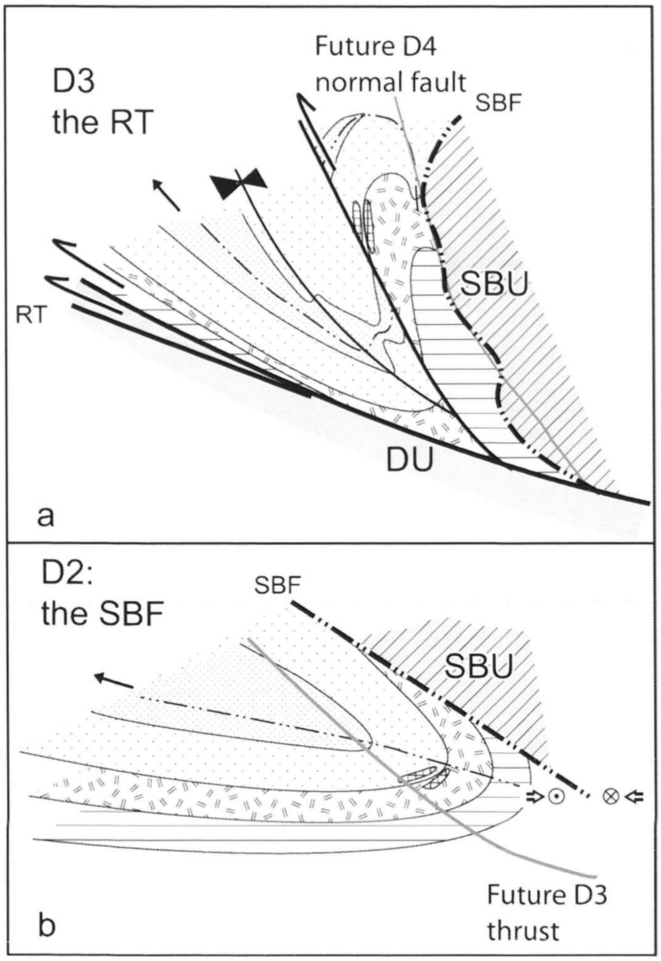

Fig. 14. Retro-deformation of poly-phase deformation in the Cheval Noir Unit (CNU) at the frontal part of cross section A-A' (see Fig. 10a). For legend see fig. 4b.
a) Retro-deformation of D4 normal faulting.
b) Retro-deformation of D3 in order to reveal geometry at the end of the regional D2 phase (locally the first phase of deformation). SBF: Subbriançonnais Front; RT: Roselend Thrust.

tures (including syn-D1 and D2 thrusts) can be followed over long distances. However, D3 is of local importance only in the SBU.

5.3 Complete cross section through the Houiller unit (Fig. 13)

Cross section C-C' (Fig. 10c) was placed into a larger scale context by constructing the profile depicted in Fig. 13, which unravels the internal structure of the Houiller unit. This profile combines own observations with data from sheet 1: 50'000 "Modane" (Debelmas 1989), Fabre (1961) and Aillères (1996).

In the area of Aiguille de Péclet (eastern termination of the HU; Fig. 1) the Houiller unit is in contact with the Briançonnais units of the Vanoise, from which it is separated by the "Gneiss du Sapey" basement slice. According to sheet 1:50'000 "Modane" (Debelmas 1989) and Fabre (1961) this contact is refolded by tight to isoclinal folds (see Fig. 1), here attributed to the second deformation phase D2. The contact of the HU with the "Gneiss du Sapey" is clearly tectonic (Bertrand et al. 1998) and pre-dates D2: it is the youngest (Permian) sediments that are in direct contact with the Gneiss du Sapey. Above this contact and along the profile trace, the S3 schistosity dips NW to WNW with 40-50° (point "a" in Fig. 13). There, its intersection with the main schistosity S2 indicates the presence of a D3 antiform further west (antiform labelled "2" in Fig. 13) and a synform further east (synform labelled "1" in Fig. 13). The existence of these D3 folds is in agreement with sheet 1:50'000 "Modane" (Debelmas 1989), as well as with the profiles of Fabre (1961). These F3 folds are backfolds exhibiting W-dipping axial planes, and they are more open compared to the F1 and F2 folds.

