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Polyphase greenschist-facies reactivation of the Dent Blanche Basal Thrust (Western Alps) during progressive Alpine orogeny

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Abstract This study assesses the significance, geometry, and kinematics of greenschist-facies deformation along the Dent Blanche Basal Thrust (DBBT), a major tectonic contact in the Internal Western Alps of Switzerland and Italy. The DBBT separates continental units of the Dent Blanche nappe, the structurally highest unit in the Western Alps, from underlying Piemont-Ligurian ophiolites. Mylonites and deformation structures along the contact provide a record of its retrograde greenschist-facies evolution after earlier high-pressure metamorphism. A first phase of foreland-directed, reverse-sense, top-(N)W shearing (D1) occurred between ca. 43 and 39 Ma, related to exhumation of the Dent Blanche nappe from high-pressure conditions. It led to the formation of mylonitic fabrics under high- to medium-grade greenschist-facies conditions along the entire DBBT. A phase of ductile normal-sense top-SE shearing (D2) at ca. 38–37 Ma was mainly localized within underlying ophiolitic units and only partly affected the DBBT. Another phase of ductile deformation (D3) under medium- to low-grade greenschist-facies conditions at ca. 36–35 Ma occurred in response to underthrusting of European continental margin units and resulted in the updoming of the nappe stack. Especially the southeastern DBBT was characterized by bulk top-NW shearing, partly conjugate top-NW/top-SE shearing, and resulting orogen-perpendicular crustal extension. Subsequently, the DBBT was affected by a phase of orogen-perpendicular shortening (D4) and formation of folds and crenulations at ca. 34–33 Ma due to increasing compressional tectonics. Finally, a phase of semi-ductile to brittle normal-sense top-NW and conjugate shearing (D5) from ca. 32 Ma onwards particularly affected the southeastern segment and indicates exhumation of the DBBT through the ductile–brittle transition. This was followed by brittle NW–SE extensional deformation. This study suggests that the DBBT experienced a polyphase deformation and reactivation history under decreasing greenschist-facies metamorphic conditions during which different segments of this major shear zone were variably affected.

Keywords Internal western Alps · Dent Blanche Basal Thrust · Shear zone reactivation · Greenschist-facies deformation · Retrograde shearing · Continental collision

1 Introduction

Collisional orogens are sites of major crustal thickening by juxtaposition of tectonic units that often experienced (ultra)high-pressure [(U)HP] metamorphism during subduction. First-order tectonic contacts often already form within the subduction channel when tectonic units are detached from the downgoing plate and their basal thrusts become the new subduction interface (e.g. Platt 1986; Ernst 2001; Angiboust et al. 2016). Such contacts, however, may be reactivated and overprinted under low-pressure conditions during subsequent exhumation of tectonic units and continuing nappe stacking (Engi et al. 2001). Since progressive orogenic deformation on the retrograde path can lead to

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reworking, reactivation, and overprinting of preexisting shear zones, assessing the extent and significance of post-HP greenschist-facies deformation, as well as the geometry and kinematics of retrograde shearing events is often crucial in reconstructing the structural evolution of major tectonic units in the course of collisional orogeny (e.g. Bucher et al. 2003; Reddy et al. 2003).

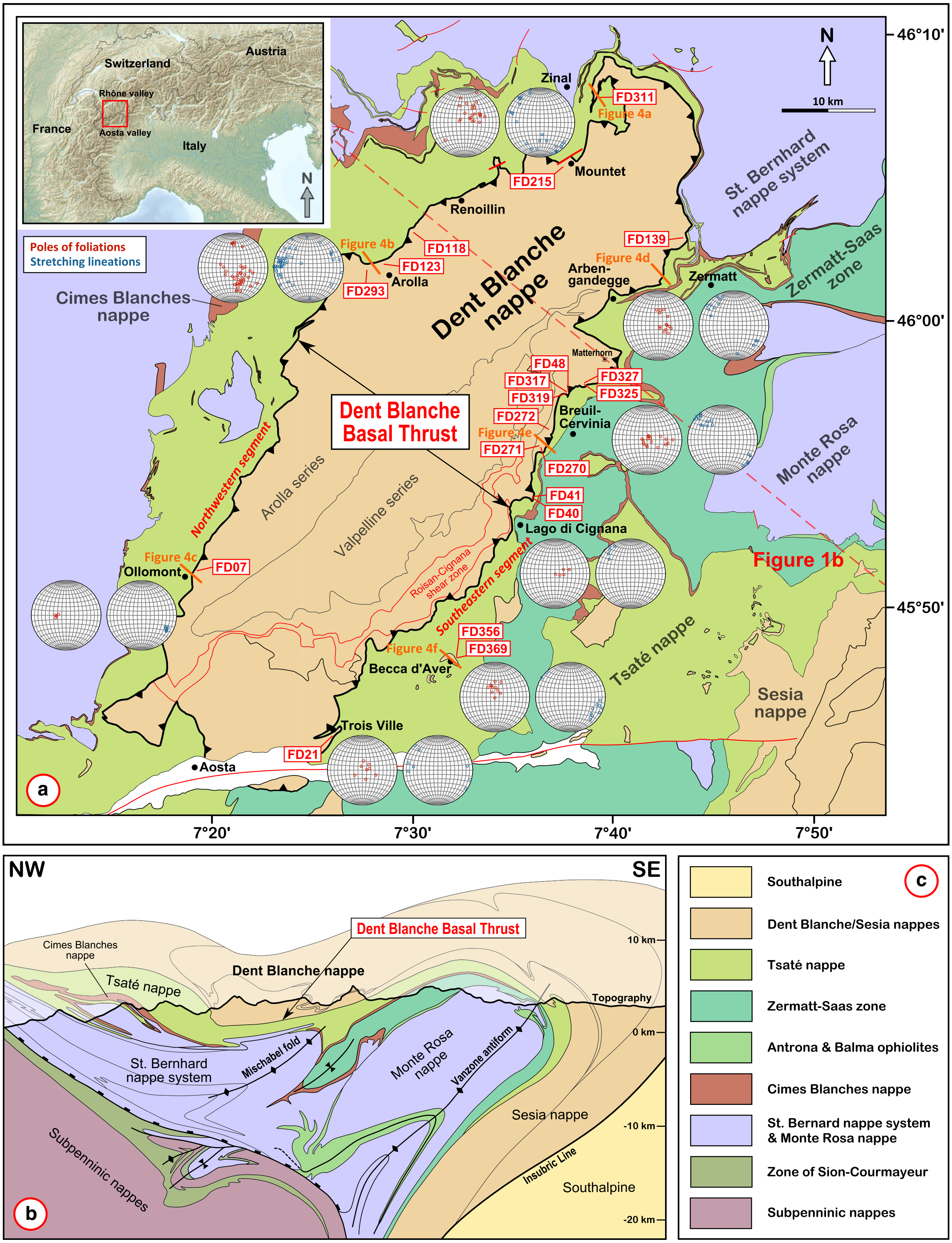
This study investigates a major tectonic contact and prominent shear zone at the base of the Dent Blanche nappe, the Dent Blanche Basal Thrust (DBBT), to constrain geometry, kinematics, and significance of greenschist-facies deformation in the tectonic context of the Internal Western Alps. The DBBT originally represents an ancient subduction interface during Paleogene SE-directed subduction of Piemont-Ligurian oceanic lithosphere beneath the Adriatic continental margin. The study area in the southern Valais and northern Aosta regions is a classic area for the study of Alpine deformation since the pioneering works of Argand (e.g. Argand 1909). The nature of the DBBT is largely agreed upon to represent a major Alpine thrust (Ballèvre et al. 1986; Mazurek 1986; Oberhänsli and Bucher 1987; Wust and Silverberg 1989; Hellweg 2003; Bucher et al. 2004; Pleuger et al. 2007; Manzotti et al. 2014a). While recent studies focused on its evolution as an ancient subduction interface at HP conditions (Angiboust et al. 2014, 2015), this study sheds light on the retrograde greenschist-facies evolution of the DBBT and aims at identifying phases of deformation, including their kinematics and nature, during reactivation of this major Alpine tectonic contact and associated shear zone.

2 Geological setting

In the Western Alps of Switzerland and Italy, a stack of continental and oceanic units from different paleogeographic domains is exposed (Fig. 1). The Late Cretaceous paleogeographic configuration (e.g. Stampfli et al. 2002; Schmid et al. 2004; Handy et al. 2010) was characterized by the continental margins of Adria and Europe in the SE and NW, respectively, and two oceanic basins, the Piemont-Ligurian ocean in the SE and the Valais trough in the NW. These were in turn separated by the Briançonnais continental spur, an assumed eastern prolongation of the Iberian plate. Crustal slices from these different domains were progressively accreted to the Adriatic continental margin during SE-directed subduction from the Late Cretaceous onwards (e.g. Handy et al. 2010).

