Chapter 4

Kinematics and mechanisms of exhuming subducted continental crust in the Sesia Zone, Western Alps

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4.1 ABSTRACT

The Sesia Zone within the arc of the Western Alps contains blueschist-eclogitic continental crust within three basement nappes that individuated during late Cretaceous subduction (60-70 Ma). The thrusts bounding these nappes developed where the crust was thinned during Jurassic rifting and was overlain by passive margin sediments. Today, these sediments separate the nappes and contain blueschist- and greenschist-facies assemblages. In mapping related structures and assemblages across the Sesia Zone, we discovered crustal-scale shear zones that overprint nappe contacts and exhumed the HP rocks within large, coherent slices of crust. Exhumation was multistage and generally proceeded from internal to external parts of the accreted continental margin. Most exhumation involved thrusting (D_1) and transpressional shearing (D_2) along a steep, E-W trending mylonitic shear zone that is preserved in fabric windows. This shear zone was active under retrograde blueschist- to greenschist-facies conditions and accommodated nearly isothermal decompression of the basement nappes (T = 500-550°C) to a common depth of about 20 km. Continued exhumation of these nappes to 10 km or less occurred in the footwall of a subhorizontal, greenschist-facies extensional shear zone (D_3) preserved in the highest mountain peaks of the Sesia Zone. This top-SE extensional exhumation involved cooling to 400° and was coeval with Early Tertiary, SE-directed subduction of oceanic Liguro-Piemont units beneath the Sesia Zone. New Rb-Sr mineral ages constrain D_2 to have occurred at about 60-65 Ma and D_3 at about 45-55 Ma. Slow cooling and exhumation of the Sesia Zone from 45 to 36 Ma occurred in the hangingwall of the Gressoney extensional shear zone (D_4). At 30 Ma years, the HP rocks of the

Sesia Zone were intruded by shallow granitic plutons and incorporated within volcanoclastic sediments. Oligo-Miocene Insubric backfolding and -thrusting (D_5) only exhumed northeastern parts of the Sesia Zone, where HP metamorphism is absent.

Most exhumation of continental HP rocks in the Sesia Zone therefore preceded Tertiary Alpine collision and coincided with Late Cretaceous to Early Tertiary subduction of the Apulian and Tethyan lithospheres. The transition from D_2 to D_3 in the Sesia Zone is interpreted to mark a first-order change from high-stress subduction and accretion of the distal Apulian continental margin to NW-retreating, low-stress subduction of the Liguro-Piemont oceanic lithosphere.

4.2 INTRODUCTION

The Sesia Zone in the inner arc of the Western Alps (Fig. 4.1) is the first location where eclogite-facies metamorphism of continentally derived rocks was recognised (e.g. Ernst, 1971; Dal Piaz et al., 1972) and interpreted in terms of subducted continental lithosphere. From the outset, metamorphic overprinting relationships indicated that this subduction occurred during the early stages of the Alpine evolution (e.g. Dal Piaz et al., 1972; Compagnoni and Maffeo 1974), prior to Tertiary nappe stacking and Barrovian-type overprinting metamorphism (Compagnoni et al. 1977). Yet, as in many areas affected by high-pressure (HP) and ultra-high-pressure (UHP) metamorphism, the exhumation mechanisms for the HP rocks of the Sesia Zone have been debated to the present day.

The Sesia Zone together with the Dent Blanche nappe and several small klippen within the oceanic realm of the Piemont Unit (Fig. 4.1) represent the remains of an Early Mesozoic passive margin of the Apulian continent (e.g. Lardeaux and Spalla 1991, Froitzheim et al. 1996). Today, the Sesia-Dent Blanche unit forms the highest tectonic unit of the Western Alps; it overlies exhumed HP and UHP relics of the Liguro-Piemontese ocean (Zermatt-Saas Zone), the ocean-continent transition (Combin Zone) and the distal part of the European continental margin (Brianconnais). These units were affected by Tertiary, SE-directed backfolds (e.g. Argand 1916) in the retro-wedge of the Alpine orogen. Further, the HP rocks of the Sesia Zone have late Cretaceous age, whereas those of the underlying units yield Early Tertiary ages for HP and UHP metamorphism (e.g. Duchêne et al. 1997, Rubatto et al. 1999).

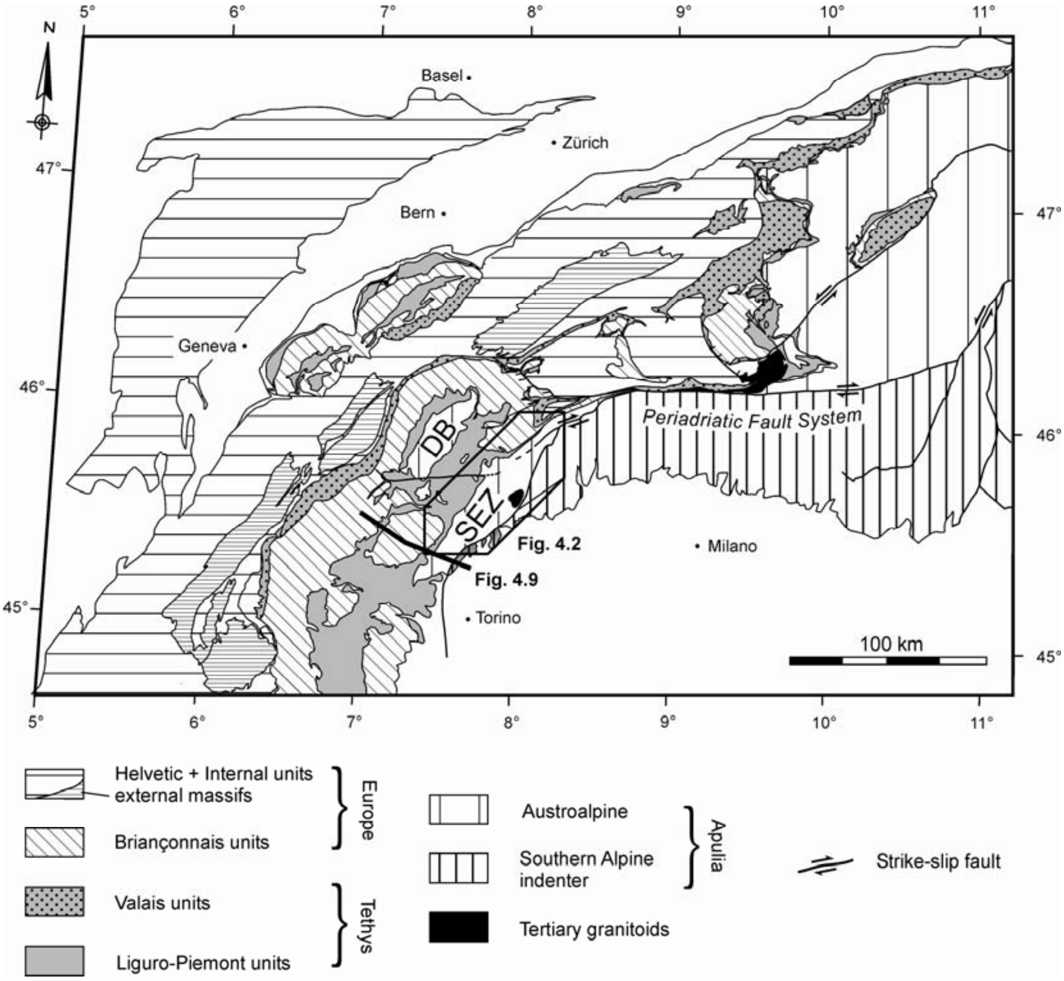


Fig. 4.1: Tectonic map of the Western and Central Alps, with box enclosing most of the Sesia Zone and adjacent tectonic units studied in this paper. The black line marks the trace of the evolutionary cross sections of Fig. 4.9, which refer to the interpretation of the ECORS-CROP seismic profile by Schmid and Kissling (2000).

Finally, the Sesia Zone is separated from the other units of the Apulian passive margin (Canavese and Ivrea Zones, Fig. 4.1) by greenschist-facies mylonites of the Insubric Line, which accommodated late-orogenic dextral strike-slip and SE-directed backthrusting in Oligo-Miocene time (Schmid et al. 1987). Unlike the Sesia Zone, however, none of these units south and east of the Insubric Line experienced HP Alpine metamorphism; indeed they attained no more than anchizone Alpine metamorphism and their pre-Alpine, amphibolite- to granulite facies rocks escaped Alpine overprinting (Zingg et al. 1990). Thus, both the northwestern and southeastern tectonic contacts of the Sesia Zone must have accommodated significant displacements related to exhumation in Late Cretaceous and Early Tertiary time. Thus, determining the age, conditions and kinematics of deformation in the Sesia Zone is the key to resolving the larger issue of how large coherent blocks of subducted continental crustal are exhumed. This is the main goal of our work presented in this paper.

Exhumation involves the movement of rock towards the Earth's surface (cf. England and Molnar 1990). Not surprisingly given the complexity of the Western Alps, many exhumation mechanisms have been proposed for the HP rocks of the Sesia Zone. Ernst (1971) reasoned that the continentally derived Sesia rocks were exhumed buoyantly due to their density contrast with surrounding mantle rocks in the purported, early Alpine subduction zone. However, buoyant rise of subducted lithosphere only occurs to the level of isostatic equilibrium, so other forces must account for complete exhumation of the Sesia Zone to the surface. Mylonitic thrusting and folding have been held responsible for exhumation and imbrication of thrust sheets with contrasting prograde and retrograde metamorphic evolutions in the Sesia Zone (Gosso et al. 1979; Pognante et al. 1987), but thrusting alone as a mechanism for the HP rocks in the Sesia Zone seems unlikely in light of other structures pointing to syn-convergent crustal extension (Inger and Ramsbotham 1997). Indeed, Platt (1986) proposed that lateral extension alternating with thrusting, and accompanied by erosional denudation acted together to exhume HP rocks in the retro-wedge of the Alpine orogen. Yet, large extensional shear zones that might have effected exhumation of the Sesia Zone have not been identified so far. Such shear zones are restricted to the Liguro-Piemontese ophiolitic units (e.g. Ballèvre and Merle 1993, Wheeler and Butler 1993), i.e., structurally below rather than above the Sesia Zone (Fig. 4.1). Based on thermal modelling of pressure-temperature (PT) paths, Rubie (1984) proposed a two-stage exhumation involving tectonic underplating of subducted continental lithosphere to the upper Apulian plate followed by backthrusting localized at the Insubric Line. In this model, removal of overburden was effected by high Tertiary glacio-fluvial erosion rates. In principle, Rubie's (1984) model is similar to later, numerical orogenic models of Escher and Beaumont (1997) in which buoyant rise of subducted HP rocks during nappe stacking is transitional to forced return flow of these rocks to the surface during backfolding and -thrusting.

Unfortunately, none of the models described above considers that HP rocks of the Sesia Zone were subducted to mantle depths (60 km, e.g. Tropper et al. 1999; Zucali et al. 2002) already in Late Cretaceous time, before or during the onset of oceanic subduction, and to depths well below the base of the Alpine orogenic wedge that evolved much later during mid- to late Tertiary collision. Moreover, existing models assume that the subduction and exhumation of Alpine HP rocks involved overall plane-strain shortening in a NNW-SSE oriented vertical section, despite the fact that paleomagnetic data (Dercourt et al. 1986) and paleogeographic reconstructions (Stampfli et al. 1998; Schmid et al. 2004) call for hundreds of km of strike-slip motion between Brianconnais and Apulia during closure of the Liguro-Piemontese ocean in Late Cretaceous to Early Tertiary time. Even numerical models of Alpine-type collision belts that incorporate sophisticated assumptions on rheology, metamorphic phase transitions and erosion (Burov et al. 2001; Gerya et al., 2002) leave us with a decidedly ambiguous assessment of exhumation mechanisms, due partly to the simple 2D kinematic constraint and partly to the choice of questionable thermal boundary conditions.

We therefore present new three-dimensional structural and kinematic data which, when regarded in the context of petrological and geochronological data, casts an entirely different light on the exhumation history of HP rocks in the Western Alps. We outline how basic lithological and metamorphic characteristics of the Sesia Zone can be interpreted in terms of primary thrust contacts between three basement nappes that individuated during subduction and subsequent exhumation. A new type of fabric map and cross sections in section 3 reveal how these primary structures were modified and locally preserved during multistage exhumation. Thermobarometric constraints for exhumation indicate that although the basement units in the Sesia Zone underwent different retrograde evolutions, their transition from eclogite- to greenschist-facies conditions involved, nearly isothermal decompression followed by cooling in Late Cretaceous to Early Tertiary time. These field-based facts form the basis for a three-dimensional kinematic model of Alpine subduction and exhumation of HP rocks. The available evidence suggests that Early Jurassic rifting exerted a strong control on the localization of first-order faults during the subduction and exhumation of HP rocks. Contrary to existing models, the geologic record suggests that most exhumation occurred during sinistral transpression in Late Cretaceous time. The paper concludes with a comparison of our field-based kinematic model with recent dynamic, physical models of exhumation.

4.2.1 Primary lithotectonic features in the Sesia Zone

The Sesia Zone is a composite unit that can be divided into three Alpine basement nappes with contrasting pre-Mesozoic lithologies, Alpine metamorphic histories, and position relative to a thin band of metasediments (Fig. 4.2):

(1) the Bard unit making up the northwestern part of the Sesia Zone comprises mostly fine-grained gneiss with predominantly greenschist-facies metamorphic overprint ("gneiss minuti" in the literature, Gastaldi 1871, Stella 1894, cited in Compagnoni et al. 1977),

(2) the Mombarone unit in the southern and eastern parts of the Sesia Zone contains predominantly eclogite-facies micaschists ("micascisti eclogitici") and subordinate late Paleozoic metagranitoid rocks, minor metabasites and marble. These rocks are intruded discordantly by Oligocene granitoids (Biella and Traversella plutons in Fig. 4.2) and, importantly, are included as xenoliths within Oligocene volcanoclastics exposed along the SW border of the Mombarone unit (Bianchi and Dal Piaz 1963),

(3) the II ZDK unit, or "Seconda Zona Dioritica Kinzigitica", is preserved within two large lozenge-like bodies in the northeastern part of the Sesia Zone, and to the southwest generally follows the contact of the Bard and Mombarone nappes (Minnigh 1977). The name of this unit belies its close lithological affinity with pre-Alpine metasediments of the Ivrea Zone (so-called kinzigites, or "Prima Zona Dioritica Kinzigitica", Carraro et al. 1970; Dal Piaz et al. 1971; Isler and Zingg 1974; Compagnoni et al. 1977). All three of these basement units experienced prograde amphibolite-facies and higher grade Variscan metamorphism, although the II ZDK followed a somewhat different evolution which allowed it to largely escape Alpine overprinting.

