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)

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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:
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 paleo faults 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. Debemas 1955; Ellenberger 1958; Baud and Septfontaine 1980; Jaillard 1988; Sartori 1990; Hürli mann 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 (Bällèvre 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; Bällèvre 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'Agno 1997; Plancher 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
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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 Prepiemont domain is exactly opposite to that of the Briançonnais s.s.: the Prepiemont is collapsing and deepening at the very moment when the Briançonnais s.s. 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 Prepiemont 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 Prepiemont 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; Allmann 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; Wüst and Baehni 1986; Escher 1988; Thélín 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 Prepiemont domain (Marthaler 1984; Escher 1988), and definitely distinct from the Briançonnais s.s. 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 calc-schists 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, Plancheirel 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)](image-url)
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 calc schists 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 albite paragneiss, 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; Schaar 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 phyl litic 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 Pennincs, the stratigraphy of the Evolène Series was for long a mystery because of poverty in biostratigraphically 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 Grep von 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) 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. 1987). 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. Vire -

daz, 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’Agno 1997, 2000; Plancher 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.
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.
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Sasseneire  Mont Fort  Rosablanche  Fionnay  Le Métailler  Pic d'Artsinol  Dix vallée  Bagnes vallée  Herens vallée  Greppon Blanc  Siviez  Madzeria  Pigne d'Arolla  Dixence  Mauvoisin  Moiry  Mont Dolin  Pointe de Vouasson  Nendaz vallée  Arolla  Les Haudères  Ferpècle  Pointe du Tsaté  Pas de Lona  Les Roux  Evolène  Rocs d'Evolène  Pointe du Vasevay  Aig. Rouges d'Arolla  Pointe du Pleureur  B  B'  C  C'

CONTACT TYPE
EVOLÈNE SERIES / MONT FORT BASEMENT:
- Preserved Triassic sequence / preserved Late Paleozoic sequence
- Mesozoic breccias / Paleozoic breccias

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: Métalier Fm. [Paleozoic (incl. Ordovician)]
Siviez-Mischabels cover: quartzites, cornièlles, dolomites, gypsum [Triassic]
Siviez-Mischabels basement [Paleozoic]

Deep rockslide

Nappe limit (Alpine thrust)
Salassi / Penninics limit
Alpine fault

02 1 kilometers
7° 20' 00'' E
7° 30' 00'' E
46°0' 0'' N
46°5' 0'' N
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
Mimicking Alpine thrusts by passive deformation of synsedimentary normal faults

Fig. 8. Cross-sections through the Roux area (Dx 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 (Allmann 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.
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 translational 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)
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

![Fig. 14](image)

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
a) Local lithologic successions

- L1: Ché Blanc (Artsinol area, Hérens valley)
- L2: Plan de l’Homme (Artsinol area, Hérens valley)
- L3: Les Flarnèches (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 Vasevey South Face (Dix valley)

b) Schematic margin geometry at Late Jurassic Time

- L11: Pointe du Vasevey West Face (Bagnes val.)
- L12: Tunnel of the road at Madora (Bagnes valley)
- L13: Lui Dzaune (Madora area, Bagnes valley)
- L14: Les Tsantons (Madora area, Bagnes valley)

EVOLÈNE SERIES

- Light grey massive limestone [U. Jurassic]
- Polymeric breccias [Upper Jurassic]
- Dolomitic breccias [L. to Middle Jurassic]
- Dark calcarenites [L. to Middle Jurassic]
- Light grey bedded limestone [Early Jurassic]
- Cornègles [Mesozoic protolith]
- Dolomites [Lower to Middle Triassic]
- Tabular quartzite [Lower Triassic]

MONT FORT PALEozoIC BASEMENT

- Greppon Blanc Fm.: Quartzschists, phyllitic quartzites, metavolcanites [Permian]
- Mètalle Fm.: Metabasites, gneisses [Paleozoic (incl. Ordovician)]
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 inverted 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 Krähenbühl 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.

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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. AP were the major contributors. All authors read and approved the final manuscript.

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