The study area is located in southern Switzerland (southern Valais region) and northern Italy (northern Aosta region) (Fig. 1). The Dent Blanche nappe is the northwestern outlier of the Dent Blanche/Sesia nappe system which represents the structurally highest unit in the Western Alps. The Dent Blanche/Sesia nappe system is interpreted to have originated from continental fragments along the Adriatic continental margin, which were separated from it during Jurassic rifting (Froitzheim et al. 1996; Dal Piaz et al. 2001; Babist et al. 2006). The nappe system consists of Paleozoic basement units as well as Mesozoic cover sequences preferentially occuring along subnappe boundaries and shear zones (Babist et al. 2006; Manzotti 2011; Manzotti et al. 2014b). The Dent Blanche nappe s.l. consists of two thrust sheets, the Dent Blanche nappe s.s. and the Mont Mary sliver (Ballèvre et al. 1986), which were amalgamated during early subduction along the Roisan-Cignana shear zone (Manzotti et al. 2014b). Both tectonic units consist of two pre-Alpine basement units, termed Arolla and Valpelline series for the Dent Blanche nappe s.s. They differ in their lithological content and their metamorphic evolution. The Arolla series mainly comprises Permian granitoids and gabbros (Bussy et al. 1998; Monjoie et al. 2005) with an Alpine HP metamorphic imprint reaching ca. 1.2–1.4 Gpa and 450–450 °C (Angiboust et al. 2014). HP deformation in this unit occurred between 48 and 43 Ma according to Rb–Sr geochronology on Arolla gneisses and mylonites (Angiboust et al. 2014). The Mesozoic cover of the Arolla series is preserved in some places, e.g. in the Roisan zone and Mt. Dolins unit; it mainly comprises breccias and dolomitic marbles (Ayrton et al. 1982; Manzotti 2011). The Valpelline series consists of pre-Alpine amphibolite- to granulite-facies metasediments (Gardien et al. 1994), which only partly experienced Alpine metamorphism and deformation (Diehl et al. 1952). Juxtaposition of the Arolla and Valpelline units occured during early subduction at ca. 58 Ma as suggested by Rb–Sr ages of mylonites along their contact (Angiboust et al. 2014). The Dent Blanche nappe shows a greenschist-facies overprint, especially along shear zones (Oberhänsli and Bucher 1987; Manzotti et al. 2014a). Its present-day structure is that of a large NE-SW trending synform. The Sesia nappe records eclogite-facies conditions around 2.0 GPa and 550 °C (e.g. Lardeaux and Spalla 1991; Regis et al. 2014). The age of this HP imprint has been dated at ca. 70–65 Ma (e.g. Inger et al. 1996; Rubatto et al. 1999) but has been proposed to have already started at ca. 85 Ma with several distinct pressure

Fig. 1 **a** Tectonic map of the study area and adjacent areas; after▶ Steck et al. (1999); location of the study area within the European Alps is shown on the topographic map (*inset*) (from Ryan et al. 2009); stereoplots of poles of foliations (*red*) and stretching lineations (*blue*) as lower hemisphere equal area projections are given for the base of the Dent Blanche nappe in the respective areas; localities of samples used for microstructural analyses as well as traces of cross-sections in Fig. 4 are indicated. **b** Cross-section through the Western Alps; after Escher et al. (1993); trace of cross-section is indicated in Fig. 1b. **c** Key to the map and cross-section



a
Switzerland
Austria
Rhône valley
France
Aosta valley
Italy
N
Poles of foliations
Stretching lineations
N
10 km
46°10'
46°00'
45°50'
7°20'
7°30'
7°40'
7°50'
Zinal
Mountet
Renoillin
Arolla
Arben-
gandegge
Zermatt
Matterhorn
Breuil-
Cervinia
Lago di Cignana
Ollomont
Becca d'Aver
Trois Ville
Aosta
FD311
Figure 4a
FD215
FD118
Figure 4b
FD123
FD293
FD139
Figure 4d
FD48
FD317
FD319
FD327
FD325
FD272
Figure 4e
FD271
FD270
FD41
FD40
Figure 4c
FD07
FD356
FD369
Figure 4f
FD21
Figure 1b
Dent Blanche
nappe
Dent Blanche
Basal Thrust
Cimes Blanches
nappe
St. Bernhard
nappe system
Zermatt-Saas
zone
Monte Rosa
nappe
Tsaté nappe
Sesia
nappe
Arolla series
Valpelline series
Roisan-Cignana
shear zone
Northwestern segment
Southeastern segment
b
NW
SE
Dent Blanche Basal Thrust
Cimes Blanches
nappe
Tsaté nappe
Dent Blanche nappe
Topography
10 km
0 km
-10 km
-20 km
St. Bernhard
nappe system
Mischabel fold
Monte Rosa
nappe
Vanzone antiform
Sesia nappe
Insubric Line
Southalpine
Subpenninic nappes
c
Southalpine
Dent Blanche/Sesia nappes
Tsaté nappe
Zermatt-Saas zone
Antrona & Balma ophiolites
Cimes Blanches nappe
St. Bernard nappe system
& Monte Rosa nappe
Zone of Sion-Courmayeur
Subpenninic nappes

peaks (Rubatto et al. 2011; Regis et al. 2014). In the present-day geometry and on a crustal scale, the Dent Blanche/Sesia nappe system is folded around the Vanzone antiform. The Combin zone below the Dent Blanche nappe is a composite unit comprising the ophiolitic Tsaté nappe and thin metasedimentary sequences of continental affinity, the Cimes Blanches and Frilihorn nappes. The Tsaté nappe consists of Jurassic to Cretaceous calcschists, metabasites, and serpentinites derived from the Piemont-Ligurian oceanic domain and is interpreted to represent a former accretionary wedge at the Adriatic continental margin (Sartori 1987; Marthaler and Stampfli 1989). The Cimes Blanches and Frilihorn nappes consist of successions of Permo-Mesozoic sediments comprising conglomerates, quartzites, marbles, and dolomites (Sartori 1987; Vannay and Allemann 1990). The Combin zone reached greenschist- to blueschist-facies conditions during Alpine subduction and accretion (Kienast 1973; Ballèvre and Merle 1993; Reddy et al. 1999) with peak estimates around 1.2 GPa and 450 °C (Bousquet 2008) and experienced a pervasive greenschist-facies overprint (Ballèvre and Merle 1993; Negro et al. 2013). It shows an internal structure of subnappes with distinct deformation ages and temperatures, increasing from higher to lower structural levels (Negro et al. 2013; Angiboust et al. 2014). The Combin zone wedges out towards the SE; there the Sesia nappe is partly in direct contact with the Zermatt-Saas zone in its footwall. The Zermatt-Saas zone is also derived from Piemont-Ligurian oceanic lithosphere and comprises metabasalts, metagabbros, metaultramafics, and metasediments. Protolith ages for metagabbros are around 164 Ma (Rubatto et al. 1998). The Zermatt-Saas zone experienced HP to UHP metamorphism between ca. 54–38 Ma during Paleocene–Eocene subduction (Bowtell et al. 1994; Rubatto et al. 1998; Amato et al. 1999; Lapen et al. 2003; Mahlen et al. 2005; Gouzu et al. 2006; De Meyer et al. 2014; Skora et al. 2015). Peak metamorphic conditions of ca. 540–600 °C and 2.3–3.0 GPa have been reported for the Zermatt-Saas zone in general (Bucher et al. 2005; Angiboust et al. 2009). However, peak conditions for coesite-bearing lithologies at the UHP locality at Lago di Cignana have been calculated to be $\geq$3.2 GPa and $\leq$600 °C (Reinecke 1998; Groppo et al. 2009; Frezzotti et al. 2011). Lower-pressure retrogression has been dated at ca. 42–38 Ma (Amato et al. 1999; Cartwright and Barnicoat 2002; De Meyer et al. 2014). The Piemont-Ligurian ophiolites are underlain by continental units of the St. Bernhard nappe system in the NW and the Monte Rosa nappe in the SE. The St. Bernhard nappe system is derived from Briançonnais continental crust and consists of Paleozoic basement and Mesozoic cover rocks, which experienced an Alpine greenschist- to blueschist-facies overprint (Bearth 1963; Sartori 1990). The Monte Rosa nappe takes up most of the core of the Vanzone antiform and may represent an eclogite-facies part of the Briançonnais (e.g. Escher and Beaumont 1997; Keller and Schmid 2001), or alternatively may be derived from the European continental margin (e.g. Froitzheim 2001; Pleuger et al. 2005). Formation of the Vanzone antiform after ca. 32 Ma (e.g. Keller et al. 2005a; Pleuger et al. 2008; and references therein) largely modified the geometry of the internal part of the Paleogene nappe stack in the Swiss-Italian Western Alps (Escher et al. 1993).

3 Methodology and structural analyses

The bulk of the deformation observed along the DBBT occurred under Alpine greenschist-facies metamorphic conditions. Such metamorphic conditions are derived using quartz recrystallization processes, diagnostic minerals, pseudosection modelling, and the ductility of deformation structures (crystal plastic vs. cataclastic). Although quartz recrystallization processes also depend on strain rate and water activity (Stipp et al. 2002 and references therein), the grade of greenschist-facies deformation can be constrained using subgrain rotation recrystallization (SGR) as an indicator of higher- to medium-grade conditions between ca. 500–400 °C and bulging recrystallization (BLG) as an indicator of medium- to lower-grade conditions between ca. 400–280 °C (Stipp et al. 2002). In this study, the term ‘ductile–brittle transition’ refers to the behaviour of quartz, which changes from dominant crystal plastic to dominant cataclastic at temperatures around 280 °C. Shear bands, grain shape preferred orientations (GSPO), mica fish, and asymmetric porphyroblasts were used to determine bulk shear senses. Overprinting relations between fabric elements give information on the sequence of shearing events. In general, the tectonites at the base of the Dent Blanche nappe have a mylonitic and “striped-gneiss” appearance. The often pronounced metamorphic layering is due to different amounts of quartz, feldspar, white mica, chlorite, epidote, and actinolite. Structural analyses were performed on thin-sections as well as on outcrops and hand-specimens. Thin-sections and hand-specimens were analysed in sections parallel to the dominant stretching lineation and perpendicular to the dominant planar fabric. Descriptions focus on exemplary localities where the DBBT is well exposed and accessible. Stereoplots were created with the software OpenStereo (Grohmann and Campanha 2010) for visualiziation of the orientation of measured foliations and lineations (Fig. 1a). Pseudosection modelling was performed with the THERIAK-DOMINO software package (De Capitani and Petrakakis 2010) and the JUN92 database, which is based on thermodynamic data by Berman (1988) to constrain pressure and temperature conditions during greenschist-facies retrogression and deformation for a mylonite sample from the northwestern DBBT. The bulk chemistry of the sample, obtained from XRF analysis at the

Steinmann-Institut in Bonn, was used as input for thermodynamic calculations. In addition to the detailed analyses of mylonites and deformation structures along the DBBT, units of the underlying Combin zone, mainly comprising calcschists and greenschists, were also examined. In the following, 'DBBT' refers to the shear zone, usually some tens of meters wide, at the base of the Dent Blanche nappe. Due to its present-day geometry and exposure, the DBBT can be divided into a northwestern and southeastern segment, respectively (Fig. 1).