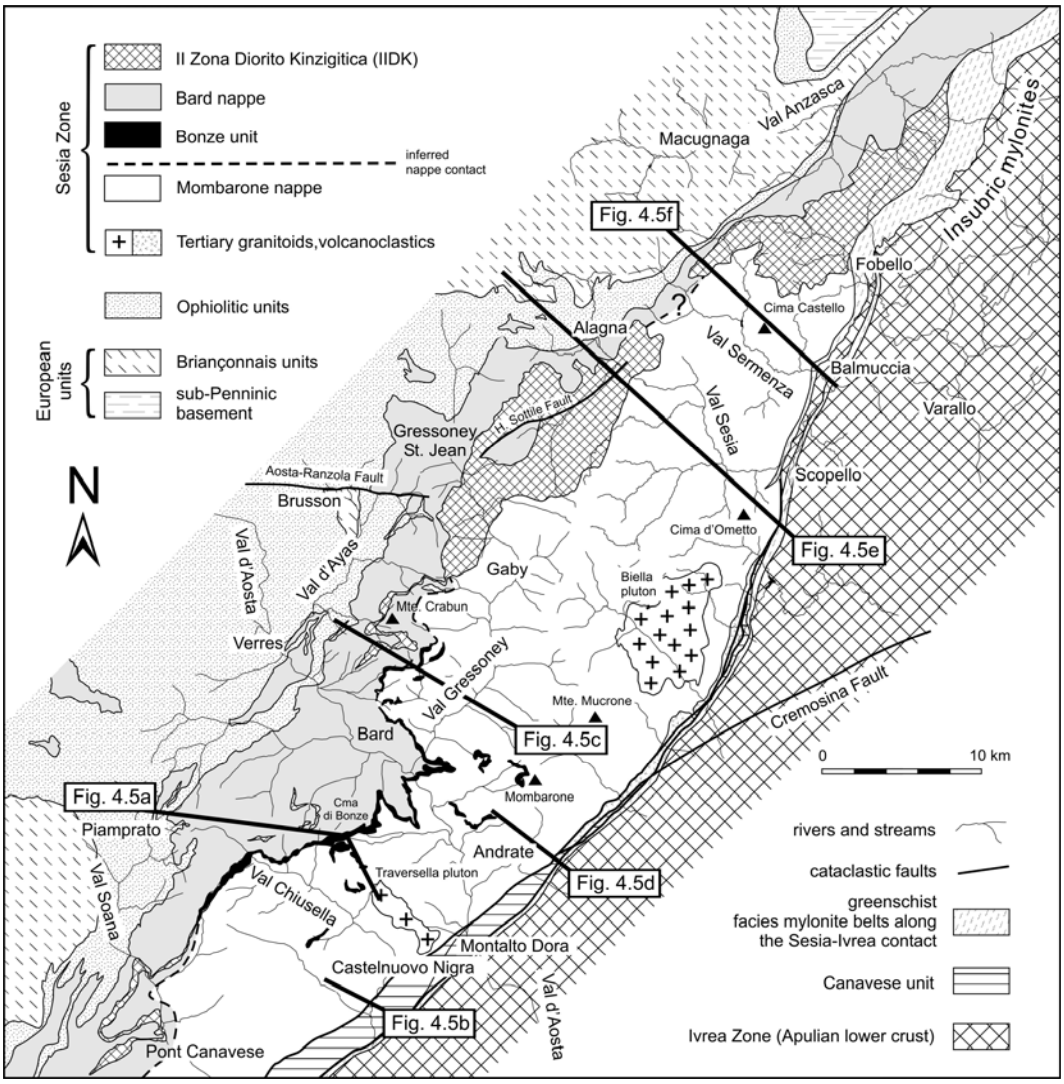
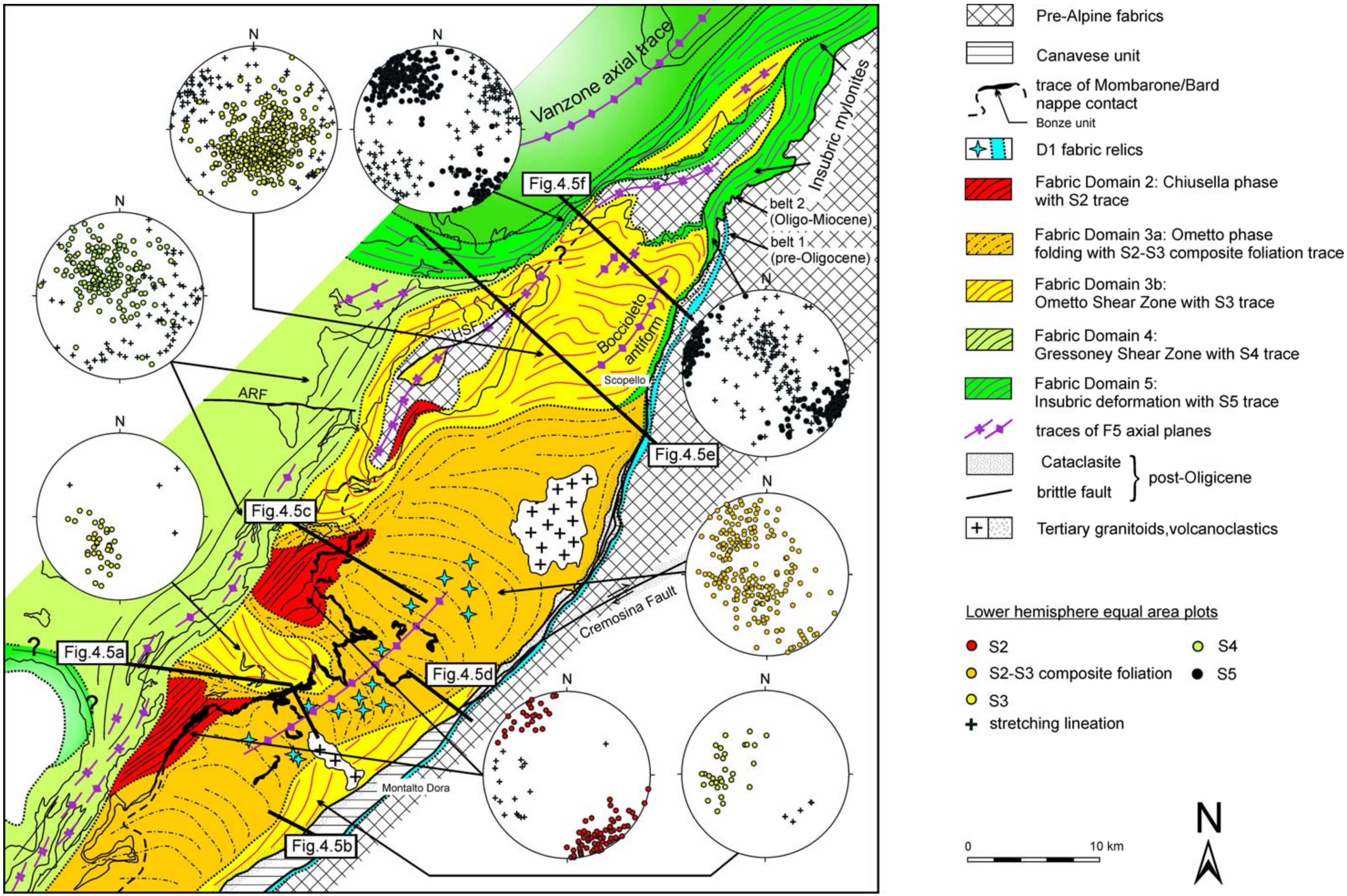


Fig. 4.2: Lithotectonic map of the Sesia Zone and adjacent tectonic units. Map shows tectonic subdivision of the basement (Mombarone, Bard and IIDK nappes), Mesozoic sedimentary units (Bonze and Canavese units) and the location of cross sections in Figure 4.5. Location names as mentioned in the text.

A thin, discontinuous strand of highly deformed Mesozoic metasediments and subordinate metabasite, the Monometamorphic Cover Complex (MCC, Venturini, 1995) in Fig. 4.2, separates the Bard and Mombarone nappes along most of their mutual contact. Although the term "Monometamorphic" is strictly seen incorrect, because these rocks experienced polyphase Alpine metamorphic overprint, it is used to separate the metamorphic evolution of these metasediments and metabasites from those rocks with a pre-Alpine metamorphic imprint, such as the other units in the Sesia Zone. The MCC sediments are very similar to Late Paleozoic to Jurassic sediments of the Canavese Zone exposed along the contact of the Mombarone nappe with the Ivrea Zone. The latter sediments represent the distal part of the Apulian passive continental margin (e.g. Biino and Compagnoni 1989; Ferrando et al. 2004). Likewise, the MCC unit contains lithologies (dolomitic marbles, manganiferous quartzites, gabbros and MORB metabasites) that are diagnostic of a distal passive margin setting (Pognante et al. 1987; Venturini et al. 1994, 1995). Both, the MCC and Canavese metasediments experienced greenschist-facies overprinting, in some places preceded by Alpine blueschist-facies metamorphism.

We note that our division of the Sesia Zone differs from its classical subdivision into "external" gneiss-minuti, "internal" eclogitici micaschisti and II ZDK units (e.g. Compagnoni et al. 1977) in two important respects: First, we use the Mesozoic sediments of the MCC unit, rather than the lithologies of the pre-Alpine basement as a criterion for delimiting the basement nappes. This approach is common in Alpine geology and, in the case of the Sesia Zone, is justified by thermobarometry indicating that the Bard and Mombarone nappes have different prograde metamorphic paths (Konrad-Schmolke et al., Chapter 3) during their subduction to different peak, blueschist-eclogite facies conditions (respectively, 1.0-1.5 GPa at 500-550°C and 1.5 and 2.0 GPa at 500 to 600°C; Desmons and O´Neil 1978; Koons 1986; Lardeaux and Spalla 1991; Tropper et al. 1999; Zucali et al., 2002). Pre-Alpine lithology is not a good criterion for differentiating basement units because our fabric mapping (Fig. 4.3) revealed that the distribution of greenschist-facies assemblages in pre-Alpine lithologies (e.g. "gneiss minuti" in the sense of Passchier et al. 1981) reflects the intensity of retrograde overprinting during exhumation, especially in the NW parts of the Sesia Zone (e.g. Stünitz 1989), rather than any primary lithological differences that delimit tectonic units. To avoid further confusion, we therefore discard the historical names "gneiss minuti" and "eclogitici micascisti" in favour of the units above which define Alpine nappes and tectonic contacts formed during subduction.


Vanzone axial trace
Insubric mylonites
belt 2
(Oligo-Miocene)
belt 1
(pre-Oligocene)
Fig.4.5f
Fig.4.5e
Fig.4.5c
Fig.4.5a
Fig.4.5d
Fig.4.5b
HSF
ARF
Boccioleto antiform
Scopello
Cremosina Fault
Montalto Dora
N
Pre-Alpine fabrics
Canavese unit
trace of Mombarone/Bard nappe contact
Bonze unit
D1 fabric relics
Fabric Domain 2: Chiusella phase with S2 trace
Fabric Domain 3a: Ometto phase folding with S2-S3 composite foliation trace
Fabric Domain 3b: Ometto Shear Zone with S3 trace
Fabric Domain 4: Gressoney Shear Zone with S4 trace
Fabric Domain 5: Insubric deformation with S5 trace
traces of F5 axial planes
Cataclasite
brittle fault
post-Oligicene
Tertiary granitoids,volcanoclastics
Lower hemisphere equal area plots
S2
S2-S3 composite foliation
S3
stretching lineation
S4
S5
0
10 km

Previous page: Fig. 4.3: Fabric domain map of the Sesia Zone and adjacent tectonic units. Criteria used to construct the map are described in the text (section 3). Orientation of main structural elements related to the different fabric domains is presented in lower hemisphere equal area plots. Note that fabric domain boundaries crosscut initial lithotectonic contacts as displayed in Fig. 4.2.

4.3 RESULTS

4.3.1 The structural-mineralogical record of exhumation

4.3.1.1 Distinguishing deformational phases and fabric domains

At the scale of the area in Figure 4.2, we distinguished five Alpine deformational phases whose areal extent is depicted in Figure 4.3 as coloured fabric domains numbered from oldest (1) to youngest (5). Within a given fabric domain, the numbered (coloured) deformational phase is observed to predominate, in the sense that it contains the main, overprinting schistosity and/or folds. Nevertheless, older phases and mineral assemblages are preserved locally in all domains, particularly where the dominant deformation is very localized.

