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ORIGINAL PAPER

Schistes Lustrés in a hyper-extended continental margin setting and reinterpretation of the limit between the Mont Fort and Tsaté nappes (Middle and Upper Penninics, Western Swiss Alps)

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Abstract

The Schistes Lustrés form a large and complex unit at the top of the Penninic nappe stack of the Alpine belt. Calcschists, partly of Late Cretaceous age, constitute the dominant lithology. They are closely associated both with blueschist facies Piemont-Ligurian ophiolites and continent-derived Mesozoic metasediments. The question of whether the Schistes Lustrés originated on continental or oceanic crust has been extensively debated among Alpine geologists and is locally still controversial. We present here new structural and stratigraphic observations, as well as Raman graphite thermometry (RSCM) data, for the Schistes Lustrés complex of the Combin zone in the Hérens, Dix and Bagnes valleys. Our observations indicate that the basal part of this Schistes Lustrés complex (defined as the Série Rousse) is systematically devoid of ophiolitic material, and rests in stratigraphic contact on the underlying Triassic - Lower Cretaceous metasediments and Paleozoic basement of the Mont Fort nappe (Prepiemont paleogeographic domain). The unconformity at the base of the Schistes Lustrés complex is interpreted as resulting from the sedimentation of the Série Rousse on a paleorelief formed by remnants of Jurassic normal fault scarps, and not as an Alpine tectonic contact, as previously proposed. The lithostratigraphic comparison with the Breccia nappe in the Prealps, as well as a foraminifer discovery, allows us to better constrain the age of the Série Rousse. It extends from the middle of the Early Cretaceous (Aptian?) to the Late Cretaceous (Campanian to earliest Maastrichtian?). In contrast, the upper contact of the Série Rousse with the ophiolite-bearing Schistes Lustrés clearly corresponds to an Alpine thrust. The thrust zone is underlined by thin and discontinuous slices of highly strained continental-margin derived Mesozoic metasediments (Frilihorn slices). RSCM data show that the recrystallization of the organic matter progressively increases on both sides towards this contact. This contact, internal to the Schistes Lustrés complex, is reinterpreted as the major tectonic contact separating the Middle Penninic Mont Fort nappe from the Upper Penninic Tsaté nappe (defined here as including only the ophiolite-bearing Schistes Lustrés and associated meta(ultra-)basites). This study clearly documents that the Schistes Lustrés consist of sediments either deposited on oceanic crust, showing locally

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preserved stratigraphic contacts with ophiolitic or serpentinized sub-continental mantle slivers, or sediments still resting stratigraphically on a former hyper-extended continental margin.

Keywords Schistes Lustrés, Combin zone, Western and Central Alps, Paleofaults, RSCM, *Globotruncana* in metamorphic rocks, Briançonnais, Prepiemont, Prépiémontais, Piemont-Liguria

1 Introduction

The Schistes Lustrés form one of the largest lithological groups in the Western Alps and Western Central Alps (Fig. 1). They crop out in the upper part of the Penninic nappe stack in an intermediate tectonic position between the units derived from the Briançonnais (s.l.) continental margin, the eclogitic Piemont-Liguria ophiolites and the units derived from the Adriatic continental margin (Fig. 1). They constitute a set dominated by calcschists showing ophiolitic intercalations, up to several hundred meters thick. The name Schistes Lustrés refers to the glossy metallic grey ("lustré") aspect of these calcschists. It is the abundance of phyllosilicates and graphite, which gives, together with the metamorphism, this characteristic aspect to their schistosity surfaces.

The question of the origin of the Schistes Lustrés has always been problematic, notably because of their close association with metabasites and mantle rocks as well as with continental margin successions. The extreme scarcity of fossils also makes the determination of their age difficult (e.g. Termier 1902; Staub 1942a). Since the emergence of plate tectonics, the question of the continental or oceanic nature of the bedrock on which the Schistes Lustrés were deposited has been extensively debated among Alpine geologists. The idea that both cases could exist, or even coexist, appeared early on and have been proposed by different authors (e.g. Staub 1942b; Lemoine 1953, 1964, 1967, 1971; Elter 1971; Bearth 1976; Bourbon et al. 1979; Caby 1981; Lemoine and Tricart 1986; Fudral et al. 1987; Lagabrielle 1987). However, in several cases the question still remains relevant today as the stratigraphic or tectonic nature of the contact between the Schistes Lustrés and the surrounding units is most often difficult to establish (Lemoine 1971; Michard and Schumacher 1973; Marthaler and Stampfli 1989). Indeed, a strong ductility contrast generally characterizes these interfaces and favors their late movements in the form of local shearing. The difficulties also result from the strong lithological similarities between the Schistes Lustrés of oceanic origin and those originating from continental margins. The contact between such units may be difficult to identify, especially since they are now involved in nappes and have undergone polyphase ductile deformation (e.g. Savary and Schneider 1983).

The present study focuses on the Schistes Lustrés of the Combin zone (Pennine Alps), in the area located NW of the Dent Blanche klippe (Fig. 1b; Canton of Valais, Switzerland).

2 Geological setting

2.1 The Schistes Lustrés in the nappe stack of the Pennine Alps

The metasediments and ophiolitic remnants constituting the Schistes Lustrés complex originated from the Mesozoic Piemont-Liguria basin and its margins. This basin, which constituted the main branch of the Alpine Tethys, was a slow-spreading small oceanic domain, resulting from the rifting between the European and Adriatic plates (e.g. Lemoine and Trümpy 1987; Lagabrielle and Lemoine 1997; Stampfli et al. 2002; Le Breton et al. 2021; Manatschal et al. 2022). Oceanization of the basin is attested since the Bajocian (Elter et al. 1966; Bill et al. 2001; Manatschal and Müntener 2009) and continued at least until the Kimmeridgian (e.g. Bill et al. 1997; Rubatto et al. 1998; Schaltegger et al. 2002; Decrausaz et al. 2021). The progressive closure of the Alpine Tethys starting in the Late Cretaceous (e.g. Caron et al. 1989; Gasinski et al. 1997; Stampfli et al. 1998; Skora et al. 2009; Rubatto et al. 2011), led to the accretion and incorporation of ophiolitic slivers and associated oceanic sediments into the orogenic prism (e.g. Lagabrielle 1987; Marthaler and Stampfli 1989; Stampfli and Marthaler 1990; Stampfli et al. 1998), and finally to the Cenozoic Alpine collision (e.g. Escher and Beaumont 1997; Schmid et al. 2017; Candioti et al. 2021).

In the nappe stack of the Pennine Alps, the ophiolitic units derived from the Piemont-Liguria basin show two types of contrasting tectono-metamorphic evolution (e.g. Kienast 1973; Dal Piaz 1974; Ernst and Dal Piaz 1978; Merle and Ballèvre 1992; Ballèvre and Merle 1993; Negro et al. 2013). (i) The structurally lower ophiolitic units (Zermatt-Saas Fee, Antrona, and Lanzo) show eclogite facies paragenesis (e.g. Bearth 1967; Pfeifer et al. 1989; Bucher et al. 2005, 2019; Angiboust et al. 2009; Dragovic et al. 2020) with local UHP relics in Zermatt-Saas Fee (e.g. Reinecke 1991, 1998; Forster et al. 2004; Frezzotti et al. 2011, 2014; Groppo et al. 2009) and a predominance of ophiolites over metasediments. (ii) The structurally upper ophiolite-bearing 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), corresponds to the

(See figure on next page.)

Fig. 1 **a** Map of the Western and Central Alps showing the Schistes Lustrés units; modified after Schmid et al. (2004, 2017), Steck et al. (1999, 2015, 2019), Ballèvre et al. (2018, 2020), Beltrando et al. (2010, 2014), Balestro et al. (2020), Dal Piaz (1999), Bigi et al. (1992), Gouffon (1993), Deville et al. (1992) and the Tectonic map of Switzerland (2005). *A*: Antrona nappe; *Ac*: Accelgio zone; *AF*: Aosta fault; *ALi*: Apenninic Ligurian nappes; *Am*: Ambin massif; *Ar*: Arpont massif; *B*: Breccia nappe; *Bi*: Biella pluton; *Br*: Brusson window; *BT*: Brèches de Tarentaise; *CB*: Pancherot - Cime Bianche - Bettaforca Series; *Ch*: Chenaillet unit; *CN*: Cheval Noir Flysch; *Dr*: Dranses nappe; *DS*: Dronero-Sampeyre unit; *Em*: Monte Emilius unit; *Ga*: Gastern massif; *Ge*: Gets nappe; *GI*: Gazzo-Isoverde unit; *Gr*: Graies Alps; *GR*: Glacier-Rafray unit; *Gu*: Gurnigel nappe; *HF*: Helminthoid Flysch; *La*: Lanzo massif, *LA*: Ligurian Alps; *LTF*: Lis-Trana fault; M: Money unit; *MF*: Mont Fort nappe; *MV*: Monviso massif; *Ni*: Niesen nappe; *NVa*: Northern Vanoise massif; *Or*: Orobic nappes; *Pg*: Portjengrat nappe; *Pi*: Pillonet unit; *R*: Ruitor unit; *RC*: Roche des Clots unit; *Ro*: Rochebrune unit; *S*: Stockhorn nappe; *Sa: Saane nappe; SaM*: Subalpine Molasse; *SC*: Sion-Courmayeur zone; *Si*: Simme nappe; *SM*: Siviez-Mischabel nappe; *SVa*: Southern Vanoise massif; *T*: Traversella pluton; *Ta*: Tavetsch nappe; *TL*: Tonale Line; *Ts*: Tsaté nappe; *V*: Voirons nappe; *Vo*: Voltri massif; *Vs*: Valsavarenche unit; *ZH*: Zone Houillère; *ZS*: Zermatt-Saas Fee nappe. **b** Map of the Schistes Lustrés of the Combin zone and surrounding units across the Bagnes, Dix, Hérens and Anniviers valleys in SW Switzerland, and the Ollomont valley and Valpelline in NW Italy; bedrock map compiled after our own and the maps of Moix and Stampfli (1980), Escher (1988), Allimann (1990), Rey (1992), Kramar (1997), Burri et al. (1998), Baillifard (1998), Steck et al. (1999), Favre (2000), Marthaler et al. (2008a, 2020a), Sartori et al. (2011), Sartori and Epard (2011), Glassey (2013) and Geocover (Swisstopo). The individualized "Tracuit - Aig. Rouges z. / Cornet U." groups together the Tracuit - Aiguilles Rouges zone with the Cornet Unit; limits after Marthaler et al. (2020b, fig. 16) and Manzotti et al. (2021, fig. 7), slightly modified. *AR*: Aiguilles Rouges d'Arolla; DB_M: Dent Blanche Mesozoic; SM_M: Siviez-Mischabel Mesozoic; ZH_M: Zone Houillère Mesozoic; ZH_P: Zone Houillère Paleozoic

Schistes Lustrés complex. It is dominated by metasediments and shows greenschist facies paragenesis with blueschist-facies relics (e.g. Caby 1981; Bousquet et al. 2004; Manzotti et al. 2021; cf. chap. 2.3.1). The lithologies and metamorphic paragenesis of (ii) are similar to those of the Schistes Lustrés of the French Western Alps (e.g. Agard et al. 2001; Plunder et al. 2012).

At its top, the Schistes Lustrés complex of the Combin zone is in tectonic contact with the Paleozoic basement of the Sesia and Dent Blanche nappes (Adriatic margin; e.g. Manzotti et al. 2014, 2017; Angiboust et al. 2014; Kirst 2017; Kirst and Leiss 2017). At its base, it rests on different tectonic units (Fig. 1): (1) the Zermatt-Saas Fee nappe (Piemont domain), in the internal part of the belt (Ballèvre et al. 1986; Bucher et al. 2004; Dal Piaz et al. 2015); (2) the Siviez-Mischabel nappe (Briançonnais domain), north of Zermatt, as well as in the Turtmann and Anniviers valleys and on the right side of the Hérens valley (e.g. Hermann 1913; Bearth 1953, 1978; Sartori 1987, 1990; Scheiber et al. 2013); (3) the Evolène Series, cover of the Mont Fort nappe (Prepiemont domain; Escher 1988; Marthaler 1984; Pantet et al. 2020), NW of the Dent Blanche klippe; or (4) directly on the Paleozoic basement of the Mont Fort nappe, if the Evolène Series is absent.

2.2 Subdivisions in the Schistes Lustrés complex of the Combin zone

After the first definition of the Combin zone by Argand (1909), as a composite tectonic unit grouping together all the Mesozoic metasediments outcropping between the basements of the Grand St-Bernard and Dent Blanche nappes, more specific studies of its Schistes Lustrés complex (*Combin zone s.str.*) were carried out, for example by Staub (1942a, 1942b, 1942c), Witzig (1948), Zimmermann (1955), Dal Piaz (1965, 1971), Bearth (1967, 1978) and Caby (1981). Further detailed studies of these Schistes Lustrés, in the area located north of the Dent Blanche klippe, allowed to individualize different lithological and tectonic units within this complex (Marthaler and Escher in Masson et al. 1980; Marthaler 1981, 1984; Escher and Masson 1984; Sartori 1987; Escher 1988; Escher et al. 1988; Fig. 2). We describe them below, from top to bottom.

1. The upper unit is mainly formed of basic and ultrabasic rock bodies reaching pluri-km sizes, associated with calcschists. This unit corresponds with the Tracuit zone (Zimmermann 1955; Escher and Masson 1984; Sartori 1987), defined in the eastern part of the study area, and with the ophiolites and associated metasediments of the Aiguilles Rouges d'Arolla (Aiguilles Rouges-Zone and Hochpenninikum höhern Schuppen, Witzig 1948; Série ophiolitique s.s., Kunz 1988; Aiguilles Rouges and Mont de l'Etoile Ophiolites, Decrausaz et al. 2021). In the following, we will use the term *Tracuit - Aiguilles Rouges zone* to refer to this unit.
2. The intermediate Schistes Lustrés unit is usually designated by the term *Série Grise* (Marthaler 1984). It is composed mostly of calcschists and other oceanic metasediments, mixed with ophiolitic lenses, which are usually smaller than those of the previous unit.
3. A thin unit of Mesozoic metasediments derived from a continental margin (0.1–20 m thick) punctuates the base of the Série Grise as discontinuous and often

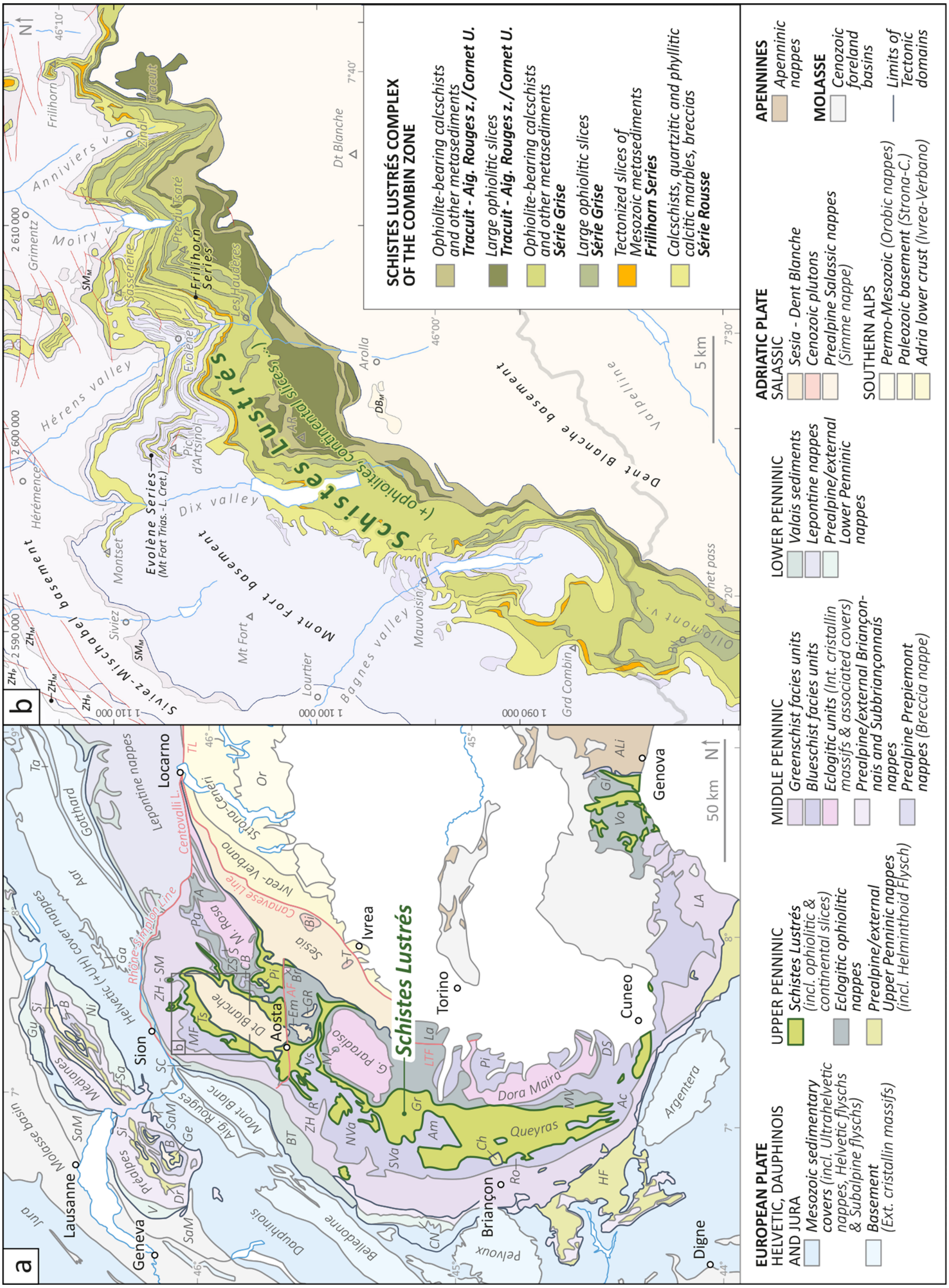

Fig. 1 (See legend on previous page.)

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<tr><th colspan="2">Authors
Units/Series</th><th>Sartori 1987</th><th>Escher et al. 1988 (=Escher et al. 1987)
Escher 1988
Marthaler & Stampfli 1989
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Deville et al. 1992</th><th>Stampfli & Marthaler 1990</th><th>Sartori & Marthaler 1994
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Negro et al. 2013</th><th>Steck et al. 1999/2001
Tectonic map of Switzerland 2005
Burri et al. 1998/1999
Marthaler et al. 2008
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Dal Piaz et al. 2015</th><th>Scheiber et al. 2013</th><th>Angiboust et al. 2014</th><th>Marthaler et al. 2020</th><th>Manzotti et al. 2021</th><th>Proposed interpretation in this study</th><th colspan="2">Authors
Units/Series</th></tr>
<tr><td rowspan="4">Schistes Lustrés complex of the Combin zone</td><td>Tracuit and Aiguilles Rouges</td><td>Tsaté nappe:
Tracuit zone</td><td>Tsaté nappe:
Tracuit - Aig. Rouges zone
or
Tracuit + Aig. Rouges zone</td><td rowspan="2">Tsaté nappe</td><td>Tsaté nappe:
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Low-T unit</td><td>Tsaté nappe:
Lower T. slice</td><td>Combin zone:
Cornet Unit</td><td>Tsaté nappe:
Tracuit - Aig. Rouges zone / Cornet Unit
(Lower metamorphic grade unit)</td><td>Tracuit and Aiguilles Rouges</td><td rowspan="4">Schistes Lustrés complex of the Combin zone</td></tr>
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Higher T. slice</td><td rowspan="3">Combin zone:
By Unit</td><td>Tsaté nappe:
Série Grise
(Higher metamorphic grade unit)</td><td>Série Grise</td></tr>
<tr><td>Frilihorn Series</td><td rowspan="4">Mont Fort nappe</td><td rowspan="4">Mont Fort nappe</td><td rowspan="4">Mont Fort nappe</td><td>Frilihorn nappe
(early incorporation in an accretionary prism)</td><td>Frilihorn nappe</td><td>Frilihorn nappe</td><td>Frilihorn «nappe»
(Siviez-Mischabel detached cover)</td><td>Frilihorn nappe</td><td>Frilihorn slices
(possible internal Mont Fort nappe)</td><td>Frilihorn Series</td></tr>
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(early incorporation in an accretionary prism)</td><td>Tsaté nappe</td><td>Tsaté nappe</td><td>Tsaté nappe</td><td>Tsaté complex:
High-T unit</td><td>Tsaté nappe:
Higher T. slice</td><td rowspan="3">Mont Fort nappe</td><td>Série Rousse</td></tr>
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(Siviez-Mischabel detached cover)</td><td>not mentionned</td><td>Sasseneire nappe</td><td rowspan="2">Mont Fort nappe</td><td colspan="2">Evolène Series</td></tr>
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Fig. 2 Tectonic attributions of the studied units/series between successive previous authors and this study

strongly tectonized slices. It constitutes the upper and outer digitation of the *Faisceau Vermiculaire* of Argand (1916a, 1916b; Escher and Masson 1984). North of the Dent Blanche klippe, its thickness is often below one meter and its maximum thickness (20 m) is reached at the Frilihorn (Fig. 1b), the summit that gave its name to this unit (Hermann 1913; Marthaler 1984; Sartori and Marthaler 1994; Stampfli and Marthaler 1990).

