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Fold interference pattern at the top of basement domes and apparent vertical extrusion of HP rocks (Ambin and South Vanoise massifs, Western Alps)

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The Ambin and South Vanoise Briançonnais basement domes, located within the HP metamorphic zone, were chosen for a reappraisal of the early tectonic evolution of the Internal Alps in their western segment. Finite strain analyses have shown that HP rocks were exhumed in two main successive stages, more or less expressed according to their structural position in the massifs. A partitioning of deformation, from core to rim of the domes, is thus evidenced. The D₁ stage was roughly coeval with the observed peak metamorphic conditions and corresponds in the core of the Ambin dome, to a non-coaxial regime with dominant horizontal shortening and N to NW movement direction. The D₂ stage, well-expressed in the upper part of the domes, took place under low-blueschist facies conditions and culminated under greenschist facies conditions. It developed a retrogressive foliation and pervasive E-verging shear-zones at all scales that locally define major Φ_2 tectonic contacts. The D₂ shearing is responsible for the development of spectacular F₁–F₂ fold interference structures recognised in the western part of the South Vanoise dome. In this area, we interpret the steeply-dipping HP-fabric (S₁) defining the axial planes of the first generation of now-upright folds (F₁) as linked to an early flat-lying nappe edifice (Φ_1) subsequently steepened by the D₂ shearing. Geometry and kinematic characteristics for the early D₁ nappe-forming event are strongly consistent with most evolutionary models assuming that oceanic to European and Apulian crust-derived nappes were initially exhumed during N to NW-verging overthrusting events, synthetic to the subduction. They tend also to suggest that the Penninic HP-units may have suffered an early exhumation by low-angle thrusting, rather than by vertical extrusion.

Keywords: High-grade rock exhumation; Fold interference pattern; Partitioning of deformation; Western Alps; Penninic domain

1. Introduction

The arcuate orogenic belt of the western Alps is located at the convergent boundary between Europe and the African promontory of Adria. The orogen is commonly regarded as a classic collisional belt representing the closure of one or more ocean basins from the Late Cretaceous to Late Eocene (~90–35 Ma) and the subsequent progressive indentation of Adria into Europe (e.g. Platt et al., 1989). The internal part of the orogen (the ‘Penninic Alps’) consists of a series

of continental terranes (the Austroalpine–Sesia zone, the Briançonnais zone and the Internal Massifs), which are aligned as arcuate ribbons parallel to the strike of the orogen (Fig. 1). These terranes are separated from each other and from the stable foreland by several ophiolitic suture (Piemont, Antrona(?), Valais), which mark the locations of consumed Jurassic to Cretaceous ocean basins (Stampfli et al., 1998; Rosenbaum and Lister, 2005).

Occurrences of high-pressure (HP) and ultra-high-pressure (UHP) rocks in the internal western Alps indicate that during orogenesis rock units were subjected to burial at depths of 40–100 km. HP and/or UHP metamorphism affected each zone within the Penninic Alps at different

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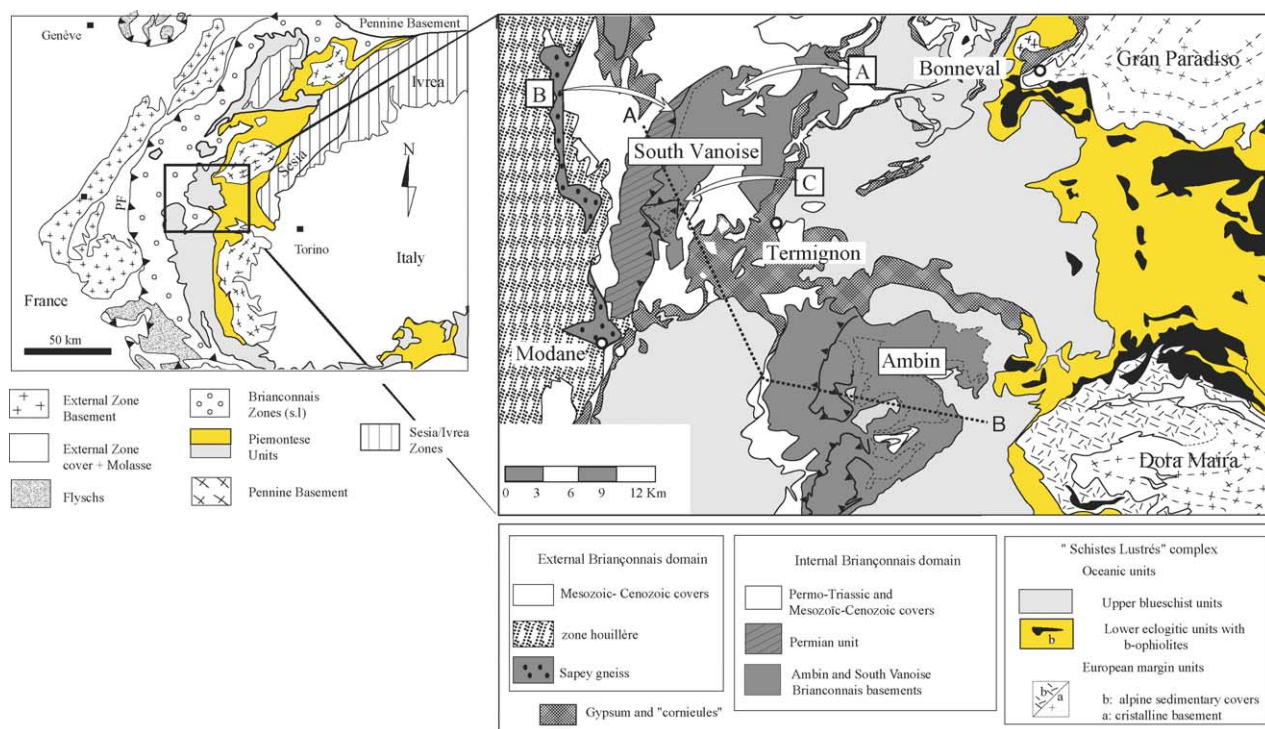


Fig. 1. Geological map of the internal zones of the western Alps showing location of the Ambin and South Vanoise massifs. Thick lines with barbules: E-verging 'backthrusts' discussed in the text: (A) Mont Pelve–Plateau de la Réchasse area; (B) La Valette area; (C) Fond d'Aussois area; PF: Penninic Front.

stages of Alpine orogenesis (e.g. 70–65 Ma in the Sesia Zone, ~44 Ma in the Piemont zone, 45–36 Ma in the Briançonnais, and ~42–35 Ma in the Internal Massifs: Duchêne et al., 1997; Gebauer et al., 1997; Markley et al., 1998; Rubatto, 1998; Rubatto and Gebauer, 1999; Rubatto and Hermann, 2003; Meffan-Main et al., 2004). These ages suggest that Alpine orogeny may have evolved during episodic collisional events associated with accretion of different continental terranes (Lister et al., 2001; Rosenbaum and Lister, 2004). In this tectonic configuration, it is possible that Briançonnais, Piemont and Internal Massifs HP rocks formed as the result of an Eocene–Oligocene accretionary event, and were subsequently rapidly exhumed (Freeman et al., 1997; Rubatto and Hermann, 2001).

These ages tend also to suggest that HP or UHP rocks may have suffered a vertical extrusion—or a fast exhumation of rigid indenters in a softer environment (Allemand and Lardeaux, 1997; Schwartz et al., 2001)—rather than low-angle motion by thrusting (Escher and Beaumont, 1997). In a more general way, the dilemma between supporters of vertical or horizontal related exhumation models result for a large part from the difficulty to infer the geometry of the deep-seated structures at the time of their formation. Structural and microstructural characteristics of the exhumation of the Briançonnais, Piemont and Internal Massifs high pressure rocks, during a complex deformation event globally called D_1 , are still

disputed (Caron, 1974, 1977; Platt et al., 1989; Philippot, 1990; Agard et al., 2001). The kinematic of early deformation in these high pressure domains is poorly known and previous observations are often contradictory (Choukroune et al. (1986) or Platt et al. (1989) for a different interpretation), due to the post- D_1 intense transposition features (Lefèvre and Michard, 1976; Philippot, 1990; Henry et al., 1993; Rolland et al., 2000; Agard et al., 2001; Wheeler et al., 2001; Reddy et al., 2003).

The Ambin and south Vanoise massifs, occupying a key position among the metamorphic units of the Internal Western Alps (Briançonnais and Piemont domains), were chosen as case studies to track the rare traces of this early alpine deformation. They are almost perfect basement domes that preserve HP–LT metamorphic assemblages. The initial geometry and strain regime of the D_1 event, together with associated metamorphic assemblages, were reconstructed in the basement units of the two massifs. This reconstruction will be used for comparison with the available alpine evolutionary models (Stampfli et al., 1998) and to discuss consequences on the knowledge of exhumation processes (e.g. Platt (1993) for a review). This structural study has been undertaken and performed in the light of a recent chemical characterisation of alpine and pre-alpine Briançonnais garnets (Ganne et al., 2003) that led us to re-interpret the garnet-bearing fabric recognised in the core of the domes as linked to an early alpine deformation now defined as D_1 (this study).

2. Geological setting of the Ambin and South Vanoise massifs

The Ambin and South Vanoise basement massifs belong to the Briançonnais Zone, which is interpreted by most workers as palaeogeographically derived from the European passive margin (Lemoine and de Graciansky, 1988) or as an allochthonous terrane (Stampfli, 1993; Bertrand et al., 2000). They form dome-shaped basement windows (Fig. 1) cropping out beneath allochthonous metamorphic envelopes of various origins (Briançonnais Mesozoic units, ocean-derived Liguria–Piemont zone units). Almost parallel envelopes define the domes (Fig. 2a). Structural discontinuities separate lithological groups previously defined by Michel (1957) and Gay (1971). They are, from bottom to top: (1) the Claréa and Ambin Groups forming the pre-Permian basement whose origin and pre-alpine tectono-metamorphic evolution are still poorly known; (2) the Etache Group, considered as Permo-Triassic in age and overlain by metasediments of Triassic to Eocene age; (3) the ‘Schistes Lustrés complex’, consisting of Jurassic to Cretaceous allochthonous metasediments of the Liguria–Piemont zone (Caron, 1977).

3. Structural evolution of the Ambin massif

The petro-structural evolution of the Ambin massif has already been addressed in a previous article (Ganne et al., 2004) and will be used, as a point of reference and comparison, to discuss the tectonic pattern on the Fond d’Aussois area (South Vanoise massif). To simplify the nomenclature and description on Fig. 2b, we have distinguished three main litho-tectonic units within the different envelopes of the Ambin massif, which have been called ‘Nappes’. The latter are separated by major discontinuities, which are thought to have a tectono-metamorphic significance (Ganne et al., 2003). These three nappes are, from bottom to top (Fig. 2c): (1) the Claréa Nappe, consisting only of pre-Permian micaschists (Claréa Group); (2) the Ambin Nappe, consisting of slices of pre-Permian basement (Claréa + Ambin Groups), Permo-Triassic and Triassic to Eocene metasediments; (3) the ‘Schistes Lustrés’ Nappe, consisting only of oceanic metasediments from the Liguria–Piemont basin. This lithostratigraphy has been established on the basis of published work, especially from the Lanslebourg–Mont d’Ambin (Fudral et al., 1994) and Modane (Debelmas et al., 1989) 1/50,000 map sheets.

