Late-stage deformation in a collisional orogen (Western Alps): nappe refolding, back-thrusting or normal faulting?

Stefan Bucher, Stefan M. Schmid, Romain Bousquet and Bernhard Fügenschuh
Department of Earth Sciences, Basel University, Bernoullistr. 32, CH-4056 Basel, Switzerland

ABSTRACT

Nappe refolding, back-thrusting and normal faulting frequently cause severe late-stage overprinting of the architecture of an orogen. A combined investigation of nappe stack polarity, kinematics of shearing and metamorphic gradients in the Western Alps develops criteria for distinguishing between these three modes of late-stage deformation. This distinction is a prerequisite for any retro-deformation necessary for understanding the main tectonic and metamorphic evolution of collisional orogens. In the case of the Western Alps overprint was by mega-scale nappe refolding in the Oligocene. This implies exhumation of the HP-rocks prior to postnappe folding, i.e. during nappe stacking and by foreland-directed ascent within a subduction channel.

Terra Nova, 15, 109–117, 2003

Introduction

Retro-deformation of the latest stages of deformation is a prerequisite for unraveling the main stages of the tectonic and metamorphic evolution of an orogen (Dewey, 1988; Platt *et al.*, 1989; Escher *et al.*, 1993; Alsop *et al.*, 2001). Such late-stage deformation may severely modify pre-existing large-scale structural and metamorphic patterns, preferentially within the more internal and metamorphic parts of the pre-existing nappe stack (Müller, 1983). Similar structures related to late-stage deformation are also observed and may also be discussed in a similar way outside the Western Alps: the Brooks Range in Alaska (Vogl, 2002), the Hercynian orogen in SW England and Spain (Coward and McClay, 1983 and Macaya *et al.*, 1991) or the Canadian Cordillera (Brown *et al.*, 1986) are several examples.

The Alps result from the collision of the European plate, with the Apulian plate, in Tertiary times (Argand, 1916; Schmid *et al.*, 1996). For large parts of the Western Alps (Fig. 1), and along the so-called ECORS-CROP seismic traverse (Roure *et al.*, 1996), all major nappe contacts and foliations are hinterland- (i.e. SE-) dipping (Fig. 2a). Yet, from the Gran Paradiso massif to some 30 km further to the north-west, foliations and major tectonic contacts are foreland- (i.e. NW-) dipping. Three mechanisms, illustrated in Fig. 2(b)–(d), have so far been proposed to produce this corridor of foreland-dipping foliations. These are: (i) hinterland-verging thrusting or 'back-thrusting' (Butler and Freeman, 1996); (ii) normal faulting, 'collapse' or hinterland-directed 'extrusion' structures (Caby, 1996); and (iii) large-scale refolding of previously stacked nappes, referred to as 'nappe refolding' (Milnes *et al.*, 1981).

Correspondence: Stefan Bucher, Department of Earth Sciences, Basel University, Bernoullistr. 32, CH-4056 Basel, Switzerland. E-mail: stefan.bucher@unibas.ch

Criteria to distinguish between back-thrusting, normal faulting and nappe refolding

Nappe stack polarity and palaeogeography

During foreland- (in the case of the Alps NW-) directed nappe stacking, palaeogeographically more internal units are emplaced over palaeogeographically more external units. Such 'in-sequence' thrusting is well preserved at the north-west front of the Alpine orogen. There the Dauphinois unit is overthrusted by the Valaisan unit (Frisch, 1979; Froitzheim *et al.*, 1996), the latter being overridden by the Briançonnais units (Fig. 2a). More internally, however, a foreland-dipping tectonic contact of uncertain origin (enigmatic tectonic contact 'ETC' in Fig. 2a) separates the Briançonnais units from the still more internal Piemont–Liguria unit. The latter, finally, overlies the Gran Paradiso massif, attributed to the most internal parts of the Briançonnais microcontinent by most workers (e.g. Stampfli, 1993).

Later modifications by back-thrusting or normal faulting (Fig. 2b–c) create new fault zones, which postdate nappe stacking. These fault zones separate two blocks with normal nappe stack polarity, except for very local overturning above the ETC in case of back-thrusting. In contrast, nappe refolding leads to an overturned nappe stack within the overturned limbs of mega-folds, and older fault zones related to nappe stacking are preserved (Fig. 2d).

Back-thrusting and nappe refolding (Fig. 2b–d) are compatible with the palaeogeographical zonation and NW-directed nappe stacking of the Alps outlined above. However, the more internal position of the Briançonnais with respect to the Piemont–Liguria ocean invokes either normal faulting (assuming earlier NW-directed nappe stacking) or 'SE-directed' nappe stacking (assuming the palaeogeographical zonation given above) (Fig. 2c), associated with NW-directed subduction.

Sense of shearing

In the case of back-thrusting, the sense of shear observed along and in the vicinity of the back-thrust will be hinterland-directed (Fig. 2b). Nappe refolding around an axis perpendicular to the direction of early nappe transport will preserve the foreland-directed sense of shearing related to former nappe stacking (Fig. 2d). Interestingly, this sense of shearing,

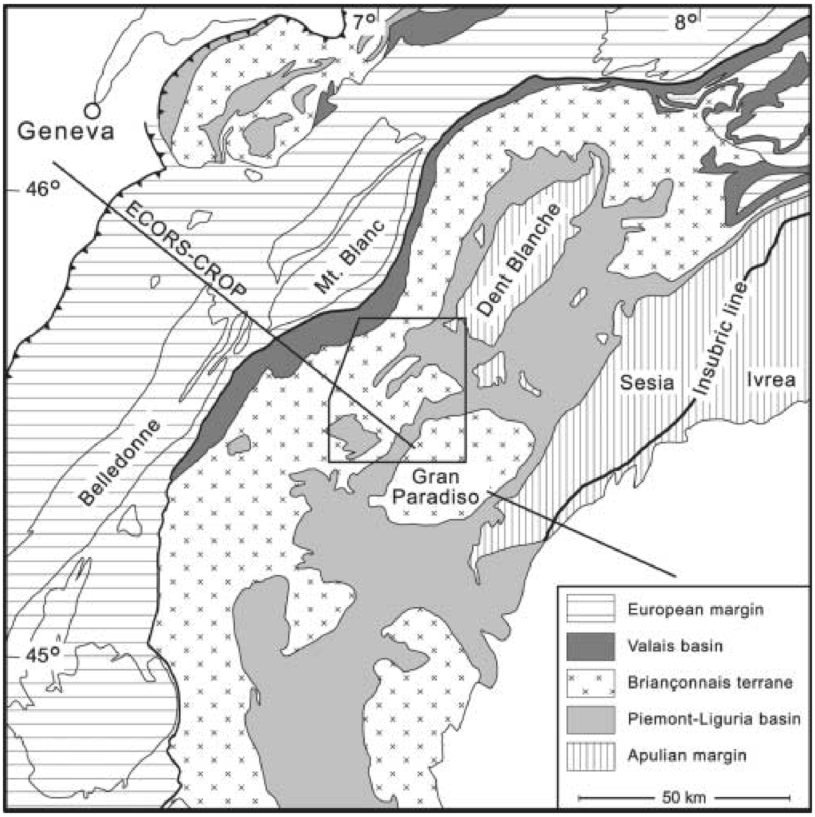

Fig. 1 Palaeogeographical map of the Western Alps after Ceriani *et al.* (2001, and references therein). The rectangle indicates the study area.

