Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 92 (1999)
Heft: 3

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DOI: https://doi.org/10.5169/seals-168677

0012-9402/99/030347-13 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 1999

Eclogae geol. Helv. 92 (1999) 347–359

Neo-Alpine structural features at the boundary between the Penninic and Helvetic domains (Prè S. Didiér – Entrèves, Aosta valley, Italy)

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Key words: Neo-Alpine tectonics, Penninic frontal thrust, exhumation, ductile to brittle shear zones

ABSTRACT

A several-kilometres wide ductile to brittle shear zone (Courmayeur deformation zone, CDZ), between the Sion-Courmayeur Zone and the Mont Blanc crystalline basement corresponds in the study area with the so-called Penninic frontal thrust (PFT). The CDZ underwent a long deformational history characterized by the development of a regional syn-metamorphic (greenschist facies) foliation (S2), which was successively reactivated by semi-brittle, transpressive-dextral, NW-vergent shear zones, giving rise to a younger (S3) foliation and often associated with large-scale open folds. NW-SE compression was predominant during this deformational stage. Brittle tectonics was later superimposed on the S3-related structures. The onset of this later cataclastic deformation is apparently not related with significant changes in the kinematics of the CDZ and adjoining units, except for the development of a SE-vergent back thrust which transported the Mt. Blanc crystalline basement onto the Ultrahelvetic covers.

The proposed kinematic interpretations are compared with the available fission track ages of the main units at both sides of the Penninic frontal thrust in order to suggest a possible model for the neo-Alpine exhumation of the Mont Blanc and Mt. Chetif units, in the light of the kinematics of the contiguous Rhone-Simplon Fault.

RIASSUNTO

Nell'area di studio affiora una zona di taglio fragile-duttile della potenza di alcuni chilometri (Zona di Deformazione di Courmayeur, CDZ). Questa zona di taglio è compresa tra la Zona Sion-Courmayeur e il basamento cristallino del Massiccio del Monte Bianco, e corrisponde al così detto Fronte Pennidico (PFT). La CDZ ha registrato una lunga storia deformativa, caratterizzata dallo sviluppo di una foliazione sin-metamorfica S2 (facies scisti verdi). La S2 è stata successivamente riattivata da zone di taglio semi-fragili transpressive destre con vergenza NW, che hanno dato origine a una foliazione S3 più giovane, spesso associata a pieghe aperte. Durante quest'ultima fase di deformazione la direzione di compressione principale aveva un'orientazione NW-SE. Deformazioni di tipo fragile sono infine sovrapposte alle strutture sincinematiche rispetto alla S3. Lo sviluppo di queste deformazioni cataclastiche apparentemente non è da mettere in relazione con cambiamenti significativi nel cinematismo della CDZ e delle unità adiacenti, eccezion fatta per lo sviluppo di un retroscorrimento a vergenza SE che ha trasportato il basamento cristallino del Monte Bianco al di sopra delle coperture Ultraelvetiche. Le interpretazioni cinematiche proposte vengono confrontate con le età delle tracce di fissione su apatiti e zirconi delle principali unità localizzate su entrambi i lati del Fronte Pennidico, nel tentativo di proporre un possibile modello per l'esumazione neo-alpina delle unità del Monte Bianco e del Mont Chetif, tenendo conto anche della cinematica della adiacente Faglia del Rodano-Sempione.

1. Introduction

The tectonic boundary between the internal Penninic-Briançonnais and the external Helvetic-Ultrahelvetic Alpine domains has been considered as a thrust front (Penninic frontal thrust, PFT), separating distinct Mesozoic paleogeographic realms with different depositional history. These differences have led to consideration of the PFT as an important suture of the Alpine chain (Argand 1911, 1916).

The PFT also separates low-grade metamorphic rocks bearing HP-LT remnants in the SE (Oberhänsli et al. 1996; Goffé & Bousquet 1997), from very low-grade metamorphic rocks which did not suffer HP-LT metamorphism in the NW (Baggio 1964; Kübler et al. 1979; von Raumer 1987). At depth it corresponds to a lithospheric discontinuity dipping toward the SE and well evidenced by reflection seismic profiles (Nicolas et al. 1990). In the M. Blanc region the PFT separates a complex of imbricated units belonging to the Paleogene Alpine orogenic wedge from the allochthonous Mesozoic cover of the M. Blanc massif, that was deposited onto the Eu-

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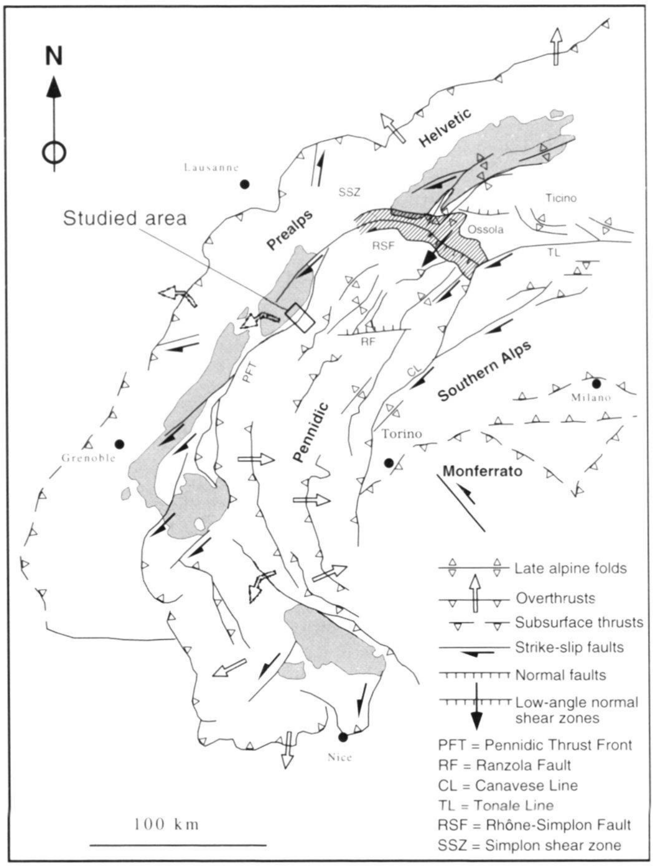

Fig. 1. Structural sketch map of the Northwestern Alps. Redrawn after Steck & Hunziker (1994).

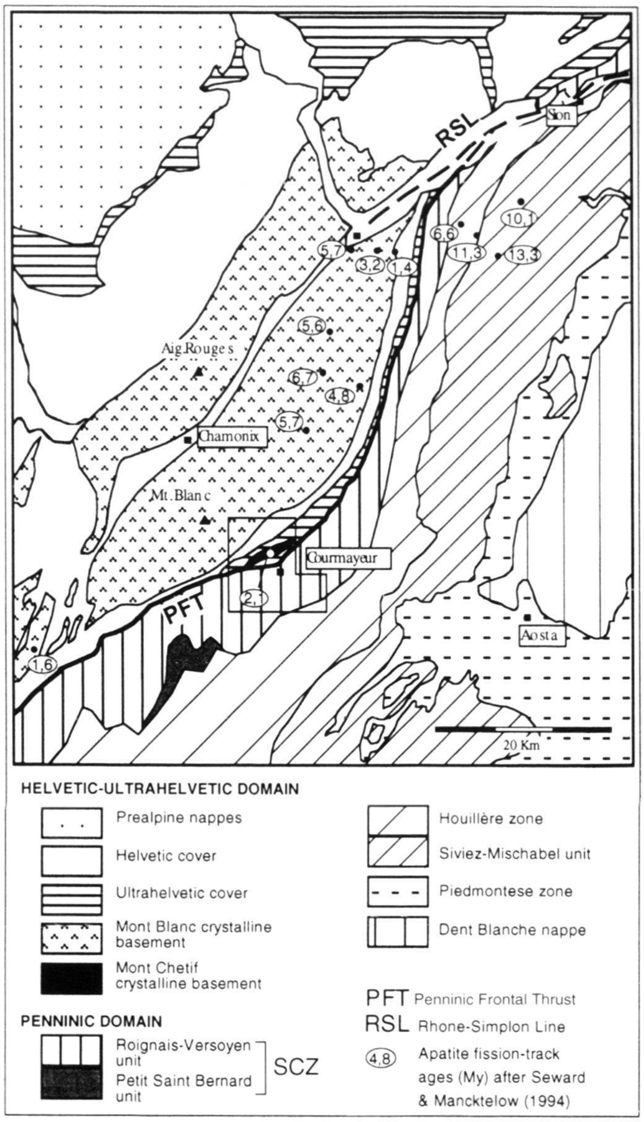

Fig. 2. Geological sketch map of the study area (inset) and surrounding region.