4 Deformation along the northwestern DBBT

4.1 Zinal

Foliations along the DBBT in the upper Val de Zinal (Fig. 1a) mainly dip to the S to W, stretching lineations generally trend NW–SE but also partly plunge to the SSW. In the eastern Val de Zinal, the DBBT is folded on a regional, outcrop and hand-specimen scale. Rocks of the lowermost Dent Blanche nappe are often quartz-rich and interfolded with calcschists of the structurally lower Combin zone (Fig. 2a). Folds are open to isoclinal and fold axes plunge to the (S)SE and are parallel to stretching lineations. L-tectonites with (W)NW-(E)SE trending lineations can be observed in some spots. Fold axial planes dip to the SE. Foliations within structurally lower calcschists of the Tsaté nappe also dip to the SE and sometimes represent an axial planar foliation of Dent Blanche folds but are sometimes folded themselves. On the hand-specimen scale, folds within Dent Blanche gneisses are occasionally overprinted by a spaced cleavage (Online Resource 1a), the planes of which dip moderately to the S, while the stretching lineation plunges to the SE. White mica is concentrated along cleavage planes and has partly been replaced by chlorite. Offset of quartz layers along shear planes mostly indicates a top-SE sense of shear. Calcschists of the Combin zone in the footwall of the DBBT are also partly folded with fold axes plunging to the (S)SE, i.e. parallel to stretching lineations. The transport direction of a drag fold suggests NW-vergent shearing during folding (Online Resource 1b). Folds and foliations are partly overprinted by ductile top-SE shear bands (Fig. 2b). Brittle top-SE shear planes cutting the foliation can occasionally be observed (Online Resource 1b). Ductile top-SE kinematic indicators are generally abundant within the uppermost Combin zone in the upper Val de Zinal, e.g. also within calcschists in the footwall of the DBBT near Lac d'Arpitetta (Fig. 2c). Top-SE kinematic indicators can also be found within Dent Blanche gneisses in the upper Val de Zinal at the locality Mountet (Fig. 1a).

4.2 Renoillin and Arolla

Near Renoillin, located along an eastern branch of Val d'Hérens, foliations along the DBBT dip steeply to the S (Fig. 1a). A crenulation with very shallowly W-plunging axes overprints the greenschist-facies fabric in most outcrops. Axes of the late crenulation are the dominant linear fabric element on the sample scale. Unambiguous kinematic indicators could not be observed at this locality.

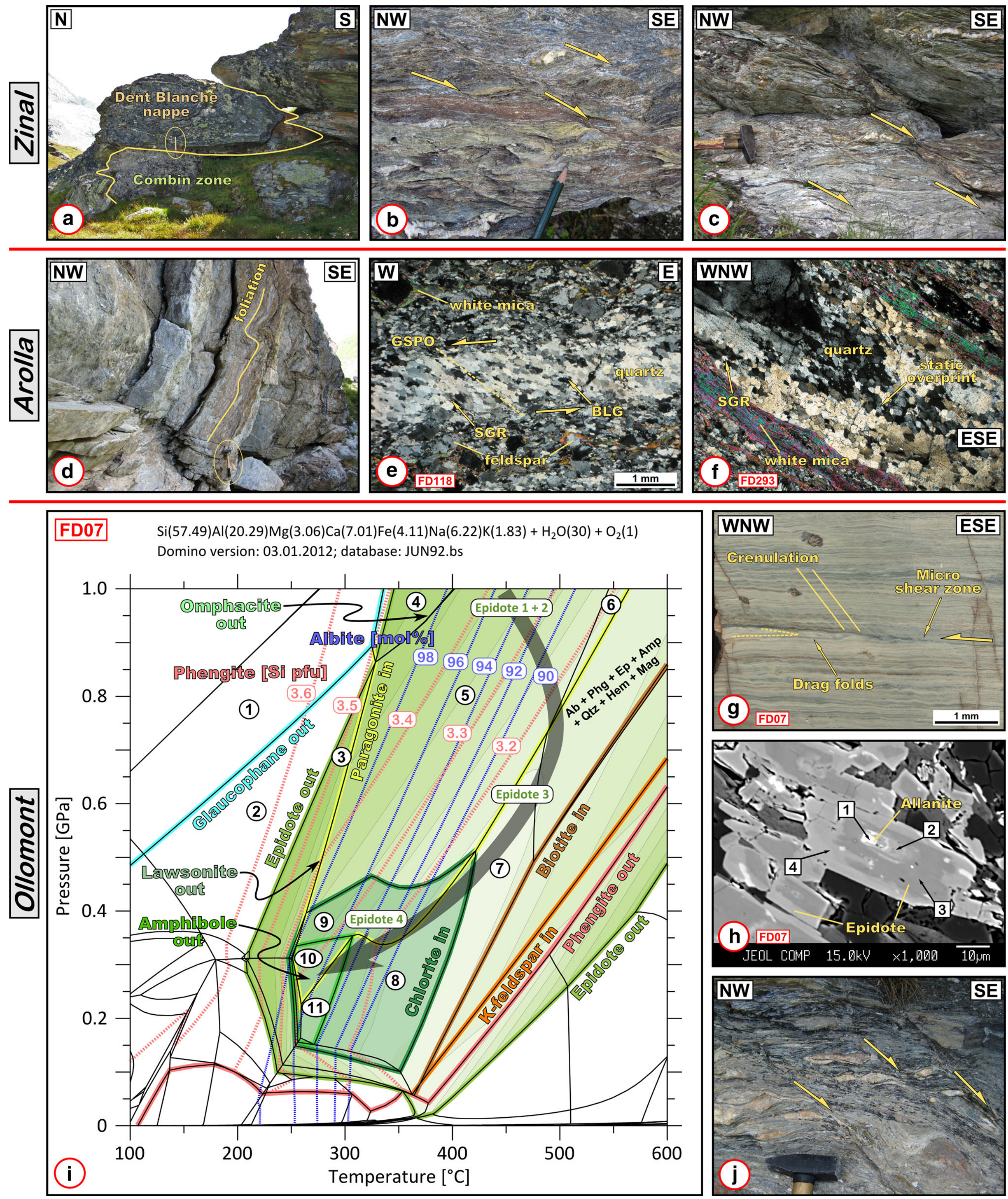
In the area around and N of Arolla in the upper Val d'Hérens (Fig. 1a), the DBBT is folded such that foliations within the lower Dent Blanche nappe often dip to the W to N and sometimes have an overturned orientation, in which case they dip steeply to the NW (Fig. 2d). Stretching lineations dominantly trend WNW-ESE, but also (W)SW-(E)NE trending lineations occur. Gneisses and mylonites of the DBBT often show top-W to top-WNW shear sense criteria, e.g. abundant GSPOs of quartz (Fig. 2e) and sigma-shaped quartz and feldspar aggregates. Quartz within sheared layers and ribbons dominantly recrystallized by SGR (Fig. 2e). Recrystallization by bulging can sometimes be observed to partly overprint SGR fabrics (Fig. 2e). Occasionally, SGR is associated with 120° triple junction of quartz grains, probably indicating a static overprint. In addition to regional folding of the DBBT, open to tight folds and crenulations with mostly NE- to E-plunging axes often deform greenschist-facies fabrics on the meso- to microscale. In thin-section, rare low-grade top-WSW shear bands can be observed to cut through microscale open to tight folds within gneisses (Online Resource 1c).

4.3 Ollomont

Near the village Ollomont in the Valpelline (Fig. 1a), rocks of the DBBT display ultramylonitic greenschist-facies fabrics (Fig. 2g). One mylonite was analysed in detail in terms of its structural and metamorphic evolution. The stretching lineation is an aggregate lineation that plunges shallowly to the ESE. The foliation of the sample dips to the E and has partly been overprinted by a SE-dipping crenulation cleavage with NE-plunging axes (Fig. 2g).

4.3.1 Petrography and petrology

The sample consists of quartz ($\sim$25 vol%) + albite ($\sim$27 vol%) + white mica ($\sim$20 vol%) + epidote ($\sim$25 vol%) + chlorite ($\sim$2 vol%) + titanite + rutile + pyrite. The mylonitic foliation corresponds to a compositional layering, which reflects different ratios of the minerals within layers. Quartz has entirely been segregated into monomineralic layers and ribbons. Mineral compositions



were measured with a Jeol JXA-8200 superprobe at the Steinmann-Institut of the University of Bonn using a beam current of 15 nA and an acceleration voltage of 15 kV (Online Resource 2). Feldspar is albitic with 96.5–98.8 mol% albite component. White mica is phengitic with 3.35–3.47 Si p.f.u. Chlorite often replaces white

◀**Fig. 2** Deformation structures along the northwestern DBBT. **a** Folded contact between rocks of the Dent Blanche nappe and the structurally lower Combin zone in the eastern Val de Zinal; quartz-rich rocks of the Dent Blanche nappe are folded while the greenschist-facies foliation of Combin calcschists partly represents an axial planar foliation and is partly folded as well. **b** Combin calcschists in the eastern Val de Zinal showing ductile top-SE shear bands. **c** Combin calcschists in the footwall of the DBBT near Lac d'Arpitetta showing ductile top-SE shear bands. **d** Overturned gneisses of the lowermost Dent Blanche nappe near Arolla. **e** Sample FD118: Gneiss from the base of the Dent Blanche nappe near Arolla; a GSPO of quartz grains indicates a top-W sense of shear; Fol (272/23) Lin (272/23); crossed polarizers. **f** Sample FD293: Gneiss from the base of the Dent Blanche nappe near Arolla; quartz layers show dynamic recrystallization by SGR and partly display 120° triple junctions; shear sense criteria in this sample indicate a top-WNW shear sense; Fol (347/46) Lin (285/26); crossed polarizers. **g** Sample FD07: Polished hand-specimen of a mylonite from the DBBT east of the village Ollomont in the Valpelline of Italy; Fol (88/23) Lin (119/19) crenulation axes (47/17); note small-scale shear zone in the middle with a crenulation cleavage in the upper part and drag folds directly below. **h** BSE-picture of zoned epidote: an allanite core is surrounded by distinct zones of relatively Fe-rich, Fe-poor, and another Fe-rich epidote; numbered points correspond to epidote measurements in Online Resource 2. **i** Equilibrium phase diagram calculated with the THERIAK-DOMINO software package (De Capitani and Petrakakis 2010) with excess water (30 H_2O) and additional oxygen (1 O_2); see text for discussion; solution models: feldspar, quartz, epidote, amphibole, biotite, lawsonite, hematite, magnetite: Berman (1988); white mica: Keller et al. (2005b); chlorite: Hunziker (2003); omphacite: Meyre et al. (1997); glaucophane: Evans (1990); numbered assemblages: (1) Ab + Ph + Omp + Hem + Lws + Qtz + Gln; (2) Ab + Ph + Omp + Tr + Hem + Lws + Qtz; (3) Ab + Ph + Omp + Tr + Hem + Lws + Qtz; (4) Ab + Ph + Pg + Omp + Ep + Hem + Qtz; (5) Ab + Ph + Pg + Ep + Prg + Hem + Qtz; 6) Ab + Ph + Pg + Ep + Prg + Hem + Mag + Qtz; (7) Ab + Ph + Ep + Prg + Hem + Qtz; (8) Ab + Ph + Chl + Ep + Prg + Hem + Qtz; (9) Ab + Ph + Pg + Chl + Ep + Prg + Hem + Qtz; (10) Ab + Ph + Pg + Chl + Ep + Hem + Qtz; (11) Ab + Ph + Chl + Ep + Hem + Qtz; mineral abbreviations according to Whitney and Evans (2010). **j** Combin calcschists in the footwall of the DBBT near Ollomont showing ductile top-SE shear bands