associated with an overturned nappe contact, is identical with that which would be produced by late-stage normal faulting (Fig. 2c). Hence, in the absence of additional criteria, sense-of-shear criteria alone are not decisive (Wheeler and Butler, 1994). Back-thrusting may be considered to have evolved from nappe refolding, with increasing-to-hinterland shearing in the reverse limb of a backfold. Also in this case, if the back-thrusting component is of importance, the proposed criteria are applicable and they would allow a relative chronology between nappe refolding and back-thrusting to be established.

Changes of metamorphic grade

Late-stage back-thrusting is expected to cause an offset of a pre-existing metamorphic zonation across a younger fault contact (Fig. 2b). Observations on metamorphic grade commonly indicate that back-thrusts displace earlier formed mineral zones, for example bringing 'hot' over 'cold' (Schmid *et al.*, 1989). The inverse applies to normal faulting which brings 'cold' over 'hot' (Mancktelow, 1992). By contrast, nappe refolding preserves the pre-existing metamorphic zonation, but reorients it together with the nappe contacts (Fig. 2d).

Regional setting of the study area

The studied area (Fig. 3a) is situated in a region where the main schistosity changes from a SE-dip to a dominant NW-dip (Caby, 1996). Four major tectonic units can be distinguished in this area, i.e. the Zone Houillère unit (ZH), the Ruitor unit (RU) and the Internal unit (IU), all parts of the Briançonnais microcontinent and the Piemont–Liguria oceanic unit (PL) (Fabre, 1961; Elter, 1972; Mercier and Beaudoin, 1987; Cigolini, 1995).

The change in dip – referred to as 'fan structure of the Briançonnais' (Fabre, 1961; Caby, 1968) – is explained by back-thrusting that followed outward-directed displacements (nappe stacking). Butler and Freeman (1996) supported this view by invoking SE shearing along a back-thrust (called the 'Entrelor shear zone', which corresponds to the 'ETC'; Fig. 2a) situated between the Briançonnais and Piemont–Liguria units. However, their interpretation of top-to-the-SE shearing (Fig. 2b) contrasts with the observations of Caby (1996), who documented top-to-the-NW displacements along this same tectonic contact, in agreement with the present authors' observations discussed later. This led Caby (1996) to interpret the ETC as a normal fault (Fig. 2c). Consequently he postulated W-directed subduction, predating extension and E-directed 'extrusion'. This scenario appears rather unlikely in the light of the seismic results obtained along the ECORS-CROP profile (Nicolas *et al.*, 1990).

New Structural and petrological data

The new set of structural data presented here (Figs 3–6) is grouped into three deformation phases, compatible with the work of previous authors (Caby, 1968, 1996; Baudin, 1987; Cigolini, 1995), who worked in the study area.

Evidently **D1** structures have been largely overprinted by subsequent deformation. Macroscopically a first foliation S1 is preserved only in F2 fold hinges. In thin section, this relict S1 is defined either by chloritoid preserved within D2 microlithons, or as an internal foliation within garnet (Fig. 6b). The D1 mineral assemblage (garnet, phengite, chloritoid) is associated with peak pressure conditions (Fig. 4). Peak pressures range from 10 to 14 kbar (at temperatures around 450 °C) in the IU to 5 kbar (at around 400 °C) in the ZH.

D2 represents the dominant deformation event, characterized by isoclinal folds on all scales. Owing to the intense transposition, the main foliation is a composite of D1 and D2. F2 folds show a wide spread in plunge azimuth from ESE to WNW between the Houiller Front and the Valgrisenche, and they plunge to the WNW over the rest of the study area. L2 stretching lineations are orientated parallel to the F2 folds (Figs 3b and 5a). The transport direction, including that observed along the