ropean plate (Polino et al. 1990; Roure et al. 1996). Since some sedimentary units of the orogenic wedge (Pierre Avoie unit) have been recently dated as Eocene (Bagnoud et al. 1998) the activity of the PFT has been interpreted as post-Eocene (Fügenschuh et al. 1999).

The PFT merges with the Rhône-Simplon line (Fig. 1, 2), a dextral transtensive fault of the Central Alps, dipping toward S or SW. This fault is the Miocene-Recent expression of the Simplon Shear Zone, an older discontinuity active from Early Oligocene (Mancktelow 1985; Steck 1990; Steck & Hunziker 1994). It has therefore been suggested that the kinematics of the Penninic Front during the Late Oligocene and Miocene should be related to shearing along the Rhône-Simplon line (Laubscher 1991).

In the Courmayeur-Mont Blanc region an increase in the apatite fission track ages across the PFT has been reported (Seward & Mancktelow 1994 and references therein). The PFT footwall (NW) indicates 1.4–5 Ma ages, whilst the hangingwall (SE) indicates 6–13 Ma (Fig. 2). This was interpreted by Hubbard & Mancktelow (1992) as due to an extensional reactivation of the PFT in the Neogene, which should have accommodated the differential uplift of the two sectors it separates.

Since the structural setting of the PFT in the Courmayeur zone is known to be very complex, it could be suggested that several differently striking brittle structures could have driven the uplift. The exhumation of the Mont Blanc Massif and adjoining units could have been driven by normal faulting or conversely by reverse faulting depending on the vergence of the main brittle structures. For these reasons, detailed structural analyses and mapping on 1:5,000–1:10,000 scale were carried out in the Courmayeur-Mont Blanc region to better constrain the structural evolution of the PFT zone.

2. Geological Setting

The studied area includes two main units (Helvetic-Ultrahelvetic Domain and Sion-Courmayeur Zone of the Penninic Domain), separated by a 3–4 km-wide tectonic slices zone roughly corresponding to the PFT (Pl. 1, Fig. 2).

The Helvetic-Ultrahelvetic Domain (HUD) is a strongly transposed metasedimentary succession resting on the Mont Blanc crystalline Massif. The Mont Blanc Massif is mainly made up of pre-Permian schists, migmatites, granites, intruded by Hercynian granitoids and acid volcanites (Baggio 1964; von Raumer 1987). The sedimentary cover consists of Jurassic sequences of limestones, black schists and calcschists (Barbier 1948; Antoine et al. 1975). At present the cover and the basement are separated by a tectonic contact and the original stratigraphic relations are only locally preserved. Basement and cover suffered an Alpine greenschist facies metamorphism that in the Mont Blanc Massif is superimposed on pre-Alpine high grade metamorphic assemblages (Baggio & Malaroda 1962).

The Sion-Courmayeur Zone (SCZ; Fig. 2) is a Cretaceous-Paleocene turbiditic sequence (Brèches de Tarentaise Auct.) divided into three parts (Barbier 1948; Barbier & Trümpy 1955; Antoine 1972). The lowest part consists of calcareous breccias and calcarenites (Couches de l'Aroley). The intermediate one consists of siliciclastic sediments (quartzites and schists) with minor calcschists, limestones and calcareous breccias (Couches de Marmontains). The top part consists of calcschists, calcarenites and minor calcareous breccias (Couches de Saint Christophe). The Sion-Courmayeur Zone also underwent Alpine greenschists facies metamorphism, though remnants of HP-LT parageneses have been recognized in some places and are usually referred to early-Alpine subduction (Oberhänsli et al. 1996).

The PFT is interposed between the HUD and SCZ. It is usually represented on geologic sketch profiles as a succession of slices separated by repeated tectonic contacts dipping 40–50° toward SSE (Elter & Elter 1965). The tectonic slices are made up of both HUD and SCZ rocks in addition to some other elements of unknown provenance, such as the Mt. Chetif slice (Fig. 2) and the Ferret Zone Auct. The Mt. Chetif slice mainly consists of meta-granites and meta-rhyolites with a strong mylonitic overprint. The Ferret zone Auct. is represented by interbedded calcschists and thin mica levels and is regarded as a peculiar facies of the Brèches de Tarentaise upper element (Antoine 1972). Other tectonic slices of the PFT include metasedimentary rocks usually considered as the substratum of the SCZ turbidites. These slices consist of schists and quartzites (Permo-Carboniferous), dolomites, dolomitic limestones and breccias (Trias), calcareous breccias (Dogger), graphitic schists and calcschists of unknown age (Barbier 1951; Antoine 1972).

A large part of the PFT slice zone is also made up of gypsum and anhydrite layers and cargneules (Trias). Some authors (Elter & Elter 1965) assume that this Triassic layer of evaporites is the main detachment level in the thrust zone.

Detailed structural studies are lacking for the study area. The cross-sections proposed by Antoine (1972) and Elter & Elter (1965) however suggest a relation between the shearing along the PFT and the folding history in the adjacent units. The large-scale NW-vergent antiforms of the SCZ are truncated at their base by shear zones related to the PFT.

In the HUD, too, NW-vergent shear zones parallel to the PFT and related NW-verging drag folds have been observed (Antoine et al. 1975).

This study uses new structural data to suggest that the present-day structural setting of the slices zone referred to as Penninic Frontal Thrust in literature, is mostly the result of deformational events post-dating and overprinting the structures developed during the main collisional Alpine phase.

The deformation belt situated between the HUD and the SCZ is here called the Courmayeur Deformation Zone (CDZ), to stress that, although it could be regarded as the PFT surface expression, it does not strictly correspond to an individual thrust surface, but to a ductile-brittle transpressive shear zone which accomodated not only reverse movements, but also consistent right-lateral displacement.

3. Structural Analysis

The detailed map of the Courmayeur-Mt. Blanc region (Pl. 1) shows that the main tectono-stratigraphic units (CDZ, HUD and SCZ) are currently separated by the φ1, φ2 and φ3 NW-vergent shear zones and by the φ4 SE-vergent shear zone. φ1, φ2 and φ3 represent the main displacements delimiting different portions of the CDZ, themselves internally deformed by minor shear zones. φ4 is a major thrust separating the Mont Blanc basement from the HUD cover, which consequently can be considered as a distinct unit from the Mont Blanc Massif.

Schist levels act as a detachment zone (φ1) at the top of the CDZ, separating it from the SCZ. At its base, the CDZ is bounded by a brittle-ductile shear zone (φ3) that separates the Mt. Chetif tectonic slice from the HUD folded rocks. These in turn are overthrusted by the Mont Blanc Massif along the φ4 Pavillon brittle back-thrust.

