Pantet *et al. Swiss J Geosci* (2020) 113:13
https://doi.org/10.1186/s00015-020-00366-2

SGG SGS sc | nat
Swiss Journal of Geosciences

ORIGINAL PAPER Open Access

Mimicking Alpine thrusts by passive deformation of synsedimentary normal faults: a record of the Jurassic extension of the European margin (Mont Fort nappe, Pennine Alps)

Adrien Pantet*, Jean-Luc Epard and Henri Masson

Abstract

The Mont Fort nappe, former uppermost subunit of the Grand St-Bernard nappe system, is an independent tectonic unit with specific structural and stratigraphic characteristics (Middle Penninic, NW Italy and SW Switzerland). It consists in a Paleozoic basement, overlain by a thin, discontinuous cover of Triassic-Jurassic metasediments, mainly breccias, called the Evolène Series. The contact of this Series over the Mont Fort basement is debated: stratigraphic or tectonic? We present new observations that support the stratigraphic interpretation and consequently imply that the Evolène Series belongs to the Mont Fort nappe. We moreover show that the Mont Fort nappe was strongly affected by normal faulting during Jurassic. These faults went long unnoticed because Alpine orogenic deformation blurred the record. Alpine strain erased their original obliquity, causing confusion with an Alpine low-angle thrust. These Jurassic faults have been passively deformed during Alpine tectonics, without inversion or any other kind of reactivation. They behaved like passive markers of the Alpine strain. Detailed field observations reveal the link between observed faults and specific breccia accumulations. Areas where the Evolène Series is missing correspond to sectors where the fault scarps were exposed on the bottom of the sea but were too steep to keep the syn- to post-faulting sediments. The Mont Fort nappe thus represents an example of a distal rifted margin. The succession of synsedimentary extensional movements followed by orogenic shortening generated a situation where passively deformed normal faults mimic an orogenic thrust.

Keywords: Western Alps, Paleofaults, Orogenic deformation, Tethyan distal margins, Hyper-extended continental margin, Penninic, Briançonnais, Prepiedmont

1 Introduction

The Pennine Alps (SW Switzerland and NW Italy) show a complex tectonic architecture resulting from the Cenozoic collision of the European and Adriatic plates (e.g. Argand 1911, 1924, 1934; Escher et al. 1988, 1993, 1997; Escher and Beaumont 1997; Dal Piaz 1999; Lemoine et al. 2000; Steck et al. 2001, 2015; Schmid et al. 2004, 2017; Beltrando et al. 2010, 2014; Mohn et al. 2014; McCarthy et al. 2018, 2020). The orogen-parallel axial plunge of the large structures, bringing all the main tectonic and paleogeographic domains of the Alps to the surface, provides one of the most complete sections through the Alpine nappe stack (Figs. 1 and 2) which consists from bottom to top of:

Editorial handling: Stefan Schmid

*Correspondence: adrien.pantet@unil.ch
Institute of Earth Sciences, University of Lausanne, Géopolis building, CH-1015 Lausanne, Switzerland

Springer Open

© The Author(s) 2020. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

1. The European continental margin, only moderately affected by the opening of the Alpine Tethys during Jurassic (Helvetic realm).
2. More distal parts of this margin, more strongly affected by the Jurassic extension and more deeply subducted during Late Cretaceous to Cenozoic plate convergence (Lower and Middle Penninic realms).
3. The ophiolitic suture of the Piedmont basin, main branch of the Alpine Tethys (Upper Penninic realm).
4. Units derived from the Adriatic plate (Sesia—Dent Blanche and Simme units).

Hence, the Pennine Alps are one of the most carefully studied sectors of the Alps, which provides an ideal object for understanding ocean opening as well as continental collision processes. The Mont Fort nappe which is the subject of the present work is of particular interest in this regard. This nappe (first defined by Escher 1988) belongs to the Middle Penninic realm and occupies a central position in the nappe stack of the Pennine Alps (Fig. 2).

This study leads to a new appraisal of the importance of extensional faulting of Jurassic age on the European margin of the embryonic Alpine Tethys. The recognition of such paleofaults mistaken for Alpine thrusts by some authors has direct consequences regarding its relationships with Upper Penninic units.

2 Geological setting: the Prepiedmont domain and the Mont Fort nappe

The Lower and Middle Penninic realms are particularly complex. They include a very important paleogeographic element: the *Briançonnais* domain. The central part of this element, as for example exposed around Briançon and in the Prealps, is characterized by Mid-Jurassic uplift and emergence (e.g. Debelmas 1955; Ellenberger 1958; Baud and Septfontaine 1980; Jaillard 1988; Sartori 1990; Hürlimann et al. 1996; Lemoine et al. 2000; Decarlis et al. 2017a; Chenin et al. 2019) that defines the domain referred to as *Briançonnais s.str.* below. In a broader sense the term Briançonnais is also used for designating a much larger area that we will refer to as *Briançonnais s.l.* (Fig. 3). It includes distinct subdomains such as the more external Subbriançonnais and the more internal Prepiedmont (see below regarding the definition of these subdomains), which were submitted to various uplift and subsidence pulses during the Jurassic. The Triassic stratigraphy of the various subdomains of the Briançonnais s.l. is more uniform and shows an up to 1000 m thick sequence of Middle to Late Triassic carbonates characterized by very specific facies (e.g. Trümpy 1960, 1980; Mégard-Galli and Baud 1977; Escher et al. 1997; Baud et al. 2016). These carbonates were deposited on a subsiding but always-shallow platform and constitute one of the best guidelines for large-scale Mesozoic Alpine reconstitutions. Another feature that seems to be shared all along the Briançonnais s.l. domain is the presence of Early Permian calc-alkaline magmatism (Ballèvre et al. 2020), whose age contrasts with the Carboniferous age of the late-Variscan magmatism in the Helvetic domain (e.g. Bussy and von Raumer 1994; von Raumer et al. 2013; Ballèvre et al. 2018). It is important to carefully distinguish the Briançonnais s.str. and s.l. domains. These two concepts are different and both necessary. The margins of the Triassic outside the Briançonnais s.str. platform, where the carbonates get thinner, are still poorly known and ill-defined but they extend largely beyond those of the Mid-Jurassic uplifted zone that defines the Briançonnais s.str.. On its external (northern) border, the gradual thinning of the typical Triassic Briançonnais s.l. facies until complete disappearance has been emphasized in the Central Alps by Galster et al. (2012). On the internal (southern) border, we fall across the problem of the Prepiedmont domain, to which the Mont Fort nappe is attributed.

There is a considerable confusion in the paleogeographic nomenclature of the domain located between the Briançonnais s.str. rise and the Piedmont oceanic basin (also referred to as Piedmont-Liguria basin by many authors). This historical confusion reflects the difficulty of the subject. Even if reputed authors used the words Briançonnais or Piedmont (sometimes tempered by various adjectives) for designating this intermediate domain, we think it to be preferable to avoid these words because in this context their use carries a great risk of increasing the nomenclatorial disorder. Here we will use the term *Prepiedmont* that was precisely defined in the seminal paper of Lemoine (1961) as a transition from the Briançonnais s.str. Jurassic rise towards the Piedmont trough. Since then this word has proved useful for describing the paleotectonic evolution of the northern margin of the Piedmont oceanic domain all along the Western Alpine arc (e.g. Caron 1977; Dumont et al. 1984; Marthaler 1984; Dall'Agnolo 1997; Plancherel et al. 1998; Decarlis and Lualdi 2011; Haupert et al. 2016), until the most recent works of Decarlis et al. (2017a, b) and Ribes et al. (2019). Our stratigraphic observations (see further) show that the Prepiedmont domain can be conveniently included as a second order subdivision into the Briançonnais s.l., beside the Subbriançonnais and the Briançonnais s.str. (Fig. 3; in agreement with the geodynamic reconstitution of Decarlis et al. 2017a, b): this is a way to reconcile different nomenclatorial propositions.

Type areas for the definition of the Prepiedmont stratigraphy are the Roche-des-Clots series in the French Alps east of Briançon (formerly the Gondran series; Lemoine et al. 1978; Dumont 1983) and the Breccia nappe in

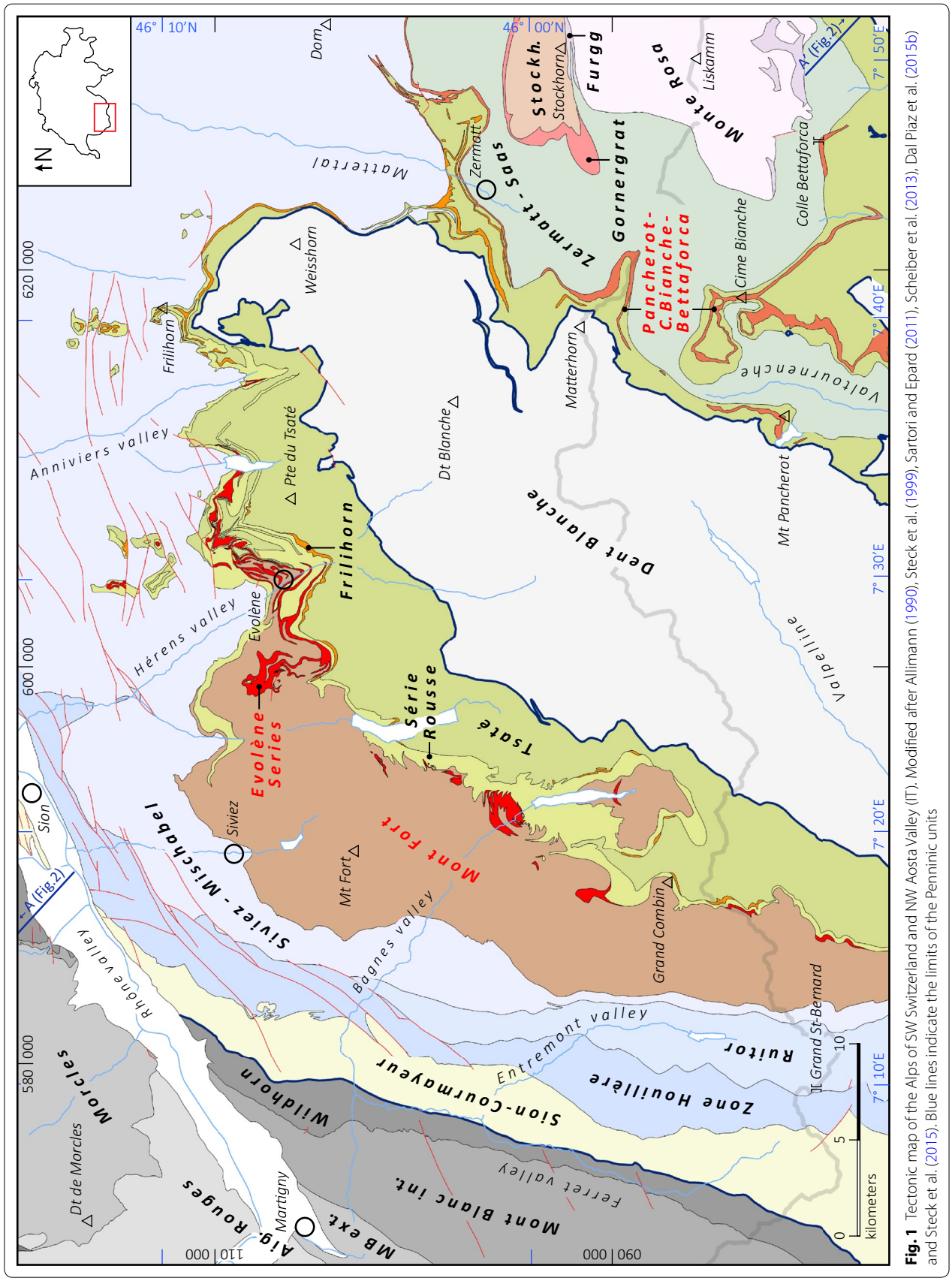


Fig. 1 Tectonic map of the Alps of SW Switzerland and NW Aosta Valley (IT). Modified after Allimann (1990), Steck et al. (1999), Sartori and Epard (2011), Scheiber et al. (2013), Dal Piaz et al. (2015b) and Steck et al. (2015). Blue lines indicate the limits of the Penninic units

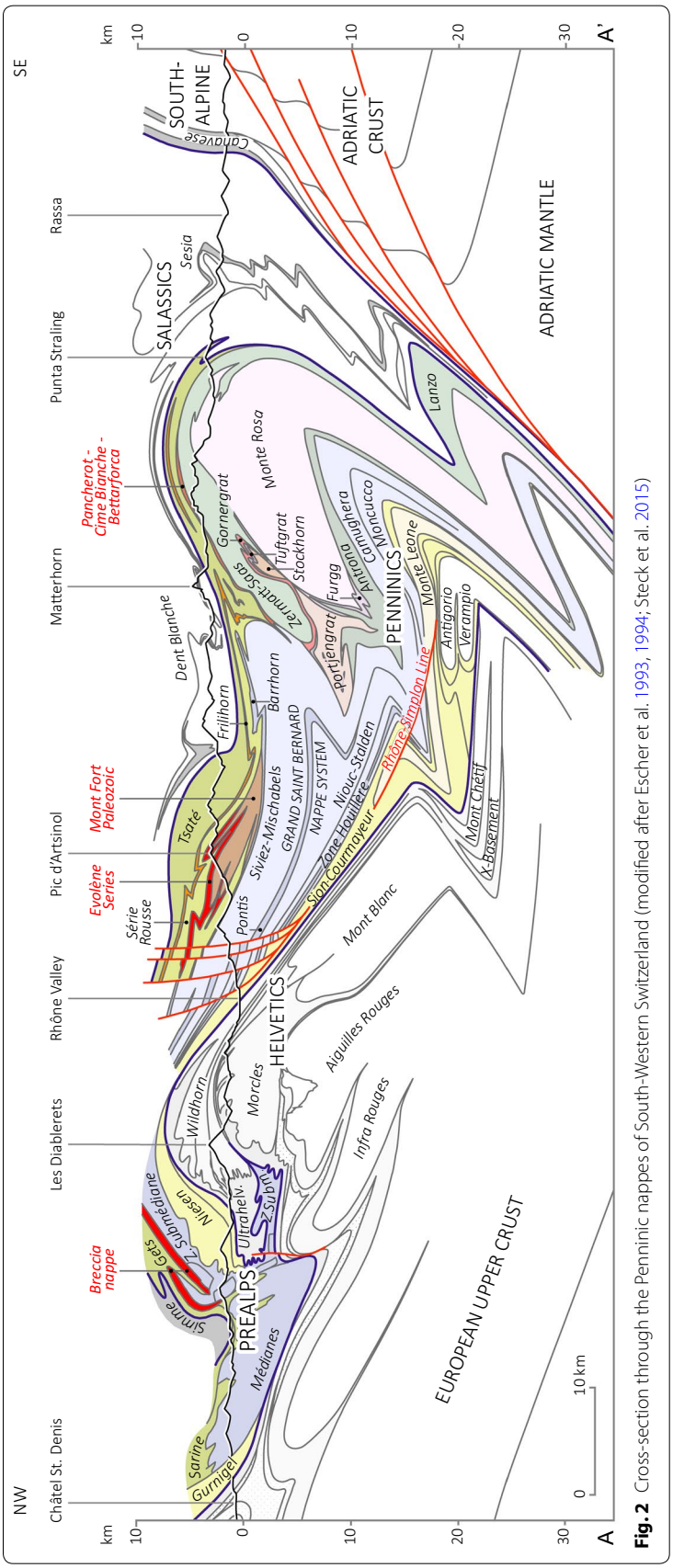


Fig. 2 Cross-section through the Penninic nappes of South-Western Switzerland (modified after Escher et al. 1993, 1994; Steck et al. 2015)

the Prealps (Lemoine 1961). This second area is particularly important for our work because of the great similarity between the Breccia and Mont Fort nappes (see further). The Middle Jurassic evolution of the Prepiedmont domain is exactly opposite to that of the Briançonnais s.str.: the Prepiedmont is collapsing and deepening at the very moment when the Briançonnais s.str. is uprising and emerging (cf. Chenin et al. 2019). This is also the time when the Piedmont ocean starts to open (e.g. Bill et al. 1997). A characteristic of the Prepiedmont Jurassic sediments is the abundance of breccias and other coarse-grained detrital sediments generated by this extension at the passive margin.