4. The lower Schistes Lustrés unit, called the *Série Rousse* (Marthaler and Escher in Masson et al. 1980; Marthaler 1981), consists mainly of calcitic marbles rich in detrital material and of calcschists. The Schistes Lustrés of this unit show a near continental margin affinity contrasting with that of the upper units, reflected in particular by the local presence of breccia levels with dolomitic clasts and by a marked quartzitic detrital component.

In the original definition of the Tsaté nappe (Sartori 1987), only the two upper units above, i.e. the Série Grise and the Tracuit (- Aiguilles Rouges) zone, were included in this nappe (Fig. 2). The two lower units (Série Rousse and Frilihorn) were attributed to the underlying Mont Fort nappe (e.g. Escher 1988; Escher et al. 1988; Allimann 1990; Deville et al. 1992).

Marthaler and Stampfli (1989) and Stampfli and Marthaler (1990) evidenced the similarities between the Tsaté nappe and modern accretionary prisms, both showing a structure composed of superimposed slices involving sediments and ophiolites. These similarities, together with the identification of large-scale unconformities at the base of the Série Rousse, led to propose the inclusion of the Série Rousse as a basal slice to the Tsaté nappe and to reinterpret the nature of the basal contact of these series as tectonic (Escher et al. 1993; Sartori and Marthaler 1994). Further evidence for local fluid circulation along the basal contact of the Série Rousse was highlighted by an isotopic profile carried out across this contact (Kramar 1997). This evidence reinforced the hypothesis of the affiliation of the Série Rousse to the Tsaté nappe, since then accepted and adopted by all subsequent authors (e.g. Escher et al. 1997; Steck et al. 1999; Tectonic map of Switzerland 2005). According to this redefinition, the Tsaté nappe would correspond to a stack of tectonic slices, grouping together all the Schistes Lustrés of the Combin zone (Fig. 2).

The different lithologies constituting the Schistes Lustrés north of the Dent-Blanche klippe are described in the following chapter. It gathers the necessary elements that allow the distinction of the different series or units defined in the literature. The new data are based on detailed mapping and tectonostratigraphic observations of key areas.

2.3 Lithologies of the Schistes Lustrés complex of the Combin zone

2.3.1 Ophiolite-bearing Schistes Lustrés and associated lithologies

We will describe the different lithologies of the ophiolite-bearing Schistes Lustrés of the Combin zone independently of the tectonic subdivisions detailed in the previous chapter, because the same lithologies are present in these different subdivisions. The ophiolitic material can be incorporated in these Schistes Lustrés as levels or lenses of variable sizes, or as a sand-sized or thinner detrital component.

2.3.1.1 Calcschists The calcschists of the ophiolite-bearing Schistes Lustrés of the Combin zone generally display a greyish and sometimes greenish tint, which may turn to russet for the levels that are the richest in calcite (Fig. 3a). The characteristic metallic gray appearance of their schistosity surfaces is due to the abundance of phyllosilicates and graphite.

Their mineralogy is generally composed of calcite, quartz, muscovite, chlorite, albite and pyrite, ± tourmaline, apatite, ankerite, zircon, rutile, pyrite and various oxides (e.g. Marthaler et al. 2008b, 2020b). Metamorphic parageneses are mostly typical of greenschist facies, but early blueschist facies parageneses are attested by the local preservation of relics of garnets, Mg-chloritoid and phengite (Burri et al. 1999; Bousquet et al. 2004, 2008), of carpholite pseudomorphs (Pfeifer et al. 1991); and of lawsonite pseudomorphs and aragonite inclusions in titanite (Manzotti et al. 2021). The local presence of fuchsite (Vogel 1995; Manzotti et al. 2021) reflects the presence of chromium in these sediments and seems to confirm their oceanic origin. Lithologies are variable and can evolve towards phyllitic and quartzitic marbles, as well as towards black shales, which are often compared to the *Palombini* shales from the Apennines (e.g. Marthaler and Stampfli 1989). In the Tsaté nappe, such dark shales and associated calcschists have been grouped together as the Garda Bordon Formation, which is supposedly of Early to "mid"-Cretaceous age (Marthaler et al. 2020b). Rhythmic alternations of shales and decimetric beds of quartzitic calcarenites, locally showing graded bedding, have been, for their part, grouped together as the Fêta d'Août Formation (Viredaz 1979; Marthaler et al. 2020b). This formation is attributed to the Early Cretaceous by analogy with the Replatte formation of the Western Alps (Lemoine and Tricart 1986).

Relics of planktic foraminifera have been described in several localities of the Série Grise (Marthaler 1981, 1984; and unpublished diploma theses from: Savary 1982; Schneider 1982; Besson 1986; Du Bois and Looser 1987; Kunz 1988). They generally come from the levels that are the richest in calcite in this unit. The strong rheological contrast between these levels and the surrounding calcschists, as well as a diagenetic replacement as Fe-carbonate (usually referred to as ankerite), seem to have allowed a local preservation of these forms, despite the intensity of deformation and recrystallization. The forms described mostly recall *Rotalipora* sp., or more rarely *Marginotruncana* sp., corresponding to Cenomanian and Turonian-Santonian age ranges, respectively (e.g. Peryt et al. 2022). Forms of the same types have also been described in various localities of the Schistes Lustrés of the Western Alps (Lemoine et al. 1984; Marthaler et al. 1986; Deville 1987; Fudral et al. 1987) and Corsica (Meresse et al. 2012).

2.3.1.2 Volcanosedimentary arkoses Volcanosedimentary levels are found in several locations in the Schistes Lustrés of the Combin zone (e.g. Kunz 1988; Decrausaz et al. 2021; Fig. 3b). Kunz (1988) describes in particular volcanosedimentary arkoses at the contact between the ophiolite bodies intercalated in the Schistes Lustrés and the overlying calcschists and black shales. The gradual transition between these lithotypes seems to indicate an original stratigraphic contact of the sediments on their ophiolitic bedrock. Volcanosedimentary levels are also described in the Schistes Lustrés of the Western Alps (e.g. Lagabrielle and Polino 1985), in particular gabbroic arenites (Le Mer et al. 1986) and basaltic sands (Lagabrielle 1987).

2.3.1.3 Calcitic marble levels Several meters to tens of meters thick levels of calcitic marbles and breccias are observed in the ophiolite-bearing Schistes Lustrés of the Combin zone (Staub 1942c; Burri et al. 1998, 1999; Marthaler et al. 2020b). Marbles containing serpentinite clasts, and sometimes abundant epidote, are locally found in stratigraphic contact with ophicarbonates and ophiolitic lenses (Vogel 1995; Marthaler et al. 2020b; Decrausaz et al. 2021; Fig. 3c, d). Such levels are also described in the Schistes Lustrés of the Western Alps and Corsica (e.g. Lemoine et al. 1970; Lagabrielle et al. 2015). Their strong analogies with limestones containing ophiolitic clasts of the Upper Penninics of Graubünden in which Weissert (1975) observed *Calpionella*, and with the *Calpionella* limestones of the supra-ophiolitic sediments of the Apennines and Corsica (Abbate and Sagri 1970; Andri and Fanucci 1973), makes their attribution to the latest Jurassic / earliest Cretaceous very likely.

2.3.1.4 Manganese-bearing quartz micaschist beds In different localities, metric levels of manganese-bearing quartz micaschists, classically interpreted as metaradio-

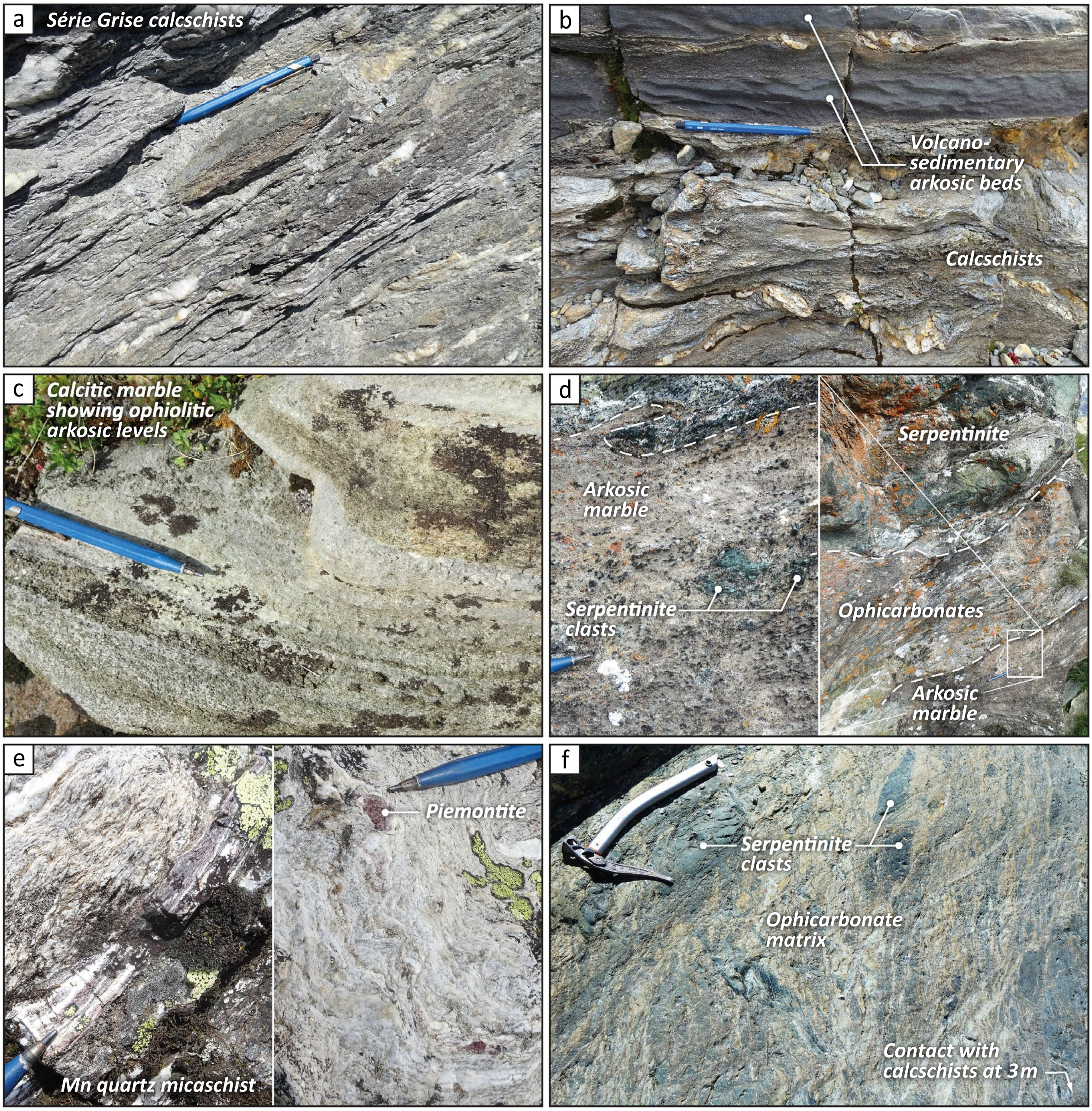

Fig. 3 Lithologies of the ophiolite-bearing Schistes Lustrés of the Combin zone. **a** Characteristic aspect of the Série Grise calcschists; Les Haudères [2′604′860/1′104′050]. **b** Graded beds of greenish to violaceous volcanosedimentary arkose interbedded in calcschists; Adlerflüe [2′620′290/1′110′560], Turtmann valley. **c** Decimetric level of greenish calcitic marble outcropping at a few meters from a plurihectometric-long ophiolitic lens (serpentinites, metabasites) of the Série Grise. Detrital mm-sized grains of ophiolitic material are visible under the pencil; Chanrion hut area [2′595′195/1′087′695], Bagnes valley. **d** Arkosic calcitic marble at the contact of a hectometric-long serpentinite lens. Note the presence of cm-sized serpentinite clasts and the green color of the ophiolitic arkosic detritus; 3 m from Fig. c. **e** Quartzmicaschists levels (1–2 m thick) interpreted as metaradiolarites (Staub 1942c; Burri et al. 1999) and locally rich in piemontite (sometimes associated to braunite); Chanrion hut area [2′595′165/1′087′700]; Mn-garnets and blue amphiboles are visible in the same level, 200 m to the NNW. **f** Serpentinite breccia observed at the contact between calcschists of the Série Grise and a plurihectometric serpentinite lens marking the contact with the Série Rousse; Giétro [2′594′360/1′094′290], Bagnes valley

larites, are intercalated in the Schistes Lustrés of the Combin zone (Staub 1942c; Hagen 1948; Witzig 1948; Bearth and Schwandler 1981; Caby 1981; Ayrton et al. 1982; Marthaler 1984; Burri et al. 1999; Marthaler et al. 2020b). Spessartine is common and is sometimes accompanied by other manganese minerals or mineralizations (e.g. Baldelli et al. 1983; Ansermet and Meisser 2012; Marthaler et al. 2020b). Piemontite, accompanied by braunite and Mn-garnets, have been observed in such levels near the Chanrion hut in the Bagnes valley (Burri et al. 1999; Fig. 3e). In the Schistes Lustrés of the Western Alps, similar quartzschist levels have yielded radiolarians of Callovian to Middle Kimmeridgian age (De Wever and Caby 1981; Deville 1987; De Wever et al. 1987).

2.3.1.5 Meta(ultra-)basites Among the ophiolitic intercalations in the Schistes Lustrés of the Combin zone, metabasites are the most abundant. Their chemistry is generally of MORB type (Dal Piaz et al. 1981; Beccaluva et al. 1984; Decrausaz et al. 2021) and their parageneses (epidote + albite + chlorite + titanite ± actinolite/tremolite ± phengite ± apatite ± calcite; e.g. Angiboust et al. 2014; Marthaler et al. 2020b; Decrausaz et al. 2021) are typical of the greenschist facies. An early, largely retromorphosed, blueschist facies paragenesis is locally preserved (e.g. Dal Piaz and Ernst 1978; Ayrton et al. 1982; Sperlich 1988; Martin and Cortiana 2001; Angiboust et al. 2014).

The metabasalts (prasinites, ovardites) form levels of very variable thickness, ranging from a few decimeters to several hundred meters. Pillow lava structures have been recognized in several locations in the Combin zone (e.g. Dal Piaz 1971; Kunz 1988; Decrausaz et al. 2021). Basaltic breccias have been described, particularly at the contact with the underlying ultramafic rocks (e.g. Caby 1981).

The metagabbros can form plurikilometric bodies, as for example in the region of the Tracuit alp; and at the Aiguilles Rouges d'Arolla (Fig. 1b), where they have been dated at 154.9 ± 2.6 Ma and 155.5 ± 2.8 Ma (U–Pb on zircon, LA-ICP-MS; Decrausaz et al. 2021).

The most common ultrabasites in the Combin zone are serpentinites. They are intercalated as lenses that can reach plurikilometric dimensions. Their mineralogy is dominated by antigorite, generally accompanied by magnetite and tremolite (Angiboust et al. 2014). The borders of the lenses can be enriched with talc, antigorite, magnesite and dolomite (Pfeifer and Serneels 1988; Angiboust et al. 2014). Serpentinite breccias can be observed locally at the top of these lenses, in contact with the metasediments, and probably result from continued Jurassic rifting (Vogel 1995; Decrausaz et al. 2021; Fig. 3f).

2.3.2 Frilihorn Series

In the study area, north of the Dent Blanche klippe, the thin and discontinuous Frilihorn Series is mostly reduced to a few tens of cm of strongly tectonized carbonate rocks. Where the series are the thickest and least deformed, different types of Mesozoic metasediments can be recognized (e.g. Hermann 1913; Witzig 1948; Marthaler 1984; Allimann 1990; Sartori 1990). Dolomites constitute the dominant lithology. They are observed in particular at the Bail de l'Ardzentière [2′594′200/1′093′000] in the Bagnes valley (Besson 1986) and NE of Molignon [2′605′540/1′104′600] in the Hérens valley. Calcitic marbles are also common, they are generally clear-colored, relatively pure and form notably the 15 m cliff of the summit of the Frilihorn (Marthaler 1984). Thin layers of dolomitic breccias intercalated within this level can be observed there. This same level can be followed through the Arpettes pass towards the Turtmann glacier (cf. Tectonic panorama from Hermann 1913), which it crosses at an altitude of 2700 m, until the NE face of the Adlerflüe, where it forms a clearly visible 10 m thick band of white calcitic marbles. There, a level of breccia, already indicated by Sartori (1990), is present at its base. The mm- to cm-sized clasts are mostly dolomitic and the matrix consists of a dark calcitic marble. Similar breccias are also observed SE of L'Ata Gieute [2′604′625/1′104′755] in the Hérens valley, where they surround a 3 m thick dolomitic level. In the study area, quartzites are very rare in this unit. A 20 cm thick level of micaceous quartzite is nevertheless present near the top of the Frilihorn, intercalated between the marbles of the upper cliffs and russet calcschists covering the summit itself. These calcschists, which contain dolomitic clasts at their base (Marthaler 1984), as well as similar calcschists and russet phyllitic marbles from a few other outcrops, are also attributed to the Frilihorn Series (Marthaler 1984; Sartori 1987; Allimann 1990).