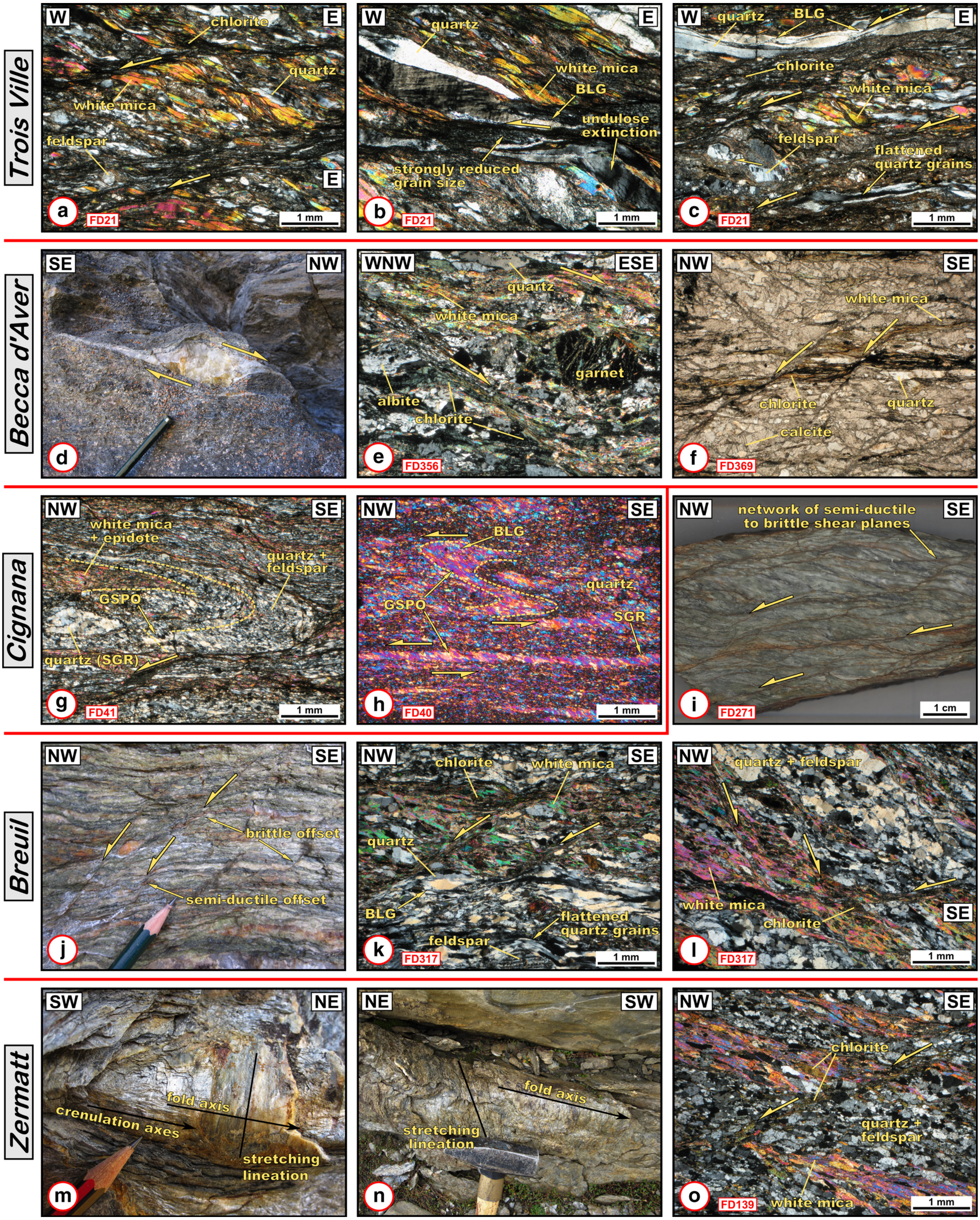
mica and often occurs as intergrowths with it. Most epidote grains display a 4-phase zonation from core to rim (Fig. 2h) with (1) allanite in the core; (2) Fe-rich Al-poor epidote; (3) Fe-poor Al-rich epidote; and (4) Fe-rich Al-poor epidote.

4.3.2 Microstructures

A GSPO of quartz within monomineralic layers and ribbons indicates top-WNW shearing. Quartz is interpreted to have recrystallized by dominant SGR. The long axis of quartz grains is sometimes parallel to crenulation planes suggesting formation of the compressional crenulation cleavage above ca. 280 °C in the field of crystal-plastic behaviour of quartz. In the hand-specimen, the mylonitic foliation is cut by a small-scale shear zone along a quartz layer slightly oblique to the main foliation (Fig. 3c). In the hanging wall of the shear zone, a crenulation cleavage formed, while in the footwall, the primary foliation has been deformed into tight to isoclinal drag folds. The transport direction of folds indicates top-WNW movement. The micro-scale shear zone itself has partly been overprinted by the crenulation cleavage, suggesting continued shortening after cessation of shear zone activity. Partial replacement of white mica suggests that chlorite grew relatively late on the retrograde path. There are no microstructural observations for post-kinematic growth of chlorite. Hence, the formation of the crenulation cleavage is interpreted to have occurred within the stability field of chlorite.

4.3.3 Pressure and temperature conditions

The calculated pseudosection is depicted in Fig. 2i. Oxygen was added to the bulk composition to obtain oxidized conditions and to stabilize epidote, which occurs as a major phase in the sample. None of the modelled HP minerals glaucophane, omphacite, or lawsonite can be observed in the sample suggesting complete reequilibration on the retrograde path. Si-rich white mica and albite-rich feldspar probably grew or reequilibrated early during the retrograde evolution at pressures around 1 GPa as suggested by modelled isolines. A paragonite-rich second white mica was calculated but cannot be observed in the sample. Its modelled abundance continuously decreases from ca. 12 vol% at high pressures and low temperatures towards its higher temperature boundary suggesting that the sample largely equilibrated outside the paragonite stability field or close to its boundary, respectively. An upper temperature limit for the retrograde evolution is given by the stability of biotite, which does not occur in the sample. The modelled stability of epidote is characterized by a decreasing Fe-content with increasing temperatures and then another increase in Fe. Epidote compositions are indicated by shadings of green in the diagram with lighter green indicating lower Fe contents. The observed 4-stage zonation in epidote can therefore be explained by progressive epidote growth along the retrograde path. The first two zones probably grew during early mylonitization with allanite cores representing reorganization of light rare earth elements due to fluid-assisted element transfer. Epidote 3 is interpreted to have grown during decreasing pressures while epidote 4 grew under low-grade greenschist-facies conditions. Chlorite probably grew relatively late along the retrograde path below ca. 0.5 GPa and 420 °C according to its modelled stability field. Only small modal amounts of $\sim 3 \pm 2$ vol% are modelled which corresponds well with observations in the sample. In addition to the observed assemblage quartz + albite + white mica + epidote + chlorite, pargasitic amphibole (~ 9 vol%) has been modelled but cannot be observed in the sample. Its abundance decreases with lower pressures and temperatures when chlorite becomes stable. Its modelled stability is interpreted


Trois Ville
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a
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1 mm
W
E
quartz
white mica
BLG
undulose extinction
strongly reduced grain size
b
FD21
1 mm
W
E
quartz
BLG
chlorite
white mica
feldspar
flattened quartz grains
c
FD21
1 mm
Becca d'Aver
SE
NW
d
WNW
ESE
quartz
white mica
garnet
albite
chlorite
e
FD356
NW
SE
white mica
chlorite
quartz
calcite
f
FD369
Cignana
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white mica + epidote
quartz + feldspar
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NW
SE
BLG
GSPO
quartz
SGR
h
FD40
1 mm
NW
SE
network of semi-ductile to brittle shear planes
i
FD271
1 cm
Breuil
NW
SE
brittle offset
semi-ductile offset
j
NW
SE
chlorite
white mica
quartz
BLG
flattened quartz grains
feldspar
k
FD317
1 mm
NW
quartz + feldspar
white mica
chlorite
SE
l
FD317
1 mm
Zermatt
SW
NE
fold axis
crenulation axes
stretching lineation
m
NE
SW
fold axis
stretching lineation
n
NW
SE
chlorite
quartz + feldspar
white mica
o
FD139
1 mm