The *Mont Fort* nappe shows typical features indicating that its paleogeographic origin has to be looked for in the Prepiedmont domain. It was defined by Escher (1988; Escher et al. 1988) as the upper tectonic subdivision of the former Grand St-Bernard (GSB) nappe system, which is the largest tectonic unit in the classical synthesis of the Pennine Alps by Argand (1911). Its name appears more or less simultaneously in the publications of several colleagues, students or visitors of Escher (e.g. Escher and Masson 1984; Allimann 1987, 1989; Sartori 1987; Woodtli et al. 1987). More recent works emphasize its tectonic independence from the former GSB nappe, from which it differs notably by:

- the absence of a structural connection: following these units towards SW in Italy, they always remain clearly separated (Gouffon 1993; Gouffon and Burri 1997);

- slightly higher pressure during Alpine metamorphism, denoted by the abundance of glaucophane in the metabasites (Wegmann 1922; Vallet 1950; Schürmann 1953; Wust and Baehni 1986; Escher 1988; Thélin et al. 1994; Steck et al. 2001: Fig. 1; Bousquet et al. 2004); however a modern mineralogical study is still lacking;

- a Mesozoic sedimentary cover rich in breccias of Jurassic age, characteristic of the Prepiedmont domain (Marthaler 1984; Escher 1988), and definitely distinct from the Briançonnais s.str. and the Subbriançonnais series that characterize the Jurassic of the rest of the former GSB nappe (Ellenberger 1952, 1958; Trümpy 1960; Escher 1988; Sartori 1990).

For all these reasons the Mont Fort nappe is considered a totally independent tectonic unit, distinct from the rest of the GSB nappe system and its subdivisions.

The Mont Fort nappe consists of a thick Paleozoic basement, overlain by a discontinuous and generally thin cover of Triassic-Jurassic sediments called the *Evolène* Series (Escher 1988). This series has been originally considered to represent the sedimentary cover of the Mont Fort nappe, stratigraphically overlying the Mont Fort basement. All our observations support this interpretation. However this view has been strongly debated during the last 25 years and confronted with a different tectonic interpretation according to which the Evolène Series is considered to represent an allochthonous slice with respect to the Mont Fort basement. According to this second model, the basal contact of the Evolène Series would be an Alpine thrust, and this series would be linked to a different tectonic unit, the Cimes Blanches nappe (e.g. Sartori and Marthaler 1994; Escher et al. 1997; Steck et al. 1999; Tektonische Karte der Schweiz 2005; Sartori et al. 2006). The choice between these two models has major implications for the tectonic reconstitution of the Pennine Alps in general. One of the aims of this study is to present the facts that support the stratigraphic interpretation of this contact and to develop its consequences.

The Evolène Series is in turn overlain by a set of calcschists and fine-grained detrital limestones called

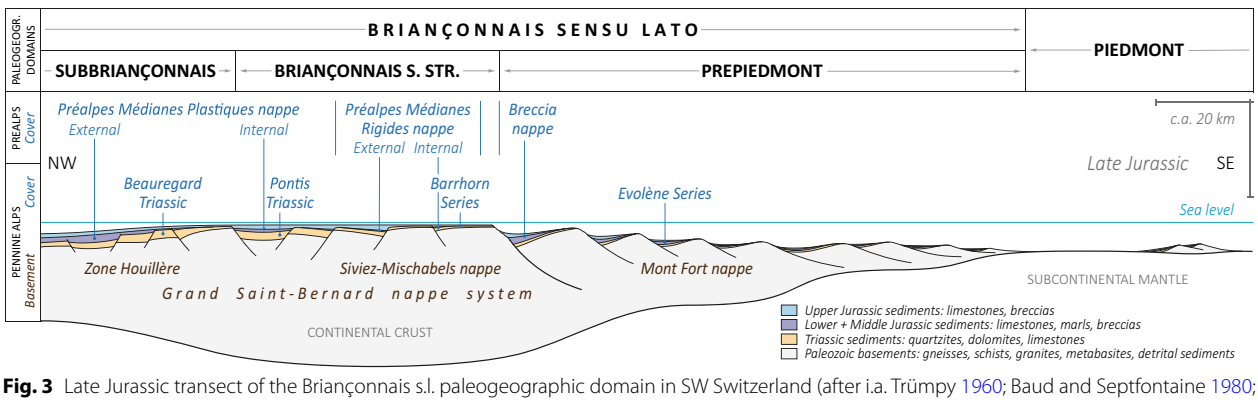


Fig. 3 Late Jurassic transect of the Briançonnais s.l. paleogeographic domain in SW Switzerland (after i.a. Trümpy 1960; Baud and Septfontaine 1980; Sartori 1990; Septfontaine 1995; Plancherel et al. 1998; Mohn et al. 2010, 2012; Decarlis et al. 2017a). The distance between the Préalpes Médianes Rigides and the Breccia nappe basins is uncertain and represents a minimal estimate (the domain separating these 2 basins is often referred to as *Ultrabriançonnais)*

the *Série Rousse* that is paleontologically dated from the base of the Late Cretaceous (Marthaler 1984). In the working region the Série Rousse forms the lower part of a thick complex of calcschists traditionally called Schistes Lustrés in the Western Alps. The contact of the Série Rousse over the Evolène Series is unconformable and its nature is the subject of current research. We will not treat here the problems posed by the Série Rousse (work in progress). Instead this paper focusses on the Evolène Series and its relations with the Mont Fort basement. Below is a short description of the local units.

3 The Mont Fort basement

The Mont Fort basement consists of the following lithostratigraphic units:

1. The older Mont Fallère unit (Gouffon 1993; Gouffon and Burri 1997) is made of rusty brown, often graphitic micaschists. This unit is poorly represented in the study area.
2. The Métailler Formation, mainly made of albitic paragneisses, is a thick detrital sequence (greywackes to arkoses and micaschists) with abundant intercalations of metabasites (including pillow basalts and sill-like bodies of gabbros). It forms the core of the nappe (Oulianoff 1954; Schaer 1960; Bearth 1963; Burri 1983; Thélin and Ayrton 1983; Gouffon 1993; Chessex 1995; Gouffon and Burri 1997; Sartori et al. 2006). Its age has long been debated, but recent LA-ICPMS U–Pb dating of magmatic zircons from two gabbros, at least partially cleared up this debate in yielding ages around 456 to 462 Ma (Ordovician) (Gauthiez et al. 2011).
3. The Greppon Blanc Fm. is an up to more than 1000 m thick sequence of continental detrital sediments, mainly quartzschists and phyllitic quartzites. It is classically ascribed to the Permian (Schaer 1960). More recently Sartori et al. (2006) defined a Col de Chassoure Fm. which is essentially identical with the Greppon Blanc Fm., but for the fact that its upper limit is placed slightly lower. For our purpose it is more convenient to keep the traditional designation Greppon Blanc with its traditional limits.

A particular feature of the Mont Fort basement is the absence of granitic intrusions, in contrast with the rest of the former GSB nappe and other Penninic nappe basements where Paleozoic granites are always present (e.g. Bearth 1964; Bussy et al. 1996a; Genier et al. 2008; Scheiber et al. 2014; Bergomi et al. 2017; Ballèvre et al. 2018, 2020). However a few intercalations of rhyolitic flows and ignimbrites, of Early to Middle Permian age, occur above the base of the Greppon Blanc Fm. (Bussy et al. 1996b; Derron et al. 2006; Sartori et al. 2006).

4 The Evolène Series: stratigraphic synthesis and new data

4.1 Introduction

The Evolène Series directly overlies the Mont Fort basement. Along the normal limb of the Mont Fort nappe, the Evolène Series is discontinuous and often incomplete or absent (Fig. 1). We will argue that such absences are due to Jurassic erosion and/or to paleofaults. The Evolène Series is best developed around the frontal folds of the Mont Fort nappe. It is lacking in the overturned limb of the nappe (Fig. 1).

Figure 4 presents a synthetic theoretical column based on combining and crosschecking all local observations. Thickness of the layers is extremely variable, both because of irregular sedimentation on a tectonically active, very mobile basin floor, and because of subsequent Alpine deformation. Relative thicknesses given in Fig. 4 are very approximate and often arbitrary because of the high amount of strain during Alpine deformation.

Robust stratigraphy is a prerequisite for unraveling tectonic structures and paleogeography. Like in many other parts of the Penninics, the stratigraphy of the Evolène Series was for long a mystery because of poverty in biostragraphically significant and well preserved fossils and because of the blurring of the sedimentary record by strong Alpine deformation. However, fortunately enough several portions of the Penninic Mesozoic sedimentary covers were “décollées”, transported and piled up in the foreland of the belt, particularly in the Prealps (Fig. 2). There they escaped most of the metamorphism and deformation. In these external zones, their study can provide useful clues on the stratigraphy of the sediments that originally bordered them but remained attached to their Penninic basement. In the case of the Triassic-Jurassic Evolène Series, two nappes of the Prealps provide crucial details for comparison: (1) regarding the Triassic, the Préalpes Médianes Rigides nappe appears to be relevant for comparison as it displays one of the most complete and typical Triassic stratigraphic sequences of the Briançonnais-derived units of the Prealps (e.g. Ellenberger 1952; Trümpy 1954; Botteron 1961; Mégard-Galli and Baud 1977; Baud and Septfontaine 1980; Hürlimann et al. 1996); (2) regarding the Jurassic, a comparison with the Breccia nappe derived from the Prepiedmont domain (Lemoine 1961; Weidmann 1972; Plancherel et al. 1998) provides a solid base for stratigraphic analysis.

4.2 Triassic of the Evolène Series: affinities with the Briançonnais s.l.

The Triassic of the Evolène Series starts with a level of pure white tabular quartzite, similar to the basal quartzite that is classical in many other Penninic cover series and traditionally ascribed to the Lower Triassic. In the Prealps Sartori et al. (2006) named this level the Sous le Rocher Member. At Evolène, if not thickened by folding, its thickness varies from 0 to 20 m, much thinner than in the typical Briançonnais s.str. series. Original thickness variations (down to local absence) can be appropriately explained by the gradual transgression of the sea upon the weak paleorelief of the Triassic peneplain.

The base of the Triassic tabular quartzite always lies with a concordant contact on top of the uppermost layers of the Greppon Blanc Fm. represented by phyllitic quartzites. A progressive transition between the two lithologies can be observed by a gradual decrease of the phyllitic component on a few dm (Allimann 1987, 1990). A similar transition is commonly observed at the Mesozoic/Paleozoic contact in the rest of the GSB nappe system (e.g. Sartori 1990; Sartori et al. 2006; Genier et al. 2008).

The tabular quartzite of the Evolène Series is followed by a carbonate sequence, mainly dolomite, whose thickness never exceeds a few tens of meters, again much thinner than in the Briançonnais s.str.. At its base it may contain very thin quartzo-micaceous bands suggestive of pelitic intercalations, a fact often observed at the base of the Briançonnais carbonate sequence (Dorchaux Member; Baud 1987). This dolomite can be accompanied by cornieule (rauhwacke), at one point by gypsum (pinched in the synclinal core of a frontal fold above Evolène; Allimann 1990) and by limestones that provide more precise stratigraphic indications. The best outcrops are observed in the cliffs of the torrent NE of Evolène (Allimann 1990). There we note the occurrence of a several meters thick layer of grey-bluish, finely laminated limestone similar to the "calcaire rubané" of the Champcella (or Wiriehorn) Fm. of the Briançonnais Triassic in the French Alps and the Prealps. This formation has been recently assigned to the Late Anisian (early Middle Triassic; Baud et al. 2016). Another noteworthy feature is the occasional presence of blocks of typical Briançonnais Triassic limestones reworked in the Jurassic breccias of the Evolène Series, in particular fossiliferous and vermiculated limestones (Allimann 1987, 1990; A. Baud, A. Escher and P. Viredaz, pers. comm.; a sample containing well preserved *Physoporella* is deposited at the Sion Museum, courtesy of N. Kramar). Some of these rocks are very characteristic of the Saint-Triphon Fm. defined in the Prealps (Early to Middle Anisian; e.g. Mégard-Galli and Baud 1977; Baud 1987).

To conclude, the Triassic of the Mont Fort nappe displays a facies identical to that of typical Briançonnais s.str. occurrences, but with a much reduced thickness. This fits well with its position at the border of a platform, progressively flooded by the transgression of the sea near the southern limit of the Briançonnais s.l. Triassic domain. In the Mont Fort nappe these formations have been largely attacked by erosion during the Early to Middle Jurassic.

4.3 Jurassic of the Evolène Series: signification of the Jurassic breccias

The Jurassic of the Evolène Series is characterized by thick layers of breccia deposited over much thinner series of limestones and marls. The latter start with a m-thick level of light grey, bedded, sometimes oolitic limestone. In the Prealps a similar level is attributed to the earliest Jurassic (Hettangian; Chessex 1959). This level is overlain by fine-grained, generally dark, (dolo)calcarenites and marls of variable thickness, coarsening upwards and gradually passing to breccias. Older authors already mentioned the presence of breccias in this position, e.g. in the Pic d'Artsinol, Sasseneire and Mauvoisin areas (Joukowsky 1907; Wegmann 1922; de Szepessy Schaurek 1949; Hagen 1951). The great analogy of the breccias of the Evolène Series with those of the Breccia nappe in the Prealps has been pointed out several times (Joukowsky 1907; Escher 1988; Escher et al. 1997; Sartori et al. 2006; Marthaler et al. 2008). Our study enhances the similarity of the Evolène breccia layers with the Jurassic of the Breccia nappe in the Prealps.