Four types of structural and metamorphic criteria were used to distinguish these fabric domains:

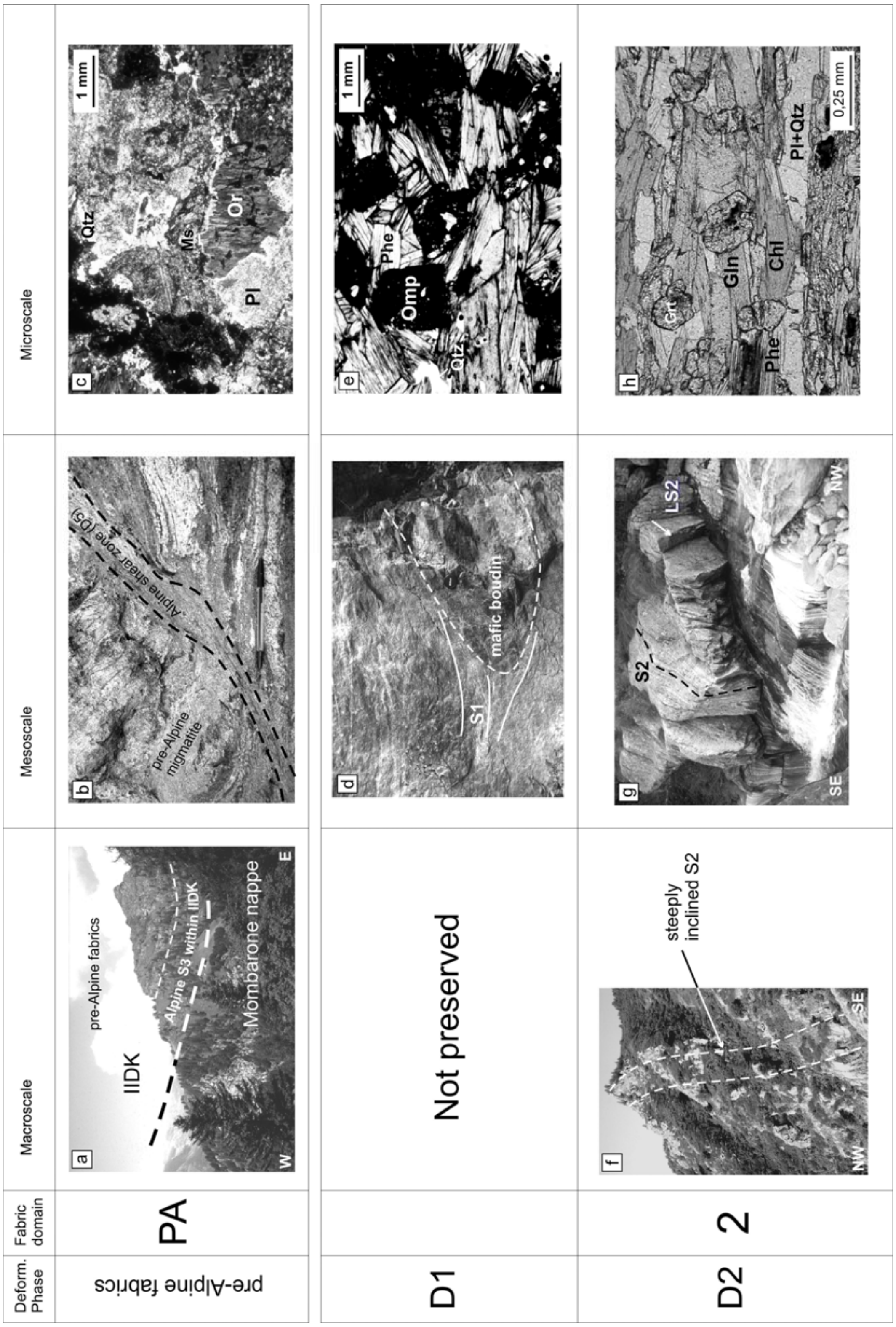
(1) the relative age of structures, metamorphic minerals and magmatic dykes based on cross-cutting relationships

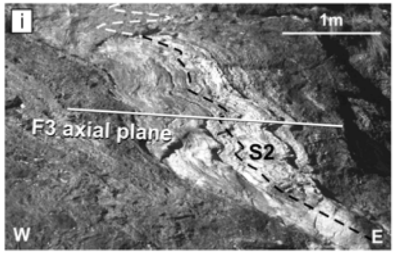
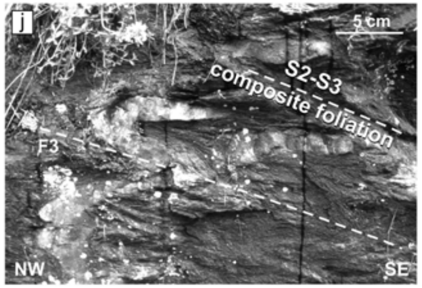
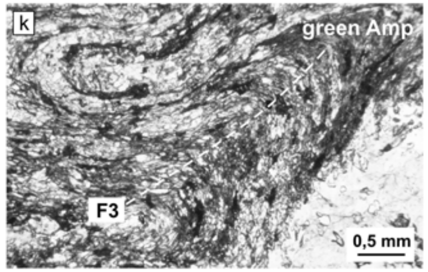
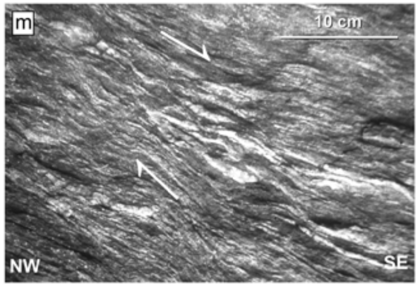
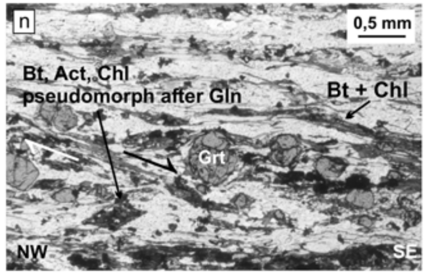
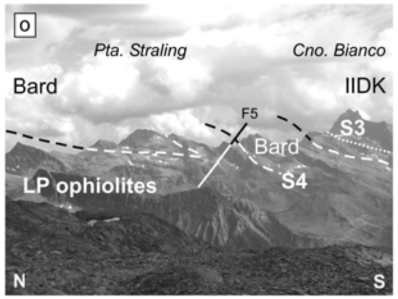
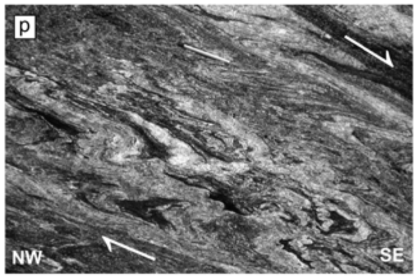
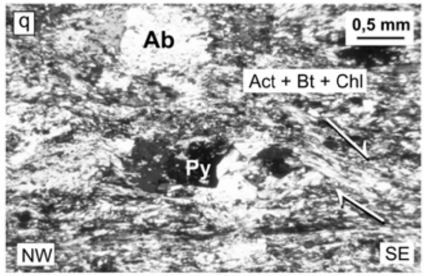
(2) structural style (e.g. kink vs. similar folds, discrete vs. distributed shearing)

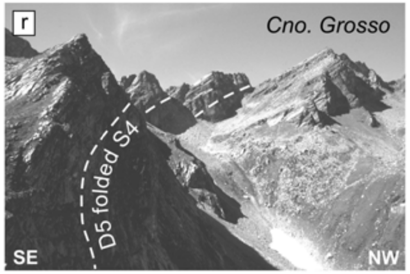
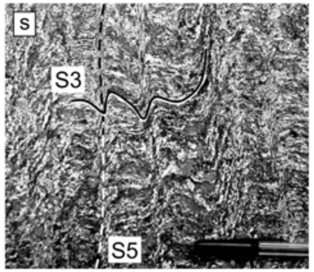
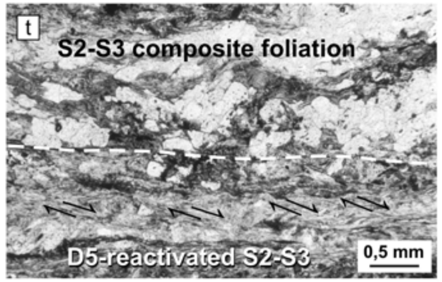
(3) the orientation of structures; and

(4) the kinematics of deformation related to those structures.

Figure 4.4 shows the key observations made on different scales in each fabric domain. Where microstructural analysis revealed that metamorphic minerals grew syn-kinematically, structures were correlated with a metamorphic event, in some cases allowing us to estimate the thermobarometric conditions of deformation (Konrad-Schmolke et al., Chapter 5), or even to determine the age of the structures. In other cases, especially where successive deformation occurred under similar, retrograde greenschist-facies conditions (D_3-D_5) or had similar kinematics (D_3, D_4), we were restricted to using structural criteria. Taken together, the suite of criteria above allowed us to map tectonometamorphic facies across pre-Alpine lithological boundaries. It turned out that these facies define crustal-scale shear zones related to exhumation of the HP rocks. The shear zones are named below after their type locality.



Deform. Phase	Fabric domain	Macroscale	Mesoscale	Microscale
D3	3a			
D3	3b			
D4	4			

Deform. Phase	Fabric domain	Macroscale	Mesoscale	Microscale
D5	5			

Previous pages: Fig. 4.4: Structures and metamorphic mineral assemblages that typify fabric domains described in the text. (a) In the macroscale, the IIDK unit preserved high temperature pre-Alpine fabrics affected only by minor Alpine deformation at its contacts (see Figs. 2 and 3). (b) Within the IIDK, with Alpine overprint is restricted to discrete greenschist-facies shear zones. - IIDK-Mombarone nappe contact in Val Sermenza. (c) Local preservation of pre-Alpine magmatic textures within the IIDK and the Mombarone units is due to heterogeneous, sometimes low-strain Alpine deformation. – pre-Alpine migmatite, St. Anna N' Rimella. (d) D_1 fabrics within the pressure shadow of a mafic boudin. – near Scalaro, lower Val d'Aosta (e) Static intergrowth of omphacite, phengite and quartz within the axial plane of a F_1 fold. (f) In the macroscale, the Chiusella Shear Zone is characterized by its steeply inclined, blueschist-facies S_2 foliation. – Tallorno, Val Chiusella (g) Ls_2 and mineral lineation within the D_2 mylonites plunge gently to SSE. – Tallorno, Val Chiusella. (h) In the microscale, S_2 is defined by the assemblage glaucophane, garnet, plagioclase, quartz and phengite and less chlorite. (i) Fabric domain 3a is characterized by D_3 folding from macro- to microscale. – Sparone, Valle dell'Orco. (j) Parallel to the flat to moderately dipping F_3 axial planes, a S_2-S_3 composite foliation developed. – Fervento, Val Sermenza. (k) At the microscale, D_3 deformation is related to the growth of green amphibole. (l) Fabric domain 3b is defined by the flat to moderately dipping S_3 of the Ometto shear zone, which is preserved in the highest mountain peaks of the central Sesia Zone. - M. Voghel, Val Gressoney. (m) Shear bands within the S_3 indicate top-E to top-SE shearing. – Boccioleto, Val Sermenza. (n) D_3 deformation is accompanied by retrogression of glaucophane to actinolite, biotite and chlorite. (o) D_4 Gressoney shearing affected the Liguro-Piemontese (LP) ophiolites and the Bard unit. In Val Gressoney, S_4 is parallel to the LP-Bard contact, slightly folded by open F_5 folds. (p) D_4 Top-SE shear bands in the Sesia streambed near Alagna. (q) During D_4, the assemblage chlorite, green biotite, actinolite albite and quartz is indicative of greenschist facies conditions. (r) In upper Val d'Otro/Val Sesia, the S_4 foliation has largely been folded by late D_5. (s) In the northwestern Sesia Zone, D_5 folding is associated with reactivation of pre-existing foliation under greenschist facies conditions. – San Giuseppe, Val Sermenza. (t) Strongly localized D_5-reactivated foliation domain with sharp contact to preserved S_2-S_3 composite foliation.

To simplify matters, we did not distinguish amongst pre-Alpine deformational phases, and we disregarded all but the largest brittle structures, most of which are related to the fifth Alpine (Insubric) deformational phase. It turned out that none of these structures is related to significant exhumation of HP rocks, although the impressive Miocene to Recent faulting and uplift in the Alps is partly responsible for the excellent exposure in the Western Alps.

Alpine glaciation has carved more than 2000 meters of vertical relief, affording a spectacular view of the three-dimensional structure of the Sesia Zone and its adjacent units. The cross-sections in Figures 4.5a-f depict this crustal scale structure, with different symbols delineating the traces of the dominant foliations in each fabric domain.

4.3.1.2 Pre-Alpine fabrics

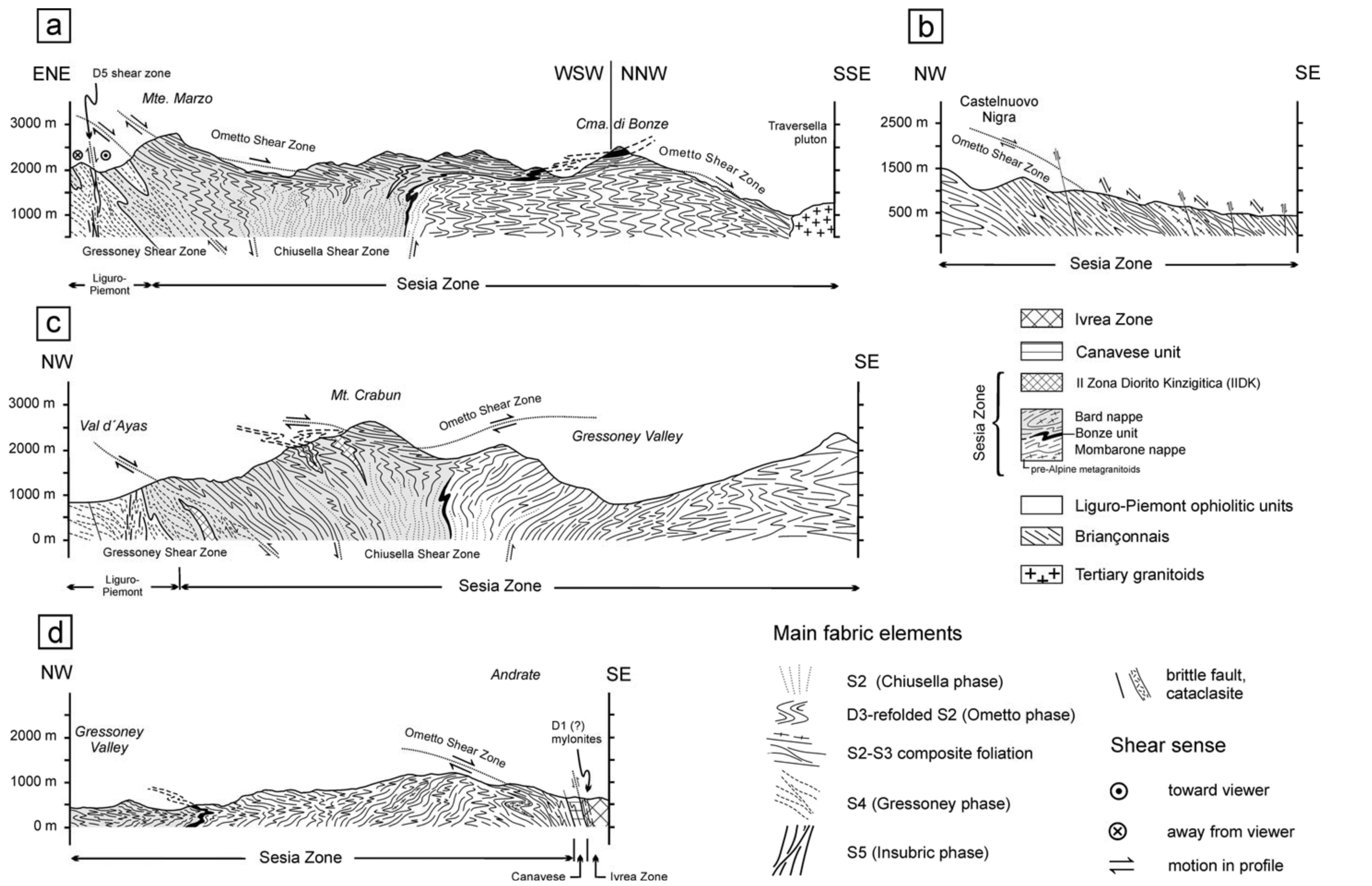
Pre-Alpine fabric relics are ubiquitous in all basement units of the Sesia Zone (e.g. Dal Piaz et al. 1972; Williams and Compagnoni 1983; Lardeaux and Spalla 1991), but form the dominant fabric only within the II ZDK unit (crosshatched areas in Fig. 4.3). There, pegmatite dykes and migmatites truncate pre-Alpine foliations and are themselves locally overprinted by Alpine blueschist- (Ridley 1989) and greenschist-facies shear zones (Fig. 4.4b). Pre-Alpine granitoids preserve their magmatic texture, even though they underwent static recrystallization at greenschist-facies conditions (Fig. 4.4c). The SW margin of the large II ZDK body in the northeastern part of the Sesia Zone was overprinted by D_5 mylonitic shearing (Isler and Zingg 1974) related to a splay of the Periadriatic Fault System.

