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Continent-derived metasediments (Cimes Blanches and Frilihorn) within the ophiolites around Zermatt: relations with the Mischabel backfold and Mont Fort nappe (Pennine Alps)

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Abstract

The region surrounding Zermatt (SW Switzerland and NW Italy) displays some classic examples of imbrications between continental and oceanic units. In particular, the studied units, called *Cimes Blanches* and *Frilihorn* or *Faisceau Vermiculaire*, consist of a set of thin bands of continent-derived metasediments intercalated at different levels within the ocean-derived units. These bands are locally reduced to only one meter thick but can be traced for several tens to more than one hundred kilometers across the Pennine Alps. The mechanisms leading to such imbrications are a long-standing and still-debated question. Based on detailed mapping and structural analysis of key areas, we present new data on the structure and stratigraphy of the Faisceau Vermiculaire in the area surrounding Zermatt, with particular focus on the Täschalpen sector, where the Faisceau Vermiculaire is locally in contact with basement units. Our observations allow: (i) to confirm the presence of widespread breccias of probable Jurassic age in the Faisceau Vermiculaire; (ii) to interpret the contacts between the Faisceau Vermiculaire and the overlying non-ophiolitic Schistes Lustrés (Série Rousse) as stratigraphic; (iii) to show that the stratigraphy of the Faisceau Vermiculaire and associated Série Rousse contrasts strongly with the cover of the Siviez-Mischabel nappe and that these sequences originate from different paleogeographic domains (Prepiemont basin and Briançonnais platform respectively); (iv) to interpret as stratigraphic the contact of the Faisceau Vermiculaire and the Série Rousse with the basement forming the Alphubel anticline; the local unconformity is interpreted as the result of the activity of synsedimentary Jurassic normal paleofaults; (v) to highlight the trace of a major Jurassic normal fault, that should have marked an abrupt thinning of the paleomargin; it corresponds now to the contact between the Faisceau Vermiculaire (and associated Série Rousse) and the Siviez-Mischabel basement in the hinge of the Mischabel backfold. We propose a new tectonic scheme for the structure of the Faisceau Vermiculaire and adjacent units involving an early northward folding of the Faisceau Vermiculaire with the Série Rousse and the ophiolitic Schistes Lustrés of the Tsaté nappe, followed by major backfolding responsible for the southward emplacement of these units above the HP Zermatt-Saas and Monte Rosa nappes. Our study at regional scale shows that the group formed by the Alphubel basement, the Faisceau Vermiculaire and the Série Rousse share a tectonic position and stratigraphic sequences identical to those of the Mont Fort nappe, which outcrops on the other side of the Dent Blanche klippe. It leads to the proposition that this group constitutes the eastern extension of the Mont Fort nappe.

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1 Introduction

The mechanisms leading to the imbrication of continent- and ocean-derived units in collision zones is a long standing and, in several cases, still debated subject in geology.

This study focuses on the region surrounding Zermatt (SW Switzerland and NW Italy), in the central zone of the Alpine Arc (Fig. 1), which exhibits some of the most classic examples of such imbrications in Alpine geology. In particular, a set of thin but widely extending bands formed by metasediments derived from a continental crust are intercalated at different levels in the thick complex of ophiolites and oceanic metasediments. The existence of these bands is known to geologists since the nineteenth century (e.g. Gerlach 1869, 1871, 1883) and have been described and mapped in detail since the beginning of the twentieth century by Emile Argand who grouped them under the name of *Faisceau Vermiculaire* (Argand 1908, 1909, 1911, 1916a, 1923). Since then, several names have been used to designate specific parts, levels or zones of the Faisceau Vermiculaire between the northern Aosta valley and SW Valais: *complesso triassico basale* (Dal Piaz 1965); *série du Frilihorn* (Marthaler 1984; Escher and Masson 1984; Sartori 1987); *Frilihorn nappe* (Escher et al., 1993); *Pancherot—Cime Bianche—Bettaforca Unit* (Dal Piaz 1988); *série des Cimes Blanches* (Vannay and Allemann 1990); and *Cimes Blanches nappe* (Escher et al., 1993; Sartori and Marthaler 1994).

These intercalations of the Faisceau Vermiculaire continent-derived metasediments within calcschists and slivers of oceanic crust around Zermatt have been extensively studied during the last century. A very wide variety of mechanisms have been invoked to explain them. The main one are: (a) stratigraphic succession in natural chronological order (Giordano 1869); (b) high amplitude isoclinal folding involving continent-derived metasediments, calcschists and ophiolites, with a vergence towards the external part of the Alpine arc, followed by large amplitude backfolding (e.g. Argand 1911, 1920, 1934; Ellenberger 1953; Milnes 1974); (c) tectonic superposition of large composite units including basal continent-derived metasediments and upper parts formed by calcschists and ophiolites, followed by later backfolding (e.g. Staub 1942a; Güller 1947; Iten 1948; Bearth 1953a, 1964a, 1976); (d) early detachment of the sedimentary cover from portions of the subducting continental margin, followed by polyphased folding of variable vergence and later backfolding (e.g. Sartori 1987, 1990; Steck 1989; Sartori et al., 1989; Vannay and Allemann 1990; Escher et al., 1993, 1997; Steck et al., 2015); (e) shallow depth offscraping, and stacking within an accretionary wedge, of slivers derived either from the continental margins, or oceanic crust and basin (Marthaler and Stampfli 1989; Stampfli and Marthaler 1990); (f) hyper-extension of the continental margin during Jurassic rifting, leading to the formation of continent-derived detachment allochthons inside the oceanic domain, and subsequent occurrence of small continental units pinched within the oceanic units in the Alpine nappe stack (Dal Piaz 1999; Beltrando et al., 2014; Dal Piaz et al., 2015a; Passeri et al., 2018); (g) emplacement of thin continent-derived sheared slices inside the ophiolitic units, along crustal scale shear zones showing a complex history and reactivations with opposite shear senses (e.g. Cartwright and Barnicoat 2002; Reddy et al., 2003; Forster et al., 2004; Groppo et al., 2009; Kirst 2017; Kirst and Leiss 2017); (h) emplacement of continent-derived detached sedimentary slivers at the interface between two distinct ophiolitic units by top-NW directed extraction (Froitzheim et al., 2006, 2019; Pleuger et al., 2007); (i) backshearing and backfolding allowing the emplacement of sheared off continent-derived metasedimentary blocks and lenses inside the ophiolites and calcschists complex (Scheiber et al., 2013); (j) diachronous juxtaposition and underplating of slices detached at different depth along the Alpine subduction interface (Angiboust et al., 2014).

(See figure on next page.)

Fig. 1 Tectonic map of the upper Matter valley and NW Aosta valley showing the intercalations of the continent-derived Faisceau Vermiculaire Permian-Jurassic series (incl. Pancherot—Cime Bianche—Bettaforca and Frilihorn) and of the non-ophiolitic Schistes Lustrés of the Série Rousse, inside the ophiolitic Tsaté nappe (or Combin zone s.str.). After Argand (1908), Güller (1947), Bearth (1953b, 1964b, 1967a, 1973), Martin (1982), Crespo (1984), Sartori (1987), Escher (1988), Girard (1995), Steck et al. (1999, 2015), Bucher et al. (2003a), Marthaler et al. (2008, 2020), Dal Piaz et al. (2015b) and observations from this study. ***A_B***: Alphubel pre-Permian basement; ***Co***: Combin zone s.str. (=Tsaté nappe); ***DB_M***: Dent Blanche Mesozoic; ***EL***: Etirol-Levaz unit; ***Fu***: Furgg Series; ***Go***: Gornergrat nappe; ***Gr***: Grundberg Series; ***PG***: Portjengrat basement; ***Pi***: Pillonet unit; ***SM_B***: Siviez-Mischabel basement; ***St***: Stockhorn basement; ***Ts***: Tsaté nappe (=Combin zone s.str.); ***Tu***: Tuftgrat Series

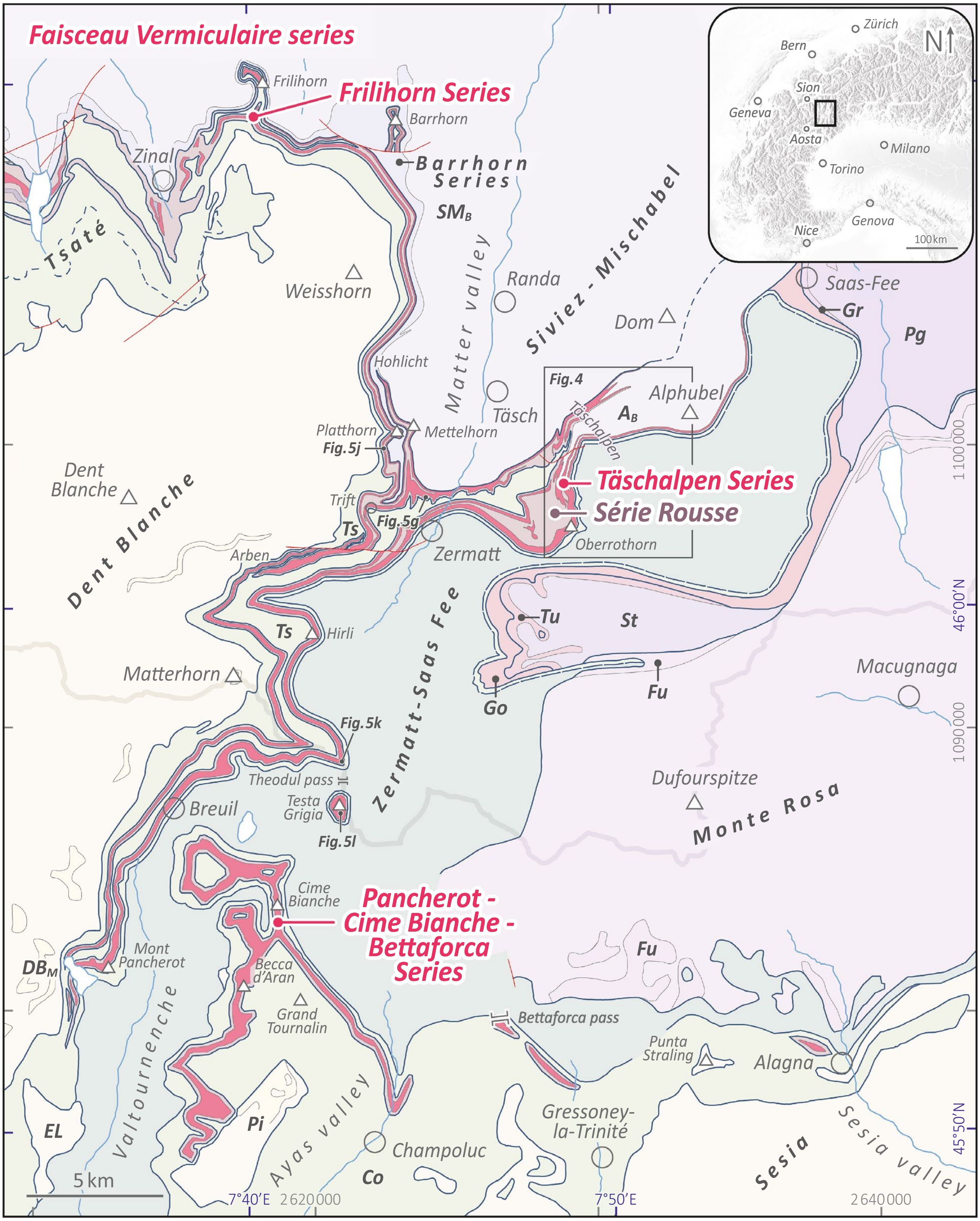


Fig. 1 (See legend on previous page.)

Despite the large number of studies that have addressed these questions, and the many and varied hypotheses that have been proposed to explain the complex tectonics of this zone, no real consensus has ever been reached within the geological community.

The present study mainly focuses on the structure and stratigraphy of the various bands constituting the Faisceau Vermiculaire in the area surrounding Zermatt and, in particular, in the Täschalpen sector (Fig. 1). At this location, the Faisceau Vermiculaire is locally in contact with Paleozoic basement; the question of the nature of these contacts is an important aspect of the study. A new detailed mapping of the outcrops was carried out at Täschalpen on both sides of the valley. Particular attention was paid to the study of basement-cover contacts on the SW slope of the Alphubel and to the associated sediments on the left side of the valley. Data from our previous work on the Mont Fort nappe in the area located to the north and west of the Dent Blanche klippe (Pantet et al., 2020, 2023) have also been integrated. Relationships between the Faisceau Vermiculaire and the Mont Fort nappe (incl. the Evolène Series and Série Rousse) are discussed. Finally, questions related to the initiation and progressive development of backfolds are briefly discussed in the light of the new data and constraints resulting from this study.

2 Geological setting

The Pennine Alps in the region surrounding Zermatt exhibit a complex nappe stack including both: (i) ophiolites and oceanic meta-sediments derived from the Mesozoic Piemont Basin (Alpine Tethys); (ii) continental basement and cover units derived from the European—Briançonnais s.l. and Adriatic continental margins that bordered the Piemont Basin to the north and south, respectively.

The uppermost unit of this nappe stack is the Adriatic margin-derived klippe of the Dent Blanche nappe (e.g. Lugeon and Argand 1905a; Argand 1911; Diehl et al., 1952; Ballèvre et al., 1986), or Dent Blanche Tectonic System (Manzotti et al., 2014, 2017), showing a greenschist- to blueschist-facies Alpine metamorphic imprint (Manzotti et al., 2020), and rooting into the partly eclogitic Sesia zone (e.g. Dal Piaz et al., 1972; Compagnoni 1977; Giuntoli and Engi 2016), which forms the southeastern part of the area (Fig. 1). The other units including basement in this area are derived from the European—Briançonnais s.l. continental margin. From an internal to an external position, they consist of: the Monte Rosa nappe (e.g. Bearth 1952; Pawlig and Baumgartner 2001; Steck et al., 2015; Vaughan-Hammon et al., 2021; Luisier et al., 2022); the Stockhorn nappe (Escher et al., 1988; Steck et al., 2001, 2015; Kramer 2002); the Portjengrat nappe (e.g. Kramer 2002; Masson 2002; Steck et al., 2015); and the Siviez-Mischabel nappe (e.g. Bearth 1963, 1964a; Escher 1988; Sartori 1990; Genier et al., 2008; Scheiber et al., 2013, 2014). Alpine metamorphic imprint in these units varies from HP/UHP eclogite facies in the Monte Rosa to greenschist facies in the Siviez-Mischabel nappe (e.g. Steck et al., 2001, 2015; Bousquet et al., 2004). Ophiolites and oceanic meta-sediments derived from the Piemont basin form a complex stack of folded slivers revealing two distinct types of metamorphic evolution (Kienast 1973; Dal Piaz 1974; Ernst and Dal Piaz 1978; Merle and Ballèvre 1992; Ballèvre and Merle 1993; Negro et al., 2013): the lower units (Zermatt-Saas Fee and Antrona) display eclogite-facies paragenesis (e.g. Bearth 1967a; Pfeifer et al., 1989; Bucher et al., 2005; Angiboust et al., 2009; Bucher et al., 2019; Dragovic et al., 2020) with a local UHP relic (e.g. Reinecke 1991, 1998; Forster et al., 2004; Groppo et al., 2009; Frezzotti et al., 2011, 2014; Luoni et al., 2021), whereas the upper unit, the Tsaté nappe (Sartori 1987; Escher 1988; Marthaler and Stampfli 1989) or Combin zone s.str. (e.g. Dal Piaz 1971; Bearth 1976; Caby 1981), displays greenschist-facies paragenesis with blueschist-facies relics (e.g. Caby 1981; Desmons et al., 1999; Bousquet et al., 2004; Manzotti et al., 2021).

The studied continent-derived metasediments constituting the different bands of the *Faisceau Vermiculaire* (Argand 1916b, 1916a), are intercalated at various levels within the Schistes Lustrés and ophiolites of the Tsaté nappe and close to its basal limit with the Zermatt-Saas Fee nappe (Figs. 1, 2). They are mainly formed of quartzites, dolomites, and various marbled and/or highly tectonized carbonates. The ages of these metasediments are mostly interpretative, classical age attributions range from Permian to Jurassic (e.g. Güller 1947; Bearth 1976). In the slopes located directly north of Zermatt (Fig. 2), it is possible to count up to twenty superimposed bands of the Faisceau Vermiculaire between the top of the ophiolites of the Zermatt-Saas Fee nappe and the base of the Dent Blanche nappe (Argand 1916a). They are interspersed and folded with the non-ophiolitic Schistes Lustrés of the Série Rousse (cf. chap. 3.2) and with the ophiolites and ophiolite-bearing Schistes Lustrés of the Tsaté nappe.

The thickness of the different bands forming the Faisceau Vermiculaire rarely exceeds a few tens of meters and is frequently reduced to a few meters or tens of cm (Fig. 3a). In some sectors, generally corresponding to fold hinges, their thickness can reach a few hundred meters (e.g. Figure 2). Despite their reduced thickness, these bands show remarkable extensions. The thickest ones can be followed almost continuously, when not masked by Quaternary deposits, from the Täschalpen sector to the NE of Zermatt, up to the crests of the upper

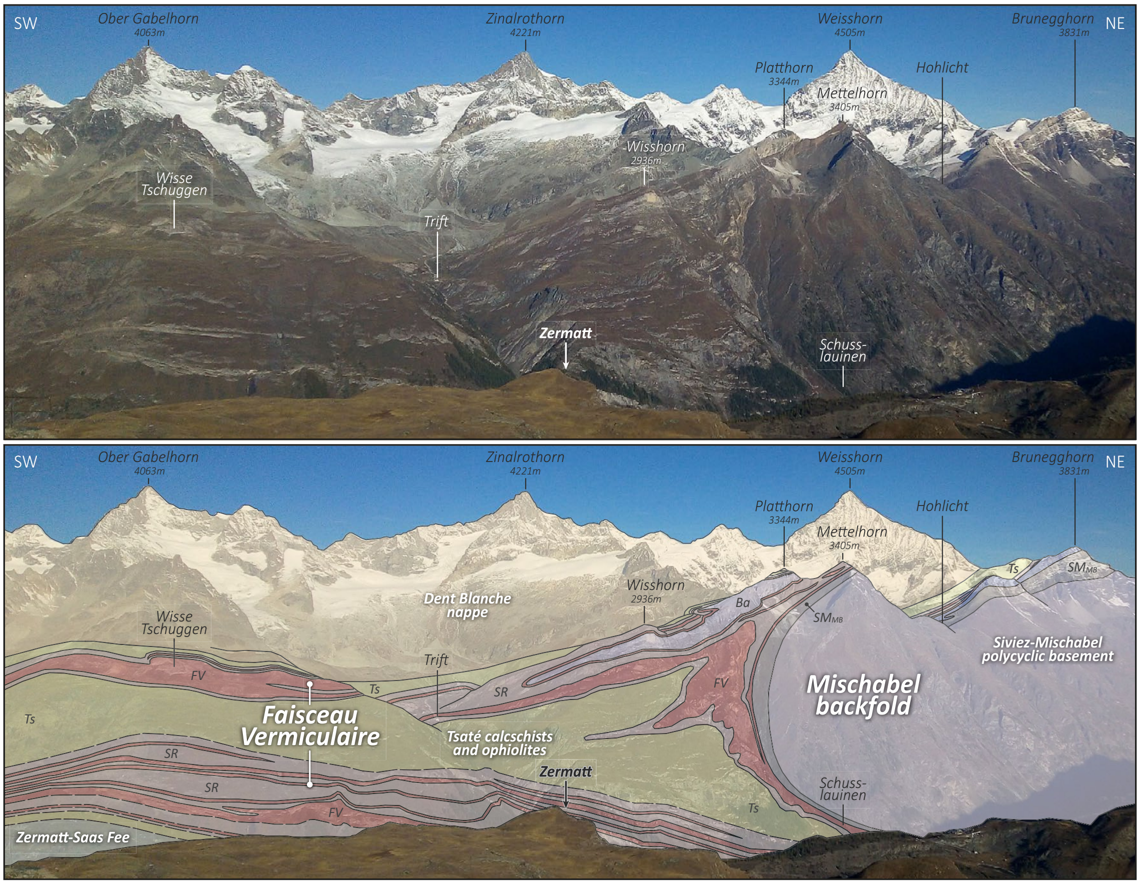


Fig. 2 Structure of the Faisceau Vermiculaire above Zermatt, in the area of the hinge of the Mischabel backfold. The Faisceau Vermiculaire is composed of various superimposed bands of Permian-Jurassic continent-derived metasediments, associated with the non-ophiolitic Schistes Lustrés of the Série Rousse. These series are folded and intercalated within the Schistes Lustrés and ophiolites of the Tsaté nappe. Picture taken from the Gornergrat area (C. Jossevel); geological limits after Argand (1908), Bearth (1953b, 1964b), Wilson (1978), Crespo (1984) and Sartori (1987); *Ba*: Barrhorn Series (Siviez-Mischabel autochthonous Mesozoic cover); *FV*: Faisceau Vermiculaire; SM_{MB}: Siviez-Mischabel monocyclic basement; *SR*: Série Rousse calcschists; *Ts*: Tsaté nappe

Valtournenche and Ayas valleys and are found even further to the SE around the Bettaforca pass and up to Alagna (Fig. 1). Further south, the Faisceau de Cogne in southern Aosta valley (e.g. Hermann 1925, 1928; Elter 1972; Beltrando et al., 2008, 2009; Loprieno and Ellero 2021) and the Faisceau de Prariond in the Vanoise massif (e.g. Ellenberger 1958; Polino and Dal Piaz 1978; Deville 1987; Deville et al., 1992) are found in a tectonic position similar to that of the Faisceau Vermiculaire and represent most likely its southern equivalents.