All the units separated by the φ1–φ4 shear zones have their deformational history recorded by the development of pervasive structural features. Structural correlations between them have been sought by comparing these features.

The main foliation recognizable in all units is a regional transpositional schistosity (here called S2) developed in response to ductile deformation coeval with greenschist facies metamorphism. Actually, S2 is not the oldest schistosity, since an earlier one (S1) is recognizable in a few outcrops and at the microscopic scale.

S2 was overprinted by a post-metamorphic deformation which gave rise to a younger schistosity (S3, see below). S3 is a penetrative feature locally recognizable in all the units and seems to have originated from different but co-genetic post-metamorphic deformations. It pre-dates the development of the late φ4 thrust system.

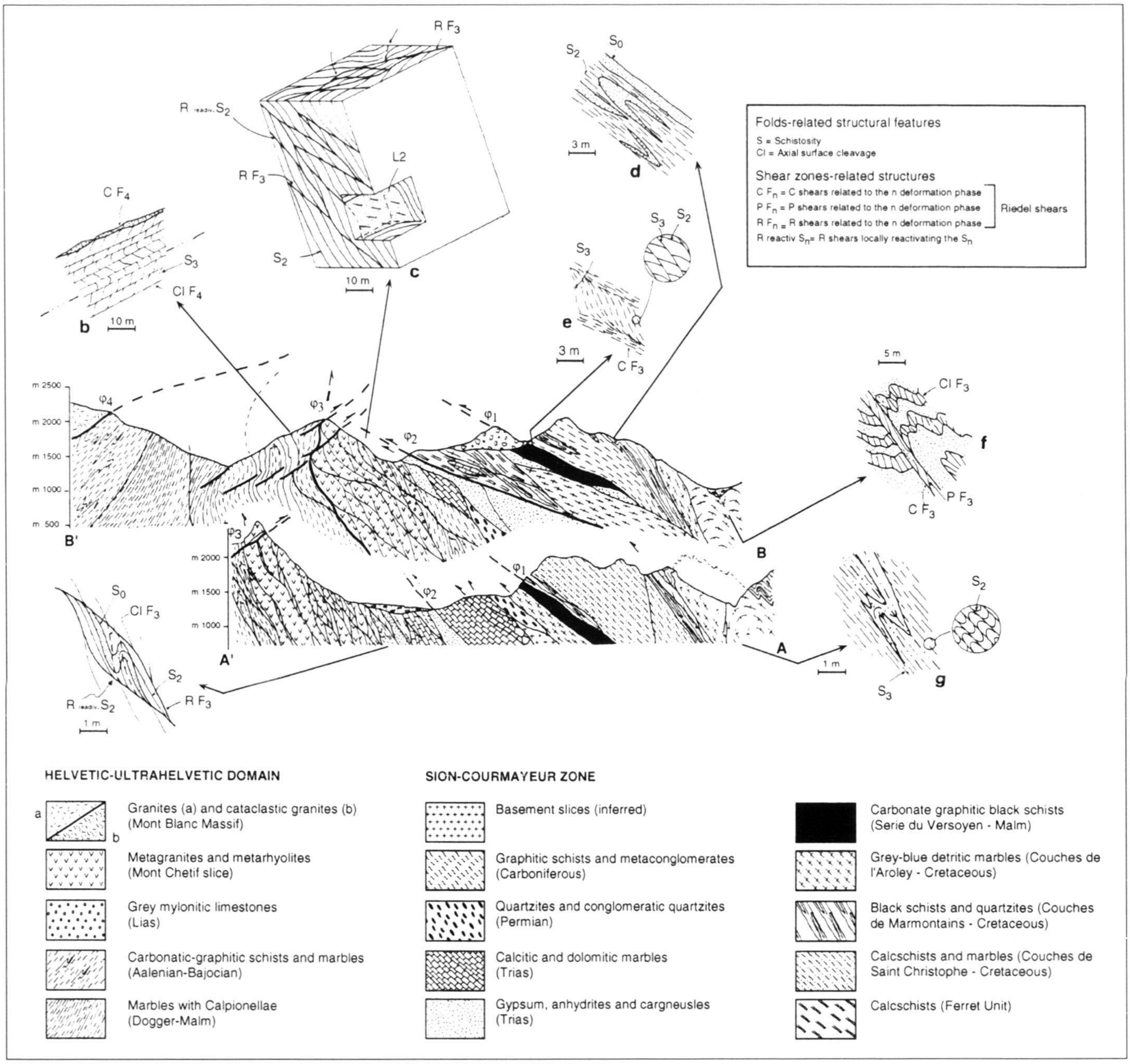

Fig. 3. Geological cross sections. See text for further details. Location in Plate 1.

S3 is differently expressed in different units. In the CDZ it corresponds to cleavages and slip planes mainly originated by brittle-ductile shear zones, whereas in the HUD and SCZ it represents the axial plane foliation of prevalent folds.

3.1. Mesoscopic features

S2 and related structures

Sion-Courmayeur Zone (SCZ) – The oldest mesoscopic element is a regional transpositional schistosity (S2) oblique to the bedding (S0) and to the pre-S2 foliation (Fig. 3d). S2 is normally defined by the preferred orientation of layer silicates in mica-bearing rocks and by a mineralogical layering in the carbonatic rocks. The development of S2 is associated with syn-kinematic greenschist facies metamorphism, (White mica, Ep, Ab, Chl) and is followed by static recrystallization of albite. S2 often corresponds at all scales to the axial plane foliation of isoclinal folds. Elongated pebbles and minerals define a stretching lineation (L2) coeval with the development of the S2. The intersection between S2 and the compositional

Fig. 4. Rock sample showing the geometrical relations between the main foliations. S2 intersects at low angle the lithological bedding (S0). These are both deformed by later folds that develop a crenulation cleavage here indicated as S3.

layering results in an intersection lineation parallel to fold axes.

Helvetic-Ultrahelvetic Domain (HUD) – As regards the S2, the structural and petrographical features of the metamorphic covers of this domain, are similar to those described for the SCZ. In the Mont Blanc basement, mylonitic shear zones locally overprinted the older granoblastic assemblages and induced a greenschist facies metamorphic re-equilibration. The basement-cover relationships west of the study area (Val Veny), are characterized by the presence of a S2 cleavage cutting a pre-existing mylonitic foliation, both in basement (migmatitic gneisses) and in cover (Jurassic limestones). Pre-mylonitic brittle fabrics also occurred in the Mont Blanc Massif (Guermani & Pennacchioni 1997) and are interpreted as markers of the early Alpine extensional tectonics.

Courmayeur deformation Zone (CDZ) – Here the main planar feature observed is a transpositional (S2) or mylonitic (Sm) foliation. In the metasedimentary cover rocks, the mylonitic foliation is often localized in more micaceous layers, which behave as detachment levels because of their lower competence with regard to the more massive carbonatic layers. In the Mt. Chetif slice, part of the rock mass is mylonitized, but less deformed lithons showing granoblastic structure are also locally preserved.

Sm is considered as mainly coeval with S2 since it shows metamorphic features similar to the S2 of the SCZ. Here S2 is hardly discernable from the subparallel Sm, though it is preserved within lithons in some places.