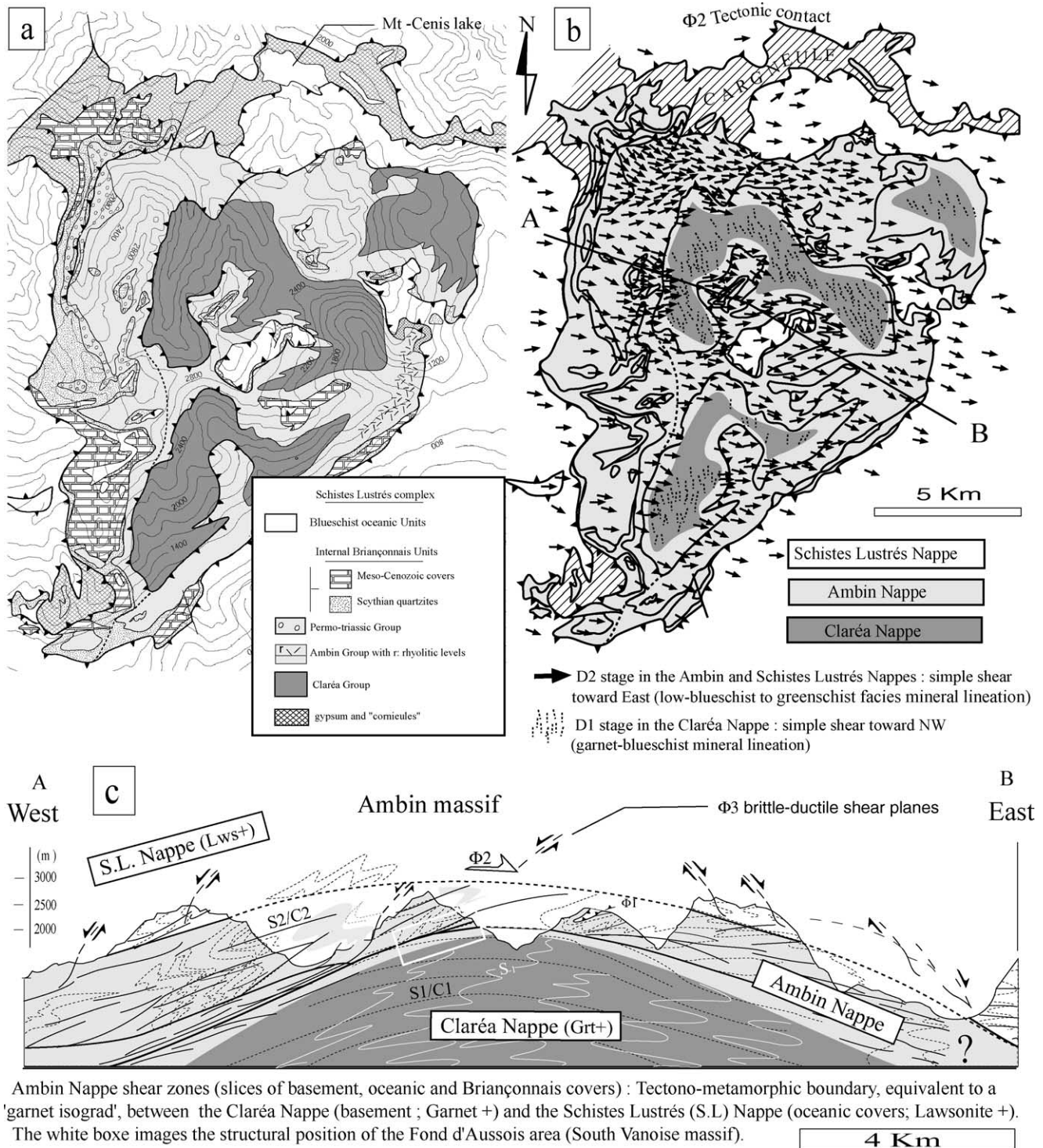
Finite strain analyses have revealed the existence of three ductile to brittle–ductile deformation phases, characterised by specific types and/or vergence of structures. Structural and metamorphic data are presented in terms of ductile D_1 , D_2 and brittle–ductile D_3 events (Fig. 3) for the purpose of comparison with earlier descriptions in adjacent areas. A critical appraisal of this classification is beyond the scope of

this study and is deferred to another paper (Ganne et al., 2004). The most obvious structures recognisable in the Ambin and Schistes Lustrés Nappes are those related to the D_2 (+ D_3) retromorphic deformations. These ductile to brittle–ductile shear events overprint pre-existing fabrics such as S_1 (D_1 event), which is the earliest alpine foliation clearly distinguishable from S_{-1} pre-Alpine fabrics and linked to the HP metamorphic peak (M_1). The D_1 event is well preserved in the Claréa Nappe, i.e. in the deeper part of the Ambin massif. The Claréa Nappe shows little evidence for D_2 deformation.

3.1. D_1 deformation structures in the Claréa Nappe

In the internal western Alps, most kinematic indicators for the early tectonic stages are ambiguous and/or obscured by later reworking (Platt and Lister, 1985a,b; Philippot, 1990; Henry et al., 1993; Michard et al., 1996). In the Ambin and Schistes Lustrés Nappes, the pre- L_2 lineation trend cannot be determined precisely. Refolded fold axes, the most conspicuous feature of a D_1 stage, are nevertheless common (Caron, 1977; Allenbach, 1982). Conversely, most folds observed in the Claréa Nappe (e.g. folds of mafic layers; Fig. 2c), seem to predate the D_2 stage. They correspond to a strong ductile deformation, responsible for the main foliation (Fig. 4a and b). Usually, the main foliation dips gently and follows the overall dome pattern. This fabric overprints an earlier fabric occurring now in microlithons (Fig. 4d). Previous authors (Borghi et al., 1999, and references therein) attributed both fabrics to pre-alpine events. Indeed, in the albite–biotite-bearing micaschists (about 70% of the Claréa Nappe), muscovite and presumed pre-alpine large biotite are similarly present in both fabrics, the growth of blue amphibole (very scarce in the albite–biotite-bearing micaschists) being interpreted as static (Monié, 1990). New observations show that in the Claréa micaschists, multi-stage garnet (Ganne et al., 2003) shows a pre-alpine core and an alpine rim systematically wrapped by the main fabric of the micaschists (Fig. 4c and d). At microscope scale, the clear-cut boundary between the two garnet components is outlined by an inclusion-rim: a very dense concentration of tiny inclusions mainly constituted by quartz, biotite and pre-alpine muscovite. However, newly crystallised alpine minerals such as blue amphibole and phengite also occur in small quantities, associated with older inherited minerals, suggesting that a strong shearing event of alpine age may have occurred under HP conditions when the rims crystallised. This observation strongly suggests that the gently dipping fabric recognised in most of the Claréa Nappe is linked to an early alpine deformation now defined as D_1 (Ganne et al., 2003). The corresponding S_1 fabric is parallel to the axial plane of F_1 folds that deform assumed pre-alpine structures (S_{-1} ; Fig. 4a).

S_1 is defined in the glaucophane-bearing micaschists (about 30% of the Claréa Nappe) by HP minerals (Fe, Ca garnets, Si-rich phengite, chloritoid, glaucophane, jadeite,



Ambin Nappe shear zones (slices of basement, oceanic and Briançonnais covers) : Tectono-metamorphic boundary, equivalent to a 'garnet isograd', between the Claréa Nappe (basement ; Garnet +) and the Schistes Lustrés (S.L) Nappe (oceanic covers; Lawsonite +). The white box images the structural position of the Fond d'Aussois area (South Vanoise massif).

Fig. 2. (a) Geological sketch map of the Ambin massif (see Fig. 1 for location) based on mapping by Gay (1971), modified. (b) Structural map of the Ambin massif (personal data). This consists of three superimposed tectonic nappes: the Claréa, Ambin and Schistes Lustrés Nappes. The upper part of the Ambin massif is affected by a pervasive D_2 shearing event with top-to-the-E movement direction. This D_2 shearing is well expressed in the Ambin Nappe where both oceanic and Briançonnais cover are strongly deformed with slices of basement (Claréa + Ambin Groups). The deeper part of the massif (i.e. the Claréa Nappe), consisting exclusively of the Claréa Group, preserves early HP structures (D_1). (c) E–W structural cross-section through the Ambin massif (see (a) for location) showing the relationships between Claréa, Ambin and Schistes Lustrés Nappes. The litho-tectonic characteristics of the Fond d'Aussois area are similar to those recognised at the Claréa–Ambin Nappes transition, in the Ambin massif (white box): a mixing between scarce slices of Mesozoic covers and dominant imbricated folds of pre-Permian basement (Claréa and Ambin Groups).

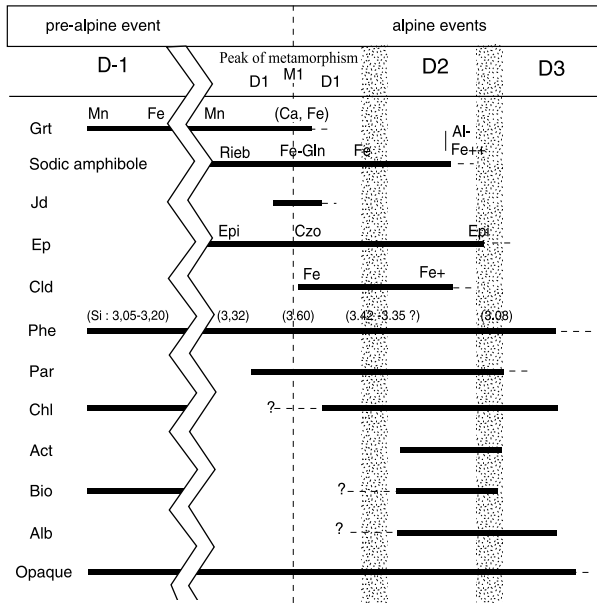


Fig. 3. Crystallisation–deformation relationships in the Ambin massif (alpine and pre-alpine minerals). Grt=garnet; Jd=jadeite; Ep (Epi)=epidote; Phe=phengite; Par=paragonite; Cld=chloritoid; Rieb=riebeckite; Gln=glaucophane; Czo=clinozoisite; Chl=chlorite; Act=actinolite; Bio=biotite; Alb=albite.

paragonite, clinozoisite). Late chloritoid and less-Si substituted phengite are also associated with the S_1 fabric and indicate that decompression occurred during the final stage of D_1 (exhumation process). Glaucophane–phengite \pm chloritoid define a mineral lineation on the S_1 foliation. Its average N–S trend is often scattered by D_2 ($\pm 40^\circ$), especially at the top of the Claréa Nappe. Field observations suggest that F_1 folds correspond to B-type folds (e.g. Ramsay and Huber, 1983) with near-E–W-trending axes but it was impossible to relate the mesoscopic D_1 structures to larger-scale features. D_1 deformation appears non-coaxial in the glaucophane-bearing micaschist as shown by meso- and microscale structures. However, the coexistence of E–W-trending B-type folds and N–S mineral lineations suggests that stretching was not very strong. Several microstructural evidences suggest that the L_1 lineation corresponds to the projection, on the S_1 plane, of the movement direction during a D_1 shearing event: asymmetric boudinage of S_1 ; asymmetric fabrics of phengite, chloritoid and glaucophane wrapped as pressure shadows or strain fringes around garnets (Fig. 4b); rotation of quartz and inherited plagioclase; sigmoid features developed in syn-kinematic garnet; trails of opaque minerals underlining S_1 and refolded during a continuous top-to-the-N shearing event (Ganne et al., 2004); folded inclusions within syn-kinematic glaucophane.