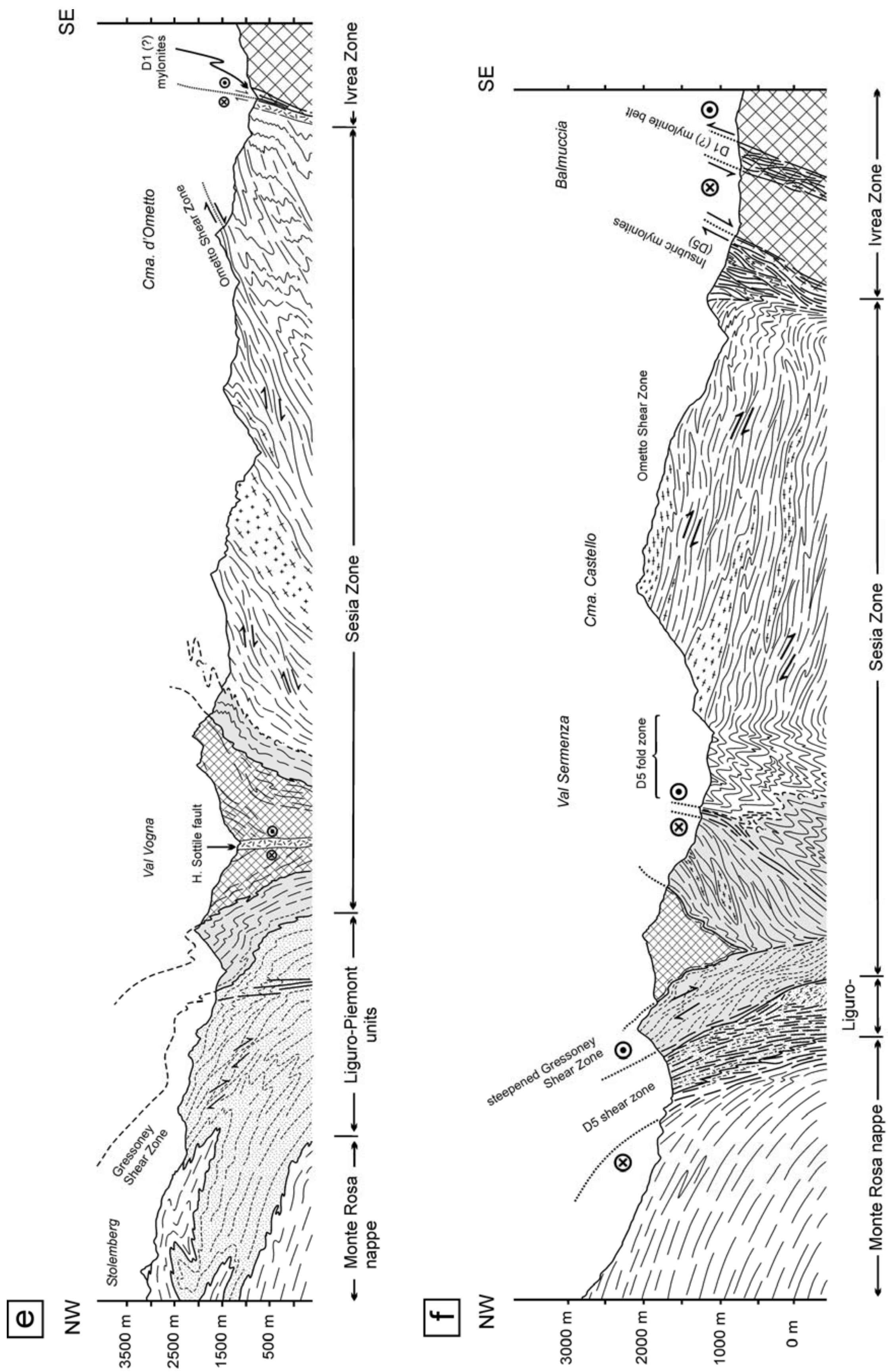
4.3.1.3 Fabrics in domain 1 - subduction

Fabric domain 1 comprises prograde, blueschist-to-eclogite facies syn-kinematic assemblages which are only locally distinguishable as structures in outcrop and thin section (e.g. Mucrone area, starred locations in Fig. 4.3, cf. Zucali et al. 2002). These include relic S_1 foliations preserved in the pressure shadows of mafic boudins (Figs. 4.4d, e) and fold hinges, or within S_2 foliation boudins (Gosso et al. 1979; Reinsch 1979) and garnets (Pognante et al., 1987). With the possible exception of the Bard-Mombarone contact, no large structures associated with subduction are preserved in the Sesia Zone (Gosso 1977; Gosso et al. 1979; Pognante et al. 1980). However, a greenschist-facies mylonite belt at the northwestern margin of the Ivrea Zone lends itself to interpretation as a D_1 shear zone, as discussed below.

4.3.1.4 Fabric domain 2 – transpressional exhumation

Fabric domain 2 is clearly exposed in two tectonic windows (red areas in Fig. 4.3, Figs 4.5a and c) in the footwall of fabric domains 3 and 4. These windows contain a steeply NW-dipping S_2 foliation (equal area plot in Fig. 4.3) that defines a km-wide shear zone (the Chiusella shear zone) overprinting part of the boundary between the Bard, Bonze and Mombarone units. The gentle to moderate plunge of the stretching lineation, Ls_2, comprising feldspar, quartz and glaucophane on this foliation (Figs. 4.4f, g) indicates a significant strike-slip component of shear during exhumation. Shear bands indicate sinistral SE-side up motion. S_2 is itself is defined by syn-kinematic, retrograde blueschist-facies assemblages grading to greenschist-facies assemblages in the NW parts of the Chiusella shear zone (Fig. 4.4h).


a
ENE
WSW
NNW
SSE
D5 shear zone
Mte. Marzo
Ometto Shear Zone
Cma. di Bonze
Ometto Shear Zone
Traversella pluton
3000 m
2000 m
1000 m
Gressoney Shear Zone
Chiusella Shear Zone
Liguro-Piemont
Sesia Zone
b
NW
SE
Castelnuovo Nigra
Ometto Shear Zone
2500 m
1500 m
500 m
Sesia Zone
c
NW
SE
Mt. Crabun
Ometto Shear Zone
Val d´Ayas
Gressoney Valley
3000 m
2000 m
1000 m
0 m
Gressoney Shear Zone
Chiusella Shear Zone
Liguro-Piemont
Sesia Zone
d
NW
SE
Andrate
Gressoney Valley
Ometto Shear Zone
D1 (?) mylonites
2000 m
1000 m
0 m
Sesia Zone
Canavese
Ivrea Zone
Ivrea Zone
Canavese unit
Sesia Zone
II Zona Diorito Kinzigitica (IIDK)
Bard nappe
Bonze unit
Mombarone nappe
pre-Alpine metagranitoids
Liguro-Piemont ophiolitic units
Briançonnais
Tertiary granitoids
Main fabric elements
S2 (Chiusella phase)
D3-refolded S2 (Ometto phase)
S2-S3 composite foliation
S4 (Gressoney phase)
S5 (Insubric phase)
brittle fault, cataclasite
Shear sense
toward viewer
away from viewer
motion in profile


e
NW
SE
3500 m
2500 m
1500 m
500 m
Stolemberg
Gressoney Shear Zone
Val Vogna
H. Sottile fault
Cma. d'Ometto
Ometto Shear Zone
D1 (?) mylonites
Monte Rosa nappe
Liguro-Piemont units
Sesia Zone
Ivrea Zone
f
NW
SE
3000 m
2000 m
1000 m
0 m
steepened Gressoney Shear Zone
D5 shear zone
Val Sermenza
D5 fold zone
Cma. Castello
Ometto Shear Zone
Balmuccia
Insubric mylonites (D5)
D1 (?) mylonite belt
Monte Rosa nappe
Liguro-Piemont units
Sesia Zone
Ivrea Zone

Previous pages: Fig. 4.5: Structural cross sections of the Sesia Zone and adjacent tectonic units: (a) Val Chiusella section; (b) Castelnuovo section; (c) and (d) Val d'Aosta sections; (e) Val Sesia section; (f) Val Sermenza section. Symbols indicate fabric domain and kinematics as described in the legend. Location of cross sections shown in Figures 4.2 and 4.3. No vertical exaggeration.

Towards the SE within this shear zone, low-strain domains preserve isoclinal F_2 folds and even relic D_1 structures with the transitional blueschist-eclogitic assemblage: garnet, omphacite, zoisite, rutile, phengitic white mica and pale blue Fe-poor glaucophane. This D_1 glaucophane is overgrown statically during D_2 by dark blue Fe-rich glaucophane (Konrad-Schmolke et al., Chapter 5). The asymmetry in the syn-kinematic metamorphic zonation of the Chiusella shear zone suggests that it accommodated differential exhumation of the Mombarone nappe. Traces of D_2 deformation are ambiguous outside of the fabric domain 2 windows mentioned above, but there is local evidence that the Chiusella shear zone extended throughout the Sesia Zone. For example, in the Val Sesia just south of the trace of the section in Figure 4.5e (see also Fig. 4.3), a D_2 blueschist-facies shear zone overprints the southern contact between the IIDK unit and the Mombarone nappe, as observed by Ridley (1989).

4.3.1.5 Fabric domain 3 –extensional exhumation

Fabric domain 3 covers most of the Sesia Zone (Fig. 4.3) and is defined by gently to moderately dipping, retrograde greenschist-facies structures. These take the form of flat-lying F_3 folds (fabric domain 4.3a, light brown area in Fig. 4.3) that tighten up-section as the folded S_2 foliation is transformed into a penetrative mylonitic S_3 foliation (fabric domain 3b, yellow area in Fig. 4.3). The change in deformational style from fold-dominated in the valleys to foliation-dominated domains at higher altitudes represents a vertical increase in D_3 strain and defines a large extensional shear zone, here named the Ometto shear zone (Fig. 4.4l). The folds at the base of this shear zone vary in size (amplitudes from centimetres to hundreds of meters, Figs. 4.4i, j, o) and flatten both the D_2 Chiusella shear zone and the Bard-Mombarone contact (Figs. 4.5a, c, d).

The mylonitic foliation of the Ometto shear zone is best exposed in the highest peaks of the Sesia Zone (e.g. Monte Marzo and Cima di Bonze in Fig. 4.5a, Mt. Crabun in Fig. 4.5c, see also Passchier et al. 1981) but also occurs at more accessible altitudes just north of Castelnuovo Nigra (Fig. 4.5b), Andrate

(Fig. 4.5d) and at the type locality of Cma. d'Ometto (Fig. 4.5e). Where unaffected by later deformation, the Ometto shear zone has a gently NE- and SW-plunging Ls_3 stretching lineation (equal area plots, Fig. 4.3) defined by dynamically recrystallized feldspar and quartz that are often also aligned parallel to the F_3 fold axes. The sense of shear parallel to Ls_3 is top-E to -SE, judging from shear bands in domain 3b (Figs. 4.4m, n) and the vergence of F_3 folds at the transition from domains 3a to 3b. However, the lack of fold vergence in large parts of domain 3a indicates that near-coaxial, vertical shortening predominates in the footwall of the Ometto shear zone.

In domain 3a, the dominant foliation is a composite of S_2 and S_3 (Fig. 4.4j). It comprises phengitic white mica, albite, minor biotite and green to colourless calcic amphibole that grew at the expense of glaucophane (Fig. 4.4k). Reequilibration during D_3 was incomplete, so that relict D_1 and D_2 assemblages are common in this domain (stars in Fig. 4.3 indicate the best preserved eclogitic relics). In contrast, S_3 transposition in domain 3b is nearly complete and eclogitic and blueschist-facies assemblages are rarely preserved (e.g. garnet in Fig. 4.4n).

