EARLY CRETACEOUS ACCRETIONARY COMPLEX OF THE VALAISAN OCEAN, WESTERN ALPS?

Gilles De Broucker*,✉, **Yves Siméon****, **Gérard M. Stampfli*****, **Denis Thiéblemont**°, **Philippe Lach**°° and **Michel Marthaler**°°°

* *Retired from Shell International, France.*
** *Retired from BRGM, France, y.simeon@bbox.fr*
*** *Professor Emeritus UNIL, Switzerland, Gerard.Stampfli@unil.ch*
° *BRGM, DGR/CGEO, Orléans, France, d.thieblemont@brgm.fr*
°° *BRGM, DEPA/ISO, Orléans, France, p.lach@brgm.fr*
°°° *Professor Emeritus UNIL, Switzerland, michel.marthaler@unil.ch*
✉ *Corresponding author, e-mail: gdebroucker@gmail.com*

Keywords: *Valaisan ocean, Versoyen Complex, accretionary prism, tectonic mélange, geochemistry, U/Pb dating, Briançonnais, Petit-Saint-Bernard Pass.*

ABSTRACT

Based on detailed field investigations and structural mapping in the Petit-Saint Bernard Pass area (French-Italian border), the Versoyen Complex is newly defined as an imbrication of four structural units. The first one is composed of the remnant of the Valaisan ocean floor ("basalt" and "black schist" formation) and the other three units -grouped under the name of "schistes à blocs"- contain blocks with different origin: oceanic, continental or a mix of both, embedded in a matrix of grey micaschists. Kinematic analysis highlights the compressional style of this complex with a well-developed stack of tectonic slivers. Rocks in the tectonic mélange include Paleozoic green gneiss and grey-green micaschists blocks, together with Upper Paleozoic granitoid and layered gabbro, which display a typical orogenic calc-alkaline signature, comparable to that of coeval plutonic rocks of the Briançonnais continental basement attributed to a late Variscan back-arc environment. A new isotopic dating on a calc-alkaline layered gabbro block gave a U/Pb zircon age of 310 ± 4 Ma, in the range of other dated plutonic rocks such as the Punta Rossa and Aiguille du Clapet megablocks. These Paleozoic continental basement rocks of the Versoyen Complex were initially rift allochthons, but are now outcropping as a tectonic mélange, with imbricated blocks and slivers within an Early Cretaceous grey micaschists matrix. Radiolarians sampled by Beltrando et al. (2012) within the grey micaschists have been attributed to the Late Jurassic - Early Cretaceous. Additional stratigraphic and geodynamic constraints allow us to restrict the deposition of the Versoyen sediments from the Aptian to Cenomanian times. The Versoyen Complex is unconformably overlain by the Valaisan Trilogy (Aroley-Marmontains-Saint Christophe) of Cretaceous age. The Turonian Aroley strata deposited on the Versoyen "schistes à blocs" units and the absence of any Aroley limestones within the underlying tectonic mélange testify a clear stratigraphic unconformity, mapped regionally, between the Versoyen Complex and Valaisan Trilogy. Both are affected by a high-pressure metamorphism related to the Alpine collision around 40 Ma and trace of former metamorphism are nowhere observed suggesting that the former mélange did not result in a significant tectonic thickening. We interpret the Versoyen Complex, as a pre-Alpine Cretaceous subduction-related accretionary prism, formed during the closure of the Valaisan Ocean. Valaisan rifting initiated during the Late Jurassic, as a consequence of an eastwards propagation of the North-Atlantic rifting towards the Alpine region. This propagation followed pre-existing Variscan structures along the Zone Houillère, explaining the present marked differences between Variscan basements on each side of the Valaisan suture (External Crystalline Massifs and Briançonnais basement). Due to the southward subduction of the Valaisan Ocean, this passive margin was later on deformed through compressional shearing tectonics, developing a "schistes à blocs" fabric and imbricating the former rift allochthons. During the Tertiary Alpine collision, Versoyen and Valaisan Trilogy units were deeply underthrusted, and then exhumed under the Subbriançonnais units - including the Petit-Saint Bernard and Arguerey Liassic calcschists, which underthrusted in turn the Briançonnais Front.

INTRODUCTION

The Valaisan domain is a major paleogeographic and structural unit in the Western Alps (Fig. 1) whose oceanic character is documented by the existence of a preserved ophiolitic complex (the Versoyen Complex) with a typical N-MORB signature (Loubat, 1968; Schürch, 1987; Cannic, 1996). The Valaisan Domain has long been considered as the remnant of a "reduced" oceanic domain opening to the northwest of the main Alpine Liguro-Piemonte ocean (Trümpy, 1954; Antoine, 1971). However, as a whole, the Valaisan domain is quite complex, particularly in the Petit-Saint-Bernard (PSB) Pass (French-Italian border) and Visp areas (Swiss Valais), including plutonic rocks which do not conform straightforwardly with an oceanic setting.

The first mention of "roches vertes" in the Haut vallon du Versoyen is found on the second edition of the "Carte Géologique de la Suisse au 380.000e" (Studer et al., 1853/1867; Schoeller, 1929), where mainly prasinites and serpentinites were mapped in the area and interpreted as the basement of the Petit-Saint-Bernard (PSB) Unit. Schoeller (1929) traced a tectonic contact between the "roches vertes"-PSB Unit and the underlying "Flysch" and made an analogy with the Mont Jovet (Vanoise massif), i.e., considering the Unit as a klippe of "schistes lustrés" and ophiolites originating from the Piedmont ocean and thrusted on the Briançonnais domain. Piero and Giulio Elter (1965) mapped in detail the Petit Saint-Bernard area, being the first to define the "zona del Versoyen" with prasinites and black schists, serpentinites, and crystalline rocks at Punta Rossa. Following Schoeller (1929), Elter and Elter (1965) also interpreted the contact between the Versoyen and the underlying Valaisan Flysch Trilogy as a tectonic contact, but recognized an overturned stratigraphy in the "Flysch". Antoine (1971), together with Loubat (1968), were the first to map a stratigraphic contact (unconformity) between the two units. This interpretation was criticized by Aubouin (1965) at the time of his book "Geosynclines", because the interpretation implied

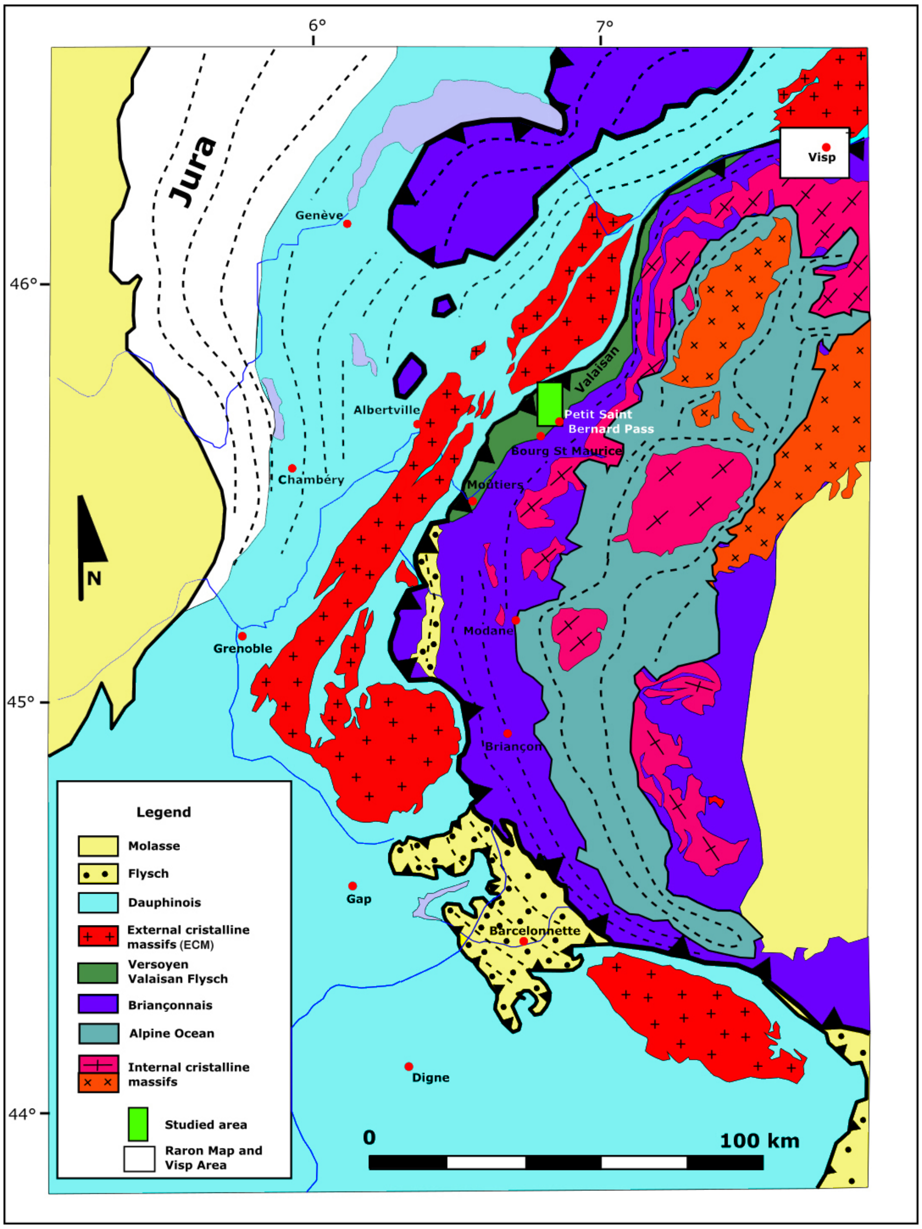


Fig. 1 - Simplified geological map of the Alps with indication of the Versoyen studied area near Petit-Saint-Bernard Pass. The Valaisan unit is outcropping from Moûtiers to Visp in Swiss Valais, between External Crystalline Massif (ECM) and the Zone Houillère / Penninic Briançonnais Domain.

that the "roches vertes" could not have been thrusted from the single Alpine Piedmont "eugeosyncline", but were formed in a second oceanic domain, located to the northwest of the Briançonnais "Géanticline".

High precision U/Pb zircon ages obtained at the end of the 90's and beginning of the 2000's severely modified the previous view of the geology of the region by demonstrating the Late Paleozoic age of many Valaisan magmatic rocks including the ophiolite itself (Cannic, 1996; Schärer et al., 2000) and adjacent massifs (Beltrando et al., 2007; Masson et al., 2008). Because of their high quality, the Permian ages obtained by Beltrando et al. (2007) on the Punta Rossa (267 ± 1 Ma) and Aiguille du Clapet (272 ± 2 Ma) massifs provide the most robust elements in favor of a pre-Alpine age of the Versoyen. On the base of these new ages, Beltrando et al. (2012) re-interpreted the Versoyen Complex in the Petit-Saint-Bernard pass area as a hyper-extended rift margin thought to create discontinuous slivers of Paleozoic basement.

The first author has been working for some years on the Valaisan domain, with special attention to the Petit-Saint-Bernard Pass area (Fig. 2), displaying probably the best outcrop area for France, Italy and Switzerland to study the oceanic relics under the Valaisan Trilogy. Another Versoyen type well-known outcrop area is situated in the Visp Valais region, in Switzerland. Despite more intense tectonics and folding, the Südegg Complex of Blatt Raron is comparable to the Versoyen Complex and sit in a very similar structural position (Jeanbourquin et al., 1991; Jeanbourquin, 1994; Sartori et al., 2017).

The present article is largely based on new lithological characterization, additional structural relationships between the different mapped Versoyen Complex units, and new geochronological and geochemical analyses (a new zircon U/Pb date and eleven whole-rock analyses). The objective is to propose a new model, which better reconciles these new analytical data and field evidence, and emphasizes the need for complementary data, such as an unequivocal dating of the Valaisan ocean floor magmatism.