In most of the recent studies, the Faisceau Vermiculaire is subdivided into two distinct tectonic units. The Frilihorn nappe groups the structurally higher bands of the Faisceau Vermiculaire that are interspersed within the Tsaté nappe, whereas the structurally lower bands, located near the basal contact of the Tsaté nappe over the Zermatt Saas zone, are linked to the Cimes Blanches nappe (e.g. Escher et al., 1993, 1997; Steck et al., 1999, 2015). The continental margin-derived Cimes Blanches metasediments are not found exactly at the contact between the Zermatt-Saas Fee and Tsaté ophiolitic nappes but structurally higher inside the Tsaté nappe. Indeed, metabasites devoid of eclogite-facies imprint (even as relict) have been identified between the lowermost bands of the Faisceau Vermiculaire and the Zermatt-Saas Fee eclogites in different localities of the

Valtournenche and Ayas valley, where they are referred to as Lower Combin Unit (Ballèvre et al., 1986; Cortiana et al., 1998; Bucher et al., 2004a; Dal Piaz et al., 2015b; Passeri et al., 2018). Metabasites devoid of eclogitic imprint have also been described in an identical tectonic position around Zermatt, in the sectors of the Oberrothorn (Bearth 1973) and Täschalpen (Cartwright and Barnicoat 2002).

In the area surrounding Täschalpen, the Faisceau Vermiculaire is composed of numerous bands which are partly folded together with the basement of the Alphubel Lappen (Staub 1942b; Güller 1947; Müller 1983), later described as the Alphubel fold (Steck 1989; Sartori et al., 1989) and attributed to the Siviez-Mischabel nappe (e.g. Escher 1988; Steck 1989; Steck et al., 1999, 2015). In this area, the distinction between the Frilihorn and Cimes Blanches units according to the criteria described above is unclear (cf. Figure 1; Steck et al., 1999). For this reason, we will rather use the term Täschalpen Series to refer to the whole set of bands constituting the Faisceau Vermiculaire in this sector.

The question of the paleogeographic origin of the continent-derived metasediments forming the Faisceau Vermiculaire remains controversial. The first hypothesis proposed was a northern origin (Argand 1909, 1911, 1916b). It has been later followed by many authors invoking a provenance from the Briançonnais (s.l.) margin (e.g. Sartori 1987; Vannay and Allemann 1990; Escher et al., 1997; Sartori et al., 2006; Steck et al., 2015), or more specifically from the Briançonnais swell (e.g. Ellenberger 1953; Scheiber et al., 2013), or from the Prepiemont domain (i.e. the distal part of the Briançonnais s.l. margin; e.g. Elter 1960, 1972; Dal Piaz 1974; Bearth 1976; Dal Piaz and Ernst 1978; Escher and Masson 1984; Marthaler 1984; Escher 1988; Deville et al., 1992). The hypothesis of a southern origin (Staub 1942b; Güller 1947; Iten 1948) has been later followed by several authors, proposing either an origin from the distal Adriatic margin (e.g. Caby et al., 1978; Caby 1981; Froitzheim et al., 2006, 2019; Pleuger et al., 2007), or from Adriatic margin-derived extensional allochthons (Lower Austroalpine outliers; e.g. Dal Piaz 1999; Dal Piaz et al., 2001, 2015a; Beltrando et al., 2014; Passeri et al., 2018).

3 Lithologies and stratigraphy of the Faisceau Vermiculaire and Série Rousse

3.1 Faisceau Vermiculaire series

The metasediments forming the Faisceau Vermiculaire are frequently reduced to thin, extremely stretched bands (Fig. 3a), sometimes less than a meter thick, in which most often only the presence of dolomites and/or of quartzites can be identified.

Nevertheless, the deformation affecting the Faisceau Vermiculaire shows strong regional variations and some sectors of particularly low strain allow interesting observations. This is the case for the area directly south of the Mischabel backfold, between the Schusslauinen and the Täschalpen (Figs. 1, 4), where the strong rheological contrast between the Paleozoic basement and the Mesozoic sediments, allows the preservation of a lower strain sector in the hinge zone of this large open backfold. In this area, some of the bands forming the Faisceau Vermiculaire reach thicknesses of several tens of meters (e.g. Figures 3b, i, 5b, d), up to a hundred meters, with well-developed stratigraphic series, involving quartzschists, phyllitic and tabular quartzites, dolomites, calcitic marbles and breccias (e.g. Figures 3b, c). These lithologies and their stratigraphic succession are described below and compared to the successions at other localities in the Faisceau Vermiculaire. The overall

(See figure on next page.)

Fig. 3 Lithologies of the Faisceau Vermiculaire Permian-Jurassic series and of the Série Rousse non- ophiolitic Schistes Lustrés (p.p. Upper Cretaceous). **a** Typical aspect of a highly stretched band of the Faisceau Vermiculaire, and associated calcschists of the Série Rousse; Adlerflüe [2ʹ620ʹ460/1ʹ110ʹ670], Turtmann valley. **b** Stratigraphic succession in the Täschalpen Series from the Faisceau Vermiculaire showing from the base to the top: Tabular Quartzites attributed to the Lower Triassic, dolomites attributed to the Middle Triassic and banded calcitic marbles showing dolomitic elements (Jurassic?); Bru [2ʹ629ʹ460/1ʹ100ʹ880]. **c** Stratigraphic contact between phyllitic quartzites ("Verrucano") attributed to the Upper Permian and Tabular Quartzites attributed to the Lower Triassic; Rinderberg [2ʹ629ʹ860/1ʹ100ʹ290]. **d** Phyllitic quartzite with cm-sized quartzitic clasts ("Verrucano" facies) attributed to the Upper Permian; Sommertschuggen [2ʹ628ʹ945/1ʹ098ʹ630]. **e** Polymict breccia of the Täschalpen Series with light grey calcitic matrix and predominantly dolomitic clasts; Sommertschuggen [2ʹ628ʹ840/1ʹ098ʹ560]; these breccias are attributed to the Upper Jurassic by comparison with the stratigraphic succession of the Breccia nappe in the Prealps. **f** Similar polymict breccia from the Cime Bianche Series of the Faisceau Vermiculaire; Col Sud des Cimes Blanches [2ʹ618ʹ630/1ʹ084ʹ180], Ayas valley. **g**, **h** Polymict breccia of the Täschalpen Series with a calcitic matrix and clasts of dolomites, calcitic marbles, Tabular Quartzites and Verrucano; Sommertschuggen; g [2ʹ628ʹ970/1ʹ098ʹ650]; h [2ʹ628ʹ720/1ʹ098ʹ540]. **i** Stratigraphic sequence (tectonically overturned) observed in the Täschalpen Series and Série Rousse. From top to bottom: Tabular Quartzites (Lower Triassic), dolomites (Middle to Upper Triassic), microbreccias (Jurassic?) and Série Rousse calcschists (p.p. Upper Cretaceous); Rotbach [2ʹ629ʹ440/1ʹ101ʹ240]. **j** Typical aspect of the Série Rousse calcschists; Bru [2ʹ629ʹ560/1ʹ101ʹ030]. **k** Stratigraphic contact between a polymict breccia of the Faisceau Vermiculaire attributed to the Jurassic and Série Rousse calcschists showing cm-sized dolomitic clasts at the base; Schusslauinen [2ʹ624ʹ280/1ʹ098ʹ110], Zermatt. **l** Calcschists of the Série Rousse showing a conglomeratic basal level, Jurassic calcitic marbles are outcropping 2 m below on the right; Rinderberg [2ʹ629ʹ660/1ʹ100ʹ155]

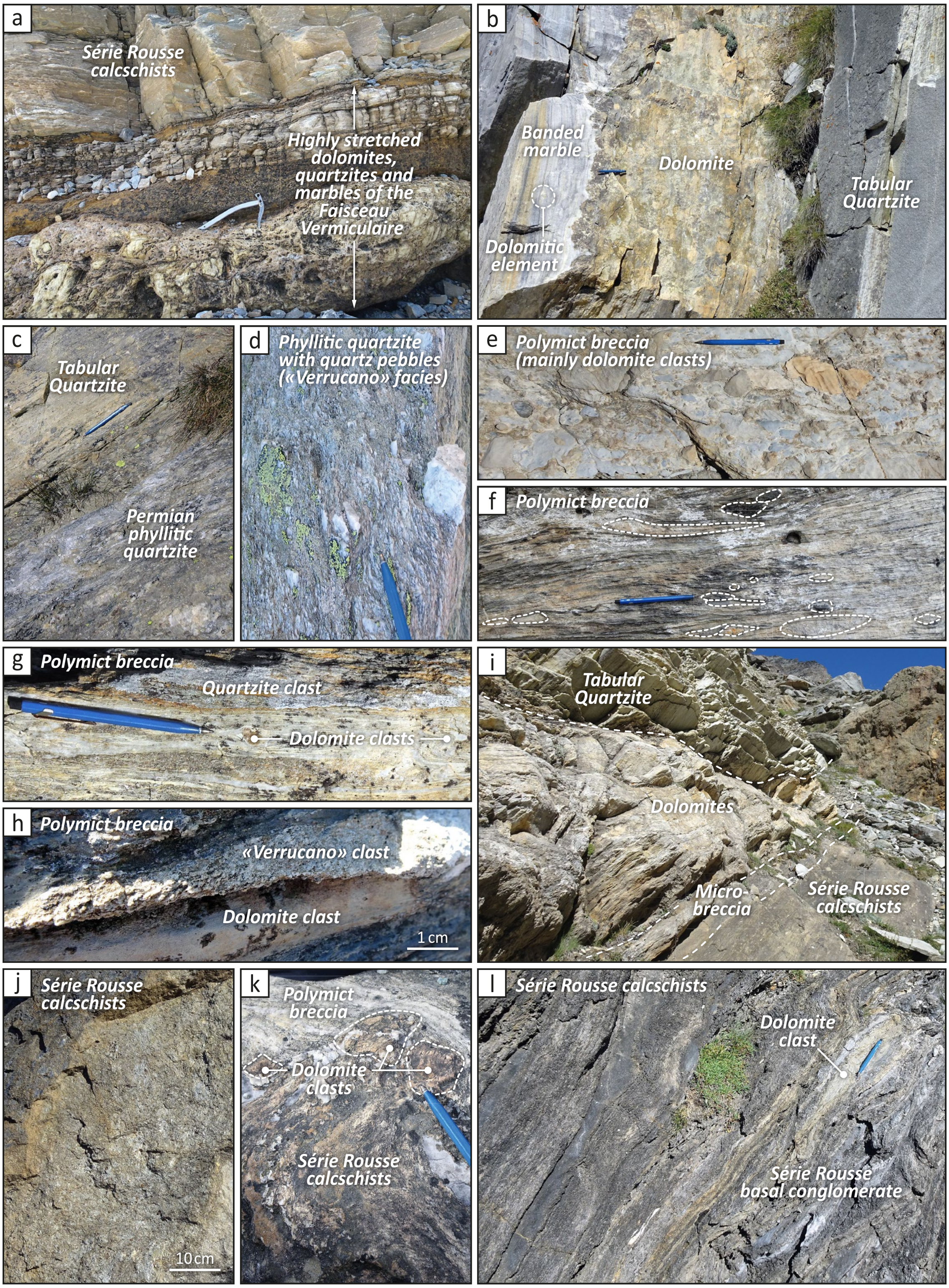


Fig. 3 (See legend on previous page.)

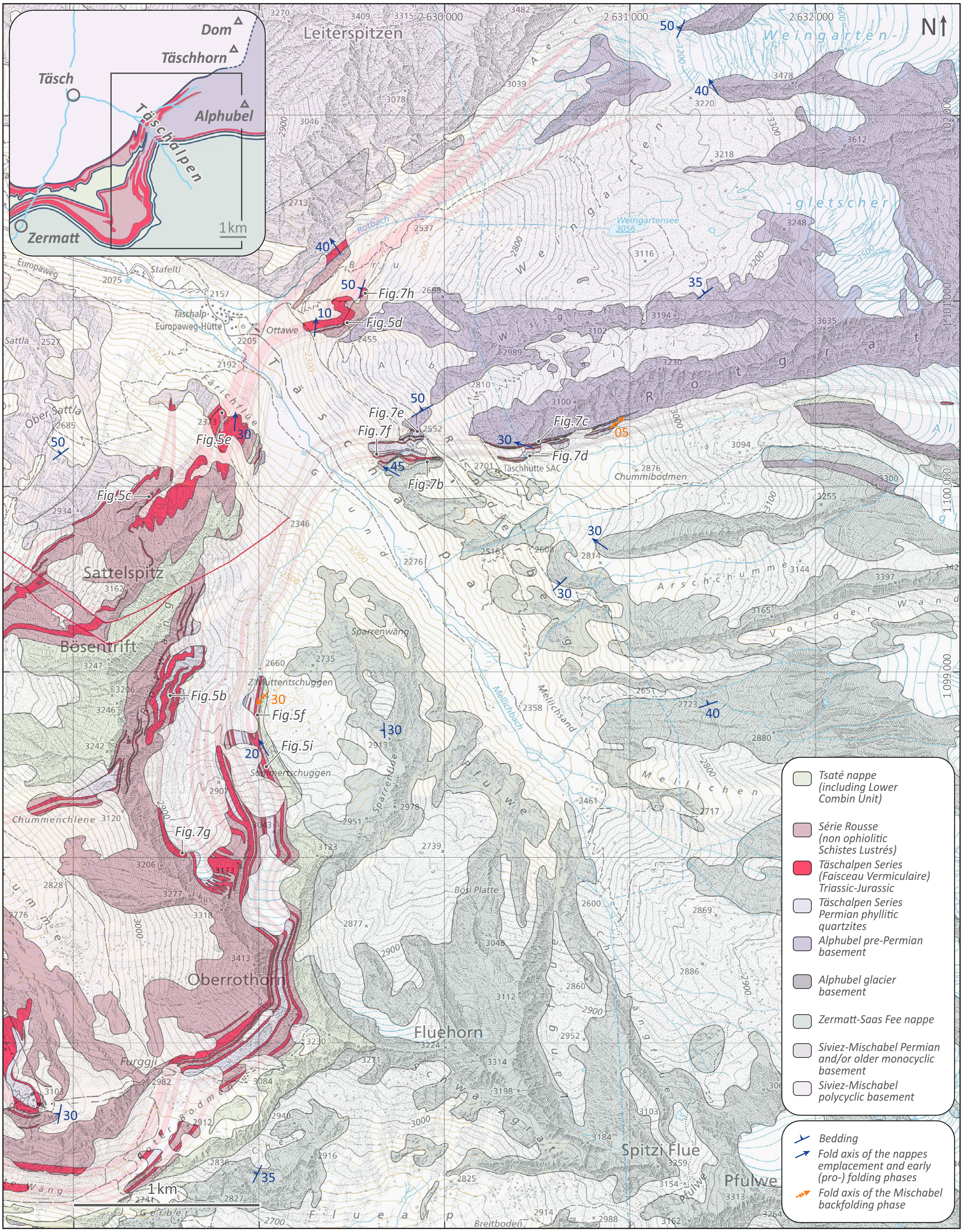


Fig. 4 Geological map of the Täschalpen area; after Güller (1947); Bearth (1953b, 1964b, 1967a, 1973); Martin (1982); Escher (1988); Ganguin (1988); Girard (1995); Steck et al., (1999, 2015) and observations from this study; basemap ©swisstopo

stratigraphic succession described below is found in almost all the different bands and series of the Faisceau Vermiculaire, nevertheless, local successions are most often reduced compared to this complete succession. Depending on the area, these reductions may be tectonic (boudinage, shearing) or stratigraphic (e.g. sedimentary gaps; cf. chapter 6.1).

3.1.1 Quartzites

The quartzschists and phyllitic quartzites are mainly composed of quartz, generally in sub-mm grains, white micas and minor chlorite, marking the penetrative cleavage, albite and K-feldspar; accessory minerals include apatite, zircon, calcite, chlorite, tourmaline, epidote, rutile and other oxides (e.g. Girard 1995; Bucher et al., 2004a; Passeri et al., 2018). At Täschalpen, especially on the left (SW) side of the valley, the quartzites have a thickness of a few tens of meters. Identical lithologies at the base of the Pancherot—Cime Bianche—Bettaforca Series in the upper Valtournenche are one hundred meters thick (cf. Passeri et al., 2018). These quartzschists and phyllitic quartzite are classically assigned to Permian (e.g. Güller 1947; Bearth 1953b, 1976). Some of these levels are characterized by the presence of abundant cm-sized, sometimes pinkish, quartz pebbles (Fig. 3d), which are commonly found in the Upper Permian levels of the units derived from the Briançonnais (s.l.). These facies are often referred to as «Verrucano» (e.g. Jäckli 1950; Trümpy 1966; Genier et al., 2008) and attributed to the Bruneggjoch Fm. (Sartori 1990; Sartori et al., 2006).

At their top, the phyllitic quartzites decrease in mica content and gradually turn into pure white quartzites (Fig. 3b, c), classically referred to as Tabular Quartzites. They are observed in numerous localities in the Faisceau Vermiculaire and reach a maximum thickness of a few tens of meters, partly resulting of duplications by isoclinal folding. They are similar to those observed at the top of the Bruneggjoch Fm. (Sous le Rocher Member; Sartori et al., 2006) in the Siviez-Mischabel nappe (e.g. Sartori 1990; Genier et al., 2008) and in the Mont Fort nappe (e.g. Allimann 1987, 1990; Pantet et al., 2020). Similar Tabular Quartzites, associated with phyllitic and conglomeratic quartzites, are also found locally at the base of the Mont Dolin Series (Hagen 1948; Ayrton et al., 1982; Burri et al., 1999), the Mesozoic cover of the Dent Blanche nappe in SW Switzerland. Quartzites are however almost absent at the base of the Roisan Series (Ballèvre et al., 1986; Dal Piaz et al., 2015a; Ciarapica et al., 2016), another Mesozoic series of the Dent Blanche Tectonic system.

3.1.2 Dolostones and associated calcitic marbles

Dolostones, sometimes associated with calcitic marbles, stratigraphically overly the quartzites (e.g. Figures 3b, i). Dolostones show different facies: either massive, dm-bedded and light-colored, with a russet or brownish patina (Fig. 3b); to fine-grained, laminated, dark-colored facies, sometimes with whitish patina (Vannay and Allemann 1990; Passeri et al., 2018). They are made up to 90% of dolomite, associated with calcite, phlogopite and white mica ± talc and Mg-clinochlore (Bucher et al., 2004a). No fossils have been found in the dolomitic levels of the Faisceau Vermiculaire, but the comparison with less deformed and fossil-bearing series of the Alps and Prealps suggests a Middle to Late Triassic age (e.g. Sartori 1987; Vannay and Allemann 1990; Passeri et al., 2018).