◀**Fig. 3** Deformation structures along the southeastern DBBT. **a** Sample FD21: Mylonite from the DBBT near the village Trois Villes showing ductile c'-type shear bands which indicate W-vergent shearing; Fol (229/20) Lin (268/16); crossed polarizers. **b** Sample FD21: Large quartz grains are flattened, show undulose extinction, deformation lamellae, and recrystallization by BLG indicating deformation at low-grade conditions between ca. 400 and 280 °C; grain sizes are strongly reduced within strained areas; crossed polarizers. **c** Sample FD21: Quartz recrystallized by BLG along top-W shear bands and between large grains leading to core-and-mantle structures; large quartz grains are strongly flattened; Fol (229/20) Lin (268/16); crossed polarizers. **d** Sheared quartz lense within metasediments at the base of the Becca d'Aver continental fragment in the western Valtournenche indicating top-NW shearing. **e** Sample FD356: Garnet-bearing metasediment from the base of the Becca d'Aver continental fragment showing top-ESE shear bands; chlorite is stable and albite is fractured along shear bands; Fol (187/22) Lin (118/07). **f** Sample 369: Becca d'Aver calcschist showing late top-NW shear bands cutting through the chlorite-bearing foliation; Fol (203/38) Lin (138/15); parallel polarizers. **g** Sample FD41: Gneiss from the DBBT at Lago di Cignana; quartz recrystallized by dominant SGR; a GSPO indicates top-NW shearing; intrafolial, isoclinal folds developed during progressive deformation; late discrete semi-ductile to brittle shear planes cut through the foliation; Fol (244/22) Lin (312/16); crossed polarizers. **h** Sample FD40: Quartzitic mylonite from the DBBT at Lago di Cignana; NW-vergent fold and GSPO of quartz indicate a top-NW shear sense; Fol (254/35) Lin (304/27); crossed polarizers and gypsum plate inserted. **i** Sample FD271: Polished hand-specimen of a mylonite from the DBBT southwest of Breuil-Cervinia showing network of slickenside-type semi-ductile to brittle top-NW shear planes; Fol (284/46) Lin (312/40). **j** Outcrop north of Breuil-Cervinia; semi-ductile to brittle top-NW shear planes cutting through the mylonitic foliation indicate top-NW deformation across the ductile–brittle transition. **k** Sample FD317: Mylonite from the DBBT north of Breuil-Cervinia showing ductile top-NW shear bands; quartz grains are flattened and recrystallized by BLG; Fol (36/13) Lin (306/01). **l** Sample FD317: Ductile top-NW shear bands are partly associated with top-SE shear bands suggesting a pure shear component during bulk top-NW shearing. **m** Folds within Combin calcschists in the footwall of the DBBT at Arbengandegge west of Zermatt deforming an earlier stretching lineation and foliation; fold and crenulation axes plunge to the northeast (48/02). **n** Folds within Combin calcschists in the footwall of the DBBT northwest of Zermatt deforming an earlier stretching lineation and foliation; fold axes plunge to the southwest (241/27). **o** Sample FD139: Gneiss from the DBBT northwest of Zermatt showing late semi-ductile top-NW shear band associated with growth of chlorite; Fol (199/40) Lin (135/21)

to be due to underestimation of the stability and modal amounts of epidote by the calculations. Modelled modal amounts of quartz and albite are relatively constant with ~25 vol% for quartz and ~30 vol%. According to the above observations and interpretations, an assumed PT path for the retrograde evolution of the mylonite sample is depicted in Fig. 4i. It starts at conditions of ca. 1 GPa and 450 °C, reaches peak-T conditions at ca. 0.7 GPa and 500 °C, and ends at conditions of ca. 0.3 GPa and 300 °C.

4.3.4 Synthesis

The Ollomont mylonite experienced penetrative deformation and fabric formation during top-(W)NW shearing under retrograde greenschist-facies conditions according to microstructural and petrological analyses as well as pseudosection modelling. The sample is interpreted to have largely equilibrated at conditions below ca. 1 GPa and between ca. 500 and 300 °C. Top-(W)NW shearing occurred mainly between 500 and 400 °C according to dominant SGR of quartz and partly continued below 400 °C as suggested by minor BLG. The sample experienced partial reequilibration during compressional deformation at conditions around 0.3 GPa and 300 °C. In contrast to observed top-(W)NW kinematic indicators within DBBT mylonites near Ollomont, calcschists of the underlying Combin zone display top-SE shear bands deforming quartz veins in a ductile manner in outcrop (Fig. 2j).

5 Deformation along the southeastern DBBT

5.1 Trois Ville

In the area near the village Trois Villes in the northern Aosta valley (Fig. 1a), the DBBT has been deformed into a tight to isoclinal fold. Foliations are corrugated on the outcrop scale such that their dip direction varies. Stretching lineations dominantly trend W-E and partly NW–SE. Mylonites of the lowermost Dent Blanche nappe display abundant c'-type shear bands, which overprint chlorite-bearing foliations. Shear bands consistently indicate top-(N)W shearing (Fig. 3a). Grain sizes are often strongly reduced within strained areas (Fig. 3b) and quartz grains are often flattened and show undulose extinction (Fig. 3b, c). The dominant recrystallization process of quartz is bulging, indicating crystal plastic deformation at temperatures between ca. 400 and 280 °C. Bulging preferentially occurs along shear bands and around larger quartz grains leading to core-and-mantle structures (Fig. 3c). Brittle offset of feldspar also suggests temperatures below ca. 450 °C (Fig. 3c; e.g. Pryer 1993).

5.2 Becca d'Aver

Around Becca d'Aver in the western Valtournenche (Fig. 1a), a continental fragment consisting of metasedimentary successions and orthogneisses is exposed at a high structural level on top of the Combin zone. Its structure is that of a SSW-closing synform as suggested by folding of a metamorphic layering within gneissic lithologies in the core of the sliver. Fold axes plunge to the (E)SE. Foliations dip to the S and stretching lineations consistently trend (W)NW-(E)SE. In the core of the Becca d'Aver synform, L-tectonites with stretching lineations parallel to fold axes occur. The structural position and lithological content of the continental fragment suggest that it represents a klippe

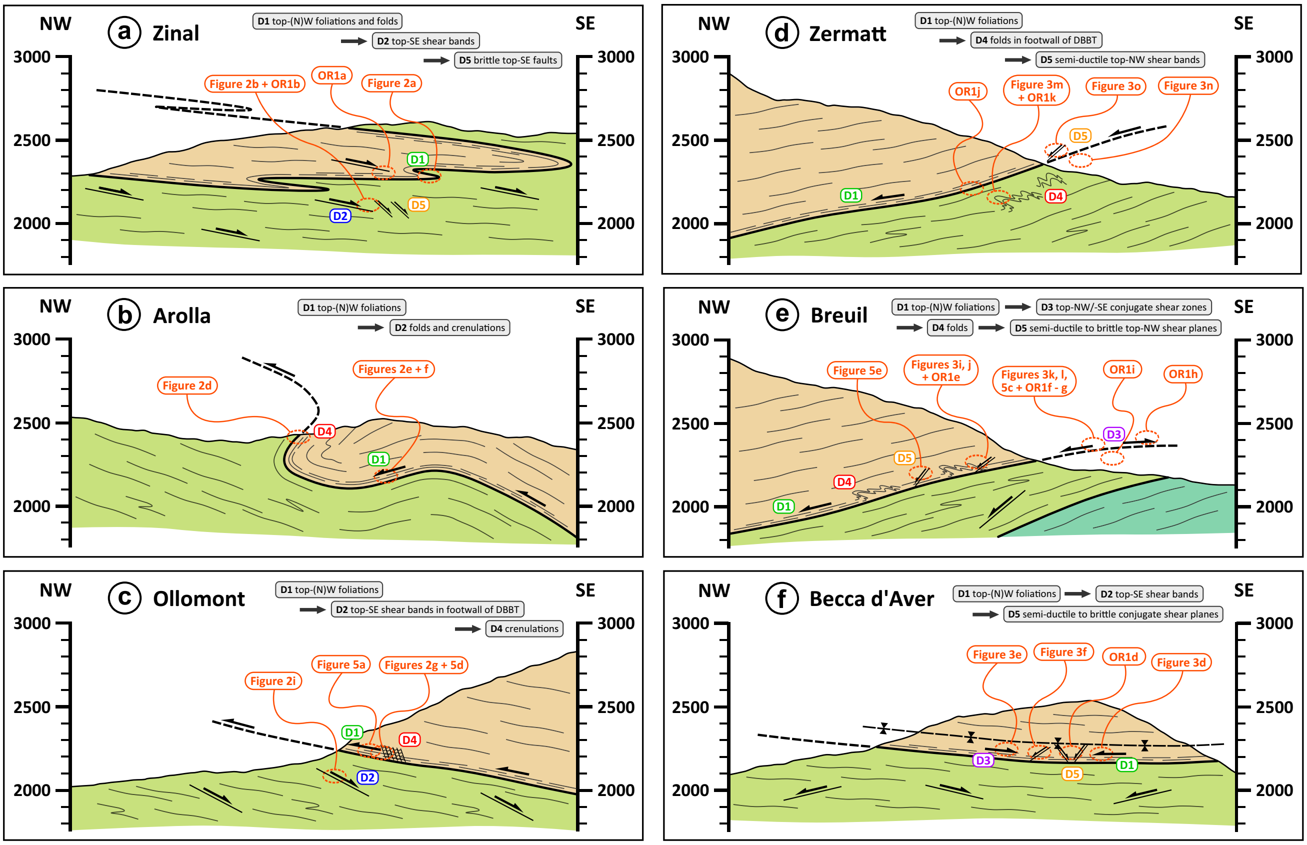


Fig. 4 Series of NW–SE striking, schematic cross-sections depicting the geometry of the DBBT, dominant shear senses, and the deformation phases affecting each respective area; colour coding corresponds to the one in Fig. 1; locations of deformation structures in Figs. 2 and 3, and online resource (OR) 1 are indicated. **a** Zinal: The DBBT is folded on a regional scale; D1 top-(N)W foliations and folds are overprinted by D2 top-SE shear bands and partly D5 top-SE brittle faults. **b** Arolla: The DBBT is folded on a regional scale due to D4 compression overprinting D1 top-(N)W foliations. **c** Ollomont: D1 top-(N)W foliations are overprinted by D4 crenulations; D2 top-SE shear bands occur within Combin calcschists in the footwall of the DBBT. **d** Zermatt: D1 top-(N)W foliations are overprinted by D5 semi-ductile top-NW shear bands; D4 upright to NW-vergent folds occur in the footwall of the DBBT. **e** Breuil: D1 top-(N)W foliations are overprinted by D3 top-NW/-SE conjugate shear zones; subsequent D4 NW-vergent folds are overprinted by semi-ductile to brittle top-NW shear bands and faults. **f** Becca d'Aver: D1 top-(N)W foliations and the DBBT are folded into a SSW-closing synform; D1 foliations are overprinted by D2 top-SE shear zones and steeply-dipping D5 semi-ductile to brittle conjugate shear bands and faults

of the Dent Blanche nappe. Its base can therefore be regarded as a southeastern continuation of the DBBT exposed in the Valtournenche area (Fig. 1a). Metasedimentary sequences along the base often show ductile top-NW kinematic indicators in outcrop, e.g. sheared quartz lenses and ribbons (Fig. 3d). Quartz-rich metasediments often contain garnet as indicator of an earlier, most likely Alpine HP imprint. They often display top-NW shear sense criteria but top-(E)SE shear bands can also be observed in thin-section within more retrogressed samples (Fig. 3e). Albite is brittely fractured and chlorite is transposed and sheared along top-(E)SE shear bands, suggesting greenschist-facies metamorphic conditions below ca. 450 °C during deformation. Ductile top-SE shear bands can also be observed in outcrop within metasediments. In thin-section, top-NW shear bands offset the chlorite-bearing foliation (Fig. 3f). Domains displaying dominant top-NW or top-SE kinematic indicators often correlate with domains of dominantly NW- and SE-dipping foliations, respectively. On the outcrop scale, steeply-dipping, semi-ductile conjugate top-NW/-SE shear bands can often be observed (Online Resource 1d). The underlying Combin zone at Becca d'Aver displays top-NW as well as top-SE shear sense criteria in thin-section.