The synform labelled "1" in Fig. 13 is seen to refold the contact of the ZH unit with the Briançonnais units of the Vanoise, its axial plane reaching the surface to the east of Fig. 13. The antiform labelled "2" in Fig. 13, however, reaches the surface within the Carboniferous of the HU. A synform with young Permian sediments in its core, situated immediately west of the contact with the Gneiss du Sapey, is interpreted to be a D2 fold (see also Aillères 1996).

Further west, and in the Col des Encombres area described in profile C-C' (Fig. 10c), however, the axial planes of F3 folds steeply dip to the east. The change in orientation of the F3 axial planes (Fig. 13) is interpreted to be due to a fanning effect, which can also be locally observed at the outcrop scale (Ceriani 2001). It is important to note, however, that the Houiller Front dips to the east all the way from Moûtiers to St. Martin de la Porte in the south (i.e. over a range of altitudes ranging from 2400m to 600m). This suggests that the amplitude of the F3 folds labelled "1" and "2" in Fig. 13 is attenuated westwards, as depicted in Fig. 13.

In summary, the Houiller unit is also characterised by the superimposition of three folding phases, each of them producing large- scale folds. Character and intensity of D3 deformation, however, change from west to east. The external parts of the HU, including the HF thrust, are only locally affected by D3 folding. Further east, the F3 structures reveal a large-scale fan-structure (Caby 1996), the axial planes changing through the vertical into west-dipping orientations.

6. Retro-deformation of superimposed deformations in the FPU

This section attempts to retro-deform the effects of D4 and D3 in order to reveal the situation during D2, i.e. immediately before collision of the FPU with the Dauphinois. Given the extremely isoclinal nature of D1 folds, no further retro-deformation, such as schematically shown in Fig. 12b for the SBU, was possible.