Sm is associated with a stretching lineation (L2; Fig. 3c) mainly defined by the elongation of quartz and feldspar aggregates. At the micro-scale, grain reduction processes related to recrystallization are widespread. In the schists of the cover succession, the mylonitic processes generated fine grained rocks where all phyllosilicates display a strong preferred orientation. In the meta-granitoid mylonites, the groundmass consists of equidimensional grains of Qz, Ab, Musc and minor Ep and Stlpn. Porphyroclasts are variously abundant and are represented by all the original magmatic phases, and are often replaced by porphyroblasts of Qz and Ab, which attest a post-kinematic reequilibration under greenschist facies metamorphic conditions similar to those of the main mylonitization event.

S3 and related structures

The S2 is locally intersected by a crenulation cleavage defining a younger schistosity (S3, Fig. 4). Development of the S3 did not induce widespread metamorphic recrystallization, but only undulatory extinction in quartz and feldspars, together with local recrystallization of quartz, chlorite and opaques.

S3 represents the axial surface foliation of tight asymmetric folds developed in all three tectono-stratigraphic units. The planar features here referred to as S3 cleavages show similar morphology in rocks of similar rheological behaviour from these units, suggesting that they formed under similar conditions everywhere.

Sion-Courmayeur Zone (SCZ) – In this domain, the S3-related folds are cylindrical at the meso-scale and often parasitic or larger-scale folds, which are roughly NE-SW trending. The S3 corresponds to a spaced axial cleavage.

Mesoscale shear zones developed locally on the limbs of S3-related folds, leading to the formation of co-genetic spaced slip-cleavages (C) roughly parallel to and coeval with the S3 foliation. These slip-cleavages drag both S2 and S3 at the millimetric and centimetric scale, and originated S-C structures where the "S" corresponds to the S2 or to the S3 (Fig. 3e). The S-C intersection angle spans from 30° to near 0°, where the S2 become parallel to the C planes, and acts as a shear plane itself.

Helvetic-Ultrahelvetic Domain (HUD) – In this domain, the S3-related folds are usually tight and have induced transposition of the preexisting schistosity in the schistose rocks,

Fig. 5. S-C type shear zone in the lower SCZ. "C" planes drag the S2 foliation with reverse sense of movement (top to NW; top to left in the figure).

where S2 and S3 are commonly sub-parallel and cannot be readily distinguished. At the meso-scale, these folds are both cylindrical and non-cylindrical.

Courmayeur deformation Zone (CDZ) – S2 and Sm are folded by tight, non-cylindrical, drag folds that originated, under plastic deformation regime, a crenulation cleavage here called S3. Especially in the more external sector of the CDZ, S3-related folds develop only at a metric to decametric scale, and their limbs are eliminated by probably coeval shear bands that are pervasive and more diffuse than the coeval S3 cleavages. Thus some sectors of the CDZ consist of C-type shear bands roughly coeval with S3, that cut and drag S2 and Sm and merge into them locally (Fig. 5). This suggests that S2 and Sm have also been reactivated as shear surfaces. The sense of shear indicates NW-directed movements. As in the SCZ, development of S3 is not related to recrystallization processes, but with semi-brittle processes, such as frictional grain reduction and undulatory extinction.

Post-S3 brittle structures

Brittle structures did not develop penetrative cataclastic fabrics, but commonly consist of discrete shear zones and faults, that locally reactivated or displaced the ductile structures (Fig. 6).

The brittle shear zones gave rise to metric or decametric fault breccias and gouges. At the micro-scale, brittle deformations are represented by grain size reduction processes, pressure dissolution and cataclastic flow (Fig. 7).

Brittle shearing originated three types of structural associations:

a) low-angle conjugate brittle shear zones, locally reactivating the S3. These structures reactivated or displaced the ductile shear zones respectively. They are usually related to the development of cataclasites and breccias in the carbonatic covers, and foliated cataclasites in the basement rocks. In a few cases, brittle shear zones are observed in association with open drag folds that deform the S3-related folds.
b) flexural slip folding at all scales, originating box or kink folds, often characterized by spaced axial surface fracture cleavages;
c) high-angle fault systems, mainly left-lateral meso-scale E-W faults and right-lateral NE-SW faults.

Kilometer-scale individual faults also crop out in the SCZ (Pré St. Didier-Mont de Nona) and Mont Chetif. They consist of plurimetric, segmented slip surfaces characterized by only small displacements. Tectonic breccias are usually associated with these faults.

Hydrothermal metasomatic bands occur in some places within the brittlely reactivated plastic shear bands (Fig. 8). Fluorite is associated with the brittle shears along the northern boundary of the CDZ, while post-kinematic micas and sulphides has been observed near the reactivated shear bands of the Mt. Chetif slice. It has not yet been established whether the hydrothermal processes are related to the S3-related semi-brittle deformations or the later reactivation.

3.2. Map-scale structural setting

As already mentioned, the NW-vergent thrust systems (φ1, φ2, φ3) separate the HUD, SCZ and the interposed CDZ units. A SE-vergent thrust (φ4), separates the M. Blanc Massif from the HUD cover (Pl. 1).

The opposing dip of the S2 foliation shown in the NW-SE cross sections of Figure 3 correlates with the opposite dip and

Fig. 6. Tectonic breccia in the Mt.Chetif tectonic slice.

vergence of the thrust systems. The present tectonic setting thus consists of a post-metamorphic doubly-vergent deformation belt, mainly related to S3 tectonics (φ1, φ2, φ3) and post-S3 tectonics (φ4). The S3-related deformation can be compared in HUD, SCZ and CDZ, despite the present thrust dissection.

Syn-S3 structures

In the SCZ the large-scale post-metamorphic geometrical features are mainly controlled by the presence of km-scale NW-verging S3-related antiforms (Pl. 1) whose axes strike approximately NE-SW as deduced from both the meso-scale fold axis measurements and the folded S2-schistosity (Fig. 9i). The axial surfaces and associated cleavages dip toward the SE (Fig. 9l). Reverse limbs of these folds are truncated by semi-brittle reverse shear zones (see 3.1) as indicated by foliation inflections. Where not affected by large-scale S3-related folding the S2 foliation generally dips to SE (Fig. 9h).

In the HUD, there are no evident large-scale S3-related folds, because of the more penetrative character of S3. The dip direction of S3 progressively rotates from SE to NW approaching the Mont Blanc Massif. Metric to decametric S3-related shear bands are locally a pervasive and common feature. Despite the presence of these shear bands, the HUD cover succession has not been included in the CDZ as it is still stratigraphically homogeneous.

The CDZ is a deformed belt that separates the SCZ and HUD and is mainly characterized by diffuse shearing during all the different stages of the tectonic evolution. It has been subdivided into an upper domain and a lower domain separated by the φ2 detachment level associated with gypsum and carnioules. This subdivision is required because S3-related shear surfaces are a very pervasive structural feature inside the lower CDZ, and all the linear elements related to the S2 have been strongly rotated (Fig. 9c), whereas in the upper CDZ the S2 transpositional fabrics are better preserved (Fig. 9b). Since the two sub-domains display lithologies that can be referred to different paleogeographic domains (Pl. 1), the φ2 could be regarded as the PFT in the strict sense.

The strike of the CDZ, as deduced from its map trace, is approximately N60 (Pl. 1), the dip is to the SE at a moderate to high angle. The orientation of the individual shear planes inside the shear zone is rather complex, since differently striking minor planes are present.

In the upper CDZ, the S2 and Sm foliations dip more or less regularly to SSE and the stretching lineation (L2) dips to S (Fig. 9b), as in the SCZ, whereas in the Lower CDZ the dip direction of the Sm locally inflect from S to E, while the associated stretching lineation Lext always strikes roughly E-W (Pl. 1; Fig. 9c).