In several sectors, light-colored, thin-bedded, and laminated calcitic marbles are intercalated within the dolomitic levels, or locally form their base; they are usually referred to the Middle Triassic (e.g. Sartori 1987; Vannay and Allemann 1990; Passeri et al., 2018). Remnants of corals and crinoids have been observed by Bucher et al. (2004a) in similar marbles from the Arben area, west of Zermatt (Fig. 1).

In several places, the dolostones and marbles of the Faisceau Vermiculaire are partly replaced by cornieules (cf. Masson 1972). The presence of gypsum is mentioned by Bearth (1976) within cornieules levels in the Oberrothorn area, east of Zermatt.

The presence of an upper yellow quartzite level, as described by Passeri et al. (2018) on the Pancherot and Becca d'Aran successions in the Valtournenche and interpreted as representing the Upper Triassic, was not observed in any of the outcrops studied in this work. High amplitude isoclinal folds have however been identified in many sectors (e.g. Figures 4, 5a) and locally induce duplications of the Lower Triassic Tabular Quartzite level. The unpublished detailed studies of the Pancherot and Eastern upper Valtournenche areas from Dentan and Menthonnex (1990) and Allemann and Vannay (1987), respectively, indicate that such high-amplitude recumbent isoclinal folds, are affecting the whole series in both Pancherot and Becca d'Aran sectors and could therefore be responsible of such duplications.

The thickness of the Triassic carbonates in the Faisceau Vermiculaire series reach locally several tens of meters, but the thickest outcrops show duplications resulting from Alpine folding.

3.1.3 Breccias and associated calcitic marbles

Well recognizable breccias have been described in multiple localities throughout the Faisceau Vermiculaire (e.g. Figures 3e-h; Güller 1947; Bearth 1953a, 1973, 1976; Dal Piaz 1965, 1974; Sartori 1987, 1990; Vannay and Allemann 1990; Dal Piaz et al., 2015a). However, because of the strong deformation, breccias are frequently difficult to recognize. Highly elongated clasts could be mistaken for thin-bedded sedimentary alternations. For this reason, the quantity of breccias in the Faisceau Vermiculaire series is probably most often drastically underestimated.

These breccias show very variable facies, all intermediates are observable between: (i) monogenic dolomitic breccias with a dolomitic matrix (e.g. Bearth 1976; Vannay and Allemann 1990; Bucher et al., 2004a); (ii) breccias made of dolomitic clasts and dark calcarenitic matrix (e.g. Bearth 1976); (iii) polymict breccias with a calcitic matrix and clasts made of different types of dolomites, limestones, sometimes of tabular quartzite (Fig. 3g) and, locally, also of Permian quartzschists (Fig. 3h); and (iv) breccias with a quartz- and phyllosilicates-rich calcitic matrix and clasts mainly consisting of dolomites and limestones (Fig. 3l; cf. chap. 3.2). The size of their respective clasts ranges from a few mm to several tens of cm.

Some of the monomict dolomitic breccias could correspond to the Upper Triassic intraformational breccias (Vannay and Allemann 1990; Bucher et al., 2004a), that have been described, for example, in the Briançonnais units of the Prealps (e.g. Baud et al., 2016) and of the Western Alps (e.g. Mégard-Galli 1972; Mégard-Galli and Faure 1988). The other types of breccias have most often been referred to the Lower or Middle Jurassic (e.g. Güller 1947; Bearth 1976; Sartori 1987; Vannay and Allemann 1990). They actually show strong similarities with, for example, the breccias dated from the Early to Middle Jurassic of the Prepiemont-derived Breccia nappe of the Prealps (attested ages from Sinemurian to Bathonian; Weidmann 1972; Stampfli and Marthaler 1990; Plancherel et al., 1998), and of the Adriatic-derived Mont Dolin Series of the Pennine Alps (Hagen 1948; Weidmann and Zaninetti 1974; Ayrton et al., 1982). However, the presence of Upper Jurassic breccias in the Breccia nappe of the Prealps (dated from Late Oxfordian to Early Tithonian; Chessex 1959; Plancherel et al., 1998) and their probable presence in the Evolène Series (Pantet et al., 2020), which both show stratigraphic series very similar to that of the Faisceau Vermiculaire, suggests that some of the breccias described here could also be Late Jurassic in age.

Various types of calcitic marbles, sometimes with an important detritic component (quartz, phyllosilicates, dolomitic grains, etc.) are closely associated with the breccias and most often referred to the Jurassic (Bearth 1976; Sartori 1987; Vannay and Allemann 1990).

3.2 Basal non-ophiolitic calcschists associated with the Faisceau Vermiculaire: the Série Rousse

Over the different bands of the Faisceau Vermiculaire, the base of the Schistes Lustrés is systematically devoid of ophiolitic material and is, on average, richer in carbonate and detrital inputs than the overlying levels of the Schistes Lustrés. The existence of such levels at the base of the Schistes Lustrés has already been observed and described by Güller (1947), Iten (1948) and Bearth (1967a, 1973, 1976). These basal levels mainly consist of calcschists with a brownish to russet patina (Figs. 3i–l), often rich in detritic quartz grains. Their mineralogy consists of calcite, quartz, white micas, chlorite, albite, pyrite, graphite, Fe-carbonates, titanite, tourmaline, clinozoisite, apatite and oxides. Potential relics of planktonic foraminifera composed of Fe-carbonates, which would indicate a Late Cretaceous age, have been described by Crespo (1984) in samples from the Série Rousse collected between Zermatt and the area surrounding Trift.

The basal contact of these ophiolite-free russet calcschists with the metasediments of the Faisceau Vermiculaire most of the time appears as a clean contact without hints of particular shearing (e.g. Figures 3i, k) and has been interpreted as stratigraphic by numerous authors (Güller 1947; Iten 1948; Bearth 1973, 1976; Chadwick 1974; Escher and Masson 1984; Sartori 1987, 1990; Dal Piaz 1988; Escher 1988; Escher et al., 1988; Sartori et al., 1989; Vannay and Allemann 1990; Gasco and Gattiglio 2011). Our observations fully confirm this interpretation. Furthermore, mm to cm dolomitic clasts are locally observed within the calcschists along this basal contact (Fig. 3k). In some outcrops, the base of the calcschists is even formed by a polymict breccia, with a matrix of calcschists and decimetric clasts of dolomites and limestones (Fig. 3l; Güller 1947, Iten 1948, Bearth 1973, 1976). This breccia level at the base of the calcschists, does not exceed a few tens of cm in thickness, locally it reaches a few meters. Upwards, these breccias rapidly evolve to standard non-ophiolitic russet calcschists, by a progressive decrease in clast content (Fig. 3l). The local occurrence of such a basal conglomerate reinforces the hypothesis of the stratigraphic nature of this contact.

Lithologies very similar to these non-ophiolitic russet calcschists are found both in the upper part of the Roisan Series (Ciarapica et al., 2016) and north of the Dent Blanche klippe, where they are referred to as the Série Rousse (Marthaler and Escher in Masson et al., 1980; Marthaler 1984) and have been interpreted as forming the upper part of the autochthonous cover of the Mont Fort nappe (e.g. Escher 1988; Pantet et al., 2023). Relics of planktonic foraminifera have been described in various localities of the Série Rousse (e.g. Marthaler 1981, 1984; Pantet et al., 2023) and indicate a Late Cretaceous age (Cenomanian—Campanian?).

The attribution of the non-ophiolitic russet calcschists from the area of Zermatt to the Série Rousse has been proposed by Sartori (1987). The cartographic continuity of the Série Rousse from the Hérens valley, where it rests on top of the Triassic—Lower Cretaceous cover of the Mont Fort nappe and its Paleozoic basement (Pantet et al., 2023), through the upper Turtmann valley, to the area of Zermatt, has then been mapped by Escher (1988). Our observations confirm that the Série Rousse outcropping north of the Dent Blanche klippe (cf. Pantet et al., 2023) is in every point identical to the above described non-ophiolitic russet calcschists from the area of Zermatt. Following the interpretation of Sartori (1987), Escher (1988) and Escher et al. (1988), they will be referred to as Série Rousse below.

4 Phases of deformation affecting the Faisceau Vermiculaire

4.1 Superimposed deformation phases in the hinge zone of the Mischabel fold

In the area of Zermatt, the Faisceau Vermiculaire shows a complex structure (Figs. 1, 2) resulting from successive ductile phases of folding. The most distinctive structure of the area is the Mischabel backfold (Studer 1851; Argand 1911). Its hinge zone, at the level of the basement, is well exposed on the left side of the Matter valley between Zermatt and Täsch and is more than 1500 m high. In this area, between the Schusslauinen and the Wisshorn, the metasediments of the Faisceau Vermiculaire form a remarkable fold cascade resulting of the interference pattern between early isoclinal folds and disharmonic open to tight folds associated to the Mischabel backfold (e.g. Figures 2, 6; Argand 1911; Güller 1947; Bearth 1964a, 1967b; Sartori 1987, 1990; Escher et al., 1997; Steck et al., 2015).

In this sector, due to the strong rheological contrast between the Faisceau Vermiculaire and the adjacent Paleozoic basement, the intensity of the deformation in the metasediments is lower compared to the surrounding areas. In this sector, two distinct phases of isoclinal folds can be recognized macroscopically (e.g. Milnes et al., 1981; Mazurek 1986; Steck 1989; Lebit et al., 2002). As these two phases are most of the time not distinguishable on the field and form together the dominant schistosity, they will be jointly referred to as “nappe emplacement and early folding phases”.

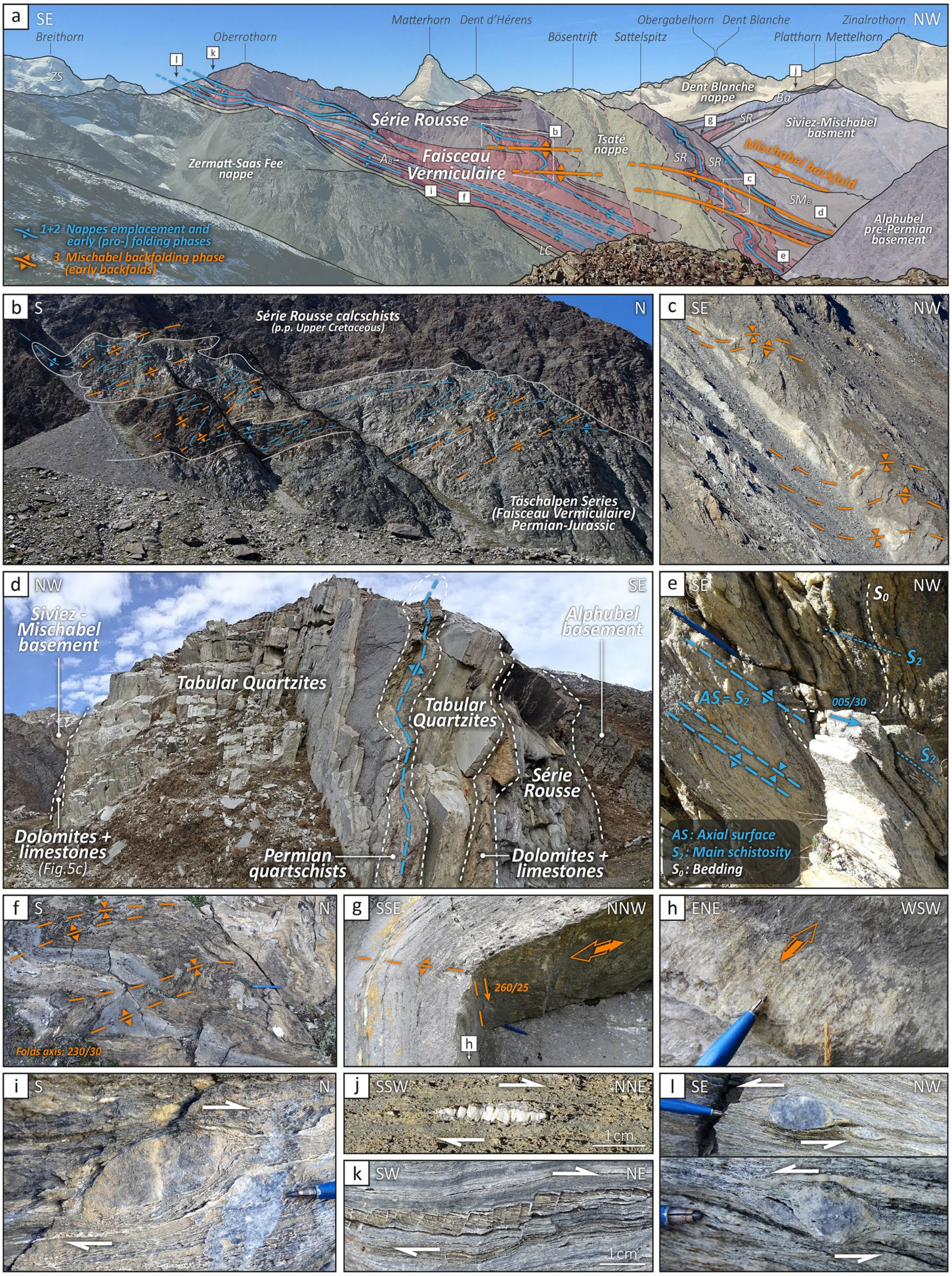
In the hinge area, the axis of the Mischabel backfold plunges to the W/SW with an angle of 20°–25° (Fig. 6, sect. Chüeberg; Lebit et al., 2002).

4.2 Täschalpen area

The Täschalpen area is located NE of the hinge of the Mischabel backfold, in the sector corresponding to the overturned limb of this fold. In this area, the Faisceau Vermiculaire is folded around the basement forming the Alphubel Lappen (Staub 1942b; Güller 1947; Müller 1983), or Alphubel fold (Figs. 4, 6; Steck 1989,

(See figure on next page.)

Fig. 5 **a** Structure of the Faisceau Vermiculaire, Série Rousse and Alphubel basement in the Täschalpen area. Isoclinal folds affecting the Permian-Jurassic Faisceau Vermiculaire (Täschalpen Series), the Série Rousse and the Tsaté nappe are visible in the south-east faces of the Oberrothorn and Bösentrift, and in the north face of Sattelspitz. These folds are in turn refolded by open to tight folds of the Mischabel phase, showing asymmetric "z" geometries that are compatible with the location in the overturned limb of the Mischabel backfold (visible in the background). Picture taken from the base of the Alphubel glacier [2ʹ631ʹ860/1ʹ100ʹ270]. A_B: Alphubel pre-Permian basement; *Ba*: Barrhorn Series; *LC*: Lower Combin Unit; SM_B: Siviez-Mischabel basement; *SR*: Série Rousse; *ZS*: Zermatt-Saas Fee nappe. **b** Hectometric fold in the Bösentrift east face showing an interference pattern between early isoclinal folds (blue) and later close to tight lower amplitude folds attributed to the Mischabel phase (orange). Asymmetric "z" geometries of the folds are compatible with the location in the overturned limb of the Mischabel backfold. **c** Enlargement of Fig. a highlighting folds of the Mischabel phase affecting the light-colored early phase isoclinal anticline formed by the metasediments of the Täschalpen Series. **d** Isoclinal early phase anticline in the Täschalpen Series showing a core of quartzschists (Permian) surrounded by Tabular Quartzites (Lower Triassic), dolomitic and calcitic marbles (Middle Triassic-Jurassic?) and calcschists of the Série Rousse (p.p. Upper Cretaceous); the dominant schistosity is parallel to the axial plane; [2ʹ629ʹ450/1ʹ100ʹ880]. **e** Hinge of an early phase isoclinal fold associated to the dominant schistosity in Tabular Quartzites of the Täschalpen Series; [2ʹ628ʹ800/1ʹ100ʹ380]. **f** Open to tight folds in the basal levels of the Série Rousse; contrary to the early phase isoclinal folds of Figs. d and e, these folds are younger than the dominant schistosity and no penetrative schistosity is visible parallel to their axial surfaces (only a poorly developed crenulation can be distinguished locally); the asymmetric "z" geometries of the folds are compatible with the location in the overturned limb of the Mischabel backfold; [2ʹ629ʹ000/1ʹ098ʹ760]. **g** Open fold of the Mischabel phase affecting calcitic marbles of the Faisceau Vermiculaire in the area of the hinge of the Mischabel backfold; slickensides can be observed on the bedding (+ dominant schistosity) surfaces on both limbs of the fold, they show opposite sense between the two limbs and are indicative of flexural slip folding mechanism; [2ʹ624ʹ000/1ʹ098ʹ100], Schusslauinen, location in Fig. 1. **h** Slickensides from the vertical limb of the fold of Fig. g. **i** Clast of calcitic marble in a breccia of the Täschalpen Series, deformed as a sigma-clast and indicating a top-N shear sense (associated to the dominant schistosity); the outcrop surface is parallel to the stretching direction of the clasts; [2ʹ629ʹ040/1ʹ098ʹ450]. **j** Early quartz vein parallel to the main schistosity, showing domino-type boudins and indicating a top-NNE shear sense, in Série Rousse calcschists; the outcrop surface is parallel to the stretching lineation (020/25); [2ʹ622ʹ490/1ʹ099ʹ870], Platthorn area, location in Fig. 1. **k** Dolomitic level showing domino-type boudins indicating a top-NE shear sense in marbles of the Faisceau Vermiculaire; the outcrop surface is parallel to the stretching lineation (215/10); [2ʹ620ʹ950/1ʹ088ʹ670], Theodulhorn, location in Fig. 1. **l** Dolomitic clasts from the base of the Série Rousse (upper picture) and marbles of the Faisceau Vermiculaire (lower picture), at Testa Grigia [2ʹ620ʹ860/1ʹ087ʹ040], location in Fig. 1; deformation as sigma-clasts indicate a top-SE shear sense; the outcrop surface is parallel to the stretching lineation (310/20); c' shear bands are visible in the same outcrop and also indicate a top-SE shear sense



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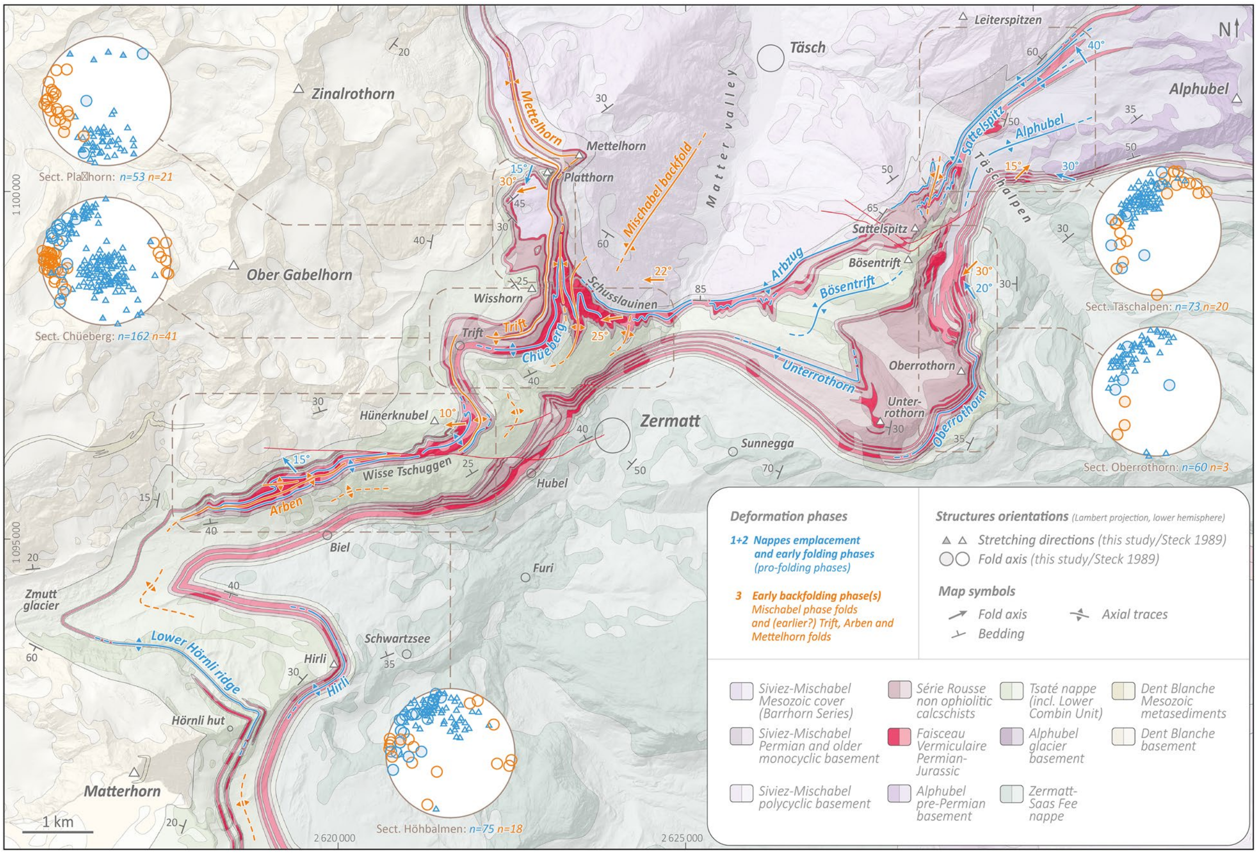

Fig. 6 Structure of the Faisceau Vermiculaire and surrounding units around Zermatt. Bedrock map compiled after Argand (1908), Güller (1947), Bearth (1953b, 1964b, 1967a, 1973), Wilson (1978), Martin (1982), Crespo (1984), Sartori (1987), Ganguin (1988), Girard (1995), Steck et al. (1999, 2015), Bucher et al. (2003a) and observations from this study; sectors covered by Quaternary deposits are indicated with lighter colors

Sartori et al., 1989). An important syncline, constituted of Schistes Lustrés and of different bands of the Faisceau Vermiculaire, separates the basement forming the Alphubel fold, of that forming the hinge of the Mischabel backfold (Figs. 4, 6). This complex syncline has been called the Rotbach syncline by Steck (1989). Its continuation to the NE of the Täschalpen is hidden by the moraines and glaciers covering the most part of this area (Fig. 4), making both the direction of its continuation and its amplitude difficult to estimate.