2.3.3 Série Rousse

The Série Rousse consists of calcschists, phyllitic and quartzitic marbles, dark shales and thin conglomeratic layers, forming the base of the Schistes Lustrés complex of the Combin zone (e.g. Marthaler 1984; Marthaler et al. 2020b). Its thickness can reach several hundred meters. The calcschists of these series are generally poorer in phyllosilicates than those of the ophiolite-bearing Schistes Lustrés, whereas the levels of calcitic marbles are more abundant and thicker. The name Série Rousse (Marthaler and Escher in Masson et al. 1980) comes from the frequent russet colored patina, typical of the sediments of these series (Fig. 4a–c). It is due to the presence

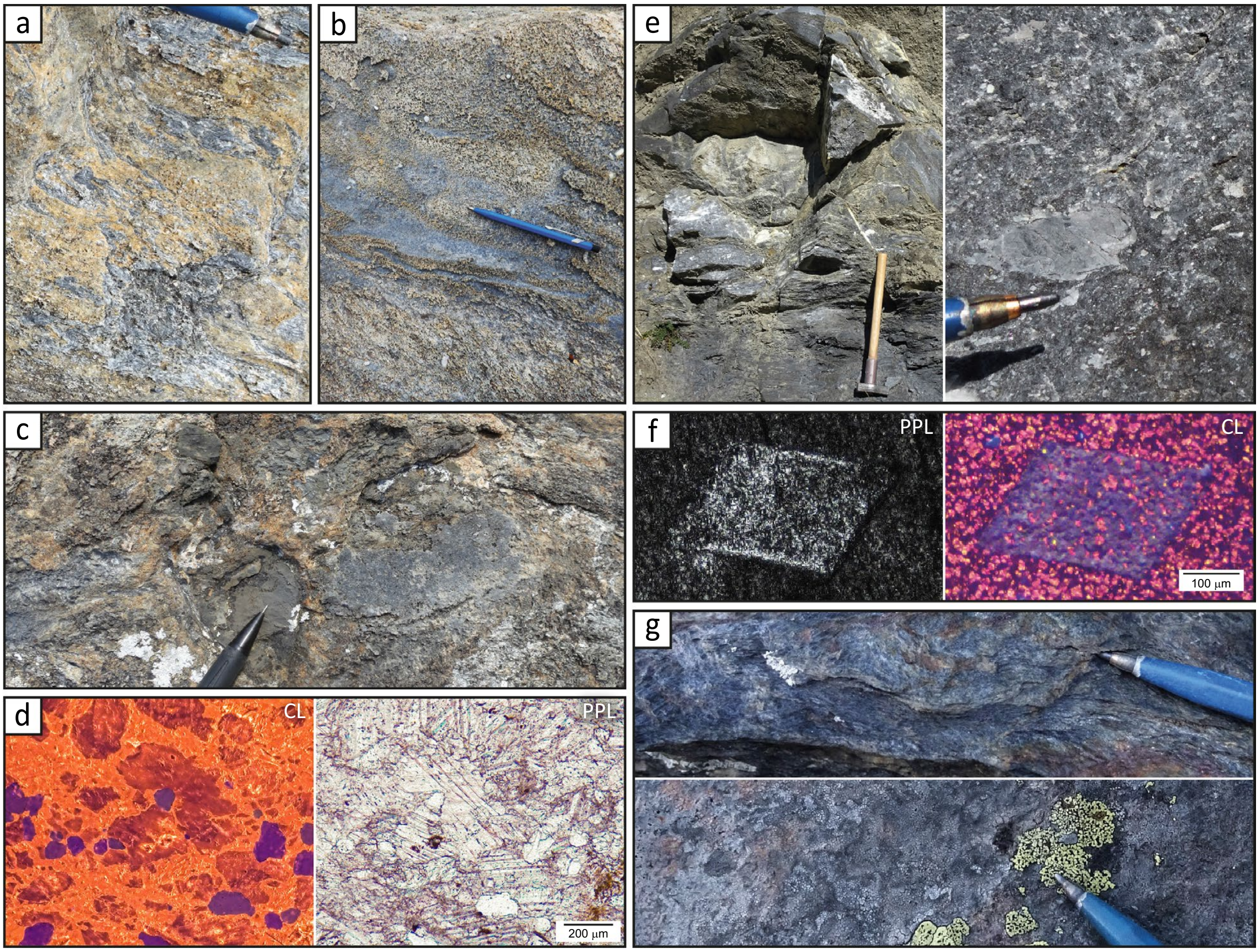

Fig. 4 Lithologies of the Série Rousse. **a** Typical glossy metallic grey appearance of the schistosity surfaces of the Série Rousse calcschists; Meina pass [2′599′280/1′105′330], Hérens valley. **b** Alternating grey calcitic marble and russet calcschist levels in the Série Rousse; dolomitic clasts are visible in the same outcrop; Rochers du Bouc [2′595′210/1′099′620], Dix valley. **c** Centimetric clasts in the Série Rousse, mainly formed by dolomites (pencil), limestones and minor quartzschists (out of the picture); Pic d'Artsinol [2′598′780/1′107′050]. **d** Microscopic aspect of a quartzitic marble from the base of the Série Rousse. CL: cathodoluminescence; PPL: plane polarized light. Well sorted rounded detrital quartz grains appear in violet in CL; dolomitic grains show mauve to dull orange colors; overgrowth (probably burial) cements are bright orange; zoning and/or dark rims are discordant with respect to the twinning (PPL) and could represent original variations of Mn^{2+} incorporation; Pic d'Artsinol [2′599′170/1′108′585]. **e** Dark levels of calcschists, calcitic marbles and dolomitic breccia (close-up picture) from the Série Rousse; La Tour [2′605′440/1′104′770], Hérens valley. **f** Rhombohedral automorph mineral observed in various thin sections of dark micritic calcitic marbles of the Série Rousse. Raman spectra indicate feldspar; Pic d'Artsinol [2′598′700/1′108′400]. Similar rhombohedron resulting from the silicification of automorph dolomite crystals are described in dark micrites of the "mid"-Cretaceous Joux Verte Fm. of the Breccia nappe (Dall'Agnolo 1997). **g** Dark non-carbonated schists outcropping 20 m above the base of the Série Rousse at La Vieille [2′602′800/1′105′540], Hérens valley

of iron oxides, associated with the detrital quartz content, and iron carbonates (e.g. ankerite) in the carbonaceous levels. The tint of the patina contrasts with the glossy metallic gray tint of the schistosity surfaces resulting from the abundance of graphite and white micas in these sediments (Fig. 4a). The mineralogy is typically composed of calcite, quartz, white micas, albite, graphite and pyrite (often idiomorphic) ± chlorite, titanite and zircons. Clasts, mostly dolomitic (Fig. 4c, d), appear in some levels (Marthaler et al. 2008b, 2020b). Garnet relics and pseudomorphs after lawsonite can be observed locally (Besson 1986; P. Manzotti pers. com.).

Relics of planktic foraminifera, diagenetically transformed into Fe–Mg carbonates, have been described in several locations in the Série Rousse (Marthaler 1981, 1984; and unpublished diploma theses from: Pilloud and Sartori 1981; Schneider 1982; Crespo 1984; Besson 1986; Schmid 1988; Salamin 1989). The described micropaleontologic content presents forms that essentially ascribe to *Rotalipora* sp. (of Cenomanian-type), with a few bicarinate forms indicating a Turonian to "early Senonian" (i.e. Coniacian-Santonian) age (Marthaler 1981, 1984), for the younger parts of the series.

3 Methods

3.1 Field observations and mapping

This study was based essentially on an extensive geological field work conducted over five consecutive seasons. A relatively large-scale approach was favored (studied area extending through the Bagnes, Dix, Hérens, Anniviers and Turtmann valleys; Fig. 1b), while the level of detail of the observations was adapted to the interest and quality of the outcrops.

3.2 Cathodoluminescence (CL)

Cathodoluminescence, or the emission of photons in the visible range of the electromagnetic spectrum under cathodic excitation, is a technique routinely used in mineralogy and sedimentary petrography, as it may enable to distinguish patterns of trace elements remaining undetectable under classical optical microscopy. CL depends on the presence of activator ions, which are stimulated to emit light when bombarded with energetic electrons, or on the presence of quencher ions. In carbonates, the best-known activator is Mn^{2+}. Bivalent iron (Fe^{2+}) is the most important quencher ion (e.g. Machel et al. 1991). In metasediments showing advanced calcite recrystallization, CL can allow to highlight the presence of microfossils or to distinguish sedimentary structures, no longer recognizable under classical optical microscopy.

CL images were obtained at the University of Lausanne using a Technosyn 8200 MkII mounted on an Olympus BH-2 microscope, and operated at 15–20 kV and 0.4–0.5 mA with an unfocused cold cathode electron beam under a He atmosphere at 0.2 torr.

3.3 Raman spectroscopy of carbonaceous material (RSCM)

Raman graphite thermometry is based on the progressive transformation of organic matter into graphite with increasing temperature. As this transformation is considered to be irreversible, the structural organization of the carbonaceous material (CM) records the maximum temperature reached during metamorphism (Wopenka and Pasteris 1993; Beyssac et al. 2002, 2003a). Beyssac et al. (2002) obtained a linear correlation between the peak temperature and the structural organization of CM (RSCM method). This method enables the determination of the peak temperature in the range of 330–650 °C with an absolute accuracy of ± 50 °C. Relative uncertainties on peak temperature may however be much smaller (e.g. Beyssac et al. 2004; Wiederkehr et al. 2011; Negro et al. 2013; Angiboust et al. 2014).

Raman spectroscopy was performed at the University of Lausanne using a HR Raman-FTIR spectrometer from HORIBA Scientific, an integrated Raman microprobe consisting of an Olympus BX41 confocal microscope coupled to an 800 mm focal-length spectrograph. A 532.12 nm frequency doubled Nd-YAG continuous wave laser was focused on the sample. The power of the laser at the surface of the sample was 9 mW. Analytical procedures from Beyssac et al. (2002, 2003b) were followed closely while also taking into account the recommendations reported in Beyssac and Lazzeri (2012): measurements were carried out on polished thin sections, and CM was systematically analyzed below a transparent adjacent mineral, most often quartz. The sampled volume was a few μm^3 using a 100 × objective. The Raman signal was collected in backscattered mode. Analyses were carried out using a grating of 1800 grooves/mm, a 150 µm slit aperture and a 150 µm hole. Spectra were recorded in extended scanning mode (1100–1800 cm^{-1}) using the LabspecTM v.4.15 software and an acquisition time of 2 × 40 s. The spectrometer was calibrated with a silicon standard before each session. Spectra were acquired in 12–35 different spots on each sample. They were processed using the PeakFit v4.12 software. A linear baseline correction was applied using systematically the same parameters (2nd derivative zero linear correction, tolerance 0.5%, zero negative correction). Peaks D1 (~ 1350 cm^{-1}), G (~ 1510 cm^{-1}) and D2 (~ 1620 cm^{-1}) were systematically fitted, peak D3 (~ 1510 cm^{-1}) was fitted additionally when present. Spectra which could not be fitted with r^2 coef. ≥ 0.995 (PeakFit variance analysis), were rejected. For each sample, temperatures calculated from 10 to 16 spectra (using equations from Beyssac et al. 2002) were averaged to obtain the peak temperature value.

4 New lithological observations

4.1 Série Rousse

4.1.1 Lithological descriptions and successions

4.1.1.1 Series devoid of ophiolitic material Following our observations, the Série Rousse is systematically devoid of ophiolitic material. A metric level of prasinites, intercalated in the calcschists between the SE side of the village of Evolène and the vicinity of the Sasseneire summit, has however been assigned to these series by some authors (Allimann 1987, 1990; Marthaler et al. 2020b) and would represent the only ophiolitic occurrence attributed to these series. According to our interpretation, these ophiolite-bearing calcschists do not belong to the Série Rousse, but to the overlying Série Grise, forming a pinched syncline in this area (Fig. 1b). Indeed, associated to these prasinites, ultrabasic rocks can also be observed locally, and in particular, a lens of several meters long of talcschists described by Gerlach (1861), Pfeifer et al. (2011), Marthaler et al. (2020b). Serpentinite lenses of a few cm are associated to the talcschists at point [2′605′040/1′106′260]. Additionally, the calcschists hosting these ophiolitic intercalations are significantly richer in phyllosilicates than those of the surrounding Série Rousse. Our RSCM data (cf. chap. 6) point to the presence of a tectonic contact located between these calcschists and the adjacent Série Rousse.

4.1.1.2 Thickness of the series The Série Rousse shows large variations in thickness. It reaches several hundred meters in several sectors of the study area (e.g. in the Dix valley), but can be reduced locally to a few tens of meters, as in the thin band bordering the frontal folds of the Mont Fort nappe, east of the village of Evolène (Fig. 1b). These important thickness reductions can be partly of tectonic origin (strongly stretched fold limbs), but can locally also have a stratigraphic origin (cf. chap. 7.1.2).

4.1.1.3 Quartz-phyllitic calcitic marbles and calcschists At the base of the Série Rousse, the lithologies are frequently massive and contain less micas over the first few meters, or sometimes several tens of meters. They generally consist of calcitic, quartzitic and phyllitic marbles. Detrital quartz, which can be very abundant, is either disseminated in the calcitic matrix, or occurs as size-sorted rounded grains of a few tens of hundreds μm size; it is sometimes accompanied by dolomitic grains of arenitic size (Fig. 4d). These basal lithologies are locally conglomeratic (cf. chap. 5.1.2). The clasts are mostly made of dolomites and limestones (Fig. 4c), sometimes of quartzite or gneiss; their size is millimetric to centimetric, sometimes metric.

The micaceous component increases upwards in the series, which is dominated by calcschists in its upper part. Calcite remains however more abundant in the calcschists of the Série Rousse than in those of the overlying ophiolite-bearing Série Grise.

4.1.1.4 Dark calcschists and marbles, black schists Dark layers are interbedded at the base of the Série Rousse in several localities of the study area. They are formed of dark, micaceous and graphitic calcschists, which alternate with dark calcitic marbles and local breccias (Fig. 4d). Such layers form the base of the Série Rousse, for example, in the area of Mauvoisin in the Bagnes valley [2′592′810/1′094′670; 2′593′490/1′093′710]; and of the Pic d'Artsinol [2′598′660/1′108′430; 2′599′150/1′108′360], St-Christophe [2′605′700/1′105′190], La Tour [2′605′440/1′104′770] and La Vieille [2′602′680/1′105′660; 2′602′800/1′105′530] in the Hérens valley. In the last locality, dark calcschists, about 20 m thick, are overlain by black siliceous and non-carbonaceous schists (Fig. 4f; Marthaler et al. 2020b). These authors note the analogy between these siliceous schists and those of the Joux Verte Fm. from the Breccia nappe in the Chablais Prealps (Dall'Agnolo 1997, 2000), dated by planktic foraminifera from the "mid"-Cretaceous (late Barremian - middle Turonian). The Joux Verte Fm. shows different levels of dark pelites, correlated at the scale of the Breccia basin and corresponding, according to Dall'Agnolo (1997, 2000), to "mid"-Cretaceous global anoxic events (e.g. Jenkyns 1980; Erbacher and Thurow 1997). The dark basal levels of the Série Rousse also show microscopic facies analogies with those of the Joux Verte Fm. In particular, dark mottled micrites contain rhombohedral automorph silicates of a few hundred μm size (Fig. 4f; Raman spectra indicate feldspar), strongly reminiscent of silicified dolomite rhombohedra described by Dall'Agnolo (1997, p. 177) in similar dark micrites containing radiolarians and echinoderm remains. The dark micrites of the base of the Série Rousse also contain locally abundant circular siliceous elements of homogeneous ca. 100 μm size that may correspond to radiolarians and possible echinoderm remains (Fig. 5d, f, g; cf. next paragraph).

(See figure on next page.)

Fig. 5 Potential microfauna observed in Série Rousse samples. CL: cathodoluminescence; PPL: plane-polarized light. **a** Thin section from a conglomerate of the very base of the Série Rousse; Pic d'Artsinol [2′599′170/1′108′585]; sampled a few meters from Fig. 8a. The thickness of the conglomeratic level does not exceed 2 m; the mm- to cm-sized clasts are mainly made of dolomites and limestones; a gradual transition is observed to the overlying typical calcschists of the Série Rousse. In comparison with the intense strain generally observed in other samples of the Série Rousse, strain is locally exceptionally low, which allows the preservation of some microfauna that is generally entirely destructed elsewhere. Rounded borders of the clasts could suggest an incomplete diagenesis of the clasts, before their reworking into the conglomerate. **b** Holothuroidea fragments from the matrix of the conglomerate in the same thin-section. **c** Holothuroidea fragment from arenitic calcschist of the Série Rousse, sampled few meters above. **d** Probable reworked echinoderm remains; shapes of the dark rims (CL) suggest stereomes of crinoid ossicles. **e** Probable planktic foraminifera observed as intraclast in a rounded, dark micritic limestone pebble. The form may correspond to *Globotruncana neotricarinata*, Petrizzo, Falzoni and Premoli Silva (2011) indicating an age range from Campanian to earliest Maastrichtian for the rounded clast. In order to preserve the observed form, the polishing protocol was not fully completed on this thin section. **f, g** Potential radiolarian from a dark micritic limestone clast from the base of the Série Rousse; fuzzy borders of the forms could indicate a partial infill of the sediment inside the pores of radiolarian tests; Evolène [2′606′105/1′109′340]

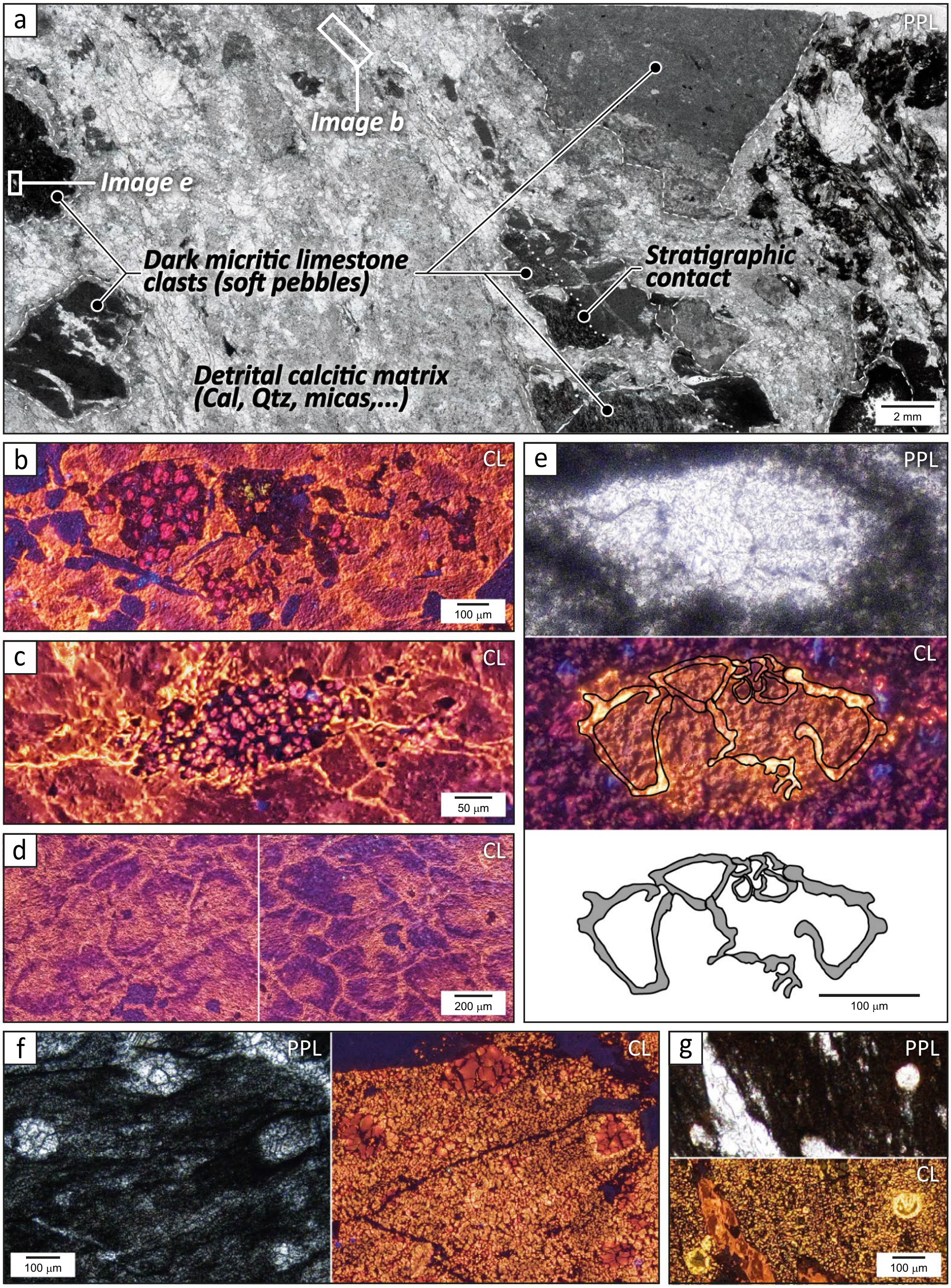

Fig. 5 (See legend on previous page.)

4.1.2 Microfauna description

Thin sections of about forty samples of the Série Rousse were examined under the microscope for the detection of microfossil relics. The study under transmitted light (TL) having proven unsuccessful, it was completed by a cathodoluminescence (CL) examination. It allowed the detection of higher Mn^{2+} trace element concentrations in microfossil relics than in the surrounding sediment, despite the high degree of recrystallization. This method allowed the identification of different biogenic features within a few samples, that were particularly spared from the intense regional deformation.

4.1.2.1 Samples from the base of the Série Rousse north of the Pic d'Artsinol Some samples collected at the base of the Série Rousse, close to the summit of the Rionde de Vendes [2′599′170/1′108′585], show little deformation, and hence, relatively well-preserved sedimentary features (Fig. 5a). The very competent lithologies of these levels and of the underlying polygenic breccias of the Evolène Series, have probably contributed to this unusual preservation. These samples consist of phyllitic and quartzitic calcitic marbles, containing mm- to cm-sized clasts of dolomite, quartz, pelagic limestone and quartzschist. Different biogenic features are observed in the thin section of Fig. 5a.