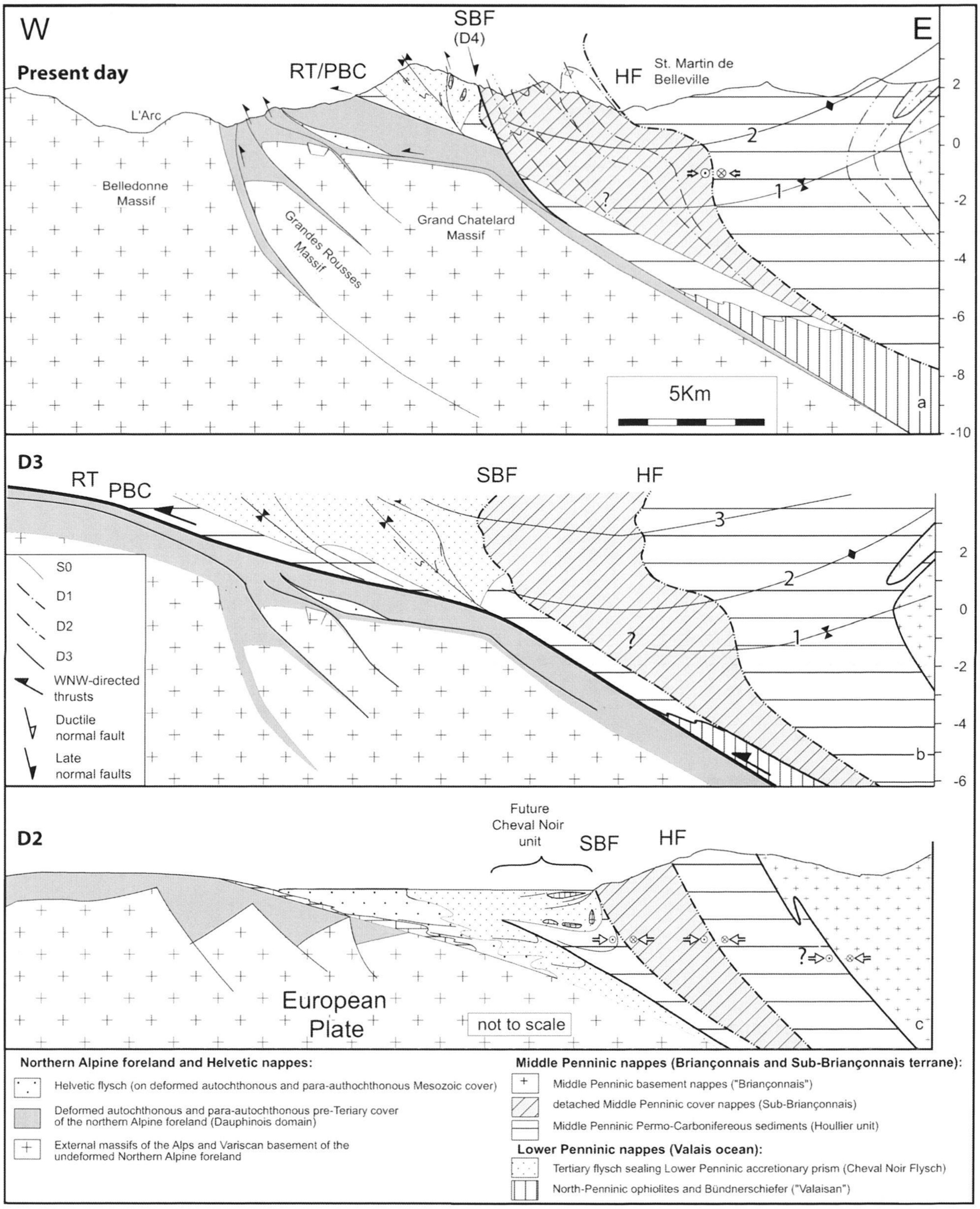

Fig. 15. Retro-deformation along profile through the frontal parts of the French-Italian Western Alps, running parallel to section A-A' (for location see Fig. 1). RT: Roselend Thrust; PBC: Penninic Basal Contact; SBF: Subbriançonnais Front; HF: Houiller Front.
a) Present-day profile.
b) Retro-deformation of D4 normal faulting.
c) Interpretative cross section, not to scale, illustrating accretionary wedge scenario immediately before collision, i.e. at the end of D2.

The cross section of Fig. 15a (Fig. 1) presents a 2D interpretation of the area down to a depth of 10 km and serves as a basis for retro-deformation. It is mainly based on profiles A-A' and C-C' (Figs. 10a and c) and on the 1:50'000 sheets "Modane" (Debelmas 1989), "La Rochette" (Barféty et al. 1983), and "St. Jean de Maurienne" (Barféty et al. 1977) of the Geological map of France.

6.1 Retro-deformation of normal faulting (D4)

D4 normal faults, such as the normal fault reactivating the syn-D2 SBF thrust (see reconstruction in Fig. 14), are known to post-date 5 Ma further to the north (Fügenschuh et al. 1999). The kinematics of this normal faulting are compatible with the present day stress field (Ceriani et al. 2001; Sue et al. 1999). Localisation of earthquake epicentres south of the study area (Sue & Tricart, 1999) indicates that extension is concentrated along the PBC at depth. Hence, these normal faults are though to be listric at depth (see D4 normal fault depicted in Fig. 15a). Retro-deformation according to this geometry leads to the reconstruction given in Fig. 15b.

6.2 Retro-deformation of post-collisional (D3) folding and WNW-directed thrusting

As depicted in Fig. 15b, the orientation of F3 axial planes changes through the study area from a dip towards the foreland in the internal FPU into a dip towards the hinterland, and parallel to the syn-D3 Roselend thrust in the external FPU. While the effects of D3 are major within the HU and particularly within the CNU, F3 folding in the Subbriançonnais unit is minor.