The fold affecting the Alphubel basement was first interpreted as a second order fold of the same phase as the Mischabel backfold (e.g. Staub 1942b; Güller 1947; Martin 1982; Müller 1983). The detailed study of the successive phases of deformation in the area of Zermatt and Täschalpen, by Steck and collaborators, led to the interpretation of the Alphubel fold as an early fold, prior to the Mischabel phase, locally refolded during this phase (Steck 1989; Sartori et al., 1989; Steck et al., 1989). This interpretation is fully confirmed by the observations detailed below.

On the left (SW) side of the Täschalpen valley, outcrops of pre-Permian basement mark the continuation of the basement fold of the Alphubel (Figs. 4, 5a). These outcrops are found in particular at the SE extremity of the Färichflüe, and in the Sommertschuggen area (e.g. around the point [2′628′960/1′098′580]; Girard 1995). In the Sommertschuggen area, the pre-Permian basement forms the core of a thin and extremely stretched isoclinal anticline and is surrounded by Permian phyllitic quartzites and Mesozoic metasediments of the Täschalpen Series and the Série Rousse. Several other similar thin and stretched anticlines are visible throughout the left side of the valley, between the east face of the Oberrothorn and the north face of the Sattelspitz (Figs. 4, 5a). Most of their anticlinal cores are formed by Permian phyllitic quartzites (e.g. Figure 5b). These stretched isoclinal anticlines constitute most likely frontal digitations of the Alphubel fold. Observations of the hinges associated to these folds show that they are coeval with the dominant schistosity (e.g. Figure 5e). Pinched isoclinal folds involving pre-Permian basement, Permian quartzites and Mesozoic metasediments of the Täschalpen Series and of the Série Rousse are also found on the right side of the valley, on both limbs of the Alphubel fold (Fig. 4). They are characterized by steeply dipping axial surfaces and are also coeval with the dominant schistosity (e.g. Figure 5d). They are interpreted as second order folds associated to the Alphubel antiform.

These stretched isoclinal folds from the Täschalpen area are refolded by open to tight folds with subhorizontal axial surfaces (e.g. Figures 5a–c) that are not associated with a penetrative schistosity, in contrast with the earlier isoclinal folds. Only a poorly developed cleavage is sometimes observable in the hinges of these later folds, parallel to their axial surfaces (e.g. Figure 5f). These interference patterns are identical to those observed in the hinge zone of the Mischabel backfold. There, early isoclinal folds, which are in continuity with those of Täschalpen, are refolded by open to tight folds of the Mischabel phase, which are also devoid of penetrative schistosity associated to their axial surfaces (Fig. 5g). The above-described late open to tight folds of the Täschalpen area, are thus interpreted as equally corresponding to the Mischabel phase. In the slopes between the Oberrothorn and the Sattelspitz, these folds show typical asymmetric "z" geometries (Figs. 5a–c, f) that are compatible with geometries expected for second order folds of the overturned limb of the Mischabel backfold.

4.3 Phases of deformation at regional scale

The same type of interference patterns between early extremely stretched isoclinal folds coeval to the dominant schistosity and later folds associated to backfolding phase(s) are recognized in the Faisceau Vermiculaire and in the surrounding Schistes Lustrés, in the whole upper Matter valley (e.g. Figure 6; Mazurek 1986; Sartori 1987; Steck 1989; Lebit et al., 2002; Bucher et al., 2004a; Steck et al., 2015), and in the northern Aosta valley (e.g. Vannay and Allemann 1990; Bucher et al., 2004a; Pleuger et al., 2007, 2008).

Folds associated to early backfolds, such as the Mischabel backfold, show a WSW-ENE mean axial direction, while most of the measured directions are comprised between SW-NE and SE-NW (Fig. 6; Steck 1989; Vannay and Allemann 1990). Early isoclinal folds, associated to the dominant schistosity, show more variable axial directions. The NW–SE to N-S axial directions could correspond to the initial dominant orientation of these early folds, which could be locally reoriented parallel to the directions of the backfold axis. Stretching directions associated with the early isoclinal folds and the dominant schistosity show a mean NNW-SSW orientation.

Early folds associated to the dominant schistosity are systematically isoclinal throughout the study area. The geometries of the backfolds affecting the Faisceau Vermiculaire, are much more variable. Open folds are observed in the cascade of disharmonic folds affecting the Faisceau Vermiculaire, directly south of the basement hinge of the Mischabel backfold. These open backfolds are associated with slickensides, indicative for flexural slip folding mechanism (Figs. 5g–h). Southward, further away from the hinge zone, geometries of the folds associated to the Mischabel phase progressively evolve to tight folds, showing a semi-ductile deformation style, with slightly bent or kinked micas and nucleation of secondary quartz, calcite and chlorite, but without development of a penetrative schistosity (Mazurek 1986). In southern part of the area (Sesia valley, Fig. 1), where the Combin zone s.l. is pinched between the Sesia zone and the Zermatt-Saas Fee and Monte Rosa nappes, folds associated to the Mischabel phase evolve to isoclinal folds (e.g. Müller 1983; Mazurek 1986; Steck et al., 2015).

A second phase of backfolding, subsequent to the Mischabel phase, affected the whole nappe stack of the Pennine Alps. It resulted in the formation of the crustal-scale Vanzone antiform, whose axial trace runs through the southern Monte Rosa nappe (e.g. Argand 1911; Milnes et al., 1981; Steck et al., 2015). In the area surrounding Zermatt, macroscopic structures associated to the Vanzone phase are inconspicuous at the outcrop scale. Late kink folds from the Täschalpen area are attributed to this phase by Müller (1983). The main effect of the Vanzone phase in the area of Täschalpen and Zermatt consists of a major tilting of the structures towards the NW.

4.4 Macroscopic shear sense indicators

Macroscopic markers indicating local shear sense are frequently observed in the metasediments of the Faisceau Vermiculaire and of the Série Rousse across the whole studied area. They mainly consist of rigid objects such as dolomitic clasts deformed within a more ductile matrix and of c'-type shear bands, systematically observed in sections oriented perpendicular to the schistosity and parallel to the stretching direction.

In the Faisceau Vermiculaire, the Série Rousse and the directly surrounding units, stretching directions associated to the dominant schistosity are mostly oriented NW–SE to N-S throughout the upper Matter valley and northern Aosta valley (Fig. 6; Steck 1989; Reddy et al., 2003; Pleuger et al., 2007; Steck et al., 2015; Kirst 2017; Kirst and Leiss 2017).

Shear senses deduced from macroscopic markers in the Faisceau Vermiculaire and the Série Rousse are, however, not constant across this area. In the sector of the Täschalpen, observed markers constantly indicate a top-N(NW) shear sense (e.g. Figure 5i). The same shear sense is also observed in different sector between Zermatt and the Platthorn (e.g. Figure 5j; top-NNE shear sense), further south in the Theodulhorn (Fig. 5k; top-NE shear sense), and locally in the continuation of the Série Rousse north of the Dent Blanche klippe (e.g. Pantet et al., 2023, Fig. 9e). In the sector of Testa Grigia (Fig. 1), the observed shear-sense markers all indicate top-SE shearing (e.g. Figure 5l). A top-SE shear sense is also reported by Reddy et al. (2003) in the Cime Bianche unit in Valtournenche. Top-S macroscopic shear indicators are also reported by Scheiber et al. (2013) in the NW continuation of the Faisceau Vermiculaire (Frilihorn Series) in the Anniviers valley. Kirst and Leiss (2017) report both top-NW and top-SE macroscopic shear sense markers for calcschists from the Combin zone, surrounding the Faisceau Vermiculaire, in the Lago di Cignana area.

These few data concerning macroscopic shear sense markers clearly indicate that such data are difficult to interpret when not associated with detailed structural studies at both microscopic and macroscopic scales. Such detailed studies have been carried in different sectors of the Faisceau Vermiculaire and surrounding units, for example by Reddy et al. (2003), Pleuger et al., (2007, 2009), Kirst and Leiss (2017). The results of these studies are discussed in chapter 6.3.

5 Contacts of the Faisceau Vermiculaire with the surrounding units between Täschalpen and Zermatt

In the area between the Täschalpen and Zermatt, the different bands forming the Faisceau Vermiculaire alternately rest in contact with different units: with the Permian and older monocyclic basement of the Siviez-Mischabel nappe in the northern part of the area; with the pre-Permian rocks forming the Alphubel fold (or Alphubel Lappen; cf. chap. 4.2) to the east; and with the ophiolitic units (Zermatt-Saas Fee nappe / Lower Combin Unit) to the south of the zone. In addition, an important syncline formed of calcschists and ophiolites of the Tsaté nappe (called here Bösentrift synform; Fig. 6) penetrates between the bands of the Faisceau Vermiculaire from the west. We detail below our observations concerning the contacts of the Faisceau Vermiculaire with each of these units.

5.1 Contacts of the Faisceau Vermiculaire with the ophiolitic units

The Permian to Jurassic metasediments of the Faisceau Vermiculaire are never in direct contact with the ophiolites in this area. They are systematically separated by at least a few meters to several tens of meters of non-ophiolitic calcschists of the Série Rousse. It is the case both within the Bösentrift synform (Fig. 6), e.g. SW of Färichflüe (Fig. 4), and below the southernmost band of the Faisceau Vermiculaire, which is outcropping close to the contact with the Zermatt-Saas Fee eclogites (e.g. Sommertschuggen and NW-Rinderberg areas; Figs. 4, 7a–b).

In this last locality, metabasalts devoid of eclogite-facies imprint are also intercalated between the Faisceau Vermiculaire (and underlying Série Rousse) and the eclogite-facies ophiolites and calcschists of the Zermatt-Saas Fee nappe. These metabasalts have been described by Cartwright and Barnicoat (2002), who attributed them to the Combin zone. According to these authors, these metabasalts show a relict blueschist facies mineralogy, corresponding to a P–T estimate of 451 ± 23 °C and 1.24 ± 0.038 GPa, strongly retrogressed to greenschist facies assemblages. These authors also show that the relict blueschist facies assemblage of these metabasalts differs from the mineralogical assemblage observed in the underlying eclogites of the Zermatt-Saas Fee nappe, by the notably less sodic composition of the amphiboles and the absence of omphacite. For the underlying Zermatt-Saas Fee eclogites, these authors obtained P–T estimates

(See figure on next page.)

Fig. 7 Contacts between the Faisceau Vermiculaire Permian-Jurassic series (Täschalpen Series) and the Alphubel pre-Permian basement, the Série Rousse and the Lower Combin Unit at Täschalpen. **a** NE side of the Täschalpen valley; picture from the Z'Muttentschuggen area; geological limits after Güller (1947), Bearth (1964b), Steck et al. (1999) and data from this study; *A_B*: Alphubel pre-Permian basement; *FV*: Faisceau Vermiculaire Permian-Jurassic series (Täschalpen Series); *LC*: Lower Combin Unit; *SM_{MB}*: Siviez-Mischabel monocyclic basement; *SM_{PB}*: Siviez-Mischabel polycyclic basement; *SR*: Série Rousse; *Ts*: Tsaté nappe. **b** Lower contact of the Faisceau Vermiculaire with the Lower Combin Unit and underlying Zermatt-Saas Fee nappe. **c** Sharp contact between Alphubel pre-Permian albitic gneisses and Triassic dolomites of the Täschalpen Series; [2′630′510/1′100′250]. **d** Contact between pre-Permian albitic gneisses of the Alphubel basement and phyllitic quartzites (Permian) forming the base of the Täschalpen Series; [2′630′440/1′100′150]. **e** Syncline formed by Tabular Quartzites of the Täschalpen Series (Lower Triassic), stratigraphically surrounded on both sides by phyllitic quartzites (Permian) and pre-Permian albitic gneisses of the Alphubel basement; [2′629′860/1′100′300]. **f** Pinched anticlinal core of pre-Permian albitic gneisses of the Alphubel basement, surrounded by phyllitic quartzites of the Täschalpen Series (Permian), and showing to the right a succession interpreted as stratigraphic of Tabular Quartzites (Lower Triassic), dolomites and marbles (Triassic-Jurassic?) and quartzitic calcschists of the Série Rousse (p.p. Upper Cretaceous); [2′629′610/1′100′170]. **g** Anticlinal hinge showing a preserved stratigraphic sequence between Tabular Quartzites (Lower Triassic), thin dolomites and marbles (Triassic-Jurassic) and Série Rousse calcschists (p.p. Upper Cretaceous); [2′628′560/1′098′050]. **h** Contact between calcschists of the Série Rousse and the Tabular Quartzite of the Täschalpen Series; [2′629′560/1′101′040]

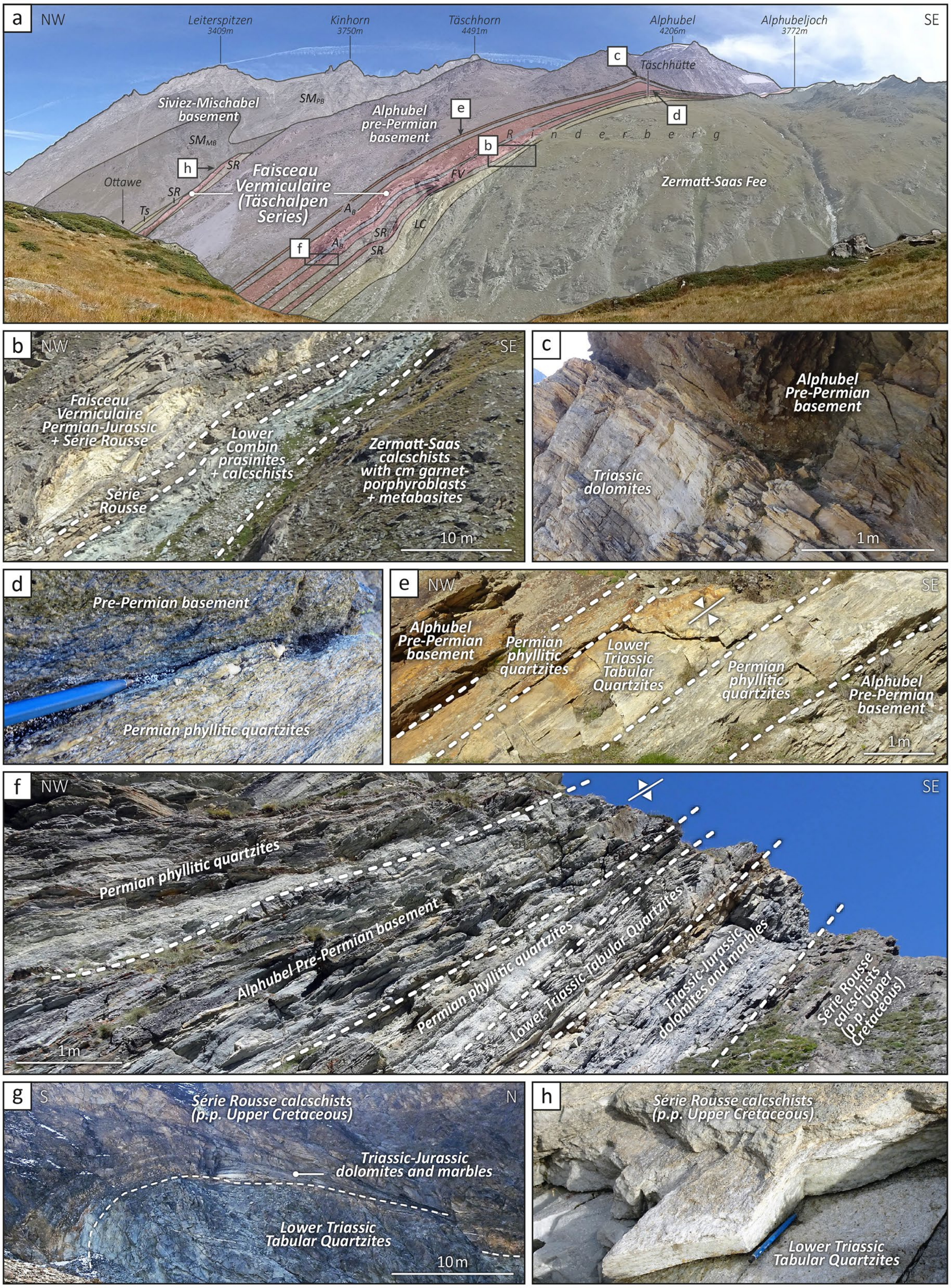

Fig. 7 (See legend on previous page.)

of 591 ± 39 °C for 1.82 ± 0.19 GPa and of 577 ± 47 °C for 1.76 ± 0.22 GPa. Our observations show that, only a few meters away from these non-eclogitic metabasalts, in the other side of a small gully, garnet porphyroblasts up to 1 cm size are abundant in the calcschists forming the south side of this depression (Fig. 7b; e.g. at point [2′629′980/1′100′130]). As cm-sized garnet porphyroblasts are frequent within calcschists and metabasites of the Zermatt-Saas Fee nappe (e.g. Bearth 1967a; Cartwright and Barnicoat 2002; Bucher et al., 2005), while garnets are rarely observed in the Tsaté nappe (Combin zone s.str.) and generally do not exceed 1 mm in diameter (e.g. Burri et al., 1999; Bucher et al., 2004a; Manzotti et al., 2021), we attribute the calcschists of the southern side of this small valley to the Zermatt-Saas Fee nappe and place the upper contact of this unit along this depression (Figs. 4, 7a, b). This interpretation is supported by the description of eclogite-facies metabasalts directly south of this area by Cartwright and Barnicoat (2002).

Metabasalts devoid of eclogitic imprint, associated with calcschists, have also been described in a same tectonic position, east of Roter Bodmen, by Bearth (1973), and later by Girard (1995) in the whole area between Roter Bodmen and Sommertschuggen (topographic names indicated in Fig. 4). These metabasalts have exactly the same tectonic position than those studied by Cartwright and Barnicoat (2002) at Rinderberg. In contrast with the metabasalts outcropping in a lower position in the Zermatt-Saas Fee nappe, these metabasalts (prasinites) are characterized by a clearer, green color, the absence of omphacite and the scarcity of garnets, Na-amphiboles and pseudomorphs after lawsonite (Girard 1995).