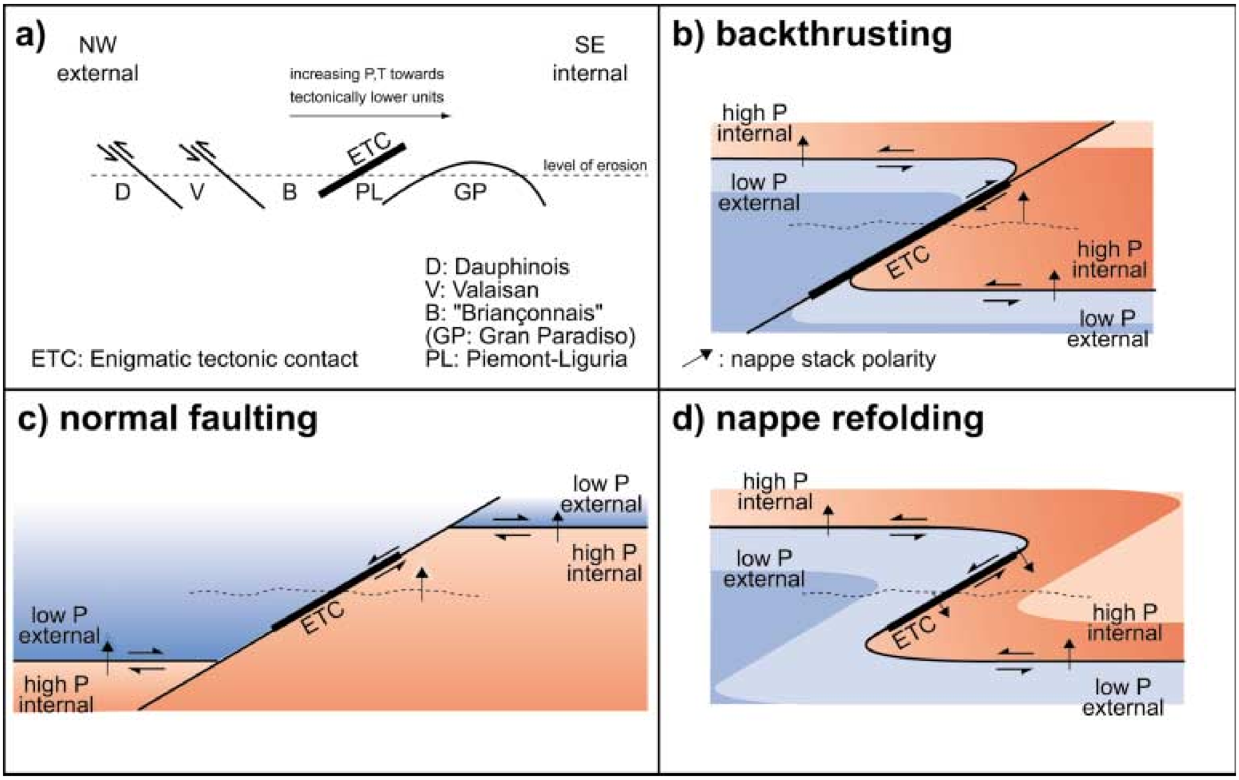

Fig. 2 (a) Schematic cross-section through the central part of the Western Alps (see Figs 4a and 5 for more realistic profiles); (b)–(d) sketches illustrating the three possible mechanisms of late-stage modifications of an original nappe stack discussed in this paper for late-stage modification.

ETC, is consistently top-to-the-WNW (Fig. 6a–e), as indicated by shear bands and asymmetric porphyroclasts. Parallelism between fold axes (F2) and stretching lineation (L2; Fig. 5a) indicates pervasive top-to-the-WNW shearing during D2. S2 in the IU is defined by the mineral assemblage garnet, phengite, epidote, chlorite and plagioclase replaces the peak-pressure mineral assemblage (Fig. 6c). P–T estimates indicate that D2 is contemporaneous with decompression from 14 to 5 kbar for temperatures around 500 °C (Fig. 4).

D3 is characterized by open mesoscale parasitic folds, refolding the composite S1/S2 main foliation (Fig. 5b) and causing a wide range of orientations of L2 stretching lineations (and F2 fold axes). D3 fold axes are moderately NE or SW plunging (Figs 3c and 5a) with gently, generally SE-dipping axial planes. An axial plane cleavage (pressure solution cleavage) is only locally observed (Fig. 5b). F3 folds become tighter towards structurally higher positions.

Based on mapping of the vergency of mesoscopic D3 folds, the axial traces of two D3 mega-folds could be identified in map (Fig. 3a) and profile (Fig. 4) view. A first and W-closing mega-fold (Ruitor mega-fold) affects all previous structures, including former nappe contacts (Fig. 4). Hence, the gradual change of the D1/D2 main schistosity (apparent 'fan-structure') from a SE-dip over a subvertical orientation into a NW-dip is a consequence of this mega-fold (Fig. 4).

A second and tectonically higher D3 mega-fold closes towards the east. It returns the whole nappe stack back into an upright position, as observed, for example, in the area of the Grande Sassière, a Piemont–Liguria klippe tectonically overlying the IU (Fig. 3a). This hitherto undetected D3 mega-fold can be correlated with the well-known Valsavaranche 'backfold' of Argand (1911) (Fig. 3a). However, because the Valsavaranche fold is not apparently linked kinematically to back-thrusting, the term Valsavaranche mega-fold is proposed.

Interpretation

D3 nappe refolding affected D1/D2 nappe contacts such as the ETC. The observed top-to-the-WNW sense of shear (Fig. 6a–d) excludes back-thrusting along the ETC. However, no significant metamorphic jump could be observed across the ETC (nor across any of the other nappe contacts; Fig. 4). This also excludes postmetamorphic normal faulting. Instead, it provides additional and independent evidence for the interpretation of the ETC and other foreland-dipping tectonic boundaries in terms of re-orientated former nappe contacts (Fig. 4).

The interpretation in terms of nappe refolding calls for a new interpretation on the kinematics of movement during the main stages of the tectonic and metamorphic evolution (see Fig. 7). In spite of uncertainties related to an accurate retro-deformation of the L2 stretching lineations (Ramsay and Huber, 1987), the senses of shear associated with L2 could not