The modifications of earlier structures by D3 (and D4) are particularly strong in the CNU, and a more detailed reconstruction of this unit based on cross section A-A' is presented in Fig. 14. After subtraction of normal faulting (Fig. 14a) the effects of D3 in this part of the profile become more evident: the RT, a D3 thrust formed in the footwall of the SBF, marks the base of the CNU while a large F3 synform within the CNU developed above the RT and in the footwall of a second D3 thrust (Fig. 14a). Retro-deformation results in a major D2 syncline within the CNU, situated in the footwall of the SBF thrust (Fig. 14b).

The geometry of the two F3 mega folds affecting the HU (labelled 1 and 2 in Figs. 13 and 15a), together with the vergence of minor F3 folds affecting the HF (Fig. 6), suggest the existence of another west-closing D3 mega-fold (labelled 3 in Fig. 15b). This mega-fold refolds the syn-D2 SBF thrust and its hinge is situated above topography as given in Fig15a. It is inferred to have refolded HF and the SBF at a large scale, inverting the present day "normal" nappe stack above its axial plane (Fig. 15b), such as observed elsewhere in the Western Alps (Bucher et al. 2003).

6.3 Reconstruction of the situation immediately before collision with the Dauphinois (syn-D2)

Thrusting of the SBU along the SBF-thrust onto the Cheval Noir unit led to the formation of a D2 synform in the CNU during a late stage of D2 (Figs. 14b and 15c). This folding is immediately preceded by the emplacement of a first series of large olistoliths embedded in the oldest Paleogene sediments (early Priabonian Wild flysch and Breccias; Figs. 9, 10 and 15c). In the southern part of the study area and in the immediate vicinity of the SBF a younger stratigraphic level containing large olistoliths (Bravard et al. 1981) is found within the Calcareous Flysch (Figs. 4 and 15c). These olistoliths are related to earlier syn-D2 tectonic activity along the SBF (Ceriani 2001, Ceriani et al. 2001), which is Late Priabonian, i.e. contemporaneous with the sedimentation of this flysch. Hence, early D2 deformation and flysch sedimentation are both contemporaneous and related to tectonic activity along the SBF. In the western Alps a similar tectonic scenario of contemporaneous folding and sedimentation is well documented for the Lower Oligocene (Rupellian) of the "Barrème basin" (Artoni & Meckel 1998, Lickorish & Ford 1998).

In summary, the interpretative E-W cross section of Fig. 15c shows a nappe stack that consists of, from bottom to top, SBU, HU and Briançonnais units of the Vanoise as parts of an accretionary wedge, whose deformation is contemporaneous with sedimentation in its frontal part, i.e. the present-day Cheval Noir unit. The external part of this Priabonian flysch basin ("Flysch des Aiguilles d'Arve", Barbier 1948, Serre et al. 1985) was in stratigraphic contact with the Priabonian flysch deposited onto the Dauphinois domain (see discussion in Ceriani et al. 2001).

Note, however, that convergence is highly oblique, since SBF and HU formed as sinistrally transpressive top-N to NNW directed thrusts. Also note that sedimentation in the Cheval Noir flysch basin seals the former suture between European plate (Dauphinois) and Subbriançonnais-Briançonnais ribbon continent (see discussion in Ceriani et al. 2001).

7. Discussion of the tectonic evolution of the Frontal Penninic units south of Moûtiers

The tectonic evolution of the FPU can conveniently be divided into three major stages of deformation. The structural data presented above will now be discussed in the context of new data on the metamorphic evolution, including timing constraints from fission track data from the FPU and Dauphinois domains (Ceriani et al. 2003; Fügenschuh & Schmid 2003).