As these metabasalts devoid of eclogitic imprint from the Täschalpen and Oberrothorn areas show an identical tectonic position and very similar parageneses and metamorphic imprint to that of the Lower Combin Unit, evidenced and described in the Valtournenche and Ayas valley (Ballèvre et al., 1986; Cortiana et al., 1998; Bucher et al., 2004a; Dal Piaz et al., 2015b; Passeri et al., 2018), we propose to attribute these metabasalts and associated calcschists from the upper Matter valley to this Lower Combin Unit. Further investigations are required to confirm the continuity of this unit between the upper Valtournenche and Oberrothorn areas.

5.2 Contacts of the Faisceau Vermiculaire with the Siviez-Mischabel basement in the hinge of the Mischabel backfold

The Faisceau Vermiculaire (and associated Série Rousse) are in direct contact with the Permian and older monocyclic basement located in the hinge of the Mischabel backfold from the Mettelhorn to the Rotbach valley, NE of Täschalpen (Figs. 4, 6; Güller 1947; Bearth 1964a, b; Sartori 1987). Throughout this area, the contact is mostly covered by Quaternary deposits, from which only patches of intensely strained carbonates and cornieules are emerging. Only a few outcrops allow detailed observations of the contact. They were described by Staub (1942b) and particularly by Güller (1947) who highlighted the tectonic nature of the contact, characterized by intense strain, the presence of a plurimeter thick level of crushed carbonates and cornieules, and locally by the direct contact between an overturned stratigraphic sequence of the Faisceau Vermiculaire Triassic levels and the Permian and older monocyclic basement. The first descriptions of this contact by Argand (1909, 1916a), actually already mention the "abnormal" nature of this contact and refer to the Faisceau Vermiculaire as "detached" from the Grand Saint Bernard nappe. Our observations confirm this interpretation, which was equally adopted and confirmed by e.g. Iten (1948), Sartori (1987), Escher (1988) and Steck et al. (2015).

These observations based on outcrops are confirmed by examination of cores from a recent borehole drilled at Lüegelti (NE of Zermatt) across this contact (Additional files 1, 2). These new observations confirm the direct contact of (Lower?) Permian rocks of the Siviez-Mischabel nappe with more than 5 m of crushed carbonates and cornieules from the Faisceau Vermiculaire, which also include a meter-thick level of non-ophiolitic calcschists interpreted as belonging to the Série Rousse. The examination of this core without any gap of observation proves the absence of Upper Permian and Lower Triassic quartzites of the Siviez-Mischabel cover and the presence, at the contact, of more than 5 m of highly strained carbonates, which both argue against a “normal” stratigraphic succession on top of the Siviez-Mischabel nappe.

It is moreover important to note that the Faisceau Vermiculaire is clearly distinct from the Mesozoic cover of the Siviez-Mischabel nappe (the Barrhorn Series), which extends up to the Wisshorn and Trift area north of Zermatt (Fig. 6). Both the nature of the contact with the Paleozoic basement and the stratigraphy of the series are different (e.g. Staub 1942b; Güller 1947; Sartori 1987, 1990; Steck et al., 2015). This last point is discussed in chapter 6.5.

5.3 Contact of the Faisceau Vermiculaire with the basement forming the Alphubel fold (Alphubel basement)

The contact of the Faisceau Vermiculaire and the Série Rousse with the pre-Permian basement forming the Alphubel fold (or Alphubel Lappen; cf. chap. 4.2) is exposed on both limbs of this fold in the NE side of the Täschalpen valley, as well as in SE-Färichflüe and Sommertschuggen areas, in the SW side of the valley (Figs. 4, 7).

Contrary to the contact with the Permo-Carboniferous metasediments forming the hinge of the Mischabel backfold described above, this contact does not show uniform or constant characteristics across the area. In particular, various lithologies of the Faisceau Vermiculaire and the Série Rousse are alternately observed in direct contact with the Alphubel pre-Permian basement. For example, a direct and sharp contact, between the pre-Permian basement and levels of Triassic dolomites from the Faisceau Vermiculaire, is visible NW of Rinderberg, at point [2ʹ629ʹ870/1ʹ100ʹ250], and is well exposed in the slopes above the Täsch hut (Fig. 7c). Crushed carbonates and cornieules are in turn in direct contact with the same basement a few hundred meters further east (e.g. [2ʹ630ʹ820/1ʹ100ʹ320], [2ʹ630ʹ850/1ʹ100ʹ300]). This pre-Permian basement is instead in contact with the Série Rousse calcschists at Bru (Sartori et al., 1989; e.g. around the point [2ʹ629ʹ510/1ʹ100ʹ860], although the exact contact is masked by Quaternary deposits in this area). Sharp contacts with phyllitic quartzschists (Permian) are also visible in several locations (e.g. Figure 7d). The discordant character of this contact, as well as the contrast between the large amount of outcrops of pre-Permian basement in the NE side of the Täschalpen valley and their scarcity in the SW side of the valley, which is dominated by calcschists, lead to interpret this contact as tectonic (Güller 1947; Bearth 1964b; Martin 1982; Sartori et al., 1989).

Further observations however show that the contact of the Alphubel pre-Permian basement with the Faisceau Vermiculaire (and the Série Rousse) locally appears as concordant, i.e. showing a lithological succession characteristic of a continuous stratigraphic sequence. This is for example the case NW of Rinderberg (Fig. 7e), where a level of Tabular Quartzites (1.5 m thick) shows progressive contacts on both sides with phyllitic quartzites and Verrucano-facies quartzites (0.5–1.5 m thick), which show in turn, unsheared contacts with the pre-Permian basement visible on both sides of the outcrop. As all the contacts observed in this outcrop appear as stratigraphic, this succession is interpreted as a pinched isoclinal syncline with a core belonging to the Faisceau Vermiculaire (Täschalpen Series) and a rim formed by the Alphubel pre-Permian basement. Another lithological succession outcropping at the base of the cliffs, NW of Rinderberg (Fig. 7f), shows a 2 m thick level of pre-Permian basement (gneisses and albitic Paleozoic metabasites), surrounded on both sides by Permian phyllitic quartzites. To the right, these phyllitic quartzites (~ 1 m thick) progressively turn to pure Tabular Quartzites attributed to the Early Triassic (~ 1 m thick), which are in contact with dolomites and marbles (Triassic-Jurassic; ~ 2 m thick), which in turn, surmount several meters of non-ophiolitic calcschists of the Série Rousse (p.p. Upper Cretaceous). Like for the previous outcrop, the contacts do not show abnormally strong shearing features, nor tectonic breccias, or cornieules, and appear as stratigraphic. This outcrop thus most likely corresponds to an anticline, whose core is formed by a pinched level of Alphubel pre-Permian basement and whose overturned (right) limb is formed by the Täschalpen Series and the Série Rousse. The lithological succession exposed on this outcrop would then correspond to a stratigraphic sequence extending at least from the Upper Paleozoic to the Upper Cretaceous. On the other side of the Alphubel fold (i.e. on the northern side), outcrops exhibiting concordant contacts between the Alphubel pre-Permian basement and the Faisceau Vermiculaire and the Série Rousse are also observable at the southern side of Färichflüe (Fig. 4). At points [2ʹ629ʹ005/1ʹ100ʹ155] and [2ʹ628ʹ975/1ʹ100ʹ110], metabasites and gneisses from the Alphubel pre-Permian basement are stratigraphically overlain by 5–10 m of quartzschists and phyllitic quartzites typical of the Permian levels of the Faisceau Vermiculaire, themselves topped by 50 cm of Tabular Quartzites typical of the Early Triassic. These quartzites are overlain by 3–15 cm of marbles (Triassic and/or Jurassic) and by quartzitic calcschists of the Série Rousse (> 20 m). All contacts visible on these outcrops are clean and do not show particular shearing or intercalations of cornieules or crushed metasediments. They appear and are interpreted as stratigraphic.

The contact between the Alphubel pre-Permian basement and the Faisceau Vermiculaire is therefore characterized by local concordant sections, where lithological successions across the contact appear as chronologically continuous and stratigraphic, as well as by large discordant sections forming large scale unconformities. The interpretation of these seemingly contradictory observations is discussed below.

6 Discussion

6.1 Nature of the contact between the Faisceau Vermiculaire (and Série Rousse) with the Alphubel basement

Different outcrops exposing the contact between the Faisceau Vermiculaire (Permian-Jurassic Täschalpen Series) and the pre-Permian basement forming the Alphubel fold (e.g. Figures 7c-f) show that this contact, at least locally, was not affected by an intense Alpine shearing, as it would be expected along a major tectonic contact separating two different tectonic units (which corresponds to the interpretation of most of the authors; this contact even corresponds to the limit between two tectonic domains, according to several authors; cf. chap. 2). Clean contacts, devoid of particular shearing and appearing as stratigraphic, are actually locally observable between: (i) the pre-Permian basement and the Permian phyllitic quartzites (e.g. Figures 7d, e); (ii) these phyllitic quartzites and the pure Tabular Quartzite (e.g. Figures 3c, 5d, 7e-f); (iii) the Tabular Quartzite and the Triassic dolomites (e.g. Figures 3i, 7f, g); (iv) these dolomites and the Triassic-Jurassic marbles and breccias (e.g. Figures 3b, 7f); and finally (v), between different levels of the Täschalpen Series and the Série Rousse (e.g. Figures 3i, k, 7f, h; cf. chap. 3.2). No intercalation of ophiolite-bearing calcschists or of ophiolites is observable along this contact. These different local observations are very unlikely to be compatible with a large detachment and translation of both the Täschalpen Series and the Série Rousse, with respect to the Alphubel pre-Permian basement. The occurrence of local lithological successions appearing as concordant and stratigraphic across the contact, as described in the previous chapter (5.3; Figs. 7d–f), corroborate this interpretation.

This contact is, however, marked by a large-scale unconformity, and along the contact, both discordant and concordant sections are alternately observable (cf. chap. 5.3). Such a configuration could be properly explained if the contact locally corresponds to synsedimentary paleofaults, as already discussed for contacts affecting the Mont Fort nappe in the Bagnes, Dix and Hérens valleys by Pantet et al., (2020, 2023). The discordant sections of the contact would then represent the paleofaults themselves, while the concordant sections would represent preserved stratigraphic successions from the footwalls and hanging walls.

Our observations in the Täschalpen area are compatible with this interpretation. In particular, the levels of coarse polymict breccia observed in the Täschalpen Series (e.g. Figures 3e–h), containing clasts up to several tens of cm made of various lithologies most probably ranging from Permian to Lower Jurassic, are actually indicative of a deposition at the immediate vicinity of high amplitude active faults. The similarities existing between these breccias and those of the Breccia nappe in the Prealps (whose ages range from Sinemurian to Early Tithonian; e.g. Chessex 1959; Weidmann 1972; Stampfli and Marthaler 1990; Plancherel et al., 1998), both in term of facies and of stratigraphic position (cf. chap. 3.1.3), suggest a Jurassic age for the main activity of these paleofaults. The presence of Jurassic high amplitude normal paleofaults (e.g. Figure 8a) could explain not only the unconformity observable at the contact between the Täschalpen Series and the Alphubel pre-Permian basement, but also the unconformity that can be evidenced at the base of the Série Rousse in this area. Indeed, the Série Rousse alternately rests on different levels of the Täschalpen Series (e.g. on Triassic to Jurassic carbonates in Figs. 3i, 7f, g; and on Lower Triassic Tabular Quartzite in Fig. 7h), although its basal contact clearly appears as stratigraphic (cf. chap. 3.2). Considering a margin geometry such as the one outlined in Fig. 8a, the stratigraphic deposition of the Série Rousse directly on top of the Early Triassic Tabular Quartzite (e.g. Figure 7h) could represent a stratigraphic sequence typical of the upper parts of tilted blocks. The same stratigraphic sequence is observed, for

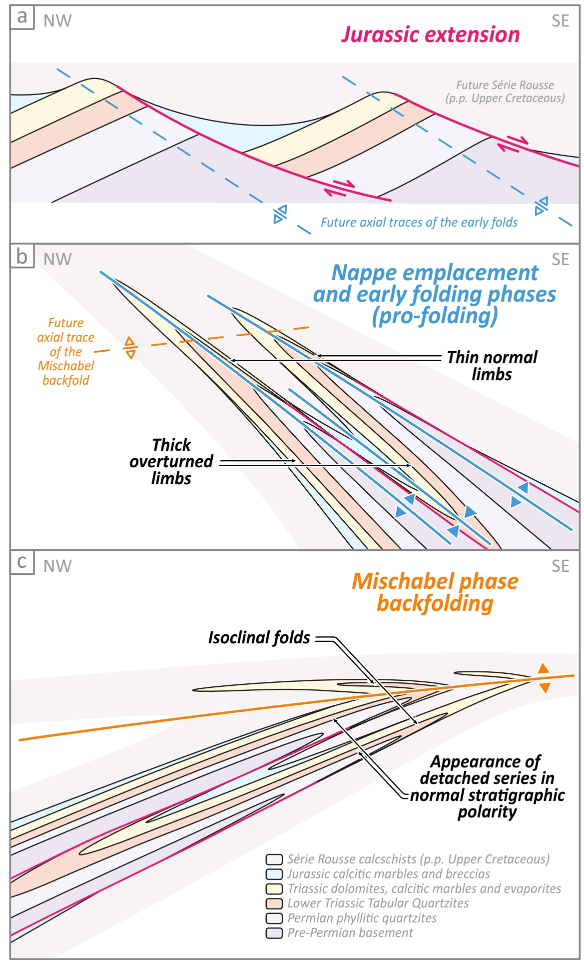

Fig. 8 Schematic sketches representing the polyphase folding of an initial configuration consisting of tilted blocks and half-grabens, in order to illustrate the different structures observed in the Faisceau Vermiculaire between the Täschalpen and Cimes Blanches areas. **a** In the proposed model, hinges of the early pro-vergent folds are localized within the summit zones of the tilted blocks. **b** Folds resulting from such an initial configuration would be strongly asymmetrical with thicker sedimentary successions in the overturned limbs, which may seem counterintuitive, as the layers are generally thinner in the overturned limb of folds due to more intense stretching. **c** After superimposed backfolding, the overturned limb of the backfold may be mistaken for a detached (thrusted) series showing a normal polarity; the isoclinal nature of the early folds is only recognizable when examining frontal hinge areas

example, in the Mont Fort nappe, east of Evolène (Pantet et al., 2023, Fig. 12, Rocs de Villa succession).

Other observations from the Täschalpen area, concerning the relative thicknesses of the limbs of early isoclinal folds affecting the Täschalpen Series, can also be explained considering the presence of synsedimentary normal faults. Different outcrops in the area show early folds, coeval to the dominant schistosity, which are characterized by thicker sedimentary successions in their (original) overturned limbs than in their (original) normal limbs (e.g. Figure 5a and the asymmetrical anticline with a core formed of Permian quartzschist around point [2′628′920/1′100′340] in Färichflüe, Fig. 4; as these folds were later overturned during the Mischabel phase, their original normal limbs are now overturned, and inversely). As layers are generally thinner in the overturned limbs of folds due to the more intense stretching, the observation of those thicker (original) overturned limbs may seem counterintuitive. Such fold geometries are however likely to result from the folding of a sequence affected by synsedimentary faults, when fold hinges develop close to the summit of tilted blocks, with axial surfaces subparallel to the paleofaults (Fig. 8; e.g. Dolivo 1982; Epard 1990; Krayenbuhl and Steck 2009; Bellahsen et al., 2012; Boutoux et al., 2016).

According to these observations, the Täschalpen Series would thus most likely constitute the autochthonous sedimentary cover, of the pre-Permian basement forming the Alphubel anticline. As all the different bands forming the Faisceau Vermiculaire seem to have direct connections with those of the Täschalpen Series (Figs. 1, 6), the Alphubel anticline (and its potential western extension at depth under the Combin zone) could thus correspond to the root zone of the whole Faisceau Vermiculaire series.

A few remarks may be added to this hypothesis. (i) Concerning the two lowermost anticlines involving Mesozoic metasediments and cores of pre-Permian basement south of the Täschalpen, an origin from a more eastern and/or internal unit than the Alphubel basement cannot be excluded. Indeed, the existence of potential synclinal hinges connecting these two lowermost anticlines to the Alphubel basement cannot be attested due to the presence of glaciers and Quaternary deposits hiding the contacts to the east of the Täschalpen (Fig. 4). These two anticlines could thus be linked either to the Alphubel basement or to more internal units, such as the Gornergrat, Stockhorn or Portjengrat. (ii) Highly stretched continental basement is outcropping to the east of the Täschalpen in the border of the Alphubel glacier, out of the studied zone. These outcrops, referred to as Alphubel glacier basement on Fig. 4, have never been studied in detail, and as their contacts with the surrounding units are mostly hidden by the ice and moraines, their relations with the surrounding units are unclear. Their tectonic position, however, seems to be structurally different from that of the Alphubel basement and Faisceau Vermiculaire, and appears to be associated with the Zermatt-Saas Fee nappe. Such a position could correspond to that of the Etirol-Levaz, Châtillon and Theodul Glacier units (e.g. Kienast 1983; Ballèvre et al., 1986; Dal Piaz 1999; Dal Piaz et al., 2001, 2015a; Weber and Bucher 2015; Fassmer et al., 2016; Bucher et al., 2020; Bucher and Stober 2021).

6.2 Relations between the Alphubel basement and the Siviez-Mischabel nappe

Based on the above observations and discussions, the metasediments of the Faisceau Vermiculaire and the Série Rousse thus appear to be in stratigraphic contact with the pre-Permian basement forming the Alphubel anticline (chaps. 5.3, 6.1), but in tectonic contact with the Permian and older monocyclic basement forming the hinge of the Mischabel backfold (chap. 5.2). In turn, the Permian metasediments of the Siviez-Mischabel nappe are stratigraphically overlaid by the Mesozoic Barrhorn Series on the normal limb of the Mischabel backfold, from the area of Hohlicht (Figs. 1, 2; Steck et al., 1999), to the north of the Barrhorn summits (Fig. 1; Sartori 1990).

Important stratigraphic differences are observable between the Barrhorn Series and the series formed by the Faisceau Vermiculaire and Série Rousse succession. These differences, already noted by Staub (1942b), Güller (1947) and Bearth and Schwander (1981), mainly concern (i) the presence in the Faisceau Vermiculaire of locally abundant breccias and calcitic marble levels reminiscent of the Lower Jurassic facies of the Prepiemont and Austroalpine series, whereas such lithologies are almost absent in the Barrhorn Series; and (ii) the differences between the younger levels of the Barrhorn Series and the Série Rousse, as quartzitic calcschists reminiscent of those of the Série Rousse are almost absent in the Barrhorn Series, whereas the metamorphic equivalent of the Couches Rouges of the Prealps and the dark Eocene Flysch, which form the upper part of the Barrhorn Series (e.g. Ellenberger 1953; Sartori 1990), do not seem to be represented in the Série Rousse. These stratigraphic differences in the post-Triassic sequences between the Barrhorn Series and the sequence formed by the succession of the Faisceau Vermiculaire and Série Rousse are too important to represent lateral facies changes inside a continuous sedimentary basin.

In its present position, the basement forming the Alphubel anticline could be separated from the one forming the hinge of the Mischabel backfold by an important tectonic discontinuity. Indeed, the complex Rotbach syncline (Steck 1989; cf. chap. 4.2), anterior to Mischabel backfolding phase and involving ophiolites of the Tsaté nappe, is deeply embedded between these two basements structures. The amplitude of this discontinuity is however difficult to assess, as the prolongation of the Rotbach syncline NE of Täschalpen is hidden by the moraines and glaciers, and as, further to the NE, a direct contact between two different basement units would be difficult to highlight inside the Mischabel massif.

For these reasons, the existence of a possible (major?) tectonic limit between the basement forming the hinge of the Mischabel backfold (Siviez-Mischabel basement) and the one forming the Alphubel anticline (associated with the Faisceau Vermiculaire series and Série Rousse) has to be considered.