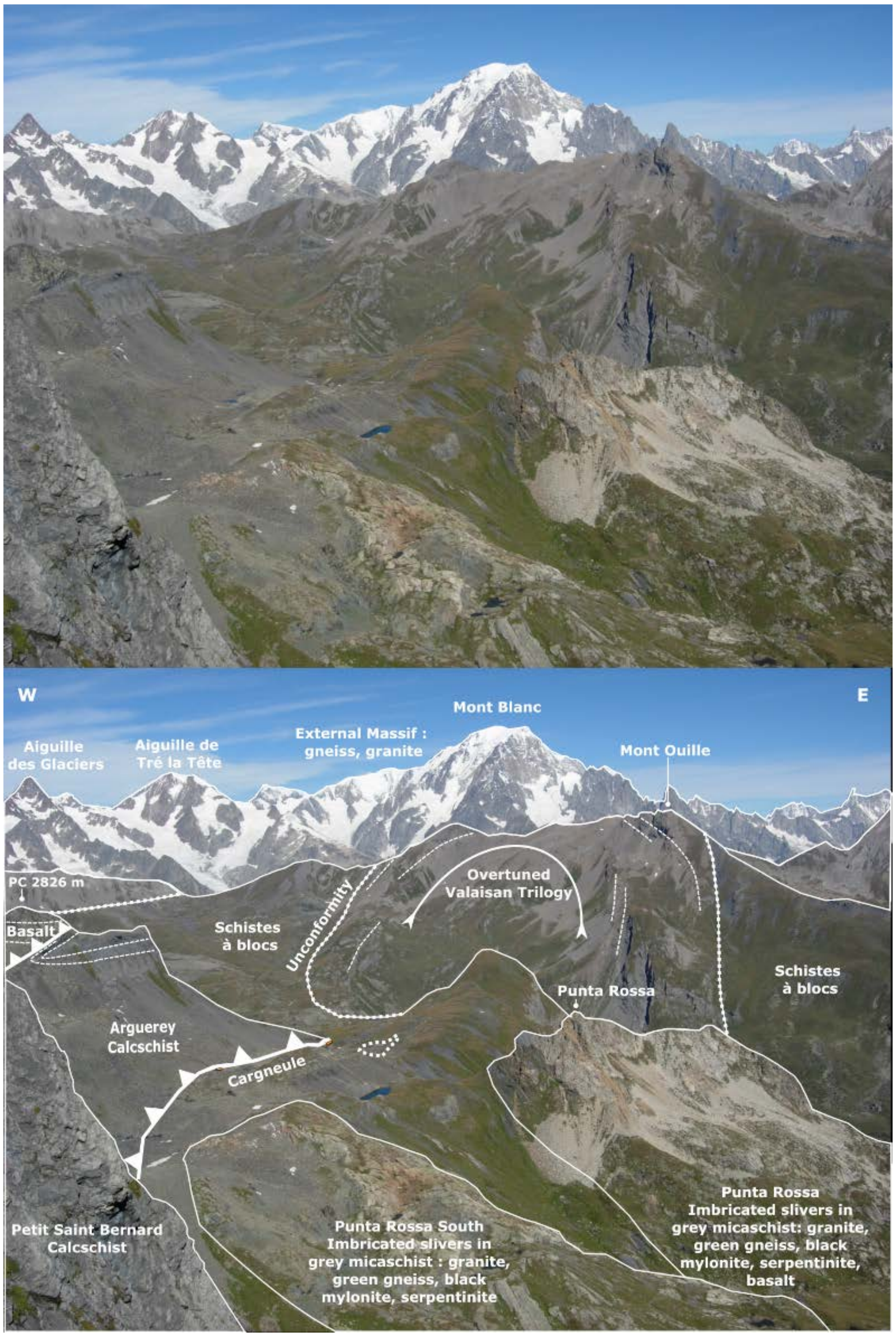


Fig. 2 - Overall view from Lancebranlette summit of the Versoyen discussed area. Simplified geological interpretation of the greater Punta Rossa area. The Punta Rossa and Punta Rossa South massifs belong to the same stack of tectonic slivers embedded in the grey micaschist matrix (schistes à blocs structuration). The Versoyen schistes à blocs are unconformably overlain by the Valaisan Trilogy on a regional syncline reverse limb against the Briançonnais Front (to the right of the photograph). Late upright refolding of the overturned flank is well visible, below Mont Blanc summit. Liassic Petit-Saint-Bernard and Arguerey Calcschists (PSBA) are in low angle Alpine thrust tectonic contact with the Versoyen Unit (cargneule locally present at the contact).

VERSOYEN COMPLEX: A NEW APPROACH

Structural map and Cross-section

For the general setting of the Valaisan domain and Versoyen Complex, we refer the reader to the comprehensive review included in Beltrando et al. (2012). Our structural map and cross-section reported in Figs. 3 and 4 match generally with the map of Beltrando et al. (2012). However, we consider the Versoyen Complex as composed of four structural units: Unit 1 + Units 2a-2b-2c (Figs. 5, 6, 7, 8). *Unit 1* consists of metabasalts and "black schists", slightly dislocated, derived from an ocean floor, referred to as the typical Versoyen lithofacies; *Unit 2* is a succession of three sub-units of a "schistes à blocs" mélange with tectonic shear structuration. The three sub-units were distinguished based on nature and origin of their blocks and slivers: *Sub-unit 2a* consists only of oceanic blocks (serpentinite and basalt), *Sub-unit 2b* contains a mix of oceanic and continental basement blocks (Punta Rossa granitoid, micaschist, green gneiss, mylonitic black shear zone, layered gabbro), and *Sub-unit 2c* is composed only of continental basement blocks (green gneiss and black shear zone).

The Valaisan Trilogy overlays unconformably the Versoyen Complex. This stratigraphic unconformity seals the pre-Alpine structuration of the Versoyen Complex. The basal Aroley is resting unconformably on the three mapped "schistes à blocs" units (Units 2a-2b-2c). The fact that the Aroley rocks are never involved in the structuration of the underlying "schistes à blocs" clearly indicates that the contact, which can be mapped and followed regionally, is a

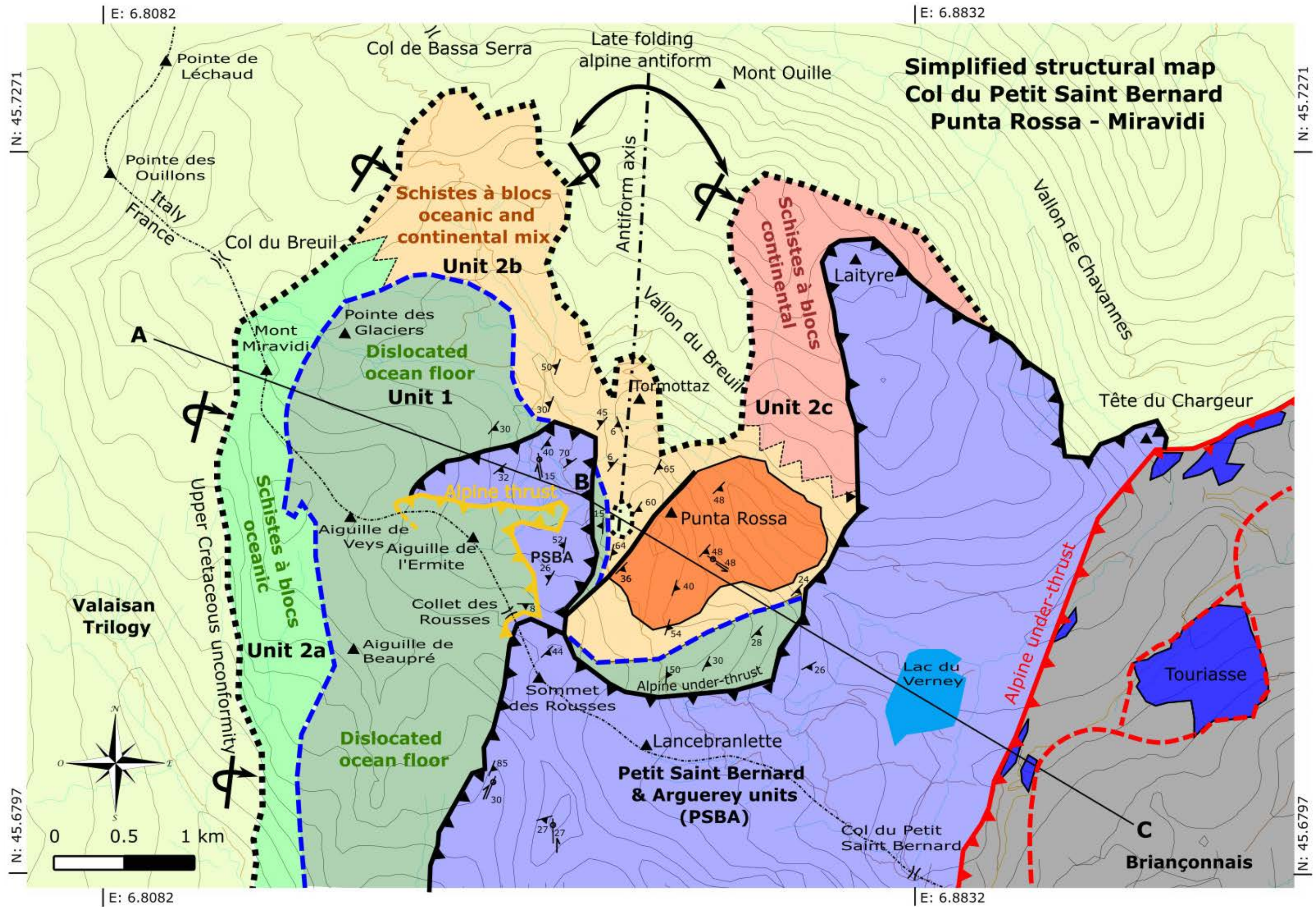


Fig. 3 - Structural map of the Versoyen and surrounding units near the Petit-Saint-Bernard Pass. See map legend on Fig. 4. This map shows the 2 structural units of the Versoyen Complex: **Unit 1**, rests of a dislocated ocean floor and Unit 2 containing schistes à blocs. Based on block lithology/origin, 3 sub-units have been mapped within Unit 2: **Unit 2a** with oceanic blocks only, **Unit 2b** with a mix of oceanic and continental basement blocks (among them the Punta Rossa megablock), and **Unit 2c** containing only continental basement blocks (green gneiss). The Valaisan Trilogy overlays unconformably the Versoyen complex. This **Turonian unconformity** is sealing the pre-Alpine structuration of the Versoyen Complex. This map displays also the low angle Alpine thrust contact (with local cargneule) of the Versoyen Complex and the Valaisan Trilogy (at Tête du Chargeur) under the **PSBA** units (black thrust contact), and similarly of the PSBA under the **Briançonnais/Zone Houillère** Front (red thrust contact).

stratigraphic unconformity. Additionally, "mariposite" (informal name given to a Cr-bearing green mica) clasts, reworked from the Versoyen serpentinite, are observed near the basal Aroley contact (Fudral and Guillot, 1988), supporting also the unconformity nature of this contact. To the southwest, the basal Aroley unconformity is overlying a Carboniferous to Liassic sequence (Antoine, 1971) within the Unité de Moûtiers.

In the map of Fig. 3, a low angle Tertiary Alpine thrust contact (black line) is shown between the Petit-Saint-Bernard - Arguerey calcschist Unit (PSBA) and the underlying Versoyen Complex. This contact is locally marked by an alignment of cargneules that attest its Tertiary Alpine origin, because in the Western Alps these rocks are unknown before the basal Oligocene (M. Lemoine, C. Kerckhove, pers. comm.). Unlike Beltrando et al. (2012), who represent the basal Arguerey tectonic contact as a vertical fault, it is interpreted by us as a low-angle thrust contact, in structural continuity with that at the base of the PSB Unit (Figs. 3 and 4).

Close to the Briançonnais Front, at the Tête du Chargeur (Fig. 3), this low-angle Tertiary Alpine thrust marks the tectonic contact between the tightly folded Valaisan Trilogy and the PSBA unit. This outcrop disproves the interpretation of Masson et al. (2008), who consider the cargneules as Triassic rocks marking a stratigraphic contact between the "Paleozoic" Versoyen Complex and the Liassic PSBA unit. On the lower right corner of the map of Fig. 3, near the Petit-Saint-Bernard Pass, the PSBA unit is overthrusted by the Briançonnais Front (red Tertiary Alpine thrust contact line).

A minor late Alpine low angle backthrust contact (yellow line, Fig. 3) has been mapped between the Aiguille de l'Hermite (Unit 1) and the top of the Arguerey calcschist and Collet des Rousses Unit. This rather late Alpine event occurred most likely towards the end of the tectonic thrusting of the PSBA unit, and is possibly linked to the late antiformal structure described below. In our opinion, this low angle fault contact observed at the top of the Arguerey Unit makes impossible a stratigraphic contact with the Hermite Unit above, as proposed by Beltrando et al. (2012). In addition, it must be noted that the Arguerey calcschists belong to the same unit as the PSB calcschists, which are in clear fault contact with the Versoyen units.

The whole stratigraphic sequence of the Versoyen Complex and Valaisan Trilogy (Fig. 5) is in an overturned position (Figs. 3 and 4), an is part of a regional syncline overturned to the northwest. This Tertiary Alpine structuration was formed towards the end of the Versoyen-Valaisan and PSBA exhumation process. Later (late Alpine), this overturned flank was refolded as evident from a well visible upright north-south antiform axis (Fig. 2 and 6h).