5.3 Cignana

At Lago di Cignana in the western Valtournenche (Fig. 1a), mylonites of the DBBT show several phases of greenschist-facies deformation (see also Kirst and Leiss 2017). Foliations dip to the W to N and stretching lineations plunge to the NW. In outcrop, ductile to semi-ductile top-NW shear bands can be observed. On the hand-specimen to thin-section scale, a pre-existing Alpine greenschist-facies fabric and metamorphic layering has often been overprinted by folding during progressive deformation. Small-scale folds are tight to isoclinal and are either intrafolial or NW-vergent (Fig. 3g, h). In thin-section, a GSPO of quartz within monomineralic layers and folds indicates top-NW shearing during formation of the main foliation as well as during folding (Fig. 3g, h). Dynamic recrystallization by SGR suggests temperatures between ca. 500 and 400 °C during fabric formation but also modification by bulging recrystallization can often be observed (Fig. 3h). Discrete semi-ductile to brittle top-NW shear bands and planes, respectively, transecting the main foliation and metamorphic layering, can be observed in thin-section (Fig. 3g). Occasionally, steeply-dipping brittle top-SE microfaults transect the foliation. Calcschists and greenschists in the footwall of the DBBT almost exclusively display top-NW shear sense criteria.

5.4 Breuil

In the area SW and W of Breuil-Cervinia in upper Valtournenche (Fig. 1a), foliations along the DBBT dominantly dip to the W to NW. Stretching lineations plunge to the NW. Shear bands and faults on the meso- to microscale have a semi-ductile to brittle character (Fig. 3i). Shear planes can often be characterized as discrete N-dipping slickensides. Stretching lineations and striations on slickensides are consistently NW-plunging. The shear sense along shear bands and faults is consistently top-NW. Shear planes are often interconnected so that they form networks (Fig. 3i). They partly deform quartz and white mica in a ductile to semi-ductile manner but also brittely transect the foliation. On a hand-specimen and thin-section scale, the primary Alpine greenschist-facies foliation has been folded into NW-vergent folds (Online Resource 1e). These folds in turn are cut and offset by top-NW shear bands. The grain size is often strongly reduced within these strained areas.

In the area north of Breuil-Cervinia, foliations of the DBBT dip to the NW to N and to the NE to E. Stretching lineations plunge gently and consistently trend NW–SE. In outcrop, semi-ductile to brittle shear planes can be observed to cut through a greenschist-facies fabric, partly offsetting quartz layers in a brittle manner (Fig. 3j). These indicate NW-vergent shearing under low-grade conditions around and below ca. 280 °C. In thin-section, the metamorphic layering of basal mylonites has often been overprinted by c'-type top-NW shear bands. Quartz grains are often flattened and show dynamic recrystallization by bulging indicating temperatures between ca. 400 and 280 °C during deformation (Fig. 3k). In some samples, conjugate top-NW/-SE shear bands overprint the primary foliation (Fig. 3l). Top-NW shear bands, however, are predominant and offset more competent epidote-rich layers in a semi-ductile to brittle manner. These are often associated with renewed synkinematic growth of chlorite (Online Resource 1f). In one sample, ductile top-SE shear bands are associated with (sub)vertical tension joints within an epidote layer (Online Resource 1g). At Croce di Carrel at the southwestern foot of the Matterhorn (Fig. 1a), ultramylonitic fabrics can be observed. These often do not display kinematic indicators, except for rare shallowly-dipping top-SE shear bands which are associated with synkinematic chlorite and brittle fragmentation of feldspar (Online Resource 3h). Calcschists in the footwall of the DBBT north of Breuil display ductile to semi-ductile top-NW shear bands in outcrop (Online Resource 1i).

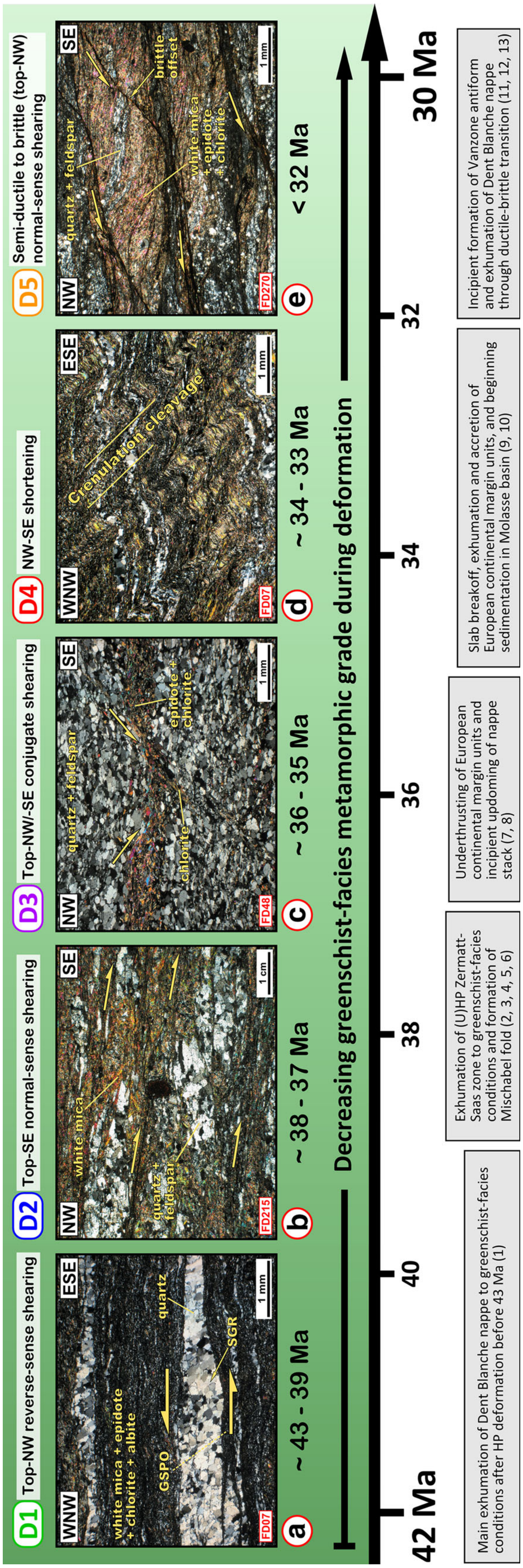
5.5 Zermatt

In the area west and northwest of Zermatt (Fig. 1a), foliations of the DBBT generally dip to the NW but also partly to the S. Stretching lineations mostly plunge to the NW. At the locality Arbengandegge, foliations in the immediate hanging wall and footwall of the Dent Blanche/Combin contact are strictly parallel (Online Resource 1j) and are not folded. The Combin zone at a slightly lower structural level, on the other hand, is folded into open to tight, NW-vergent folds with SW-NE trending axes. These folds deform a preexisting foliation and stretching lineation (Fig. 3m; Online Resource 1k). A crenulation with axes parallel to main fold axes can also be observed. Upright to NW-vergent folds with SW-NE trending axes also occur in the footwall of the DBBT northwest of Zermatt (Fig. 3n). These folds again deform a preexisting foliation and stretching lineation while the DBBT itself is not folded. Rocks of the DBBT display semi-ductile top-NW shear bands, which cut through the foliation and are associated with renewed growth of chlorite (Fig. 3o).