The individualization of the Alphubel basement from the basement forming the northern part of the Mischabel massif (i.e. Täschhorn, Dom, etc.) has previously been proposed by Staub (1942b) and Güller (1947), who individualized the "Alphubellappen" (or "Alphubel Keil"), from the "Dom-Täschhorn-Keil"), and by Müller (1983), who distinguished the "Alphubel-Lappen" as a subunit of the Siviez-Mischabel nappe, mainly for structural reasons.

6.3 Structure of the Faisceau Vermiculaire and its relations with the Mischabel and Vanzone folds

6.3.1 General structure of the Faisceau Vermiculaire and Combin zone

An interpretation of the structure of the Faisceau Vermiculaire and Combin zone for the area surrounding Zermatt is given in the bedrock and axial traces maps of Fig. 6 and in the cross-sections of Fig. 9. This interpretation is essentially based on an attempt to synthesize the stratigraphic and structural observations at the outcrop scale, and the interpretation of axial traces on bedrock maps compiled from detailed geological maps and data.

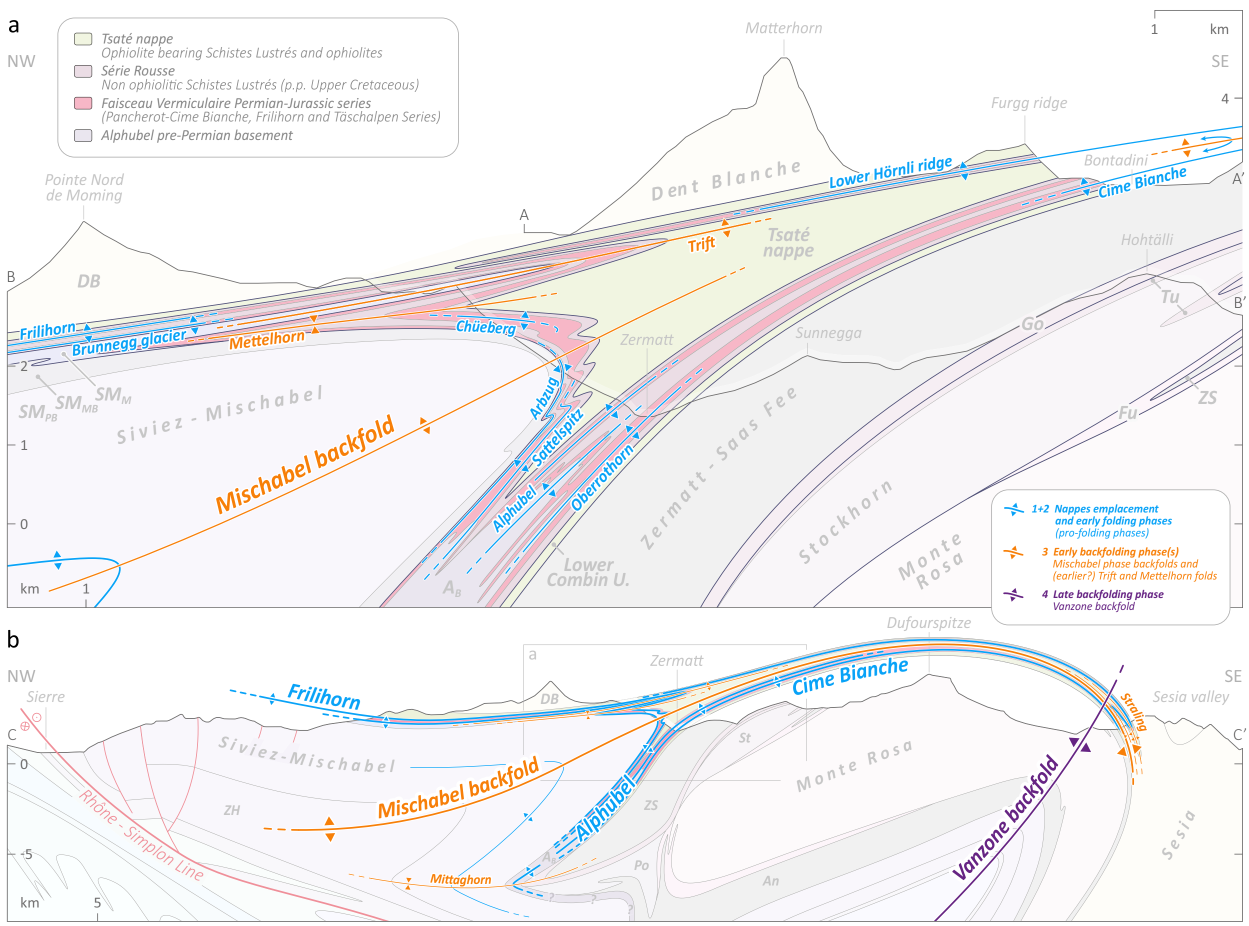

Fig. 9 **a** Geological cross-section through the upper Matter valley showing axial traces of early folds (blue) refolded by early backfolds (orange); A [2′615′030/1′094′070], A′ [2′620′610/1′087′450], B [2′619′540/1′103′570], B′ [2′629′180/1′092′120]; locations on Fig. 10a; **b** Geological cross-section through the Pennine Alps between the Rhône and Sesia valleys; modified after Steck et al. (2015); location on Fig. 10b. *An*: Antrona zone; A_B: Alphubel pre-Permian basement; *DB*: Dent Blanche nappe; *Fu*: Furgg zone; *Go*: Gornergrat nappe; *Po*: Portjengrat nappe; SM_M: Siviez-Mischabel Mesozoic cover; SM_{MB}: Siviez-Mischabel monocyclic basement; SM_{PB}: Siviez-Mischabel polycyclic basement; *St*: Stockhorn basement; *Tu*: Tuftgrat Series; *ZH*: Zone Houillère; *ZS*: Zermatt-Saas Fee nappe

The proposed tectonic scheme involves: a first stage of deformation associated with the developments of high amplitude, N/NW vergent, folds (pro-movements) that corresponds to the individualization and emplacement of the nappes, followed by a second stage of deformation with S/SE vergent folds (retromovements), including the high amplitude Mischabel early backfold and the later crustal-scale Vanzone open backfold.

According to this interpretation, the Faisceau Vermiculaire is rooted on the Alphubel basement (or eventually on a more internal Prepiemont-derived basement unit, for its lowermost part; cf. chap. 6.1). The formation of the different highly strained bands of the Faisceau Vermiculaire and their folding within the Schistes Lustrés and ophiolites of the Combin zone (incl. the Tsaté nappe and Lower Combin Unit), are interpreted to occur during the early N/NW-vergent (pro-)movements. The whole nappe stack would then be strongly refolded during the Mischabel backfolding phase. With the development of the Mischabel backfold, the Faisceau Vermiculaire would be displaced and sheared towards the internal part of the belt. As the Faisceau Vermiculaire is mainly located in the lower limb of the Mischabel backfold, it would be almost entirely overturned during this phase. Following Argand (1911, 1916a) and Steck et al. (2015), we interpret hinges in the Combin zone and the Faisceau Vermiculaire in the area of Alagna and Punta Straling as associated to the main hinges of the Mischabel backfold (Figs. 1, 9b). The very thin bands from the Faisceau Vermiculaire that are intercalated in the upper part of the Combin zone, as the meter-thick bands outcropping on the lower section of the Hörnli ridge of the Matterhorn (Argand 1909; Müller 1984; Bucher et al., 2003a; Figs. 6, 9), are interpreted as representing the prolongation in the upper limb of the Mischabel backfold, of the thicker lower bands of the Faisceau Vermiculaire belonging to the lower limb of this fold. The later development of the crustal-scale Vanzone open backfold is responsible for the tilting towards the N of the structures in the northern part of the area and for their folding (of very large amplitude) in the hinge zone located in the Monte Rosa massif. A significant thinning of the structures in the sectors corresponding to the limbs of the Vanzone fold (Fig. 9) is likely to occur during this phase, and would concern in particular the rheologically weaker metasedimentary units, such as the Combin zone (including the Faisceau Vermiculaire).

The proposed structural interpretation is compatible with the main results of the detailed structural studies carried out in different parts of the Faisceau Vermiculaire, and surrounding units in the Italian side of the area, by Reddy et al. (2003), Pleuger et al., (2007, 2009) and Kirst and Leiss (2017). These different studies all provided microstructural evidences for top-(N)NW shearing during synkinematic greenschist facies recrystallisation. Neutron texture goniometry on quartzites from the Faisceau Vermiculaire show that, during this phase, top-(N)NW-directed rotational component of shear was small and that pure shear was the dominant deformation mechanism (Pleuger et al., 2007; Kirst and Leiss 2017). The microstructural studies of Reddy et al. (2003) and Pleuger et al., (2007, 2009) show that this phase clearly predates a later top-SE shearing phase, characterized by a strong rotational shear component, and that locally almost completely reworked earlier structures. This later top-SE shearing is associated with the Mischabel phase by Pleuger et al., (2007, 2009). The macroscopic shear sense markers observed around Zermatt (Figs. 5i–k; chap. 4.4), indicating foreland-directed shearing, are interpreted as being associated with the early foreland-directed phase evidenced in the Italian side of the belt by the above-mentioned authors. The top-SE macroscopic shear sense indicators observed in the area located further south of Zermatt (e.g. at Testa Grigia; Fig. 5l) are interpreted to be associated with later backfolding, locally overprinting earlier structures in the areas where the Combin zone is thinner and the Mischabel fold tighter (Fig. 9).

The internal structure of the different bands forming the Faisceau Vermiculaire locally clearly corresponds to hyper-stretched recumbent isoclinal anticlines. Sheath folds can be suspected in such ductile highly strained area. Sheath folds, up to several kilometers in size, have been described in different sectors of the internal belt of the Alps (e.g. Minnigh 1979; Lacassin and Mattauer 1985; Steck et al., 2019; Maino et al., 2021). It is difficult to conclude whether the present-day distribution of the early fold axes, locally parallel to stretching lineation (Fig. 6), results from the formation of sheath folds during the early phases of nappe emplacement, or from the later strong shearing related to early backfolding. Both result in strongly curvilinear axes for the isoclinal folds of the Faisceau Vermiculaire.

The isoclinal folding of the Faisceau Vermiculaire is observable, for example, in the area of the Cime Bianche and Gran Sometta (Vannay and Allemann 1990), at the Bettaforca pass (Gasco and Gattiglio 2011), in the Hirli summit (Müller 1984) and in the lower Hörnli ridge (Argand 1909). Isoclinal anticlinal hinges are visible, for example, in the E faces of the Oberrothorn, Sattelspitz and Bösentrift (Figs. 5a-b, 7g; Güller 1947), at the base of the thick band of Arben (Güller 1947, Fig. 15) and in the NE face of the Grand Tournalin (Allemann and Vannay 1987; Ellis et al., 1989). These isoclinal folds are often strongly asymmetrical (cf. chap. 6.1; Fig. 8) and the thinner limbs are regularly reduced to a hyper stretched level of crushed carbonates, sometimes less than one meter thick (e.g. Figure 5d), which may locally give the appearance of a detached series (Fig. 8c).

The tectonic scheme proposed here appears to be actually very close to that proposed by Argand (e.g. 1911, 1916a) concerning the first order scheme. The main differences concern: (i) our more detailed descriptions of the structures in the sector of the overturned limb of the Mischabel backfold, and a more detailed description of the links between the Faisceau Vermiculaire and the Paleozoic basement in this sector; (ii) our proposition to subdivide Argand's Grand St-Bernard nappe into two different tectonic subunits in the sector of the overturned limb of the Mischabel backfold; and (iii) the interpretation of the detailed structure of the Faisceau Vermiculaire in the Zmutt valley, west of Zermatt, where we propose to link the thick band of the Faisceau Vermiculaire outcropping in Arben to that of Chüeberg (Fig. 6), following Sartori (1987) and Steck et al., (1999, 2015) and contrary to Argand who linked the band of Arben to that of the lower Hörnli ridge. Following our interpretation, the continuation of the band of the lower Hörnli ridge, in the northern side of the Zmutt valley, corresponds to the meter-thick levels of quartzite and cornieules that are locally observable inside the Schistes Lustrés and ophiolites above the thick principal band of the Faisceau Vermiculaire in Arben (Mazurek 1986, Fig. 2; Bucher et al., 2003a) and in the Wisse Tschuggen (e.g. [2′621′660/1′096′640]; Crespo 1984).

6.3.2 Local structures

Different interpretations have been proposed concerning the phase of deformation attributed to some specific folds in the area located directly north and west of Zermatt, the Trift anticline (Sartori 1987) and the Mettelhorn syncline (called Platthorn syncline by Sartori 1987), which are represented in Figs. 6 and 9a. These two backfolds have classically been attributed to the Mischabel phase (Argand 1909, 1911, 1916a; Staub 1942b; Güller 1947; Ellenberger 1953; Bearth 1967b; Müller 1983; Mazurek 1986; Bucher et al., 2004a). According to the interpretation of Crespo (1984), Sartori (1987) and Steck (1989), these folds would however be older than the Mischabel backfold, as their axial trace would be refolded by folds of the Mischabel phase in the sector of Arben. A detailed structural study would be necessary to confirm this interpretation and to exclude that the axial trace of the Trift fold would rather be linked to the late open folds of the sector of Arben, than to the earlier isoclinal folds observed in this sector.

In the Barrhorn area, in the upper Turtmann valley, recent glacial retreat allows the observation of new outcrops of dolomites, marbles, quartzites and cornieules located at the top of the Barrhorn Series and forming the base of the Série Rousse, east of the Adlerflüe (Fig. 10a), just above the small lake that formed at the front of the Brunegg glacier. These metasediments form a 15 m thick highly strained level, surmounting the dark Eocene Flysch of the uppermost syncline of the Barrhorn Series (Barr syncline; Sartori 1987, 1990). The basal contact of this level, with the Flysch, is masked by the lake. This level is in turn directly overlaid by the Série Rousse (Fig. 3a). Sartori (1990) describes the direct prolongation of this level 300 m to the NW, as well as in other sectors of the upper Turtmann and Matter valleys. He proposes an origin either from the Barrhorn Series or from a more internal unit, for this tectonized level. The polished surfaces of the new outcrops allow to observe the presence of metric levels of breccias, composed of a light-colored calcareous matrix and clasts made of dolomites and limestones, up to 30 cm in size at point [2′620′490/1′110′670]. They alternate with decimetric beds of dolomites, and quartzites. Cornieules are also present at the top of this level (Fig. 3a). The presence of such breccias, not observed anywhere else in the Barrhorn Series, as the tectonic position of this level, strongly suggest its attribution to the Faisceau Vermiculaire. We interpret this level, corresponding to the *Brunegg glacier* axial trace in Figs. 9, 10, as the prolongation to the north of the most external band of the Faisceau Vermiculaire of the area of Zermatt. This external band, partly made of cornieules, is in direct contact with the Permian and/or older monocyclic basement of the Siviez-Mischabel nappe in the hinge of the Mischabel backfold (e.g. Güller 1947; Bearth 1964b; Arbzug axial trace in Figs. 6, 9, 10) and is also found further west around the Trift anticline (Fig. 6; Argand 1908; Bearth 1964b; Crespo 1984).

6.4 Relations of the Alphubel basement, Faisceau Vermiculaire and Série Rousse with the Mont Fort nappe

As evidenced in chapter 6.1, the Alphubel basement, the Faisceau Vermiculaire and the Série Rousse appear to form together a coherent tectonic unit, separated from the Siviez-Mischabel nappe by an important discontinuity (chap. 6.2). Its structural position with respect to both the Siviez-Mischabel and Tsaté nappes, when considered at regional scale (Fig. 10), appears to be identical to that of the Mont Fort nappe (such as described in Pantet et al., 2023). The Alphubel basement and most part of the Faisceau Vermiculaire are located in the overturned limb of the Mischabel backfold, whereas north and west of the Dent Blanche klippe (e.g. in the Hérens valley), the position of the Mont Fort nappe corresponds to the normal limb of this fold (Fig. 11). In addition to sharing an identical tectonic position, the Mont Fort nappe and the ensemble formed by the Alphubel basement, the

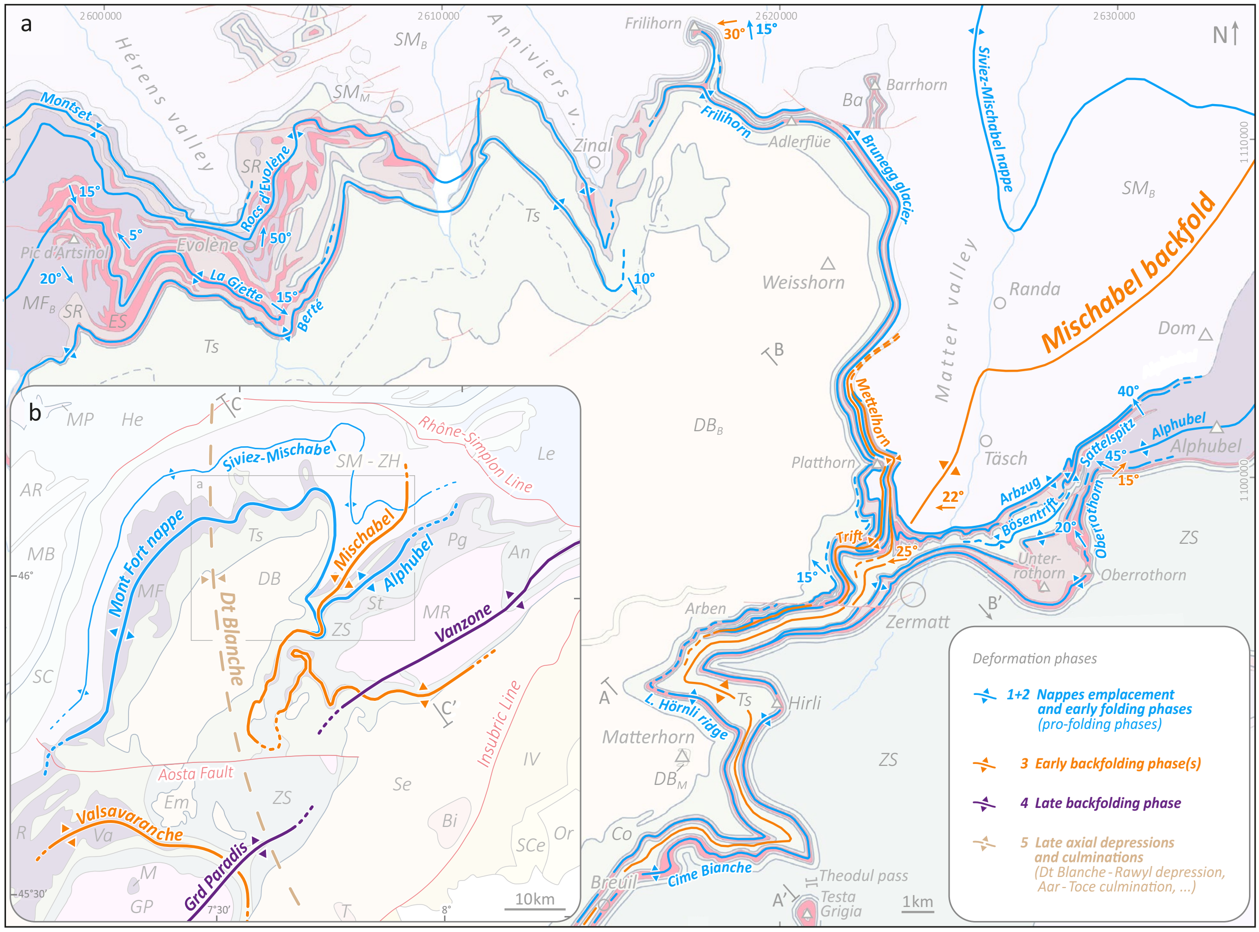

Fig. 10 Axial traces of the successive folding phases affecting the Mont Fort and Alphubel basements and associated Mesozoic series (Evolène Series and Faisceau Vermiculaire series); *AR*: Aiguilles Rouges massif; *An*: Antrona zone; *Ba*: Barrhorn Series; *Bi*: Biella pluton; *Co*: Combin zone s.str. (=Tsaté nappe); *DB*: Dent Blanche nappe; DB_M: Dent Blanche Mesozoic; DB_B: Dent Blanche Paleozoic; *Em*: Monte Emilius unit; *ES*: Evolène Series; *GP*: Grand Paradis massif; *He*: Helvetic and Ultrahelvetic nappes; *IV*: Ivrea-Verbano zone; *Le*: Lepontine nappes; *M*: Money unit; *MB*: Mont Blanc massif; *MF*: Mont Fort nappe; MF_B: Mont Fort basement; *MP*: Médianes Prealps; *Or*: Orobic nappes; *Pg*: Portjengrat nappe; *R*: Ruitor unit; *SC*: Sion-Courmayeur zone; *SCe*: Strona-Ceneri zone; *Se*: Sesia zone; SM_M: Siviez-Mischabel Mesozoic; SM_B: Siviez-Mischabel basement; *SM—ZH*: Siviez-Mischabel nappe and Zone Houillère; *SR*: Série Rousse; *T*: Traversella pluton; *Ts*: Tsaté nappe; *Va*: Valsavaranche unit; *ZS*: Zermatt-Saas Fee nappe; A-A', B-B' and C–C' indicate the location of the cross-sections of Fig. 9. **a** Axial traces, fold axis and stretching directions in the upper Hérens, Anniviers, Turtmann, Matter and Valtournenche valleys; basemap after Argand (1908), Güller (1947), Bearth (1953b, 1964b, 1967a, 1973), Milnes et al. (1981), Crespo (1984), Sartori (1987, 1990), Escher (1988), Allimann (1990), Girard (1995), Steck et al. (1999, 2015), Bucher et al. (2003a), Marthaler et al. (2008, 2020), Dal Piaz et al. (2015b) and data from this study. **b** Axial traces at regional scale (SW Switzerland and NW Italy); basemap modified after Schmid et al. (2004, 2017), Steck et al. (1999, 2015, 2019), Ballèvre et al. (2018, 2020), Beltrando et al. (2010a, 2014), Balestro et al. (2020), Bigi et al. (1992), Gouffon (1993), Deville et al. (1992) and the Tectonic map of Switzerland (2005)