In the Prealps it is modern practice to still use the old stratigraphic nomenclature of Lugeon (1896; e.g. Chessex 1959; Weidmann 1972; Dall'Agnolo 1997, 2000; Plancherel et al. 1998). The Jurassic columns of the Mont Fort and Breccia nappes are so similar that this practice has been successfully extended to the Evolène Series (Fig. 4). This Fig. 4 will exempt us from a detailed description. Below we only add the following remarks:

1. A commonly accepted mechanism for the origin of these submarine, often massive breccias has been proposed in the classical works of Trümpy (1960), Lemoine (1967) and Weidmann (1972): their genesis would result from very active extensional faulting followed by the collapse of fault scarps and the transport of the debris on the bottom of the sea by various kinds of gravity-driven down-slope currents. Certainly, this mechanism is very plausible, but in the areas discussed here (Mont Fort and Breccia nappes) the existence of important faults of Jurassic age has rarely been confirmed by direct field observations. Our work will show that these faults are indeed well

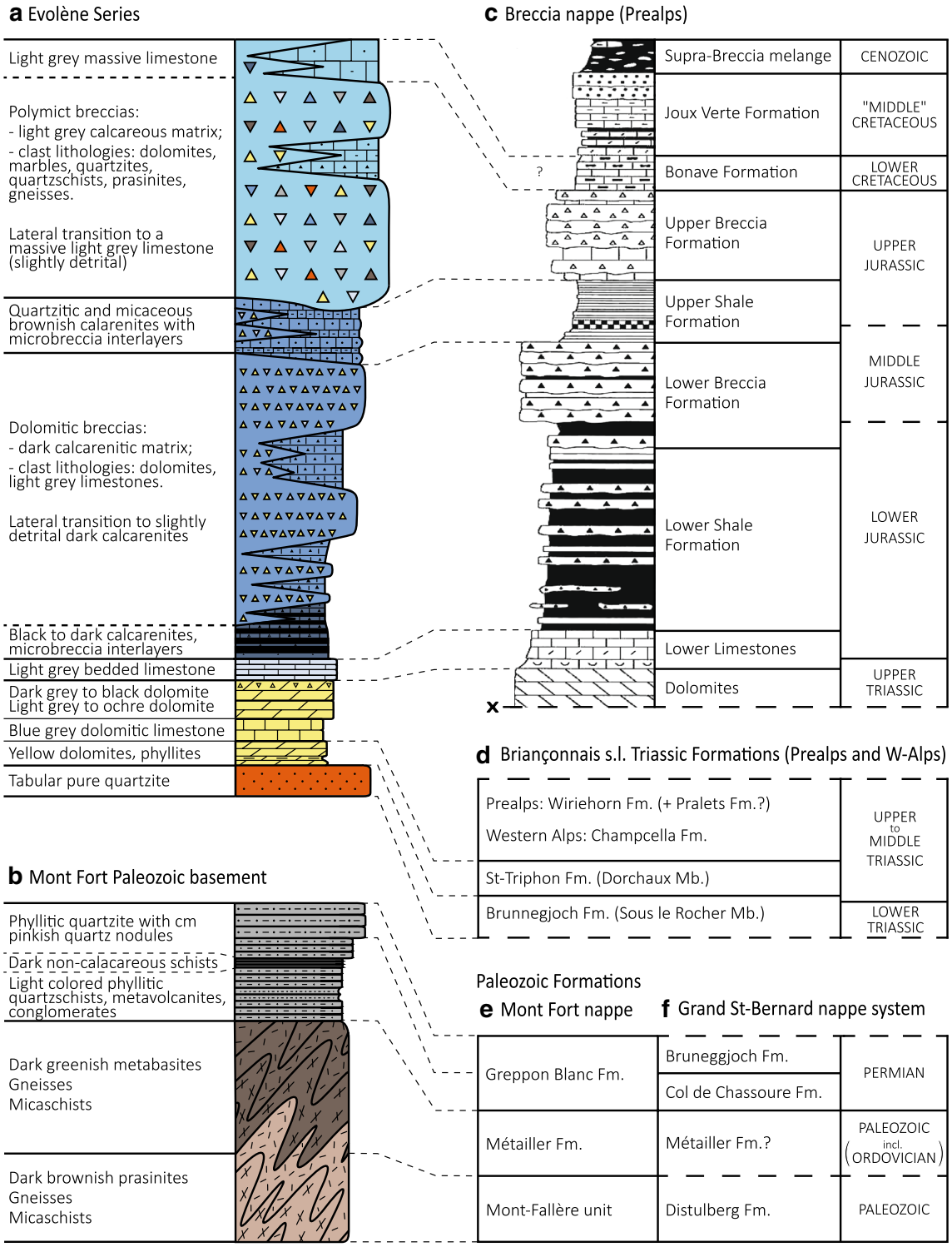


Fig. 4 Stratigraphy of the Evolène Series and Mont Fort basement compared to the Prealps and the rest of the former GSB nappe. **a** Synthetic stratigraphic column of the Evolène Series. **b** Synthetic stratigraphic column of the Mont Fort Paleozoic basement. **c** Synthetic stratigraphic column of the Breccia nappe in the Prealps (modified after Dall'Agnolo 1997, 2000). **d** Triassic Formations of the Briançonnais s.l. domain (Prealps and Western Alps). Only the Briançonnais Triassic Formations having an observed equivalent in the Mont Fort nappe are listed. **e** Geological Formations defined in the Mont Fort Paleozoic basement. **f** Geological Formations defined in the GSB Paleozoic basements. Scales in (**a**) to (**e**) are different and arbitrary

developed, but, because of intense Alpine deformation, they remained unrecognized until nowadays.

2. The Lower Breccia (late Early to Middle Jurassic) and the Upper Breccia (latest Jurassic) represent distinct events, always separated by a time interval (estimated at ca. 10 Ma in the case of the Breccia nappe) that is dominated by pelitic to fine-grained detrital sedimentation. The formation of the oldest Piedmont ophiolites (166 Ma, on the OCT in the Gets nappe; Bill et al. 1997) is approximately synchronous with the last episodes of deposition of the Lower Breccia. These deposits thus mark the final break-up of the continental crust. The youngest preserved Piedmont ophiolites (155 Ma, in the Tsaté nappe; Decrausaz et al. 2019, 2020) fall into the period of relative quiescence between the two Breccia Formations. This means that at that time the continental margin was stabilized and that extension was localized in the exhumed mantle. However, the geodynamic interpretation of the movements that generated the Upper Breccia remains enigmatic.
3. The nature of the components of the breccias reflects the progressive erosion of the source areas. Thus the breccias display a kind of "inverse stratigraphic column" of the source areas. The first layers of breccia are often made only of dolomitic Triassic clasts, tightly packed in a rare, very fine-grained matrix (Fig. 5a). These monomict breccias can be very easily confused with a genuine Triassic dolomite ("reconstituted" or "regenerated Triassic" in the sense of Lemoine 1967), and this confusion has sometimes been an important cause of mistakes even in the non-metamorphic and little deformed Breccia nappe in the Prealps. This is still more the case in the strongly deformed Mont Fort nappe, where the distinction of the Jurassic Breccia from the Triassic dolomite can become extremely difficult and the resulting confusions may lead to a gross overestimation of the amount of Triassic formations. The clasts of Lower Triassic quartzites and Paleozoic basement rocks (Fig. 5b, c) only become frequent higher up, particularly in the Upper Breccia.

5 Alpine thrust or deformed normal faults?

5.1 The cover/basement contact: stratigraphic or tectonic?

As mentioned above, the contact of the Evolène Series upon the Mont Fort Paleozoic basement was initially considered as stratigraphic (e.g. Wegmann 1922; Allimann 1987; Escher 1988). However several authors soon proposed that it would be a tectonic contact, namely an Alpine thrust (e.g. Sartori and Marthaler 1994; Steck et al. 1999; Sartori et al. 2006; Marthaler et al. 2008). This second interpretation rapidly became dominant in the literature and official documents (e.g. Tektonische Karte der Schweiz 2005). It is based on the fact that the contact is often discordant at the map scale, with a small angular obliquity on both sides of the discontinuity: (1) on one side the Mesozoic Evolène Series can overly various levels of the Paleozoic basement; and (2) on the other side various levels of the Mesozoic series can form its base and rest over the basement (Figs. 6, 7, 8, 9 and 10). The angular obliquity between basement and cover is usually small, not exceeding a few degrees. It is understandable that, at first sight, this situation might give the impression of a tectonic contact representing a low-angle thrust fault.

In the framework of the tectonic interpretation of this contact, the Evolène Series was considered as allochthonous with respect to the Mont Fort basement and would belong to a distinct tectonic unit, namely the so-called Cimes Blanches nappe (e.g. Sartori and Marthaler 1994; Escher et al. 1997; Steck et al. 1999; Sartori et al. 2006). However some of these authors left small basal portions of the Evolène Triassic in the Mont Fort nappe. The type locality of the Cimes Blanches nappe is found elsewhere, namely in the Cime Bianche summits located southeast of the Dent Blanche nappe (Fig. 1). These summits exhibit one of the largest outcrops of a slice of metasediments well exposed around and south of Zermatt, the Pancherot – Cime Bianche – Bettaforca Unit (Dal Piaz 1988, 1999; Vannay and Allemann 1990). Stratigraphy, internal structure and origin of this unit are still poorly known and problematic (Dal Piaz et al. 2015a; Steck et al. 2015; Passeri et al. 2018; work in progress). In any case it is important to note that the Pancherot – Cime Bianche – Bettaforca occurrences of the Cimes Blanches nappe are totally disconnected from the Evolène Series in map and profile view (Figs. 1 and 2).

We are thus confronted with a conflict between two opposite interpretations of the contact between Mont Fort Paleozoic basement and overlying cover of Mesozoic sediments: stratigraphic or tectonic? We will present new field observations that support the stratigraphic interpretation. In other words we will show that the Evolène Series is the original autochthonous cover of the Mont Fort basement. But we will also show that the geometry of the contact has been deeply influenced, first by the activity of synsedimentary normal faults, then by the subsequent deformation of these faults during the Alpine orogeny. The key factor for our interpretation is the demonstration that the angular discordance of these normal faults with bedding was erased by Alpine tectonic strain.

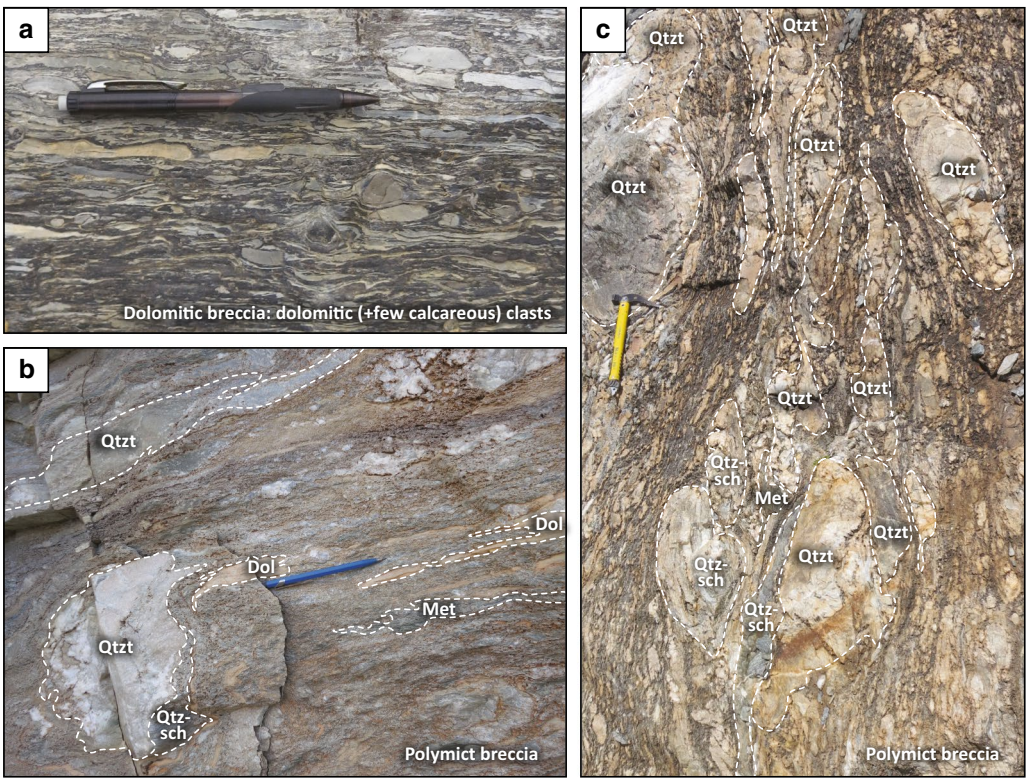


Fig. 5 Typical facies of the Evolène Series breccias. **a** Matrix-supported dolomitic breccia: clasts are mainly dolomitic; matrix is dark and calcarenitic [599′460/267′340]. **b** Clast-supported polymict breccia [595′370/101′930]. Main clasts lithologies: pure quartzite (**Qtzt**), quartzschists (**Qtz-sch**), metabasites (**Met**) identical to those of the Métailler Fm. (Mont Fort basement), dolomites (**Dol**). **c** Clast-supported coarse polymict breccia. Block fallen from the Pointe du Vasevay southern face [593′810/097′240]

5.2 The case of a concordant contact

The basal contact of the Evolène Series is not always discordant on top of the underlying basement. Locally it can also be concordant and reveal a complete stratigraphic sequence on both sides, without any important gap with respect to the reference column of Fig. 4. Here we present an example that is observable in the Roux area (Fig. 11).

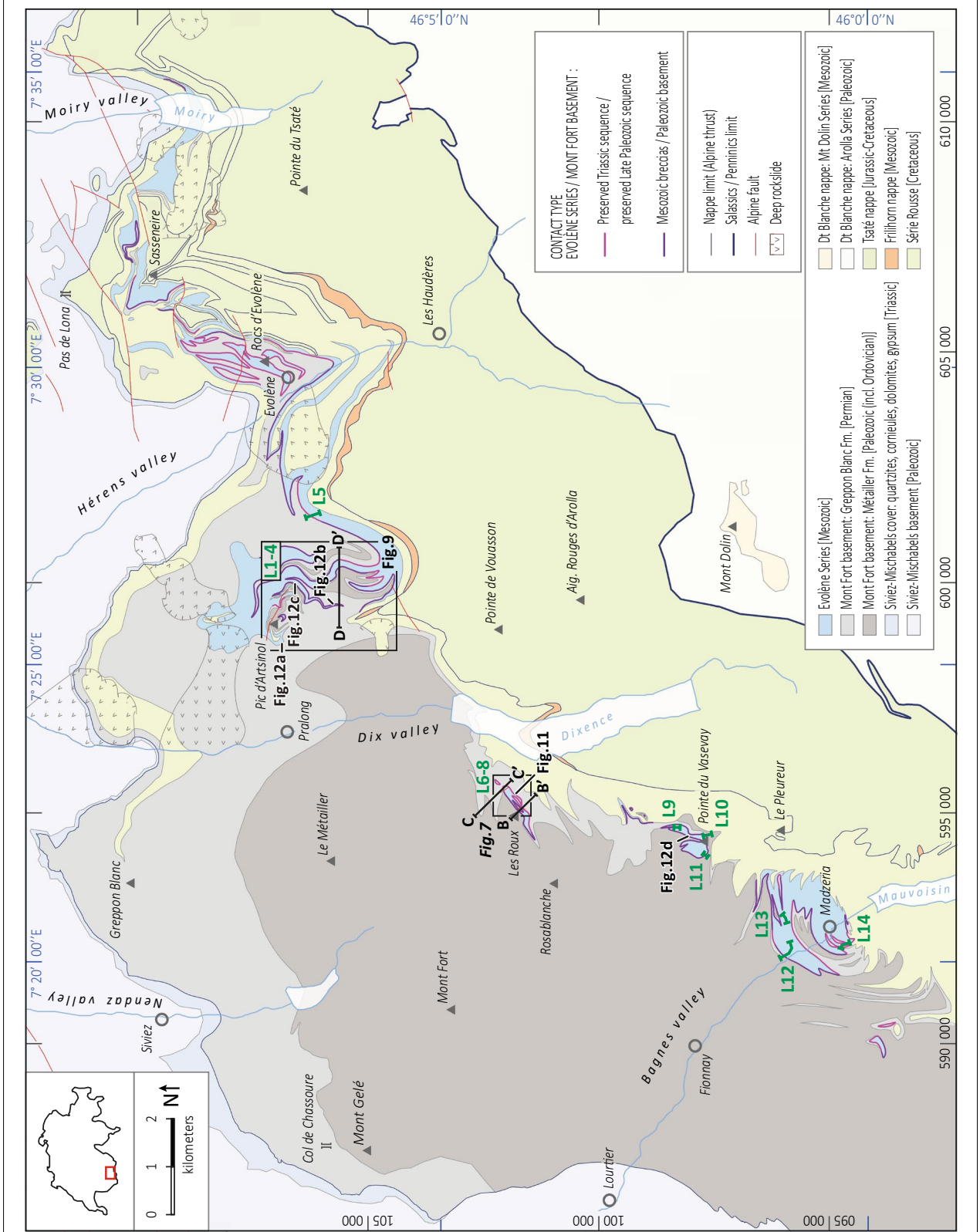
This outcrop exposes the normal superposition of all the stratigraphic formations from the Permian Greppon Blanc in the basement, up to the Jurassic breccia in the cover. Although these rocks are all affected by a rather strong Alpine deformation, no formation is missing. We note that the base of the Mesozoic sequence is essentially complete and relatively well preserved. The type and the intensity of deformation along, or in the vicinity of the contact, are similar to those in the rest of the outcrop. There is no hint of any important translation of the Evolène Series with respect to the basement. We can repeat similar observations at several places along the contact (sections of the contact outlined in pink on Fig. 6).

5.3 The case of a basal gap

As mentioned above, the superposition of the Mesozoic Evolène Series over the Mont Fort Paleozoic basement is frequently discordant, with an angular obliquity of a few degrees, often only noticeable at the map scale (Figs. 6, 7, 8, 9 and 10). This obliquity causes a gap of variable importance along the cover/basement contact, such that any layer of the Evolène Series, Triassic or Jurassic, may rest upon the Mont Fort Paleozoic.

(See figure on next page.)