The upper CDZ consists of several tectonic slices mainly related to the syn-S2 and syn-Sm transposition and mylonitization. Pluri-decametric S3-related shear zones and folds further complicate this geometrical setting. As in the SCZ, these folds have SE-dipping axial surfaces and NE-SW striking axes (Fig. 9e). The S3-related shear zones are local features that develop either along the reverse limbs of the folds or in mica-rich levels, and reactivate or cut S2 at a low angle. S-C structures mainly suggest reverse or oblique shearing along these shear zones.

The southern boundary of the upper CDZ corresponds to the φ1 shear zone, which was reactivated during the S3-related deformations as a detachment level of black micaceous schists.

Inside the lower CDZ, the S3-related shear surfaces merge and diverge from each other at a metric to decametric scale, creating a sort of anastomosing pattern (Fig. 3c; Fig. 3 sections A and B). S3-related folds develop only on a metric to decametric scale, since they are truncated by shear zones, and they have scattered axes orientation (Fig. 9g).

Near the northern and southern boundaries of the lower CDZ the Sm and S3 related shears are roughly parallel with the φ3 and φ2 thrusts, whereas they bend to a N-S direction in the central part of the shear zone (Fig. 9c, 9n).

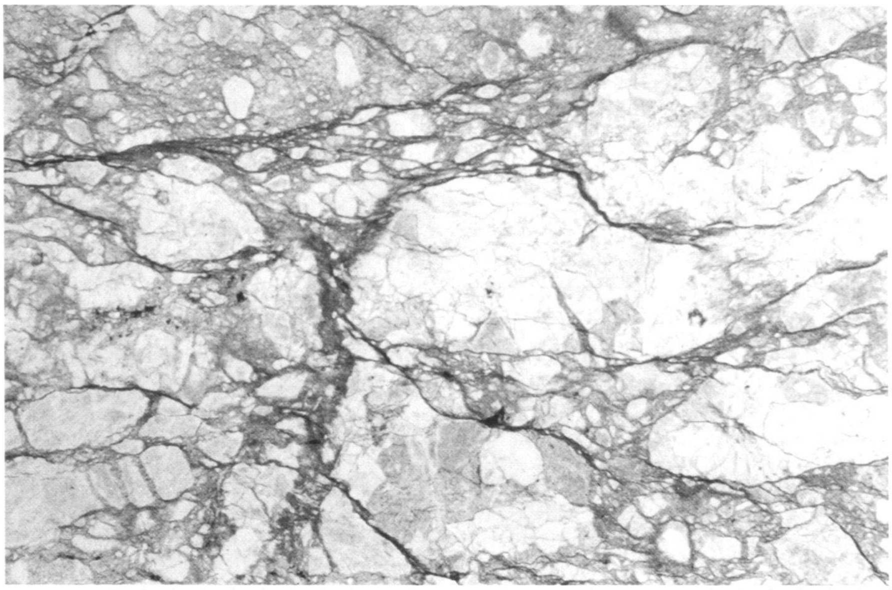

Fig. 7. Cataclasite microtextures on the metagranitoids of the Pavillon thrust zone (20x). Cataclastic flow processes have been developed along mm-spaced shear zones.

Fig. 8. Brittlely reactivated NW-vergent ductile shear zones in the lower CDZ, related to late hydrothermal alteration.

The kinematic indicators on the S3 shears (C surfaces) mainly suggest dextral strike-slip and reverse movements (Fig. 10i). In the central portion of the lower CDZ, where the shear surfaces strike N-S, the sense of movement is mainly reverse, while in sectors where the shear surfaces strike E-W to NE-SW the sense of movement is mainly dextral with local reverse component (Pl. 1).

Post-S3 structures

In the CDZ many semi-brittle S3-related shear zones have been reactivated as brittle mainly reverse shear zones often associated with post-S3 NW-verging drag folds (Fig. 9e, 9o). Brittle tectonics has also given rise to a SE-verging major thrust (Pavillon brittle thrust, φ4) overriding the Mont Blanc crystalline basement onto the HUD cover. The Pavillon thrust corresponds to a belt of foliated cataclasites which separates the Mont Blanc Massif from the HUD cover. The thickness of this belt is of the order of tens of meters. On map scale, the HUD foliations are dragged toward parallelism with the Pavillon thrust and show a progressive rotation from a SE to a NW dip (Fig. 9a).

This thrust has been interpreted by Butler (1985) as a pre-existing normal fault backsteepened to the SE while the S3

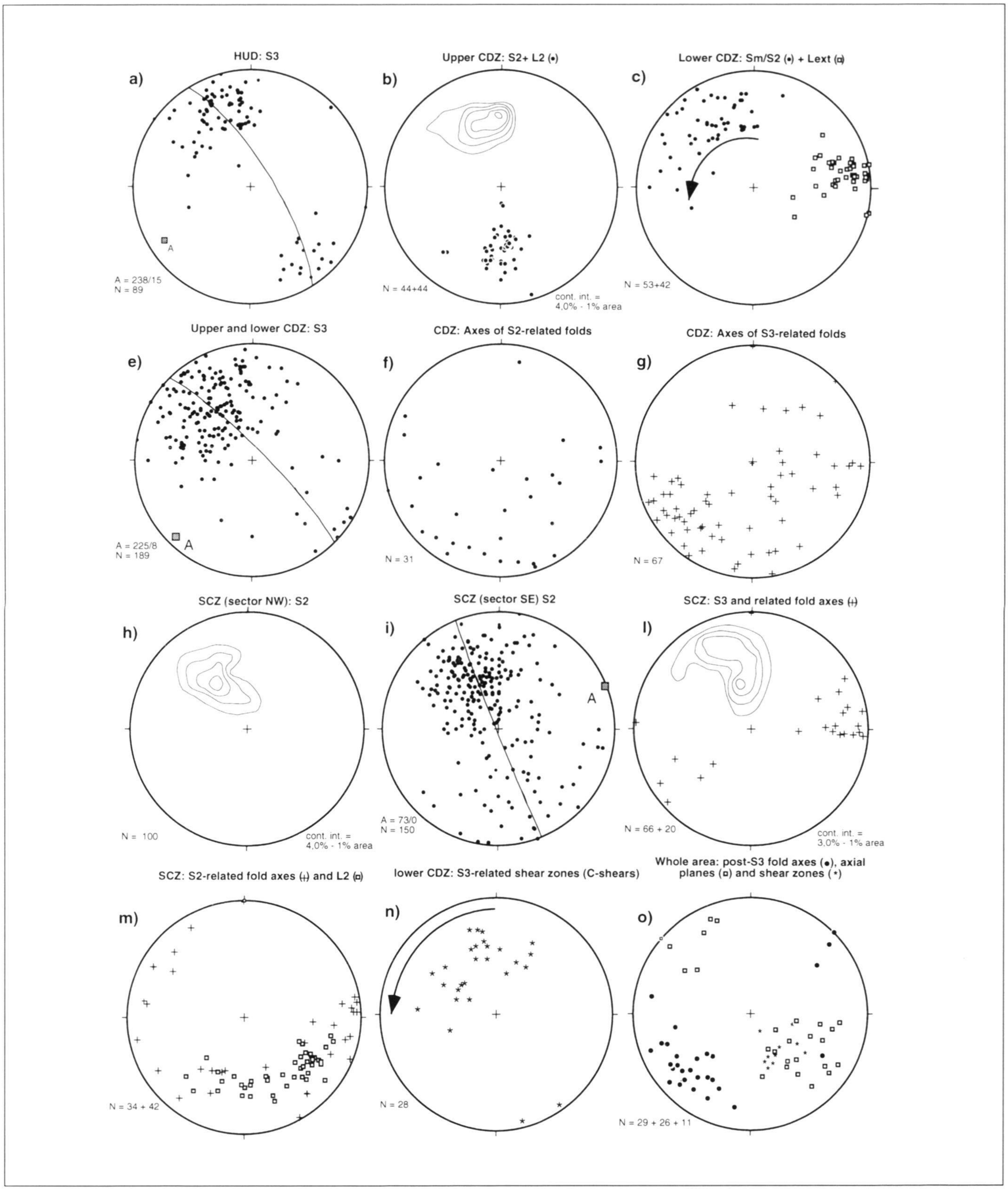

Fig. 9. Lower hemisphere stereographic projection of the structural elements. See text for explanation. N: number of data, A: dip and dip direction of the fold axes calculated from the cylindrical best fit of the foliation poles. In c and n the curve arrows indicate the scattering related to the inflexion of foliations inside the lower CDZ.