Faisceau Vermiculaire and the associated Série Rousse show identical stratigraphic successions, both regarding lithologies and stratigraphic sequences (cf. chap. 3). They both also show the presence of large unconformities and important local stratigraphic gaps which are best interpreted as resulting from the activity of synsedimentary paleofaults (cf. chaps. 5.3, 6.1; Pantet et al., 2020, 2023). For these reasons, we propose that the Alphubel basement, the Faisceau Vermiculaire and associated Série Rousse constitute together the southeastern prolongation of the Mont Fort nappe. This nappe would be folded obliquely around the Mischabel backfold, so that north and west of the Dent Blanche klippe, its position corresponds to the normal limb of the backfold, while to the southeast it corresponds to its overturned limb (Figs. 10, 11; Pantet 2022, Fig. 5–1). The prolongation of the hinge of the Mischabel backfold (at the level of the Paleozoic basement) reappears to the SW, on the other side of the Dent Blanche axial depression and Aosta fault, to form the Valsavaranche backfold (Fig. 10b; e.g. Lugeon and Argand 1905b; Argand 1911; Hermann 1925, 1928; Bucher et al., 2003b, 2004b). Due to this axial direction,

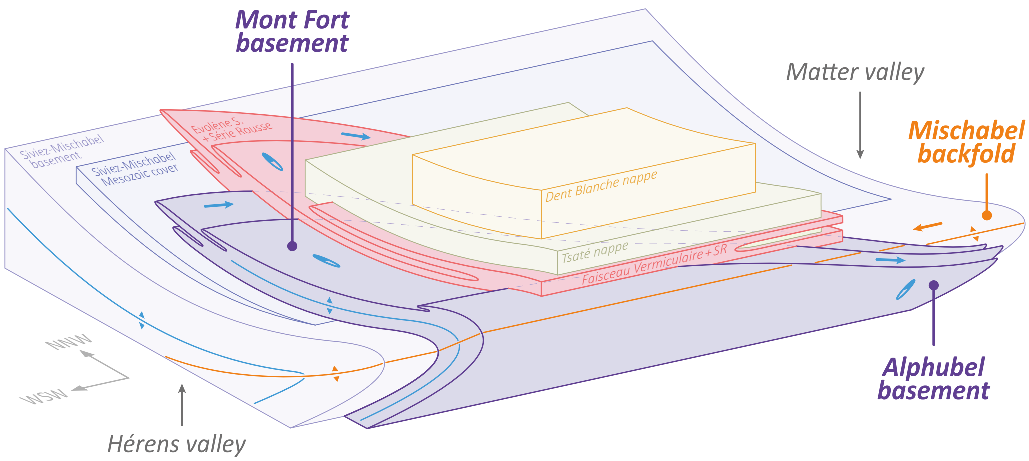

Fig. 11 Schematic block-diagram representing the oblique folding of the Mont Fort—Alphubel basement around the Mischabel backfold. The left side of the block-diagram corresponds to the nappe stack in the Hérens valley, whereas the right side corresponds to the Matter valley; connection between the Mont Fort and Alphubel basements is not outcropping (cf. Figure 10), due to the presence of the Dent Blanche (+Tsaté) klippe; arrows represent fold axis orientations; ellipses indicate stretching directions; orange colors correspond to the Mischabel backfolding phase, blue colors to the nappes emplacement and early (pro-)folding phases; *SR*: Série Rousse

the hinge of the Mischabel backfold is not outcropping north and west of the Dent Blanche klippe. It is located in a more internal position under the Dent Blanche nappe and Combin zone (e.g. Argand 1911; Hermann 1925; Steck et al., 1997). Between the westernmost outcrops of the Alphubel pre-Permian basement in the Täsch valley and the northernmost outcrops of the Mont Fort pre-Permian basement in the Hérens valley, the proposed connection between these basements is hidden by the Dent Blanche and Tsaté klippe (Figs. 10, 11). The Série Rousse can however be traced almost continuously from the Täsch valley where it is associated with the Faisceau Vermiculaire and the Alphubel basement, through the Matter, Turtmann and Anniviers valleys, to the Hérens and Bagnes valleys, where it rests in stratigraphic contact with the Evolène Series and western Mont Fort nappe (Figs. 1, 10; Sartori 1987, 1990; Escher 1988). Only small sections are covered by Quaternary deposits or still hidden by glacier remnants. The connection between the Faisceau Vermiculaire in the east and the Evolène Series in the west also appears as almost continuous through the Matter, Turtmann and Anniviers valleys, along the thin bands interpreted as extremely stretched isoclinal anticlines that are referred to as *Brunegg glacier* and *Frilihorn* axial traces in Fig. 10a. It is interesting to note that this connection has already been proposed by Argand (1911) and drawn on his 1:500′000 tectonic map and associated cross-sections.

The affiliation of the Faisceau Vermiculaire to the Mont Fort nappe (together with the Série Rousse) has later been proposed by Escher and Masson (1984), Sartori (1987, 1990), Escher (1988) and Escher et al. (1988). However, contrary to our hypothesis, these authors didn't include the Alphubel basement into the Mont Fort nappe but rather into the underlying Siviez-Mischabel nappe. A different tectonic scheme was then proposed by some of these authors, stating that most of the Permian-Jurassic metasediments overlapping the Mont Fort basement to the west were linked to the Faisceau Vermiculaire to form together the Cimes Blanches nappe, but detached both from the underlying Mont Fort basement and from the overlying Série Rousse (Escher et al., 1993, 1997; Sartori and Marthaler 1994; Steck et al., 1999, 2001). On the other hand, Müller (1983) already noted the similarities between the Alphubel basement and the Métailler Paleozoic (now included in the Mont Fort nappe) regarding their tectonic positions and relations to the Combin zone.

6.5 Constraints from the stratigraphic sequences of the Faisceau Vermiculaire and Barrhorn series on the Briançonnais-Prepiemont paleomargin evolution

Some characteristic lithological successions through the Faisceau Vermiculaire, the Série Rousse, the Barrhorn Series (the Siviez-Mischabel autochthonous cover), and across their contacts with the underlying basements, have been reported in Figs. 12a, b. The study of these lithological successions provides interesting clues regarding the structure of the Jurassic-Cretaceous southern paleomargin of the Briançonnais s.l. domain.

As already mentioned in chapter 6.2, the stratigraphic sequences observed in the ensemble formed by the Faisceau Vermiculaire series and the Série Rousse show strong discrepancies with those observed in the Barrhorn

Series (Staub 1942b; Güller 1947; Bearth 1964a, 1976; Sartori 1987, 1990; Steck et al., 2015). While stratigraphic sequences from the Barrhorn Series are typical of the Briançonnais domain (e.g. Ellenberger 1952, 1953, 1958; Escher 1988; Sartori 1990), those from the Faisceau Vermiculaire and Série Rousse are typical of the Prepiemont domain (e.g. Escher and Masson 1984; Escher 1988).

The Barrhorn Series is characterized by large stratigraphic gaps in the Triassic-Jurassic sequence, resulting from an Early to Middle Jurassic erosion and emersion and attested by metabauxites representing paleokarstic infill (Sartori 1990; Schöllihorn profile, Fig. 12b). In the whole series, Lower Jurassic levels are completely missing (e.g. Ellenberger 1952; Bearth 1980; Sartori 1990). The stratigraphic gap is less important in the northern sector of the Barrhorn Series (e.g. Stellijoch and Barr profiles, Fig. 12a, b), where Upper Triassic levels (locally containing gypsum) are partly preserved from the erosion (Sartori 1990), and where sedimentation most probably starts again since the Middle Jurassic as levels similar to the Mytilus Beds from the Prealps and Vanoise series are observed in this sector (Ellenberger 1952, 1953; Sartori 1990). The stratigraphic gap is gradually more important to the south, forming a large-scale unconformity, clearly highlighted by Sartori (1990, Fig. 19). In the southernmost outcrops of the Barrhorn Series above Zermatt, in the slopes of the Platthorn and Wisshorn for example, the Upper Jurassic marble directly onlaps the Lower Triassic Tabular Quartzite (Sartori 1990; Platthorn profile, Fig. 12b). Another stratigraphic gap is observed at the top of the Upper Jurassic marble. In the northwestern part of the Barrhorn Series, this marble is overlapped by a local mm ferruginous crust and by an Upper Albian to Lower Cenomanian dark marble (Complexe schisteux intermédiaire; Sartori 1990; Barr profile, Fig. 12b). Elsewhere in the Barrhorn Series, the Upper Jurassic marble is directly overlaid by an orange to greenish micaceous marble constituting the metamorphic equivalent of the Couches Rouges (Ellenberger 1953; Sartori 1990), whose ages extend from the Turonian to the Ypresian in the Médianes Prealps (Guillaume 1986). A dark Flysch forms the top of the Barrhorn Series, its age is most likely Eocene (Ellenberger 1952, 1953; Sartori 1990). The stratigraphic sequences from the central and northern parts of the Barrhorn Series are typical of the Briançonnais swell (Briançonnais s.str. domain), whereas the stratigraphic sequences of the southern part of the series show similarities with some sequences described in the Gummfluh area in the Swiss Prealps (Hürlimann et al., 1996), and particularly with the Ultrabriançonnais domain of the French-Italian Alps (e.g. Lefèvre and Michard 1976; Lefèvre 1982; Lemoine et al., 1986; Michard et al., 2022).

Stratigraphic sequences observed in the different bands of the Faisceau Vermiculaire and associated Série Rousse systematically contrast with those of the Barrhorn Series. While breccia levels of probable Jurassic age (cf. chap. 3.1.3) are widespread in the Faisceau Vermiculaire series, they are completely absent in the Barrhorn Series (Fig. 12b). In this series, there is also no equivalent of the dark calcarenites with mm-cm dolomitic clasts that are observed in various localities in the Faisceau Vermiculaire (Güller 1947; Bearth 1976; Sartori 1990; Färichflüe and Becca d'Aran profiles, Fig. 12), and show strong analogies with the Sinemurian to Aalenian "Schistes inférieurs" of the Breccia nappe. Another major difference between these series is the abundance of cornieules levels in the Faisceau Vermiculaire (locally associated with gypsum; Bearth 1976), whereas these lithologies are almost absent in the Barrhorn Series. An exception is observed in the northernmost outcrops of the series, where these levels escaped the Early to Middle Jurassic erosion, which was less deep in this sector (Sartori 1990). Finally, quartzitic calcschists similar to those of the Série Rousse are not developed in the Barrhorn Series, while conversely, equivalent of the metamorphic Couches Rouges and of the dark Eocene Flysch do not seem to be present in the Série Rousse. The sedimentation in the Faisceau Vermiculaire and Série Rousse during the Jurassic and Cretaceous thus appears as locally more continuous than in the Barrhorn Series, with the presence of presumably widespread Upper Triassic and Lower Jurassic levels. It is also characterized by an important detritic and clastic input that is completely missing in the Barrhorn Series during these periods. The stratigraphic sequences observed in the Faisceau Vermiculaire and Série Rousse are however extremely variable, and locally, unconformities and large stratigraphic gaps are also documented (chap. 6.1; e.g. Bru profile, Fig. 12b).

From the area of Hohlicht (Fig. 12a), southward and eastward towards the Mischabel massif, the Barrhorn Series progressively disappears on the top of the Siviez-Mischabel basement. Between the Mettelhorn and the Weingarten glacier, east of Täschalpen, the Barrhorn Series is totally absent on top of the Siviez-Mischabel basement, and this basement is in direct contact with the Faisceau Vermiculaire and the Série Rousse (cf. chap. 5.2). In this sector, the upper part of the basement is formed of quartzitic and micaceous metasediments, locally graphitic, that are attributed depending on the authors to the Permian and/or Carboniferous (e.g. Argand 1908; Bearth 1964b; Steck et al., 2015) or to the early Paleozoic (Sartori et al., 2006, Fig. 2). Quartzites similar to those of the base of the Bruneggjoch Fm. (Late Permian to earliest Triassic; Sartori 1990) are not observed in this sector and

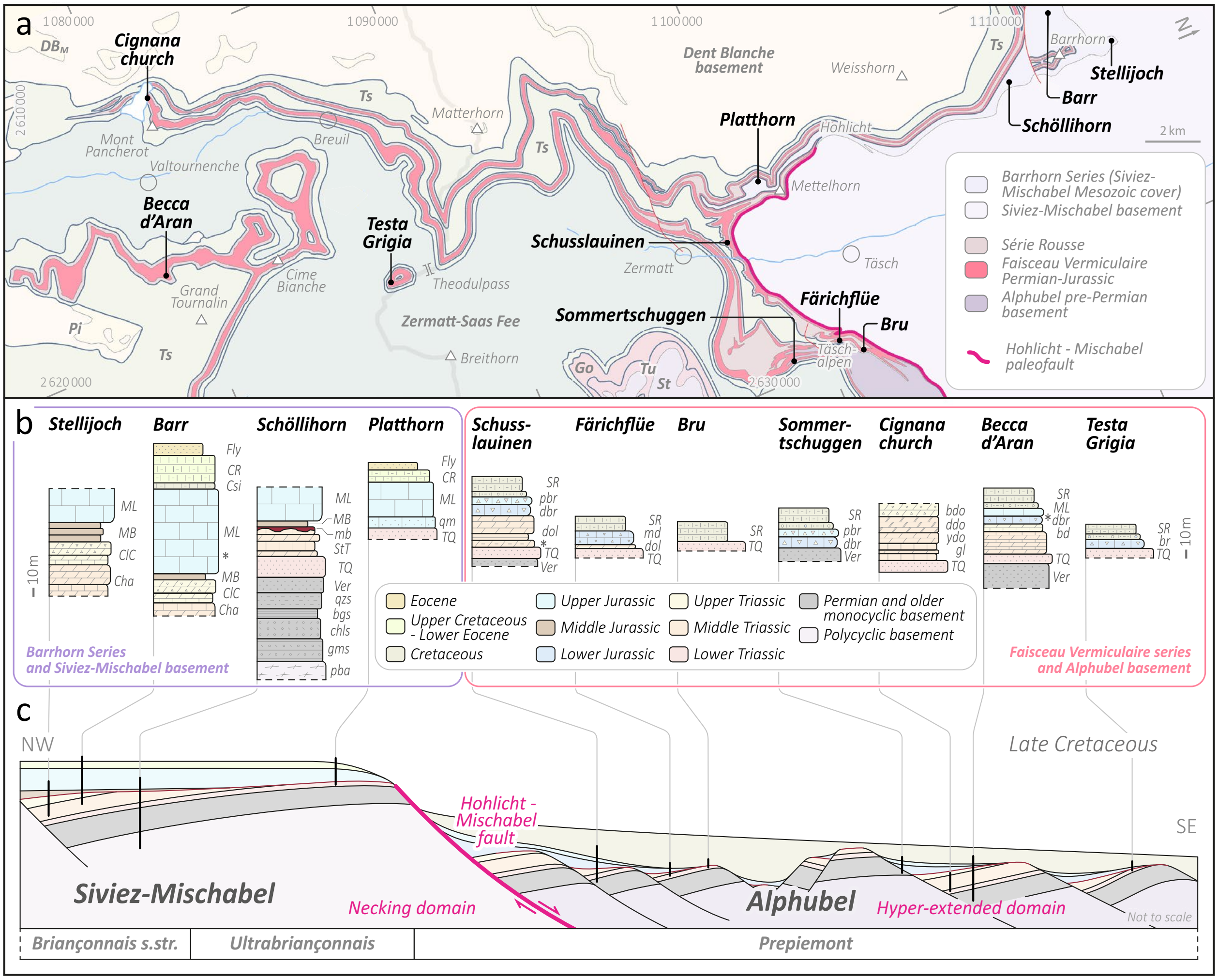

Fig. 12 Stratigraphic profiles across the Barrhorn Series, Faisceau Vermiculaire and associated basements (Siviez-Mischabel and Alphubel respectively), through the Matter valley and Valtournenche. **a** DB_M: Dent Blanche Mesozoic; *Go*: Gornergrat nappe; *Pi*: Pillonet unit; *St*: Stockhorn basement; *Ts*: Tsaté nappe; *Tu*: Tuftgrat Series; basemap cf. Figure 1; profile locations: Stellijoch [2′623′220/1′112′940—2′623′110/1′113′100]; Barr [2′620′590/1′111′510—2′621′740/1′111′400]; Schöllihorn [2′623′650/1′110′140—2′623′110/1′109′680]; Platthorn [2′622′740/1′099′800—2′622′670/1′099′950]; Schusslauinen [2′624′100/1′098′200—2′624′260/1′098′090]; Färichflüe [2′628′880/1′100′380—2′628′830/1′100′370; Bru [2′629′550/1′101′030—2′629′580/1′101′060]; Sommertschuggen [2′628′990/1′098′640—2′628′980/1′098′650]; Testa Grigia [2′620′890/1′086′980—2′620′860/1′087′040]; Cignana church [2′611′590/1′081′510—2′611′600/1′081′570]; Becca d'Aran [2′617′240/1′079′770—2′617′740/1′079′920]. **b** Stratigraphic profiles. Stellijoch, Barr and Schöllihorn profiles after data from Sartori (1990); Platthorn, Schusslauinen, Färichflüe, Bru, Sommertschuggen and Testa Grigia profiles after data from this study; Cignana church profile after Dentan and Menthonnex (1990) and data from this study; Becca d'Aran profile after Passeri et al. (2018), modified according to our observations. Local level duplications due to isoclinal folding (*) are not represented; age attributions are partly hypothetical. *bd*: bedded dark and light colored dolomitic and calcitic marbles; *bdo*: brecciated dolomitic marbles; *bgs*: black graphitic schists; *br*: breccia (calcitic matrix, dolomitic and calcitic cm-sized clasts); *Cha*: metamorphic equivalent of the Champcella (Wiriehorn) Fms.; *chls*: chlorite-schists and metabasites; *ClC*: metamorphic equivalent of the Clôt la Cime Fm.; *CR*: metamorphic Couches Rouges; *Csi*: Complexe schisteux intermédiaire; *dbr*: breccia with dolomitic clasts; *pbr*: polymict breccia; *ddo*: dark dolomites; *dol*: dolomites; *Fly*: flysch; *gl*: grey marmorized limestone (St-Triphon Limestone?); *gms*: graphitic micaschist; *mb*: metabauxite (paleokarst); *MB*: metamorphic Mytilus Beds; *md*: marbles with discontinuous dolomitic layers (probable stretched breccias); *ML*: metamorphic Upper Jurassic Massive Limestones; *pba*: polycyclic basement (amphibolites, gneisses,…); *qm*: quartzitic marble; *qzs*: Permian quartzschists; *StT*: metamorphic equivalent of the St-Triphon Fm.; *SR*: Série Rousse (incl. local conglomeratic base); *TQ*: Tabular Quartzite; *Ver*: Permian «Verrucano»; *ydo*: yellow dolomites. **c** Margin restoration attempt at Late Cretaceous Time, before the onset of Alpine deformation in that area; black strikes indicate approximate pre-orogenic locations of the profiles of Fig. b; brown strikes represent Early to Middle Jurassic erosion levels

also lack at the contact examined in the core samples of the Lüegelti borehole (Additional files 1, 2).