3.2. Ductile D_2 structures in the Ambin and Schistes Lustrés Nappes

The most obvious ductile structures—foliation and

small-scale shear zones aligned by micas—are those related to D_2 . The D_2 stage is characterised by well-developed shear planes (Fig. 2b) and by the gently-dipping S_2 foliation observed in most of the Ambin and Schistes Lustrés Nappes. The corresponding deformation pattern may be described as ductile syn-foliation C_2 – S_2 shear bands (Berthé et al., 1979), which correspond to type-I C–S bands (Lister and Snoke, 1984). The angle between the C_2 and S_2 planes is usually low (typically 10 – 20°). S_2 is either parallel to axial planes of F_2 folds and deforming an earlier S_1 foliation, or corresponds to a composite surface resulting from transposition of S_1 . In the latter case, S_1 is preserved in micro-folds within S_2 -defined microlithons. Mesoscale F_2 folds are mostly observed in the well-layered Claréa Group, at the bottom of the Ambin Nappe (Fig. 2c), whilst the composite foliation and tight isoclinal F_2 folds rather characterise the Ambin Group. F_2 folds deform indifferently the earlier S_0/S_1 fabric and the main tectonic Φ_1 contact, which separates the basement and Mesozoic cover from the Schistes Lustrés (Malavielle, 1982; Fig. 2c). Fold axes are horizontal and N–S- to NW–SE-trending. At all scales penetrative ductile shear zones dip toward W or E according to the general shape of the dome. Shear bands and S_2/C_2 fish-like structures always indicate a top-to-E movement. The Φ_2 tectonic contacts actually correspond to strong concentrations of C_2 – S_2 shear bands (Fig. 2c) together with the appearance of mylonitic fabrics. An E–W mineral and stretching lineation is ubiquitous on C_2 and S_2 planes (Fig. 2b). It is marked by elongated quartz grains or stretched phengite–chlorite–epidote–actinolite fibrous aggregates. At the bottom of the Ambin Nappe, S_2 and L_2 are defined by mixed aggregates of chlorite and actinolite where blue amphibole is often broken. In a few cases, the growth of blue amphibole seems to be contemporaneous with the D_2 stage. Indeed, in the Schistes Lustrés Nappe, blue amphibole together with chloritoid defines a strong lineation in the S_2 foliation, with a remarkably consistent N.100 trend ($< 20^\circ$ spread). The S_2 foliation reworks here an earlier HP–LT alpine fabric (Caron, 1977). Such evidence argues for recrystallisation and/or growth of blue amphibole during D_2 .

3.3. Ductile to brittle D_3 structures in the Ambin and Schistes Lustrés Nappes

D_3 deformation features include large-scale open folds affecting the previous S_2 foliation and a locally developed micaceous crenulation. D_3 is commonly marked in the Schistes Lustrés Nappe by small-scale N–S-trending crenulation-folds overprinting the D_2 structures. In the carbonaceous Briançonnais covers, D_3 is outlined by the crystallisation of quartz–chlorite–phengite and/or calcite veins. Brittle–ductile shear bands (C_3) crosscut the D_2 fabrics at high angle. An E–W-trending stretching lineation is observed on most C_3 planes, marked by small stretched quartz and calcite grains but also by phengite and chlorite. Kinematic indicators—conjugate extensional C_3 shear

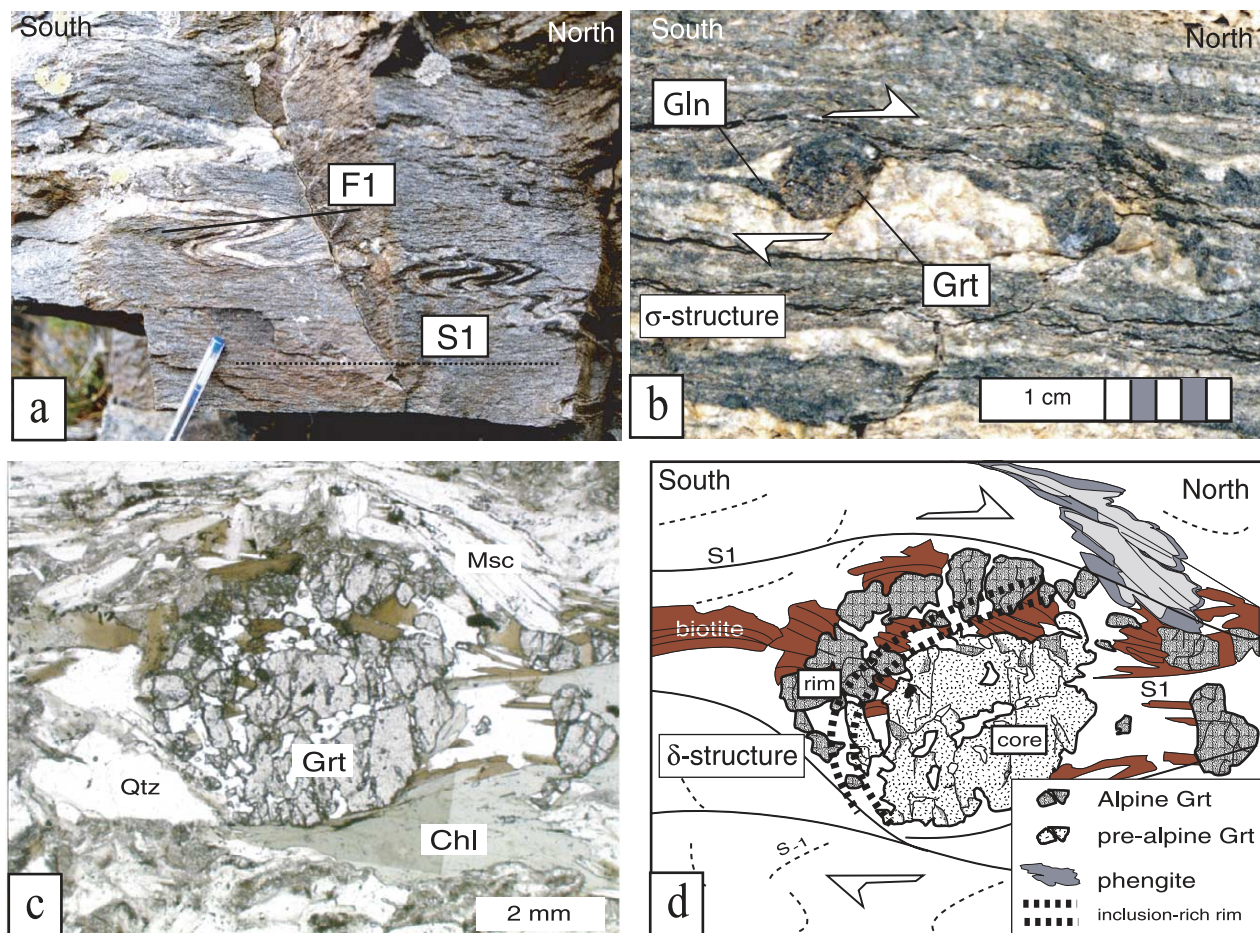


Fig. 4. D₁ deformation structures in the Claréa Group. (a) Pre-alpine mineral foliation of biotite (dark bands)—muscovite–quartz refolded by alpine F₁ fold; alpine HP mineral assemblage grows in the S₁ axial planar foliation (albite–biotite-bearing micaschists). (b) Alpine syn-kinematic garnet (Grt) surrounded by HP minerals forming a strain fringe of glaucophane (Gln) ± chloritoid ± phengite (glaucophane-bearing micaschists). (c) and (d) Textural relations between alpine rim and pre-alpine cores of garnet (sample Ga-22, Ambin massif). The inclusion-poor garnet core is fragmented during the D₁ north-verging simple shear deformation regime and wrapped by the main alpine fabric (S₁). Inclusion-rich rims of alpine garnets and high-Si substituted phengites grow at the expense of the pre-alpine clasts, forming a strain fringe. Relics of muscovites (Msc), outlining the pre-alpine foliation (S₋₁), are marginally replaced by phengite. Chl: chlorite; Qtz: quartz. Note the microstructural difference between the σ-structure on (b) and δ-structure on (d).

bands, symmetric micro-boudinage of pre-D₃ crystals of poihiloblastic albite, deformed vertical veins—point to an overall-coaxial deformation. Along the western edge of the Ambin dome, extensional C₃/Φ₃ shear planes preferentially indicate a top-to-the-W movement whilst east of the dome, the C₃/Φ₃ shear planes preferentially are top-to-the-E (Fig. 2c). This feature clearly indicates that the dome structure was formed during the D₃ stage.

4. Structural evolution of the South Vanoise massif: insights from the Fond d’Aussois area

The structural setting of the South Vanoise massif is mainly controlled by an E-verging shear deformation (classically called ‘backthrusting’ by different authors, e.g. Platt and Lister, 1985a,b) which produced a complex stack

of large-scale tectonic slices. Thus, the *Fond d’Aussois* area (‘C’ in Figs. 1 and 5) shows the superposition of three main tectonic slices delimited by shear zones (Fig. 6).