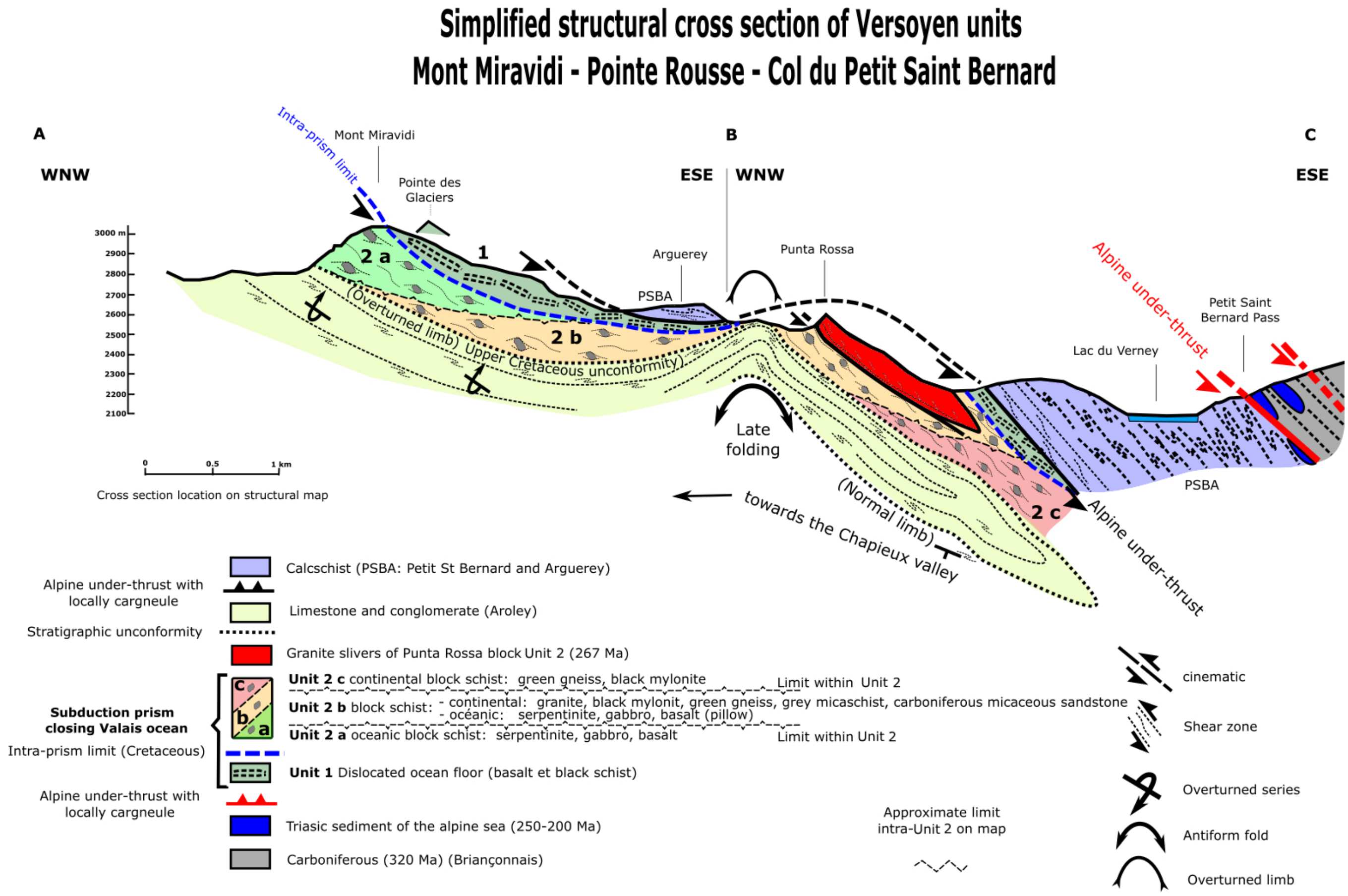


Fig. 4 - Structural cross section from Mont Miravidi to the Petit-Saint-Bernard Pass. For explanations, refer to Fig. 3 caption.

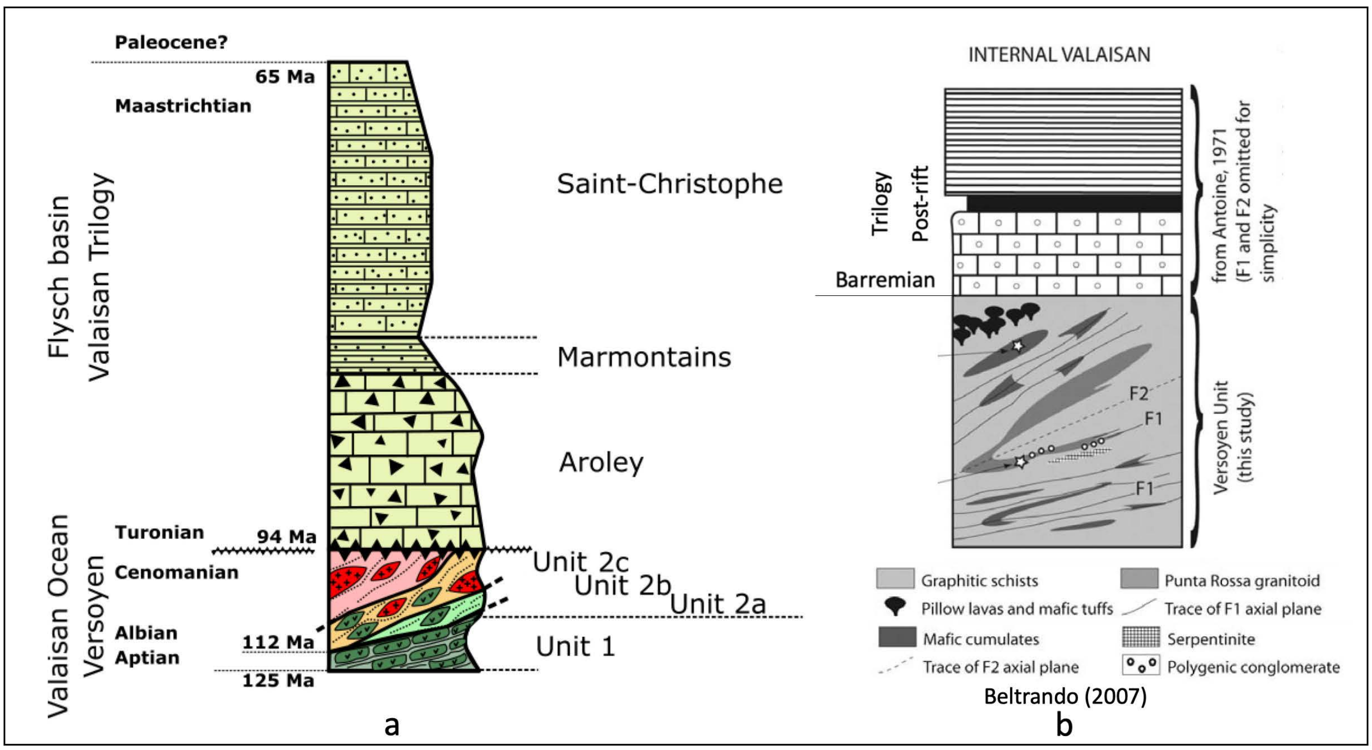


Fig. 5 - Lithostratigraphic summary log of the Versoyen and Valaisan Trilogy. **(a)** This study. The Versoyen Complex is made of 4 structural units: remnant of Valaisan ocean floor Unit 1 and 3 sub-units of schistes à blocs differentiated by the nature/origin of their blocks (units 2a, 2b and 2c). Based on Stampfli and Hochard (2009) model, we attribute an Aptian age to the transcurrent Valaisan ocean floor creation, following a Valaisan rifting period from 150 to 125 Ma. The Versoyen Complex shows a Cretaceous pre-Alpine structuration, as it is unconformably overlain by the Aroley (Turonian age) and the rest of the Valaisan Trilogy. The grey micaschist matrix of the schistes à blocs of Unit 2 contains Early Cretaceous radiolarians (found by Beltrando, 2012). The structuration of the schistes à blocs takes place therefore over the time period 112-94 Ma (Albian and Cenomanian). Cargneule, younger than 35-40 Ma and associated with Tertiary Alpine collision thrusts, is never observed at the contact or within any of the four Versoyen structural units. **(b)** Internal Valaisan lithostratigraphy from Beltrando et al. (2007). In this interpretation Alpine folding (F1 and F2) affect both the Versoyen Unit and the Valaisan Trilogy.

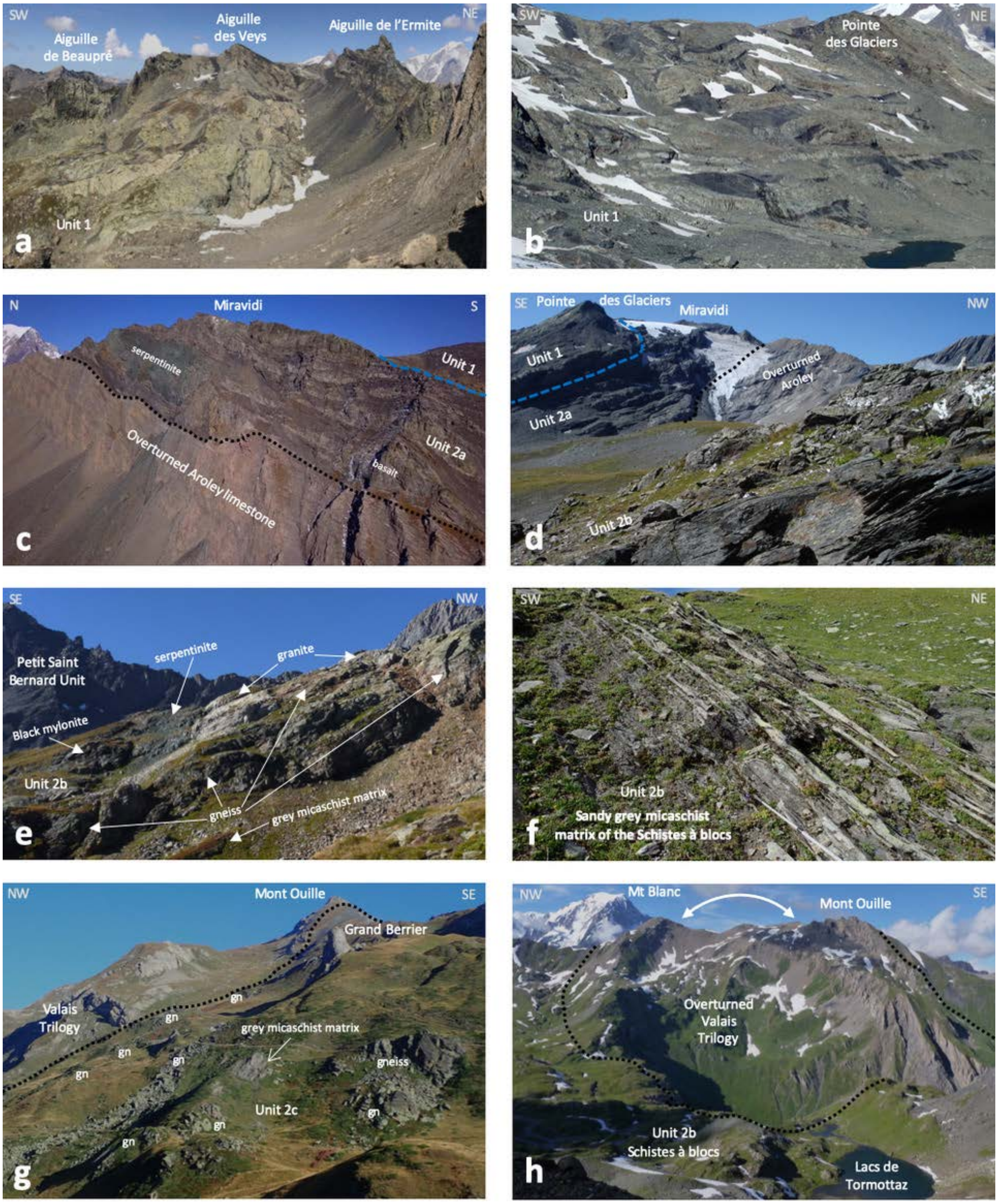


Fig. 6 - Landscape interpreted geophotos describing the four different structural units of the Versoyen complex near the Petit-Saint-Bernard Pass. **(a)** Unit 1 in Haut vallon de Beaupré. Oceanic floor outcrop, basalt and black schist, dislocated within an accretionary prism. **(b)** Unit 1 at Pointe des Glaciers. Oceanic floor outcrop, basalt and black schist, dislocated within an accretionary prism. **(c)** Unit 2a on Mont Miravidi cliff. Oceanic schistes à blocs unconformably overlain by the Valais Trilogy (overturned). **(d)** Units 1, 2a, 2b in Vallon de Bassa Serra. Oceanic schistes à blocs (2a) and continental - oceanic schistes à blocs (2b). **(e)** Unit 2b in Punta Rossa South massif. Imbricated continental and oceanic slivers. **(f)** Early Cretaceous radiolaria-bearing sandy grey micaschists under the Punta Rossa Pass, matrix of units 2b & 2c. **(g)** Unit 2c in Mont Laytire to Mont Ouille slope. Continental schistes à blocs with only green gneiss (gn) blocks and associated black mylonite. **(h)** Late alpine large antiform fold with overturned Valais trilogy resting unconformably on Unit 2b schistes à blocs. Unit 1 (6a-6b-6d) shows the dislocated rests of the Valaisan ocean floor with basaltic sills and pillowed lava flows intercalated with black schists. Unit 2a (6c-6d) shows the schistes à blocs fabric with oceanic blocks (serpentinite and basalt). This unit is naturally in contact with oceanic Unit 1. Unit 2b (6e-6h) shows the schistes à blocs fabric with a mix of oceanic and continental basement (granite, gneiss, micaschist) blocks. This unit has been logically mapped (Fig. 3) between Unit 2a (oceanic blocks only) and Unit 2c (continental blocks only). Unit 2c (6g) shows the schistes à blocs fabric with only continental basement blocks (green gneiss). The matrix (6f) of all these schistes à blocs is a sandy grey micaschists containing Early Cretaceous radiolarians (Fig. 1S).