4.3.1.6 Fabric domain 4 – the Gressoney shear zone

Fabric domain 4 overprints the NW margin of the Bard nappe and large parts of the Liguro-Piemontese unit. (light green area in Fig. 4.3). This fabric domain corresponds to the Gressoney shear zone, first described by Wheeler and Butler (1993). It is defined by a retrograde greenschist-facies S_4 schistosity oriented parallel to the base of the Bard nappe (equal area plots in Fig. 4.3, Fig. 4.4o) as well as by open to tight folds (amplitudes from cm to tens of meters) with gently SE-dipping axial planes. These orientations are affected locally by D_5 folds and later brittle faults, especially in the NE part of the area in Figure 4.3. Where S_4 is undisturbed, however, it contains a stretching lineation, Ls_4 that plunges gently to the E to SE (equal area plot, Fig. 4.3). The sense of shear parallel to Ls_4 is consistently top-E to -SE (shear bands in Figs. 4.4p, q), as also documented by Wheeler and Butler (1993). We distinguished D_4 from D_3 fabrics based on refolded F_3 folds (Fig. 4.4p) as well as on the different behaviour of feldspar: In D_4 fabrics, feldspar displays both cataclasis and limited dynamic recrystallization, whereas in D_3 fabrics it shows only dynamic recrystallization. The D_4 assemblage in granitoid rocks includes dynamically recrystallized quartz, green biotite, chlorite, epidote and albite (Fig. 4.4q). Taken together, these observations indicate that the part of the Gressoney shear zone that overprinted the Bard nappe was active at slightly lower temperature, greenschist-facies conditions than the Ometto shear zone in its hangingwall. Where the Ometto shear zone is not well developed, D_4 directly overprints even older fabrics, for example in the Val d'Ayas (Fig. 4.5c) where it deforms D_2 fabrics of the Chiusella shear zone, or in the Val Sermenza (Fig. 4.5f) where it cuts pre-Alpine fabrics of the II ZDK unit.

4.3.1.7 Fabric domain 5 –the Periadriatic shear zone

D_5 fabrics are characterized by steeply dipping, retrograde greenschist-facies structures that occur predominantly in the NE part of the Sesia Zone and overprint tectonic units to the north (dark green areas in Fig. 4.3). These structures include shear zones ranging in width from tens to hundreds of meters, and upright, acylindrical folds with amplitudes from cm to hundreds of meters. Most prominent amongst these folds is the Vanzone antiform in the Monte Rosa nappe (e.g. Keller et al. 2005), but related D_5 folds in the Sesia Zone deform the S_3 foliation of the Ometto Shear Zone into large, open antiforms and narrow D_5 synforms. The Boccioleto antiform (Fig. 4.3) and the antiform in the central part of the Mombarone nappe are broad F_5 folds that arched the S_3 foliation (see F_5 axial traces and curved S_3 traces in Fig. 4.3). The F_5 folds tighten parallel to their gently plunging axes until they merge down-plunge with greenschist-facies mylonitic shear zones. These shear zones are well developed in the NE part of the Sesia Zone, where they envelop lozenges of older fabric domains and are contiguous with the greenschist-facies mylonite belts along the contact between the Sesia and Ivrea Zones (Fig. 4.3). Handy et al. (2005) interpreted these shear zones to be mylonitic splays of the Periadriatic fault system.

Several overprinting relationships are key to distinguish D_5 structures from earlier fabrics formed under similar greenschist facies conditions: A large F_5 fold in the southern limb of the Vanzone antiform steepens domain 4 fabrics of the Gressoney shear zone at the base of the Bard nappe (Figs. 4.4r, 4.5f). A widespread observation made is that earlier foliations were reactivated and transposed during F_5 folding, leading to the development of S_4 in the limbs of F_4 folds (Figs. 4.4s, t) to the exclusion of an axial plane foliation. Fold style and particularly the microstructural behaviour of feldspar also help to differentiate D_5

from D_3 and D_4 structures. F_5 folds form chevrons and kinks in micaceous rocks, whereas quartz-rich rocks generally have similar folds. Feldspar clasts in a matrix of quartz and mica fracture and undergo dynamic recrystallization, suggesting that D_5 folding occurred at the ductile to brittle transition of feldspar. Likewise, quartz aggregates in D_5 mylonites show dynamic recrystallization (subgrain rotation und bulging recrystallization) transitional to cataclasis at the Sesia-Ivrea contact (e.g. Schmid et al. 1987).

4.3.1.8 The Sesia-Ivrea contact

The contact between the Sesia and Ivrea Zones warrants separate consideration because it is the site of several complex, key relations. Greenschist-facies mylonite along this contact is well-known in the literature ("Scisti di Fobello e Rimella", mylonite belt 2 of Schmid et al. 1989) and is laterally continuous with D_5 mylonitic splays in the Sesia Zone, as described in the previous section (areas coloured dark green in Figure 4.3). This mylonite belt accommodated oblique, top-E backthrusting parallel to a steeply plunging stretching lineation (equal area plot in Fig. 4.3) and effected exhumation of the Sesia Zone onto the Ivrea Zone, probably in Oligo-Miocene time (Schmid et al. 1989, Zingg and Hunziker 1990). This mylonite belt can be mapped as far southwest as Scopello in Val Sesia (Fig. 4.3), where part of it appears to splay eastward into the Mombarone nappe. The other part is transitional southwestward to cataclasite that overprints the Oligocene volcanoclastic cover of the Sesia Zone (Fig. 4.3, Schmid et al. 1989).

Another greenschist-facies mylonite belt strikes parallel to the belt above, but deforms the northwestern margin of the Ivrea Zone (thin blue band in Fig. 4.3). It is cut by the Tertiary mylonite belt above and by mafic dykes of inferred Oligocene age (mylonite belt 1 of Schmid et al. 1989). These relations are consistent with the prevalence of late Cretaceous (60-75 Ma) K-Ar formational white mica ages in Canavese metasediments overprinted by this older mylonite (Zingg and Hunziker 1990). Kinematic indicators in this mylonite belt show dextral, oblique-slip motion of the Ivrea Zone parallel to a gently SW-plunging stretching lineation (Schmid et al. 1989). However, paleomagnetic work on the cross-cutting mafic dykes indicates that the pre-Oligocene orientation of the mylonitic foliation was gently SE-dipping (Schmid et al. 1989), such that mylonitization involved oblique, W-directed thrusting of the Ivrea Zone. This mylonite belt can be traced from the Val Sesia (Fig. 4.5f) to the southwest as far as the lower Val d'Aosta (Figs. 4.5d, e). There, they are juxtaposed with D_3 greenschist-facies mylonite along the eastern margin of the Mombarone nappe (fabric domain 3b in Fig. 4.3). In the sections below, we argue that this older mylonite belt probably formed during D_1.

Brittle faults along the southwestern segment of the Sesia-Ivrea border have both extensional and dextral strike-slip components (Fig. 4.5b), which may be attributed partly to activity of the Cremosina fault (Fig. 4.3, "external" and "internal Canavese Lines" of Biino and Compagnoni 1989, Schumacher et al. 1997). Although the details of the brittle deformational history are unresolved, this late faulting evidently lead to pinching of the Oligocene volcanoclastic cover of the Mombarone nappe together with the Mesozoic Canavese metasediments and the Ivrea Zone (Schmid et al. 1989).

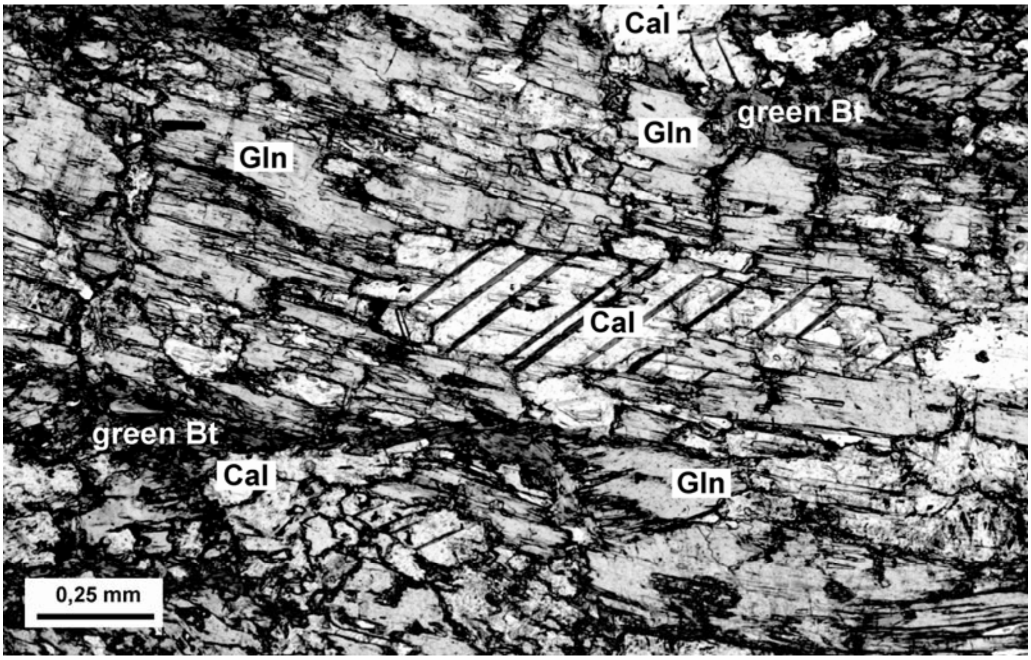


Fig. 4.6: Na-amphibole in Mesozoic metasediment of the Canavese Zone at Scopello, Val Sesia (location in Figs. 4.2 and 4.3). Swiss Coordinates: 615.180/69.185.

The Mesozoic Canavese metasediments are deformed by all of the aforementioned mylonite belts and faults (Zingg and Hunziker 1990). In most locations, including the type locality in the lower Val d'Aosta (Montalto Dora in Fig. 4.3), these metasediments are affected only by greenschist-facies metamorphism and deformation (Zingg et al. 1976, Biino and Compangnoni

1989). However, we discovered that they also contain blue, Na-rich amphibole (Fig. 4.6) at Scopello in Val Sesia (Fig. 4.2). Although blueschist-facies metamorphism in the Canavese sediments is so far limited to this single locality, it indicates that the Sesia-Ivrea contact was the southern limit of Alpine subduction. This is consistent with the occurrence of prograde blueschist-facies mylonites along the southeastern margin of the Sesia Zone, SW of the area in Figure 4.2 (Pognante 1989). Hence, pre-Oligocene mylonitic deformation along the Sesia-Ivrea contact must have involved exhumation and juxtaposition of subducted and non-subducted fragments of the Canavese sediments.

To summarize section 3, fabric mapping reveals crustal-scale shear zones that developed under retrograde metamorphic conditions and overprint all subduction-related structures, including the thrust contact between the Bard and Mombarone basement nappes. These shear zones are responsible for exhuming the HP rocks in the Sesia Zone, beginning with oblique-slip D_2 deformation under retrograde eclogite- to blueschist- to greenschist-facies conditions and followed by D_3 top-E to -SE extensional shearing under retrograde greenschist-facies conditions. D_4 extensional shearing exhumed HP rocks in the footwall of the Sesia Zone, whereas D_5 Insubric deformation effected differential exhumation only of the northeastern part of the Sesia Zone. The Sesia-Ivrea contact was a site of repeated Alpine movement, beginning with subduction and recurring during all of the exhumational phases described above.

4.3.2 Pressure-temperature-time evolution of HP rocks in the Sesia Zone

Figure 4.7 shows the pressure-temperature-time (PTt) paths of the Mombarone, Bard and II ZDK basement nappes in the vicinity of the cross section in Figure 4.5d, i.e., away from areas with pervasive D_5 deformation. Age ranges for the Alpine fabric domains are based on radiometric, stratigraphic and paleobotanical data discussed and cited below.

The age of prograde blueschist- to eclogite-facies metamorphism (D_1) is constrained only by high-retentivity ages in the Mombarone nappe that range from 65 Ma (U-Pb SHRIMP zircon ages on leucosome in eclogite, Rubatto et al. 1999) to 69 Ma (Hf-Lu ages on coexisting garnet and phengite, Duchêne et al. 1997). Eclogite-facies metamorphism in the Bard nappe has not been dated yet.