The ‘Fond d’Aussois’ shear zone, which has a W–NW shallow-dipping appearance, cross-cuts basement units and Briançonnais cover and individualizes two slices:

- (i) A lower slice mainly constituted of paleozoic basement units (Claréa and Ambin Groups), associated with a few thinned shreds of mesozoic covers (Permo-Triassic to Triassic located at the north of the *Plan d’Amont* dam). The lower part of this slice is unknown.
- (ii) A medium slice in which are mixed, from west to east, basement units, Triassic cover units and Liassic units belonging to the ‘Dent Parrachée nappe’ (Platt et al., 1989). This latter consists of Norian to Eocene sediments (Deville, 1987). The Fond d’Aussois shear zone extends further to the east, in the *Fournache*

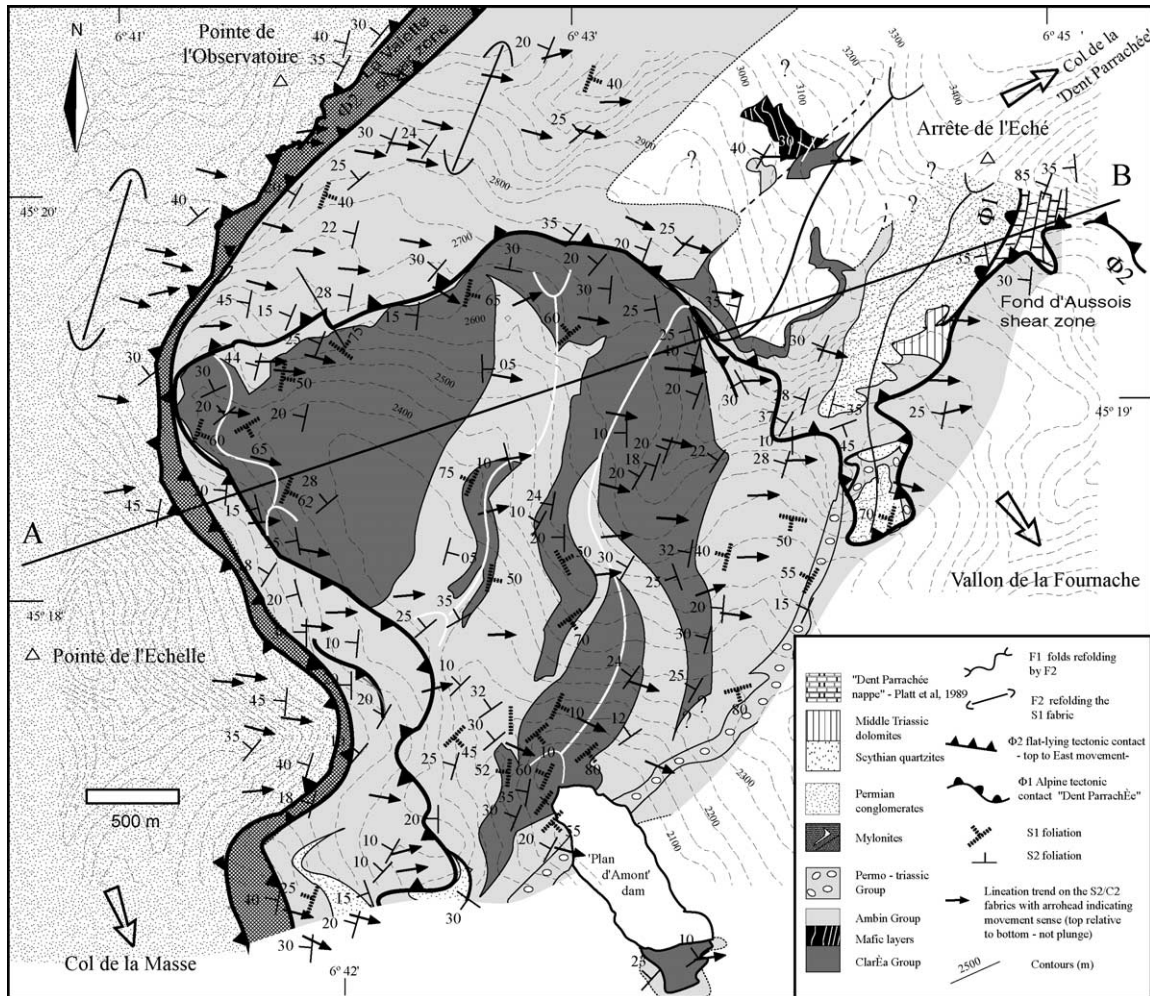


Fig. 5. Geological map of the Fond d'Aussois area; location: 'C' in Fig. 1.

valley, cropping out below the Scythian quartzites of l'Arrête de l'Eché (Fig. 5).

The 'La Valette' shear zone corresponds to the 'thrust' (Platt et al., 1989) of *La Pointe de l'Echelle-Rateau d'Aussois* (upper slice exclusively constituted by conglomeratic Permian) at the top of the medium slice. This 'thrust' is accommodated by a thick level (1~3 m) of chlorito-albitic schists (corresponding probably to mylonites of basement) that can be followed from the *Col de la Masse* in the south, to the *Col de la Valette-Col du Tambour* (Fig. 7) in the north, through the *Col du Génepy*. This mylonitic contact outlines the limit of extension toward the east of the conglomeratic Permian of Vanoise (Fig. 8), so-called 'Permien du col d'Aussois' (Ellenberger, 1958; Détraz and Loubat, 1984). The 'La Valette' shear zone extends geometrically above the carbonaceous level of the *Dent Parrachée*. Its prolongation toward the east (or of one of its ramifications) probably passes below the important tectonic pile of the *Mont Pelve-Plateau de la Réchasse* quartzites ('A' in Fig. 1) and Liassic calcareous levels of *La Grande Casse* (work in progress).

4.1. D_1 and D_2 ductile stages

Thus, the tectonic pattern of the Fond d'Aussois area is comparable to the lower part of the Ambin Nappe, defined in the Ambin massif (Fig. 2c): a complex litho-tectonic interface in which scarce slices of Mesozoic covers are mixed with imbricated folds of pre-Permian basement (Fig. 6). The two main ductile stages of deformation, D_1 and D_2 , previously described in the Ambin Nappe, have been recognized in the slices of Fond d'Aussois. The expression and style of structures is strongly dependent on the nature of the rocks.

The Claréa Group is marked by a penetrative and non-coaxial D_1 deformation, syn-metamorphic to crystallisation of alpine garnet (helicitic growth of this latter). The steeply-dipping S_1 foliation is outlined by elongated crystals of glaucophane and chloritoid, between which occur grains of clinozoisite, jadeite or sphène (Fig. 9a). Fibres of phengite have crystallised parallel to glaucophane and chloritoid crystals, sometimes at the expenses of pre-alpine muscovites reworked in the S_1 foliation (Fig. 9b). Pre-alpine fabric is badly preserved: S_{-1} is commonly observed

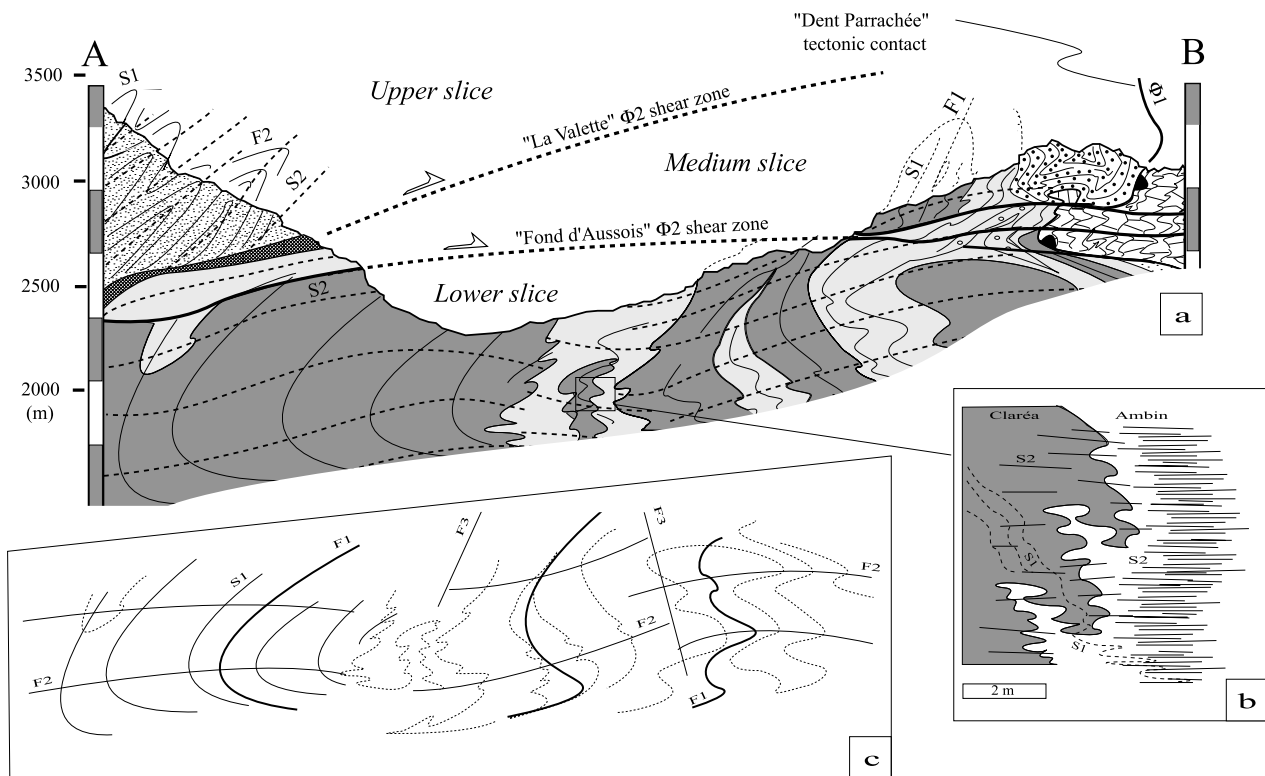


Fig. 6. Geological cross-section through the Fond d'Aussois area showing the stacking of three main slices (upper, medium and lower slices). Claréa and Ambin Groups do not follow a regular dome structure but are implicated in imbricate large-scale F_1 isoclinal folds (steeply-dipping axial plans and associated S_1 fabric), which predate the main S_2 foliation (Fig. 5b). F_1 – F_2 interference patterns (Fig. 5c) are easily recognisable on map (see Fig. 4). Two major Φ_2 tectonic contacts have been mapped: (1) the 'Valette' shear-zone separates the basement from an overlying tectonic unit comprising a possible equivalent of the Etache group stratigraphically overlain by a thick Permian conglomerate formation (Pointe de l'Echelle, Rateau d'Aussois). (2) The 'Fond d'Aussois' shear zone cuts through the upright F_1 folds. The footwall of the 'Fond d'Aussois' shear-zone is marked by a mesoscale F_2 fold. The F_2 fold is characterised by the growth of glaucophane + chloritoid in its axial plan. The early D_1 'Dent Parrachée nappe', constituted by Liassic formations, tectonically overlies the eastern flank of the basement and attached discontinuous lenses of Triassic quartzites and dolomites. This latter contact is intensely folded by D_2 (the flat-lying S_2 being axial planar to these folds) and carried toward the east by the 'Fond d'Aussois' shear zone.

in microlithons between S_1 plans (Fig. 9d), outlined by muscovite or brown biotite, sometimes by pseudomorphs of staurolite. The early S_1 alpine foliation is parallel to early Φ_1 tectonic features including the contact between the 'Dent Parrachée nappe' and the Scythian quartzites of l'Arête de l'Eché (Fig. 5). It corresponds also to the axial plane of F_1 upright folds, of metre to kilometre scale, transposing the Claréa–Ambin Group contact (Fig. 6a). The axial direction of the F_1 folds is scattered between N.160 and N.35, as shown by the cartography of the Claréa–Ambin Group contact in the lowest slice of Fond d'Aussois (Fig. 5). Such scattering is the result of interference between the F_1 and F_2 folds (Fig. 6c).