7.1 Pre- to syn-collisional stage of subduction and nappe stacking (D1+D2, Eocene)

Early during this first stage of deformation, comprising tectonic phases D1 and D2 (Table 1), SBU and HU were detached from their unknown former substratum and underwent strong internal deformation. A combination of fission track analysis and Illite crystallinity data indicates that the metamorphic conditions in these FPU range from high anchizonal to epizonal (Ceriani et al. 2003). The highest metamorphic temperatures (~300°C, i.e. Epizone) were deduced for the HU and for the base of the CNU, while the SBU only reached the high anchizone. Metamorphism was diachroneous, however since the HU reached peak temperatures already during D1 (Ceriani et al. 2003, Fügenschuh & Schmid 2003). Already during D2 this unit occupied a higher tectonic position in comparison to the underlying Subbriançonnais unit (Fig. 15c), and fission track data indicate that it started to cool at around 35 Ma ago (Fügenschuh & Schmid 2003). This indicates that the temperature peak in the HU, and consequently D1, predates 35Ma.

Sedimentation of the Priabonian (37-33.7 Ma) found in the CNU unit, however, at least partly post-dates D1 and these sediments are not affected by D1. The Briançonnais-type substratum of these Tertiary sediments, however, is thought to have reached its position in front of the Alpine accretionary wedge already during D1.

The second deformation phase D2 produced the final nappe stack within the FPU south of Moûtiers, initially contemporaneous with ongoing sedimentation in the CNU, as is depicted in Fig. 15c. The metamorphic peak within SBU and CNU (high anchizonal epizonal, respectively) was reached late during D2, probably due to over-thrusting of the HU and SBU units, respectively (Ceriani et al. 2003). In the CNU this metamorphism took place under a low geothermal gradient (Ceriani et al. 2003) and it predates the onset of cooling at around 32Ma (Fügenschuh & Schmid 2003). Termination of D2-deformation at around 32Ma, or shortly before, agrees with the Priabonian age of syntectonic sedimentation in the CNU and provides a solid age constraint for the end of this first stage of subduction of the Valaisan units and nappe stacking at around the Eocene/Oligocene boundary.

The N-S orientation of L1 and L2 stretching lineations (Fig. 3) suggests that this stage of subduction and nappe stacking developed within a sinistrally transpressive tectonic scenario, as was previously described on a smaller scale in respect to individual syn-D2 oblique thrusts, such as the SBF and the HF. Very early on during this stage, the Valaisan units were completely subducted in the area of investigation, but subsequently exhumed in the Versoyen, exposed further to the north (see discussion in Ceriani et al. 2001; Fügenschuh et al. 1999; Loprieno 2001). Later, at the end of D2, Europe collided with the Subbriançonnais-Briançonnais ribbon continent (Ceriani 2001; Fügenschuh et al. 1999). Now the FPU, which previously remained at a shallow tectonic level in the frontal part of the accretionary wedge, also got involved in deformation and metamorphism. This sinistrally transpressive tectonic scenario is compatible with N-S collision between Adria and Europe, during which Europe and the FPU remained in a lateral position in respect to Adria, as previously proposed by Choukroune et al. (1986), Ricou & Siddans (1986), and Schmid & Kissling (2000).

7.2 Post-collisional folding and WNW-directed thrusting (D3, Oligocene to Early Miocene)

The onset of this second stage of deformation is characterised by a significant change in kinematics. Top-north nappe stacking is now followed by top-WNW thrusting of the FPU nappe stack along the Roselend thrust (RT) onto the Dauphinois domain. This thrusting is contemporaneous with refolding of this nappe stack during D3.

The HU and its contact with the more internal Briançonnais units (Gneiss de Sapey and the Briançonnais of the Vanoise) is refolded by post-nappe mega-folds, characterised by flat lying to gently foreland dipping axial planes (Figs. 13 and 15). This leads to an apparent fan-structure of the main schistosities (S1 and S2), a geometry that strongly reminds refolding of the Briançonnais and Piemont-Liguria nappe stack further north (east of Cormet de Roselend, Fig. 1), recently described by Bucher et al. (2003). These authors attribute this D3 post nappe folding to the WNW-directed indentation of the Gran Paradiso massif, which occurred later than 35 Ma ago, but before fast cooling of zircon through the partial annealing zone for fission tracks between 31-29 Ma (Hurford & Hunziker 1989).