Fig. 6 The Mont Fort nappe and surrounding tectonic units in SW Switzerland. Own data completed with a synthesis of the existing maps (Allimann 1990; Burri et al. 1998; Gabus et al. 2008; Sartori and Epard 2011; Sartori et al. 2011; Swisstopo Geocover mapping; and the unpublished diploma theses of the University of Lausanne from: Moix and Stampfli 1980, Rey 1992, Kramar 1997, Baillifard 1998, Favre 2000 and Glassey 2013). The location of the outcrops of Fig. 12 are indicated by Fig. 12a, b, etc. The location of the logs of Fig 14 is indicated by **L1-L14**. The position of the cross-sections of Figs. 8 and 10 is labeled **B-B′**, **C–C′** and **D-D′**


7° 35' 00"E
7° 30' 00"E
7° 25' 00"E
7° 20' 00"E
46°5' 0"N
46°0' 0"N
590 000
595 000
600 000
605 000
610 000
095 000
100 000
105 000
Moiry valley
Moiry
Pointe du Tsaté
Sasseneire
Pas de Lona
Rocs d'Evolène
Evolène
Les Haudères
Hérens valley
L5
L1-4
Fig.12b
Fig.12c
Fig.12a
Fig.9
D
D'
Pic d'Artsinol
Pralong
Pointe de Vouasson
Aig. Rouges d'Arolla
Mont Dolin
Dix valley
Dixence
L6-8
Fig.7
C
C'
B
B'
Fig.11
Les Roux
Le Métailler
Greppon Blanc
Nendaz valley
Siviez
Mont Fort
Rosablanche
Pointe du Vasevay
L9
L10
L11
Fig.12d
Le Pleureur
Mauvoisin
Madzeria
L13
L12
L14
Bagnes valley
Fionnay
Col de Chassoure
Mont Gelé
Lourtier
0 1 2 kilometers
N
CONTACT TYPE
EVOLÈNE SERIES / MONT FORT BASEMENT :
Preserved Triassic sequence / preserved Late Paleozoic sequence
Mesozoic breccias / Paleozoic basement
Nappe limit (Alpine thrust)
Salassics / Penninics limit
Alpine fault
Deep rockslide
Dt Blanche nappe: Mt Dolin Series [Mesozoic]
Dt Blanche nappe: Arolla Series [Paleozoic]
Tsaté nappe [Jurassic-Cretaceous]
Frilihorn nappe [Mesozoic]
Série Rousse [Cretaceous]
Evolène Series [Mesozoic]
Mont Fort basement: Greppon Blanc Fm. [Permian]
Mont Fort basement: Métailler Fm. [Paleozoic (incl. Ordovician)]
Siviez-Mischabels cover: quartzites, cornieules, dolomites, gypsum [Triassic]
Siviez-Mischabels basement [Paleozoic]

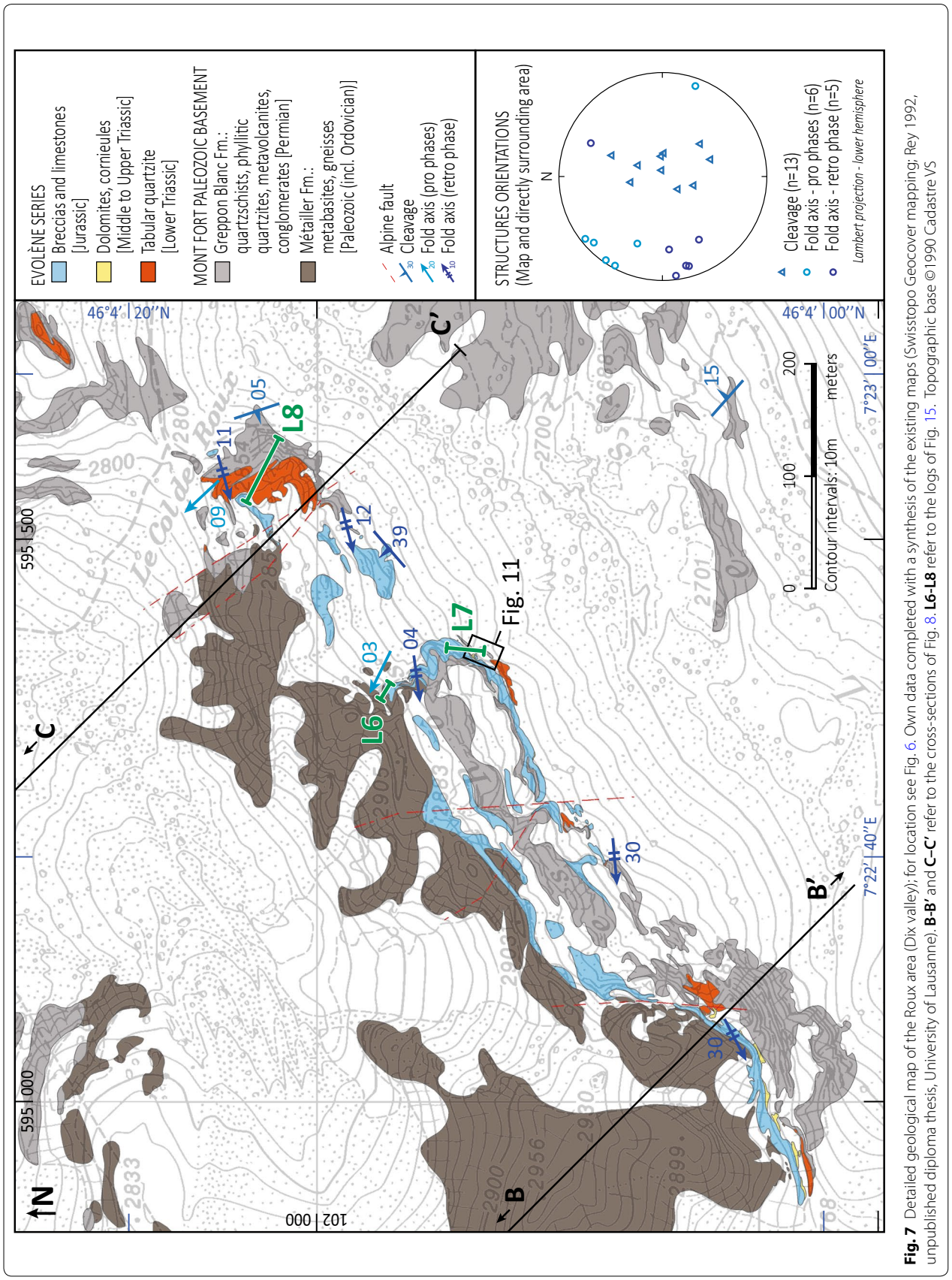


Fig. 7 Detailed geological map of the Roux area (Dix valley); for location see Fig. 6. Own data completed with a synthesis of the existing maps (Swisstopo Geocover mapping; Rey 1992, unpublished diploma thesis, University of Lausanne). **B-B'** and **C–C'** refer to the cross-sections of Fig. 8. **L6-L8** refer to the logs of Fig. 15. Topographic base ©1990 Cadastre VS

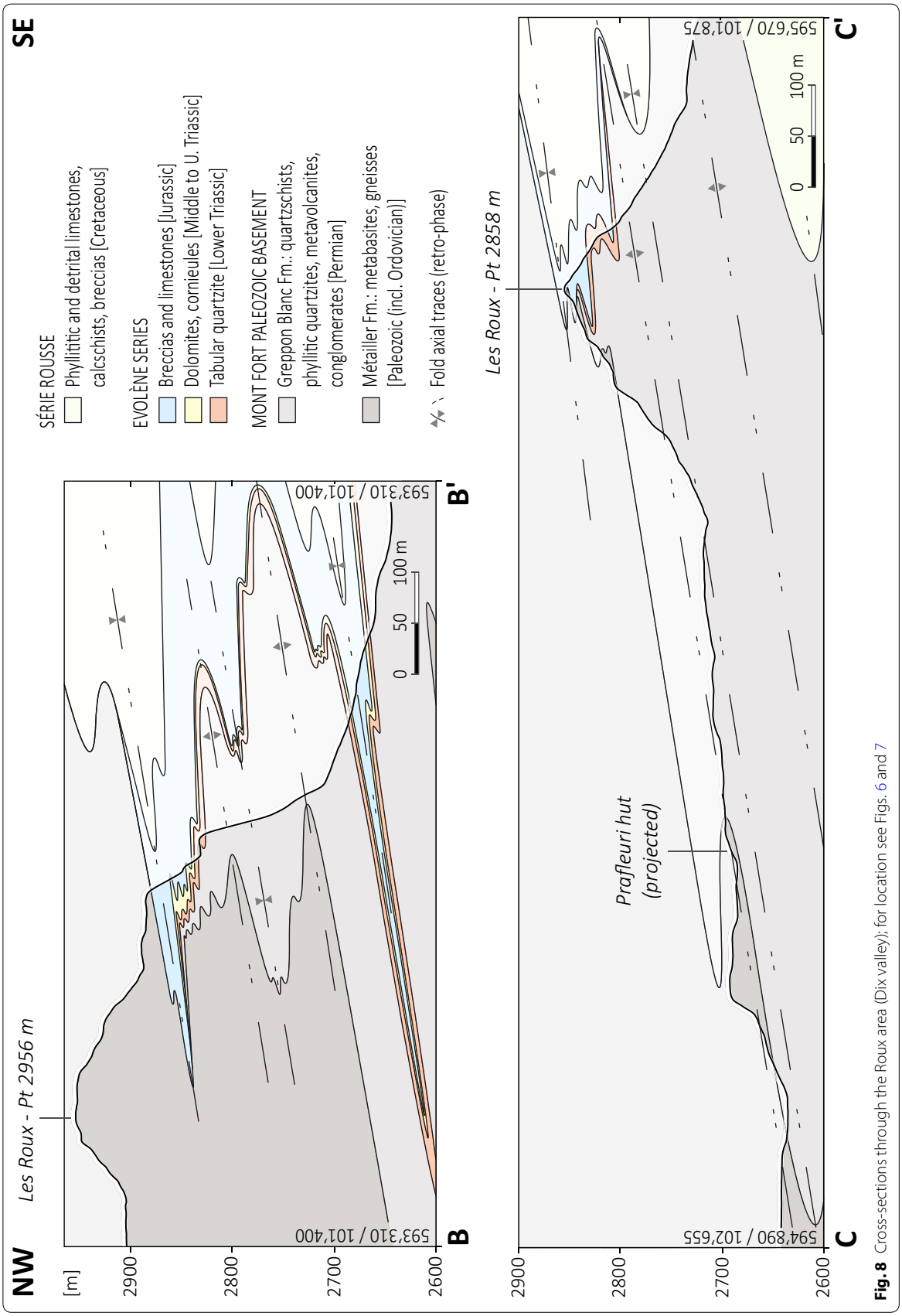


Fig. 8 Cross-sections through the Roux area (Dix valley); for location see Figs. 6 and 7

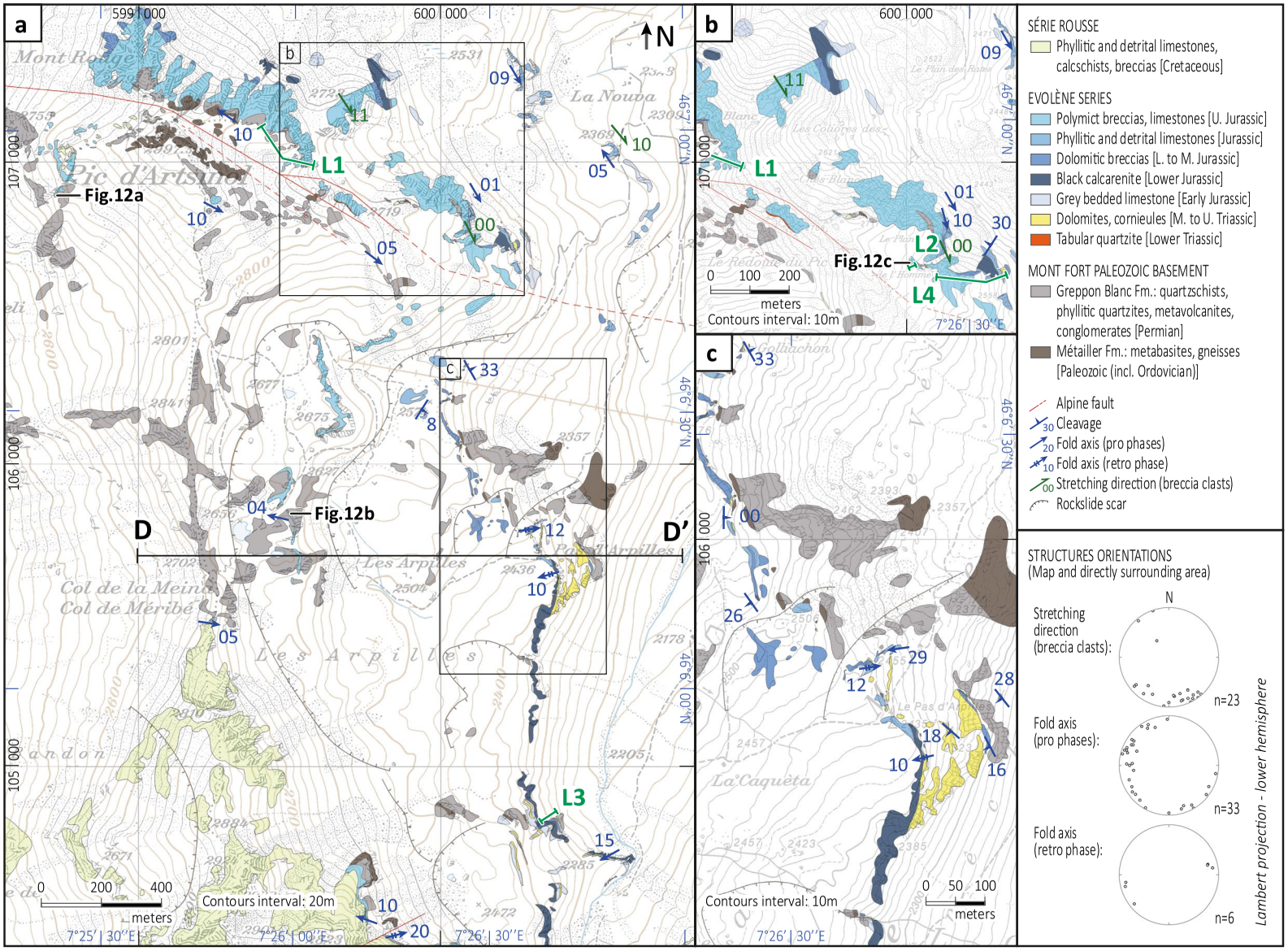


Fig. 9 Detailed geological maps of the Artsinol area (Hérens and Dix valleys). Own data completed with a synthesis of the existing maps (Allimann 1990; Swisstopo Geocover mapping; and the unpublished diploma theses of the University of Lausanne from Moix and Stampfli 1980 and Kramar 1997). **Fig. 12a, Fig.12b**, etc. refer to the locations of the outcrops of Fig. 12. **D-D'** refer to the cross-section of Fig. 10. **L1-L4** refer to the logs of Fig. 15. **a** General map. Topographic base © swisstopo (BA20045). **b** Detailed map of the Plan de l'Homme area. Topographic base ©1990 Cadastre VS. **c** Detailed map of the Pas d'Arpilles area. Topographic base ©1990 Cadastre VS

Fig. 10 Cross-section through Les Arpilles and Col de la Meina, in the Artsinol area (Hérens valley) based on the cross-section from N. Kramar 1997 (unpublished diploma thesis, University of Lausanne); for location see Fig. 9

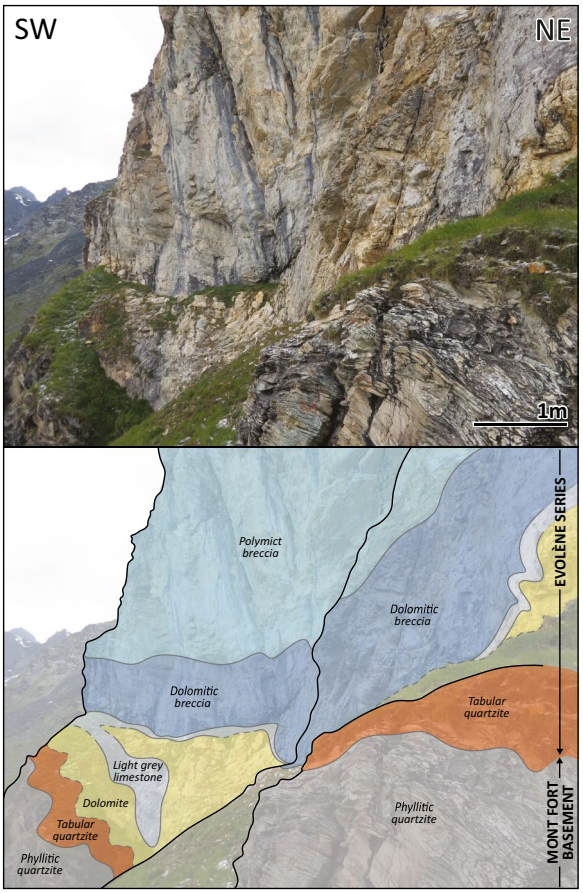


Fig. 11 Contact of the Mesozoic Evolène Series over the Mont Fort Paleozoic basement in the Roux area at locality [595′420/101′870] (cf. Figs. 6–8). The basement is formed by a phyllitic quartzite that belongs to the uppermost levels of the Permian Greppon Blanc Fm.. The cover exposes the normal succession of the L. Triassic pure quartzite, M. to U. Triassic dolomite, Early Jurassic bedded limestone and the thick L. to U. Jurassic breccias. The contacts between the formations are concordant although affected by a strong Alpine deformation

This discordance has been at the origin of the proposition that this contact is a thrust and corresponds to a nappe boundary. However, like in the concordant case, we do not observe abnormally high deformation along this discontinuity of the sort we could expect if it would separate two tectonic units. There is no particular increase in strain intensity, no hint of more intense shearing of the rocks. At the microscopic scale, the contact is sharp and shows no particular mark of movement (Fig. 12a, b). We did not observe any structure that would suggest that this contact is an Alpine thrust.