Fig. 7 - Detail of the main blocks and slivers lithologies (oceanic and continental) from the Versoyen Complex (schistes à blocs - units 2a, 2b and 2c). **(a)** Green serpentinite tectonic sliver (Unit 2a) at Mont Miravidi. **(b)** Metabasalt tectonic sliver (Unit 2a) south of Mt Miravidi. **(c)** Metagranitoid large tectonic sliver (Unit 2b) in Punta Rossa massif. **(d)** Green gneiss block (Unit 2b) East of Tormottaz Lake. **(e)** Grey green micaschist block (Unit 2b) East of Tormottaz Lake. **(f)** Layered metagabbro block (Unit 2b) East of Tormottaz Lake. **(g)** Black mylonite transition with white metagranitoid block (Unit 2b) in Vallon du Breuil. **(h)** Green gneiss block (Unit 2c) between Grand Berrier and Laityre summit.

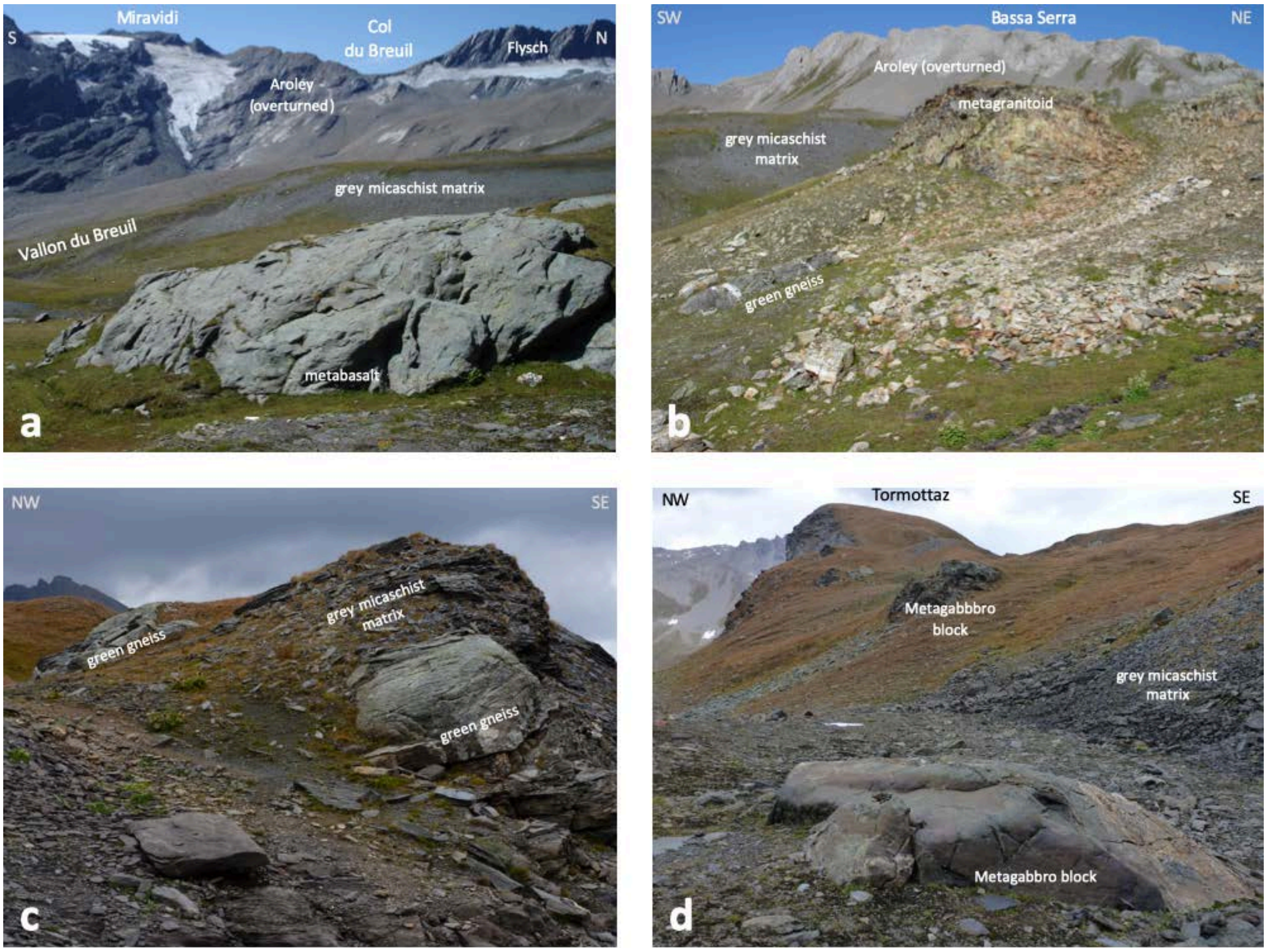


Fig. 8 - Landscape geophotos describing the tectonic mélange structuration (schistes à blocs and slivers) of the Versoyen complex (here only Unit 2b). **(a)** Metabasalt green block within grey micaschist matrix (Unit 2b) in Upper Vallon du Breuil. **(b)** Metagranitoid and green gneiss blocks in grey micaschist matrix (Unit 2b) in Upper Vallon du Breuil. **(c)** Two green gneiss blocks within grey micaschist matrix (Unit 2b) on the path between Punta Rossa and Tormottaz. **(d)** Two metagabbro blocks within grey micaschist matrix (Unit 2b) South of Tormottaz. The matrix around all these continental basement and oceanic blocks and slivers is a sandy grey micaschist containing Early Cretaceous radiolarians (Fig. 1S).

Beltrando et al. (2012) separate two Versoyen units (Punta Rossa and Hermite) by a *"late Alpine shear zone"*. Instead, our interpretation is that the contacts between our four Versoyen units are all pre-Tertiary and Cretaceous in age because sealed by the deposition of the Turonian Aroley unit, which rests unconformably on the Versoyen Complex (Antoine, 1971). No cargneule are associated with any of the tectonic contacts within the Versoyen Complex and sealed by unfaulted basal Aroley unconformity, which suggests a pre-Alpine origin of these contacts.

A Barremian to Aptian age was historically ascribed to the base of the Valaisan Trilogy and this age was adopted by Beltrando et al. (2007) and Loprieno et al. (2011). This age is based on the first fossil findings, mostly orbitolines (Elter, 1954; Trümpy, 1955; Sodero, 1968). However, the Turonian Globotruncana (*G. lapparenti coronata*, Bolli), later discovered by Antoine (1971) and Fudral (1973) in the basal section of the Aroley, led Jeanbourquin and Burri (1991) and Trümpy himself (Antoine, pers. comm.) to consider the orbitolines as reworked fossils. Such reworking at the base of the Valaisan flysch sequence is consistent with significant erosion occurred at the basin margin. This flysch basin has been deposited when the ocean was closing and not on a passive margin during the extensional phase. The end of oceanic extension and initiation of compression is placed around 110 Ma (see below), in good agreement with the Turonian unconformity sealing the Cretaceous deformation of the Versoyen.

Valaisan ocean and Briançonnais Paleozoic continental basement lithologies

The Permian ages obtained by Beltrando et al. (2007) on the Punta Rossa and Clapet massifs provide strong constraints on the Versoyen Complex formation and its regional geodynamic interpretation. It is worth noting that Permian magmatism rarely occurs in the Alpine external crystalline basement (ECM) but is widespread in the internal Briançonnais basement domain (Barféty et al., 1993; Cannic et al., 2001; Ballèvre et al., 2018).

The main lithologies of tectonic slivers and blocks in the "schistes à blocs" of sub-units 2 are illustrated in Fig. 7 and the tectonic mélange structure is described in Fig. 8. Besides serpentinite and metabasalt blocks, interpreted as deriving from an ocean floor (unit 2a), a wide range of continental basement lithologies in units 2b and 2c was observed, including white metagranitoid, green gneiss (referred to by Beltrando et al., 2012 as *"masses of metamafic rocks"*), grey-green micaschist, layered gabbro and black mylonite. Black mylonites are always found in transitional or sharp contacts with the white Permian metagranitoid or the green gneiss. According to Burri (pers. comm. in the field), the green gneiss blocks appear very similar to the gneiss observed in the internal Briançonnais basement (Grand Saint Bernard zone). Likewise, grey-green micaschist blocks do resemble foliated metamorphic rocks from the Bellecôte and Mont-Pourri massifs in Vanoise, which were dated at around 500 Ma (Guillot, 1987; Guillot et al., 2012).

The Paleozoic layered mafic rocks are cropping out in the Aiguille du Clapet massif and found as blocks near Tormottaz. Late Variscan diorites comparable to the mafic blocks in the Versoyen Complex occur in the Briançonnais (Piantone, 1980; Barféty et al., 1993). New geochemical data are presented later, which clearly highlight geochemical similarities between the Versoyen and Briançonnais mafic rocks but discard any resemblance between them and the coeval (i.e., Upper Carboniferous) plutons in the ECM.

In the field, structural alignment and analysis of deformation criteria (lineation, stretching and kinematics) clearly indicate that the Punta Rossa and Clapet massifs are large blocks or rather tectonic slivers, in tectonic contact but not linked to any Versoyen primary oceanic lithologies of Unit 1. The EDF tunnel under the Clapet Massif encountered no Clapet-type gabbro lithologies (Antoine et al., 1992). In our model, like all other smaller size Paleozoic continental basement blocks of the Versoyen "schistes à blocs" complex, the blocks were tectonically associated to the Valaisan oceanic domain lithologies during an accretionary prism process in Cretaceous times. The subduction under the Briançonnais continental basement created the Versoyen tectonic mélanges observed today in the Petit-Saint-Bernard pass area.

Our model, which does not consider an original geological link among the Punta Rossa granitoid, the Clapet gabbro and the Versoyen Unit, makes neither the existence of a Permian magmatism associated with the Versoyen Unit nor the need for an *"intrusion into the Valaisan basement"* (Beltrando et al., 2007). The association of granitoid and gabbro in the Versoyen Unit led Beltrando et al. (2007) to conclude that *"Permian magmatism in the Versoyen Unit was unrelated to the Cretaceous formation of the Valaisan Basin"*. However, this interpretation is abandoned in Beltrando et al. (2012; 2014a) where the granitoid and gabbro blocks are considered Paleozoic basement extensional allochthons formed in a rift margin, which we do agree with.

Versoyen Complex Cretaceous structuration

Punta Rossa Massif and Punta Rossa South tectonic slivers

The Punta Rossa imbricated slivers can be observed in two different settings. The northern part (Fig. 9 a and b), referred to as the Main Punta Rossa massif, on a cross-section from the summit towards the Punta Rossa Pass, contains the largest white metagranitoid tectonic sliver and several slivers, which are imbricated with the following lithologies: chloritite, black mylonite, green gneiss, sheared metagranitoid, serpentinite and metabasalt, and sandy grey schists. The southern part (Fig. 6e), which is in structural continuity across the valley, shows a ridge with the same slivers lithologies as in the Punta Rossa massif (Beltrando et al., 2014: fieldtrip location) but here the glacial erosion cuts at a much lower angle the structural dip of the slivers, providing greater planar views of each sliver (Fig. 6e).

Beltrando et al. (2014) focused their interpretation and model on these slivers, mainly exposed to the South Punta Rossa massif and one near Tormottaz. In today's structural setting, these imbricated slivers form a tectonic mélange with a "schistes à blocs" fabric, the radiolaria-bearing grey micaschist playing the role of a matrix embedding these imbricated slivers such as near Tormottaz and the Vallon du Breuil (Fig. 8).

Versoyen Complex blocks: Olistolith deposition or Tectonic mélange?

Beltrando et al. (2012) recognize that within the Punta Rossa Unit *"the radiolarian grey micaschists are not only draping over the basement: Relatively large outcrops of metamafics* (for us mostly green gneiss) *and black schists* (for us black mylonite) *are sometimes found within the grey micaschists. They possibly originated as blocks. They may represent olistoliths, re-sedimented from neighboring basement highs, or fold hinges"*. From field observations, we consider these features as resulting from a structurally deeper process related to an intense shearing deforming metagranitoid and green gneiss. This deformation is mimicking pseudosedimentary conglomerate / breccia lithofacies and tectonic "schistes à blocs" through compressional imbrication and shearing of grey micaschist with oceanic and continental basement slivers (Fig. 6-7-8, Fig. 10-11). Blocks can only be called olistoliths if they occur in a syn-sedimentary environment, which we do not observe for the Versoyen outcrops. Blocks are only oceanic, plutonic and metamorphic basement in nature, no sedimentary rocks were found.

Surface fault breccia or deep mylonitic shear zone?