The matrix contains some rare dark (TL and CL) round elements of ± 200 µm size, showing regular round openings filled with carbonate of dull orange CL-emission. We interpret these features as originally pyritized and now oxidized holothurian skeletal elements (Fig. 5b; a similar form was found in the sample of Fig. 5c, few meters above). In the matrix of the first sample, some dolomitic laminae most probably represent reworked echinoderm remains (Fig. 5d). Particular shapes of the dark rims (CL) actually suggest stereomes of crinoid ossicles. As both crinoids and holothurians have existed throughout the Mesozoic from shallow shelf to deeper marine environments, they are not age diagnostic, but are, nevertheless, indicative of a higher nutrient environment in their source area, perhaps on an outer slope. Pyrite is preserved in some thin sections and the pyritization of echinoderm remains is common in nutrient-rich paleoenvironments.

Some mm- to cm-sized disrupted clasts of pelagic limestone show preserved lamination and organic matter. These clasts show two distinct lithologies in original sedimentary contact, which can be followed across adjacent fragments (Fig. 5a): a lighter grey micrite; and a dark grey, mottled micrite rich in carbonaceous material (confirmed by Raman). The mottles are in fact flattened flakes that could represent original faecal pellets. The borders of the pelagic limestone clasts are fuzzy, suggesting penecontemporaneous reworking into a pebbly sandstone. In CL, the two pelagic lithologies show uniform mauve colors with some blue specks (disseminated biogenic quartz?) and rare bright yellow-orange lens-shaped structures that could represent fossil remains. The mauve color of the pelagic matrix (e.g. Fig. 5e) indicates a mixture of the intrinsic blue (± 410 nm) calcite CL, with very low (< 1 ppm) Mn^{2+} orange (600 nm) activation, while the possible fossil remains contain > 10 ppm of Mn^{2+}. The orange colored intraclast of Fig. 5e shows bright yellow outlines (CL) that strongly suggest a double-keeled planktic foraminifer.

This form suggests a low trochospiral test with a convex spiral side and two equidistant keels, parallel to the coiling axis and separated by a narrow band. Chambers of the last whorl are inflated and trapezoidal on the umbilical side, with an apparent third keel. Such a description would correspond to *Globotruncana neotricarinata* Petrizzo, Falzoni and Premoli Silva (2011). This species has, according to Petrizzo et al. (2011), a diachronous first appearance ranging from the late Santonian (Exmouth Plateau, NE Australia) to the base of the Campanian (Bottacione, Umbria, Italia). It disappears within the *Gansserina ganseri* Zone, which reaches the earliest Maastrichtian. Hence, a Campanian to earliest Maastrichtian age range for the pelagic limestone clasts can be inferred. This age is thus slightly younger than the one deduced from the foraminifera described in the Série Rousse so far (cf. chap. 2.3.3). Unfortunately, this finding cannot be confirmed for now with more material. A Campanian maximum age of the Série Rousse must remain a working hypothesis.

4.1.2.2 Sample from a micritic limestone clast from the Série Rousse NE of Evolène A sample from a meter-sized clast of micritic limestone, included at the very base of the Série Rousse, SW of the Sasseneire in the Hérens valley [2′606′105/1′109′340], shows in thin section numerous circular features, white in TL, of a homogeneous size of about 100 µm (Fig. 5f, g). Their color contrasts strongly with the very dark color of the rock (micritic limestone transformed into calcitic marble). The observation of these features in CL allows to highlight chemical variations between their internal part (appearing orange red; Fig. 5f CL), their border (appearing bright yellow; Fig. 5f, g) and the surrounding sediment. Their shape, size, distribution in the sediment and the aspect of their borders (appearing fuzzy in TL and discontinuous in CL; Fig. 5f, g), suggest that these forms correspond to radiolarians. These border aspects could reflect their porous nature and the partial filling of these pores by the surrounding sediment.

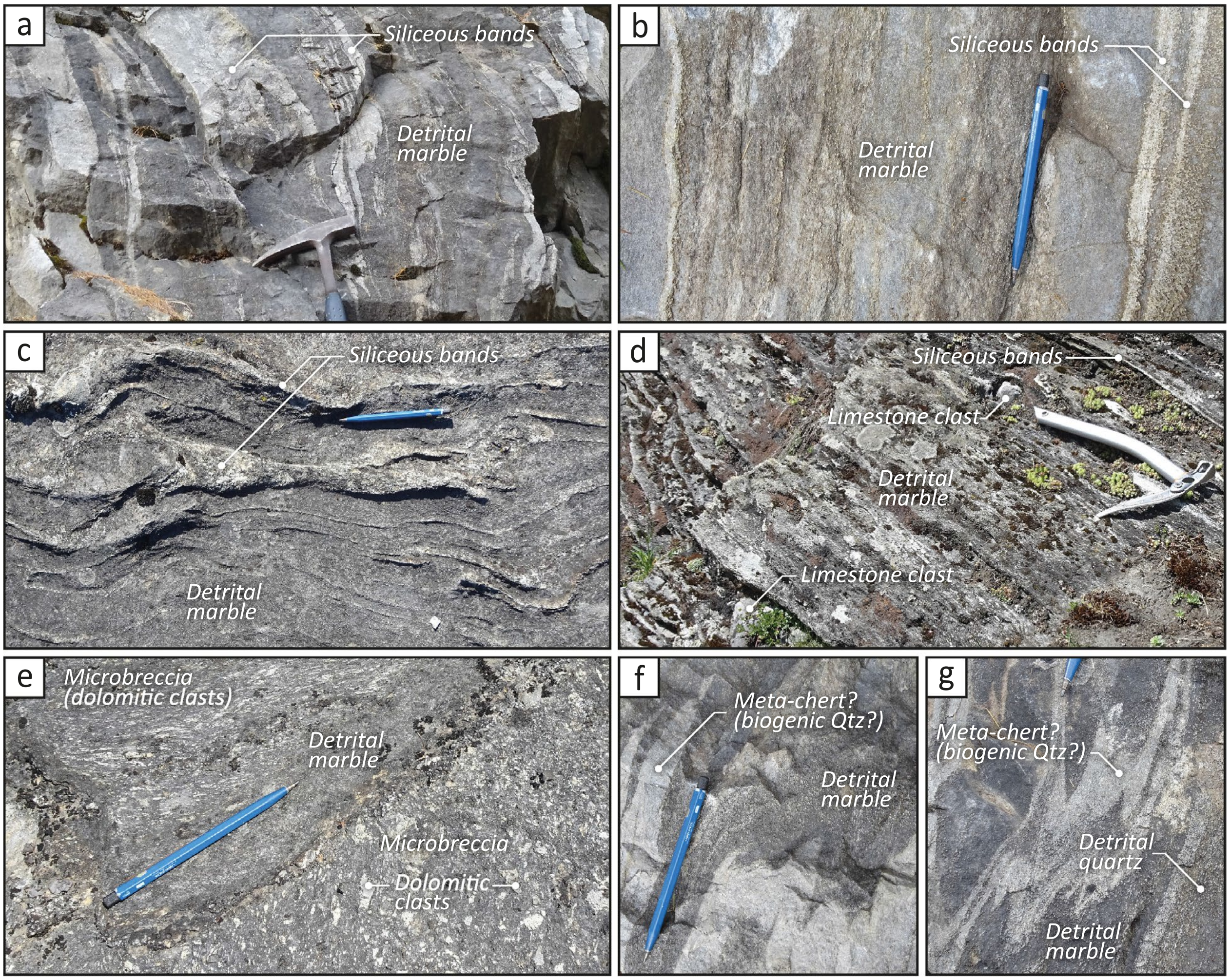

Fig. 6 Characteristic facies of the Mauvoisin marbles. **a, b** Slightly detrital calcitic marble with siliceous mm-cm thick bands; Mauvoisin [2′592′650/1′094′510]. **c** Similar lithology at La Tour [2′605′310/1′104′860], Hérens valley. **d** Detrital calcitic marble with mm-cm thick siliceous bands and sparse cm-dm thick limestone clasts (dolomitic clasts appear out of the picture); Giétro [2′593′690/1′092′930], Bagnes valley. **e** Alternating layers of detrital calcitic marble and dolomitic microbreccia; 10 m from Fig. c. **f, g** Details of the outcrops of Figs. a and b. In **g** sharp borders are observed at the contact between the siliceous bands and the surrounding marble, whereas a progressive transition is visible to the more carbonaceous inner parts of these bands. As this characteristic is typical of cherts that are not fully silicified in their inner parts, it supports the biogenic nature of these siliceous bands

4.2 Mauvoisin marbles

Massive, slightly detrital siliceous calcitic marbles (Fig. 6) form the bedrock of the Série Rousse in several sectors of the study area. They are best developed in the area of the Mauvoisin dam, where they reach several hundred meters in thickness (Fig. 7a). On the 1:25’000 geological map (Burri et al. 1998, 1999), they are referred to as “unité de Mauvoisin”, one of the tectonic units defined in the Tsaté nappe by these authors. We propose to use the term *Mauvoisin marbles* to designate this lithostratigraphic formation.

These characteristic siliceous calcitic marbles can be recognized in other zones of the studied area, in particular in the Hérens valley, where they form massive cliffs, well exposed under the villages of La Sage and Villa. In this zone, the best outcrops can be observed south of the hamlet of La Tour, at that of L’Ata Gieute, at Plan Tsardon [2′603′250/1′105′680], at La Vieille [2′602′680/1′105′660] and at La Noûva [2′600′320/1′107′300; 2′600′260/1′107′840].

The characteristic facies of the Mauvoisin marbles is a massive, quartzitic and slightly phyllitic calcitic marble in decimetric to metric beds, showing millimetric to pluricentimetric thick siliceous bands, often standing out in relief on outcrop surfaces (Fig. 6a–c). The mineralogy is composed of calcite, quartz, white mica, albite, chlorite,

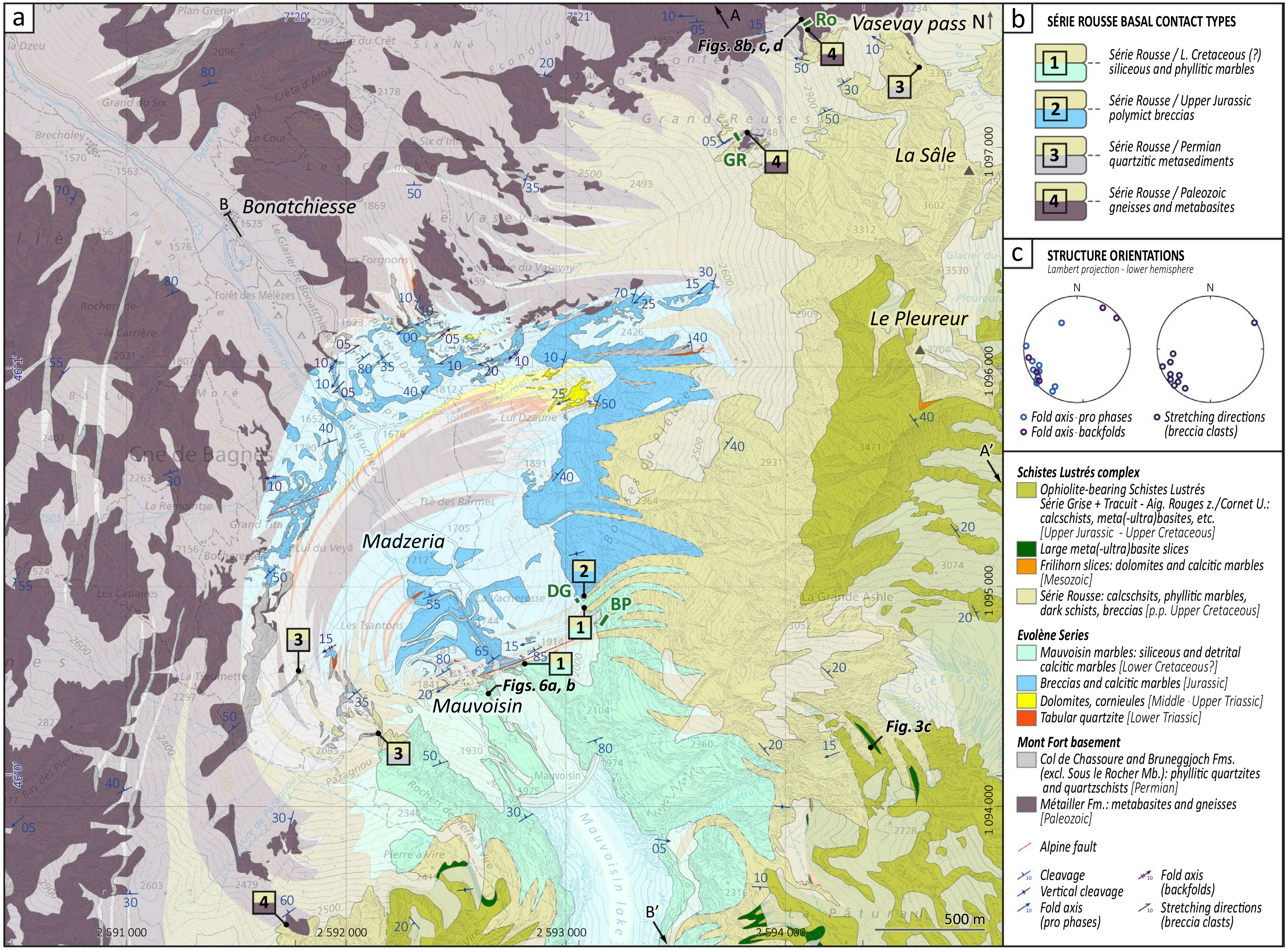

Fig. 7 **a** Detailed geological map of the Mauvoisin area, Bagnes valley; after observations from this study and maps from Baillifard (1998), Burri et al. (1998), Steck et al. (1999) and Dal Piaz et al. (2015). Topographic base ©Swisstopo 2016; contour intervals: 20 m. 1, 2, 3, 4 refer to Fig. b; Locations of the cross-sections of Fig. 11a are indicated by A, A', B, B'; *Fig.x* refer to pictures from other figures; locations of the stratigraphic columns of Fig. 11b are indicated in green. **b** Types of basal contacts of the Série Rousse in the area covered by the map. **c** Fold axis and stretching directions in the area covered by the map

graphite and oxides ± epidote, tourmaline, apatite and titanite; in the siliceous levels, quartz can constitute more than 80% of the rock (Burri et al. 1999). Locally, millimetric to centimetric clasts are present; they are mainly made of dolomites and limestones (Fig. 6d). In places, these clasts can be relatively abundant and a few levels of breccia, generally matrix supported and sometimes slightly graded, are visible (Fig. 6e). The siliceous banded calcitic marbles described above may also evolve into very siliceous and massive calcitic marbles in some areas.

Although these different levels have sometimes been grouped together with the overlying Schistes Lustrés (e.g. Gouffon and Burri 1997; Burri et al. 1998, 1999), or more specifically with the Série Rousse (Allimann 1990; Steck et al. 1999), their massive aspect and their calcite- and quartz-rich composition clearly distinguish them from these units (cf. Sartori and Marthaler 1994).

No fossils have been found in the Mauvoisin marbles. Some authors have proposed an Early Jurassic age for part of these levels (Sartori and Marthaler 1994; Burri et al. 1999; Marthaler et al. 2020b; , by analogy with some facies of the Briançonnais Lower Jurassic. Marthaler et al. (2020b) also note analogies between the siliceous banded calcitic marbles from La Vieille [2′602′680/1′105′660] and lithologies of the Bonave Fm. from the Breccia nappe in the Prealps, which have been dated by *Calpionella* from latest Jurassic/Early Cretaceous (Dall'Agnolo 1997, 2000). Sartori et al. (2006, fig. 18) suggest the same correlation for similar white marbles, overlying the polygenic breccias of the Pic d'Artsinol area.

Our observations throughout the study area confirm the clear analogy between the dominant facies of the Mauvoisin marbles (slightly micaceous siliceous marbles with mm-cm thick siliceous bands) and those described in the Bonave Fm. In particular, the following similarities can be noted. (1) Layers of graded breccias, with clast sizes up to a few cm, occur at various levels of the Bonave Fm. (Dall'Agnolo 1997, 2000), similar to those observed in the Mauvoisin marbles (Fig. 6e). (2) In the Mauvoisin marbles, some siliceous bands show sharp external borders and locally a progressive passage towards a less siliceous internal part (Fig. 6f), arguing for a biogenic origin of silica, diagenetically concentrated in replacement chert bands. They could thus correspond to metamorphic equivalents of the characteristic siliceous levels and cherts of the Bonave Fm. (3) In the upper levels of the Bonave Fm., the cherts and siliceous levels become less abundant and a more diffuse silicification of the limestone is observed, while the detrital component and the frequency of marly interlayers increase (Dall'Agnolo 2000). A similar facies evolution can be observed, e.g. at Mauvoisin along the road between the hotel and the base of the dam. A transition is observed here from facies showing sharply individualized siliceous bands (Fig. 6a, b), to massive, almost non-bedded, very siliceous calcitic marbles [2′592′740/1′094′350], that are surrounded by thin layers of micaceous calcschists.

The marked similarities between the Mauvoisin marbles and the lithologies of the Bonave Fm. thus suggest a Late Jurassic to Early Cretaceous age for the Mauvoisin marbles. They would therefore constitute the youngest levels of the Evolène Series.

5 Description of the contacts

5.1 Basal contact of the Série Rousse

5.1.1 Basal unconformity

In the study area, the Série Rousse systematically overlies the Paleozoic basement of the Mont Fort nappe or its Lower Triassic to Lower Cretaceous autochthonous cover (the Evolène Series; cf. Pantet et al. 2020). In the region of Evolène, of the Sasseneire and of Moiry (Fig. 1b), the Série Rousse envelops the frontal folds of the Evolène Series and forms to the east highly stretched isoclinal folds, which can be followed up to the Turtmann and Matter valleys (Sartori 1987, 1990; Marthaler et al. 2008a).

The map in Fig. 1b shows that the Série Rousse lies either on the Evolène Series, or alternately directly on the Paleozoic basement of the Mont Fort nappe. This second case is observed in several sectors of the normal limb of this nappe, e.g. in the Col du Vasevay and La Sâle area in the Bagnes valley (Fig. 7; Gerlach 1871), in the Lac des Dix area, and in part of its reverse limb (between Evolène and the Montset). Our detailed mapping shows that the Série Rousse actually overlies different levels of the Mont Fort basement and of the Evolène Series (Fig. 7); levels whose ages probably range from Ordovician (Gauthiez et al. 2011) to Early Cretaceous (cf. chap. 4.2). The basal contact of the Série Rousse over the Mont Fort nappe is therefore characterized by a major unconformity.

5.1.2 Deformation along the contact: localized shearing due to rheological contrasts and locally unsheared contact

A strong rheological contrast often characterizes the contact between the Série Rousse and the underlying levels of the Mont Fort basement and Evolène Series. Indeed, lithologies constituting the Mont Fort nappe are mostly rheologically strong (e.g. gneisses and metabasites of the Paleozoic basement; breccias, dolomites and quartzites of the Evolène Series), whereas most of the lithologies of the Série Rousse are rich in phyllosilicates and are rheologically weak. These contrasting competences frequently lead to a local shearing of the contact.

However, along the sections of the contact where the base of the Série Rousse is itself composed of rheologically strong lithologies (quartzitic marbles, conglomerates), no hint of particular shearing can be detected at the contact (cf. Fig. 8a, e, f).

These observations indicate that the basal contact of the Série Rousse over the Mont Fort nappe does not correspond to a major tectonic contact.

5.1.3 Basal conglomerates

A conglomeratic level is locally observed at the base of the Série Rousse. Its thickness can reach a few meters, e.g. west of the Vasevay pass in the Bagnes valley (Figs. 7, 8b), where it was already mentioned by Hagen (1951). Most often its thickness is limited to a few tens of centimeters, or a few centimeters only (Fig. 8e, f). Although these conglomerates can be observed in many localities in the study area (Fig. 8i), they are most often absent.

The matrix of these conglomerates is of the same composition as the overlying calcschists of the Série Rousse. A gradual transition can be observed between the conglomerates and the calcschists, by progressive increase of the proportion of matrix. These conglomerates are generally polymict. The clasts mostly consist of dolomites, limestones and pure or phyllitic quartzites, sometimes of prasinites/ovardites. Locally, clasts made of breccias (dolomitic clasts and calcitic matrix) can also be observed (Fig. 8d). The presence of these breccia clasts and the abundance of phyllosilicates and detrital quartz in the matrix distinguish these conglomerates from the polymict breccias of the Evolène Series of presumed Late Jurassic age (cf. Pantet et al. 2020), even if these two formations are sometimes directly in contact (e.g. Fig. 8a). The discovery of a form probably corresponding to a *Globotruncana* sp. in a clast of this basal conglomerate of the Série Rousse (cf. chap. 4.1.2), as well as the various presumed relics of *Rotalipora* sp. and bicarinate planktic foraminifera observed in the matrix of other levels of the Série Rousse (cf. chap. 2.3.3), would indicate a Late Cretaceous age for these conglomerates.