The D_2 deformation is strongly expressed in the Ambin Group (Fig. 6c), developing, at all scales of observation, S_2/C_2 shear fabrics in the axial plane of F_2 sub-horizontal isoclinal folds. The S_1 foliation, outlined by fibres of phengite, is badly preserved in microlithons between the S_2/C_2 planar fabric. The L_2 lineation on S_2/C_2 planes indicates a direction of movement toward the ESE (Fig. 5). It consists of stretched quartz aggregates or the greenschist-facies mineral association chlorite–phengite \pm chloritoid.

This D_2 deformation is locally concentrated in shear-zones, of metre to decametre scale ('Fond d'Aussois' and 'La Valette' Φ_2 shear zones). The operation of both shear zones during the D_2 shear event seems to have occurred at different structural levels and metamorphic conditions:

- the operation of the 'Fond d'Aussois' shear zone is contemporaneous with the formation of the intra-slice large-scale fold structures. The fold of 'Fond d'Aussois', outcropping in the lowest slice of the Fond d'Aussois area (Figs. 5 and 10), is one of the most spectacular examples of D_1 – D_2 interference structure recognised in the Ambin and South Vanoise massifs. This upright fold, consisting of a core of Claréa Group, corresponds originally to the hinge of a F_1 fold that has subsequently been turned back and sheared at its top by the operation of the 'Fond d'Aussois' shear zone. The S_2/C_2 fabric, badly expressed in this core of Claréa micaschist, is defined by a discrete alignment of glaucophane, chlorite, phengite and chloritoid in the axial plane of open F_2 folds transposing the S_1 foliation (Fig. 9). The L_2 mineral lineation, carried by the S_2/C_2 fabric, is marked by

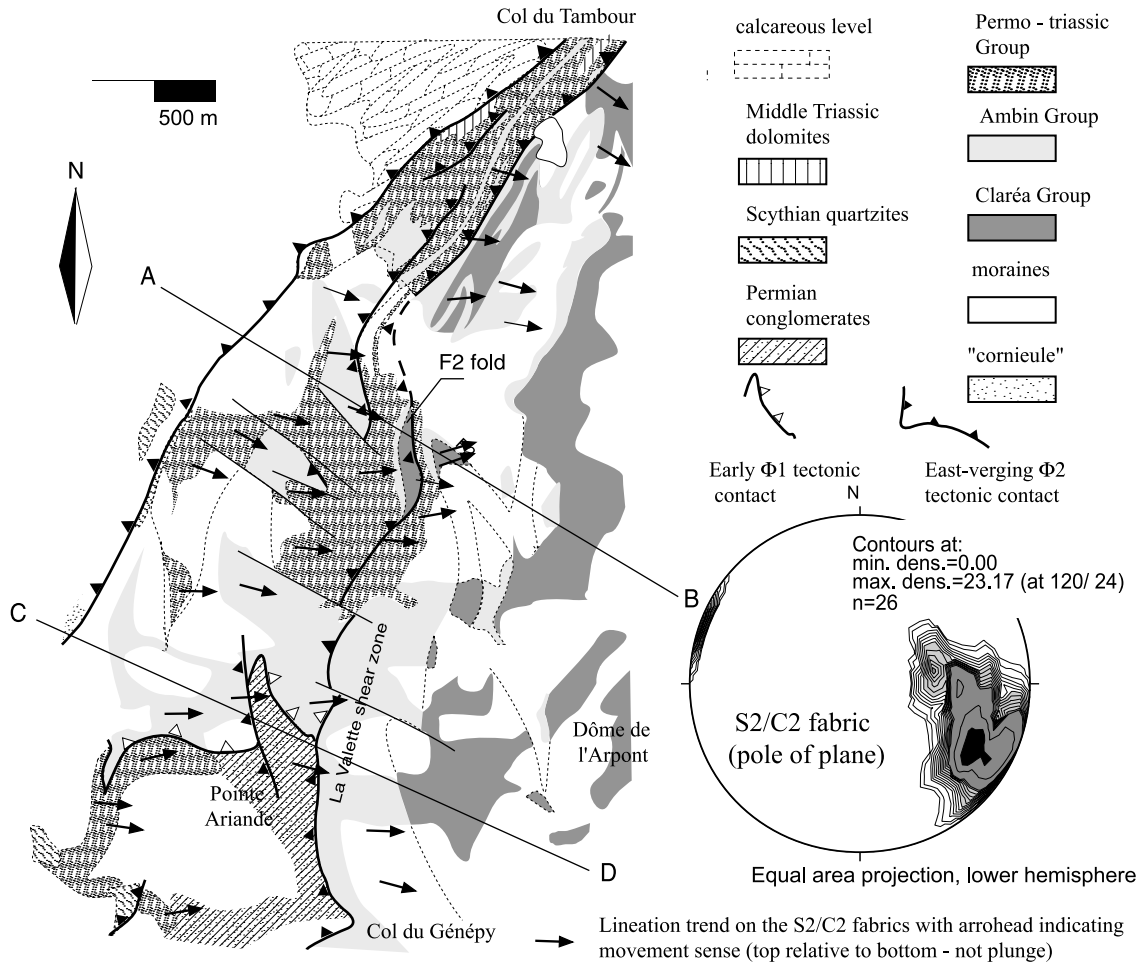


Fig. 7. Geological map of the La Valette area; location: 'C' in Fig. 1. The D_3 doming of the south Vanoise massif has steepened the S_2/C_2 fabrics, which at present dips steeply west. The interference pattern between F_1 and F_2 folds, not easily recognisable on map, is shown on A–B and C–D cross-sections (see Fig. 8). Note the F_2 fold cross-cut by the 'La Valette' shear zone.

glaucophane–chloritoid and phengite growing in N.095 orientation. The 'Fond d'Aussois' shear zone can be considered as an early D_2 shear zone, syn-metamorphic during crystallisation of glaucophane.

- the operation of the 'La Valette' shear zone post-dates the formation of the intra-slice large-scale fold structures. The stretched limbs of the F_2 isoclinal folds, defined in the upper slice of Fond d'Aussois by regular alternations between carbonaceous and conglomeratic levels, are cut by the shear zone. This is consistent with structural observations carried out more to the north, in the *La Valette* area (Fig. 1B), where the 'La Valette' shear zone cross-cuts a F_2 fold consisting of a core of Claréa Group (Figs. 7 and 8). Chemical compositions of phengites that crystallised in the 'La Valette' shear zone indicate pressures lower than for the 'Fond d'Aussois' shear zone (the complete dataset can be downloaded on http://tel.ccsd.cnrs.fr/documents/archives0/00/00/69/44/index_fr.html). The 'La Valette' shear zone can be considered as a late D_2 shear zone, formed under greenschist-facies conditions. The retrograde

metamorphic assemblage, carried by the D_2 shear fabrics (blueschist to greenschist facies), obviously reflects a post- D_1 exhumation process.

4.2. Ductile to brittle D_3 stage

A late, post- D_2 event, deforms the tectonic pile of Fond d'Aussois. It consists of large-scale undulations deforming Φ_2 shear zones and S_2/C_2 fabrics (Fig. 10). Normal brittle–ductile faults are locally associated with this plicative deformation, as well as a crenulation or solution cleavage (S_3), which increases progressively in the south part of the massif (*Plan d'Avaldam*, La Fournache valley, 'nappe des cornieules'; Fig. 11). Pre-existing D_2 structures exhibit a staircase geometry: alternation between sub-horizontal, or shallowly SE-dipping steps, and steeply-dipping jumps associated with an intense S_3 crenulation. Close to *Termignon*, D_2 structures are straightened out to the vertical, and disappear below the gypsum formation of the *Arc* valley. A roll-over of D_2 structure at the footwall and hanging-wall of the brittle *Arc* fault is strongly suspected to

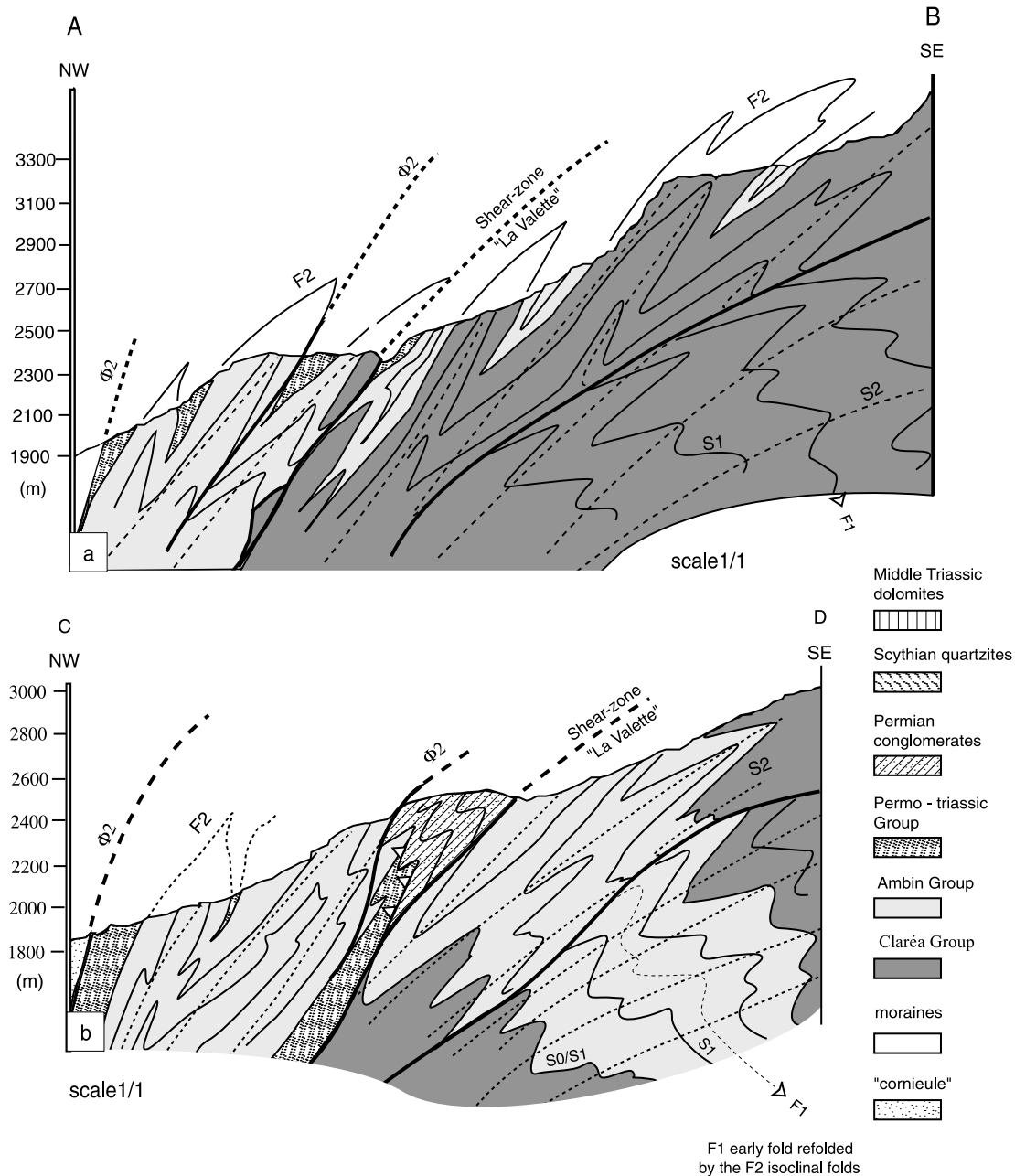


Fig. 8. E-W geological cross-sections through the La Valette area, showing F_1 - F_2 fold interference. The repetition of thin levels of Ambin microconglomerates within the massive metapelitic Claréa Group (cross-section A-B) can be explained by interference between pre-existing large-scale F_1 folds (fan-shaped edifice of F_1 folds shown on Fig. 10) and E-verging F_2 recumbent folds affecting the limbs of the F_1 folds (cross-section C-D).

explain the doming of the Ambin and south Vanoise massifs (work in progress).