The Punta Rossa "metabreccia" (Fig. 10) has a dark micaschist matrix. Beltrando et al. (2012) interpreted the formation of this "metabreccia" by a process of brittle cataclastic deformation. However, we observe locally a severe and intense shearing of the white metagranitoid leading to dark mylonite and possibly blastomylonite structures (Fig. 11) with C/S criteria showing underthrust kinematics (reverse fault). The deformation within the blocks is always the same with uniform shear criteria showing the same consistent kinematics. Such deformation occurs at a much greater depth than surface fault depth. We agree that this deformation (normal fault) occurred early and *"predates polyphase Alpine metamorphism"* (Beltrando et al., 2012). The fact that *"clast composition is strongly controlled by the neighboring lithofacies"* (Beltrando et al., 2012) is indeed consistent with a structural and mylonite related origin of such lithofacies. The clasts (Fig. 10) are always observed on planes perpendicular to the stretching mineral lineation (real pencil). The deformation being intense, the clasts observed correspond to perpendicular sections of pencils, their appearance mimicking a breccia. Fig. 11(g-h) shows the blastomylonitic process affecting different lithologies of the green gneiss and displaying an apparent polygenic pseudo breccia lithofacies. In our view, the black matrix is not of sedimentary origin, but is a finely recrystallized material created by deep mylonitic shear zones. The deformation of the initial rock is such that the original granulometry (e.g., Punta Rossa white granitoid) is progressively reduced to give way to a fine black recrystallized matrix (blastomylonitisation). This black matrix preserves the C/S criteria showing its tectonic origin (Fig. 11e-f). The key to reading these outcrops is to look for the stretched mineral lineation highlighting severe shear deformation. According to Beltrando et al. (2014)

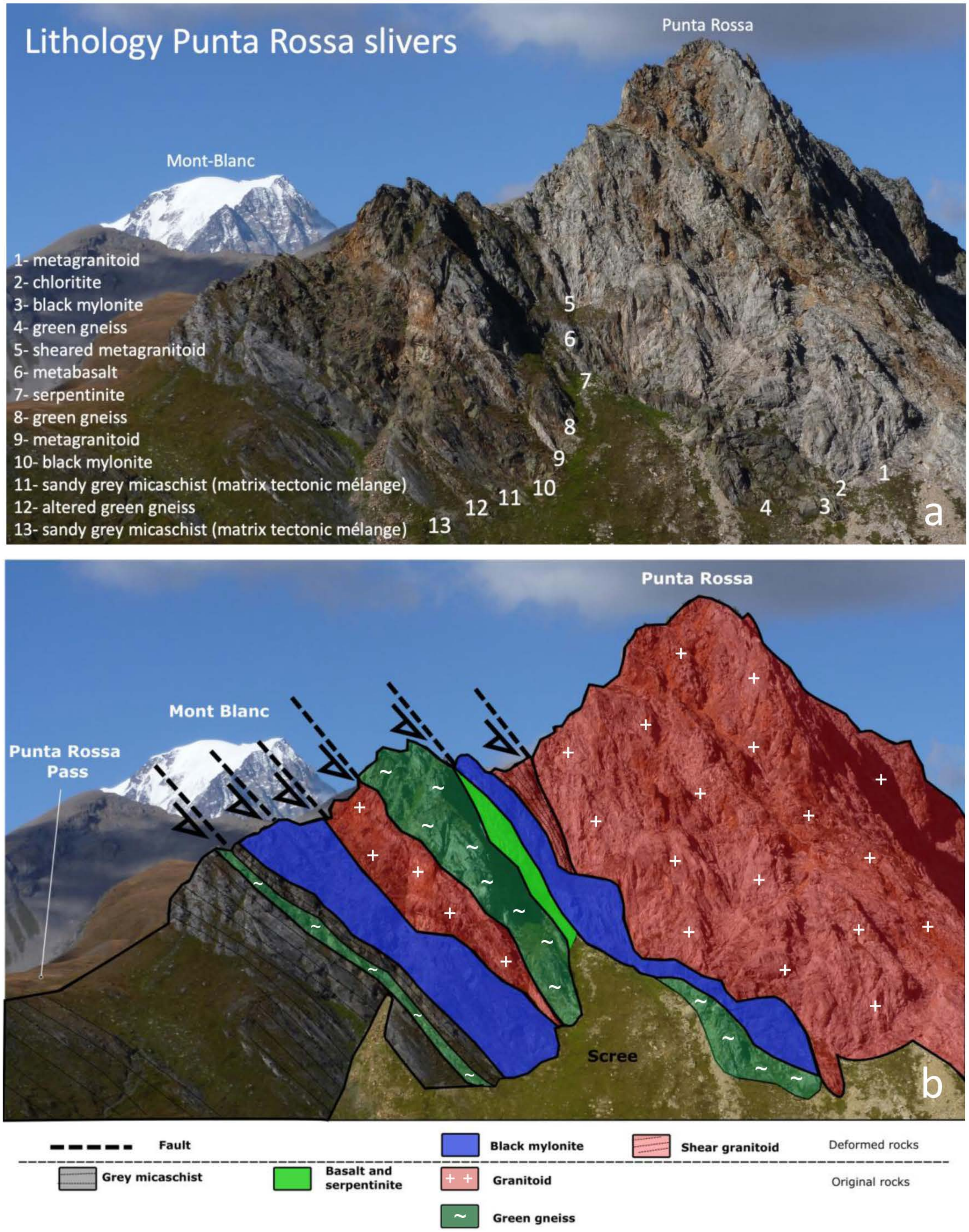


Fig. 9 - Punta Rossa massif ("schistes à blocs" Unit 2b) showing the same imbricated tectonic slivers as Punta Rossa South outcrop area (Fig. 6e) . On Figure 6e, the erosional cut has a low angle with the structural dip of the tectonic slivers. **(a and b)** Photo cross-section of the imbricated tectonic slivers of the Punta Rossa massif. Numerous tectonized slivers are stacked against each other from the Punta Rossa summit to the Punta Rossa Pass. All of these imbricated slivers are embedded in the Early Cretaceous sandy grey micaschist matrix, well developed at the pass and towards the beginning of the ridge (11 and 13). The first thin sliver of altered green gneiss (12) is completely imbricated within that micaschist matrix. Sliver lithologies are mostly continental in origin (granitoid, gneiss, mylonite, 1 to 5, 8 to 10 and 12) but oceanic slivers also occur in the middle part (serpentinite and basalt, 6 and 7), therefore the Punta Rossa massif and Punta Rossa South outcrop area belong to Unit 2b. It is important to realise that all the observed structuration and mylonite deformation has been acquired in pre-Alpine Cretaceous time, before the Turonian and younger Valaisan Trilogy deposition, as never can we observe Trilogy rocks involved in the schistes à blocs fabric.

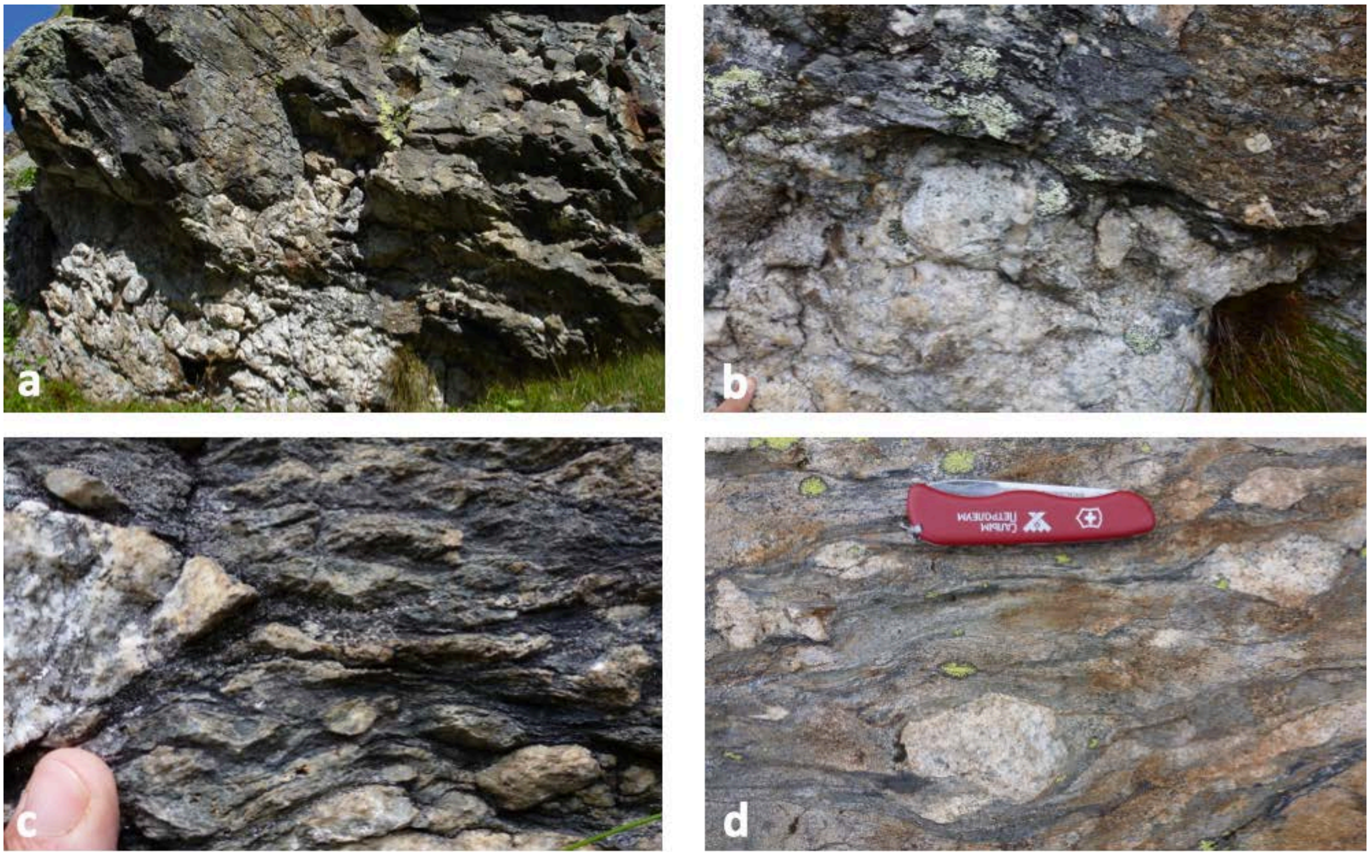


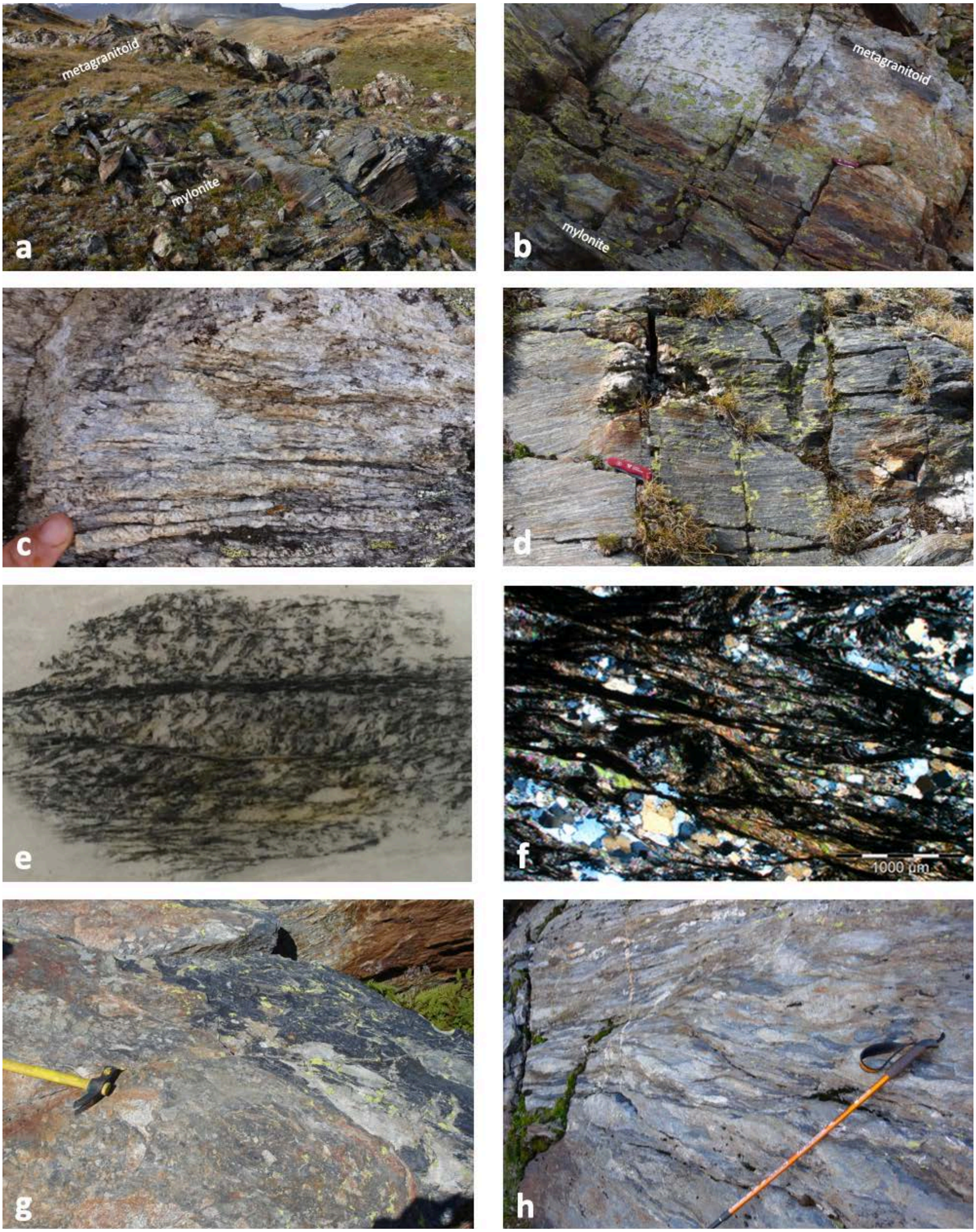
Fig. 10 - Mylonite formation process within a fractured metagranitoid displaying a "pseudo breccia" fabric within Punta Rossa massif. **(a)** White fractured metagranitoid and black mylonite. **(b)** Contact of fractured white metagranitoid with black mylonite. **(c)** Detail of intensely sheared metagranitoid being mylonitized (black mylonite), stretch mineral lineation perpendicular to the view. **(d)** Apparent « metaconglomerate » : sheared mylonitized metagranitoid, stretch mineral lineation perpendicular to the view. This historic outcrop, at the base of the large Punta Rossa granitoid sliver, close to the path leading to the Punta Rossa Pass, has been interpreted in the 1950s by F. Ellenberger and M. Vuagnat as the "basal conglomerate" of the later called Versoyen (P. Antoine, comm. pers.). The fractured granitoid (15a-b) is passing with a sharp contact (15b) to a sheared black schist containing mm to dm size granitoid lenses-fragments (15c-d). A detail look shows that the black schist "apparent matrix" is not a sedimentary matrix but a fine and intensely sheared destruction of the granitoid within a mylonitic deformation corridor. The elements of this pseudo "conglomerate-breccia" are observed perpendicular to the stretching lineation and therefore correspond to sections of the stretched elements (pencils cut perpendicularly) hence the confusion made in previous interpretations.

the fact that *"Cataclastic basement deformation predated the oldest metamorphic fabric seen…"* testifies that *"these cataclasites are Mesozoic fault breccia"*. The fact is also true if the breccias are deep compressional mylonitic "pseudobreccias" as shown by the observed deformation criteria. Metabreccias of clear sedimentary origin associated with the PSBA calcschists are indeed observed within the Subbriançonnais Domain (Arguerey and PSB Collet des Rousses areas), but they cannot be grouped or compared with any of the Punta Rossa tectonic metabreccias.