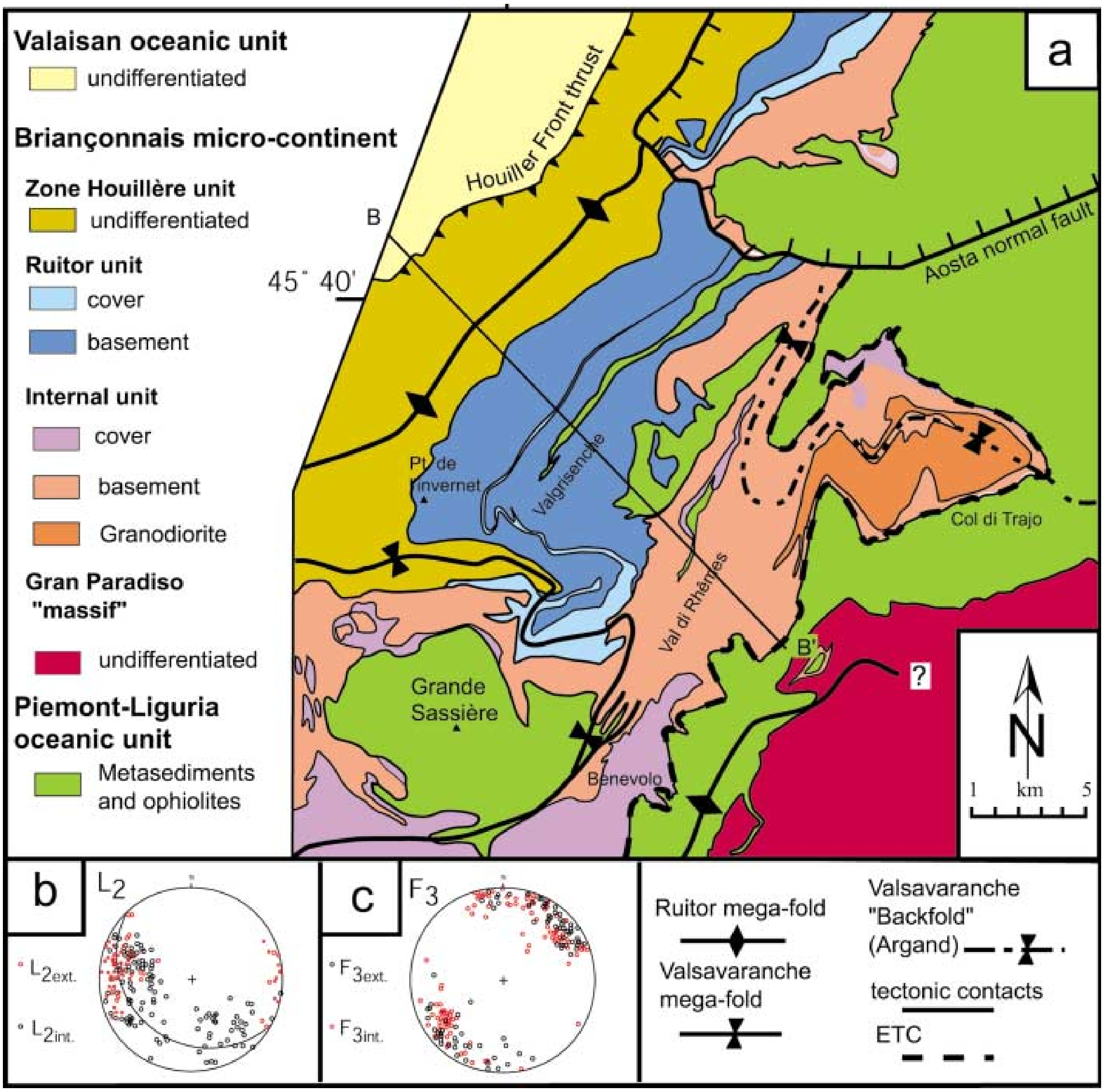

Fig. 3 (a) Geological map of the study area. B–B′ indicates the trace of the cross-section of Fig. 4(a). (b) L2 stretching lineations ($L2_{int.}$, area from the Front Houiller to the Valgrisenche; $L2_{ext.}$, area SE of the Valgrisenche) and (c) F3 fold axes ($F3_{ext.}$ and $F3_{int.}$, same separation as L2).

have been inverted because L2 is orientated perpendicular to the D3 fold axes. Hence, qualitative retro-deformation around D3 suggests that these folded tectonic contacts represent original top-to-the-W–N thrusts formed during the final stages of nappe stacking (D2). These thrusts emplaced higher grade metamorphic units (P and T) over lower grade metamorphic units. This inverse metamorphic field gradient, together with decompression documented during D2 (Fig. 4), suggests that the HP units came to lie over the LP units during exhumation, during the final stages of top-to-the-W–N nappe stacking (D2). D2 (Fig. 7c) immediately followed subduction and deformation under peak metamorphic conditions (Fig. 7d). Hence, exhumation of HP units is unrelated to late-stage normal faulting and/or back-thrusting. Instead, it is suggested that ascent and extrusion of HP units did occur within and parallel to a subduction channel, by active 'extrusion' (Burov *et al.*, 2001) and/or buoyant ascent (fig. 13 of Wheeler, 1991). Given top-to-the-W–N senses of shear during exhumation, the present study area must have been located near the lower (i.e. European) interface of the extruding HP units (Fig. 7c).

At the scale of the orogen (Fig. 7b), the subhorizontal Ruitor and Valsavaranche axial planes suggest vertical shortening of a part of the nappe pile. Commonly, vertical shortening is associated with crustal thinning. However, this classical interpretation would demand that the thrust contacts were steeply dipping originally, implying in turn a steeply dipping subduction channel. Because thrust contacts are flat in other parts of the orogen (i.e. below the Dent Blanche

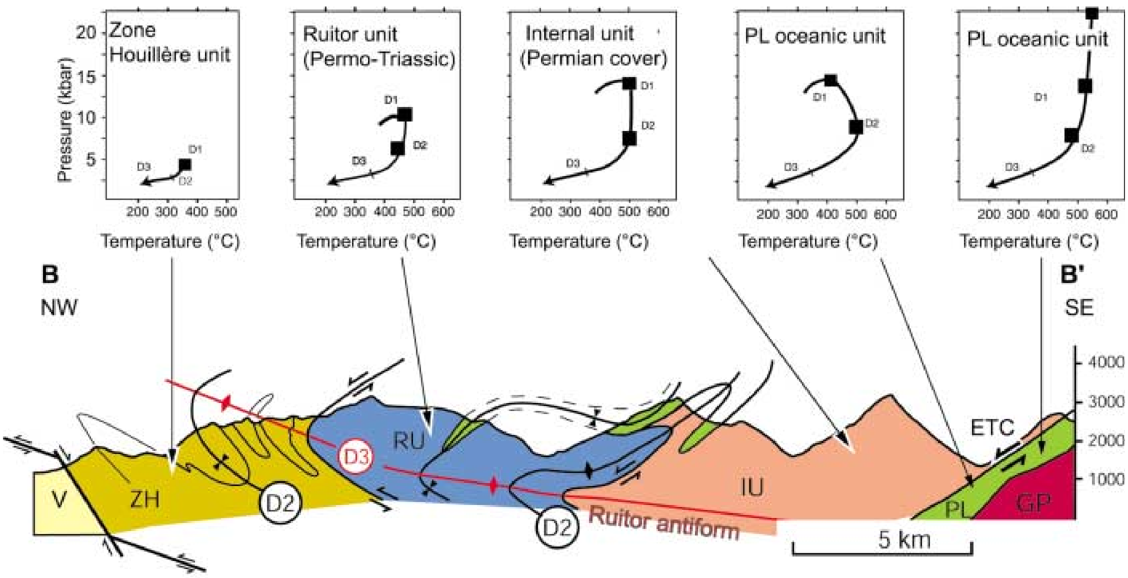

Fig. 4 Schematic cross-section B–B′ (for location see Fig. 3) and P–T path of different tectonic units in the study area. P–T conditions were calculated using GE0-CALC software (Brown *et al*., 1988) on the updated JAN92.RGB thermodynamic database (Berman, 1988), and Mg-chloritoid data from B. Patrick (listed in Goffé and Bousquet, 1997). The chlorite and mica solid-solution models and their thermodynamic properties are from Vidal *et al*. (2001) and Vidal and Parra (2000). Atom-site repartition for the micas from Bousquet *et al*. (2002). V, Valaisan oceanic unit; ZH, Zone Houillère unit; RU, Ruitor unit; IU, Internal unit; GP, Gran Paradiso 'massif'; PL, Piemont–Ligurian oceanic unit; ETC, Enigmatic tectonic contact.