In the frontal HU the gently foreland dipping to flat-lying D3 axial planes gradually rotate into the dip to the east (Fig. 13b), which is characteristic for the external CNU, significantly deformed during this stage (Figs. 14a and 15b). Here D3 is directly related to WNW-directed thrusting along the Roselend Thrust, that post-dates deposition of the Priabonian flysch (Ceriani et al. 2001). Fission track data indicate that F3 folds folded the isotherms formed during syn-D2 metamorphism. The latter are coeval with the onset of cooling of the CNU after 32 Ma ago (Ceriani et al. 2003; Fügenschuh & Schmid 2003).

Deformation related to thrusting along the RT (D3) also affects the Dauphinois domain of the footwall (Ceriani 2001, Table 1), affected by only one major phase of deformation (i.e. the regional D3). This, together with data on metamorphism and fission track dating (Ceriani et al. 2003; Fügenschuh & Schmid 2003), clearly indicates that the metamorphism in the Dauphinois post-dates that of the FPU. Metamorphism in the Dauphinois is due to burial and heating, caused by post-32 Ma over-thrusting of the FPU along the syn-D3 Roselend thrust. Thrusting along this post-collisional thrust can be followed all along the arc of the Western Alps (Ceriani et al. 2001) and is contemporaneous with exhumation and cooling of the FPU in its hanging wall.

The end of this second stage of deformation in the FPU is poorly constrained. Cooling ages in the Dauphinois have been interpreted to date the onset of thrust-propagation into the external massifs, situated within the more external Dauphinois. This thrusting started some 20–15 Ma ago (Fügenschuh & Schmid 2003) and marks the onset of further foreland-propagation of WNW-directed thrusting. This late stage of post-collisional shortening in the most external foreland is not recorded in the FPU. Hence, D3-deformation and thrusting along the RT only covers the time span between 32 and 20-15 Ma ago.

7.3 Normal faulting (D4, Pliocene-present)

In the study area after the Oligo-Miocene thrusting phase (D3) no evidence for further tectonic activity was recognized until the start of the D4 deformation phase. D4 normal faulting, reactivating former thrusts, started about 5 Ma ago (Ceriani et al. 2003; Fügenschuh et al. 1999; Fügenschuh & Schmid 2003) and is still going on today (Sue et al. 1999). Present-day normal faulting with orogen-perpendicular extension, as observed in the study area, affects the entire Penninic core of the Western Alps (Sue et al. 1999), but is contemporaneous with ongoing compression in the Po-plain and in the European foreland. Gravitational collapse (Sue et al. 1999) might be the cause for this ongoing normal faulting

8. Conclusions

The FPU represent an important geometrical link between the internal and highly metamorphic Penninic units and the external fold-and thrust-belt formed by the Dauphinois units. Their poly-phase deformation analysed by this work documents (1) progressive foreland-propagation of post-collisional deformation and (2) two well-dated changes in the kinematic framework.

The first stage of pre- to syn-collisional stage of subduction and top-N nappe stacking during the Eocene to early Oligocene was markedly oblique to the strike of the Western Alps and evolved in a sinistrally transpressive regime.

The second stage of post-collisional folding and WNW-directed thrusting of in the Oligocene to early Miocene carried the FPU onto the Dauphinois domain. This thrusting, related to WNW-directed indentation of the Adriatic plate (Schmid & Kissling 2000; Ceriani et al. 2001), also led to post-nappe refolding in the hangingwall, also observed elsewhere in the Penninic units of the Western Alps (Bucher et al. 2003) at about the same time.

After a period of tectonic quiescence in the FPU, due to foreland propagation of WNW-directed thrusting into the external massifs, deformation by normal faulting resumed after 5 Ma ago and is still ongoing presently.

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