Multiply folded or sheared interfaces within the Punta Rossa and Hermite units?

Assuming an isoclinal folding of the Punta Rossa Unit, Beltrando et al. (2012) placed all the metabreccias on one stratigraphic level directly above the Paleozoic basement. We see no evidence of such intra Versoyen folding but rather an intense shearing and a random position of the mylonitised metagranitoid and green gneiss blocks and slivers, consistent with the interpretation of the Punta Rossa Unit as a tectonic mélange with blocks and slivers embedded within the radiolaria-bearing grey micaschists (Fig. 8).

According to Beltrando et al. (2014) *"The overall architecture of the (Versoyen) Hermite and Punta Rossa Units, in the Breuil valleys, is mainly controlled by two large recumbent folds"*. We do not see such intra Versoyen isoclinal folding, but rather series of sheared slivers in an overall "schistes à blocs" tectonic mélange structure, as already pointed out in the Swiss Valais (Visp area) by Jeanbourquin (1994). The authors recognized that *"fold hinges are rare… folding not seen, inferred from polarity of stratigraphic sequence"*. We indeed observed intense shearing throughout the Punta Rossa unit, no clear evidence of folding and impossibility to recognize any stratigraphic polarity, as expected from a tectonic metabreccia. Pillow lava shape in Unit 1 does indicate local polarity (normal or reversed), as reported e.g., by Loubat (1968), Schürch (1987), Lassere and Lavergne (1976) and Cannic (1996). However, in such tectonised units, the regional interpretation of local polarity indicators is somewhat questionable, especially if one considers the "schistes à blocs" fabric of the Versoyen Complex. It is worth noting that any pre-Aroley structure inside the Versoyen complex must be distinguished from the later Tertiary Alpine recumbent regional synclinal folding, which causes the overturning of the regional unconformity between the Versoyen Complex and Valaisan Trilogy.


metagranitoid
mylonite
a
metagranitoid
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b
c
d
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h

In Beltrando et al. (2012), cross sections show the Aroley facies as folded together with the Punta Rossa unit, considering a stratigraphic continuity of the Aroley with the underlying Punta Rossa unit without any unconformity. From our observations, these Aroley facies appear clearly discordant (Fig. 3) as interpreted by Antoine (1971) on the Punta Rossa Unit. Lithologies of the Aroley are never involved in the deformation of the "schistes à blocs" complex. The only outcrop of Aroley visible towards Pointe Rousse corresponds to a window through the "schistes à blocs" due to late Alpine antiform folding (Fig. 4).

We note that the Valaisan Trilogy metasediments, as well as the PSBA calcschists, are internally intensely folded (often isoclinally). On the contrary, the stratigraphic contacts between the main units, such as between Aroley - Marmontains - St Christophe, are well preserved, mappable regionally and much less affected by intense folding (Fig. 3 and 4). This has been noted as a structural common characteristic within the Penninic Alps (Sartori et al., 2017). However, tectonic deformations observed within the Versoyen "schistes à blocs" and stacked slivers are essentially deformed by shearing related to the Versoyen Complex tectonic mélange. The Valaisan Trilogy is never involved in that deformation and therefore cannot be part of the underlying tectonic mélange itself. The deformed Versoyen Complex, together with the Valaisan Trilogy, was affected later by the Tertiary Alpine collision tectonics.

Versoyen Complex Late Jurassic to Middle Cretaceous radiolaria

Occurrence of microfossils in the Versoyen Complex and the overlying Valaisan Trilogy rock pile is very rare. The discovery by Marco Beltrando of microfossils within the grey micaschists of the Punta Rossa Unit (Fig. 1S) is therefore extremely valuable. P. de Wever identified *Dictyomitra*, indicating late Jurassic to Middle Cretaceous age (pers. comm.), whereas Luis O'Dogherty answered that it is impossible to determine these radiolarian fragments only based on the 2D sections available. However, these microfossils resemble those (*Adelocyrtis, Cenosphaera* or *Tricolocapsa*) discovered by Burri (1958) in the Marmontains Formation - base St Christophe Flysch (most likely reworked) near Sion.

The set of better-preserved radiolarians, described by Burri, (1958) within the Valaisan Trilogy (Marmontains-Flysch) are typical Late Jurassic to Early Cretaceous forms, and cannot be Late Cretaceous. Therefore, the radiolaria described by Burri (1958) in the Sion region are indeed regarded as reworked in the Marmontains distal fan turbidites. A similar fauna has been found in younger Valaisan series (St. Christophe) and also in the Tertiary Pierre Avoi flysch (Bagnoud et al., 1998), where they include foraminifers ranging from Albian-Aptian to Paleogene in age.

We postulate that the Late Jurassic to Early Cretaceous radiolarians of Burri (1958), together with the Albian-Aptian foraminifers, date the oceanic pelagic sequence of the Valaisan Ocean before its closure. That sequence was imbricated and uplifted in the late Cretaceous Versoyen Complex tectonic mélange and its fauna recycled in younger flysch series.

Petit-Saint-Bernard, Arguerey and Collet des Rousses: all parts of the same sedimentary unit

Beltrando et al. (2012) have interpreted the Petit-Saint-Bernard calcschist Unit (PSB) as *"a distinctive Alpine tectonometamorphic unit… separated from mafic/ultramafic bearing units underneath by Alpine shear zone"* and containing locally cargneule. We associate to that unit also the Arguerey calcschists on the basis of identical lithofacies, age, structural setting and intensity of deformation (Fig. 2S). Raman spectroscopy *T* values by Beltrando et al. (2012) confirm that the PSB and Arguerey have similar high intensity of deformation (PSB value range 458-467ºC, and Arguerey value 426ºC). Belemnites were found by Franchi (1900) in the PSB unit and by R. Barbier (pers. comm. to P. Antoine) in the Arguerey calcschists. Both contain the special Collet des Rousses metasedimentary breccia, whose stratigraphic position is quite hard to establish in view of the intense deformation with isoclinal folding and internal shearing. The PSB and the Arguerey calcschists are bound by a Tertiary Alpine thrust with cargneules at their base and by the Aiguille de l'Hermite metabasalts at their top (Fig. 12). This interpretation allows to place both the Subbriançonnais PSB and Arguerey calcschist Unit (PSBA) on the SE margin of the Valaisan ocean, close to the Briançonnais basement, but clearly distinct in Cretaceous times from the oceanic domain. Similar calcschists have been deposited into an internal Briançonnais Liassic graben environment in Vanoise (Grande Casse, Grande Motte and Dent Parachée). Beltrando et al. (2012) do not correlate the Arguerey Unit with the PSB one but place the Arguerey calcschists and Collet des Rousses metabreccia as part of the Versoyen Hermite Unit, thought to have been deposited above the Hermite metabasalts and black schists.

Fig. 11 - Mylonite deformation developed on metagranitoid and gneiss blocks and slivers. **(a)** White metagranitoid block (above) with transition to thick black mylonite (Unit 2b) in Vallon du Breuil. **(b)** White metagranitoid block with transition to black mylonite (Unit 2b) in Vallon du Breuil. **(c)** Detail of a sheared metagranitoid of Punta Rossa type (Unit 2b) in Vallon du Breuil. **(d)** Metagranitoid dark mylonite (Unit 2b) in Vallon du Breuil. **(e)** Thin section photograph of a mylonitized metagranitoid (Unit 2b), stretch mineral lineation parallel to the view in Vallon du Breuil. **(f)** Thin section, cross nicols view, metagranitoid black mylonite (Unit 2b), stretch mineral lineation parallel to the view in Vallon du Breuil. **(g)** Sheared green gneiss being mylonitized and black mylonite : tectonic « breccia » (planar view) in Punta Rossa South massif. **(h)** Sheared green gneiss being mylonitized : tectonic « breccia » (cross section view) in Punta Rossa South massif. Numerous blocks of granitoid and green gneiss within schistes à blocks units 2b and 2c are associated in sharp (11b) or transitional (11c) contacts to meter - 10m thick dark mylonitic schists (16a-d) created by local severe deformation, destruction and shearing of the granitoid mass. All stages can be observed from minor deformed granitoid to intense fracturation (10a), shearing (11c) and pure dark mylonitic fabric (11d). Photo micrograph display the same fabric at microstructure scale (11-e-f). The outcrops and thin sections are observed in the direction of the stretching lineation (parallel to the pencils) and therefore no elements of the pseudo-conglomerate are seen. Only the stretching deformation is observed. Mylonite formation process is displaying green gneiss "pseudo metabreccia fabric" (11-g-h). In the context of the observed widespread severe mylonitic deformation of the granitoid (Figs. 10 and 11) and also green gneiss within the schistes à blocs units 2a and 2b, it is easier to recognize in the planar view (11g) that the apparent sedimentary breccia fabric is indeed tectonic in origin as the matrix is mylonitic and not a grey or black shale from sedimentary origin. The dark band corresponds to privileged deformation corridors where everything is crushed and recrystallized (blastomylonite) typical of shear zone (ultimate phase of deformation). The cross-section view (11h) highlights the severe shearing creating all the observed gneissic fragments. Again here, the elements of this pseudo "conglomerate-breccia" are observed perpendicular to the stretching lineation and therefore correspond to sections of the stretched elements (flattened pencils cut perpendicularly) hence the confusion made in previous interpretations.

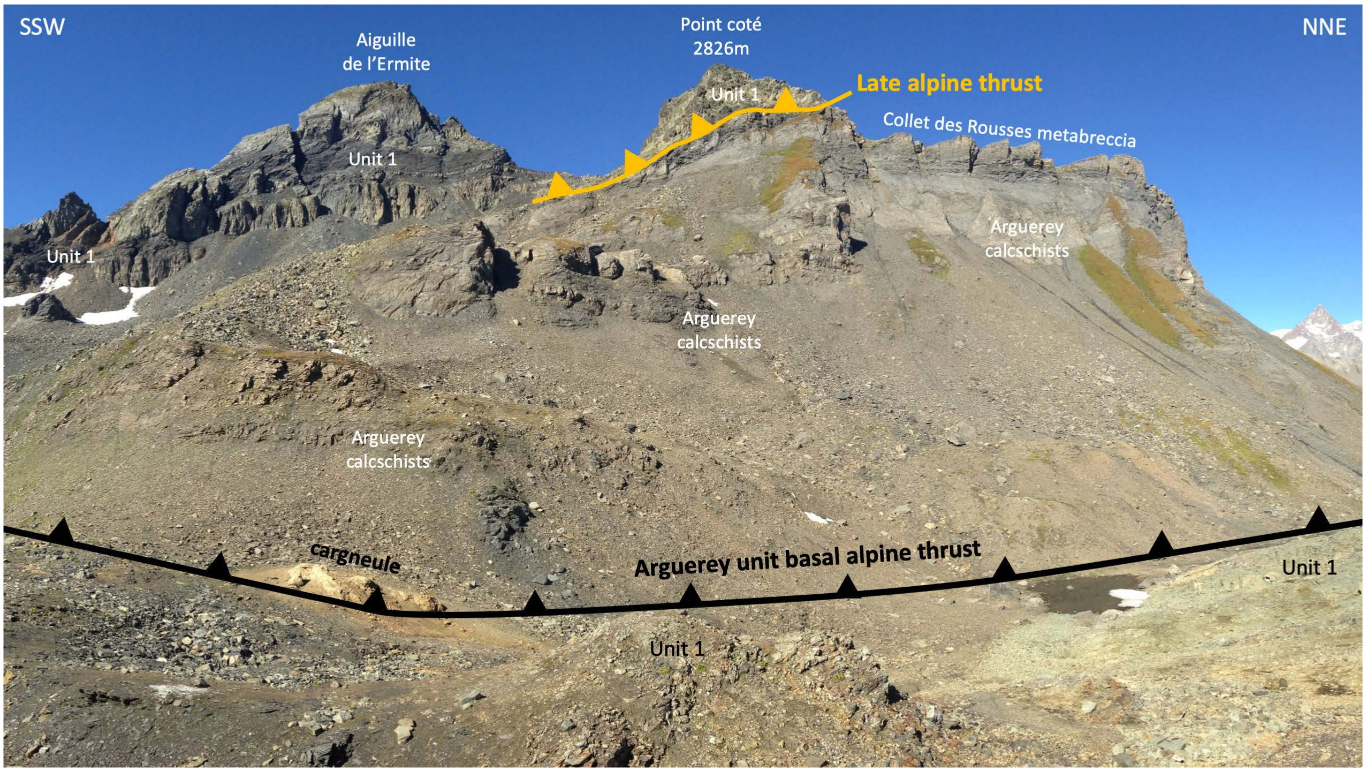

Fig. 12 - Arguerey calcschist unit cliff with Alpine tectonic contact at the base and the top. Cargneule is found occasionally all along the low angle basal contact of the PSBA calcschists on the Versoyen units. We conclude that this contact represents the Alpine (around 25 Ma) thrust fault contact (see Fig. 3 and 4) of the Versoyen and Valaisan units underthrusted below the Subbriançonnais PSBA units. A structural complication occurs then at the top of the Arguerey cliff, where the metabasalt from Aiguille de l'Hermite (Unit 1) are locally backthrusted over the Arguerey calcschists (Fig. 3). This low angle thrust contact can be followed above the Glacier Septentrional de l'Hermite.