In different zones of the study area, a correlation can be established between the nature of the clasts of the basal conglomerate of the Série Rousse and the underlying rocks of the Mont Fort nappe. For example, west of the Vasevay pass (Fig. 7), the Série Rousse is in contact with Paleozoic metabasites of the Mont Fort basement (Métailler Fm.) and its basal conglomerate contains here numerous clasts of identical lithology (Fig. 8b, c). Such a relationship can also be observed near the Col des Roux, where the base of the Série Rousse is locally formed by a conglomerate rich in decimetric clasts of pure quartzites, identical to the Tabular Quartzites of the Evolène Series, underneath the contact (Fig. 8e). On the other hand, no clast observed in this conglomerate consists of a rock that does not form the Evolène Series or the basement of the Mont Fort nappe (such as e.g. granites or serpentinites). On the contrary, the clasts made of breccias (calcitic matrix, dolomitic clasts), observed in this conglomerate at some localities (e.g. Fig. 8d), are particularly typical of the Evolène Series. These observations thus argue for a deposition of the Série Rousse in the immediate vicinity of the rocks constituting the present-day Mont Fort nappe.

On some outcrops preserved from a too strong deformation, it is possible to note the rounded shape of some clasts of the conglomerate (e.g. Fig. 8f), which is indicative of rolling of the clasts (mechanical abrasion) and argues for a formation of the conglomerate in a context of stratigraphic onlap on a relief.

These different observations thus clearly indicate the stratigraphic nature of the basal contact of the Série Rousse over the Mont Fort nappe.

5.1.4 Basal hardground

Strongly oxidized crusts of a few mm thickness are locally observed at the basal contact of the Série Rousse (Fig. 8f, g), on top of Jurassic breccias of the Evolène Series, or of

(See figure on next page.)

Fig. 8 Conglomerates and hardground from the basal contact of the Série Rousse. **a** Contact between a polymict conglomerate forming the base of the Série Rousse (russet phyllitic and quartzitic calcitic matrix) and a polymict (Upper Jurassic?) breccia from the Evolène Series. The conglomeratic base of the Série Rousse is only of a few meters thick. A gradual transition is observed with the overlying calcschists of the same series. Rionde de Vendes [2′599′180/1′108′600], Dix valley. **b** Overturned contact between the Mont Fort Paleozoic basement (Métailler Fm.) and a polymict conglomerate forming the base of the Série Rousse and gradually passing to the typical calcschists of these series (base of the outcrop); Col du Vasevay [2′594′090/1′097′560], Bagnes valley. **c** Close-up view on locally abundant green clasts of the basal conglomerate; their lithology is identical to that of the overlying Paleozoic metabasites of the Métailler Fm. **d** Close-up view on clasts of the same conglomerate made of dolomites, limestones and breccias (dolomitic clasts, calcitic matrix). **e** Basal conglomerate of the Série Rousse showing dm-sized clasts made of the same lithology than the adjacent Tabular Quartzites of the Evolène Series; Col des Roux [2′595′580/1′102′090], Dix valley. **f** Oxidized crust (hardground) marking the base of the Série Rousse over a light grey (Upper Jurassic?) calcitic marble of the Evolène Series; the dolomitic clast visible at the very base of the Série Rousse shows a rounded shape indicative of the locally low strain and the absence of particular shearing along the contact (the clast is truncated orthogonally to its elongation), as well as the rolling of the clast; Pic d'Artsinol area [2′599′250/1′107′940]. **g** Basal hardground of the Série Rousse; same location. **h** Oxidized clasts (reworked hardground) observed in the Série Rousse basal conglomerate; Pic d'Artsinol area [2′600′115/1′105′950]; [2′600′210/1′105′840]; [2′600′100/1′105′965]. **i** Occurrences of the basal conglomerate and basal hardground of the Série Rousse (map from Fig. 1b)

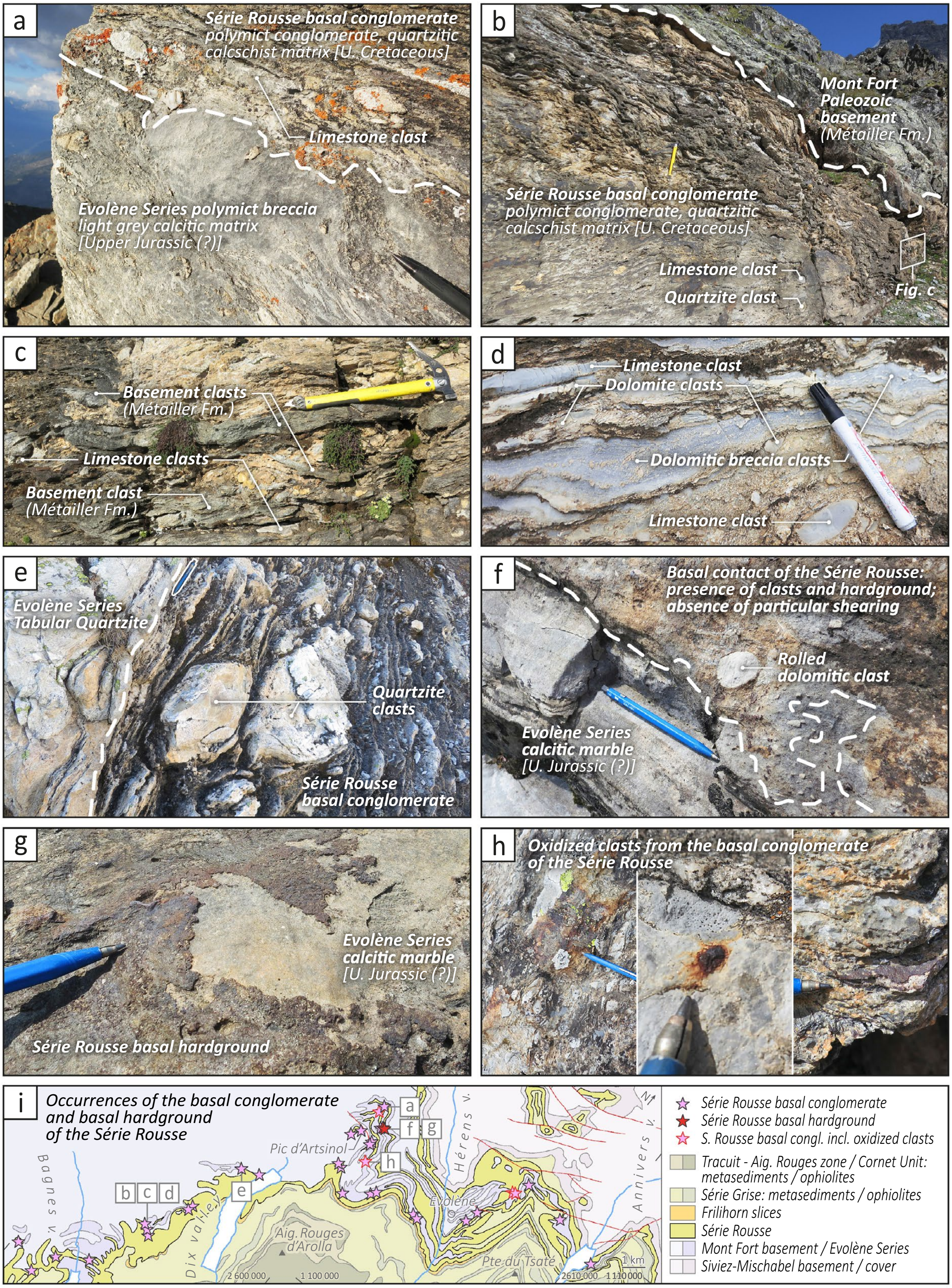

Fig. 8 (See legend on previous page.)

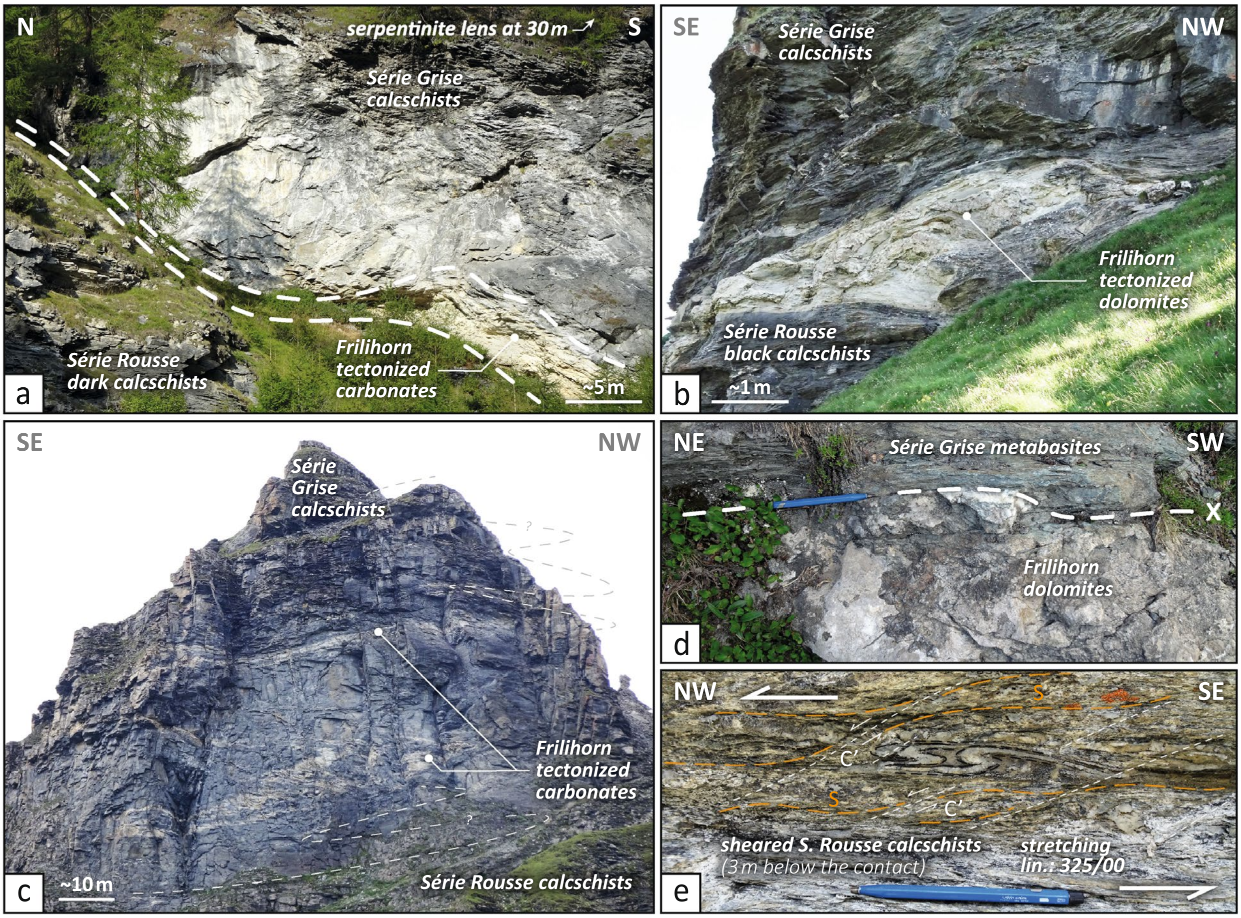

Fig. 9 Upper contact of the Série Rousse with the ophiolite-bearing Série Grise and the Frilihorn slices. **a** Tectonized Frilihorn carbonates (partly dolomitic) marking the contact between the Série Rousse and the Série Grise; La Sage [2′606′330/1′105′640], Hérens valley. **b** Frilihorn dolomitic boudins along the same contact; Plan Tsardon [2′603′400/1′105′470], Hérens valley. **c** Thin Frilihorn tectonized and folded bands (polyphase folding of a single band); Meina pass area [2′599′360/1′104′680], Hérens valley. **d** Sharp contact between Frilihorn dolomites and Série Grise metabasites; the Série Rousse is outcropping a few meters below; Palantse de la Cretta west face [2′600′990/1′104′380], Hérens valley. **e** Strongly sheared Série Rousse calcschists, 3 m below its upper contact with the Série Grise; the outcrop is parallel to the marked stretching lineation; asymmetric folds and C′ structures indicate a top to the NW shear-sense; S: schistosity; C′: extensional shear bands; Mel de la Niva [2′601′850/1′105′750], Hérens valley

calcitic marbles that would constitute their distal equivalents. Locally, these crusts mostly cover the basal surface of the Série Rousse. We interpret them as corresponding to a hardground. Strongly oxidized mm- to dm-sized clasts are locally observed in the basal conglomerate of the Série Rousse and would correspond to a reworking of such crusts (Fig. 8h). The presence of this hardground suggests a significant stratigraphic gap and confirms the stratigraphic nature of the basal contact of the Série Rousse.

5.2 Upper contact of the Série Rousse with ophiolite-bearing Schistes Lustrés and Frilihorn slices

Thin discontinuous tectonized slices of the Frilihorn Series (Triassic-Jurassic/Cretaceous; cf. chap. 2.3.2) frequently mark the contact between the Série Rousse and the overlying ophiolite-bearing Série Grise (Fig. 9a–c). They rarely exceed a few meters in thickness, but can be present along the contact for several kilometers. Such slices are also observed in the same tectonic position, south of the study area, in the Ollomont valley (P. Manzotti and M. Ballèvre, oral communication) and in the Rhèmes valley (Adatte et al. 1992). Where the Frilihorn slices are absent or hidden by recent deposits, the contact between the Série Rousse and the Série Grise may be difficult to identify. The presence in the calcschists of ophiolitic lenses, of ophiolite-derived detrital material, or locally of fuchsite, sometimes allows the identification of the Série Grise, but the contact is often difficult to follow due to the presence of numerous isoclinal folds (Fig. 9c).

Table 1 RSCM temperatures data

Series	Sample nb	Thin section nb	Coordinates (MN95)		Calculated temperatures (Beyssac et al. 2002)					
			X	Y	Measur. nb.[1]	Min. T [°C][1]	Max. T [°C][1]	STD (σ)[1]	Conf. Int.[1,2]	Mean T [°C][1]
Hérens valley										
SR	AP16035	S6-5	2′599′230	1′105′410	13	388	445	19	11	416
SR	AP16036	S5-14	2′599′230	1′105′410	16	365	448	27	14	408
SR	AP16055	S6-18	2′599′170	1′108′585	12	381	501	32	20	460
SR	AP17007	S6-1	2′599′786	1′106′673	10	381	457	22	15	423
SR	AP17017	S5-17	2′605′156	1′106′891	15	400	435	12	7	420
SR	AP17040	S5-8	2′605′156	1′106′888	15	389	467	21	12	427
SR	AP17C4	S6-10	2′605′303	1′107′142	12	396	486	24	15	423
SR	AP1907	S7-6	2′603′082	1′105′740	13	411	473	21	13	439
SR	AP2091	S9-3	2′602′061	1′108′060	13	380	458	18	11	414
SR	AP2032	S9-5	2′605′443	1′104′767	11	431	513	23	16	467
SG	AP17009	S5-15	2′605′004	1′106′290	16	397	458	18	10	436
SG	AP17036	S5-9	2′605′228	1′106′869	13	412	507	29	17	466
SG	AP19001	S7-1	2′605′385	1′103′175	15	388	507	32	18	435
SG	AP19003	S7-5	2′604′862	1′104′049	15	424	495	23	13	446
SG	AP1910	S7-3	2′602′498	1′105′612	13	417	465	15	9	442
SG	AP1912	S8-14	2′603′410	1′105′465	14	416	511	26	15	450
SG	AP2080	S9-2	2′604′400	1′103′220	12	391	451	17	11	411
TAR/C	AP2083	S9-1	2′604′255	1′100′215	11	326	373	13	9	354
Bagnes valley										
SR	AP1925	S7-2	2′594′349	1′094′318	12	437	537	33	21	483
SR	AP1926	S9-6	2′594′217	1′094′242	11	436	541	31	21	459
ES	AP15014	S1-17	2′591′951	1′095′923	14	418	549	31	18	484
ES	AP2007	S8-7	2′592′654	1′094′496	13	433	541	34	20	480

See Additional file 1 for detailed measurements and calculations data. SR: Série Rousse; SG: Série Grise; TAR/C: Tracuit - Aig. Rouges zone / Cornet Unit; ES: Evolène Series

[1] Retained measurements (spectra that could be fitted with $r^2 \geq 0.995$)

[2] Confidence interval (Student Law): $1 - \alpha = 95\%$

Deformation is generally extremely strong in the vicinity of the contact. It is demonstrated in particular by the intense stretching and boudinage observable in the Frilihorn slices (e.g. Fig. 9a, b). North of the Dent Blanche klippe, these slices are systematically affected by an intense shearing and are locally reduced to only a few dm-thick tectonized and highly fractured carbonates (e.g. Fig. 9c, d). An intense shearing is also observable within the calcschists directly surrounding the contact (e.g. Fig. 9e).

The contact is also characterized by the local abundance of quartz veins, that are more than 50 cm thick in several localities (e.g. [2′599′320/1′104′600], [2′601′700/1′105′640], [2′602′800/1′105′510]) and reach a thickness exceeding 1 m at point [2′601′010/1′104′460], SW of the Palantse de la Cretta in the Hérens valley.

Our observations thus confirm the tectonic nature of the upper contact of the Série Rousse with the ophiolite-bearing Schistes Lustrés, as postulated by all previous authors.

The question of the importance of this tectonic contact, in particular whether it corresponds to a major tectonic contact marking a nappe boundary, or even a tectonic domain boundary (Upper/Middle Penninic Domains), as proposed, for example, by Escher (1988); or whether it is a contact of lesser importance, internal to the Tsaté nappe as proposed, for example, by Sartori and Marthaler (1994), will be discussed in chapter 7.3.

6 Raman graphite thermometry

RSCM analyses conducted by Negro et al. (2013), Angiboust et al. (2014), Decrausaz et al. (2021) and Manzotti et al. (2021) reveal significant variations in RSCM temperatures (cf. Beyssac et al. 2002) within the Schistes Lustrés of the Combin zone (Fig. 10c). In order to better characterize the variability of RSCM temperatures between the different units and series of this Schistes Lustrés complex (cf. chap. 2.2), and in particular between

(See figure on next page.)

Fig. 10 Geothermometry by Raman spectroscopy of carbonaceous material (RSCM) in the Schistes Lustrés and adjacent lithologies across Hérens valley and surrounding areas of SW Switzerland and NW Aosta valley (IT). **a** RSCM temperatures [°C] across Hérens valley: data from this study (circles) compared with available data from the literature (squares and triangles); background map from Fig. 1b. **b** RSCM temperatures [°C] across Hérens valley plotted on a geological cross-section constructed through the area (modified after Escher 1988; Escher et al. 1988, 1993, 1994); location indicated in Fig. a. **c** RSCM temperatures [°C] at regional scale: literature data (squares, pentagons and triangles) and data from this study (circles); background map from Fig. 1b (SE zone modified after Steck et al. 1999, 2015; Dal Piaz et al. 2015). **d** RSCM temperatures [°C] from Figs. a-b (Hérens valley) plotted against the distance of the outcrops to the contact between the Série Rousse (SR) and the Série Grise (SG); distances are calculated orthogonally to the mean local orientations of the structures (cf. Additional file 3); °T error bars: 1σ; Dist. error bars: 75%

the Série Rousse and the Série Grise, additional samples were analyzed during this study (Table 1). Sampling was concentrated on a limited area (Hérens valley sector; Fig. 10a) in order to avoid possible biases related to regional variations in the intensity of metamorphism. In addition, four samples were collected in the Mauvoisin area (Bagnes valley), in order to compare our results with previous studies and better characterize the regional variability of the RSCM temperatures within the different studied units (Fig. 10c). Two samples (AP2007 and AP2080) were intentionally collected in close proximity to samples from previous studies (CO0712 from Negro et al. 2013 and #62 from Angiboust et al. 2014, for AP2007; CO092 from Negro et al. 2013 for AP2080). The comparison between the RSCM temperature obtained for these samples show that RSCM temperature values are comparable between our study and these previous studies (values overlap within a 2σ error range for both locations).