5. Discussion

5.1. Tectonic evolution of the basement domes

Structural investigations carried out in parallel in the Ambin and South Vanoise massifs appear strongly consistent. They yield a coherent tectonic pattern resulting from D_2

deformation partitioning and differences in preservation of D_1 structure, that have been clearly evidenced between the core and the rim of the Ambin dome.

5.1.1. D_2 partitioning of deformation

From top to bottom of the tectonic piles, a clear structural layering was thus observed (Fig. 12): (i) S_2 and D_2 - to D_3 -related shear bands are dominant in the Schistes Lustrés Nappe surrounding the domes. (ii) S_2 is superimposed on a well-preserved S_1 in the Ambin Nappe (Briançonnais cover slices + pre-Permian slices of Ambin and Claréa Groups

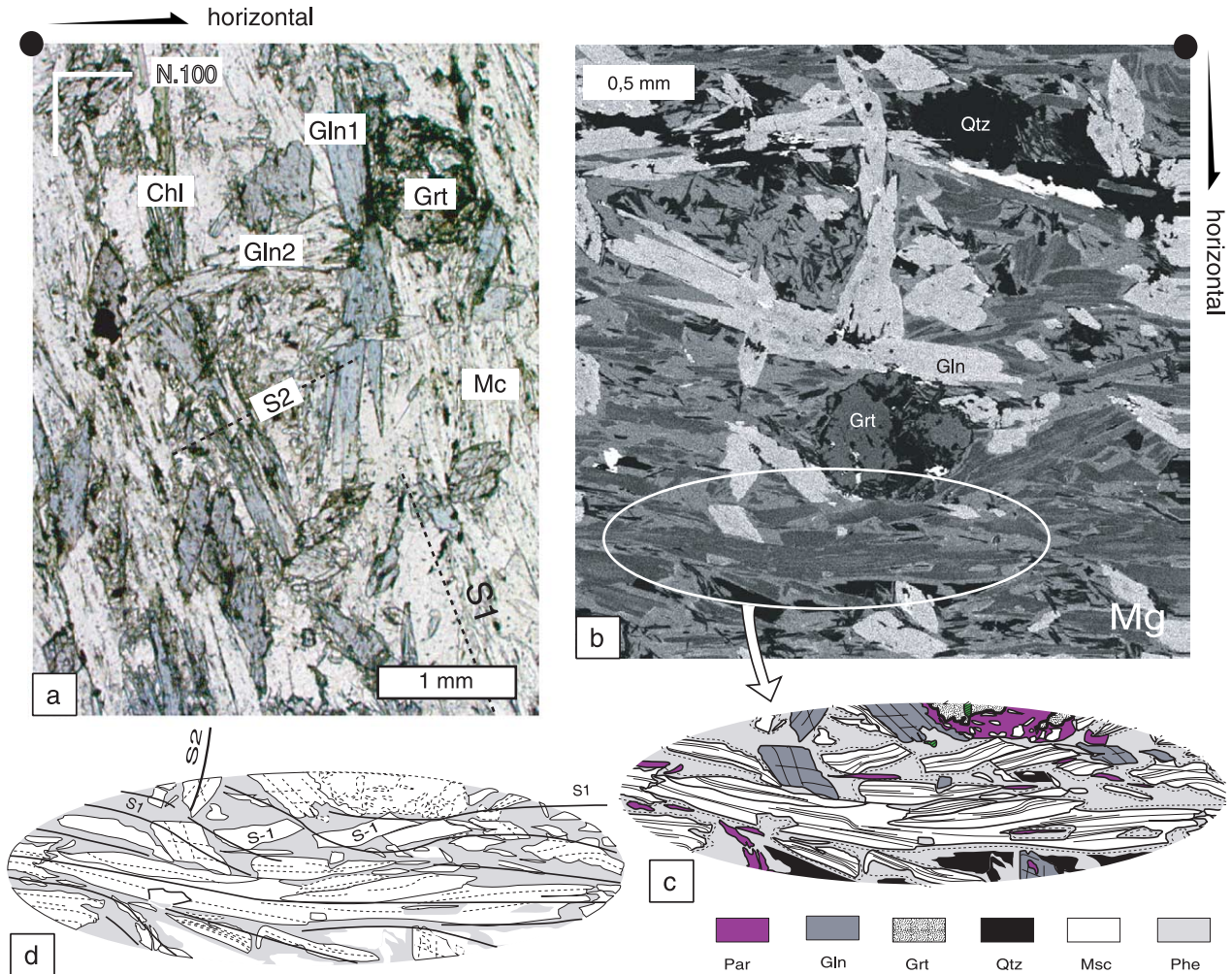


Fig. 9. Distribution of Fe-glaucophane in the same thin section (sample Ga-78: glaucophane-bearing micaschist sampled in the footwall of the 'Fond d'Aussois' shear-zone, South Vanoise massif). (a) Microphotographs showing the relationship between the discrete S_2 fabric (blueschist assemblages with glaucophane, phengite, paragonite, \pm chloritoid, \pm chlorite, \pm clinozoisite, \pm jadeite). (b) X-ray map of microphotograph a: relative content of magnesium (Mg) varying from low (dark) to high (white); note that Gln1 and Gln2 are indistinguishable on X-ray maps (same composition). Grt: alpine garnet, Gln1: D_1 -related glaucophane, Gln2: D_2 -related glaucophane, Chl: chlorite, Msc: inherited muscovite, Mc: mixing between high-P alpine phengites and destabilised inherited muscovite, Qtz: quartz. (c) and (d) Sketch detailing the microstructural and mineralogical relationships between the S_{-1} pre-alpine fabric, badly preserved in microlithons, and the pervasive S_1 alpine fabric. Note that the pre-alpine muscovites (Msc), outlining the S_{-1} fabric, are destabilised at their expense by alpine phengite (Phe) and paragonite (Par). The complete chemical dataset can be downloaded by readers using the following URL address: http://tel.ccsd.cnrs.fr/documents/archives/00/00/69/44/index_fr.html.

mixed together). S_2 is dominant in the upper part of the Ambin Nappe defined in the Ambin massif, leading to an almost complete transposition, together with Φ_2 shear zones. S_2 is less pervasive at the bottom of the Ambin Nappe studied in the Fond d'Aussois area, leading to an incomplete transposition of the D_1 fabric between the Φ_2 shear zones (spectacular D_1 - D_2 interference features). It is during D_2 deformation that the F_1 folds of the Fond d'Aussois area are straightened out to the vertical and sheared. The D_2 E-verging simple shear is locally concentrated in shear-zones formed under blueschist ('Fond d'Aussois' shear zone) to greenschist-facies conditions ('La Valette' shear zone). (iii) The gently dipping foliation that occurs in the very core of the Ambin dome

formed by the Claréa Nappe was interpreted as a penetrative alpine S_1 fabric with characteristic HP mineral assemblages that grades upward to D_1 - D_2 interference features.

5.1.2. Geometry and kinematics of the early D_1 alpine tectonic contacts

D_1 is the earliest alpine ductile deformation recognised so far in the field. It is well preserved in the deepest part of the Ambin massif (i.e. the Claréa Nappe) whereas in the overlying units (i.e. the Schistes Lustrés and Ambin Nappes) a more or less complete transposition occurred during D_2 . D_2 shearing, strongly expressed at the top of the domes, grades downward to large-scale D_1 - D_2 interference features characterising the tectonic pattern of the Fond

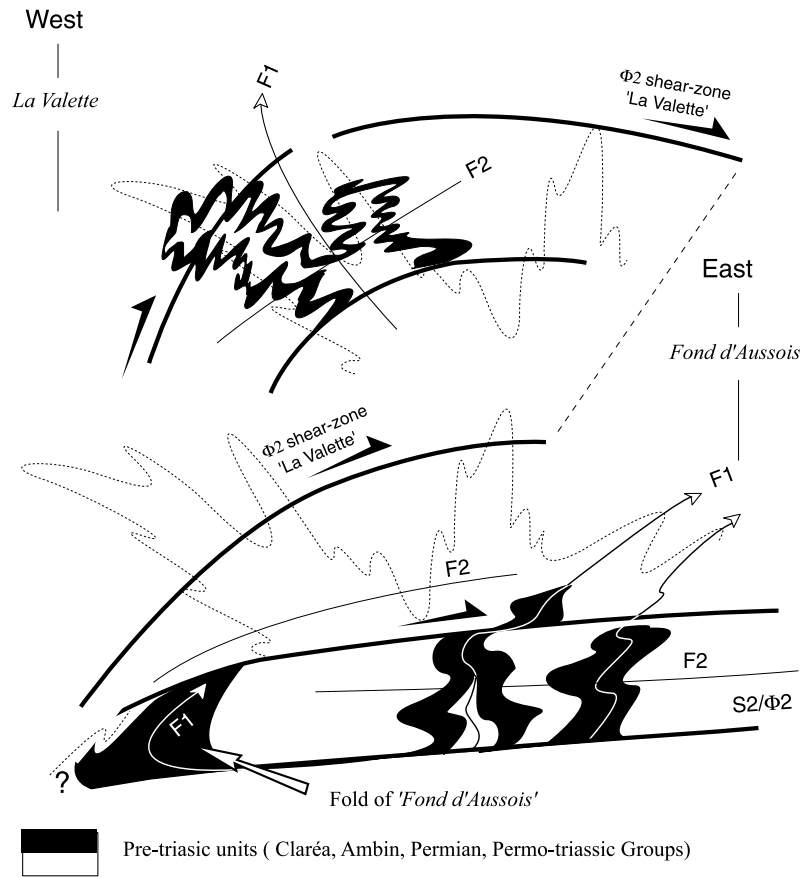


Fig. 10. Summary of structural information, collected in the western part of the South Vanoise massif, across two synthetic E–W geological cross-sections (La Valette and Fond d’Aussois areas). A D_1 -related fan shaped edifice of F_1 folds can be imaged. Such geometry could be interpreted, in first approximation, as resulting from a vertical tectonic process. It corresponds in fact to a flat-lying nappe- and folds edifice, which has been subsequently steepened by D_2 shearing and then weakly fanned out by D_3 doming. Note that in both areas, D_2 shearing is responsible for the development of spectacular F_1 – F_2 fold interference patterns, including the ‘Fond d’Aussois’ fold discussed in the text.

d’Aussois area. Exposure conditions of the deepest parts of the South Vanoise massif (i.e. the equivalent of the Claréa Nappe in the Ambin massif) do not allow recognition of the original flat-lying geometry of the D_1 nappe edifice as in the Fond d’Aussois area. This early geometry has been inferred from the deepest part of the Ambin massif, which preserves HP–LT structures related to a D_1 event forming horizontal nappes. D_1 in the Claréa Nappe corresponds to a non-coaxial deformation with a dominant near-horizontal N–S component. The N–S component is suggested by the L_1 lineation. This direction is similar to that observed in the less metamorphosed external units of the north Penninic domain (Baudin et al., 1993; Ceriani et al., 2001) and consistent with slip vectors deduced from geodynamic reconstruction (Platt et al., 1989).