GEOCHRONOLOGIGAL AND GEOCHEMICAL DATA

Considering the well-documented MORB affinity of the Versoyen magmatic rocks (Loubat, 1968; Cannic, 1996; Mugnier et al., 2008) and the controversy on their age (Upper Paleozoic or Jurassic/Cretaceous?), a precise account of the geochemical signature of the dated rocks is a necessary prerequisite before assigning any age to the oceanic stage of the Versoyen Complex.

Eleven new geochemical analyses (major and trace elements) and one U/Pb zircon dating have been obtained in the frame of our study in order to complete the preexisting data corpus.

New geochronological data

A sample from the Tormottaz area (TOR0001A, Table 1S, Fig. 13a) has been selected for dating. Analytical procedures are detailed on Fig. 3S. The rock is coarse-grained and rather leucocratic, being designated as a leucodiorite. Its chemical composition (Table 2S) is slightly felsic (SiO_2 = 63.68 wt.%) with a large predominance of Na_2O (5.9 wt.%) over K_2O (0.1 wt.%), and a low FeO_t/MgO ratio (1.4) typical of calc-alkaline rocks. From these geochemical characteristics, the rock should best be designated as a low-K tonalite. The zircons of the TOR0001A tonalite constitute a heterogeneous population of rather elongated small zircons. They are either subhedral, pink and translucent or totally rounded and slightly translucent. Among them, some crystals exhibit smoky grey colors. Amongst the thirty analyses performed on thirty grains, only one (analysis 19) was not exploitable because of signal instability. All the analyses obtained on the 29 spots are reported in Table 1S. The ages obtained show a large range, from c. 1800 Ma to 300 Ma, suggesting multiple heritages (Fig. 3Sa). 26 analysis plot along the Concordia with ages between 550 and 300 Ma (Fig. 3Sb). Two ages may be defined by more than one point: (i) 455 ± 3 Ma (5 analyses) (Fig. 3Sc) and (ii) 310 ± 4 Ma (5 analyses) (Fig. 3Sd). The Carboniferous age is considered as the most probable for the tonalite emplacement, the other ages attest for multiple heritages with a predominance of Ordovician zircons.

New geochemical data

Eleven new analyses have been performed on samples collected in different places of the Versoyen Complex (Table 2S, including sample coordinates). After preparation in the BRGM laboratories, samples have been sent to the ALS geochemical laboratory (Loughrea, Ireland). The standard «batch» of high precision measurements has been selected including analyses of trace elements by ICP-MS and major elements by XRF. The analyzed samples are from three different Versoyen Sub-units as shown on Fig. 3 and 13a: 1- the oceanic sequence (Unit 1); 2- the "schistes à blocs" of Unit 2a with oceanic blocks; 3- the "schistes à blocs" of Unit 2b containing a mix of oceanic and continental basement blocks (among them the Punta Rossa mega block). One peridotite (Unit 2a) and one black schist (Unit 2a) have also been analyzed but they will not be commented further.

The Versoyen Complex: Geochemical signatures and Ages

Radiometric datings have been obtained by Cannic (1996), Schärer et al. (2000), Giroud and Meilhac (2002), Beltrando et al. (2007), and Masson et al. (2008). Geochemical analyses are reported in different theses (Loubat, 1968; Lasserre et Lavergne, 1976; Schürch, 1987; Cannic, 1996; Giroud and Meilhac, 2002), and articles (Schärer et al., 2000; Masson et al., 2008). Only the trace element representative of the geochemical signature (i.e., those constraining the source of the original magmas) are considered here by using a $(Th/Ta)_N$ vs. $(Tb/Ta)_N$ diagram (Thiéblemont et al., 1994) (Fig. 13b), which clearly discriminates the mid-ocean ridge basalts (N- and E-type MORB) from any other terrestrial basaltic lavas. As a whole, the 31 rock analyses (including our nine) plotted in the diagram (Fig. 13b) cover two main fields: N-MORB and calc-alkaline lavas (CAB). The former includes all the intrusive (sill) and effusive (pillow lava) terms of the Versoyen Complex located in our structural Units 1, 2a and a few in 2b (Fig. 13a) and in the Visp Complex of Swiss Valais. None of those rocks have actually been dated. As depicted in Fig. 13b, the dated samples plot in two different fields; continental tholeiites (CFB field) and calc-alkaline lavas (CAB). In the CFB field plots only one sample, which corresponds to the leucogabbro (sample 94-104) dated by Schärer et al. (2000) and described by Cannic (1996) as a felsic dyke crosscutting the ophiolitic succession. Their radiometric ages i.e., 294 ± 10 Ma and 309 ± 6 Ma respectively and correspond to the lower intercept of a discordia with an upper intercept at 3240 ± 34 Ma. Sample 94-104 is in fact a basic and mafic rock (SiO_2 = 48,65 wt.%, MgO = 7,04 wt.%). Its CFB-type affinity (Fig. 13b) results from a Th content significantly higher than that of the N-MORB type Versoyen lavas and sills (i.e., 1.14 ppm vs 0.46 ± 0.18 ppm). Other differences are mentioned by Schärer et al. (2000); sample 94-104 is richer in alumina

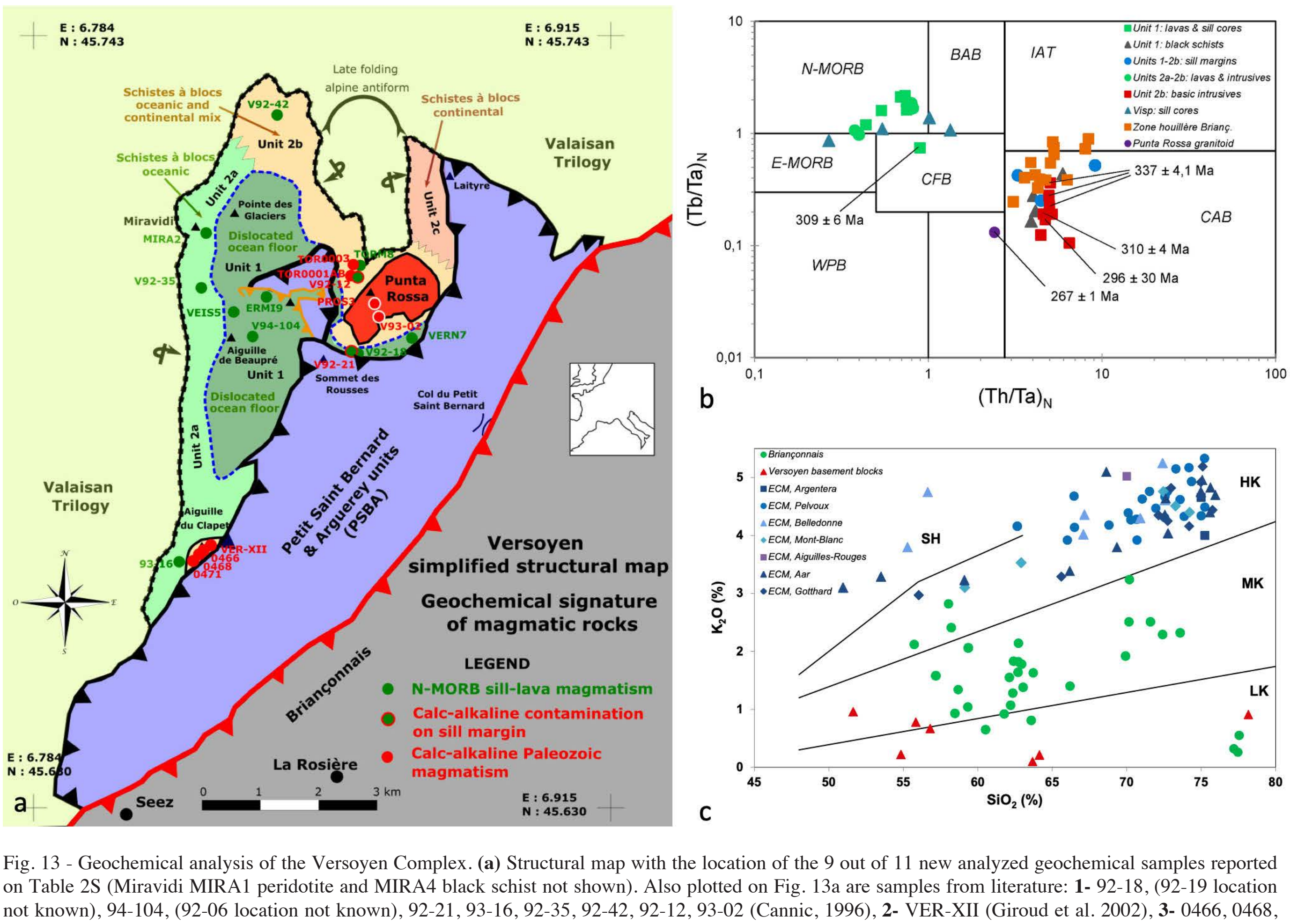

Fig. 13 - Geochemical analysis of the Versoyen Complex. **(a)** Structural map with the location of the 9 out of 11 new analyzed geochemical samples reported on Table 2S (Miravidi MIRA1 peridotite and MIRA4 black schist not shown). Also plotted on Fig. 13a are samples from literature: **1-** 92-18, (92-19 location not known), 94-104, (92-06 location not known), 92-21, 93-16, 92-35, 92-42, 92-12, 93-02 (Cannic, 1996), **2-** VER-XII (Giroud et al. 2002), **3-** 0466, 0468, 0471 (Masson et al., 2008). Visp Area samples from Swiss Valais: VA5, VA11, VA12, VA16 (Cannic, 1996) are plotted on Fig. 13b. **(b)** $(Th/Ta)_N$ vs $(Tb/Ta)_N$ (Thiéblemont et al., 1994) for the rocks of the different tectonic units of the Versoyen complex with indication of the age obtained on dated samples. *N-MORB* – field of N-type MORB; *E-MORB* –E-type MORB; *BAB* – Oceanic back-arc basin basalt; *WPB* – Within-plate basalt (transitional and alkaline); *CFB* – Continental tholeiite; *IAT* – Island-arc tholeiite; CAB – Subduction-related calc-alkaline lava. For some analyses with no Tb measurement (data of Cannic, 1996), the Tb_N value has been substituted by $(Gd_N+Dy_N)/2$. Data plotted from this paper (11 analyzes, Table 2S), Cannic, 1996; Giroud et al. 2002 and Masson et al., 2008. Samples are reported on Fig. 13a. Analyses of the basic to intermediate intrusives of the Zone Houillère Briançonnaise (from Cannic et al., 2011; Thiéblemont, unpublish.) are reported for comparison. **(c)** SiO_2 vs K_2O diagram (Peccerillo and Taylor, 1976) with comparison between the plutonic rocks occurring as blocks within the Versoyen schistes à blocs complex, the Carboniferous granites of the External Crystalline Massifs and the intrusive units cutting across the sedimentary series of the Zone Houillère. Note that points for the ECM correspond to average compositions of individual plutons (Debon and Lemmet, 1999), whereas whole rocks analyses are plotted in the cases of Versoyen and Zone Houillère (Briançonnais) (analyses from Cannic et al., 2001; Thiéblemont, unpublish.). To prevent the effect of alteration the analyses with > 3% volatile contents (LOI on Table 2S) have been discarded amongst the Briançonnais samples.

(16.66 wt.% vs 14.52 ± 0.74 wt.%) and its REE pattern is LREE-enriched and HREE-depleted, not LREE-depleted like N-type MORB. Despite these clear petrological differences, Schärer et al. (2000) considered this leucogabbro as having a «strong affinity with the intruded massive gabbros». Indications provided by Cannic (1996) did not allow us to locate the dated dyke.