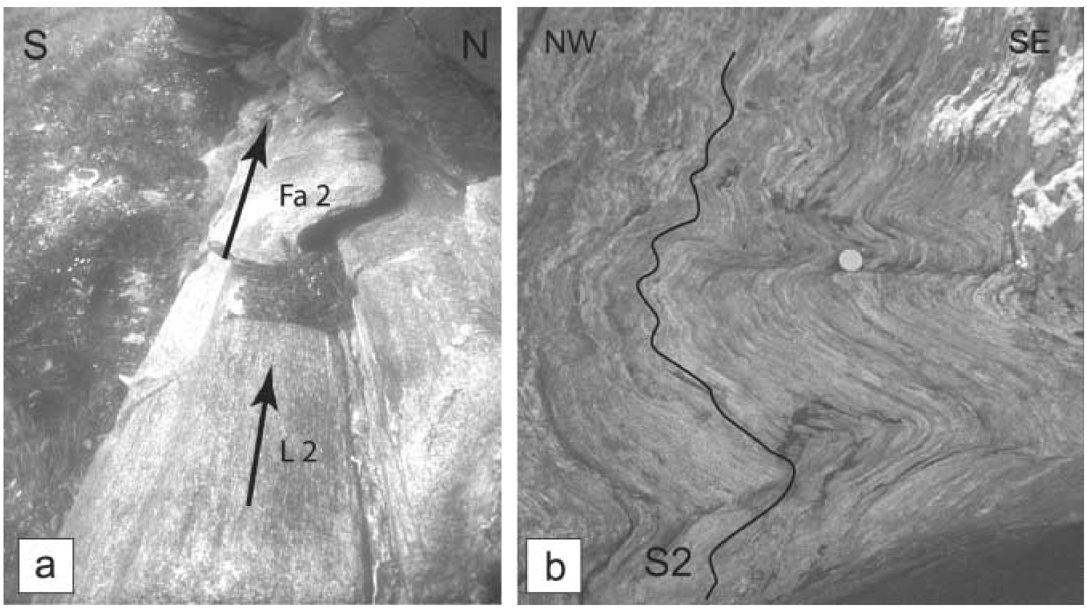

Fig. 5 (a) E–W-orientated L2 stretching lineation, parallel to the F2 fold axes on the eastern flank in the uppermost Val di Rhêmes. (b) M-shaped open D3 folds from the hinge area of the Ruitor mega-fold in the external part of the study area.

nappe; Fig. 7a) and steep subduction is unlikely in a collisional scenario, it is proposed that, at the scale of the orogen, vertical shortening associated with D3 mega-folding is of local significance only. As discussed elsewhere (Fügenschuh *et al*., 1999; Schmid and Kissling, 2000; Ceriani *et al*., 2001), late-stage out of sequence top-to-the-WNW thrusting along the Penninic front is related to postcollisional lithosphere-scale thrusting of the Briançonnais microcontinent over the European margin in the Oligocene. During this stage, the Gran Paradiso unit moved differentially to the WNW with respect both to the Valaisan suture and the overlying