5.4 Local source of the clasts

We already noted that the clasts of the Evolène breccias reproduce an "inverse stratigraphy" of the source areas. It is customary that the Jurassic erosion first destroyed the Mesozoic carbonates before attacking the basement, an evolution that eventually gave birth to the polymict rocks that are much more abundant higher in the column. This applies particularly to those breccias whose basal contact is concordant and whose sequence respects the stratigraphic order. However, when discordances and gaps put the polymict breccias in direct contact with the Paleozoic basement, it is interesting to note that the composition of this local basement exerts a control over the nature of the clasts, as already noted by Allimann (1987). For instance, when in contact with quartzschists of the Mont Fort Greppon Blanc Fm., the breccia is often rich in quartzschist clasts (Fig. 12c). When in contact with the Mont Fort Métailler Fm., the polymict breccia generally contains metabasite elements (Fig. 12d). In the same order of ideas, it is striking that the Evolène breccias, that surmount a basement exceptionally poor in Paleozoic granites, never contain clasts of granite, contrary to other Penninic detrital series that often contain material of granitic origin. A similar correlation between the clasts of the breccias and the rocks exposed in the neighboring basement has been noted in the Prepiedmont domain of the French Alps by Lemoine (1967).

6 Discussion: passive ductile orogenic deformation of synsedimentary faults

The concordant contacts are clearly stratigraphic. Not only are they the base of essentially complete sequences (with respect to the reference stratigraphic column Fig. 4), but also they never display any hint of translation or unusual shear movement. This type of contact, although it can only be observed in good conditions at a few places, is crucial for the regional interpretation. These places are like pins that fix the Evolène Series to the underlying basement. It would be extremely difficult to imagine a mechanism that would fix the cover at some places and authorize large displacements at others. This constitutes a very strong argument for the autochthony of the Evolène Series as a whole, over the Mont Fort basement.

This interpretation is confirmed by the local provenance of the detrital material. This observation strongly suggests that the Evolène breccias formed in close vicinity of the parts of the Mont Fort basement with which they are today in contact. In other words, this proofs that this contact is original and stratigraphic.

The above-mentioned observations support the stratigraphic interpretation of the concordant as well as discordant contacts. However, an explanation of the

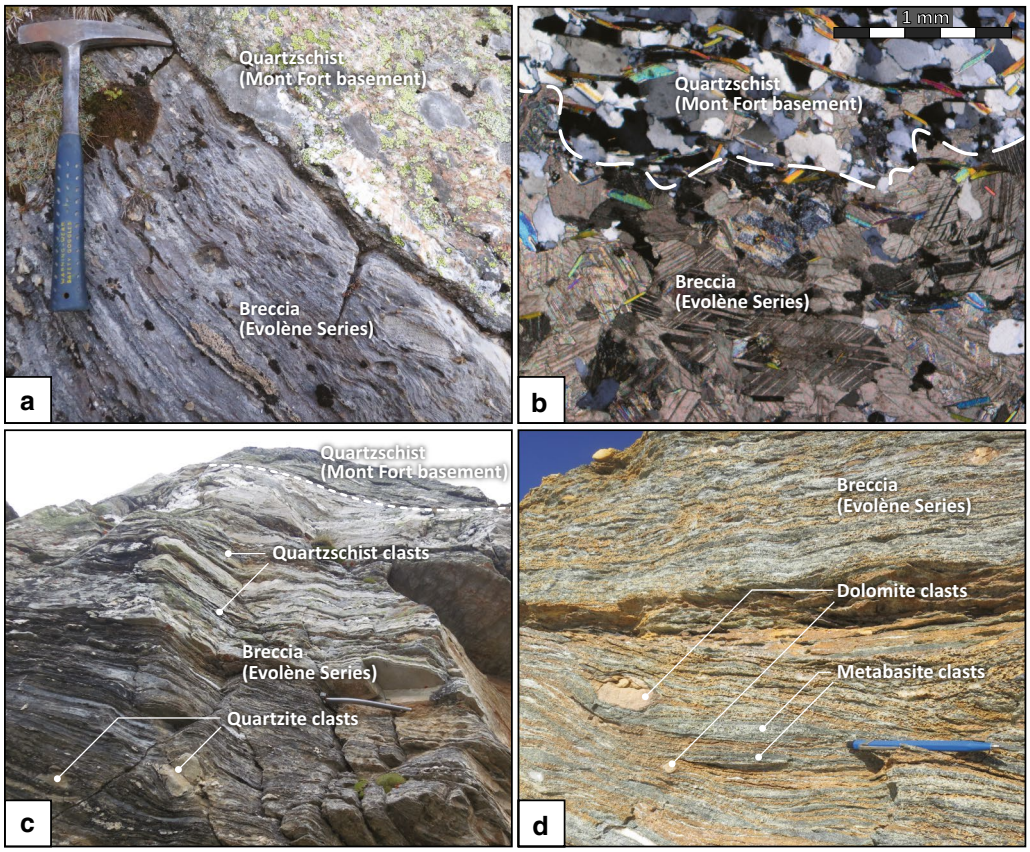


Fig. 12 Contacts between the Evolène Series Jurassic breccias and the Mont Fort Paleozoic basement. **a** Overturned contact between the Evolène U. Jurassic polymict breccia and the Mont Fort Permian quartzschists [598′730/106′890]. Note the absence of mylonitic levels or abnormal rock deformation at contact. Location on Fig. 9a. **b** Same type of contact, observed in thin-section (cross-polarized light), [599′440/105′890]. No abnormal deformation is observed even at the grain scale. Location on Fig. 9a. **c** Overturned contact between the Evolène U. Jurassic polymict breccia and the Mont Fort Permian quartzschists [600′010/106′750]. Within the first 3 m from the contact, the breccia is very rich in quartzschist clasts (reconstituted basement). Location on Fig. 9b. **d** Evolène U. Jurassic polymict breccia showing an abundance of metabasite clasts [594′470/098′040]. The clast lithology is identical to that of the Mont Fort metabasites (Métailler Fm.) which are outcropping less than 10 m away. Location on Fig. 6

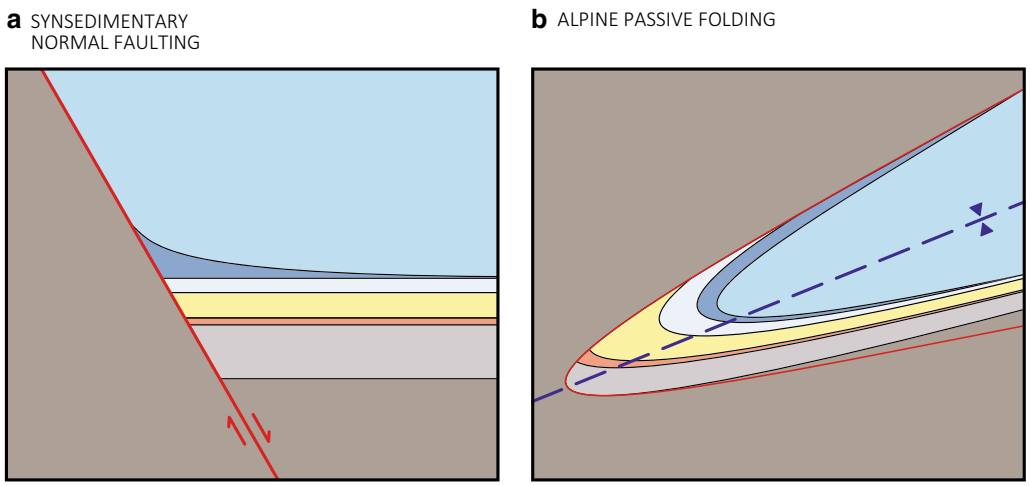


Fig. 13 Conceptual model of passive deformation of a pre-existing discordance. **a** Initial geometry resulting from the movement of a high-angle synsedimentary normal fault. **b** Transformation of the initial geometry by heterogeneous simple shear (sinusoidal function). Modeling was performed using the Shear2F software (Rey 2002)

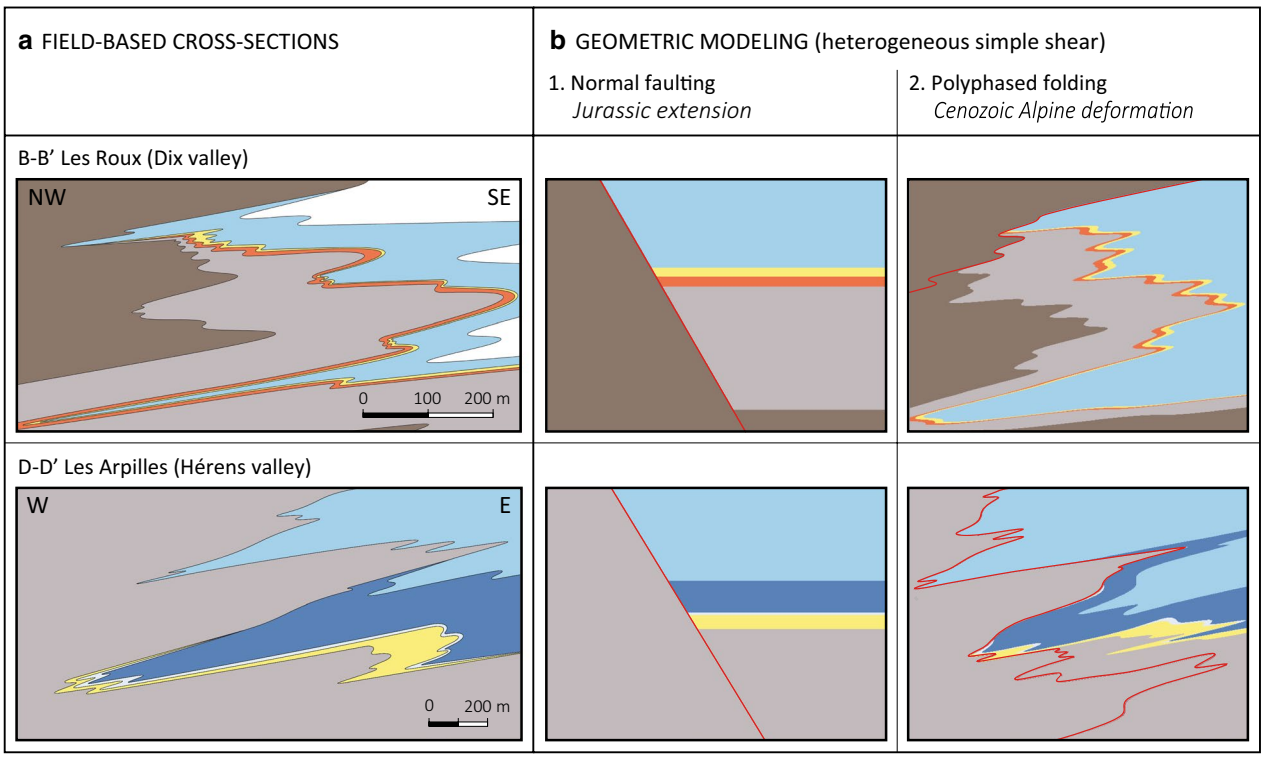


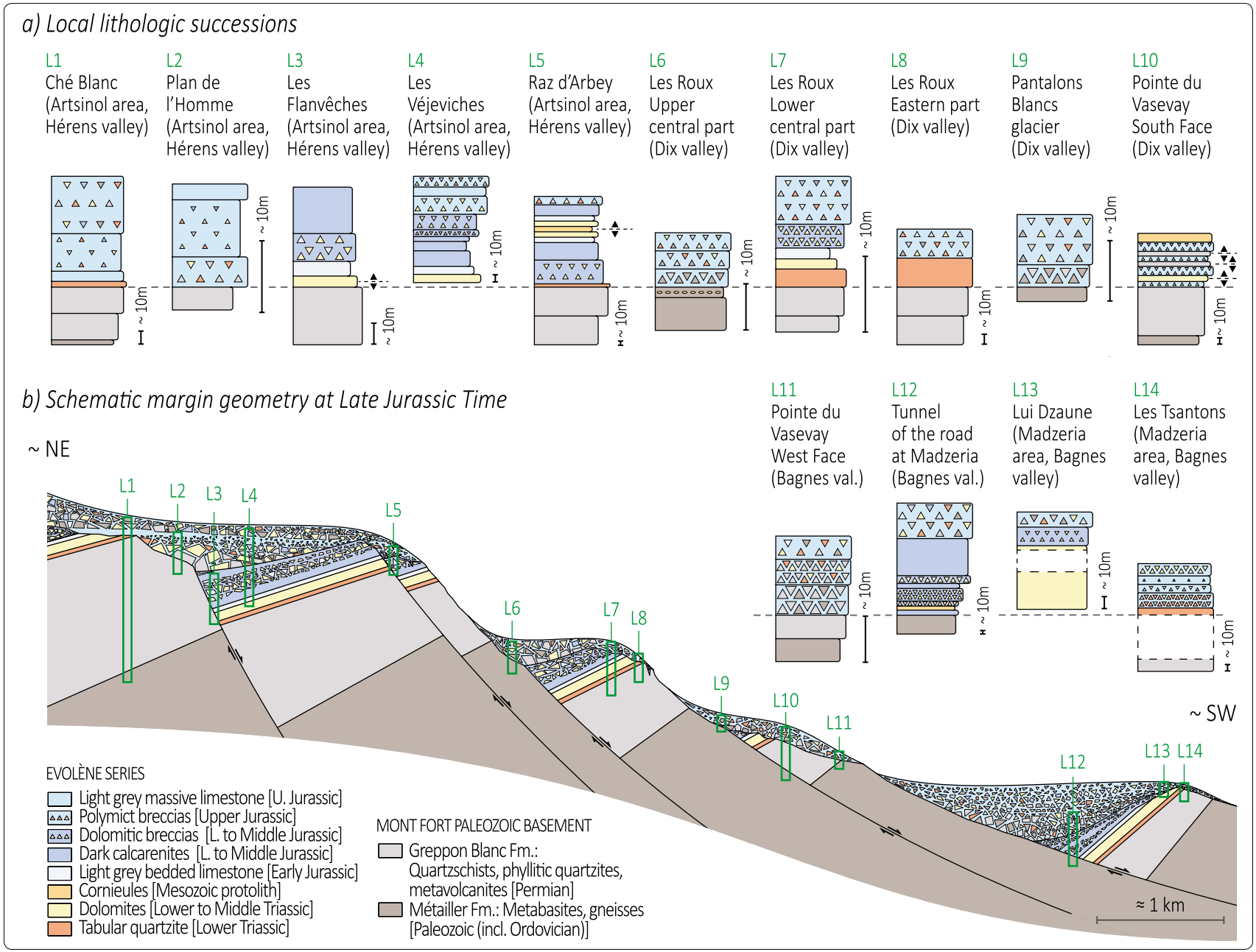
Fig. 14 Pre-folding restoration of the cross-sections of Figs. 8 and 10 by geometrical modeling. **a** Simplified cross-sections B-B' and D-D' (Figs. 8 and 10). **b** Geometric models obtained by heterogeneous simple shear superimposed on an initial normal fault. Modeling performed with Shear2F software (Rey 2002). Model outputs are vertical cross-sections through the 3D models. Detailed parameters of the applied deformations are given as Additional files (1 and 2). This demonstrates that the observed present-day geometry can be obtained by folding on an initial normal-fault

frequent gaps and discordances is needed. The absence of any particular deformation along most surfaces marking a lithological discontinuity suggests that these surfaces existed before the deposition of the sediments that surmount them. On the other hand, the fact that the same discontinuities cut large parts of the stratigraphic column implies that they must be younger. This apparent contradiction is interpreted to mean that these discontinuities are semi-contemporaneous in respect to the deposition of the breccias. The formation of the Evolène breccias can thus be considered as a consequence of the movement along these discontinuities, by coupled erosion and deposition.