6 Sequence and regional distribution of greenschist-facies deformation

Structural analyses of gneisses and mylonites of the DBBT suggest that they experienced polyphase deformation under greenschist-facies metamorphic conditions. The main phase of greenschist-facies retrogression and deformation (D1) led to formation of foliations and mylonitic fabrics, which can be observed in all areas along the DBBT (Fig. 4). This phase is interpreted to have largely occurred at temperatures between ca. 500 and 400 °C as suggested by abundant SGR of quartz. SGR can be observed along both fault segments, e.g. within mylonites in the areas around Arolla, Ollomont, and Lago di Cignana. Quartz microstructures have partly been modified by BLG, suggesting continuing deformation below ca. 400 °C, e.g. in the areas around Arolla and Lago di Cignana. GSPOs of quartz resulting from dynamic recrystallization consistently indicate top-(N)W shearing, which is interpreted to reflect thrusting along the DBBT. Metamorphic conditions deduced from pseudosection modelling in combination with microstructural, textural, and petrological observations from the Ollomont mylonite also suggest that fabric formation started under upper greenschist-facies conditions around ca. 500 °C and 1.0 GPa and then continued under decreasing metamorphic conditions. Progressive deformation during late stages of D1 top-(N)W shearing led to meso- to macro-scale folding of the DBBT with (W)NW-(E)SE trending axes, e.g. in the areas around Zinal (Fig. 4a), Trois Ville, and Becca d'Aver (Fig. 4f). Microscale isoclinal intrafolial and tight to isoclinal NW-vergent folds within mylonites, e.g. in the Cignana area, are also ascribed to D1 shearing. In the Zinal area, mesoscale D1 folds are overprinted by ductile top-SE shear bands within Combin calcschists in the footwall of the DBBT but only partly within gneisses of the DBBT (Fig. 4a). Top-SE kinematic indicators are also abundant in the footwall of the DBBT near Ollomont (Fig. 4c). Top-SE shear zones observed along the northwestern DBBT are ascribed to D2 normal-sense shearing, mainly localized within the underlying Combin zone. Domains of ductile top-SE shear can also partly be observed along the southeastern DBBT but these are usually closely associated with domains of top-NW shear, e.g. in the areas around Becca d'Aver and Breuil (Fig. 4e, f). Abundant top-NW kinematic indicators along the southeastern segment formed under medium- to low-grade conditions at temperatures between ca. 400 and 280 °C as suggested by associated BLG of quartz. Such structures occur in the areas around Trois Ville, Cignana, and Breuil and suggest that the southeastern DBBT was affected by another phase of ductile top-NW shearing (D3). Evidence for penetrative lower-grade GS-facies top-NW shearing is missing along the northwestern DBBT. This suggests that renewed foreland-directed shearing was not strictly parallel to the contact. This top-NW shear zone probably cut down-section into the footwall with respect to tectonostratigraphy since there is no evidence for a greenschist-facies top-NW shear zone re-emerging to a higher structural level of the Dent Blanche nappe. Association of top-NW deformation structures with conjugate structures and domains of top-SE shear along and especially SE of the current exposure of the DBBT is interpreted to reflect a regional pure shear geometry and orogen-perpendicular crustal elongation along already (sub-) horizontally orientated units and contacts. During late stages of ductile deformation, the DBBT was affected by increasing orogen-perpendicular shortening. Macro- to microscale folding and formation of crenulations (D4) under low-grade greenschist-facies conditions can be observed to overprint greenschist-facies fabrics along the northwestern DBBT, e.g. in the areas around Arolla and Ollomont (Fig. 4b, c). Open to tight, mostly NW-vergent folds as well as crenulations deforming older foliations and stretching lineations can be observed along the southeastern DBBT, e.g. in the areas around Breuil and Zermatt (Fig. 4d, e). These mostly formed within rocks of the Combin zone in the footwall of the contact but also partly within Dent Blanche mylonites. Only along the southeastern segment are compressional structures as well as mylonitic fabrics often cut by discrete semi-ductile to brittle top-NW shear bands, shear planes, and slickensides, e.g. in the areas around Breuil, Becca d'Aver, Cignana, and Zermatt (Fig. 4d–f). The southeastern DBBT is therefore interpreted to have experienced a phase of D5 NW-vergent shearing during its exhumation through the ductile–brittle transition. Since low-grade top-NW deformation structures are missing along the northwestern DBBT, the southeastern segment is interpreted to have had an already NW-dipping orientation due to continuing updoming of the nappe stack. Also, semi-ductile to brittle conjugate top-NW/-SE structures along the southeastern DBBT as well as brittle top-SE faulting along the northwestern segment (Fig. 4a), which has also been reported by Wust and Silverberg (1989), suggest that semi-ductile to brittle shearing occurred in a conjugate manner on a regional scale and therefore reflects orogen-perpendicular (NW–SE) crustal extension. Rare low-grade top-(W)SW shear bands along the northwestern DBBT probably result from a minor component of orogen-parallel shearing during late-stage deformation.

Structural observations suggest that the northwestern and southeastern segments of the DBBT partly experienced different structural evolutions and that the observed deformation phases affected the analyzed areas to different extents (Fig. 4a–f). D1 mylonitization during top-(N)W thrusting was penetrative along the DBBT and can be observed in all areas. Foliations are parallel to the contact, and they were variably affected by subsequent, less penetrative shearing events. Kinematic indicators are mostly GSPOs of quartz within monomineralic ribbons and layers. Formation of c'-type shear bands cannot be observed during D1. D2 top-SE structures are less abundant along the DBBT, which is most likely the result of strain localization within relatively incompetent Combin calcschists. The shift from this normal-sense shearing event to subsequent D3 bulk top-NW shearing along the southeastern DBBT and associated conjugate top-SE shearing may have been transitional since both reflect orogen-perpendicular crustal extension. The conjugate character of D3 ductile shearing due to regional-scale updoming is supported by the fact that top-NW and top-SE domains often correlate with NW- and SE-dipping foliations, respectively. During this phase, c'-type shear bands abundantly formed and were mainly localized within white mica-rich domains. Also, abundant recrystallization by



◀**Fig. 5** Chronogram linking greenschist-facies microstructures along the DBBT with their respective deformation phase and tectonic events in the Western Alps between ~43 and 30 Ma; all photomicrographs were taken with crossed polarizers. **a** Sample FD07: Ultramylonite from the DBBT near Ollomont; a GSPO of quartz, recrystallized by SGR, indicates top-WNW shearing during formation of the D1 mylonitic foliation; Fol (88/23) Lin (119/19). **b** Sample FD215: Gneiss from the locality Mountet in the upper Val de Zinal showing D2 top-SE shear bands; Fol (243/42) Lin (312/22). **c** Sample FD48: Mylonite from the DBBT north of Breuil-Cervinia showing D3 conjugate top-NW/-SE shear bands which overprint the preexisting metamorphic layering; Fol (222/03) Lin (312/01). **d** Sample FD07: A SE-dipping D4 crenulation cleavage overprints the mylonitic foliation. **e** Sample FD270: Mylonite from the DBBT SW of Breuil-Cervinia showing networks of mainly brittle top-NW shear planes; Fol (270/63) Lin (326/47); References: (1) Angiboust et al. (2014); (2) Barnicoat et al. (1995); (3) Amato et al. (1999); (4) Reddy et al. (1999); (5) Cartwright and Barnicoat (2002); (6) Skora et al. (2015); (7) Herwartz et al. (2011); (8) Sandmann et al. (2014); (9) Davis and von Blanckenburg (1994); (10) Schlunegger and Kissling (2015) and references therein; (11) Keller et al. (2005a) and references therein; (12) Hurford et al. (1991); (13) Bistacchi et al. (2001)

bulging within quartz-rich domains occurred. The southeastern DBBT was penetratively affected by D3 bulk top-NW shearing. D4 compressional deformation modified the large-scale geometry of the DBBT, especially the northwestern segment, by folding, while fabrics were only locally and non-penetratively affected by formation of crenulations. Static recrystallization of quartz within D1 fabrics along the northwestern DBBT supports the interpretation that units in its hanging wall did not experience any significant overprinting by ductile deformation after fabric formation except for D4 folding. D4 folds are often cut by D5 late semi-ductile to brittle shear bands and planes. These do not follow rheological weak zones or certain mineral domains but usually transect preexisting fabrics at high angles. In general, deformation became increasingly more localized from D1 to D5 suggesting progressively decreasing greenschist-facies metamorphic conditions during deformation and continuous exhumation of the Dent Blanche nappe. While quartz was the dominant mineral to be deformed at higher temperatures, strain was increasingly distributed into mica-rich domains at lower temperatures. On a regional-scale, rheological contrasts between the relatively competent Dent Blanche nappe in the hanging wall of the DBBT and calcschists of the Combin zone in the footwall probably also played a major role in the distribution and localization of strain.

7 Greenschist-facies structural evolution of the DBBT

In this section, the proposed sequence of greenschist-facies deformation is linked to major tectonic events (Fig. 5) and embedded into the structural and tectonic evolution of the Western Alps (Fig. 6).