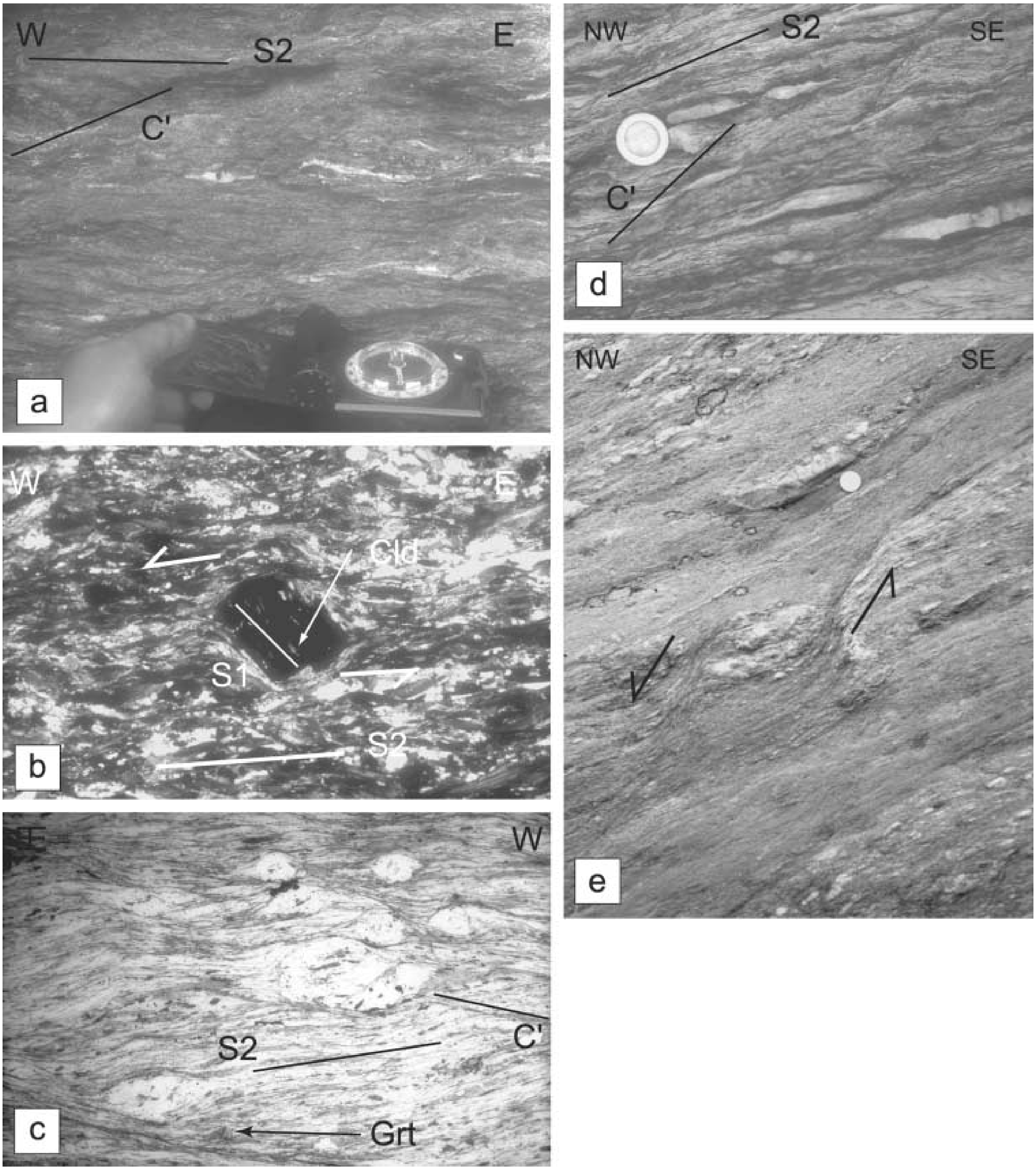

Fig. 6 (a) Macroscopic top-to-the-W sense of shear immediately below the ETC in the SL near the Col di Trajo. (b) Top-to-the-W sense of shear at the ETC in the Conge area (micrograph with crossed polarizers). (c) Top-to-the-W sense of shear at the ETC on the eastern flank in the uppermost Val di Rhêmes (micrograph without polarizers). (d) Macroscopic top-to-the-W sense of shear in the Permo-Triassic cover near the Rifugio Benevolo. (e) Macroscopic top-to-the-W sense of shear at the tectonic contact between RU and the ZH. (east of the Pointe de l'Invernet)

Austroalpine units (Dent Blanche nappe). It is proposed that this mega-folding occurred in front of and above the relatively rigid Gran Paradiso unit by a combination of inhomogeneous simple shearing and vertical shortening during the differential WNW-directed movement of the Gran Paradiso unit (Merle and Guillier, 1989).

Subduction and foreland-directed extrusion of the HP units occurred during D1/D2 nappe stacking (Fig. 7c–d) in the Eocene (Schmid and Kissling, 2000) and was top-

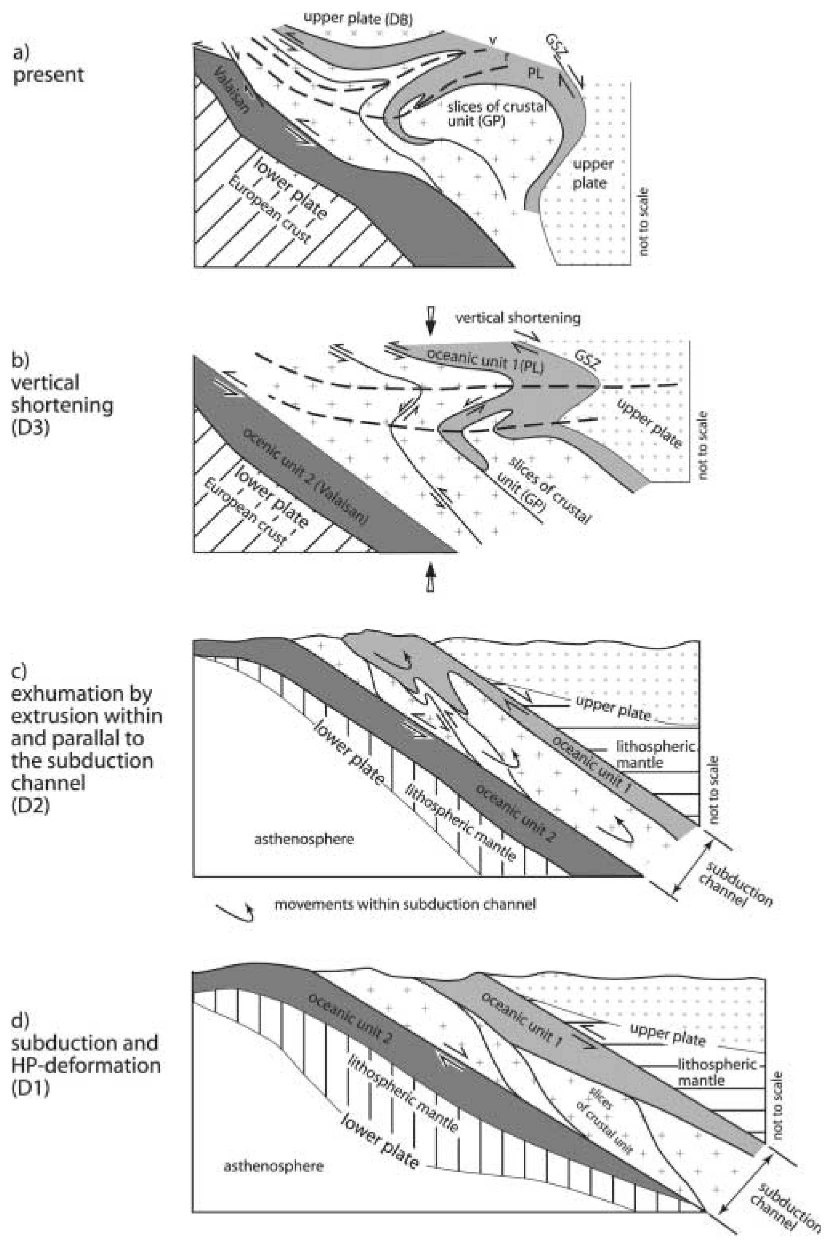

Fig. 7 Sketch of the tectonic evolution of the Western Alps. (a) Present situation. (b) Evolution of the large-scale nappe refolding (D3). Note refolding of the nappe contacts without inversion of the sense of shear. Similar structures are shown in the models of Pfiffner *et al.* (2000). (c) Exhumation by extrusion within and parallel to the subduction channel (D2). Note that in such a situation exhumation takes place during the final steps of nappe stacking and that the sense of shear is inverted with respect to the situation during the subduction on top of the subduction channel. Movements within the subduction channel derive from the models of Burov *et al.* (2001). (d) Subduction and deformation at peak metamorphic conditions. r, Ruitor mega-fold; v, Valsavaranche mega-fold; GP, Gran Paradiso 'massif'; DB, Dent Blanche unit; PL, Piemont–Ligurian oceanic unit; GSZ, Gressonney shear zone.

to-the-NNW–N according to Ceriani *et al.* (2001). The working area examined herein exposes the lower parts of the HP internal Penninic units extruded during D2. Extrusion of the upper parts of these HP units towards the foreland must be associated with hinterland-directed, i.e. 'normal fault mode' shearing. They are evident near the base of the Dent Blanche nappe ('Combin fault' of Ballèvre and Merle, 1993), and at the NW margin of the Sesia zone ('Gressoney Shear Zone' of Reddy *et al.*, 1999), GSZ in Fig. 7(a)–(b).