A straightforward explanation of such gaps and discordances would be stretching by normal faulting of the area forming the future Mont Fort nappe, predating Alpine folding and thrusting. An episode of brittle faulting during Jurassic times would be in agreement with commonly accepted views on the paleotectonic evolution of the Alpine Tethys and its margins. In the case of our

(See figure on next page.)

Fig. 15 Local lithologic successions observed in the Mont Fort nappe and hypothetical Late Jurassic margin reconstruction. **a** Local lithologic successions observed in the Evolène Series and in the Mont Fort basement along their contact. The locations of the logs are given on Figs. 6, 7 and 9. The coordinates of their topographic bases and tops respectively are indicated below: **L1** (tectonically overturned) [599′410/107′106] to [599′577/106′990]; **L2** (tectonically overturned) [600′005/106′755] to [600′023/106′752], the picture of Fig. 12c is from the topographic upper part of the log; **L3** [600′400/104′840] to [600′340/104′810]; **L4** [600′250/106′720] to [600′070/106′700]; **L5** [601′590/106′620] to [601′655/106′270]; **L6** [595′355/101′940] to [595′370/101′930], the picture of Fig. 5b is from the middle part of the log; **L7** [595′400/101′850] to [595′405/101′880], the picture of Fig. 11 corresponds to the main part of the log; **L8** [595′600/102′040] to [595′535/102′065]; **L9** [594′673/098′370] to [594′687/098′357], the base of the breccia is extremely rich in Métailler clasts (similar to the picture of Fig. 12d); **L10** [594′520/097′630] to [594′460/097′760], modified after Gouffon and Burri (1997); **L11** [594′112/097′742] to [594′122/097′745]; **L12** [591′870/096′090] to [592′260/095′840]; **L13** [592′905/095′960] to [593′005/096′035]; **L14** [591′995/094′615] to [591′910/094′690]. **b** Reconstruction of the structure of the Mont Fort basement and Evolène Series at Late Jurassic Time. All the lithologic successions described in **a** can fit in this reconstruction, with a position in accordance with their current structural location. Relative thickness of the formations differs in **a** and **b**, due to highly heterogeneous Alpine deformation


a) Local lithologic successions
L1 Ché Blanc (Artsinol area, Hérens valley)
L2 Plan de l'Homme (Artsinol area, Hérens valley)
L3 Les Flanvêches (Artsinol area, Hérens valley)
L4 Les Véjeviches (Artsinol area, Hérens valley)
L5 Raz d'Arbey (Artsinol area, Hérens valley)
L6 Les Roux Upper central part (Dix valley)
L7 Les Roux Lower central part (Dix valley)
L8 Les Roux Eastern part (Dix valley)
L9 Pantalons Blancs glacier (Dix valley)
L10 Pointe du Vasevay South Face (Dix valley)
~ 10m
b) Schematic margin geometry at Late Jurassic Time
~ NE
~ SW
L11 Pointe du Vasevay West Face (Bagnes val.)
L12 Tunnel of the road at Madzeria (Bagnes val.)
L13 Lui Dzaune (Madzeria area, Bagnes valley)
L14 Les Tsantons (Madzeria area, Bagnes valley)
EVOLÈNE SERIES
Light grey massive limestone [U. Jurassic]
Polymict breccias [Upper Jurassic]
Dolomitic breccias [L. to Middle Jurassic]
Dark calcarenites [L. to Middle Jurassic]
Light grey bedded limestone [Early Jurassic]
Cornieules [Mesozoic protolith]
Dolomites [Lower to Middle Triassic]
Tabular quartzite [Lower Triassic]
MONT FORT PALEOZOIC BASEMENT
Greppon Blanc Fm.: Quartzschists, phyllitic quartzites, metavolcanites [Permian]
Métailler Fm.: Metabasites, gneisses [Paleozoic (incl. Ordovician)]
≈ 1 km

working area the interpretation of such discontinuity surfaces in terms of normal faults is not obvious because the observed obliquity to the layering is usually very small. This is probably the reason why they have not been recognized as such previously.

The strain related to Alpine shortening in all these rocks is so strong that the original angular relationships are only rarely preserved. Alpine deformation is indeed spectacular, both at the hm to km scale, as is revealed by the tight folding of the whole stratigraphic sequence (Figs. 8 and 10), and, at the cm to dm scale, by the shapes of the clasts (Figs. 5 and 12).

The theory of the deformation of oblique surfaces by tectonic strain has been developed by Ramsay (1967 chap. 9). This author demonstrated that, in general, increasing strain results in a progressive obliteration of angular discordances (in special cases the obliquity can increase, but in practice this is rare). This theory has been extensively applied, most notably to the deformation of discordant dykes in high-grade rocks. These dykes are gradually parallelized to older structures such as bedding and foliation (Escher et al. 1975; Escher and Watt 1976). Faults are planar markers that respond to later strains the same way: their obliquity is gradually erased by increasing strain until they become subparallel to the stratigraphic layering (Figs. 13 and 14). If applied to normal faults, this evolution will generate a situation where these faults will be, at first sight, easy to confuse with thrusts, all the more since the trace of the fracture in the basement can be very difficult to detect. This geometric transformation can be modeled by software that treats this problem in a rigorous quantitative way, as discussed in the next chapter.

An important vertical component of movement along these faults is revealed by the paleobathymetric evolution of the Prepiedmont domain during Jurassic (from shallow to deep-water sediments) and by the evolution of the source of the clasts (from younger to older). A horizontal, transcurrent component is also possible, but we have no way to reckon it.

During Alpine shortening our synsedimentary normal faults behaved like *passive markers* of strain. This merits to be underlined, because it is in contrast with numerous cases described in the literature where pre-existing faults are remobilized, often with a different sense of movement, e.g. normal faults inversed as thrusts (cf. Bonini et al. 2012 and references therein). Indeed such cases of remobilization of an older fault are by far the most frequently described ones and have become classical. This is, however not the case in the Mont Fort nappe, where older faults are deformed without being reactivated. We do not doubt that remobilization of pre-existing discontinuities may frequently occur elsewhere. However, we also think that the occurrence of ductile, passive deformation of faults has been underestimated. This mechanism might play an important role when the deformation takes place at depth in a thick-skin type tectonic context (cf. Epard and Escher 1996; Lafosse et al. 2016; Spitz et al. 2020). In all the examples presented here, Alpine deformation of the Jurassic synsedimentary faults is passive. This is not completely new: other examples of passive ductile deformation of paleo-normal faults have been described in the Alps, e.g. in the Helvetic realm by Krayenbuhl and Steck (2009) who showed how ductile folding of normal fault blocks, without reactivation, can generate structures that at first sight simulate thrusted slices.

The areas located in the normal limb of the Mont Fort nappe where the Evolène Series is missing (Fig. 6) correspond to the sectors where the fault scarps were exposed on the bottom of the sea, but were too steep to keep the syn- to post-faulting sediments (Fig. 15). In these sectors the Mont Fort basement is today covered either by post-Jurassic sediments or by a higher tectonic unit.

According to our reconstitution the Mont Fort nappe appears as a typical example of a distal rifted margin. The modern concept of distal margins has been particularly well developed on the Adriatic margin of the Alpine belt (e.g. Froitzheim and Eberli 1990; Florineth and Froitzheim 1994; Froitzheim and Manatschal 1996; Manatschal et al. 2003; Mohn et al. 2011, 2012; Epin et al. 2017; Ribes et al. 2019), less on the European side. This is probably due, in part, to the fact that on the NW border of the Tethys the corresponding series in this paleogeographic position have often been affected during orogeny by much more intense ductile deformation, creating supplementary difficulties and traps that are exemplified in the Mont Fort nappe.

7 Geometric modeling

Geometric modeling has been performed using the Shear2F software (Rey 2002), in order to apply passive folding deformation on initial geometries corresponding to normal faults (Figs. 13 and 14). The aim of this modeling is to argue that the mechanism of passive folding of an initial normal fault geometry is suitable to explain the origin of the complex structures observed along the basal contact of the Evolène Series. The objective here is not to reproduce all details and complexity of the Alpine tectonic history of the Mont Fort nappe, but only to show that the structures observed at the basal contact of the Evolène Series can be reproduced by deformation of discordances originally formed by normal faults.

The Shear2F software allows applying multiphase passive superimposed deformation on initial 3D pixel-sets. These initial pixel-sets are composed of different horizontal layers, whose number, individual thickness and colors can be parameterized. For 3D simple-shear

deformations, the following parameters can be set: (1) the orientation of the shear plane; (2) the orientation of the flow direction of the material in the shear plane (vector "a", shear displacement, in Ramsay 1967); (3) the variation of the amplitude of the vector "a", which is determined by a function, as e.g. a composite sine-function in which the amplitudes and the wavelengths can be parameterized (other types of function are also available such as a step function to model fault, or freely drawn function to model more complex structures).

For the two models presented in Fig. 14b, the parameters of the multiphase deformations were adjusted in such a way that the final geometries of the models approximate the ones of the field cross-sections (Figs. 8, 10 and 14a). Three successive phases of deformation were applied on initial 3D horizontal-layered pixel-sets:

- one step-function allowing introducing a high-angle normal fault in the pixel-set, in order to model the effect of the Jurassic extension;
- two superimposed composite phases of heterogeneous simple-shear, in order to model the Cenozoic Alpine deformation.

Detailed parameters of the applied deformation functions are given as Additional files (1 and 2). The model outputs presented in Fig. 14b are 2D cross-sections through the 3D models.

Since the presented modeling is able to reproduce the main characteristics of the observed structures, it confirms the view that that passive folding of an initial normal fault geometry can explain the complex structures observed along the basal contact of the Evolène Series.

8 Conclusions

The main results of this study are the following:

1. The Evolène Triassic-Jurassic Series represents the Mesozoic cover of the Mont Fort nappe. It stratigraphically overlies the Mont Fort Paleozoic basement.
2. Discordant contacts, accompanied by a gap of variable importance, frequently observed along the cover/basement boundary, represent paleo-normal faults of Jurassic age.
3. The usually very small angular discordances result from the erasing of the original obliquity of the faults by Alpine strain (Fig. 14). This geometric transformation is responsible for the misleading appearance of these normal faults as representing a thrust.
4. Collapse and syntectonic erosion of the active faults provided the material that forms the Jurassic breccias. This study reveals the link between observed faults and specific breccia accumulations (Fig. 15).
5. Our model explains the discontinuous localization of the Evolène Series upon the Mont Fort basement. Its absence corresponds to places where the denuded faults were exposed at the bottom of the sea (Fig. 15).
6. According to our reconstitution the Mont Fort nappe appears as a typical example of a distal rifted margin (Fig. 3).
7. Contrary to examples frequently described in other regions, the Jurassic faults of the Mont Fort nappe were not reactivated during Alpine tectonics. They responded passively to ductile Alpine deformation such as to mimic a thrust.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s00015-020-00366-2.

Additional file 1. Shear2F models parameters.

Additional file 2. Shear2F freely drawn profile function for the Roux model 1st order retro folds (heterogeneous simple shear).

Abbreviations

GSB: Grand St-Bernard; OCT: Ocean-Continent transition; [xxx′xxx/yyy′yyyy]: Geographic coordinates refer to the Swiss grid CH1903.

Acknowledgements

The authors would like to thank the following people, who were of great support in carrying out this study: Michel Ballèvre and Paola Manzotti for guiding us in the Mont Pancherot; Gianreto Manatschal, Yves Gouffon and Mario Sartori for the highly interesting discussions regarding the results and interpretations; Charlotte Ribes for her advices and for accompanying us on the field in the Artsinol and Pointe de Chalune areas; Albrecht Steck for the discussion about the regional geological structure; Aymon Baud for his advices concerning the Triassic stratigraphic interpretations. We are grateful to M. Ballèvre and an anonymous reviewer for the constructive reviews that improved the manuscript and to S. Schmid for handling of the paper and constructive comments.

The many unpublished diploma/master theses of the University of Lausanne focusing on various parts of the study area constituted a fundamental basis for its geological description and understanding. They were carried out by Jean-Rodolphe Moix and Etienne Stampfli (1980), Jean Savary (1982), Olivier Besson (1986), Jean-Marc Rey (1992), Nicolas Kramar (1997), François-Joseph Baillifard (1998), Olivier Favre (2000), Pierre-Alain Wülser (2002), Laure Gauthiez (2011) and Jérémie Glassey (2013).

Authors' contributions

AP carried out the main part of the field study, data analyses, figures elaboration and initial manuscript writing. JLE and HM participated in field study, data interpretation, discussion and conclusions elaboration. All authors participated in the redaction of the final manuscript, HM and AP were the major contributors. All authors read and approved the final manuscript.

Funding

This study was funded by University of Lausanne.

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

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 31 March 2020 Accepted: 18 August 2020
Published online: 29 September 2020

References

Allimann, M. (1987). La nappe du Mont Fort dans le Val d'Hérens. *Bulletin de la Société Vaudoise des Sciences Naturelles, 78*(372), 431–444. https://doi.org/10.5169/seals-278921.

Allimann, M. (1989). Les brèches de la région d'Evolène (Nappe du Mont Fort, Valais, Suisse). *Schweizerische Mineralogische und Petrographische Mitteilungen, 69*(2), 237–250. https://doi.org/10.5169/seals-52791.

Allimann, M. (1990). La nappe du Mont Fort dans le Val d'Hérens (Zone Pennique, Valais, Suisse) [Thèse de doctorat, Université de Lausanne].

Argand, E. (1911). Les nappes de recouvrement des Alpes Pennines et leurs prolongements structuraux. *Matériaux pour la Carte Géologique de la Suisse [n.s.], 31*(1), 1–29.

Argand, E. (1924). La tectonique de l'Asie. In *Congrès géologique international (XIIIe session), Belgique 1922* (Vol. 1/5, pp. 171–372). Liège: Vaillant-Carmanne.

Argand, E. (1934). La zone pennique. In *Guide géologique de la Suisse. Fasc. III: Introductions générales* (Société Géologique Suisse., pp. 149–189). Basel: Wepf.