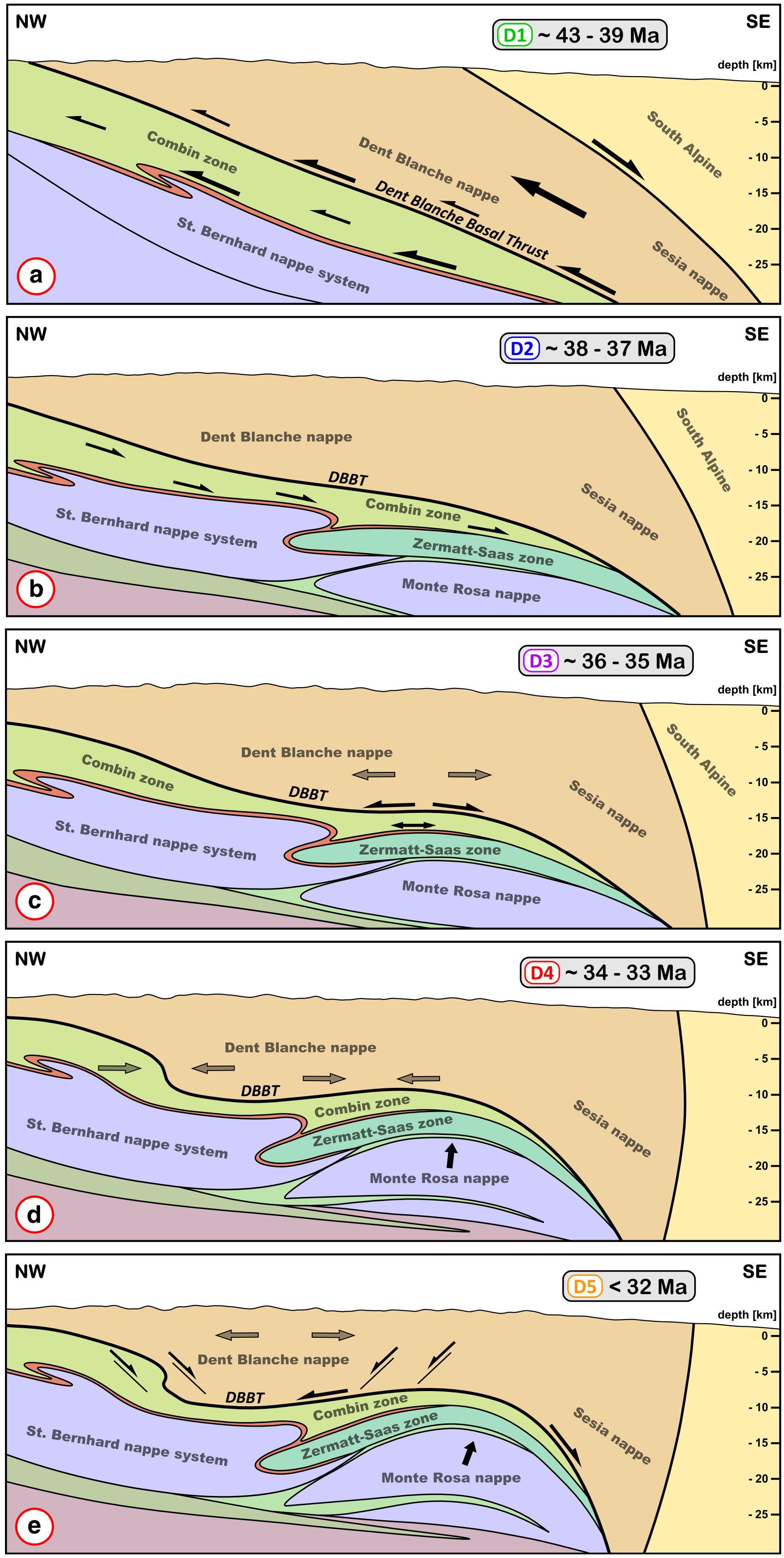


Fig. 6 Model of the greenschist-facies structural evolution of the DBBT between ~43 and 32 Ma; *black arrows* indicate movement directions; *grey arrows* indicate areas of dominant compression and extension, respectively. **a** ~43–39 Ma: Ductile top-(N)W shearing along the DBBT led to formation of greenschist-facies mylonitic fabrics; this phase was associated with main exhumation of the Dent Blanche nappe from high-pressure to greenschist-facies conditions and reactivation of the former subduction interface along the DBBT as a thrust; GS-facies deformation and retrogression also penetratively affected the underlying Combin zone. **b** ~38–37 Ma: A phase of normal-sense top-SE shearing was mainly localized within rheologically weak Combin calcschists, while the DBBT experienced only partial reworking. **c** ~36–35 Ma: Ductile deformation under medium- to low-grade greenschist-facies conditions due to increasing underthrusting of European continental margin units and resulting updoming of the nappe stack; bulk top-NW shearing along the southeastern DBBT was accompanied by conjugate top-SE shearing, especially towards the SE, interpreted to reflect a regional pure shear geometry during NW–SE directed crustal extension. **d** ~34–33 Ma: The DBBT was subject to orogen-perpendicular shortening due to an increase in Europe-Adria convergence leading to formation of folds and crenulations. **e** ~32 Ma: Exhumation of the DBBT across the ductile–brittle transition during incipient formation of the Vanzone antiform led to bulk normal-sense top-NW shearing along the southeastern DBBT and conjugate top-NW/-SE shearing

7.1 D1 top-(N)W reverse-sense shearing

During Paleogene SE-directed subduction, the DBBT represented the subduction interface between the Dent Blanche/Sesia nappe system in the hanging wall and the Piemont-Ligurian oceanic lithosphere in the footwall (Angiboust et al. 2014, 2015). This contact was later reactivated during a period of foreland-directed thrusting which is interpreted to represent the main stage of greenschist-facies mylonitization along the DBBT and exhumation of the Dent Blanche nappe from HP depths (Figs. 5a, 6a, b). The age of the HP imprint within Arolla series rocks of the lower Dent Blanche nappe has been constrained by Angiboust et al. (2014) via Rb–Sr geochronology. Analyses yielded ages of ~48–43 Ma, which have been interpreted to reflect the timing of blueschist-facies metamorphism and associated deformation. According to these ages, greenschist-facies deformation along the DBBT can be considered to have started after ca. 43 Ma. During this phase of main exhumation of the Dent Blanche nappe, a great part of retrograde greenschist-facies deformation must have been localized along its base, while internal deformation of the nappe system most certainly played an important role during accretion and HP deformation (Angiboust et al. 2014) as well as during subsequent retrogression (see Manzotti et al. 2014a, b for discussions). Reverse-sense shearing at its base must have been accompanied by top-SE normal-sense shearing and normal faulting at a high structural level, i.e. along the top of the Dent Blanche/Sesia nappe system (Fig. 6a), to geometrically explain ascent and exhumation of these units (e.g. Ernst 2001; Wheeler et al. 2001; Kurz and Froitzheim 2002). Remnants of such a top-SE normal-sense shear zone at a high structural level within the Sesia nappe have been reported by Babist et al. (2006) who suggested that exhumation of the nappe system partly occurred in the footwall of this top-SE shear zone prior to the onset of continental collision.

7.2 D2 top-SE normal-sense shearing

A subsequent phase of normal-sense ductile top-SE shearing is held responsible for observed top-SE structures in the footwall of the northwestern DBBT. Rapid exhumation of the (U)HP Zermatt-Saas zone to crustal levels in the footwall of the Combin Fault is interpreted to have occurred during this phase (Figs. 5b, 6b). HP metamorphism within this unit lasted until ca. 40–39 Ma (Skora et al. 2015), while the greenschist-facies overprint occurred at ca. 38 Ma (Amato et al. 1999). The Mischabel fold is interpreted to have formed during a late stage of top-SE shearing at ca. 37 Ma (Barnicoat et al. 1995; Cartwright and Barnicoat 2002; Scheiber et al. 2013). Strain during D2 ductile top-SE shearing was mostly localized within the relatively incompetent Combin zone as well as in the footwall of the Combin Fault and only subordinately affected the DBBT (Wust and Silverberg 1989; Ring 1995; Lebit et al. 2002; Kirst and Leiss 2017).

7.3 D3 bulk top-NW and conjugate ductile deformation

After the nappe stack in the Internal Western Alps was complete, the DBBT experienced another phase of reactivation under medium- to low-grade greenschist-facies conditions. While the southeastern DBBT experienced ductile bulk top-NW shearing, partly associated with conjugate top-SE shearing, top-SE kinematic indicators become more abundant towards the SE, e.g. along the basal contact of the Sesia nappe (Wheeler and Butler 1993; Reddy et al. 1999; Babist et al. 2006). This distribution of shear zones is interpreted to reflect a regional pure shear geometry due to incipient updoming of the nappe stack (Figs. 5c, 6c; Reddy et al. 2003; Forster et al. 2004; Gasco et al. 2013; Kirst and Leiss 2017). This phase is interpreted to have occurred at around 36–35 Ma in response to incipient collision between the European and Adriatic plates and Late Eocene underthrusting of European continental margin units. European continental margin units experienced a cycle of subduction, exhumation, and accretion between ca. 38 and 33 Ma (e.g. Herwartz et al. 2011; Sandmann et al. 2014). Underthrusting at depth is therefore held responsible for observed orogen-perpendicular mid-crustal extension to maintain a stable wedge geometry (Platt 1986), which led to modification and overprinting of preexisting ductile shear zones in the Internal Western Alps.

7.4 D4 formation of folds and crenulations

Collisional tectonics are likely to have intensified around 34–33 Ma when the Molasse basin at the northern margin of the Alps started to form (Schlunegger and Kissling 2015 and references therein). This phase is interpreted to reflect dominant orogen-perpendicular shortening which led to the formation of folds and crenulations deforming greenschist-facies fabris along the DBBT (Figs. 5d, 6d). Between ca. 35 and 32 Ma slab breakoff of European lithosphere occurred and resulted in the generation and subsequent intrusion of magmas, e.g. the Bergell pluton (Davis and von Blanckenburg 1994; Schlunegger and Kissling 2015).

7.5 D5 semi-ductile to brittle top-NW and conjugate shearing

From ca. 32 Ma onwards, continuing updoming of the nappe stack due to ongoing Europe-Adria collision led to semi-ductile to brittle shearing along the DBBT (Fig. 6e). Especially the southeastern DBBT was reactivated as a semi-ductile to brittle top-NW fault. During incipient Vanzone-phase folding, this segment was progressively rotated into a NW-dipping orientation so that NW-vergent shearing along the southeastern DBBT during this stage is interpreted to have had a normal-sense orientation. Development of the overall synformal structure of the Dent Blanche nappe is also attributed to this phase. Semi-ductile to brittle shear sense criteria (Fig. 5e) indicate exhumation of the DBBT through the ductile–brittle transition. Zircon fission track ages of ca. 30 Ma for the Dent Blanche nappe (Hurford et al. 1991), together with apatite fission track ages between ca. 29 and 19 Ma (Bistacchi et al. 2001), support exhumation through the ductile–brittle transition before ca. 30 Ma. Brittle faulting along both fault segments is attributed to upper-crustal extension in response to continuing exhumation of the nappe stack during late stages of this phase. After ca. 30 Ma, buoyancy-driven rapid uplift of the Western Alps occurred due to completed slab breakoff. Subsequent deformation was mainly accompanied by slip along the Insubric Line and the Penninic front (Schlunegger and Kissling 2015).

8 Conclusions

Structural analyses of mylonites and deformation structures along the DBBT in the Swiss-Italian Internal Western Alps revealed a polyphase deformation of this major tectonic contact and repeated reactivation under decreasing greenschist-facies metamorphic conditions during progressive Alpine orogeny.

- The main phase of reactivation of the DBBT occurred under high- to medium-grade greenschist-facies conditions during exhumation of the Dent Blanche nappe from high-pressure conditions. During this phase, between ca. 43 and 39 Ma, foreland-directed, reverse-sense top-(N)W shearing (D1: Fig. 6a) led to the formation of mylonitic fabrics along the DBBT.
- Subsequent top-SE normal-sense shearing (D2: Fig. 6b) at ca. 38–37 Ma was mainly localized within underlying, rheologically weak Combin calcschists. It only partly affected the DBBT and led to partial reworking of primary top-(N)W fabrics. Exhumation of the (U)HP Zermatt-Saas zone to crustal levels and formation of the Mischabel fold are attributed to this phase.
- A later phase of ductile deformation (D3: Fig. 6c) under medium- to low-grade greenschist-facies conditions occurred at ca. 36–35 Ma. Underthrusting of European continental margin units led to incipient updoming of the nappe stack and NW–SE directed, mid-crustal extension. The southeastern DBBT already had a (sub) horizontal orientation and experienced bulk top-NW and partly conjugate top-NW/top-SE shearing while the northwestern DBBT was not affected.
- Subsequently, the DBBT again experienced orogen-perpendicular crustal shortening (D4: Fig. 6e) and associated formation of fold and crenulations deforming preexisting greenschist-facies fabrics as a result of an increase in the rate of Europe-Adria collision.
- From ca. 32 Ma onwards, ongoing collision and updoming of the nappe stack led to exhumation of the DBBT through the ductile–brittle transition. Especially the southeastern segment was characterized by semi-ductile to brittle bulk top-NW normal-sense and conjugate shearing (D5: Fig. 6f) on the northwestern limb of the forming Vanzone antiform. Finally, both segments of the DBBT were affected by brittle NW–SE deformation.

In summary, the DBBT experienced multiple reactivation as a thrust and normal fault under greenschist-facies conditions post-dating high-pressure metamorphism. Different fault segments were variably affected by the proposed phases of deformation leading to distinct structural differences and histories.

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