Examination of the entire set of RSCM temperatures then available for the samples located in the Série Rousse and the Série Grise shows that no significant difference in temperature exists between these two series. Indeed, in the Hérens valley, these temperatures range from 408 ± 27 °C to 467 ± 23 °C for the Série Rousse (mean val. = 430 ± 20 °C; n = 10) and from 411 ± 17 °C to 466 ± 29 °C for the Série Grise (mean val. = 441 ± 16 °C; n = 8); in the Bagnes valley, between 457 ± 14 °C and 494 ± 7 °C for the Série Rousse (mean val. = 477 ± 15 °C; n = 7) and between 461 ± 4 °C and 487 ± 23 °C for the Série Grise (mean val. = 475 ± 9 °C; n = 8); the few values available in the Anniviers valley (incl. the Moiry valley) range between 441 ± 12 °C and 451 ± 5 °C for the Série Rousse (mean val. = 447 ± 5 °C; n = 3) and between 437 ± 14 °C and 458 ± 16 °C for the Série Grise (mean val. = 446 ± 10 °C; n = 5); see Additional file 2 for details.

These data show, however, a significant variation in RSCM temperatures between the different sectors of the study area. The amplitude of this variation is equivalent for the Série Rousse and the Série Grise. This regional variation of the peak temperatures can be explained by differences in tectonic positions (Fig. 14a, b). Indeed, the most external sectors, characterized by a shallower burial depth, such as those of the Hérens and Anniviers valleys, show lower temperatures than the more internal ones, such as the Bagnes valley, which are characterized by higher burial depths. The dense data set obtained for the Hérens valley (Additional file 3) allows to quantify the distribution and variability of the RSCM temperatures through the whole Schistes Lustrés complex in this sector (Fig. 10a, b).

The samples providing the highest RSCM temperatures are those from the immediate vicinity of the contact between the Série Rousse and the Série Grise. The maximum RSCM temperatures are identical for both series (467 ± 23 °C for the Série Rousse and 466 ± 29 °C for the Série Grise) and are obtained from the samples located closest to this contact (< 10 m). Figure 10d displays the distribution of RSCM temperatures as a function of their distance from the contact between the Série Rousse and the Série Grise. An increase in temperatures centered on this contact can be clearly evidenced.

The relative influence of factors that control the processes of crystallization and recrystallization of organic matter during metamorphism and rock deformation is still not fully established and quantified (e.g. Nakamura et al. 2017; Beyssac et al. 2019). Nevertheless, the following causes can be suspected to be responsible for the particular distribution of RSCM temperature evidenced through the contact between the Série Rousse and the Série Grise. (1) A local temperature increase along an Alpine thrust. (2) Recrystallization of the organic material facilitated by fluid flow in the contact zone; and/or (3) by more intense deformation in the contact zone. These different hypotheses are not mutually exclusive and are all compatible with a contact of tectonic nature, as suggested by previous studies (cf. chap. 2.2) and the observations of the previous chapter (5.2).

Regarding the first hypothesis, a temperature increase associated to faulting, and shearing along ductile shear zones, has been documented in numerous natural examples, at various scales and magnitudes of temperature variations (e.g. Nicolas et al. 1977; Scholz 1980; England and Molnar 1993; Leloup and Kienast 1993; Nabelek

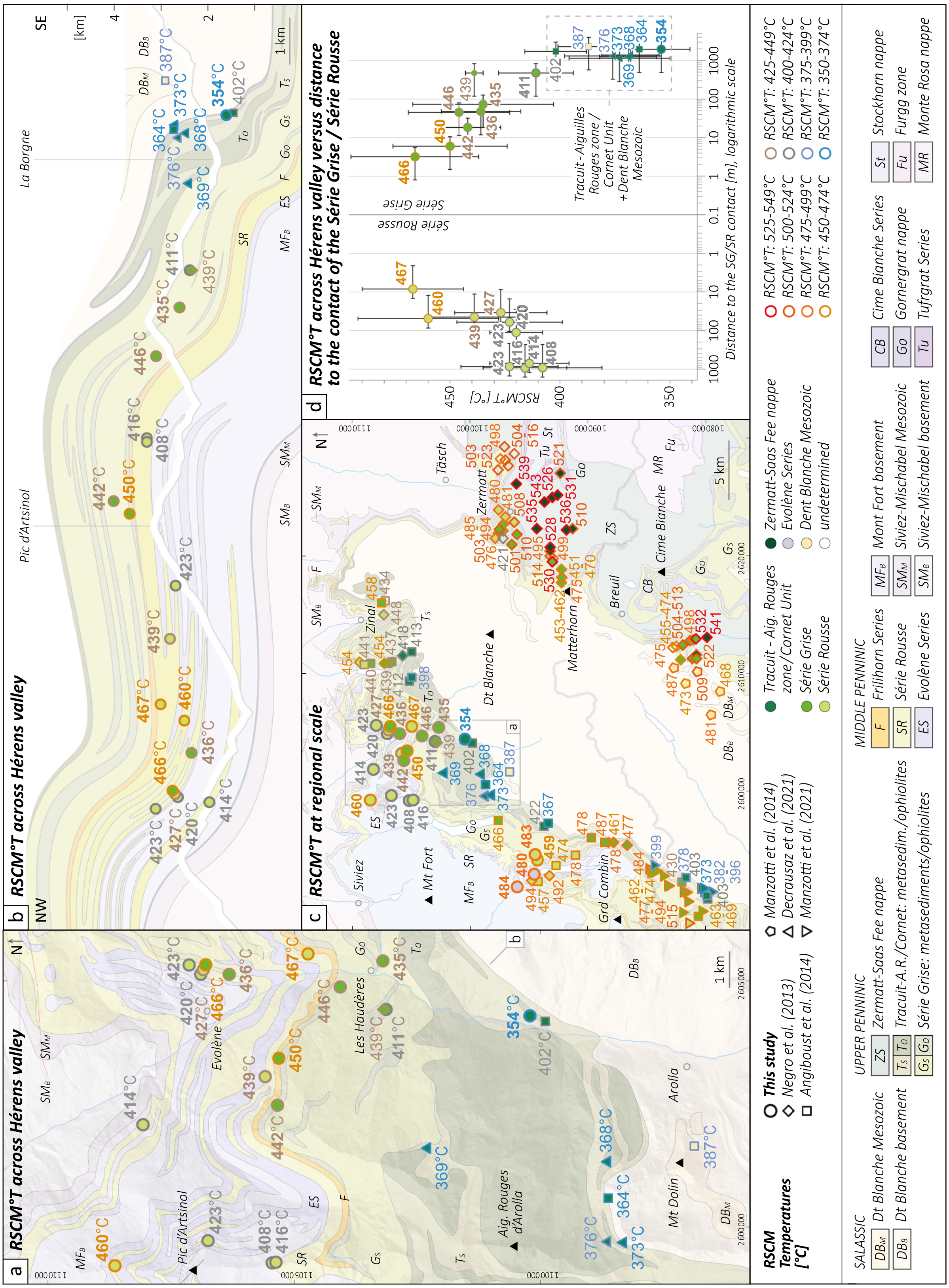

Fig. 10 (See legend on previous page.)

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Fig. 11 **a** Geological cross-sections through the Mauvoisin area, Bagnes valley; modified after Argand (1911), Witzig (1948), Hagen (1951), Gouffon and Burri (1997), Burri et al. (1999); locations on Fig. 7a; A [2′593′530/1′097 ′900]; A′ [2′596′320/1′093′260]; B [2′591′460/1′096′700]; B′ [2′594′410/1′091′790]; locations of the stratigraphic columns of Fig. b are indicated in green. **b** Characteristic lithostratigraphic successions through the base of the Série Rousse across the study area; scales differ between the stratigraphic columns (grey strokes represent ca. 20 m); triangles indicate breccia levels; circles, conglomerates; black points, detrital quartz; black dashes, dark calcschists; black lines, black schists. Stratigraphic columns acronyms and coordinates: PV [2′594′390/1′097′950]—[2′594′400/1′097′970], tectonically overturned; Sa [2′594′555/1′097′430]—[2′594′580/1′097′430]; Ro [2′594′110/1′097′570]—[2′594′090/1′097′560], tectonically overturned, pictures Fig. 8b-d; GR [2′593′780/1′097′055]—[2′593′780/1′097′045], tectonically overturned; DG [2′593′050/1′094′945]—[2′593′065/1′094′930], tectonically overturned; BP [2′593′130/1′094′830]—[2′593′160/1′094′860]; EG [2′593′710/1′092′930]—[2′593′615/1′092′930], tectonically overturned, Fig. 6d from the lower part of the profile. **c** Proposed pre-orogenic restoration (Late Cretaceous) of the cross-section of a; approximate pre-orogenic locations of the lithostratigraphic successions of Fig. b are indicated in green

et al. 2001; Stipp et al. 2002; Petroccia et al. 2022). The mechanism of shear heating (or strain heating) and their resulting thermal anomalies, associated both with brittle and ductile deformation, have been extensively studied through thermomechanical modeling (e.g. Molnar and England 1990; Leloup et al. 1999; Nabelek et al. 2001; Burg and Gerya 2005; Duprat-Oualid et al. 2015; Schmalholz and Duretz 2015; Aharonov and Scholz 2018; Mako and Caddick 2018; Kiss et al. 2019). The thermal anomaly pattern evidenced by our study across the thrust surface and adjacent areas is compatible, in term of amplitude and spatial extension, with the results of the recent thermomechanical modeling studies from Mako and Caddick (2018) and Kiss et al. (2019), for example.

The respective influences of strain and fluid flow on graphite (re)crystallization, as evoked in the second and third hypotheses, are poorly constrained for natural settings and geological time scales. Both parameters seem, however, to influence and enhance graphitization kinetics as shown by laboratory experiments (e.g. Ross and Bustin 1990; Bustin et al. 1995; Beyssac et al. 2003a; Nakamura et al. 2017) and some natural examples (e.g. Luque et al. 1998; Luque and Rodas 1999; Kirilova et al. 2018; Wang et al. 2019; Petroccia et al. 2022).

Regardless of the mutual influence of the factor(s) controlling the evidenced distribution of the RSCM temperatures measured across the Hérens valley, these results emphasize the importance of the tectonic contact of the Série Grise on the Série Rousse and reinforce the observations and conclusions of chap. 5.2.

The Schistes Lustrés samples from the Hérens valley with the lowest RSCM temperatures are from metasediments associated with the large ophiolitic masses of the Tracuit - Aiguilles Rouges zone (Fig. 10a, c; Decrausaz et al. 2021, fig. 2). The RSCM temperatures of these samples range from 354 ± 13 °C to 402 ± 14 °C, they are therefore significantly lower than those of both Série Grise and Série Rousse in the same area, which together range there from 408 ± 27 °C to 467 ± 23 °C. This contrast in RSCM temperature is of the same order as that described by Manzotti et al. (2021) between the Cornet Unit (373 ± 13 °C - 403 ± 9 °C) and the By Unit (462 ± 12 °C - 515 ± 23 °C) in the Ollomont valley (IT). The Cornet Unit is located in the direct continuation of the Tracuit - Aiguilles Rouges zone, in an identical tectonic position (Fig. 1b). These two units are therefore probably equivalent. The Low-T slice (360–410 °C) of the Tsaté complex highlighted by Angiboust et al. (2014) in this same region as our study (without being mapped) also likely corresponds to these units.

7 Discussion

7.1 Evolène Series - Série Rousse succession compared to stratigraphic series from the Prealps and Western Alps

The detailed observations along the basal contact of the Série Rousse presented in chapter 5.1 clearly suggest the stratigraphic nature of this contact, as pointed out in particular by the local identification of a basal conglomerate and a basal hardground, and by the absence of any hint of particular shearing across various sections of the contact. The interpretation of this contact as stratigraphic, as already proposed by e.g. Escher (1988; cf. Fig. 2), clarifies various points concerning the evolution of the Prepiemont domain (cf. Lemoine 1961; Pantet et al. 2020), which are discussed below. In particular, the study of the facies distribution within the Série Rousse and the underlying formations of the Mont Fort basement and Evolène Series provides interesting insights regarding the Cretaceous paleogeographic and sedimentological evolution of the Prepiemont domain and the tectonic correlations between the Prepiemont units outcropping in the Pennine Alps and those transported in the Prealps.

7.1.1 Characteristic successions of siliceous limestones and black detrital limestones

Different local stratigraphic columns showing the lithological successions outcropping on both sides of the basal contact of the Série Rousse are presented in Fig. 11b for the Mauvoisin area (Bagnes valley); and in Fig. 12b for

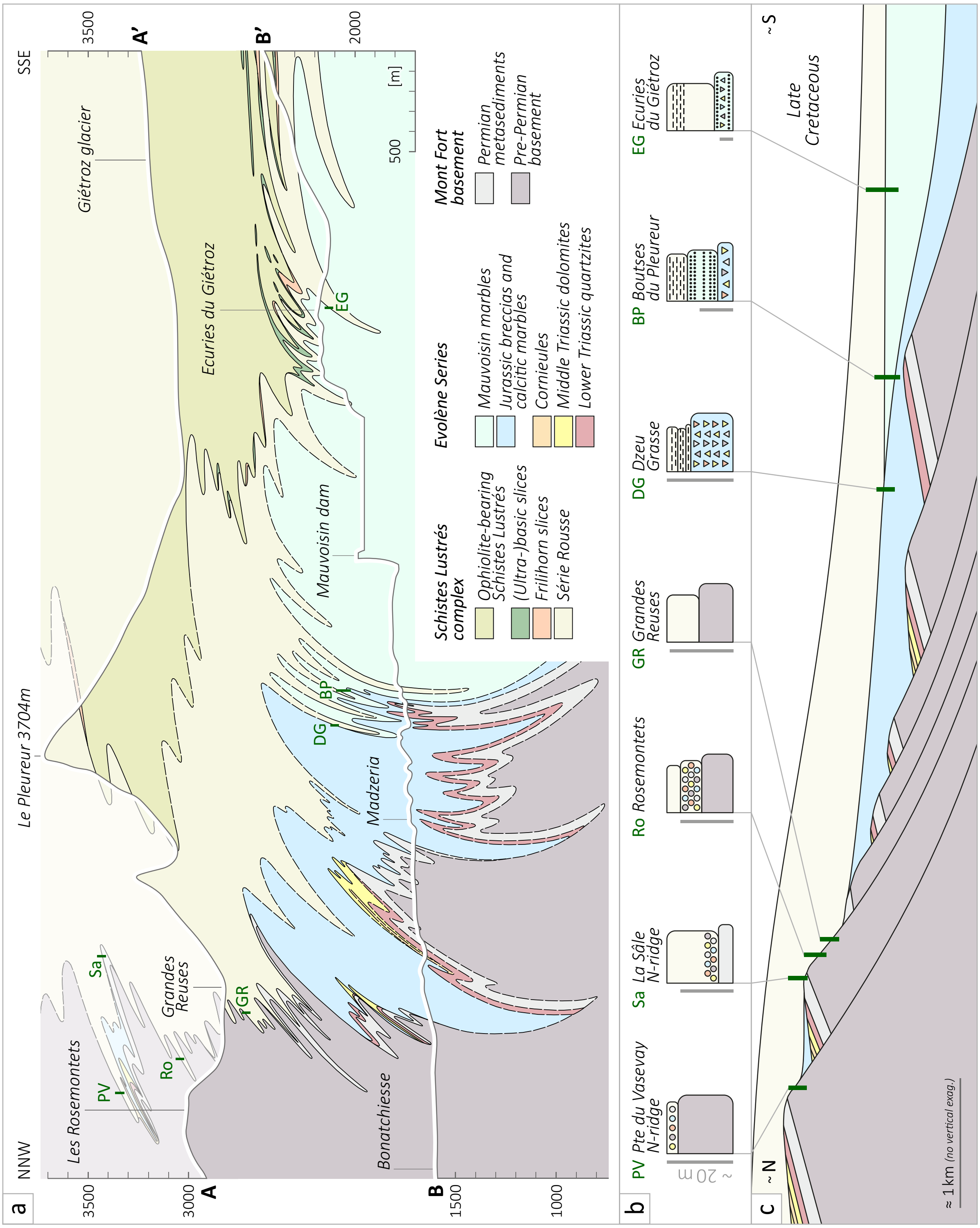

Fig. 11 (See legend on previous page.)

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Fig. 12 **a** Bedrock map of the Evolène area (Hérens valley); compiled after data from this study and existing maps (Moix and Stampfli 1980, 1981; Schneider 1982; Escher 1988; Allimann 1990; Kramar 1997; Steck et al. 1999; Sartori and Epard 2011; Glassey 2013; Marthaler et al. 2020a; Swisstopo Geocover); background altitude model ©Swisstopo; locations of the stratigraphic columns of Fig. b are indicated in green. **b** Characteristic lithostratigraphic successions through the base of the Série Rousse along the Hérens valley; scales differ between the stratigraphic columns (grey strokes represent ca. 20 m); triangles indicate breccia levels; circles, conglomerates; black points, detrital quartz; black dashes, dark calcschists; black lines, black schists; brown line, hardground. Stratigraphic columns acronyms and coordinates: Co [2′600′850/1′108′710], tectonically overturned, cf. Allimann (1990); Be [2′605′485/1′108′880]-[2′605′510/1′108′870], cf. Glassey (2013); MB [2′605′260/1′107′190]—[2′605′320/1′107′130]; RV [2′605′130/1′106′900]—[2′605′180/1′106′880]; Ts [2′600′050/1′107′940]—[2′599′790/1′107′790]; Vi [2′602′710/1′105′660]—[2′602′800/1′105′520], tectonically overturned, Fig. 4g from the center of the profile; PT [2′602′950/1′105′540]—[2′603′415/1′105′460], Fig. 9b from the top of the profile; SC [2′605′545/1′105′230]—[2′605′740/1′105′185]; SN [2′599′285/1′107′975]—[2′599′290/1′107′895], Fig. 8f–g from the center of the profile; MP [2′599′250/1′105′470]—[2′599′235/1′105′450]. **c** Pre-orogenic restoration attempt, reproducing lithological contacts and successions observed and reported in Fig. a-b

the Hérens valley area. A well-developed conglomerate or hardground is observed at the base of the Série Rousse when the underlying Evolène Series is devoid of Mauvoisin marbles (e.g. Fig. 11b: Sa and Ro logs; Fig. 12b: MB, RV and SN logs). This suggests a marked sedimentation gap, that should span from the Late Jurassic to the Late Cretaceous.

On the other hand, when the Série Rousse rests on the Mauvoisin marbles, its basal part generally includes dark levels, rich in phyllosilicates and organic matter (e.g. Fig. 11b: DG, BP and EG logs; Fig. 12b: Ts, Vi, PT and SC logs). Good examples of such successions can be observed near the Mauvoisin Hotel at [2′592′710/1′094′620] and [2′592′820/2′094′650]; and in the Hérens valley, in the vicinity of La Vieille (Fig. 12, Vi log; Marthaler et al. 2020a, 2020b), near the St-Christophe chapel (Fig. 12, SC log) and SE of La Tour between [2′605′290/1′104′860] and [2′605′460/1′104′760] (Figs. 4e, 6c, 6e). These successions, characterized by the superposition of light-colored siliceous calcitic marbles, with quartzitic mm-cm thick levels, attributed to the Mauvoisin marbles (cf. chap. 4.2), surmounted by dark calcschists or detrital calcitic marbles of the Série Rousse (cf. chap. 4.1.1), recall the stratigraphic superposition of the Bonave Fm. (Upper Tithonian - Valanginian/Barremian) and the glauconite-bearing Joux Verte Fm. (Upper Barremian - Middle Turonian) described in the Breccia nappe of the Chablais Prealps (Dall'Agnolo 1997, 2000; Fig. 13a).

In the Briançonnais domain s.l. (incl. Prepiemont), the stratigraphic succession of light-colored, massive limestones (or breccias with light-colored limestone matrix of the same age), of cherty light-colored pelagic limestones, and of darker phyllitic and sometimes anoxic limestones, is in fact very characteristic of the superposition of Upper Jurassic, Lower Cretaceous and "mid"-Cretaceous levels (Bourbon et al. 1979). Such successions can be observed in many and less metamorphosed and deformed stratigraphic successions of the Western and Central Alps, e.g. in the Plastic Median Prealps (e.g. Plancherel et al. 2020), the Roche des Clots Series (e.g. Lemoine et al. 1978), or the Chabrière Series (Lemoine and Tricart 1986).