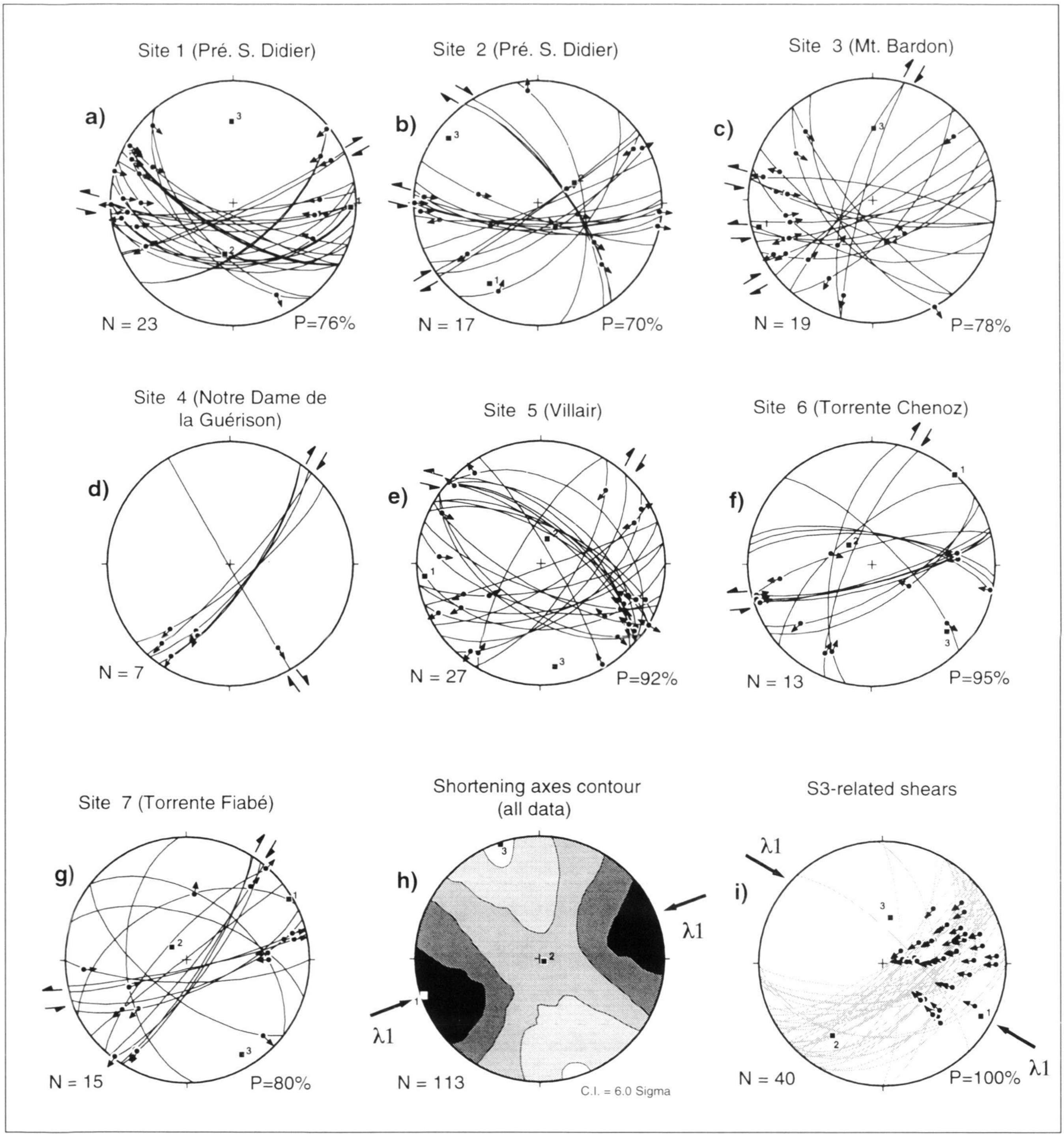

Fig. 10. Lower hemisphere stereographic nets: a–g) Post-S3 faults; h) contour diagram for shortening axes of faults for the whole study area; i) projection of S3-related shear planes with relative slip vectors (arrow). In all nets the arrows indicate the movement of the upper block, 1>2>3: principal shortening axes calculated with the Angelier & Mechler (1977) graphic method, λ1: calculated main shortening direction, N: number of data, P: percentage of data fitting the calculated strain axes.

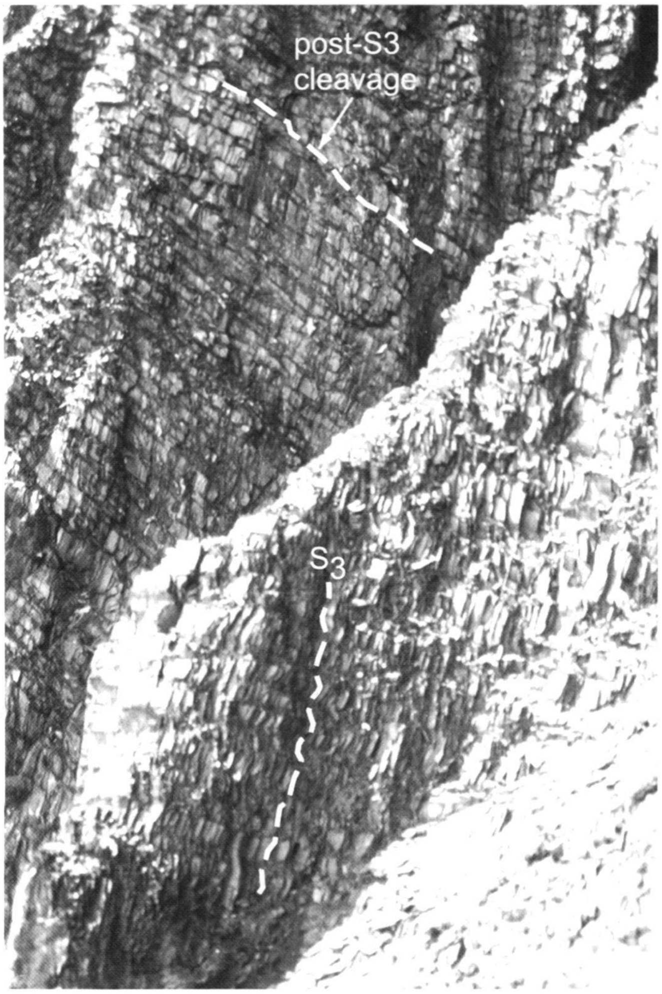

Fig. 11. NW-dipping cataclastic spaced cleavage superimposed on the mylonite rocks of the Mt. Chetif tectonic slice.

foliation was backfolded. At any event, post-S3 contractional tectonics is needed for backfolding of the HUD foliations.