5.2. Toward a model of exhumation for alpine HP-rocks

Can we interpret and fit field observations of early D_1 fabrics, presented at the scale of the Ambin and South Vanoise massifs, into a general model for exhumation of HP-rocks? Several mechanisms have already been proposed

in the literature to explain the exhumation of alpine high pressure units (for review see Platt (1993)): erosion and isostatic adjustment (Ernst, 1971; England and Richardson, 1977); tectonic denudation without lithospheric delamination (Merle and Ballèvre, 1992; Avigad et al., 1993; Michard et al., 1993), corner flow circulation within the accretionary wedge (Cowan and Shilling, 1978; Cloos, 1982; Platt, 1986), crustal extrusion related to indentation during convergence (Merle and Guillier, 1989), or forced return flow along the Benioff plane (Dal Piaz et al., 1972; Michard et al., 1993). For the deepest and most important part of the exhumation trajectory, Duchêne et al. (1997) have shown that the chronology of the retrogressive metamorphism excludes gravitational collapse as the major exhumation mechanism. According to the same authors, material balance and structural arguments also exclude isostatically assisted erosion processes. Subduction dynamics and tectonically assisted erosion are the most likely mechanisms accounting for the exhumation. Isostasy-assisted erosion and shallow-level extension are nevertheless required to eventually bring the high-pressure rocks to the exposure. In the Alpine collisional belt, geological,

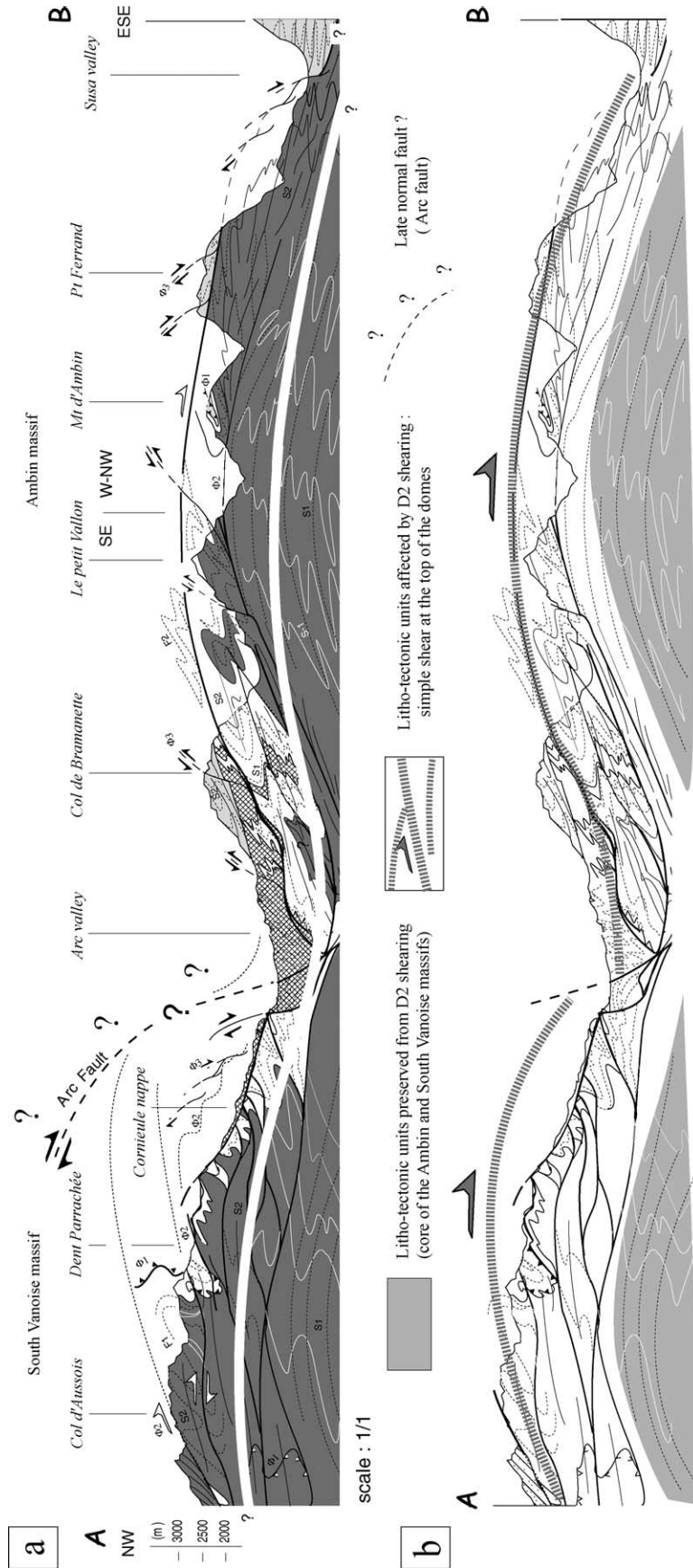


Fig. 1. Summary of structural information across geological (a) and schematic (b) cross-sections through the western Alpine internal zones. Tectonic symbols (Φ_1 , Φ_2 , S_1 , S_2 , F_1 , F_2) are given in the text. An E-verging (post HP) shearing deformation, the D_2 stage, is responsible for the main structural pattern observed in both basement and cover units of the Ambin and South Vanoise massifs (geological information is given in Fig. 1). Syn-metamorphic deformation occurred under low blueschist conditions (glaucophane–chloritoid assemblage) down to greenschist facies conditions (chlorite–albite assemblage). (b) A N to NW verging, syn-garnet–blueschist facies deformation stage is poorly preserved in the upper units but well-preserved in the core of the Ambin and probably also South Vanoise massifs. The so-defined D_1 stage corresponds to the pressure and temperature peak (garnet–jadeite assemblage).

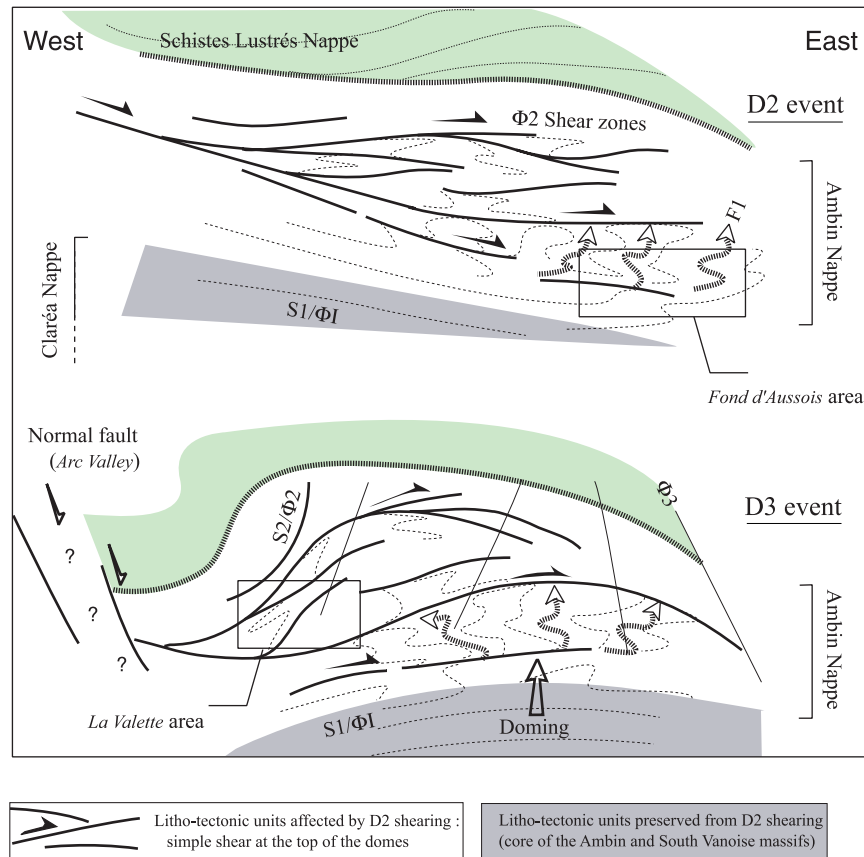


Fig. 12. Synthetic sketch to explain the doming of the Ambin and south Vanoise massifs by roll-over on both side of the Arc valley. The extensional geometry of D_2 fabrics before D_3 doming is discussed in previous papers (Ganne et al., 2003; 2004). Note that D_2 shearing decreases downward in the core of the massifs (bottom of the Ambin Nappe), leading to the development of spectacular D_1 – D_2 interference features. At the western part of the South Vanoise massif (Fond d'Aussois area; Fig. 4), the D_1 – D_2 interference features are outlined by the Ambin and Claréa Group contacts and are easily recognisable. This is not the case in the western part of the Ambin massif where the contact between the Ambin and Claréa Group is sheared by D_2 (see Fig. 2a).

petrological and chronological evidences indicate that HP–LT metamorphic rocks have been generated in the subduction zone which existed before the collisional event (see Dal Piaz and Lombardo (1986), Polino et al. (1990) or Pognante (1991) for reviews). From these data, two main models have been developed and numerically explored in which blueschist and eclogite facies rocks were formed then exhumed while subduction of oceanic lithosphere was still active.