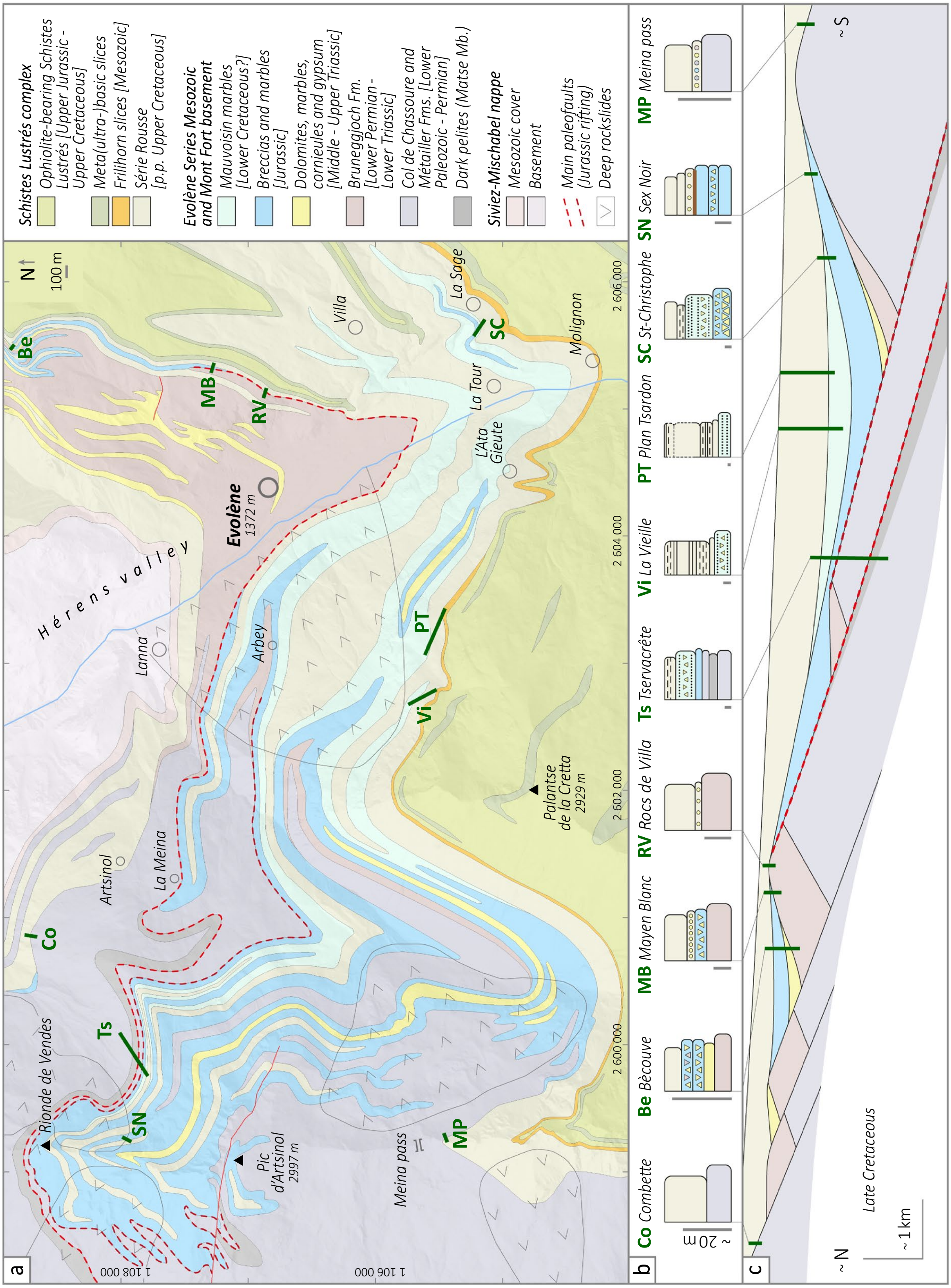
The characteristic superposition of these facies on different sections of the contact between the Evolène Series and the Série Rousse constitutes therefore another strong argument to consider this contact as stratigraphic.

7.1.2 Stratigraphic comparison with the Breccia nappe in the Prealps

The stratigraphy of the Breccia nappe in the Prealps (Fig. 13a; e.g. Lugeon 1896; Chessex 1959; Weidmann 1972; Dall'Agnolo 1997, 2000; Plancherel et al. 1998) shows very strong similarities with the entire Evolène Series. These similarities have been pointed out several times in the literature (Joukowsky 1907; Escher 1988; Kramar 1997; Sartori et al. 2006; Marthaler et al. 2008b; Glassey 2013; Marthaler et al. 2020b). It has recently been discussed in detail by Pantet et al. (2020), who highlight a strong correlation between these two stratigraphic successions.

The correlations proposed here between the Bonave Fm. and the Mauvoisin marbles (upper part of the Evolène Series), and between the Joux Verte Fm. and the lower part of the Série Rousse, further strengthen the correlation between the Breccia nappe and the whole Mesozoic series associated to the Mont Fort nappe (Fig. 13).

The few differences between these two stratigraphic successions are minor. The absence of Lower and Middle Triassic levels in the Prealps is simply explained by the detachment of the stratigraphic successions above the Carnian evaporites (Caron in Debelmas 1970; Weidmann 1972). Differences also appear concerning the thickness of the Jurassic and Cretaceous levels between the two stratigraphic columns of Fig. 13. They are however not really significant, since these synthetic columns



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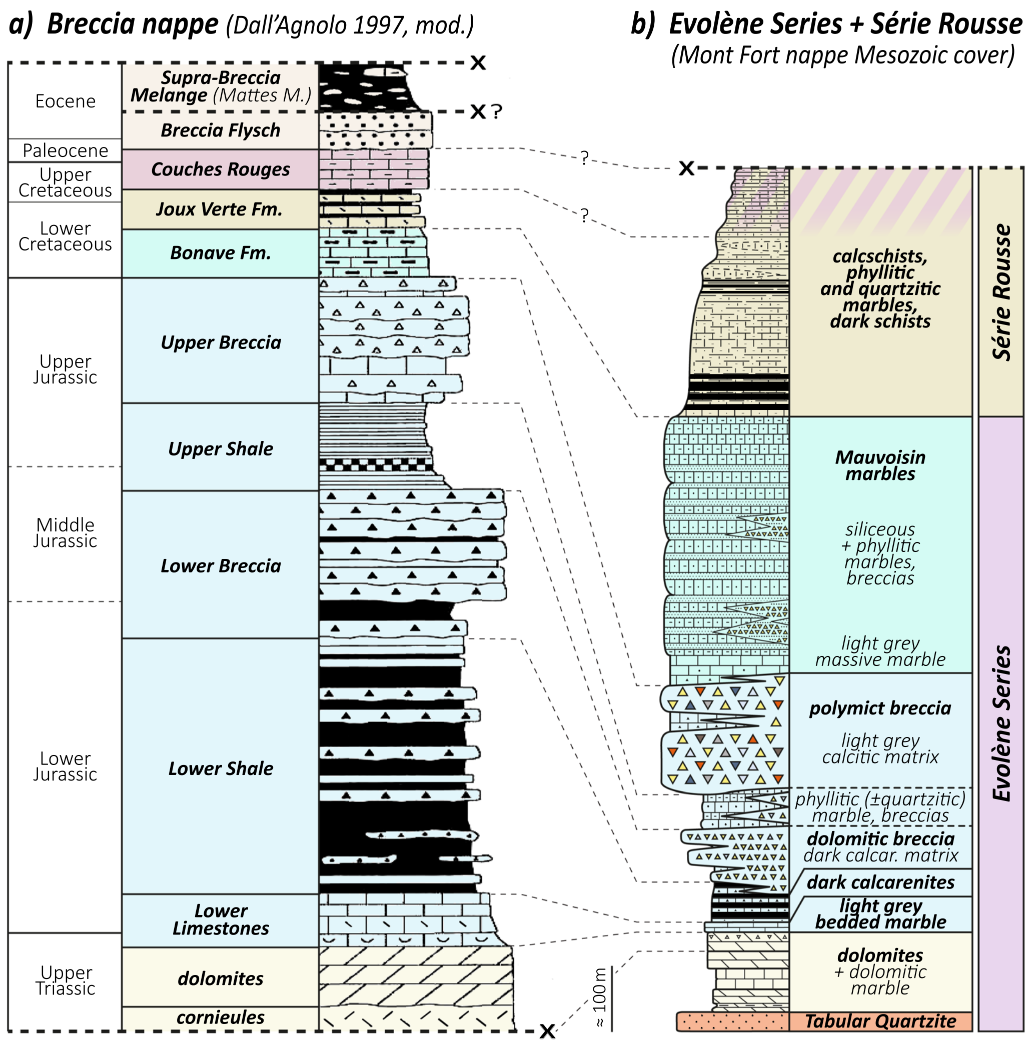


Fig. 13 **a** Synthetic stratigraphic columns of the Breccia nappe in the Prealps (modified after Dall'Agnolo 1997), compared to **b** the Evolène Series and Série Rousse superimposed synthetic stratigraphic columns (modified after Kramar 1997; Sartori et al. 2006; Pantet et al. 2020); complete stratigraphic successions of the series are represented, widespread local stratigraphic gaps are ignored

only indicate maximum thicknesses, whereas considerable thickness variations are observable within the series themselves for these levels (Dall'Agnolo 1997, 2000; Figs. 7, 11, 12). Regarding the Breccia nappe, these thickness variations are mainly of stratigraphic origin, whereas for the units associated with the Mont Fort nappe, their origin is not only stratigraphic, but also partly tectonic, given the strong Alpine deformation affecting these units. Finally, another difference between the two columns concern the flysch and the melange (Suprabrekzienmelange/Mélange Supra-Brèche; Dall'Agnolo 1997, 2000; Mattes Melange; Plancherel et al. 2020) overlying the stratigraphic series of the Breccia nappe (Dall'Agnolo 1997, 2000), and for which, no equivalent has been recognized at the top of the Série Rousse. However, the relationship of this melange to the Breccia nappe is possibly tectonic (De Lepinay 1981; Dall'Agnolo 1997) and its potential equivalent at the top of the Série Rousse (as well as the overlying levels) may have been tectonically replaned by the overthrusting of the Upper Penninic units.

Strong stratigraphic similarities can therefore be evidenced between the Breccia nappe in the Chablais Prealps and the ensemble formed by the Evolène Series and the Série Rousse. They lead us to consider this ensemble as a single entity, whose stratigraphic successions extend from the basal Triassic to the Upper Cretaceous at least.

7.2 The basal unconformity: progressive infill and sealing of the remnants of the Jurassic fault scarps

The basal contact of the Série Rousse is characterized by an unconformity described in chap. 5.1.1. This unconformity has led various authors (Escher et al. 1993; Sartori and Marthaler 1994) to consider this contact as being of a tectonic nature. All our observations however consistently show that the contact is primarily stratigraphic (cf. chaps. 5.1.2–5.1.4, 7.1) and that the unconformity can be explained by deposition on a paleorelief of former syn-sedimentary faults (Figs. 11c, 12c), following a model already developed by Pantet et al. (2020). These syn-sedimentary faults, mostly active during the Jurassic, delimit small basins formed by tilted blocks (half-grabens), whose movement is at the origin of the locally large breccia accumulations observed in the Evolène Series. The thinness of the breccia deposits in the Série Rousse (in general < 10 cm, never exceeding 3 m) seems to indicate that these faults were no longer active or less active during the Late Cretaceous. A submarine relief formed by the Jurassic fault scarps should have remained, allowing the local erosion of the Evolène Series and of various Paleozoic levels of the Mont Fort basement. The activity of Cretaceous faults or rejuvenation of Jurassic faults during the Cretaceous has nevertheless been documented in other areas of the Alps (e.g. Claudel et al. 1997; Michard and Martinotti 2002; Bertok et al. 2012; Cardello and Mancktelow 2014; Michard et al. 2022).

Our detailed mapping (Figs. 7a, 12a) shows that the different lithological successions along the basal contact of the Série Rousse (e.g. Figs. 11b, 12b), as well as their distribution, are compatible with the hypothesis of a progressive filling of such half grabens by the Série Rousse.

For example, the conglomerate, locally present at the base of the Série Rousse, is better developed where the Evolène Series is absent or reduced to a small thickness. Following our restoration attempts of the structures preceding the Alpine collision (Figs. 11c, 12c), the areas yielding these basal conglomerates would correspond either to areas characterized by the sedimentation of the Série Rousse directly on ancient fault scarps (e.g. Fig. 11b, PV, Sa and Ro logs; Fig. 12b, MP log), or to the upper parts of tilted blocks (e.g. Fig. 12b, MB and SN logs). The area where a hardground is observed and document a large stratigraphic gap (Triassic levels and Mauvoisin marbles missing; Fig. 12b, SN log), would correspond, following the restoration attempt of Fig. 12c, to the highest part of a tilted-block. Areas where the Série Rousse overlies the Mauvoisin marbles and shows dark facies (e.g. Fig. 11b, BP log; Fig. 12b, Vi, PT and SC logs) correspond, in contrast, to the depocenters of the half graben basins, where sedimentation continued during the Cretaceous with a smaller stratigraphic gap than in adjacent areas.

The different points discussed above show strong evidences for the onlap and sealing by the Série Rousse, during the Late Cretaceous, of a paleotopography characterized by fault scarps resulting of the Jurassic development and activity of large synsedimentary extensional faults.

The Série Rousse therefore represents the sedimentary continuation of the Evolène Series and should consequently not be considered as an independent allochthonous tectonic unit.

7.3 Tectonic limits and units in the Schistes Lustrés complex of the Combin zone

Taken together, our observations thus indicate that the Série Rousse constitutes the youngest part of the autochthonous sedimentary cover of the Mont Fort nappe, rather than a basal slice of the Tsaté nappe. They also show that the upper contact of the Série Rousse with the ophiolite-bearing Schistes Lustrés of the Série Grise is clearly of tectonic nature (cf. chaps. 2.2, 5.2, 6). This contact corresponds to the Alpine thrust separating the Tsaté and Mont Fort nappes. According to our interpretation, the contact between these two nappes is therefore not located at the base of the Série Rousse, but at its top. This contact, which corresponds to the major tectonic limit that separates the Upper Penninic ocean-derived units from the continental margin-derived Middle Penninic units, is thus located within the Schistes Lustrés complex of the Combin zone (Figs. 2, 14).

According to the proposed interpretation, the ensemble constituted by the Evolène Series and the Série Rousse thus forms the relative autochthonous sedimentary cover of the Mont Fort nappe, whereas the Tsaté nappe is restricted to the Série Grise and the Tracuit - Aiguilles rouges zone / Cornet Unit. The thin Frilihorn slices are located at the contact of the two nappes rather than within the Tsaté nappe. This interpretation corresponds in fact to the first hypothesis adopted when these different units were defined (Fig. 2; Marthaler and Escher in Masson et al. 1980; Marthaler 1981, 1984; Escher and Masson 1984; Sartori 1987; Escher 1988; Escher et al. 1988) and before the subsequent reinterpretation of this tectonic scheme by some of these authors (e.g. Escher et al. 1993; Sartori and Marthaler 1994; cf. chap. 2.2).

The interpretation of the tectonic position of the Frilihorn slices, at the base rather than within the Tsaté nappe, is interesting with respect to the questions of the origin and tectonic attribution of these slices. In the studied area, north of the Dent Blanche klippe, all the observed Frilihorn slices are located along the contact between the

Série Rousse and the ophiolite-bearing Schistes Lustrés (which is locally redoubled by isoclinal folds; Fig. 9c). These observations actually seem hardly compatible with the hypothesis of an Adriatic origin of these slices (e.g. Staub 1942d; Caby et al. 1978; Dal Piaz 1999; Froitzheim et al. 2006; Pleuger et al. 2007; Passeri et al. 2018). It is indeed extremely difficult to imagine a mechanism able to insert slices of Adriatic origin in this position without inserting ophiolite-bearing Schistes Lustrés below these slices. However, a provenance from the Briançonnais s.str. swell and a southward emplacement, as proposed by Scheiber et al. (2013), also seems unlikely to be compatible with the widespread breccia layers observed within the calcitic marbles of these slices (cf. chaps. 2.3.2, 5.2); and with the top-NW shear sense associated to the main schistosity that is observed in some localities (Fig. 9e). According to the observations above, a Prepiemont origin (i.e. derived from the southern distal margin of the Briançonnais s.l. domain; Fig. 15b), as proposed for example by Elter (1960, 1972; Dal Piaz (1974), Bearth (1976), Marthaler (1984), Escher (1988), seems, therefore, more likely. Considering such a Prepiemont origin, two different possibilities concerning the origin and tectonic attribution of the Frilihorn slices could be envisaged: (1) a more distal origin than the Mont Fort nappe on the distal Prepiemont margin, the Frilihorn slices would hence constitute an independent tectonic unit, thrusted along the base of the Tsaté nappe; (2) an origin corresponding to the most internal part of the Mont Fort nappe, folded and boudinaged under the Tsaté basal thrust (similarly e.g. to the Helvetic Drône anticline under the Penninic thrust; Steck et al. 1989; Escher et al. 1997; Cardello et al. 2019).

The existence of an Alpine tectonic contact within the ophiolite-bearing Schistes Lustrés (i.e. the Tsaté nappe as redefined above) has been postulated by Angiboust et al. (2014). Its existence has been recently confirmed by Manzotti et al. (2021) based on metamorphic arguments. Indeed, on each sides of this contact in the Ollomont valley (IT), both the RSCM temperatures and the metamorphic paragenesis are strongly contrasted. In this sector, the lower part of the Schistes Lustrés complex (By Unit) shows parageneses characterized by the presence of pseudomorphs after lawsonite, aragonite inclusions in titanites and the local presence of small garnets in quartzitic schists. Its peak P–T conditions are estimated at ca. 16–17 kbar and 460–480 °C. In the Cornet Unit, which represents there the uppermost unit of the Schistes Lustrés complex, the parageneses mentioned above are completely absent and the peak P–T conditions are estimated at ca. 8 ± 1 kbar and 370–400 °C.