Minor cataclastic NW-dipping shear zones and spaced cleavage (Fig. 9o) crosscutting the S3 have been observed in the HUD near the top of the Mt. de La Saxe (Fig. 11). Dragging of the foliation near these surfaces suggests reverse shearing, also indicated by the presence of SE-verging open folds and kinks (Fig. 9o). NW-dipping cataclastic shear zones have also been described by Bertini et al. (1985) in the southern sector of the Mont Blanc Massif.

The Pavillon thrust and its related brittle structures suggest a NW-SE shortening. Anyway it cannot be extrapolated along the entire contact between the Mont Blanc Massif and the HUD cover, which is poorly exposed. More to the SW (Val Veny) and outside the study area, the same contact corresponds to an earlier ductile shear zone.

The fault slip data sets (Fig. 10a–10g) are instead consistent with local ENE-WSW shortening directions (Fig. 10h). These faults are mostly steeply dipping and have not significantly displaced the structural setting imposed by the earlier ductile and brittle deformations. They could represent a younger kinematic event whose age cannot be assessed, since precise timing constraints are lacking. Even so, these data fit with the regional strain axes inferred from the fault plane solutions of some recent earthquakes in this area (Eva et al. 1998).

4. Discussion

In the Aosta Valley and adjoining regions the PFT is regarded as separating the Sion Courmayeur Zone from the Helvetic-Ultrahelvetic Domain (Argand 1911; 1916; Polino et al. 1990). The structural features of the area examined in this paper suggest that it corresponds indeed to a km-wide deformation belt, here called Courmayeur Deformation Zone, involving different tectono-stratigraphic units. This deformed belt underwent a long deformational history.

Our reconstruction starts from the event which produced the main regional foliation (S2), though structural remnants of older ductile tectonic events are locally preserved. The CDZ is a zone where the effects of the regional shearing were mainly concentrated, starting from the syn-metamorphic S2 and Sm-related deformation. The onset of the S2 regional foliation should be related with the mesoalpine collisional tectonic.

A discontinuous static growth of albite marks the transition between the ductile S2-related deformation and the following semi-brittle events. These latters induced the development of the S3 foliation and are recorded by NW-vergent tight folds and S to SE dipping semi-brittle shear zones that reactivated and/or displaced the syn-metamorphic fabrics. These shear zones mainly developed within the CDZ, they are locally associated with large-scale folds (S3-related structures of the SCZ).

The geometric and kinematic features of the lower CDZ indicate that during the S3-related deformation a strain partitioning occurred between E-W to ENE-WSW striking surfaces accomodating a right lateral to oblique displacement, and NNE-SSW shear surfaces accommodating a reverse displacement. In the lower CDZ the extensional lineation (Lext), associated with S2 and Sm strikes approximately E-W (Fig. 9c), in contrast with their N-S striking in other sectors (Fig. 9m). We interpreted this as the result of rotation of the schistosity and associated lineation induced by the dextral shearing that affected the lower CDZ during the S3-related deformation. The E-W trend of the Lext is in fact consistent with the E-W shearing along the deformation belt. Alternatively, the E-W trend of the Lext could be due to strike-parallel shearing in the lower CDZ during the Sm development. In this case the lower CDZ should have accomodated strike-slip displacement during both the S2- and S3-related deformations. Strain partitioning consistent with roughly NW-SE shortening should have occurred within a transpressive shear zone (CDZ) during the S3- and perhaps the S2-related deformation (Fig. 12).

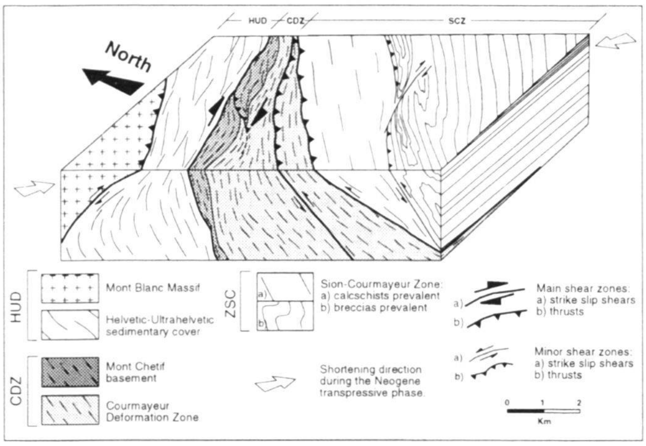

Fig. 12. Schematic block diagram of the study area representing the main structural features related to progressive Neogene transpressive tectonics.

Brittle tectonics is later superimposed on these S3-related structures. The onset of cataclastic deformation does not seem to be related to a change in kinematics of the CDZ and adjoining units. The kinematic indicators demonstrate that the reactivation of the S3-shear surfaces is compatible with continued NW-SE compression. SE-ward back-vergent structures consistent with the NW-SE compression (Pavillon thrust) also developed during this event, probably because the NW-ward propagation of the thrust system was hindered by the Mont Blanc Massif.

We have therefore related these features to a progressive structural evolution from a plastic to frictional deformation in a dextral transpressive context that produced double-vergent shear zones. Strain partitioning occurred within the CDZ since both reverse and dextral shearing, consistent with tectonic transports towards the western quadrants, can be observed.

Our kinematic interpretation should be compared with the distribution of fission track ages reported by Seward & Mancktelow (1994, Fig. 2) which indicates differential uplift across the PFT. They found that neo-Alpine deformations induced the Tortonian-Pliocene uplifting of the Mont Blanc basement and Mt. Chetif slice and related it to the coeval transtensional regime of the PFT in the Mont Blanc region, which is physically linked to the Rhone-Simplon transtensional fault zone.

Our data are instead consistent with exhumation of the Mt. Chetif slices by squeezing or lateral block extrusions within the transpressive CDZ. The Mont Blanc Massif may have been exhumated along φ4-type thrust systems and along the opposing verging thrust systems described by Bertini et al. (1985) at its northern boundary.

Moreover the local transpression along the PFT predicted by Hubbard & Mancktelow (1992) as due to strain partitioning along the Rhone-Simplon Fault, can be seen as consistent with the thrusting and right lateral transpression described in this paper.

5. Concluding Remarks

This work has led to a better understanding of the structural evolution of the Penninic frontal thrust (PFT) across the Aosta Valley traverse.

The post-metamorphic evolution of this major tectonic boundary of the North-Western Alps is mainly related to a continuous right-lateral transpression regime (Fig. 6) that led to the development of progressive deformation concentrated in narrow, strongly deformed belts and characterized by constant NW-SE shortening directions.

This work suggests that this area cannot provide detailed information about the early Alpine structural evolution of the PFT. The metamorphic and paleogeographic break between the Helvetic and Penninic domains here corresponds to a neo-Alpine ductile to brittle shear zone.

The present interpretations identify the PFT as either a large deformed belt interplaced between the Sion-Courmayeur Zone and the Mont Blanc crystalline basement or as a narrower (2–3 kilometers wide) shear zone (Courmayeur deformation zone, CDZ). To the NE, the neo-Alpine CDZ merges with the Rhone-Simplon Fault zone (Fig. 1; Laubscher 1991), which cuts across the Penninic zone, whereas to the SW it probably continues into the Helvetic zone, between the Belledonne and Pelvoux Massifs (Hubbard & Mancktelow 1992). Thus the CDZ-Simplon fault system and the PFT should be considered as two distinct features that locally merge in a single one.

There is thus a need to re-examine the PFT concept itself, since it has been mainly postulated from the sharp tectonic boundary between the Penninic and Helvetic Domains in the Mont Blanc region. For instance, in the Gotthard-Ossola region the transition between Penninic and Helvetic domains does not correspond to any major shear zone or main paleogeographic break, but to a gradual transition from less to more deformed zones with an increasing metamorphic grade from NW to SE (Steck 1990).