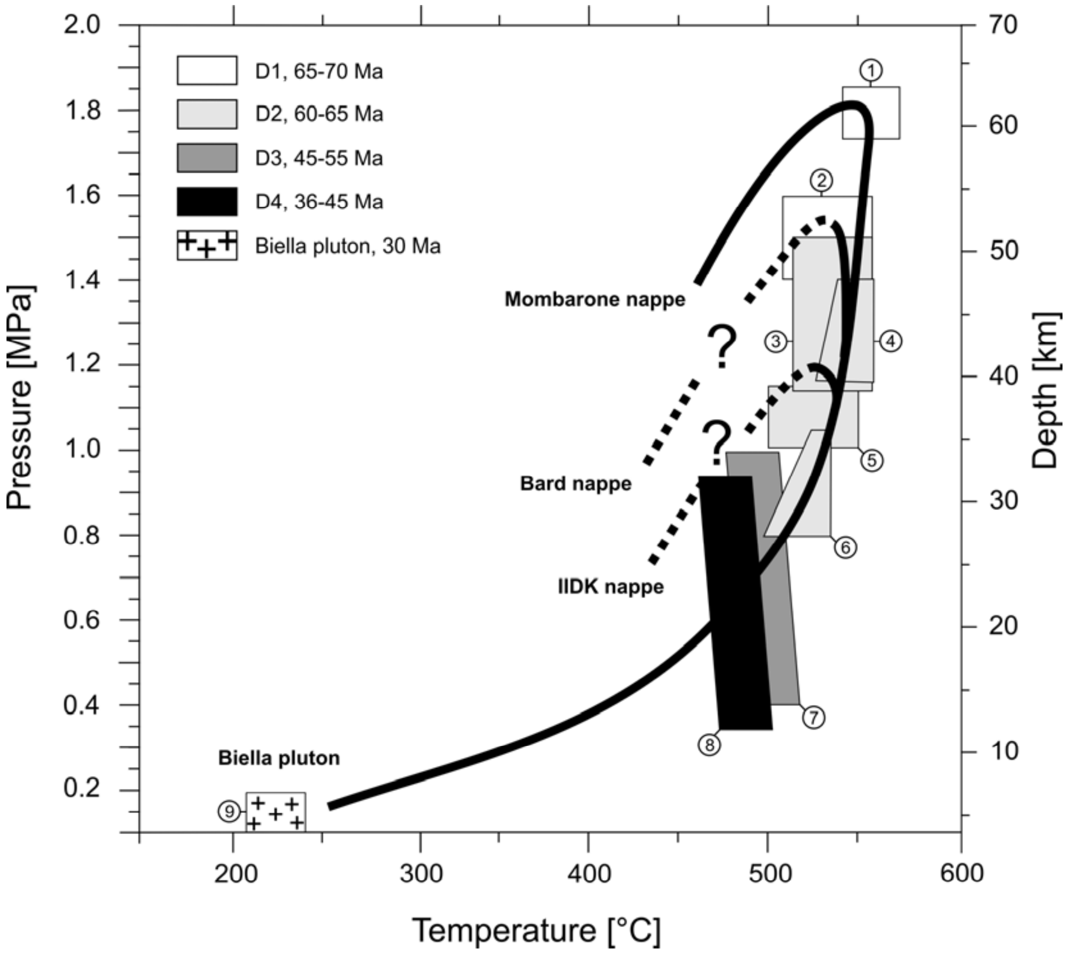


Fig. 4.7: Pressure-temperature plot showing the thermobarometric evolution of the Mombarone, Bard and II ZDK basement nappes in the vicinity of the cross section in Figure 4.5d. Solid part of the PT curve for the Mombarone nappe taken from the thermodynamic modelling of Konrad-Schmolke et al. (Chapter 5); curves for the Bard and II ZDK nappes are constructed from constraints in the boxes. Dashed parts of curves are speculative. Numbered boxes show the PT constraints obtained with various petrological methods: (1) peak conditions in the Mombarone nappe, Lardeaux et al. 1982; (2) peak conditions in the Bard nappe, Lardeaux and Spalla 1991; (3) peak conditions/late D1 conditions in the Bonze unit, Venturini 1994; (4) early D2 conditions from thermodynamic forward modelling of glaucophane zonation patterns, Konrad-Schmolke et al., Chapter 5; (5) thermobarometric multi-equilibrium calculation (TWQ, Berman 1991) of the syn-D2 assemblage ab + gln + grt + chl + qtz; (6) late D2 conditions from thermodynamic forward modelling of calcic amphibole zonation patterns, Konrad-Schmolke et al., Chapter 5; (7) amphibole geothermometry of syn-D3 calcic amphiboles after Holland and Blundy 1994, Konrad-Schmolke et al., in review; (8) amphibole geothermometry of syn-D4 calcic amphiboles after Holland and Blundy 1994, Konrad-Schmolke et al., Chapter 5; (9) intrusion depth of Biella pluton, Rosenberg 2004. Shading of boxes refers to the Alpine fabric domain to which the PT estimates apply. Age ranges for the Alpine fabric domains are based on radiometric, stratigraphic and paleobotanical data discussed in the text. Depth axis calculated with an assumed density of 2.8 g/cm³.

The fact that peak pressures in the Mombarone nappe exceed those in the Bard nappe, and that both units experienced D_2 shearing at somewhat lower pressures (Fig. 4.7) indicates that the Mombarone nappe was exhumed relative to the Bard nappe before or during the early stages of D_2 Chiusella shearing. Certainly, thrusting along the nappe contact marked by the MCC unit (Fig. 4.2) preceded greenschist-facies shearing of both basement nappes by the end of D_2. Synkinematic phengite and feldspar making up S_2 yield a 63 Ma Rb-Sr phengite-feldspar isochron (see appendix), interpreted here as a formational age during D_2 deformation. This age falls near the upper limit of a broad range of previously published 60-90 Ma Rb-Sr phengite ages (see Handy and Oberhänsli 2004, and references therein), all from the Mombarone nappe, spanning the time for D_1 deformations, as well as for the D_2 transition from eclogite facies to retrograde blueschist- and greenschist-facies conditions. The youngest ages within this range probably date D_2, based on the proximity of the 500°C closing temperature in the Rb-Sr phengite system to the maximum temperatures (530 +/- 35°C, Fig. 4.7) that prevailed at, or soon after the baric peak of metamorphism during D_2 shearing. The near-isothermal decompression path for D_2 in the Mombarone unit (Fig. 4.7) combined with the preserved syn-kinematic, blueschist-to-greenschist-facies field gradient across the Chiusella shear zone suggest that late Cretaceous D_2 exhumation was rapid, possibly occurring within only a few million years of the baric peak.

Peak pressures in the II ZDK unit (1.0-1.2 GPa) are less than those attained in the Mombarone and Bard nappes (Fig. 4.7), but within the same range of peak values obtained for D_2 Chiusella shearing (1.05 GPa). This corroborates previous work indicating that the blueschist facies metamorphism is prograde in the II ZDK unit, but retrograde with respect to the eclogite-facies assemblages in the Mombarone unit (Ridley 1989). Thus, the II ZDK nappe was juxtaposed with the other two basement units under blueschist-facies conditions (Dal Piaz et al. 1971; Pognante et al. 1987; Ridley 1989) during D_2 Chiusella shearing, but before D_3, which affected all three basement units.

D_3 Ometto extensional shearing involved pronounced cooling relative to decompression (Fig. 4.7) in all three basement units. It obviously occurred after D_2, but its maximum age is otherwise unconstrained. A minimum age for D_3 is provided by an undeformed andesitic dyke that cuts the S_2-S_3 composite foliation in fabric domain 3a of the Mombarone nappe (Fig. 4.8a). A Rb-Sr feldspar-hornblende isochron defines an age of 44.2 ± 2.4 Ma, which is interpreted as the minimum age of dyke intrusion and therefore, also of D_3 (Fig. 4.8b, Häußler 2005).

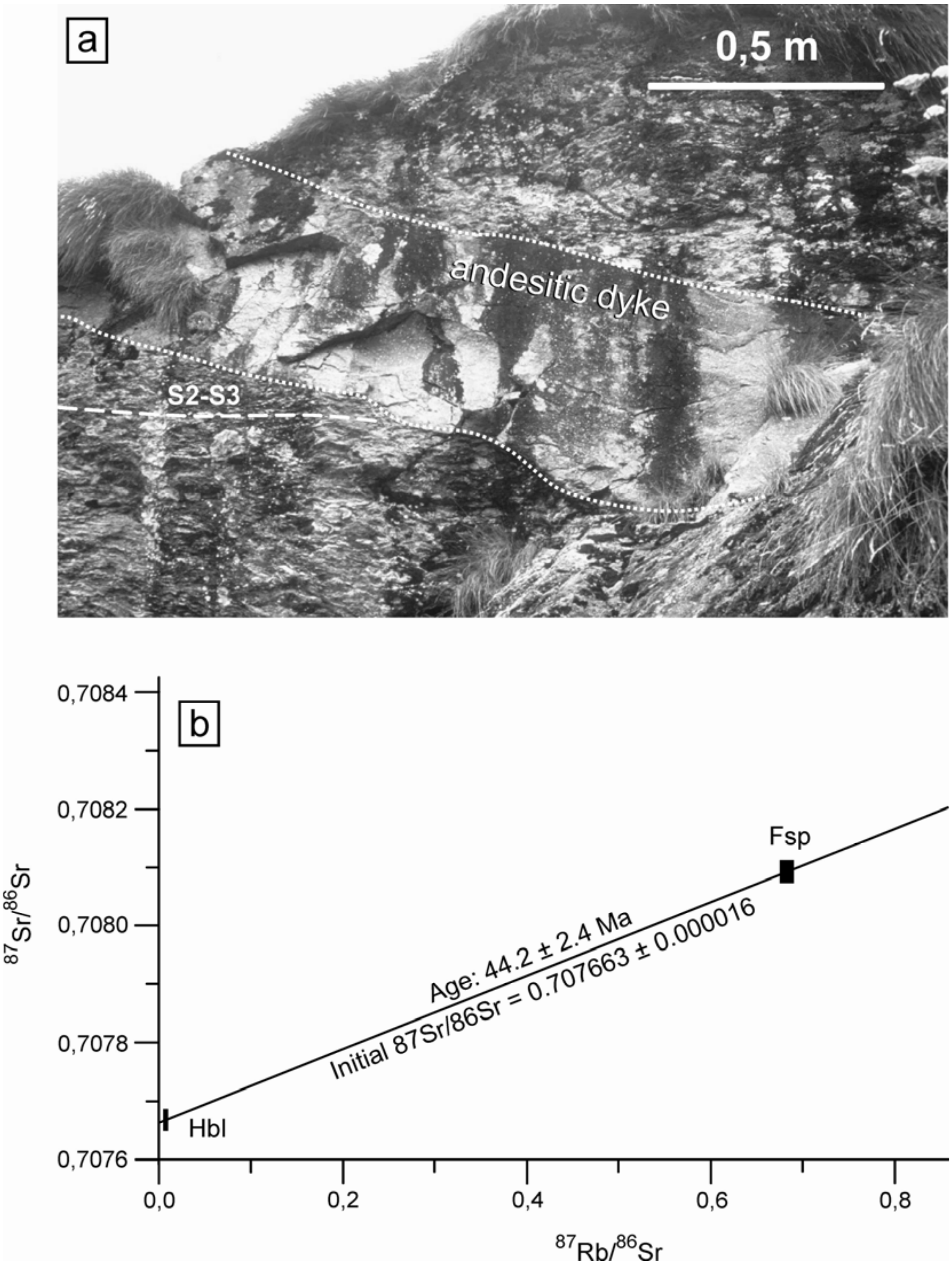


Figure 4.8: Structural marker for minimum age of Ometto shear zone: 44 Ma old andesitic dyke truncates S_2-S_3 composite schistosity in fabric domain 3a in the Mombarone nappe. Location: Lower Val Chiusella.

This minimum D_3 age is consistent with overprinting relations along the northwestern margin of the Bard nappe, indicating that D_3 must be older than the onset of D_4 Gressoney shearing at about 45 Ma (Rb-Sr phengite ages in Reddy et al. 2003). D_4 Gressoney extensional shearing in the Liguro-Piemontese units lasted until about 36 Ma (Reddy et al. 1999), but probably stopped much earlier in the overlying Bard nappe (ca. 40-45 Ma) based on the progressive decrease in Rb-Sr phengite ages down into the Tertiary nappe pile (Reddy et al. 1999). The Gressoney shear zone affected the base of the Sesia Zone, so it cannot have exhumed the Sesia HP rocks in its hangingwall. However, it is potentially responsible for exhumation of Early Tertiary HP rocks in its footwall, as discussed in the next section. From 45 Ma until the end of D_4 shearing at 36 Ma, the Bard and Mombarone nappes experienced only modest decompression (Fig. 4.7). During this time and until 30 Ma, both nappes cooled from about 440° (Konrad-Schmolke et al. Chapter 5) to below 225°C (Fig. 4.7), as documented by Rb-Sr mica cooling ages (Hunziker et al. 1992, Reddy et al. 1999) and zircon fission track ages (Hurford and Hunziker 1985, Hurford et al., 1991, Bistacchi et al. 2001). This prolonged cooling may be responsible for the partial annealing of D_3 and older fabrics in the Sesia Zone. The Oligocene Biella and Traversella plutons are shallow intrusions and the part of the Mombarone nappe adjacent to the Ivrea Zone is overlain by 33 Ma volcanoclastic sediments containing boulders of Sesia eclogite (Scheuring et al. 1974). Thus, the HP rocks of the central and southern Sesia Zone had reached the surface before the onset of D_5 deformation.

D_5 mylonitic backthrusting along the Sesia-Ivrea contact exhumed the northeastern part of the Sesia Zone by some 10 km in the interval of 30 to 19 Ma (Handy et al. 2005 and references therein). Zircon and apatite fission track ages in this area are only about 27 and 9 Ma, respectively (Hurford et al. 1991). This contrasts with the lack of ductile D_5 deformation and exhumation of the Sesia Zone southwest of the section in Figure 4.5e, where zircon and apatite yield ages are only 32-39 Ma (Hurford et al. 1991) and 24-29 Ma (Bistacchi et al. 2001). Thus, post-Insubric exhumation of the northeastern part of the Sesia Zone probably occurred less than 9 Ma ago and amounted to no more than a few km. This may be related to post-D_5 brittle faulting observed throughout the area (e.g. Aosta-Ranzola and Hospize-Sottile faults Figs. 4.2 and 4.3, Diamond and Wiedenbeck 1986; Hurford et al. 1991; Bistacchi et al. 2001).

To conclude this section, the HP rocks of the Sesia Zone were exhumed mostly in late Cretaceous time, during D_2 Chiusella transpressional shearing, and to a lesser extent in Early Tertiary time in the footwall of the D_3 Ometto extensional shear zone. The HP rocks cooled slowly from 45 to 30 Ma, when they were exposed to erosion at the surface. Since then, brittle deformation had little effect on D_2 and D_3 structures, except in the northeastern part of the Sesia Zone where all tectonic units remained buried at about 10 km depth until their exhumation by middle Tertiary D_5 backfolding and –thrusting and post-Oligocene brittle faulting.

4.3.3 A kinematic model for exhuming HP rocks

4.3.3.1 Original orientation of subduction and exhumation structures

Any kinematic reconstruction must account for the modifying effects of post- Early Tertiary deformation on the orientation of D_1, D_2 and D_3 structures responsible for subducting and exhuming the HP rocks in the Sesia Zone. Fortunately, most of this late deformation is restricted to the southeastern margin of the Mombarone unit south of the Biella pluton (Fig. 4.2), where brittle faults at the confluence of the Sesia-Ivrea contact and the Cremosina fault overprint mylonites described above (Fig. 4.3). There, paleomagentic data of Lanza (1979) from the Oligocene volcanoclastic cover of the Mombarone nappe indicate that the adjacent Sesia basement rocks underwent a post-Oligocene clockwise rotation of some 40° (looking NNE about a horizontal axis). This rotation diminishes to 0° towards the axial trace of the broad antiform within the Mombarone Unit, suggesting that at least some of the 40° rotation can be attributed to folding in the southeastern limb of this F_5 antiform (Figs. 4.3, 4.5c, d), as already suspected by Lanza (1979) and Gosso et al (1979). Other post-Oligocene brittle faults incurred minor displacement (2000–3000 m of N-block down extensional displacement on the Aosta-Ranzola normal fault, Figs. 4.2, 4.3; Diamond and Wiedenbeck 1986; Hurford et al. 1991; Bistacchi et al. 2001) and are located away from areas containing HP rocks (e.g. Hospizio Sottile Fault, Fig. 4.5e). The kinematic model discussed below therefore applies to that part of the Sesia Zone which contains HP rocks and is unaffected by D_5 faulting and differential exhumation.