Ballèvre, M., Camonin, A., Manzotti, P., & Poujol, M. (2020). A step towards unraveling the paleogeographic attribution of pre-Mesozoic basement complexes in the Western Alps based on U-Pb geochronology of Permian magmatism. *Swiss Journal of Geosciences*. https://doi.org/10.1186/s00015-020-00367-1.

Ballèvre, M., Manzotti, P., & Dal Piaz, G. V. (2018). Pre-Alpine (Variscan) inheritance: A key for the location of the future Valaisan Basin (Western Alps). *Tectonics, 37*(3), 786–817. https://doi.org/10.1002/2017TC004633.

Baud, A. (1987). Stratigraphie et sédimentologie des calcaires de Saint-Triphon: (Trias, Préalpes, Suisse et France). *Mémoire de Géologie (Lausanne), 1*, 326.

Baud, A., Plasencia, P., Hirsch, F., & Richoz, S. (2016). Revised middle Triassic stratigraphy of the Swiss Prealps based on conodonts and correlation to the Briançonnais (Western Alps). *Swiss Journal of Geosciences, 109*(3), 365–377. https://doi.org/10.1007/s00015-016-0226-3.

Baud, A., & Septfontaine, M. (1980). Présentation d'un profil palinspastique de la nappe des Préalpes médianes en Suisse occidentale. *Eclogae Geologicae Helvetiae, 73*(2), 651–660. https://doi.org/10.5169/seals-164982.

Bearth, P. (1963). Contribution à la subdivision tectonique et stratigraphique du Cristallin de la nappe du Grand-St-Bernard dans le Valais (Suisse). In Société Géologique de France (Ed.), *Livre à la Mémoire du Professeur Paul Fallot. Tome II: L'évolution paléogéographique et structurale des domaines méditerranéens et alpins d'Europe* (pp. 407–418). Paris.

Bearth, P. (1964). Blatt 1328 Randa—Geologischer Atlas der Schweiz 1: 25 000, Erläuterungen 43.

Beltrando, M., Compagnoni, R., & Lombardo, B. (2010). (Ultra-) High-pressure metamorphism and orogenesis: An Alpine perspective. *Gondwana Research, 18*(1), 147–166. https://doi.org/10.1016/j.gr.2010.01.009.

Beltrando, M., Manatschal, G., Mohn, G., Dal Piaz, G. V., Vitale Brovarone, A., & Masini, E. (2014). Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: The Alpine case study. *Earth-Science Reviews, 131*, 88–115. https://doi.org/10.1016/j.earscirev.2014.01.001.

Bergomi, M. A., Dal Piaz, G. V., Malusà, M. G., Monopoli, B., & Tunesi, A. (2017). The Grand St Bernard-Briançonnais Nappe System and the Paleozoic Inheritance of the Western Alps Unraveled by Zircon U-Pb Dating. *Tectonics, 36*(12), 2950–2972. https://doi.org/10.1002/2017TC004621.

Bill, M., Bussy, F., Cosca, M., Masson, H., & Hunziker, J. C. (1997). High-precision U-Pb and 40Ar/39Ar dating of an Alpine ophiolite (Gets nappe, French Alps). *Eclogae Geologicae Helvetiae, 90*(1), 43–54. https://doi.org/10.5169/seals-168144.

Bonini, M., Sani, F., & Antonielli, B. (2012). Basin inversion and contractional reactivation of inherited normal faults: A review based on previous and new experimental models. *Tectonophysics, 522–523*, 55–88. https://doi.org/10.1016/j.tecto.2011.11.014.

Botteron, G. (1961). Etude géologique de la région du Mont d'Or (Préalpes romandes). *Eclogae Geologicae Helvetiae, 54*(1), 29–106. https://doi.org/10.5169/seals-162815.

Bousquet, R., Engi, M., Gosso, G., Oberhänsli, R., Berger, A., Spalla, M. I., et al. (2004). Transition from the Western to the Central Alps. Metamorphic structure of the Alps: explanatory notes to the map 1:100 000. *Mitteilungen der Oesterreichischen Mineralogischen Gesellschaft, 149*, 145–156.

Burri, M. (1983). Le front du Grand St-Bernard du val d'Hérens au val d'Aoste. *Eclogae Geologicae Helvetiae, 76*(3), 469–490. https://doi.org/10.5169/seals-165373.

Burri, M., Allimann, M., Chessex, R., Dal Piaz, G. V., Della Valle, G., Dubois, L., Gouffon, Y., Guermani, A., Hagen, T., Krummenacher, D., & Looser, M.-O. (1998). Feuille 1346 Chanrion, avec partie nord de la feuille 1366 Mont Vélan—Atlas géologique de la Suisse 1:25 000, Carte 101.

Bussy, F., Derron, M.-H., Jacquod, J., Sartori, M., & Thélin, P. (1996a). The 500 Ma-old Thyon metagranite: a new A-type granite occurrence in the western Penninic Alps (Wallis, Switzerland). *European Journal of Mineralogy, 8*(3), 565–576. https://doi.org/10.1127/ejm/8/3/056.

Bussy, F., Sartori, M., & Thélin, P. (1996b). U-Pb zircon dating in the middle Penninic basement of the Western Alps (Valais, Switzerland). *Schweizerische Mineralogische und Petrographische Mitteilungen, 76*, 81–84. https://doi.org/10.5169/seals-57689.

Bussy, F., & von Raumer, J. F. (1994). U-Pb geochronology of Palaeozoic magmatic events in the Mont-Blanc crystalline massif, Western Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen, 74*, 514–515. https://doi.org/10.5169/seals-56355.

Caron, J.-M. (1977). Lithostratigraphie et tectonique des schistes lustrés dans les Alpes cottiennes septentrionales et en Corse orientale [Thèse de doctorat, Université Louis Pasteur de Strasbourg]. *Sciences Géologiques Mémoire, 48*, 171.

Chenin, P., Manatschal, G., Decarlis, A., Schmalholz, S. M., Duretz, T., & Beltrando, M. (2019). Emersion of distal domains in advanced stages of continental rifting explained by asynchronous crust and mantle necking. *Geochemistry, Geophysics, Geosystems, 20*(8), 3821–3840. https://doi.org/10.1029/2019GC008357.

Chessex, R. (1959). La géologie de la haute vallée d'Abondance, Haute-Savoie (France). *Eclogae Geologicae Helvetiae, 52*(1), 295.

Chessex, R. (1995). Tectonomagmatic setting of the Mont Fort nappe basement, Penninic Domain, Western Alps, Switzerland. In Ö. Pişkin, M. Ergün, M. Y. Savaşcin, & G. Tarcan (Eds.), Proceedings of the International Earth Sciences Colloquium on the Aegean Region, Izmir - Güllück, Turkey (Vol. 1, pp. 19–35).

Dal Piaz, G. V. (1988). Revised setting of the Piedmont zone in the northern Aosta Valley. *Western Alps. Ofioliti, 13*(2–3), 157–162.

Dal Piaz, G. V. (1999). The Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys. *Memorie di Scienze Geologiche, 51*(1), 155–176.

Dal Piaz, G. V., Bistacchi, A., Gianotti, F., Monopoli, B., & Passeri, L. (2015a). *Note illustrative della Carta Geologica d'Italia alla scala 1: 50.000, Foglio 070 Monte-Cervino*. Roma: Servizio Geologico d'Italia.

Dal Piaz, G. V., Bistacchi, A., Gianotti, F., Monopoli, B., & Passeri, L. (2015b). *Carta Geologica d'Italia alla scala 1: 50.000, Foglio 070 Monte-Cervino*. Roma: Servizio Geologico d'Italia.

Dall'Agnolo, S. (1997). Die Kreide und das Tertiär der Brekziendecke in den französischen und schweizerischen Voralpen: Stratigraphie, Sedimentologie und Geodynamik (These Nr. 1146) [Ph.D. thesis, Universität Freiburg, Schweiz].

Dall'Agnolo, S. (2000). Le Crétacé de la Nappe de la Brèche (Préalpes franco-suisses) Données nouvelles et essai de synthèse stratigraphique et paléogéographique. *Eclogae Geologicae Helvetiae, 93*(2), 157–174. https://doi.org/10.5169/seals-168814.

de SzepessySchaurek, A. (1949). Geologische Untersuchungen im Gd. Combin-Gebiet zwischen Dranse de Bagnes und Dranse d'Entremont [Ph.D. thesis, ETH Zürich]. *ETHZ Repository*. https://doi.org/10.3929/ethz-a-000099247.

Debelmas, J. (1955). Les zones subbriançonnaise et briançonnaise occidentale entre Vallouise et Guillestre (Hautes Alpes) - Alpes françaises [Thèse de doctorat, Université de Grenoble]. HAL Archives Ouvertes. https://hal.archives-ouvertes.fr/tel-00563860

Decarlis, A., Beltrando, M., Manatschal, G., Ferrando, S., & Carosi, R. (2017). Architecture of the distal piedmont-ligurian rifted margin in NW Italy: Hints for a flip of the rift system polarity. *Tectonics, 36*(11), 2388–2406. https://doi.org/10.1002/2017TC004561.

Decarlis, A., Fellin, M. G., Maino, M., Ferrando, S., Manatschal, G., Gaggero, L., et al. (2017). Tectono-thermal Evolution of a Distal Rifted Margin: Constraints From the Calizzano Massif (Prepiedmont-Briançonnais Domain, Ligurian Alps). *Tectonics, 36*(12), 3209–3228. https://doi.org/10.1002/2017TC004634.

Decarlis, A., & Lualdi, A. (2011). Synrift sedimentation on the northern Tethys margin: an example from the Ligurian Alps (Upper Triassic to Lower Cretaceous, Prepiedmont domain, Italy). *International Journal of Earth Sciences, 100*(7), 1589–1604. https://doi.org/10.1007/s00531-010-0587-1.

Decrausaz, T., Müntener, O., Manzotti, P., Lafay, R., & Spandler, C. (2019). Fossil oceanic core complexes in the Alps. New constraints from the Tethyan Aiguilles Rouges ophiolite (Val d'Hérens, Western Alps, Switzerland). In 14th Emile Argand Conference on Alpine Geological studies (Sion), Abstract Volume (p. 19).

Decrausaz, T., Müntener, O., Manzotti, P., Lafay, R., & Spandler, C. (2020). Fossil oceanic core complexes in the Alps. New constraints from the Tethyan Aiguilles Rouges ophiolite (Val d'Hérens, Western Alps, Switzerland). Swiss Journal of Geosciences, submitted.

Derron, M.-H., Jacquod, J., & Sartori, M. (2006). The Goli d'Aget Member: Early Permian volcanoclastic and volcanic rocks within the Briançonnais Grand St-Bernard Nappe (Valais, Switzerland). *Eclogae Geologicae Helvetiae, 99*(3), 301–307. https://doi.org/10.1007/s00015-006-1194-9.

Dumont, T. (1983). Le chaînon de Rochebrune au Sud-Est de Briançon : évolution paléogéographique et structurale d'un secteur de la Zone Piémontaise des Alpes Occidentales. [Thèse de doctorat, Université Scientifique et Médicale de Grenoble]. HAL Archives Ouvertes. https://tel.archives-ouvertes.fr/tel-00541937

Dumont, T., Lemoine, M., & Tricart, P. (1984). Tectonique synsédimentaire triasico-jurassique et rifting téthysien dans l'unité prépiémontaise de Rochebrune au Sud-Est de Briançon. *Bulletin de la Société Géologique de France, (7), 26*(5), 921–933. https://doi.org/10.2113/gssgfbull.S7-XXVI.5.921.

Ellenberger, F. (1952). Sur l'extension des faciès briançonnais en Suisse, dans les Préalpes médianes et les Pennides. *Eclogae Geologicae Helvetiae, 45*(2), 285–286.

Ellenberger, F. (1958). Étude géologique du pays de Vanoise [Thèse de doctorat, Université de Paris, 1954]. Mémoires pour servir à l'explication de la carte géologique détaillée de la France, 662 pp.

Epard, J.-L., & Escher, A. (1996). Transition from basement to cover: a geometric model. *Journal of Structural Geology, 18*(5), 533–548. https://doi.org/10.1016/S0191-8141(96)80022-8.

Epin, M.-E., Manatschal, G., & Amann, M. (2017). Defining diagnostic criteria to describe the role of rift inheritance in collisional orogens: the case of the Err-Platta nappes (Switzerland). *Swiss Journal of Geosciences, 110*(2), 419–438. https://doi.org/10.1007/s00015-017-0271-6.

Escher, A. (1988). Structure de la nappe du Grand Saint-Bernard entre le val de Bagnes et les Mischabel. *Rapports géologiques du Service hydrologique et géologique national*, *7*, 1–27.

Escher, A., & Beaumont, C. (1997). Formation, burial and exhumation of basement nappes at crustal scale: a geometric model based on the Western Swiss-Italian Alps. *Journal of Structural Geology, 19*(7), 955–974. https://doi.org/10.1016/S0191-8141(97)00022-9.

Escher, A., Escher, J. C., & Watterson, J. (1975). The Reorientation of the Kangâmiut Dike Swarm, West Greenland. *Canadian Journal of Earth Sciences, 12*(2), 158–173. https://doi.org/10.1139/e75-016.

Escher, A., Hunziker, J. C., Marthaler, M., Masson, H., Sartori, M., & Steck, A. (1997). Geologic framework and structural evolution of the western Swiss-Italian Alps. In O. A. Pfiffner, P. Lehner, P. Heitzmann, S. Mueller, & A. Steck (Eds.), *Deep structure of the Swiss Alps: results of NRP 20* (pp. 205–221). Basel: Birkhäuser Verlag. **10.1007/978-3-0348-9098-4_16**.

Escher, A., & Masson, H. (1984). Le Cervin: un dessin géologique inédit d'Emile Argand (1929) et son interprétation actuelle. *Travaux du Comité Français d'Histoire de la Géologie, (2), 2*(8), 95–127.

Escher, A., Masson, H., & Steck, A. (1988). Coupes géologiques des Alpes occidentales suisses. *Mémoires de Géologie (Lausanne), 2*, 11.

Escher, A., Masson, H., & Steck, A. (1993). Nappe geometry in the Western Swiss Alps. *Journal of Structural Geology, 15*(3–5), 501–509. https://doi.org/10.1016/0191-8141(93)90144-Y.

Escher, A., Masson, H., Steck, A., Epard, J.-L., Marchant, R., Marthaler, M., et al. (1994). *Coupe tectonique des Alpes de Suisse occidentale*. Section des sciences de la terre: Université de Lausanne.

Escher, A., & Watt, W. S. (1976). *Geology of Greenland*. Copenhagen: Grønlands geologiske undersøgelse.

Florineth, D., & Froitzheim, N. (1994). Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland): Evidence for Early Cretaceous opening of the Valais ocean. *Schweizerische Mineralogische und Petrographische Mitteilungen, 74*(3), 437–448. https://doi.org/10.5169/seals-56358.

Froitzheim, N., & Eberli, G. P. (1990). Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. *Geological Society of America Bulletin, 102*(9), 1297–1308. https://doi.org/10.1130/0016-7606(1990)102<1297:EDFITE>2.3.CO;2.

Froitzheim, N., & Manatschal, G. (1996). Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). *Geological Society of America Bulletin, 108*(9), 1120–1133. https://doi.org/10.1130/0016-7606(1996)108<1120:KOJRME>2.3.CO;2.

Gabus, J. H., Weidmann, M., Bugnon, P.-C., Burri, M., Sartori, M., & Marthaler, M. (2008). Feuille 1287 Sierre—Atlas géologique de la Suisse 1:25 000, Carte 111.

Galster, F., Cavargna-Sani, M., Epard, J.-L., & Masson, H. (2012). New stratigraphic data from the Lower Penninic between the Adula nappe and the Gotthard massif and consequences for the tectonics and the paleogeography of the Central Alps. *Tectonophysics, 579*, 37–55. https://doi.org/10.1016/j.tecto.2012.05.029.

Gauthiez, L., Bussy, F., Ulianov, A., Gouffon, Y., & Sartori, M. (2011). Ordovician mafic magmatism in the Métailler Formation of the Mont-Fort nappe (Middle Penninic domain, western Alps)—geodynamic implications. In 9th Swiss Geoscience Meeting (Zürich), Abstract volume (pp. 110–111).