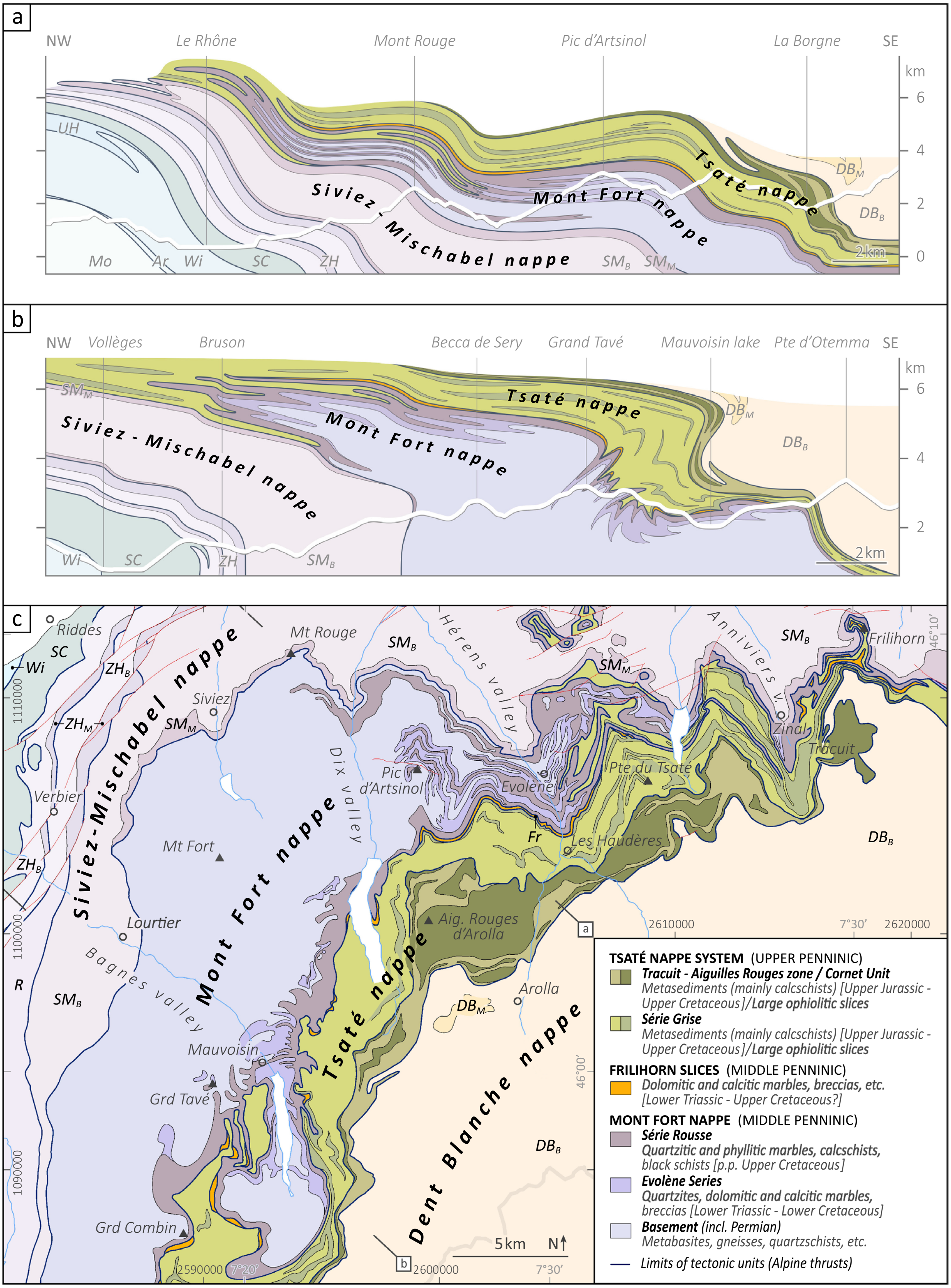
According to these authors, the metamorphic evolution is similar between the Cornet Unit and the overlying Dent Blanche nappe. The upper limit of the Schistes Lustrés complex of the Combin zone would therefore not correspond to an important metamorphic limit. The same seems to be true for the lower limit of this complex. Indeed, as highlighted above, this limit is stratigraphic in nature and is internal to the Mont Fort nappe, which is not compatible with a metamorphic limit. Available data concerning the metamorphic evolution of the different units composing this nappe are consistent with this interpretation (sodic amphiboles, chloritoid, epidotes and HP white micas in the Paleozoic basement; Schaer 1960; Bearth 1963; Thélin et al. 1994; Steck et al. 2001; Bousquet et al. 2004; Evolène Series RSCM°T ranging from 484 ± 31 °C to 480 ± 34 °C, Table 1, Fig. 10c; Série Rousse RSCM°T ranging from 408 ± 27 °C to 494 ± 7 °C, Additional file 2; pseudomorphs after lawsonite in the Série Rousse in the Bagnes valley, Besson 1986 and in the Ollomont valley, P. Manzotti, pers. com.). The limit between the Mont Fort and Tsaté nappes (i.e. between the Série Rousse ± Frilihorn slices and the Série Grise), although clearly of tectonic nature, neither corresponds to an important metamorphic limit (cf. chap. 6). Contrary to the hypothesis of Angiboust et al. (2014), the intensity of metamorphism does not appear to increase between the middle and basal parts of the Schistes Lustrés complex.

The most important metamorphic boundary in the whole Mont Fort, Tsaté and Dent Blanche nappe stack therefore corresponds to the limit between the Série Grise and the Tracuit - Aiguilles Rouges zone / Cornet Unit. The question of the origin of such a metamorphic discontinuity is beyond the scope of this article and will not be further discussed here.

Although the Schistes Lustrés complex of the Combin zone has been considered by many authors as a single tectonic entity, the above data and discussions show that it is instead composed of different tectonic units, separated by (1) a major tectonic contact that corresponds to the Middle-Upper Penninics limit, separating the lower

(See figure on next page.)

Fig. 14 Reinterpreted schematic cross-sections and tectonic map of the studied area; *Ar*: Ardon nappe; DB_B: Dent Blanche basement; *Fr*: Frilihorn slices; *Mo*: Morcles nappe; *R*: Ruitor basement; *SC*: Sion-Courmayeur zone; SM_B: Siviez-Mischabel basement; SM_M: Siviez-Mischabel Mesozoic; *UH*: Ultrahelvetic nappes; *Wi*: Wildhorn nappe; *ZH*: Zone Houillère; ZH_B: Zone Houillère basement; ZH_M: Zone Houillère Mesozoic. **a** Schematic geological cross-section through the Hérens valley; modified after Escher (1988), Escher et al. (1988, 1993, 1994), Schaer (1960); location indicated in Fig. c. **b** Schematic geological cross-section through the Bagnes valley; location indicated in Fig. c. **c** Tectonic map of the upper Bagnes, Dix, Hérens and Anniviers valleys (SW Switzerland); compiled after data from this study and existing maps (see Fig. 1b for references)



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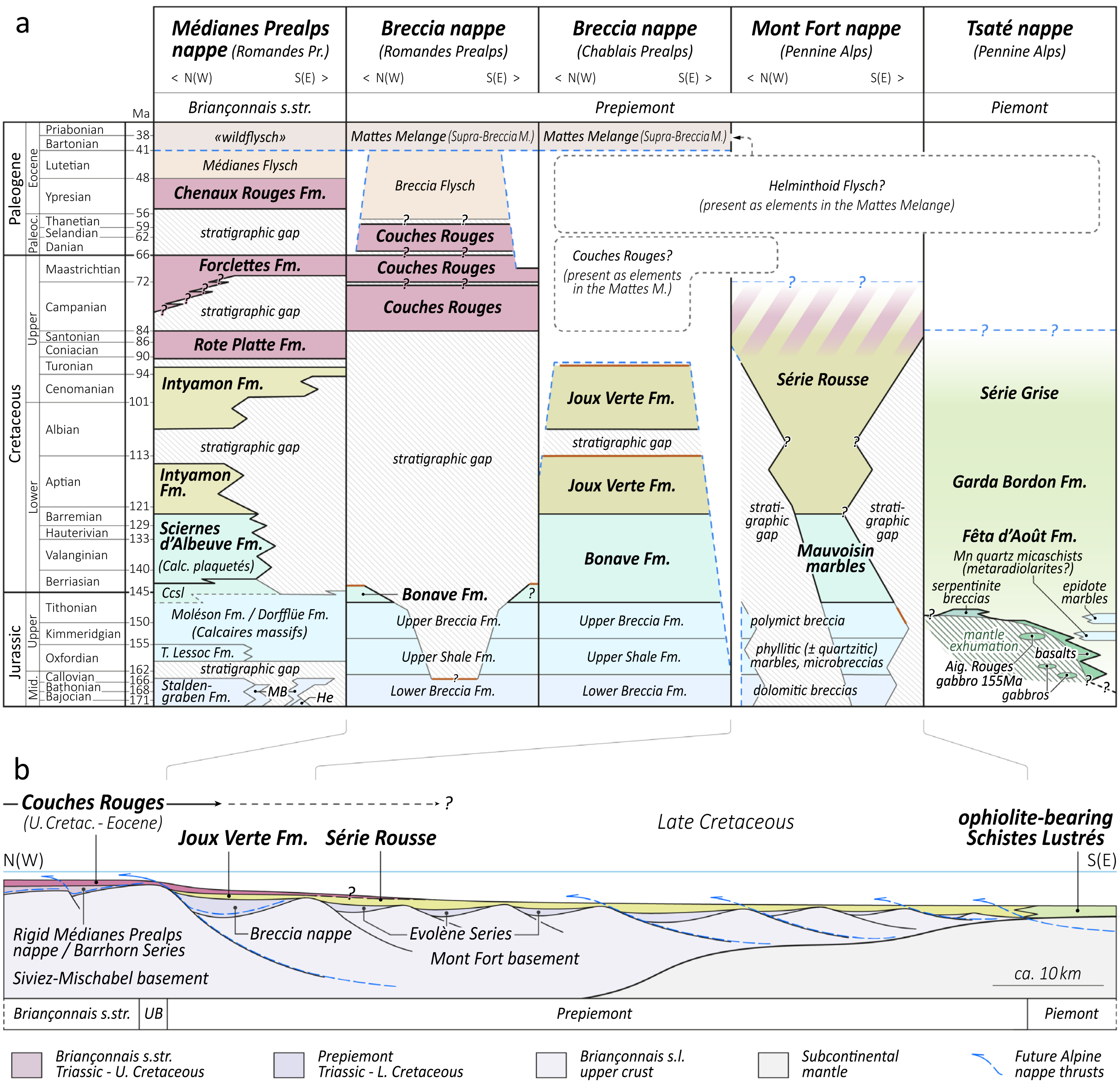

Fig. 15 **a** Correlations between the lithostratigraphic formations of the Breccia, Médianes, Mont Fort and Tsaté nappes (Prealps and Pennine Alps) for the Jurassic, Cretaceous and Paleogene periods; in this representation, only the time-extensions of the formations are indicated, independently of their actual thickness; modified after Dall'Agnolo (1997, 2000); Mosar et al. (1996, fig. 4); Stampfli et al. (1998, 2002); Plancherel et al. (1998, 2020); Decrausaz et al. (2021); Marthaler et al. (2020b); brown lines represent hardgrounds; blue dashed lines indicate probable tectonic contacts; *Ccsl*: Calcaires compacts et sublithographiques; *MB*: Mytilus Beds; *He*: Heiti Fm. **b** Restoration attempt of the South Briançonnais - Prepiemont margin at Late Cretaceous Epoch, before the onset of Alpine deformation in that area; modified after Stampfli and Marthaler (1990); Stampfli et al. (1998, 2002); Mohn et al. (2010); Pantet et al. (2020); *UB*: Ultrabriançonnais domain

and middle units of this complex, i.e. the Série Rousse and the Série Grise respectively, and (2) by a major metamorphic discontinuity, separating the middle from the upper unit of this complex (Tracuit - Aig. Rouges zone / Cornet Unit). It is particularly interesting to note that these two contacts do not correspond to marked lithological limits, they are even sometimes extremely inconspicuous, which may explain why their importance has been underestimated by most authors. In the light of these new data, the structure of the Combin zone is thus comparable to that of the Schistes Lustrés of the Western Alps, also characterized by a tectonic juxtaposition of different units showing distinct metamorphic evolutions (e.g. Fudral et al. 1987; Rolland et al. 2000; Plunder et al. 2012; Agard 2021; Herviou et al. 2022).

7.4 Cretaceous-Paleogene sedimentation along the Briançonnais-Prepiemont margin and Piemont basin

The Briançonnais s.str. domain, its hyperextended SE-margin (Prepiemont domain; Lemoine 1961) and the Piemont basin are characterized by a deep-water, clastic, hemipelagic and pelagic sedimentation throughout the Cretaceous (Fig. 15). Thus, until the end of this period, these realms remained essentially unaffected by the subduction and the onset of the Alpine collision that started along the Adriatic margin and southern Piemont-Liguria basin at that time. The onset of the convergence is attested since the late Cenomanian to early Turonian by the first Alpine flysch units, containing material of the Adriatic margin and now constituting the Simme nappe (Caron et al. 1989; Gasinski et al. 1997), and by the age of the prograde HP metamorphism starting at ca. 85 Ma in the Adriatic and Piemont derived units of the Pennine Alps (Skora et al. 2009; Rubatto et al. 2011; Manzotti et al. 2014; Regis et al. 2014). Stratigraphic data from the Briançonnais s.l. series in the Swiss Prealps (Fig. 15a) show that pelagic to hemipelagic sedimentation extends into the Paleocene in the external part of the Prepiemont domain (Couches Rouges of the Breccia nappe; Dousse 1965; Dall'Agnolo 1997) and into the early Eocene in the Briançonnais s.str. domain (Chenaux Rouges Fm.; Guillaume 1986). It is then relayed by flysch deposition, until middle Eocene (Guillaume 1986; Dall'Agnolo 1997; Hable 1997).

Alpine metamorphism and deformation in the Briançonnais s.l. and surrounding units of the Pennine Alps are dated to the late Eocene, with ages ranging in Western Switzerland between 37–40 Ma for the Prepiemont domain and 35–40 Ma for the Briançonnais s.str. domain (e.g. Markley et al. 1998; Gebauer 1999; Angiboust et al. 2014). The sedimentation gaps, sometimes large, revealed at different levels in the Cretaceous and Paleocene of these series (Fig. 15a) are interpreted as resulting from the progression of the lithospheric bulge associated with the progressive subduction of the Piemont domain under the Adriatic plate (Stampfli et al. 1998).

The sedimentary evolution during the Late Cretaceous - Paleogene is less constrained in the internal Prepiemont domain and Piemont domain (corresponding to the domains of deposition of the Série Rousse and Série Grise respectively), given the poor preservation of microfossils in the Pennine Alps and the lack of complete corresponding series in the Prealps. The few biochronological data available indicate a Cenomanian to earliest Maastrichtian minimal age for the Série Rousse (cf. chaps. 2.3.3, 4.1.2) and a Cenomanian to Santonian minimal age for the Série Grise (cf. chap. 2.3.1). The presence of well-developed dark anoxic levels in these series may, in turn, argue for their partly "mid"-Cretaceous age. The ages that can be inferred for these series are thus comparable with those indicated by Dall'Agnolo (1997, 2000; cf. Fig. 15a) for the Joux Verte Fm. (late Barremian - middle Turonian) and for the base of the Couches Rouges from the Breccia nappe (Campanian - Paleocene) as well as for the Couches Rouges included in the Mattes Melange (or Supra-Breccia Melange; late Campanian - early Paleocene; Dall'Agnolo 1997, 2000; Plancherel et al. 2020). As the Mattes Melange contains lenses of Couches Rouges and lenses of Helminthoid Flysch and is intercalated between the Breccia nappe and the upper Prealps nappes (Badoux 1962; Caron 1966, 1972; Caron and Weidmann 1967; Dall'Agnolo 1997), the origin of these lenses must therefore correspond either to the internal part of the basin of the future Breccia nappe or to a more internal domain, i.e. to the inner part of the Prepiemont domain or the Piemont domain. Lithological successions unambiguously corresponding to Couches Rouges or flysch units have however not been recognized at the top of the Série Rousse or Série Grise. The lithologies observed in these series differ from the Couches Rouges of the Médianes Prealps and of their metamorphic equivalents of the Barrhorn Series, by systematically higher quartz and organic matter contents (in the Couches Rouges and their metamorphic equivalents, quartz content is usually < 2–5% and CM is very scarce; Guillaume 1986; Sartori 1990; Dall'Agnolo 1997). The Couches Rouges described in the Breccia nappe and in the Mattes Melange seem however to have a higher detrital input (Dousse 1965; Dall'Agnolo 1997) and could partly correspond to the upper part of the Série Rousse (Figs. 13 and 15). The lithologies of the upper part of the Série Rousse are also further distinguished from the Breccia Flysch, by the scarcity of graded beds and the non-cyclic character of the sedimentation. It is nevertheless possible that the Couches Rouges and flysch, included as lenses in the Mattes Melange, may have first been deposited at the top of the Série Rousse and/or of the Série Grise, but that these sequences were then locally detached and transported to the Prealps. Such a detachment seems to have affected the Breccia nappe in the Chablais Prealps, where it would have occurred at the level of the of the "mid"-Cretaceous anoxic shales (De Lepinay 1981; Dall'Agnolo 1997). It is reflected by the absence of levels younger than the middle Turonian and by an important unconformity at the top of the internal part of the Breccia nappe.

A general slope from the Briançonnais swell towards the Piemont basin (Fig. 15b) is documented by an overall proximal to distal and upward fining of the Cretaceous detrital sediment component. Indeed, during the whole period from the Early Cretaceous to the early Late Cretaceous, the detrital input is significantly larger in the Prepiemont domain than in the Briançonnais s. str. domain (cf. Dall'Agnolo 1997, 2000; Plancherel et al. 2020). While submarine topographic highs of the Briançonnais were sheltered from such a detrital input and were the site of hemipelagic to pelagic sedimentation (which continued until the end of the Couches Rouges deposition), sedimentation in the Prepiemont domain was characterized by an input of quite mature quartz and detrital carbonate sands and episodic breccias intercalations. The presence of large fault scarps in the Prepiemont domain, preserved from the Jurassic extension and exposing both lower Mesozoic and Paleozoic rocks at the seafloor (cf. chap. 7.2), are very likely to constitute the main source of this detrital input in the Prepiemont Cretaceous formations.

8 Conclusion

Our study shows that the Schistes Lustrés complex of the Combin zone in Western Switzerland consists of several lithologically distinct and tectonically independent series.

The lower Schistes Lustrés unit, the Série Rousse, is non-ophiolitic and consists mainly of detrital calcitic marbles and calcschists with continental affinities. We argue that the discontinuity characterizing the basal contact of these series results rather from the passive onlap and progressive sealing of remnants of Jurassic extensional fault scarps, than from a tectonic contact between different slices emplaced in an accretionary prism context, as previously proposed. The stratigraphic nature of the basal contact of the Série Rousse is attested by (1) the occurrence in several sectors of a basal conglomerate, sometimes reworking directly underlying formations of the Mont Fort nappe, (2) the local preservation of a hardground at the actual base of the series, and (3) the absence of particular shearing along different sections of the contact. The Série Rousse therefore belongs to the relative autochthonous Mesozoic cover of the Mont Fort nappe, which it forms together with the Evolène Series (cf. Pantet et al. 2020), as previously proposed by Escher (1988) for example.

The stratigraphic sequence composed by the superposition of the Evolène Series and the Série Rousse shows very strong similarities with the stratigraphy of the Breccia nappe in the Prealps. The comparison of the Série Rousse with the Breccia nappe, which is better constrained biochronologically, as well as the discovery in the Série Rousse of a form corresponding to *Globotruncana neotricarinata*, allows us to better constrain its age. It probably extends from the Early Cretaceous (Aptian?) to the Late Cretaceous (Campanian to earliest Maastrichtian?).

The median Schistes Lustrés unit, the ophiolite-bearing Série Grise, overlies the Série Rousse by a tectonic contact corresponding to the Upper/Middle Penninic limit. It is underlined by tectonized slices (Frilihorn Series), whose origin corresponds either to the internal part of the Mont Fort nappe, or to a more internal Prepiemont unit. The performed RSCM analyses show that the recrystallization of the organic matter progressively increases towards this contact. RSCM temperatures calculated in the Hérens valley for samples taken in the immediate vicinity of the contact (< 10 m) reach 467 ± 23 °C for the Série Rousse and 466 ± 29 °C for the Série Grise, whereas the lowest values obtained for both series in this same valley come from the areas most distant from the contact (408 ± 27 °C and 411 ± 17 °C respectively). This temperature increase centered on the contact may reflect a shear heating effect, associated with the intense strain localized along this major tectonic contact.

The upper unit of the Schistes Lustrés complex, the Tracuit - Aiguilles Rouges zone, very likely corresponds to the Cornet Unit individualized by Manzotti et al. (2021) in the Ollomont valley. Our data indicate that the metamorphic limit highlighted by these authors at the base of the Cornet Unit is also found at the base of the Tracuit - Aiguilles Rouges zone. This limit appears as the most important metamorphic discontinuity inside the Mont Fort, Tsaté and Dent Blanche nappe stack.

Although the Schistes Lustrés complex of the Combin zone has been regarded by many authors as a single tectonic entity, our study thus confirms and details that it is instead composed of different tectonic units separated by major metamorphic and/or tectonic contacts.

Our study moreover clearly documents that the Schistes Lustrés consist of both sediments deposited on oceanic crust, which locally show preserved stratigraphic contacts with ophiolitic or serpentinized sub-continental mantle slivers, as well as of sediments still resting stratigraphically on a former hyper-extended continental margin.

Abbreviations

CL	Cathodoluminescence
CM	Carbonaceous material
Fm.	Formation
HP	High pressure
RSCM	Raman spectroscopy of carbonaceous material

RSCM°T	Temperature calculated following RSCM method (peak temperature)
TL	Transmitted light
UHP	Ultra high pressure
[Geographic coordinates]	refer to the Swiss grid MN95

Supplementary Information

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Additional file 1. Detailed RSCM°T calculations.

Additional file 2. Série Rousse and Série Grise mean RSCM°T and series attributions.

Additional file 3. Hérens valley RSCM°T and distances to the Série Grise / Série Rousse contact.

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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. CBM and POB contributed in the description and interpretation of potential microfauna, microscopic sedimentological descriptions and chap. 7.4 elaboration. LB contributed in the RSCM data processing and interpretation. All authors read and approved the final 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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The authors declare that they have no competing interests.

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