Discussion

Overturned nappe stacks linked directly to large-scale nappe refolding are known along the entire Alpine arc. In the external southern Western Alps similar large-scale nappe refolding and refolded tectonic contacts with a top-to-the-W sense of shear are described by Tricart (1984). Philippot (1990), Henry *et al.* (1993) and Agard *et al.* (2001) show evidence for ductile top-to-the-W shearing in the internal parts (Queyras, Mont Viso and Dora Maira). Similar structures are described by Müller (1983) and Schreurs (1990) in the western and central Swiss Alps. Hence the understanding of these structures is essential for reconstructing the evolution of the entire Western and Central Alps. Moreover similar structures are also observed in other orogens, as mentioned in the introduction.

Conclusions

Nappe refolding, back-thrusting and normal faulting cause severe late-stage modifications of the architecture of an orogen. The combined investigation of nappe stack polarity, kinematics of shearing and metamorphic gradients in the Western Alps presented herein presents criteria for distinguishing between these three modes of late-stage deformation.

Nappe refolding, rather than normal faulting or back-thrusting, severely overprinted the internal parts of the ECORS-CROP seismic profile during the Oligocene. Retro-deformation of this mega-folding implies exhumation of the HP rocks prior to nappe refolding, during nappe stacking in the Eocene. This exhumation was by ascent and extrusion of HP units within and parallel to a subduction channel.

Acknowledgments

We thank our colleagues from the 'Groupe Briançonnais' and of Basel S. Ceriani, A. Loprieno, G. Trullenque, and Ch. Ulardic (Freiburg) for stimulative discussions.

N. Mancktelow, J. Wheeler, J. Malavieille and C. Sue provided constructive reviews. Substantial funding by the Swiss National Science Foundation (project 20-63391.00 and precursor projects) over many years is gratefully acknowledged.

References

Agard, P., Jolivet, L. and Goffé, B., 2001. Tectonometamorphic evolution of the Schistes Lustrés complex: implications for the exhumation of the UHP rocks in the western Alps. *Bull. Soc. Géol. Fr.*, **172**, 617–636.

Alsop, G.I., Bryson, R. and Hutton, D.H.W., 2001. Tectonic and kinematic evolution within mid-crustal orogenic root zones: a case study from the caledonides of northwestern Ireland. *Geol. Mag.*, **138**, 193–211.

Argand, E., 1911. Sur les plissements en retour et la structure en éventail dans les Alpes occidentales. *Bull. Soc. Vaud. Sc. Nat.*, **XLVII**.

Argand, E., 1916. Sur l'arc des Alpes Occidentales. *Eclog. Geol. Helv.*, **XIV**, 146–151.

Ballèvre, M. and Merle, O., 1993. The Combin Fault: compressional reactivation of a Late Cretaceous-Early Tertiary detachment fault in the Western Alps. *Schweiz. Mineral. Petrogr. Mitt.*, **73**, 205–227.

Baudin, T., 1987. *Étude géologique du Massif du Ruitor (Alpes franco-italiennes): Evolution structurale d'un socle briançonnais*. Unpubl. doctoral dissertation, University of Grenoble, 259 pp.

Berman, R.G., 1988. Internally-consistent thermodynamic data for minerals in the system Na_2O-K_2O-Ca-MgO-FeO-Fe_2O_3-Al_2O_3-SiO_2-TiO_2-H_2O-CO_2. *J. Petrol.*, **29**, 445–522.

Bousquet, R., Goffé, B., Vidal, O.R., and Patriat, M., 2002. The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: New constraints on the evolution of the Alps. *Bull. Geol. Soc. Am.*, **114**, 207–225.

Brown, T.H., Berman, R.G. and Perkins, E.H., 1988. Ge0-CALC: software package for calculation and display of pressure-temperature-composition phase diagrams using an IBM or compatible personal computer. *Comput. Geosc.*, **14**, 279–289.

Brown, R.L., Journeay, J.M., Lane, L.S., Murphy, D.C. and Rees, C.J., 1986. Obduction, backfolding and piggyback thrusting in the metamorphic hinterland of the southeastern Canadian Cordillera. *J. Struct. Geol.*, **8**, 255–268.

Burov, E., Jolivet, L., Le Pourhiet, L. and Poliakov, A., 2001. A thermomechanical model of exhumation of high pressure (HP) and ultra-high pressure (UHP) metamorphic rocks in Alpine-type collision belts. *Tectonophysics*, **342**, 113–136.

Butler, R.W.H. and Freeman, S., 1996. Can crustal extension be distinguished from thrusting in the internal parts of mountain belts? A case history of the Entrelor shear zone, Western Alps. *J. Struct. Geol.*, **18**, 909–923.

Caby, R., 1968. Contribution à l'étude structurale des Alpes occidentales: subdivisions stratigraphiques et structure de la zone du Grand Saint-Bernard dans la partie sud du val d'Aoste (Italie). *Geol. Alpine*, **44**, 95–111.

Caby, R., 1996. Low-angle extrusion of high-pressure rocks and the balance between outward and inward displacements of Middle Penninic units in the western Alps. *Eclog. Geol. Helv.*, **89**, 229–267.

Ceriani, S., Fügenschuh, B. and Schimd, S.M., 2001. Multi-stage thrusting at the 'Penninic Front' in the Western Alps between Mont Blanc and Pelvoux massif. *Int. J. Earth Sci.*, **90**, 685–702.

Cigolini, C., 1995. Geology of the Internal Zone of the Grand Saint Bernard Nappe: a metamorphic Late Paleozoic volcano-sedimentary sequence in South-Western Aosta Valley (Western Alps). In: *Studies on Metamorphic Rocks and Minerals of the Western Alps. A Volume in Memory of Ugo Pognante* (B. Lombardo, ed.). *Boll. Mus. Reg. Sci. Nat., Torino*, **13,** 293–328.

Coward, M.P. and McClay, K.R., 1983. Thrust tectonics of S Devon. *J. Geol. Soc. London*, **140**, 215–228.

Dewey, J.F., 1988. Extensional collapse of orogens. *Tectonics*, **7**, 1123–1139.

Elter, G., 1972. Contribution à la connaissance du Briançonnais interne et de la bordure piémontaise dans les Alpes Graies nord-orientales et considérations sur les rapports entre les zones du Briançonnais et des Schistes lustrés. *Mem. Ist. Geol. Univ. Padova*, **28**, 1–18.

Escher, A., Masson, H. and Steck, A., 1993. Nappe geometry in the Western Swiss Alps. *J. Struct. Geol.*, **7**, 955–974.