Genier, F., Epard, J.-L., Bussy, F., & Magna, T. (2008). Lithostratigraphy and U-Pb zircon dating in the overturned limb of the Siviez-Mischabel nappe: a new key for Middle Penninic nappe geometry. *Swiss Journal of Geosciences, 101*(2), 431–452. https://doi.org/10.1007/s00015-008-1261-5.

Gouffon, Y. (1993). Géologie de la "nappe" du Grand St-Bernard entre la Doire Baltée et la frontière suisse (Vallée d'Aoste-Italie). *Mémoires de Géologie (Lausanne), 12*, 150.

Gouffon, Y., & Burri, M. (1997). Les nappes des Pontis, de Siviez-Mischabel et du Mont Fort dans les vallées de Bagnes, d'Entremont (Valais, Suisse) et d'Aoste (Italie). *Eclogae Geologicae Helvetiae, 90*(1), 29–41. https://doi.org/10.5169/seals-168143.

Hagen, T. (1951). Über den geologischen Bau des Mont Pleureur (Val de Bagnes, Wallis). *Eclogae Geologicae Helvetiae, 44*(2), 299–306.

Haupert, I., Manatschal, G., Decarlis, A., & Unternehr, P. (2016). Upper-plate magma-poor rifted margins: Stratigraphic architecture and structural evolution. *Marine and Petroleum Geology, 69*, 241–261. https://doi.org/10.1016/j.marpetgeo.2015.10.020.

Hürlimann, A., Besson-Hürlimann, A., & Masson, H. (1996). Stratigraphie et tectonique de la partie orientale de l'écaille de la Gummfluh (Domaine Briançonnais des Préalpes). *Mémoires de Géologie (Lausanne), 28*, 183.

Institut für Geologie, Univesität Bern, & Bundesamt für Wasser und Geologie. (2005). *Tektonische Karte der Schweiz 1:500 000*. Bern: Bundesamt für Landestopografie.

Jaillard, E. (1988). Une image paléogéographique de la Vanoise briançonnaise (Alpes françaises). *Eclogae Geologicae Helvetiae, 81*(3), 553–566. https://doi.org/10.5169/seals-166193.

Joukowsky, E. (1907). Communication sur une coupe du Massif d'Arzinol. *Archives des Sciences Physiques et naturelles (Genève), 4*(24), 99–100.

Krayenbuhl, T., & Steck, A. (2009). Structure and kinematics of the Jungfrau syncline, Faflertal (Valais, Alps), and its regional significance. *Swiss*

Journal of Geosciences, 102(3), 441–456. https://doi.org/10.1007/s00015-009-1333-1.
Lafosse, M., Boutoux, A., Bellahsen, N., & Le Pourhiet, L. (2016). Role of tectonic burial and temperature on the inversion of inherited extensional basins during collision. *Geological Magazine, 153*(5–6), 811–826. https://doi.org/10.1017/S0016756816000510.
Lemoine, M. (1961). La marge externe de la fosse piémontaise dans les Alpes occidentales. *Revue de géographie physique et de géologie dynamique, (2), 4*(3), 163–180.
Lemoine, M. (1967). Brèches sédimentaires marines à la frontière entre les domaines briançonnais et piémontais dans les Alpes occidentales. *Geologische Rundschau, 56*(1), 320–335.
Lemoine, M., Bourbon, M., & Tricart, P. (1978). Le Jurassique et le Crétacé prépiémontais à l'est de Briançon (Alpes occidentales) et l'évolution de la marge européenne de la Téthys : données nouvelles et conséquences. *Comptes Rendus de l'Académie des sciences (D), 286*(3), 1237–1240.
Lemoine, M., de Graciansky, P., & Tricart, P. (2000). *De l'océan à la chaîne de montagnes: Tectonique des plaques dans les Alpes*. Paris: Gordon and Breach Science Publishers.
Lugeon, M. (1896). La région de la Brèche du Chablais (Haute Savoie). *Bulletin des Services de la carte géologique de la France et des topographies souterraines, 49*(7), 337–642.
Manatschal, G., Müntener, O., Desmurs, L., & Bernoulli, D. (2003). An ancient-ocean-continent transition in the Alps : the Totalp, Err-Platta, and Malenco units in the eastern Central Alps (Graubünden and northern Italy). *Eclogae Geologicae Helvetiae, 96*(1), 131–146. https://doi.org/10.5169/seals-169013.
Marthaler, M. (1984). Géologie des unités penniques entre le Val d'Anniviers et le Val de Tourtemagne (Valais, Suisse). *Eclogae Geologicae Helvetiae, 77*(2), 395–448. https://doi.org/10.5169/seals-165516.
Marthaler, M., Sartori, M., Escher, A., & Meisser, N. (2008). Feuille 1307 Vissoie. - Atlas géologique de la Suisse 1:25 000, Notice explicative 122.
McCarthy, A., Chelle-Michou, C., Müntener, O., Arculus, R., & Blundy, J. (2018). Subduction initiation without magmatism: The case of the missing Alpine magmatic arc. *Geology, 46*(12), 1059–1062. https://doi.org/10.1130/G45366.1.
McCarthy, A., Tugend, J., Mohn, G., Candioti, L., Chelle-Michou, C., Arculus, R., et al. (2020). A case of Ampferer-type subduction and consequences for the Alps and the Pyrenees. *American Journal of Science, 320*(4), 313–372. https://doi.org/10.2475/04.2020.01.
Mégard-Galli, J., & Baud, A. (1977). Le Trias moyen et supérieur des Alpes nord-occidentales et occidentales : données nouvelles et corrélations stratigraphiques. *Bulletin du Bureau de Recherche Géologiques et Minières (BRGM), (2), 4*(3), 233–250.
Mohn, G., Manatschal, G., Beltrando, M., & Haupert, I. (2014). The role of rift-inherited hyper-extension in Alpine-type orogens. *Terra Nova, 26*(5), 347–353. https://doi.org/10.1111/ter.12104.
Mohn, G., Manatschal, G., Beltrando, M., Masini, E., & Kusznir, N. (2012). Necking of continental crust in magma-poor rifted margins: Evidence from the fossil Alpine Tethys margins. *Tectonics*. https://doi.org/10.1029/2011TC002961.
Mohn, G., Manatschal, G., Masini, E., & Müntener, O. (2011). Rift-related inheritance in orogens: a case study from the Austroalpine nappes in Central Alps (SE-Switzerland and N-Italy). *International Journal of Earth Sciences, 100*(5), 937–961. https://doi.org/10.1007/s00531-010-0630-2.
Mohn, G., Manatschal, G., Müntener, O., Beltrando, M., & Masini, E. (2010). Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. *International Journal of Earth Sciences, 99*(S1), 75–101. https://doi.org/10.1007/s00531-010-0566-6.
Oulianoff, N. (1954). Note concernant l'origine et le métamorphisme des "schistes de Casanna" (massif du Métailler dans le Val de Nendaz, en Valais). *Bulletin de la Société Vaudoise des Sciences Naturelles, 66*(288), 77.
Passeri, L., Ciarapica, G., & Dal Piaz, G. V. (2018). The problematic origin of the Pancherot-Cime Bianche-Bettaforca unit (PCB) in the Piemonte zone (Western Alps). *Italian Journal of Geosciences, 137*(3), 478–489. https://doi.org/10.3301/IJG.2018.21.
Plancherel, R., Caron, C., & Broquet, P. (1998). *Notice explicative de la carte géologique de la France 1:50 000. 655, Samoëns - Pas-de-Morgins*. Orléans: BRGM.
Ramsay, J. G. (1967). *Folding and fracturing of rocks*. New York: McGraw-Hill.
Rey, D. (2002). Shear2F: un logiciel de modélisation tectonique. *Mémoire de Géologie (Lausanne), 37*, 45.
Ribes, C., Ghienne, J.-F., Manatschal, G., Decarlis, A., Karner, G. D., Figueredo, P. H., et al. (2019). Long-lived mega fault-scarps and related breccias at distal rifted margins: insights from present-day and fossil analogues. *Journal of the Geological Society, 176*(5), 801–816. https://doi.org/10.3301/IJG.2018.21.
Sartori, M. (1987). Structure de la zone du Combin entre les Diablons et Zermatt (Valais). *Eclogae Geologicae Helvetiae, 80*(3), 789.
Sartori, M. (1990). L'unité du Barrhorn (zone pennique, Valais, Suisse). *Mémoires de Géologie (Lausanne), 6*, 156.
Sartori, M., Burri, M., Epard, J.-L., Masson, H., & Pasquier, J.-B. (2011). Feuille 1306 Sion. - Atlas géologique de la Suisse 1:25 000, Carte 130.
Sartori, M., & Epard, J.-L. (2011). Feuille 1306 Sion—Atlas géologique de la Suisse 1:25 000, Notice explicative 130.
Sartori, M., Gouffon, Y., & Marthaler, M. (2006). Harmonisation et définition des unités lithostratigraphiques briançonnaises dans les nappes penniques du Valais. *Eclogae Geologicae Helvetiae, 99*(3), 363–407. https://doi.org/10.1007/s00015-006-1200-2.
Sartori, M., & Marthaler, M. (1994). Exemples de relations socle-couverture dans les nappes penniques du Val d'Hérens: Compte-rendu de l'excursion de la Société Géologique Suisse et de la Société Suisse de Minéralogie et Pétrographie (25 et 26 septembre 1993). *Schweizerische Mineralogische und Petrographische Mitteilungen, 74*, 503–509. https://doi.org/10.5169/seals-56365.
Schaer, J.-P. (1960). *Géologie de la partie septentrionale de l'éventail de Bagnes: entre le Val d'Hérémence et le Val de Bagnes, Valais, Suisse* [Thèse de doctorat, Université de Neuchâtel]. Bibliothèque numérique réro. https://doc.rero.ch/record/4448
Scheiber, T., Berndt, J., Mezger, K., & Pfiffner, O. A. (2014). Precambrian to Paleozoic zircon record in the Siviez-Mischabel basement (western Swiss Alps). *Swiss Journal of Geosciences, 107*(1), 49–64. https://doi.org/10.1007/s00015-013-0156-2.
Scheiber, T., Pfiffner, O. A., & Schreurs, G. (2013). Upper crustal deformation in continent-continent collision: A case study from the Bernard nappe complex (Valais, Switzerland). *Tectonics, 32*(5), 1320–1342. https://doi.org/10.1002/tect.20080.
Schmid, S. M., Fügenschuh, B., Kissling, E., & Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae, 97*(1), 93–117. https://doi.org/10.1007/s00015-004-1113-x.
Schmid, S. M., Kissling, E., Diehl, T., van Hinsbergen, D. J. J., & Molli, G. (2017). Ivrea mantle wedge, arc of the Western Alps, and kinematic evolution of the Alps-Apennines orogenic system. *Swiss Journal of Geosciences, 110*(2), 581–612. https://doi.org/10.1007/s00015-016-0237-0.
Schürmann, H. M. E. (1953). Beiträge zur Glaukophanefrage. II (Queensland, Cuba, Californien, Val de Bagnes (Schweiz)). *Neues Jahrbuch für Mineralogie - Abhandlungen, 87*, 303–394.
Septfontaine, M. (1995). Large scale progressive unconformities in Jurassic strata of the Prealps S of Lake Geneva: Interpretation as synsedimentary inversion structures; paleotectonic implications. *Eclogae Geologicae Helvetiae, 88*(3), 553–576. https://doi.org/10.5169/seals-167687.
Spitz, R., Bauville, A., Epard, J.-L., Kaus, B. J. P., Popov, A. A., & Schmalholz, S. M. (2020). Control of 3-D tectonic inheritance on fold-and-thrust belts: insights from 3-D numerical models and application to the Helvetic nappe system. *Solid Earth, 11*(3), 999–1026. https://doi.org/10.5194/se-11-999-2020.
Steck, A., Bigioggero, B., Dal Piaz, G. V., Escher, A., Martinotti, G., & Masson, H. (1999). *Carte tectonique des Alpes de Suisse occidentale, 1:100 000. Carte géologique spéciale N° 123*. Berne: Service hydrologique et géologique national.
Steck, A., Epard, J.-L., Escher, A., Gouffon, Y., & Masson, H. (2001). *Carte tectonique des Alpes de Suisse occidentale, 1:100 000. Carte géologique spéciale N° 123, Notice explicative*. Berne: Office fédéral des eaux et de la géologie.
Steck, A., Masson, H., & Robyr, M. (2015). Tectonics of the Monte Rosa and surrounding nappes (Switzerland and Italy): Tertiary phases of subduction, thrusting and folding in the Pennine Alps. *Swiss Journal of Geosciences, 108*(1), 3–34. https://doi.org/10.1007/s00015-015-0188-x.
Thélin, P., Gouffon, Y., & Allimann, M. (1994). Caractéristiques et métamorphisme des phyllosilicates dans la partie occidentale de la super nappe du Grand St-Bernard (Val d'Aoste et Valais). *Bulletin de la Société Vaudoise*

des Sciences Naturelles, 83(2), 93–145. https://doi.org/10.5169/seals-280523.
Thélin, Ph, & Ayrton, St. (1983). Cadre évolutif des événements magmatico-métamorphiques du socle anté-triasique dans le domaine pennique (Valais): données récentes, synthèse chronologique et suggestions de recherches ultérieures. *Schweizerische Mineralogische und Petrographische Mitteilungen, 63*(2–3), 393–420.
Trümpy, R. (1954). La zone de Sion-Courmayeur dans le haut Val Ferret valaisan. *Eclogae Geologicae Helvetiae, 47*(2), 315–359. https://doi.org/10.5169/seals-161837.
Trümpy, R. (1960). Paleotectonic evolution of the central and western Alps. *Geological Society of America Bulletin, 71*(6), 843. https://doi.org/10.1130/0016-7606(1960)71[843:PEOTCA]2.0.CO;2.
Trümpy, R. (1980). *Geology of Switzerland: a guide-book Part A: An Outline of the Geology of Switzerland (Schweizerische Geologische Kommission)*. Basel, New York: Wepf & Co., Publishers.
Vallet, J.-M. (1950). Etude géologique et pétrographique de la partie inférieure du Val d'Hérens et du Val d'Hérémence (Valais). *Schweizerische Mineralogische und Petrographische Mitteilungen, 30*(2), 322. https://doi.org/10.5169/seals-24449.
Vannay, J.-C., & Allemann, R. (1990). La zone piémontaise dans le Haut-Valtournanche (Val d'Aoste, Italie). *Eclogae Geologicae Helvetiae, 83*(1), 21–39. https://doi.org/10.5169/seals-166575.
von Raumer, J. F., Bussy, F., Schaltegger, U., Schulz, B., & Stampfli, G. M. (2013). Pre-mesozoic alpine basements—their place in the European Paleozoic framework. *Geological Society of America Bulletin, 125*(1/2), 89–108. https://doi.org/10.1130/B30654.1.
Wegmann, E. (1922). Zur Geologie der St. Bernharddecke im Val d'Hérens (Wallis). *Bulletin de la Société Neuchâteloise des Sciences naturelles, 47*, 3–63.
Weidmann, M. (1972). Le front de la Brèche du Chablais dans le secteur de Saint-Jean-d'Aulph (Haute-Savoie). *Géologie Alpine, 48*(2), 229–246.
Woodtli, R., Jaffé, F., von Raumer, J., & Della Valle, G. (1987). Prospection minière en Valais: le projet Uromine. Matériaux pour la géologie de la Suisse. *Série géotechnique, 72*, 179.
Wust, G. H., & Baehni, L. A. (1986). The distinctive tectonometamorphic evolution of two basement complexes belonging to the Grand-Saint-Bernard nappe (Val de Bagnes, Valais). *Schweizerische Mineralogische und Petrographische Mitteilungen, 66*(1–2), 53–71. https://doi.org/10.5169/seals-50881.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen journal and benefit from:

- ► Convenient online submission
- ► Rigorous peer review
- ► Open access: articles freely available online
- ► High visibility within the field
- ► Retaining the copyright to your article

Submit your next manuscript at ► springeropen.com