5.2.1. Low-angle thrusting synthetic to the subducted plate

The most classic model showing the effects of both simple shear and pure shear during simultaneous underplating of the lithosphere and exhumation of the upper crust (Fig. 13a) has been proposed for the Alps by Escher and Beaumont (1997). These authors take up and elaborate the model of Eparard and Escher (1996) to give a geometrical and mechanical explanation for the initiation and subsequent exhumation and stacking of basement nappes. Their model is based on several geological factors and previously published ideas. An essential consideration is that originally deep basement

rocks displayed a penetrative early foliation and stretching lineation, implying strong deformation throughout most of the rock volume. The model of Escher and Beaumont for the Alps resembles that of Chemenda et al. (1995) inasmuch as they also suggest that a slice of upper continental crust is detached at the front of the subducted lithosphere and that this slab moves back to the surface while the rest of the lithosphere continues to be subducted. The mechanism of ascent is, however, different as it is proposed that buoyancy forces and erosion only assist the process but are not the dominant factor. Instead it is proposed, similarly to the channel flow model, that exhumation of the detached crustal slab is the result of combined simple shear and pure shear. In other words, once a crustal slab is detached from the subducting lithosphere, further descent of this slab is hindered at a certain point and these now high-grade rocks are then flattened through pure shear between the two converging plates. The flattening of the slab implies a decrease in thickness and an increase in length. The additional length cannot be accommodated downwards and the slab is thus laterally expelled or 'squeezed out' to the surface.

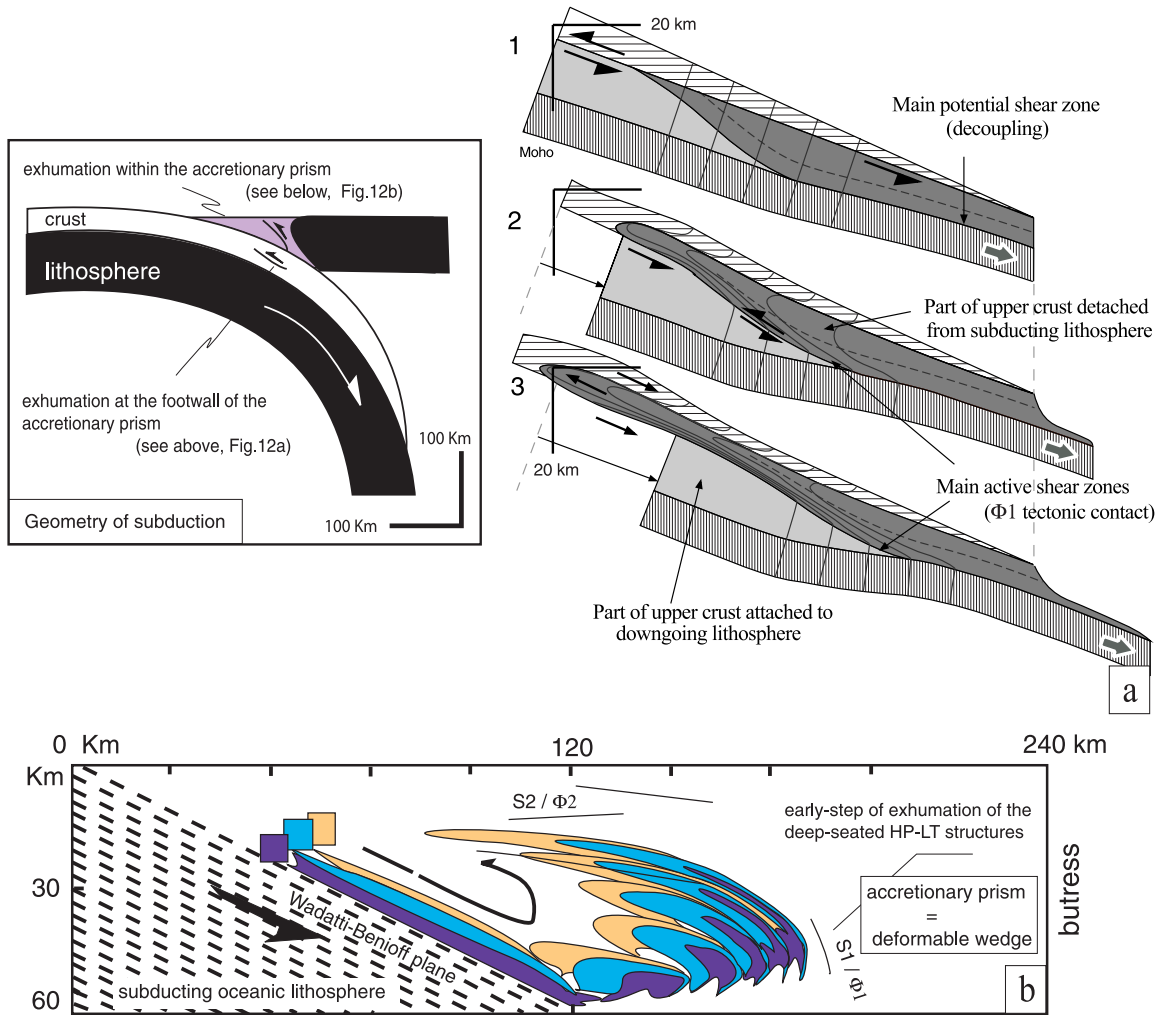


Fig. 13. Dynamic of subduction and mechanism for exhumation of alpine HP-rocks. (a) Near-horizontal thrusting synthetic to the subducted plate. Two-dimensional reconstruction showing the geometric consequence of combined simple and pure shear in a system envisaged to have generated the extrusion of nappe in the Alps (s.s.). Stage 1 is similar to stage 1 in the model of Chemenda et al. (1995). Also in this model, Escher and Beaumont (1997) propose that buoyancy forces assist the oblique escape of deep-seated material but are not considered as the dominant factor. (b) Geometry, parameter and mechanism of the corner flow model (Cloos, 1982), numerically explored by Allemand and Lardeaux (1997), modified. The different stages of deformation as well as the geometry of structures associated (deep-seated S_1 foliation, early Φ_1 slices, late flat-lying S_2 fabric and Φ_2 shear-zones) are predicted by the numerical model.

5.2.2. Vertical extrusion induced by the dynamics of the prism

Another popular model assumes that rocks are buried then uplifted within an accretionary prism overlying the subduction zone (Fig. 13b). The corner flow model has been proposed by Cowan and Shilling (1978) and numerically explored by Cloos (1982) and then Allemand and Lardeaux (1997) to discuss its application to the internal part of the Alps, taking into account the metamorphic, structural and geochronological data. Both analogue and numerical models show that prisms are affected by internal deformation. The flow pattern is sustained by the continuing subduction and is limited by the hanging wall, which acts as a rigid buttress (Platt, 1986), or induces channel flow in a small angle wedge (Cloos, 1982). Prism mechanisms seem to represent an efficient way of uplifting rocks trapped as

fragments of oceanic and continental crust. They differ from the previous mechanisms by: (1) the existence of very strong velocity gradients, which allows rocks metamorphosed at different pressure conditions to be brought in contact; (2) the capability of prisms to operate at a steady state. As the shape of the prism is controlled by equilibrium between tectonic forces, progressive underplating must be compensated by either erosion or near-surface extension (Davis et al., 1983; Platt, 1986). The characteristic time of the exhumation is scaled by the subduction rate and should be in the order of a few million years (Cloos, 1982; Allemand and Lardeaux, 1997). Early exhumation of eclogite and blueschist facies rocks, most probably while subduction is still active, is expected (Platt, 1986). To portray the strain partitioning related to this velocity field the evolution of the shape of an initial circular object has

been studied by the authors. This object behaves as a passive marker that in cross-section has the surface of an Alpine nappe scaled to the model. The exhumation phase begins by the development of a 'head' in the internal part of the wedge and of a 'tail', which remains attached at the base of the wedge. The development of the 'head' results from the decrease of the horizontal component of the velocity and the increase of the vertical component of the velocity at the base of the wedge. The associated fabric would be vertical. When the head finally enters the extensional field (0 to ~15 km), it becomes progressively elongated. The associated fabric would be horizontal. This evolution is independent from the initial shape of the object. From a metamorphic point of view, each phase will overprint the pre-existing structure, and relics of structure will thus not be interpretable in terms of kinematics at the scale of the outcrop.

5.2.3. Summary

Spatial and kinematic variations of fabric orientation predicted by both models provide key elements for understanding the overall deformation history of the western Penninic domain. Despite the different mechanisms involved in exhumation, the models yield a fundamental result, strongly consistent with our structural data. The early steps of exhumation of HP-rocks will develop a strongly penetrative and non-coaxial deformation, corresponding to the D₁ event in the Ambin and South Vanoise massifs. The major difference is in the geometry and in the preservation of this D₁-related HP-fabric. The corner flow model predicts a reworking of the deep-seated steeply-dipping slices subsequent to their vertical extrusion. Conversely, the model of Escher and Beaumont (1997) assumes low-angle forethrusting for the initiation and subsequent exhumation and stacking of basement nappes.

Field data, performed in the core of the Ambin and South Vanoise domes, led us to favour Escher and Beaumont's (1997) model as the best candidate accounting for the development and preservation of flat-lying HP-nappes. However, it must be kept in mind that our choice is strongly dependant on the numerical result of Allemand and Lardeaux (1997), which shows that during the exhumation processes, the deep-seated slices will preferentially undergo an obliteration of their steeply-dipping fabric rather than a gentle tilting into a horizontal position. New computing of corner flow circulation, taking into account the difference in rheology between units and their variations of density and viscosity with depth, should therefore be tested.

6. Conclusion

Data and field observations of early HP-LT horizontal structures and a related nappe-forming event, presented at the scale of the Ambin and South Vanoise massifs, are still difficult to interpret and to fit with certainty into a general

model. There are still too few constraints, in the western Penninic domain, on the initial geometry of the slices of continental and oceanic crust formed during the early alpine steps of exhumation, and that might be compared with our D₁ HP-nappes. In the more internal units of the western Penninic domain (e.g. Gran Paradiso), the corresponding D₁ kinematics (or equivalent according to authors) become highly hypothetical and previous observations are often totally contradictory (Choukroune et al. (1986) or Platt et al. (1989) for different interpretations), due to the post-D₁ intense transposition features (Lefèvre and Michard, 1976; Philippot, 1990; Henry et al., 1993; Rolland et al., 2000; Agard et al., 2001; Wheeler et al., 2001; Reddy et al., 2003). Despite the lack of other critical examples to corroborate our assumption, we propose to regard the geometric and kinematic characteristics of the Ambin and South Vanoise HP-nappes as representative of the early alpine steps of exhumation in the western transect of the Alpine chain (s.s.). Our assumption strongly relies on the now well-constrained geometry and kinematics of the north Penninic nappes (Baudin et al., 1993; Ceriani et al., 2001). The non-coaxial and flat-lying HP-structures observed in the core of the Ambin massif suggest that they were probably acquired during the ascent path, along a gently dipping slope. We may therefore speculate that the early steps of HP-rocks exhumation induced some kind of flat-lying nappes with an overall N to NW-directed movement, as classically advocated in previous models (e.g. Escher and Beaumont, 1997), rather than protracted extrusion of vertical (or fan-shaped) slices (Allemand and Lardeaux, 1997).

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