Fabre, J., 1961. Contribution à l'étude de la Zone Houillère en Maurienne et en Tarentaise (Alpes de Savoie). *Mém. Bur. Rech. Géol. Min.*, **2**, 308 pp.

Frisch, W., 1979. Tectonic progradation and plate tectonics of the Alps. *Tectonophysics*, **60**, 121–139.

Froitzheim, N., Schmid, S.M. and Frey, M., 1996. Mesozoic paleogeography and timing of eclogite-facies metamorphism in the Alps: a working hypothesis. *Eclog. Geol. Helv.*, **89**, 81–110.

Fügenschuh, B., Loprieno, A., Ceriani, S. and Schmid, S., 1999. Structural analysis of the Subbriançonnais and Valais units in the area of Moûtiers (Savoy, Western Alps): paleogeographic and tectonic consequences. *Int. J. Earth Sci.*, **88**, 201–218.

Goffé, B. and Bousquet, R., 1997. Ferrocarpholite, chloritoïde et lawsonite dans les métapelites des unités du Versoyen et du Petit St Bernard (zone valaisanne, Alpes occidentales). *Schweiz. Mineral. Petrogr. Mitt.*, **77**, 137–147.

Henry, C., Michard, A. and Chopin, C., 1993. Geometry and structural evolution of ultra-high-pressure and high-pressure rocks from the Dora-Maira massif, Western Alps, Italy. *J. Struct. Geol.*, **18**, 965–981.

Macaya, J., Gonzàlez-Lodeiro, F., Martìnez-Catalán, J.R. and Alvarez, F., 1991. Continuous deformation, ductile thrusting and backfolding of cover and basement in the Sierra de Guadamarrama, Hercynian orogen of central Spain. *Tectonophysics*, **191**, 291–309.

Mancktelow, N., 1992. Neogene lateral extension during convergence in the Central Alps: Evidence from interrelated faulting and backfolding around the Simplonpass (Switzerland). *Tectonophysics*, **215**, 295–317.

Mercier, D. and Beaudoin, B., 1987. Révision du Carbonifère Briançonnais: Stratigrahpie et évolution du bassin. *Geol. Alpine*, **13**, 25–31.

Merle, O. and Guillier, B., 1989. The building of the Central Swiss Alps: an experimental approach. *Tectonophysics*, **165**, 41–56.

Milnes, A.G., Gfeller, M. and Müller, R., 1981. Sequence and style of major post-nappe structures, Simplon-Pennine Alps. *J. Struct. Geol.*, **3**, 411–420.

Müller, R., 1983. Die Struktur der Mischabelfalte (Penninische Alpen). *Eclog. Geol. Helv.*, **76**, 391–416.

Nicolas, A., Hirn, A., Polino. R., Nicolich, R. and ECORS-CROP Working Group, 1990. Lithospheric wedging in the western Alps inferred from the ECORS-CROP traverse. *Geology*, **18**, 587–590.

Pfiffner, O.A., Ellis, S. and Beaumont, C., 2000. Collision tectonics in the Swiss Alps: Insight from geodynamic modeling. *Tectonics*, **19**, 1065–1094.

Philippot, P., 1990. Opposite vergence of nappes and crustal extension in the French-Italian Western Alps. *Tectonics*, **9**, 1143–1164.

Platt, J.P., Lister, G., Cunningham, P. *et al.*, 1989. Thrusting and backthrusting in the Briançonnais domain from the Western Alps. In: *Alpine Tectonics* (M. Coward *et al.*, eds). *Spec. Publ. Geol. Soc. London*, **45,** 135–152.

Ramsay, J.G. and Huber, M.I., 1987. *The Techniques of Modern Structural Geology, Vol. 2*: Folds and Fractures: Academic Press, San Diego.

Reddy, S.M., Wheeler, J. and Cliff, R.A., 1999. The geometry and timing of orogenic extension: an example from the

Western Italian Alps. *J. Metamorph. Geol.*, **17**, 573–589.
Roure, F., Bergerat, F., Damotte, B., Mugnier, J.-L. and Polino, R., 1996. The ECORS-CROP Alpine seismic traverse. *Mém. Soc. Géol. Fr.*, **170**, 113 pp.
Schmid, S.M. and Kissling, E., 2000. The arc of the Western Alps in the light of new data on deep crustal structure. *Tectonics*, **19**, 62–85.
Schmid, S.M., Aebli, H.R., Heller, F. and Zingg, A., 1989. The role of the Periadriatic Line in the tectonic evolution of the Alps. In: *Alpine Tectonics* (M. Coward *et al.,* eds). *Spec. Publ. Geol. Soc. London*, **45,** 153–157.
Schmid, S.M., Pfiffner, O.A., Froitzheim, N., Schönborn, G. and Kissling, E., 1996. Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. *Tectonics*, **15**, 1036–1064.
Schreurs, G., 1990. Structural analysis of the Schams nappes and adjacent tectonic units: implications for the orogenic evolution of the Penninic zone in the eastern Switzerland. In: *Deep Structure of the Alps* (F. Roure *et al.*, eds). *Mém. Soc. Géol. Fr.*, **156,** 415–435.
Stampfli, G.M., 1993. Le Briançonnais, terrain exotique dans les Alpes? *Eclog. Geol. Helv.*, **86**, 1–45.
Tricart, P., 1984. From passive margin to continental collision: a tectonic scenario for the Western Alps. *Am. J. Sci.*, **284**, 97–120.
Vidal, O. and Parra, T., 2000. Exhumation of high pressure metapelites obtained from local equilibria for chlorite phengite assemblage. *Geol. Mag.*, **35**, 139–161.
Vidal, O., Parra, T. and Trotet, F., 2001. A thermodynamic model for Fe-Mg aluminous chlorite using data from phase equilibrium experiments and natural pelitic assemblages in the 100–600 °C, 1–25 kbar range. *Am. J. Sci.*, **301**, 557–592.
Vogl, J.J., 2002. Late orogenic backfolding and extension in the Brooks Range collisional orogen, northern Alaska. *J. Struct. Geol.*, **24**, 1753–1776.
Wheeler, J., 1991. Structural evolution of a subducted continental sliver: the northern Dora Maira massif, Italian Alps. *J. Geol. Soc.*, **148**, 1101–1113.
Wheeler, J. and Butler, R.W.H., 1994. Criteria to identify crustal extension. *J. Struct. Geol.*, **16**, 1023–1027.

Received 11 July 2002; revised version accepted 23 December 2002