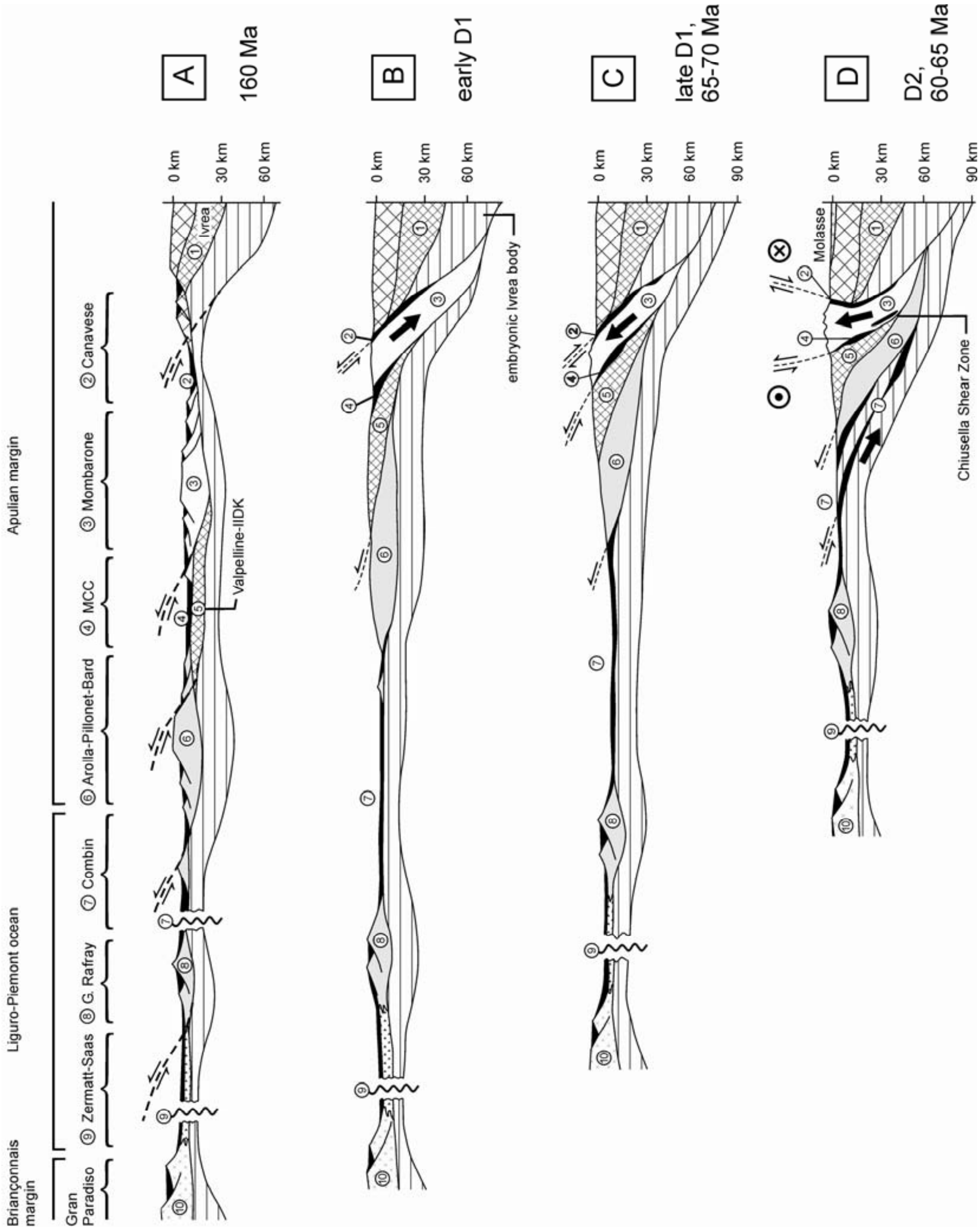
Unlike the Sesia Zone, the Ivrea Zone experienced significant Tertiary block rotation (Schmid et al. 1989, Handy et al. 1999). This entailed a post-Oligocene clockwise rotation of 60-85° looking northeast about a NE-SW trending, subhorizontal rotational axis. As discussed above, this rotation implies that the late Cretaceous, greenschist-facies mylonite belt at the northwestern rim of the Ivrea Zone (blue in Fig. 4.3) was originally gently ESE-dipping.

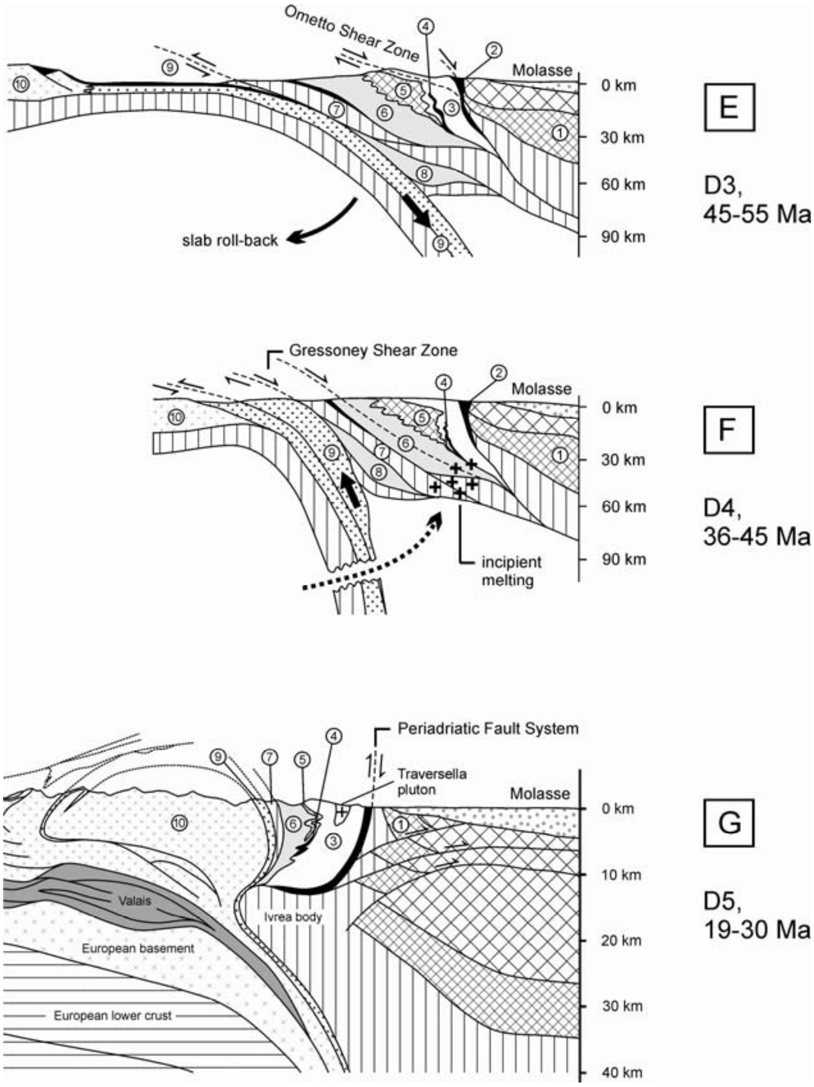
4.3.3.2 From rifting to subduction and early exhumation

The individuation of basement nappes along narrow zones containing Early Mesozoic metasediments in the Sesia Zone reflects the important role played by rift tectonics during later subduction and exhumation in the Western Alps. The series of cross sections in Figure 4.9 shows the evolution of the Apulian continental margin since the end of rifting and subsidence in Jurassic time. Although the evolution is depicted in cross sections, we emphasize the importance of motions perpendicular to these sections for the exhumational history, as discussed below.

The Austroalpine units (Sesia Zone, Dent Blanche and Pillonet klippe, Austroalpine outliers) are interpreted to have formed extensional allochthons at the distal part of this margin just prior to oblique-sinistral opening of the Liguro-Piemontese ocean in Middle Jurassic time (e.g. Dal Piaz et al. 2001). We positioned the Canavese and MCC metasediments, respectively, at the junction of the Ivrea crustal section and the Mombarone unit, and between the Mombarone and Bard nappes, in accordance with their present position between these basement units. The occurrence of metabasites with MORB signatures in the MCC unit (Venturini, 1995) as well as the preservation of chrome spinel within the Canavese metasediments (see Froitzheim et al., 1996) suggest that the thinned continental lithosphere at these localities had been the site of decompressional melting and incipient spreading at the top of the exhuming mantle lithosphere.

Thrusting at the onset of D_1 (Fig. 4.9b) localized at the necks of the extensional allochthons, probably by reactivating Jurassic extensional faults. This lead to the individuation of the basement nappes along the Mesozoic metasediments seen today. The southern border of this subduction zone is marked by prograde blueschist-facies assemblages in the Mesozoic Canavese sediments along the Sesia-Ivrea contact (Fig. 4.6), and possibly also by the late Cretaceous, greenschist-facies mylonite belt at the rim of the Ivrea Zone (marked blue in Fig. 4.3) that accommodated ESE-directed thrusting of the Ivrea Zone. The latter belt may represent a higher structural level within the subduction-accretion complex and was later juxtaposed with blueschist-facies mylonites along the Sesia-Ivrea contact (e.g. Pognante 1989) during D_2 and D_3 exhumation.





Previous and this page: Fig. 4.9: Model for the evolution of the Apulian continental margin and Tethyan ocean since Early Mesozoic time: (a) Apulian passive margin with location of future thrust planes during subduction; (b) incipient subduction of the Apulian margin, early D_1 thrusting and HP metamorphism of the Mombarone nappe (unit 1); (c) subduction of the IIDK and Bard nappes (units 2, 3) in external parts of the Apulian margin during late D_1 thrusting and initial exhumation of the Mombarone nappe; (d) D_2 transpressional exhumation of the Apulian margin involving thrusting and strike-slip shearing during high-stress oblique subduction of LP oceanic lithosphere; (e) D_3 extensional exhumation of Apulian margin in the upper plate of a low-stress, retreating subduction zone; subduction and HP-UHP metamorphism of LP oceanic lithosphere; (f) slow cooling and erosional denudation of the Apulian margin during rapid D_4 exhumation of HP-UHP rocks of the LP oceanic lithosphere, subduction of European (Briançonnais) and Valais oceanic lithosphere, incipient magmatism; (g) present lithospheric structure along ECORS-CROP section (Fig. 4.1) showing D_5 doming, Insubric shearing and Oligocene plutons.

At least three nappes developed within the subducting Austroalpine margin, as shown in Figure 4.9b. At the base of this margin, the Bard and Dent Blanche units are depicted as a continuous thrust sheet due to their close lithological affinity (gneiss minuti of the Bard unit correlated with the Arolla Series of the lower part of the Dent Blanche klippe, Compagnoni et al. 1977).

Likewise, the similarity of lower crustal rocks in the upper part of the Dent Blanche klippe (the Valpelline Series) to the II ZDK lithologies (Compagnoni et al. 1977) betrays a common origin within the former passive margin, possibly beneath part of the Bard unit or the MCC unit (Fig. 4.9a). Note that our reconstruction of the II ZDK-Valpelline nappe contrasts with all earlier interpretations in which the II ZDK nappe is derived directly from the Ivrea Zone (e.g. Compagnoni et al. 1977). Today, the basal thrust of the Bard and Dent Blanche units, as well as the overlying thrust within the Dent Blanche klippe and at the base of the II ZDK nappe are no longer continuously traceable at the surface due to Tertiary backfolding and erosion (Fig. 4.2).

The Mombarone nappe is interpreted to have reached its maximum depth of subduction during early D_1, somewhat before maximum subduction of the Bard nappe during late D_1 (Fig. 4.9c). Initial exhumation of the Mombarone nappe from greater depth is inferred to have involved D_1 thrusting at its base in order to account for the fact that the mutual contact of the Mombarone and Bard nappes is overprinted by the D_2 Chiusella shear zone. Subduction and initial exhumation during D_1 is inferred to have progressed from the SE to the NW, i.e., from left to right in Figures 4.9b and c. Accordingly, exhumation of the Mombarone nappe occurred directly beneath a mantle wedge formed when the distal continental margin was subducted beneath cold, rigid lithospheric mantle that had already been extensionally exhumed during Early Mesozoic rifting (Schmid et al. 1987).

4.3.3.3 Transpressional exhumation

D_2 shearing is responsible for transpressional exhumation of the HP rocks in late Cretaceous time (Fig. 4.9d). The retrograde blueschist- to greenschist-facies zonation across the steep D_2 Chiusella Shear Zone (Figs. 4.5a, c) is consistent with nearly isothermal E-side-up exhumation of the Mombarone nappe with respect to the Bard nappe. However, subhorizontal to moderately plunging Ls_2 stretching lineations (Fig. 4.3) suggest strike-slip or oblique-slip motion. Taken together, these structural and metamorphic features indicate an overall transpressional setting, as indicated in Figure 4.9d. As argued in the previous section, D_2 transpressional shearing also subducted the II ZDK nappe to its greatest depth, where it was juxtaposed with the Bard and Mombarone units.

For kinematic reasons, D_2 transpression must have involved another major shear zone along the Sesia-Ivrea contact to accommodate W-side-up exhumation of the Mombarone unit with respect to the Alpine unmetamorphosed rocks of the Ivrea Zone (Fig. 4.9d). This shear zone remains a kinematic necessity in need of verification in the field, as no late Cretaceous mylonite with kinematics appropriate for exhuming the Sesia Zone in its footwall has been found to date, mostly due to poor exposure of the mylonitic rocks in the central and southern segment of the Sesia Zone.

Regarded in a plate tectonic context, transpression during D_1 and D_2 is consistent with paleomagnetic and paleogeographical data calling for eastward displacement of the Ibero-Brianconnais peninsula with respect to both Europe and Apulia from late Cretaceous to Early Tertiary time (e.g. Dewey et al. 1989, Stampfli et al. 1998). Estimates of this displacement vary with the plate tectonic reconstruction, but most authors agree that a minimum displacement of 500 kilometres is necessary to allow for subduction of the Liguro-Piemontese ocean (e.g. Schmid et al 2004). We suspect that only a minor proportion of this amount was taken up by D_2 shear zones in the accreted continental crust represented by the Sesia Zone; most was accommodated by oblique subduction along a Late Cretaceous to Early Tertiary trench at the southern limit of the Liguro-Piemont ocean, as documented by Late Cretaceous flysch in thrust nappes of the Prealpes (Fig. 4.1).