A possibility to explain such a complete lack of the Mesozoic and latest Permian levels in this sector is to interpret it as representing the remnant of an important Jurassic normal fault that would have separated the Siviez-Mischabel basement and Barrhorn Series from the Alphubel basement and the overlying Faisceau Vermiculaire and Série Rousse (Hohlicht-Mischabel paleofault; Fig. 12c). As a direct contact is observable in this sector between the Siviez-Mischabel basement and the Faisceau Vermiculaire and Série Rousse, without the intercalation of another tectonic unit in between, such as the Tsaté nappe which is intimately folded with the Série Rousse, Faisceau Vermiculaire and Evolène Series in other sectors (Figs. 4, 6, 10), it is likely that the Siviez-Mischabel basement, the Série Rousse and the Faisceau Vermiculaire have already been juxtaposed before the Alpine nappe stacking. This interpretation is corroborated by various observations deriving from the examination of the Lüegelti borehole cores (Additional files 1, 2). The presence of more than 6 m of crushed carbonates, cornieules and non-ophiolitic calcschists (Série Rousse) directly at the contact between the Siviez-Mischabel basement and the Faisceau Vermiculaire strongly argues for the tectonic nature of this contact. The absence of ophiolitic material seems to exclude a large thrust involving the Tsaté nappe. The abundance of quartz veins (up to 7 cm thick) and the locally pervasive pyrite mineralization (Additional file 2, Fig. g) in the basement rocks at the contact probably result from strong fracturing and fluid circulation associated with the development of what we interpret as a large synsedimentary normal fault.

The restoration of the southern Briançonnais-Prepiemont continental paleomargin derived from the interpretation of this contact as an important Jurassic normal fault is fully consistent with the observed variations in the stratigraphic sequences across the Barrhorn Series, Faisceau Vermiculaire and Série Rousse (Figs. 12b-c). This interpretation allows to explain the stratigraphic variations within the Barrhorn Series, which evolves towards the very lacunary sequence observed in the southernmost outcrops of the series (Platthorn profile, Fig. 12), interpreted as the upper part of the necking domain of the paleomargin (e.g. Sutra and Manatschal 2012; Peron-Pinvidic et al., 2019). It also explains the abrupt disappearance of the Mesozoic series in the Hohlicht area (Fig. 12a), which is interpreted as corresponding to the summit of the paleofault scarp. The stratigraphic sequences observed in the Faisceau Vermiculaire and Série Rousse are interpreted as representing sedimentation in a deeper basin, where sediments, and in particular breccias, were deposited during the emersion characterizing the Briançonnais swell at Early to Middle Jurassic Time. The variability of the stratigraphic sequences formed by the Faisceau Vermiculaire and Série Rousse, the local identification within these series of large stratigraphic gaps, affecting sectors of relatively small extension, as well as the importance in the Série Rousse of the detritic input, argue for the sedimentation of these series in a basin formed by half grabens and tilted blocks. The stratigraphic sequences observed in the Faisceau Vermiculaire and Série Rousse therefore argue for an origin of these series in the hyperextended domain of a distal continental margin (e.g. Mohn et al., 2010; Haupert et al., 2016; Ribes et al., 2019).

According to this interpretation, the Hohlicht-Mischabel paleofault would represent a major Jurassic normal fault separating the Briançonnais swell (Briançonnais s.str. and Ultrabriançonnais domains) from the Prepiemont basin. The contrasting and characteristic stratigraphic successions observed in the footwall and hanging wall of this presumed paleofault would indicate that it corresponded to a first order discontinuity inside the southern Briançonnais s.l. Jurassic margin, comparable to the mega fault-scarps described and studied by Ribes et al. (2019). Such major discontinuities could correspond to an abrupt thinning of the continental crust, which can typically vary from 30 ± 5 km in the necking domain to only 10 ± 5 km in the hyper-extended domain (e.g. Sutra and Manatschal 2012; Haupert et al., 2016; Ribes et al., 2019).

6.6 Mischabel and Vanzone backfold development and proposed relations with the European—Briançonnais (s.l.) paleomargin structure

Backfolds are structuring the overall tectonic architecture of the Western Alps and in particular of the Pennine Alps, where their importance have been highlighted notably by Argand (1911, 1916b, 1920) and Hermann (1925, 1928), and more recently by Klein (1978), Milnes et al. (1981), Müller (1983), Steck (1984, 1990, 2008), Ballèvre and Merle (1993), Escher and Beaumont (1997), Kramer (2002), Keller et al. (2005), Pleuger et al., (2007, 2008) and Steck et al. (2015) for example.

Backfold development starts in the Late Eocene to Early Oligocene in the Pennine Alps. The dating of these structures is partly based on indirect data and is therefore subject to interpretation, hence the discrepancies sometimes appearing between the ages proposed by the different authors. Ages proposed for the development of the Mischabel backfolding phase range between 40 and 30 Ma (e.g. Barnicoat et al., 1995; Cartwright and Barnicoat 2002; Pleuger et al., 2008; Scheiber et al., 2013; Steck et al., 2015; Kirst 2017; Kirst and Leiss 2017). For the SW prolongation of the Mischabel backfold in the

French-Italian Alps, an age range from 35–31 Ma has been proposed for the development of the Valsavarance backfold (and associated Ruitor backfold; Bucher 2003; Bucher et al., 2004b; Schmid et al., 2017). This first backfolding phase shortly follows the NW-directed emplacement of the Siviez-Mischabel nappe, dated at 41–36 Ma (40Ar/39Ar ages of synkinematically grown micas; Markley et al., 1998, 2002), and is partly coeval to the ongoing NW-directed movements (Escher and Beaumont 1997; Markley et al., 1998; Bucher et al., 2004b; Scheiber et al., 2013; Schmid et al., 2017). Proposed development age for the Vanzone backfold is in the 35–10 Ma interval (Pettke et al., 1999; Keller et al., 2005; Pleuger et al., 2007, 2008; Steck 2008; Steck et al., 2015; Kirst 2017; Kirst and Leiss 2017). The initiation of backfold development in the Penninic units is coeval to a period of major changes in the evolution of the Alpine orogen. It is characterized by the development of crustal-scale transpressional shear zones, such as the Insubric line (ductile shearing at least during the 32–25 Ma time interval; e.g. Schmid et al., 1989; Steck and Hunziker 1994; Steck et al., 2013) and the Rhône-Simplon shear zone (active since c.a. 35 Ma; e.g. Steck 1990; Mancktelow 1992; Steck and Hunziker 1994; Steck et al., 2015), associated with a southwestward movement of the entire Pennine Alps (and Graian Alps) nappe pile (e.g. Gouffon 1993; Gouffon and Burri 1997; Bistacchi et al., 2000; Egli and Mancktelow 2013; Schmid et al., 2017). These movements are associated with magmatism along the Insubric line, with the emplacement of the mantle-derived 42–21 Ma Bergell, Biella and Traversella plutons (e.g. von Blackenburg 1992; Berger et al., 1996; Kapferer et al., 2012; Ji et al., 2019) and with 42–25 Ma aplite and pegmatite dykes (e.g. Romer et al., 1996; Schärer et al., 1996; Rubatto et al., 2009; Bergomi et al., 2015). This period is also characterized by a rapid uplift and cooling of the Pennine and Lepontine Alps (e.g. Hurford et al., 1991; Hunziker et al., 1997; Bistacchi et al., 2001; Steck et al., 2013) and the overfilling of the foreland basins corresponding to the transition from flysch to molasse sedimentation at ca. 30 Ma (e.g. Schroeder and Ducloz 1955; Homewood and Lateltin 1988; Sinclair and Allen 1992; Schlunegger and Kissling 2015; Jaquet et al., 2018). Following this period, a later phase of backfold development (incl. e.g. the Glishorn, Berisal and Evêque backfolds) affects the more external Lower Penninic and Helvetic nappes (e.g. Steck 1984, 2008; Escher et al., 1994; Steck et al., 1997). Their development is estimated to occur during the ca. 15–5 Ma time interval (e.g. Steck and Hunziker 1994; Steck 2008; Krayenbuhl and Steck 2009) and is likely to be more or less coeval with the end of the activity along the basal thrusts of the Helvetic nappes at ca.16–10 Ma (Crespo-Blanc et al., 1995; Kirschner et al., 1996).

The tectonostratigraphic reconstructions proposed in this work tend to indicate a possible link between the localization of the first backfolds developing within the orogenic wedge and the structure of the southern European—Briançonnais s.l. paleomargin. Indeed, the hinge of the Mischabel backfold developed on a position interpreted as constituting a possible first order discontinuity regarding the crustal thickness of this paleomargin (cf. chap. 6.5; Figs. 13a-b). Contrary to the later crustal-scale Vanzone backfold, which is affecting the entire nappe stack (Figs. 9b, 13c), the earlier Mischabel backfolding phase only developed in the Grand St-Bernard nappe system and overlying units, and do not affect lower units such as Lower Penninic and Helvetic nappes. It is shown in particular by the studies of Milnes et al. (1981) and Steck (e.g. 1984, 2008; Steck et al., 2015), which indicate that the axial traces of the Mischabel backfold and associated lower Mittaghorn syncline do not cross the

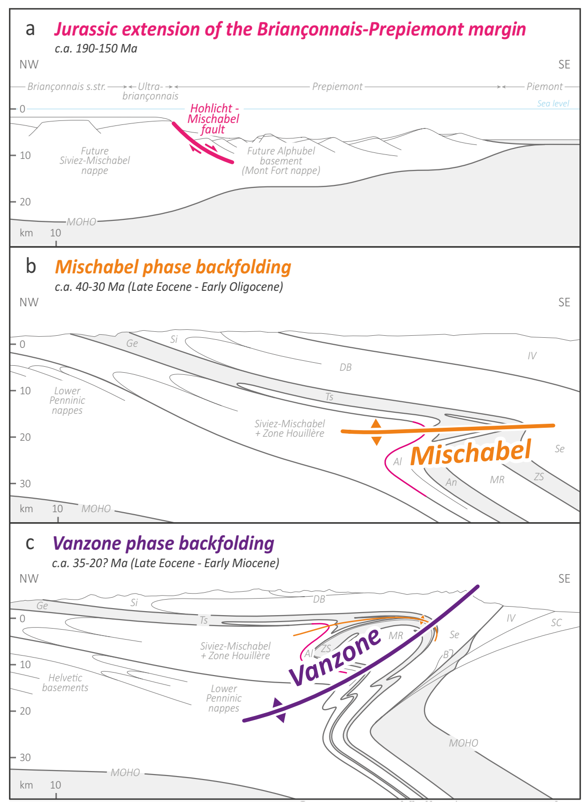

Fig. 13 **a** Schematic restoration attempt of the Briançonnais-Prepiemont margin after the Jurassic extension. **b**, **c** Schematic restoration attempts of backfolds development for the Pennine Alps transect; modified after Steck (2008) and Steck et al. (2015); *Al*: Alphubel—Mont Fort nappe; *An*: Antrona zone; *B*: Biella pluton; *DB*: Dent Blanche Tectonic system; *Ge*: Gets nappe; *IV*: Ivrea-Verbano zone; *MR*: Monte Rosa nappe; *SC*: Strona-Ceneri zone; *Se*: Sesia zone; *Si*: Simme nappe; *Ts*: Tsaté nappe; *ZS*: Zermatt-Saas Fee nappe

Rhône-Simplon ductile shear zone. These particular positions and structural characteristics of the Mischabel phase backfolds may indicate their possible development in response to the subduction, and incorporation in the accretionary wedge, of the thicker and more buoyant continental crust from the proximal domain of the Briançonnais s.l. margin.

This hypothesis is consistent with the short time interval separating the development of the Mischabel backfold from the subduction and prograde metamorphism of the Siviez-Mischabel nappe. Indeed, the Mischabel backfold developed during Late Eocene to earliest Oligocene, in the 40–30 Ma time range (cf. last paragraph), whereas the Eocene Flysch, stratigraphically deposited on top of the Barrhorn Series, predates subduction. Microfossils in the equivalent flysch from the Médianes Prealps indicate a Lutetian age (Caron et al., 1980). As for the NW-directed emplacement of the Siviez-Mischabel nappe, it is dated at 41–36 Ma (Markley et al., 1998, 2002), an age that partly overlaps with the one inferred for the development of the Mischabel backfold. Our hypothesis is also consistent with the contrasting metamorphic imprint existing between the Siviez-Mischabel nappe and the more internal Mont Fort nappe. The Siviez-Mischabel nappe shows a greenschist-facies Alpine metamorphic imprint (e.g. Thélin et al., 1994; Steck et al., 2001; Bousquet et al., 2004) with HP-greenschist-facies paragenesis described in Al-rich metasediments from the Barrhorn Series (estimated P–T: 0.3–0.8 GPa, 400–450 °C; Sartori 1990; Chopin et al., 2003). In the Mont Fort nappe, the presence in the Paleozoic basement of glaucophane (locally abundant), chloritoid, epidote, garnet and HP white micas (e.g. Wegmann 1922; Argand 1934; Vallet 1950; Bearth 1963; Thélin et al., 1994; Steck et al., 2001, Fig. 1) are interpreted as representing Alpine epidote-blueschist-facies conditions (Bousquet et al., 2004). Pseudomorphs after lawsonite have been described in the Série Rousse in Ollomont valley (P. Manzotti, pers. com.) and the Bagnes valley (Besson 1986). Raman spectroscopy on graphite from metasediments of the Mesozoic cover of the nappe (Evolène Series and Série Rousse) indicates peak temperatures of 410–490 °C (Pantet et al., 2023).

The proposed hypothesis concerning the development of the earlier backfolds corroborates the hypothesis from Groppo et al., (2009; see also Beltrando et al., 2010b) who proposed to explain the Late Eocene decrease of the thermal gradient at the subduction zone evidenced in the Zermatt-Saas Fee nappe by the "locking" of the Alpine subduction in response to the arrival in the subduction zone of the buoyant Briançonnais block. It also corroborates the more general assumption of Escher and Beaumont (1997) and Beaumont et al. (1996) concerning the direct link proposed between incorporation of thicker continental crust into the subduction zone and the initiation of backfolding and the development of a doubly-vergent orogenic wedge (see also Pfiffner et al., 2000). Compared to the slab breakoff model that has been frequently invoked to explain the development of retromovements in the orogenic wedge (e.g. Davies and von Blanckenburg 1995; von Blanckenburg and Davies 1995; Sinclair 1997; Schlunegger and Kissling 2015), the proposed model allows to explain both: the development of multiple successive backfolding phases (such as the Mischabel, Vanzone and Glishorn-Berisal phases) related to the complex structure and multiple thickness variations of the subducting paleomargin; and the out-of-sequence development of the backfolds in the Western Alps.

7 Conclusion

This study focuses on the structure and stratigraphy of the Permian-Jurassic Faisceau Vermiculaire series (incl. Cimes Blanches and Frilihorn) and associated non-ophiolitic p.p. Upper Cretaceous calcschists (Série Rousse), which are both intercalated within the ophiolitic units in the area around Zermatt. It allows to revise several tectonic and paleogeographic attributions and to present a new tectonic model for the area.

Our lithological and stratigraphic observations allow: (i) to bring out the presence in the Faisceau Vermiculaire of widespread breccias, for the most part of probable Early to Late Jurassic age, that are intensely stretched and therefore locally difficult to recognize; they have often been misinterpreted as non-brecciated Triassic or Jurassic formations; (ii) to confirm the interpretation of the first authors suggesting the stratigraphic nature of the contacts between the Faisceau Vermiculaire and the overlying non-ophiolitic, p.p. Upper Cretaceous, calcschists of the Série Rousse, which constitute the lower part of the Schistes Lustrés complex; (iii) to highlight a strong contrast in the Jurassic to Cretaceous/Paleogene stratigraphic sequences between the autochthonous cover of the Siviez-Mischabel nappe (Barrhorn Series, Briançonnais s.str.) and the series formed by the Faisceau Vermiculaire and Série Rousse, which is characteristic of a sedimentation in a deeper basin with an important clastic and detritic input (Prepiemont domain); (iv) to interpret as stratigraphic the contact of the Faisceau Vermiculaire and the Série Rousse with the basement forming the Alphubel anticline east of Zermatt; the locally discordant character of this contact would be the result of the activity of synsedimentary Jurassic normal faults.

The Faisceau Vermiculaire and the Série Rousse are in tectonic contact with the Siviez-Mischabel basement north of Zermatt. This basement is also separated from the Alphubel anticline by a deep early syncline cored by sediments and ophiolites of the Tsaté nappe. The eastward prolongation of this syncline in the Mischabel massif is hidden by moraines and glaciers but for tectonic reasons and the stratigraphic observations stated above, the Alphubel basement has to be separated from the Siviez-Mischabel nappe by a tectonic contact.

We propose a new tectonic scheme for the structure of the Faisceau Vermiculaire and adjacent units. It involves an early northward folding of the Faisceau Vermiculaire together with the Série Rousse and the ophiolitic Schistes Lustrés of the Tsaté nappe, followed by major backfolding responsible for the southward emplacement of these units above the HP Zermatt-Saas Fee and Monte Rosa nappes.

The Alphubel basement, Faisceau Vermiculaire and Série Rousse collectively constitute a group that shares both an identical tectonic position with respect to the Siviez-Mischabel and Tsaté nappes and mostly identical stratigraphic sequences, as the Mont Fort nappe exposed to the north and west of the Dent Blanche klippe. Recent glacial retreat also reveals that the Série Rousse appears to be continuous from Zermatt to the north of the Dent Blanche klippe, where it overlies stratigraphically the older levels of the Mont Fort nappe. Therefore, we propose that the Alphubel basement and the Faisceau Vermiculaire (with associated Série Rousse) constitute the southeastern prolongation of the Mont Fort nappe exposed in the lower limb of the Mischabel backfold.

The disappearance of the Barrhorn Series north of Zermatt and the complete absence of Upper Permian and younger levels on top of the Siviez-Mischabel basement, from this area to the Mischabel massif in the east, may indicate the remnant of a major Jurassic paleofault scarp located between the Briançonnais swell and the Prepiemont basin. This paleofault potentially corresponds to a first order discontinuity in the southern Briançonnais s.l. Jurassic margin. Our study highlights specific links between the structure of the paleomargin and the development of the successive deformation phases, in terms of the location of the nappe boundaries in the early formation of the orogenic wedge, and later, with respect to the location of the first backfolds that develop along a major paleomargin discontinuity.

Abbreviations

Fm.	Formation
HP	High pressure
P–T	Pression-Temperature
UHP	Ultra high pressure
[Geographic coordinates]	refer to the Swiss grid MN95

Supplementary Information

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Additional file 1. Siviez-Mischabel—Faisceau Vermiculaire contact in the Lüegelti borehole (Zermatt): drill core description.

Additional file 2. Siviez-Mischabel—Faisceau Vermiculaire contact in the Lüegelti borehole (Zermatt): borehole location and drill core pictures.

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Author contributions
AP carried out the main part of the field study, data analyses, figures elaboration and manuscript writing. JLE and HM participated in field study, data interpretation and discussion and conclusion elaboration, as well as in revising and improving the manuscript. All authors read and approved the submitted version of the manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

Consent for publication
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The authors declare that they have no competing interests.

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