Acknowledgments

The Authors are indebted to F. Lamanna for his contribution in the field work, to N. Mancktelow, S.M. Schmid for the accurate revision of the manuscript and to B. Fugenschuh, A. Guermani, R. Polino and G. Venturini for their critical suggestions.

SEA Consulting s.a.s., Torino, is thanked for technical support.

Financial support was provided by Dipartimento di Scienze della Terra, Torino and CNR – Centro di studi sulla geodinamica delle catene collisionali, Torino (dir. R. Polino).

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Manuscript received February 1, 1999
Revision accepted October 10, 1999

Plate 1. Geological map of the studied area.

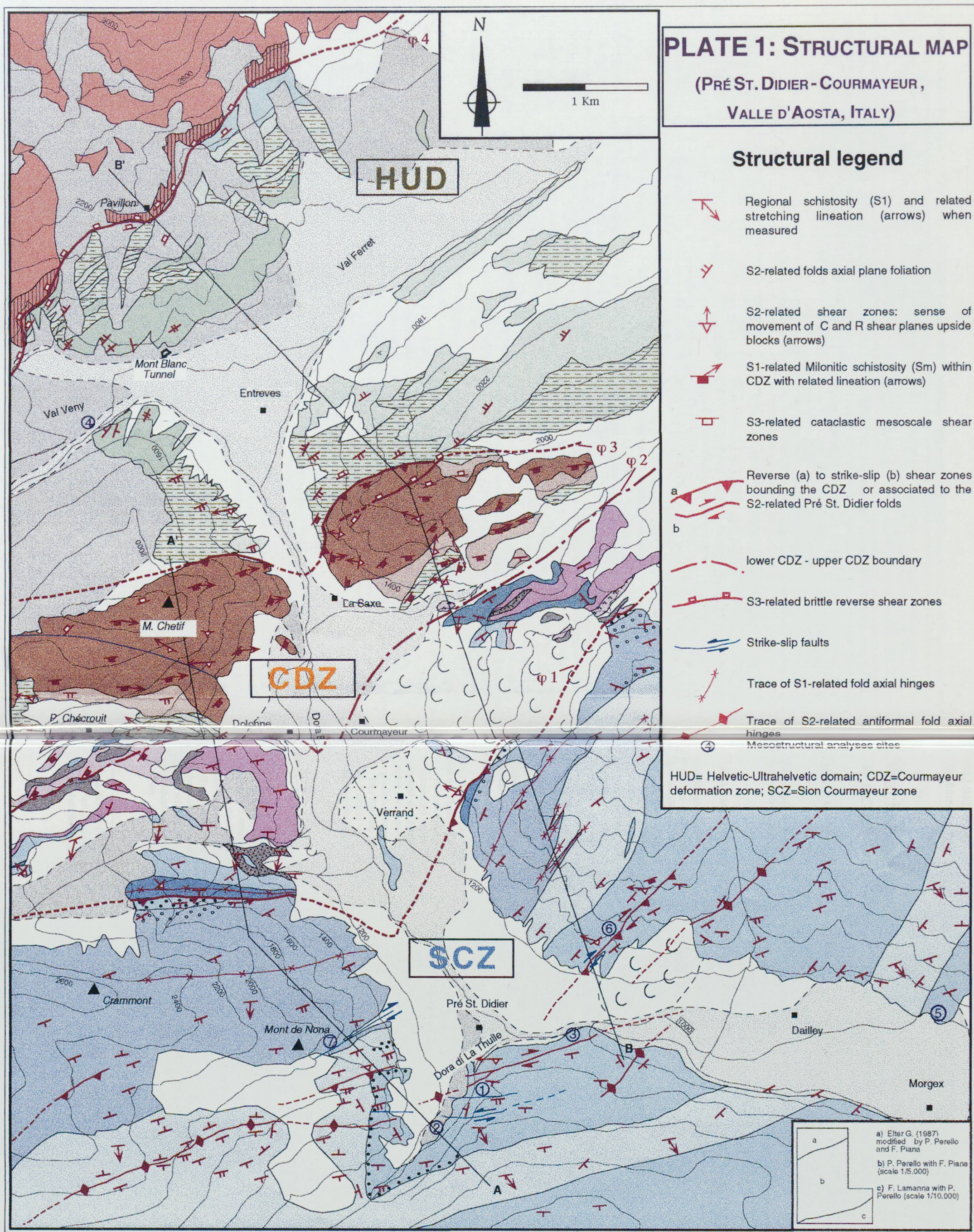

PLATE 1: STRUCTURAL MAP

(PRÉ ST. DIDIER - COURMAYEUR, VALLE D'AOSTA, ITALY)

Structural legend

- Regional schistosity (S1) and related stretching lineation (arrows) when measured
- S2-related folds axial plane foliation
- S2-related shear zones: sense of movement of C and R shear planes upside blocks (arrows)
- S1-related Milonitic schistosity (Sm) within CDZ with related lineation (arrows)
- S3-related cataclastic mesoscale shear zones
- Reverse (a) to strike-slip (b) shear zones bounding the CDZ or associated to the S2-related Pré St. Didier folds
- lower CDZ - upper CDZ boundary
- S3-related brittle reverse shear zones
- Strike-slip faults
- Trace of S1-related fold axial hinges
- Trace of S2-related antiformal fold axial hinges
- Mesostructural analyses sites

HUD= Helvetic-Ultrahelvetic domain; CDZ=Courmayeur deformation zone; SCZ=Sion Courmayeur zone

Lithological Legend

Sion-Courmayeur Zone (SCZ)

- Interbedded detritic marbles and calcschists with minor metaconglomerates layers (dots). (Couches de St. Christophe Auct.; Cretaceous-Paleocene ?)
- Black schists with interbedded quarzitic layers and metamorphic calcareous breccias (dots) (Couches de Marmontains Auct.; Cretaceous?)
- Grey-blue detritic marbles with minor calcschists, commonly interbedded with metaconglomerates and breccias; (Couches de l'Aroley Auct.; Cretaceous ?)
- Black carbonatic-graphitic schists (Serie di Versoyen Auct.; Malm ?)
- Calcschists (Ferret Unit Auct.)
- Calcitic and dolomitic marbles (Trias - Lias ?)
- Gypsum and anhydrites with dolomitic and schist pebbles (Trias?)
- Carbonatic tectonic breccias (Cargneules), often affected by carstic processes inducing the deposition of non metamorphic calcarenites
- Quartzites and conglomeratic quartzites (Permian)
- Graphitic schitsts and microconglomerates (Carboniferous ?)

Helvetic - Ultrahelvetic Domain (HUD)

- Fine-grained marbles with Calpionellae fragments (Dogger-Malm)
- Greyish to blue carbonatic schists (Callovian - Oxfordian ?)
- Dark-gray marbles with interbedded quartzites and quartzitic conglomerates (Bajocian)
- Carbonatic-graphytic schists (Aalenian)
- Grey limestones, locally mylonitized, including Crinoid fragments (Lias ?)
- Mylonitic granites and metarhyolites. (M. Chetif-M. de La Saxe tectonic slices)
- Granites and mylonitic granites (M. Bianco "Protogino" Auct.)
- Cataclastic granites and metagranites

Quaternary depostis

- Detritic and colluvial deposits
- Alluvial deposits
- Landslides
- In situ collapsed rock outcrops
- Glacial tills

Redrawn from original 1:5.000 and 1:10.000-scale geologic maps by P. Perello, F. Lamanna and F. Piana
Structural analyses by P. Perello and F. Piana