4.3.3.4 Pre-collisional extensional exhumation

Early Tertiary D_3 deformation exhumed the Sesia Zone in the footwall of the Ometto extensional shear zone (Fig. 4.9e). The southern limit of this extensional shear zone was the southeastern margin of the Mombarone nappe along the Sesia-Ivrea contact (Fig. 4.3). The minimum age of Ometto shearing (45 Ma) falls within the 44-55 Ma age range for HP and UHP metamorphism in the underlying Liguro-Piemontese units (Handy and Oberhänsli 2004 and references therein). This supports the idea that D_3 extensional shearing in the Sesia Zone was coeval with subduction of oceanic lithosphere in its footwall, as depicted in Figure 4.9e. Thus, the entire Sesia Zone containing partly exhumed HP rocks from different depths of the accreted basement wedge was extruded toward the foreland and juxtaposed in its roof with rigid pre-Alpine rocks of the Ivrea Zone. We note that Inger and Ramsbotham 1997) also proposed coeval extension and thrusting as a means of exhuming the HP rocks in the Mombarone unit (their eclogitici micaschisti unit), but that they mistakenly related D_3 extensional shearing to purported blueschist-facies thrusting at the contact with the Bard nappe (their gneiss minuti unit). As shown in the previous section, blueschist-facies mylonites at this contact are related to D_2 Chiusella shearing.

D_4 Gressoney shearing represents a continuation of extensional shearing into the footwall of the Sesia Zone (Fig. 4.9f). This shearing is related to top-SE extensional shearing within the Liguro-Piemontese units (Combin shear zone of Ballèvre and Merle 1993) and effected extensional exhumation of HP and UHP rocks in the oceanic Zermatt-Saas units (e.g. Reddy et al. 2003). In the hangingwall of this extensional system, the Sesia Zone experienced only slow cooling and minor exhumation (Fig. 4.7).

4.3.3.5 Collisional exhumation

D_5 backfolding of the entire Tertiary nappe stack during the late stages of collision modified the former subducted Apulian margin, as shown in Figure 4.9g for the ECORP-CROP transect (Fig. 4.1). D_5 exhumation of the Sesia Zone in this section was minor, but as pointed out above, this exhumation increased toward the northeast along the strike of the Western Alpine arc. This D_5 exhumation gradient probably reflects an eastward increase in the amount of Oligo-Miocene north-south shortening combined with wedging of the Apulian lower crust beneath the retro-wedge of the Alpine orogen, as discussed in Schmid and Kissling (2000).

4.4 DISCUSSION OF EXHUMATION MECHANISMS

The kinematic model for exhuming HP rocks of the Sesia Zone presented above departs from existing kinematic and physical models of exhumation in several respects. First, we have shown that the Sesia Zone is a composite unit whose basement nappes followed different subduction and exhumation paths. Second, the exhumation of the HP rocks within these nappes is multistage during Late Cretaceous to Early Tertiary time. Third, most exhumation occurred in a transpressional, pre-orogenic setting and involved significant sinistral strike-slip motion. These aspects have major implications for assessing the mechanisms of exhuming HP rocks.

From the start, certain previously proposed mechanisms can be ruled out for the Sesia Zone. Exhumation of the Sesia Zone by corner flow within a low-viscosity accretionary wedge bounded above by the rigid Ivrea upper mantle body (Schmid et al. 1987) is incompatible with the preservation of coherent basement nappes within the Sesia Zone. There is no evidence in the exhumed Sesia rocks for the kind of laminar return flow required for corner flow (Cowan and Silling 1978) or channel flow (Cloos 1982). A period of plate-scale extensional exhumation between subduction and collisional episodes can be excluded in light of evidence that the convergence of Europe and Apulia continued uninterrupted from Late Cretaceous to Early Tertiary times (Schmid et al. 1996, Schmid and Kissling 2000). Arguments against other, older models of exhumation in the Sesia Zone center on dated or questionable assumptions regarding the age, conditions and kinematics of exhumation, as reviewed in the introduction. We therefore focus the remainder of this discussion on possible mechanisms for D_2 transpressional exhumation, and D_3 and D_4 extensional exhumation.

A recurring theme in discussions of exhumation is the relative roles played by buoyancy, isostacy, lithospheric rheology, and tectonic and erosional denudation. In the case of the HP rocks of the Sesia Zone, the importance of these factors changed both in time and space. The Mombarone nappe was subducted beneath a dense upper mantle wedge (Fig. 4.9b-d), leading to large density contrasts with the overlying rocks. Thus, buoyancy is a viable force for initial exhumation of the HP rocks during late D_1 and D_2 transpression. Buoyancy forces may have driven exhumation up to about 20-30 km depth, especially if the rising Mombarone rocks heated and hydrated the surrounding rocks, thus reducing their viscous shear strength (Konrad-Schmolke et al., Chapter 5).

Buoyancy-driven exhumation obviously did not work where the nappes containing the HP rocks were too small, where they were surrounded by rocks of similar density, or where shear resistance to their rise was too great. This pertains to the II ZDK nappe and probably also to the Bard nappe, because these two units occupied the core of the subducted and accreted continental crust (Figs. 4.9c, d). Their exhumation may have involved tectonic wedging during oblique-slip on steep shear surfaces in a downward tapered continental accretion zone (Fig. 4.9d). This tapered geometry is favoured at depth by the combination of confining pressure and horizontal maximum force acting during sinistral transpression.

Indeed, exhumed HP rocks are widely observed at restraining bends in strike-slip fault systems (Mann and Gordon 1996). A close relationship of exhumed HP rocks to NNW-trending strike-slip faults was noted in the Western Alps (Ricou and Siddans 1986, Pfiffner 1992), but in contrast to our study, these faults were attributed to N- to NW directed Tertiary motion of Apulia before the ages of either the faults or of the HP metamorphism in the Western Alps were known. The NNW trend of these purported strike-slip faults is clearly incompatible with the observed E-W trend of the late Cretaceous Chiusella shear zone documented above.

The switch from D_2 transpression to D_3 extension in the Sesia Zone was associated with an increase in cooling rather than heating during decompression. This is important because cooling during D_3 extensional exhumation rules out two other exhumational processes that are associated with heating. The first is extension of crust that thickened after buoyancy-driven exhumation stopped, as observed in HP rocks of the Variscan orogen (e.g. O’Brien 1997) and in UHP rocks of the Western Gneiss Region in Norway (Walsh and Hacker 2004). There, the rising HP rocks were flattened under amphibolite facies conditions during their emplacement between the continental crust and hot lithospheric mantle of the upper plate. The second is Tertiary break-off of the Liguro-Piemontese oceanic slab, which acting on its own, leads to the buoyant rise and heating of the overlying crust (von Blanckenburg and Davies 1995, Ernst et al. 1997).

Therefore, the mechanism that best fits the D_3 thermal and kinematic history of the Sesia HP rocks involves D_3 extension in the upper plate as the trench retreated to the NW under the weight of the cold, dense Liguro-Piemont slab (Fig. 4.9e). Heating of the extending crust in the upper plate was prevented by the accretion of cold slices of transitional (Combin Zone) and oceanic (Zermatt-Saas Zone) lithosphere in its footwall. These slices effectively “refrigerate” the upper plate and maintain a low geotherm. A similar scenario of retreating subduction was also proposed for Late Cretaceous extensional exhumation of the accreted Apulian margin in Eastern Alps (Handy 1996; Froitzheim et al. 1997), and before that, for Miocene extension of the Pannonian basin behind the retreating Carpathian orogen (e.g. Jolivet et al., 2004). Extensional exhumation of HP rocks during thrusting and subduction has also been propounded for Eocene HP and UHP rocks in the Liguro-Piemont and

Brianconnais units (e.g. Wheeler et al. 2001). As in the Sesia Zone, these rocks experienced decompression from blueschist- to greenschist-facies conditions (Lapen et al. 2003; Keller et al. 2005), precluding heating during exhumation and supporting the hinge-rollback model of subduction in Figure 4.9f.

The sophistication of numerical codes in recent years has allowed modellers to differentiate the competing effects of rheology, metamorphic phase transitions and erosion on the PTt paths of subducted crust during Alpine-type orogenesis (Burov et al. 2001; Gerya et al., 2002). The model of Burov et al (2001) predicts that crust which is subducted and metamorphosed at depths of about 100 km can return to the surface by a combination of thermally induced buoyant rise through a crustal channel in the hangingwall of the downgoing slab, and corner flow at depths less than 40 km. Buoyant rise within the crustal channel is enhanced by incomplete metamorphic equilibration under eclogite facies conditions. The model of Gerya et al. (2002) goes further in predicting that subducted crustal fragments can rise buoyantly through a convecting mantle wedge in the upper plate. Whether such buoyant-convective exhumation actually occurred in the HP rocks of the Western Alps is doubtful given the high geothermal gradient assumed for the upper plate. Mineral isotopic cooling ages from the Sesia and Ivrea Zones indicate that the upper plate was cool and rigid already prior to the onset of subduction (Zingg et al. 1990).

Though these models are fascinating for the animated details they provide, their only testable features are the synthetic PTt paths and the structures produced by the end of the numerical experiments. No matter how sophisticated models may become, their usefulness will be limited by the fidelity of their boundary conditions and by comparison of their predictions with ground truth in the field.

4.5 CONCLUSIONS

Our work has shown that the exhumation of continental HP rocks in the Sesia Zone preceded Tertiary Alpine collision and coincided with Late Cretaceous to Early Tertiary subduction of the Apulian and Tethyan lithospheres. The three basement nappes making up the Sesia Zone (the Bard, Mombarone and II ZDK nappes) are exhumed slivers of subducted and accreted Apulian continental margin. The HP rocks in these nappes experienced quite different pressure-temperature time paths that can be related to crustal-scale structures formed during subduction and multistage exhumation. Subduction and exhumation generally proceeded from internal to external parts of the accreted continental margin, i.e., from SE to NW across the Sesia Zone.

The Bard and Mombarone basement nappes individuated during late Cretaceous subduction (60-70 Ma) and the thrust separating them appears to have nucleated where the continental crust was previously thinned during Jurassic rifting. The Mesozoic cover sediments of this passive margin presently occupy two narrow zones –the MCC and Canavese Zones- that separate, respectively, the Bard and Mombarone nappes and the Mombarone nappe and Ivrea Zone. Both sedimentary units contain blueschist- and greenschist-facies assemblages, indicating that they also underwent subduction and exhumation.

By mapping related structures and mineral assemblages across the Sesia Zone, we were able to define km-scale shear zones that overprint nappe contacts and exhumed the HP rocks within large, coherent slices of crust. Most early exhumation involved thrusting (D_1) at the base of the Mombarone nappe and transpressional shearing (D_2) along a steep, E-W trending mylonitic shear zone (the Chiusella shear zone) that overprints the nappe base. This km-wide shear zone was active under retrograde eclogite- to blueschist- to greenschist-facies conditions and accommodated both dip-slip and strike-slip motion. Exhumation of the Mombarone nappe was nearly isothermal (T = 500-550°C) and rapid, judging from the synkinematic blueschist- to greenschist-facies field gradient preserved across the shear zone. D_2 transpressional shearing also juxtaposed the II ZDK nappe with the Bard and Mombarone nappes at about 30-40 km before exhuming the amalgamated nappes to a common depth of about 20 km. New Rb-Sr ages on synkinematic phengite and feldspar constrain D_2 to have occurred at about 60-65 Ma.

Continued exhumation of the amalgamated basement nappes to 10 km or less occurred in the footwall of a subhorizontal, greenschist-facies extensional shear zone (D_3, the Ometto shear zone) that accommodated top-SE motion. This shear zone is best exposed in the highest mountain peaks of the Sesia Zone, but in lower structural levels along valley walls is manifested by recumbent folds that flatten older foliations. D_3 extensional exhumation involved cooling to 400° and was broadly coeval with Early Tertiary, SE-directed subduction of oceanic

Liguro-Piemont units beneath the Sesia Zone. A new Rb-Sr feldspar-amphibole mineral age on a cross-cutting dyke combined with existing mineral ages constrain D_3 to have occurred at about 45-55 Ma.

Slow cooling and exhumation of the Sesia Zone from 45 to 36 Ma occurred in the hangingwall of the Gressoney and Combin extensional shear zones (D_4, Wheeler and Butler 1993; Ballevre and Merle 1993). These greenschist-facies shear zones accommodated top-SE motion, mostly within the oceanic Liguro-Piemont units but also along the northwestern margin of the Sesia Zone (Bard nappe). D_4 extensional shearing was broadly coeval with HP and UHP metamorphism in the Zermatt Saas and Monte Rosa units beneath the Sesia Zone, as proposed in previous work (e.g. Reddy et al. 2003).

At 30 Ma years, the HP rocks of the Mombarone unit were intruded by the shallow Biella and Traversella plutons and incorporated within volcanoclastic sediments, at or near the surface. Oligo-Miocene Insubric backfolding and -thrusting under greenschist facies conditions (D_5) only exhumed northeastern parts of the Sesia Zone, where Alpine HP metamorphism is absent. The southeastern rim of the Sesia Zone and its mutual border with the Ivrea Zone preserves evidence of repeated pre-Oligocene movement, including blueschist- and greenschist-facies mylonite belts that are locally overprinting by cataclasites.

Regarded from a plate tectonic perspective, the transition from D_2 to D_3 deformation in the Sesia Zone coincided with first-order change in the nature of Tethyan subduction, from high-stress transpressional subduction and accretion of the Apulian continental margin to low-stress subduction of the Liguro-Piemont oceanic lithosphere. This change had a profound impact on the mechanisms of exhumation within the accreted Apulian crust. Whereas initial exhumation from depths within the mantle was probably buoyancy-driven (Konrad-Schmolke et al., Chapter 5), initial transpressional subduction favoured tectonic wedging and forced upward extrusion within the crust. At the onset of low-stress subduction in Early Tertiary time, the main driving mechanism of exhumation switched to a combination of extension and erosion of the accreted margin above the rolling, NW-retreating hinge of the subducting Liguro-Piemont oceanic lithosphere.

Finally, we emphasize the value and necessity of mapping fabric domains in large tracts of deeply eroded crust. Only structures and metamorphic assemblages that are related in time and correlated with radiometric ages can be interpreted in a regional context. This is time-consuming but forms the basis for the next generation of tectonic models.

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