The geochemical signature of all the other dated rocks is clearly different, being calc-alkaline (Fig. 13b). The Aiguille du Clapet massif (location Fig. 13a), which constitutes the larger gabbroic body in the Petit-Saint-Bernard area, has been selected by Masson et al. (2008) for radiometric dating because it appears as relatively more evolved (i.e., more felsic) than the other gabbros of the Versoyen Complex and therefore more suitable for zircon extraction. Three U/Pb ages have been obtained which enabled them to propose a mean crystallization age of 337 ± 4 Ma (Masson et al., 2008). They noted, as already pointed out by Loubat, (1968), that the whole-rock chemistry and trace element signature (e.g., LREE enrichment) of the Clapet rocks are significantly different from those of the ophiolitic terms, but due to contamination of the gabbroic magma by the water-rich sedimentary country rocks. Such a mechanism is in fact observed at the margin of the doleritic sills of the Versoyen ophiolite (Cannic, 1996). Analyses performed in such sill margins reveal a contamination process (e.g., Th contamination), which drives them to the calc-alkaline field overlapping the field of the enclosing black schists (Fig. 13b). However, attributing the calc-alkaline signature of the Clapet massif to contamination raises the problem of the possible inherited origin of the zircons. This hypothesis was not totally ruled out by Masson et al. (2008) but considered as less probable than that of an Early Carboniferous intrusion age. Our conclusion is that the geochemical signature is clearly different from that of the Versoyen sill-lava rocks (Fig. 13b), making the correlation between the two units rather disputable. Conversely, considering the calc-alkaline affinity well identified in the upper Paleozoic magmatism of the Briançonnais zone (Piantone, 1980; Cannic et al., 2001), the calc-alkaline nature of the Clapet massif is consistent with our interpretation of this massif as being a Briançonnais Paleozoic independent block within the Cretaceous accretionary prism (Unit 2b; Fig. 13a). Results obtained previously by Giroud and Meilhac, (2002) on the Clapet massif also indicate a calc-alkaline affinity (Fig. 13b) and a significantly younger (though rather imprecise) age of 296 ± 30 Ma. Finally, a third dating by Beltrando et al. (2007) on a Clapet leucogabbro gave a precise U/Pb age of 272 ± 2 Ma, but unfortunately no geochemical analysis of the dated rock is given.

Beltrando et al. (2007) provided another well-defined Permian age of 267 ± 1 Ma for the Punta Rossa massif. We have analyzed a rock from the same granitoid block/tectonic sliver (Table 2S). It displays a highly acidic (SiO_2 = 78,17 wt.%) and sodic (Na_2O = 6.23 wt.%, K_2O < 1 wt.%) composition. The trace element signature is clearly "orogenic" (CAB field in Fig. 13b), making this sample similar to most trondhjemites. Analyses provided by Barfety et al. (1995) (Table 1, p. 44) and Cannic et al. (2001) (Table 3, p. 84) show that such Na-rich felsic rocks occur in the Briançonnais Zone Houillère and one sample dated by Cannic et al. (2001) displays a Ar/Ar amphibole age of 278.8 ± 6.6 Ma. The coarse-grained tonalite from the Tomottaz area we have dated is a block within a grey micaschist matrix. Located in the CAB field of the discriminant diagram (Fig. 13b), this block has a typical orogenic geochemical signature, its U/Pb zircon age of 310 ± 4 Ma is in the range of the other plutonic rocks included in the tectonic mélange. This dated block is part of our unit 2b, which also comprises the neighbouring Punta Rossa and Aiguille du Clapet massifs (Fig. 13a).

Geochemical regional comparisons

In a regional perspective (Fig. 1), the blocks of magmatic rocks included in the "schistes à blocs" of the Versoyen Complex may be supposed to have two provenances: 1- an external provenance, with origin in the belt of Carboniferous plutons, which extends from the Gotthard to the Argentera massif (the External Crystalline Massifs or "ECM") (Debon and Lemmet, 1999) and up to Maures - Estérel (Duchesne et al., 2012; Amenzou, 1988; Poitrasson and Pin, 1998), located on the northern margin of the Valais rift; 2- an internal provenance, where the most proximal source should be the Zone Houillère (Briançonnais domain), and more specifically the basic to felsic rocks, that locally appear as dense swarms of intrusives cutting across the upper Carboniferous sedimentary succession (Barféty et al., 1993; Piantone, 1980).

An extensive overview of the main geochemical characteristics of the ECM plutons was published by Debon and Lemmet (1999) that includes average compositions of individual plutons of each massif for which the authors collected a total of some 900 geochemical analyses. For the Zone Houillère, analyses have been obtained from Piantone (1980), Barféty et al. (1993), Cannic et al. (2001), and Thiéblemont (unpublished data).

Comparisons have been made using the conventional SiO_2 vs. K_2O diagram (Peccerillo and Taylor, 1976) (Fig. 13c), which discriminates between low-K, medium-K, high-K and shoshonitic series.

The plutons of the ECM display a uniform high-K to shoshonitic affinity consistent with their mainly subalkaline (or alkalicalcic) nature (Debon and Lemmet, 1999), which are distinctly different from the Versoyen plutonic blocks, mostly of low-K type. The Carboniferous Briançonnais intrusives are always less potassic than the plutons of the ECM, but generally more potassic than the partly overlapped Versoyen blocks. Derivation of the Versoyen Carboniferous basement blocks from the ECM should be excluded because of the homogeneous high-K character of the ECM plutons, which are significantly different from the low-K blocks of the Versoyen.

The basic to intermediate intrusive rocks of the Zone Houillère, analysed by Cannic et al. (2001) and Thiéblemont (unpubl. data) are plotted in the $(Th/Ta)_N$ vs. $(Tb/Ta)_N$ discrimination diagram (Fig. 13b) together with the Versoyen blocks of unit 2b. Both analysis sets plot mainly in the calc-alkaline field (CAB) and partly overlap each other. The $(Tb/Ta)_N$ ratio of the Zone Houillère intrusives is generally higher causing a slight overlap to the Island arc tholeiite (IAT) field. A common characteristic of both groups is calc-alkaline and slightly potassic, which makes them different from the ECM plutons, suggesting a totally different Carboniferous tectonic setting, far from each other before the final Alpine shortening (e.g., Fig. 6 of Stampfli, 1993).

We conclude that the geochronological and geochemical data reported above are well consistent with our structural model considering the plutonic rocks of the tectonic mélange as blocks and slivers of Upper Paleozoic calc-alkaline rocks derived from the Briançonnais continental margin. As noted by Masson et al. (2008), the Late Carboniferous age obtained by Schärer et al. (2000) on a leucogabbro crosscutting the ophiolite is too controversial to be considered as a definite argument against the field evidence supporting a Cretaceous age of the Versoyen Complex. It is worth mentioning here two papers that reported Paleozoic U-Pb ages of zircons extracted from present-day MORB or 1.0 Ma-old gabbro near the Mid-Atlantic Ridge (Pilot et al., 2000; Skolotnev et al., 2010). We consider the sill and pillow lava preserved in Units 1, 2a and some blocks of Unit 2b as the remnants of the Cretaceous Valaisan ocean floor.

DISCUSSION

Valaisan rifting and ocean floor evidence: Hyper-extended rift margin model

The Valaisan rift opened some 155 million years ago (Stampfli and Hochard, 2009 and references therein), when Spain separated from Newfoundland in correspondence to a late Variscan transcurrent fault zone (Stampfli, 1993; Fudral, 1998; Ballèvre et al., 2018). In the Alpine area, the opening took place within the Subbriançonnais domain. The Oxfordian Télégraphe fault breccia was formed in that rift environment (Ferrari and Luzieux, 2002). At the eastern end of the Valais Ocean, in eastern Switzerland, sediments attributed to the Late Jurassic are also found resting on continental allochthons and exhumed mantle rocks (Ribes et al., 2020). We interpret our unit 1 (Fig. 3 and 4), a typical Versoyen lithology of basaltic lava flows and sills (N-MORB) associated to black schists, as representing the relics of the Valaisan ocean floor.

The use of the term "Valaisan ocean" is appropriate and justified in our opinion, based on the observed dismantled relics within the Versoyen Complex of an ophiolitic suite: a pelagic sequence of schists with radiolarians, MORB-type basalt sills and pillow lavas (Unit 1), MORB-type gabbros as blocks in Unit 2b (Table 2S, TORM8) and many blocks and slivers of serpentinised peridotite within Units 2a and 2b (depleted harzburgite, Table 2S, MIRA1). It has long been observed that the actual volume of oceanic relics within a mountain chain ocean suture has no correlation with the original size of the oceanic domain. Clear examples were described in the Taconian ocean suture in the Appalachians, with only a few meters left of oceanic rocks (St-Julien et al., 1976), and for Neotethys and Paleotethys sutures, with only a few seamounts stuck in the accretionary sequence in Oman (Pillevuit et al., 1997), Turkey (Moix et al., 2011) or Iran (Bagheri and Stampfli, 2008).

The geological cross section proposed by Beltrando et al. (2012) (Fig. 14), highlighting a hyper-extended rift margin, was probably the correct geologic setting at the time of the deposition of the grey micaschist with radiolarians, on the Briançonnais side (period 155-110 Ma, rifting and oceanisation) draping over exhumed mantle and crustal blocks of the Valaisan ocean passive margins.

On the contrary, we disagree with Beltrando et al. (2012) that consider the breccias associated to the rift faulting and we interpret them as deep structural "pseudo breccias" created as a result of intense compression and shearing (see above). The Punta Rossa granitoid generates monomict "pseudo breccias" and green gneiss can generate polymict "pseudo breccias". Another key field observation is the absence of stratigraphic continuity between the Valaisan Trilogy and the underlying "schistes à blocs "(units 2a, 2b, 2c, Fig. 3) made of imbricated (stacked) tectonic slivers, which represent the destroyed rift margin with remnants of the lost ocean floor (unit 1). The Valaisan Trilogy was therefore deposited with an angular unconformity, not over a rifted margin (Beltrando et al., 2012), but over a Cretaceous tectonic mélange developed against the Subbriançonnais and Briançonnais continental basement. The Miravidi cliff section is a convincing example of such stratigraphic and structural fabric unconformity (Fig. 15b). In the restricted preserved outcrops of the studied area, it is unlikely

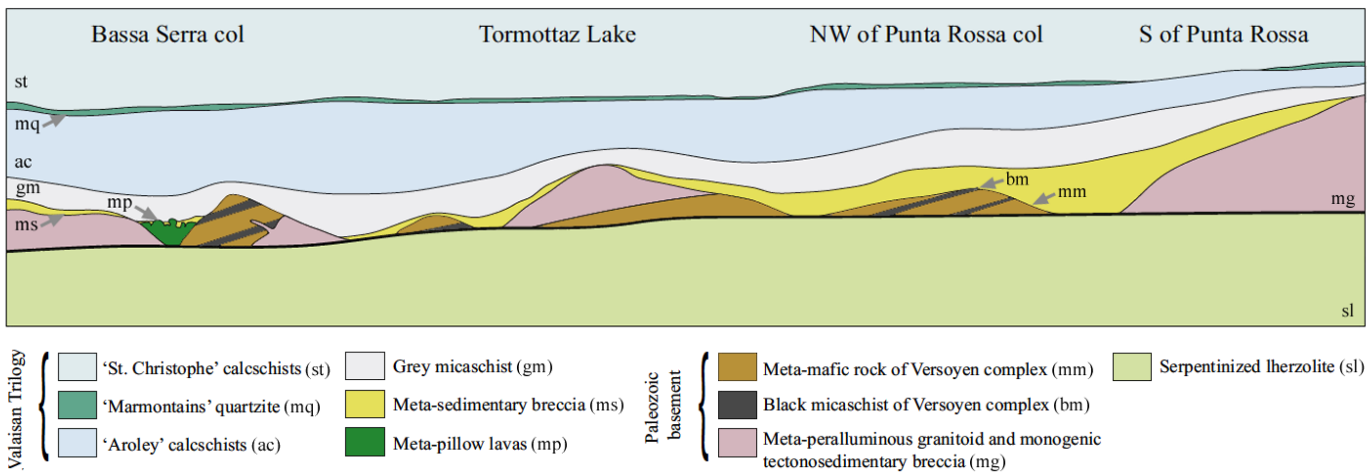

Fig. 14 - Hyper-extended rift margin model, Petit-Saint-Bernard pass area proposed by Beltrando et al., 2012. This geological section represents the Valaisan rift margin on the Briançonnais side with all the rift basement allochtons observed in the Petit-Saint-Bernard pass area. In our opinion this is a correct representation before the Albian (110 Ma) with the grey micaschist draping the blocks and excluding the Valaisan Trilogy above. A key point to realise from our field observations and regional mapping, as highlighted on our structural map and section (Fig. 3 and 4), is that this rift section has been completely imbricated in a schistes à blocs and slivers fabric during the closure of the Valaisan ocean, which we interpret as an accretionary complex against the Briançonnais microcontinent. On this Versoyen imbricated complex (rift margin and geometry destroyed) was unconformably deposited the Valaisan Trilogy, starting in Turonian time. Therefore, we do not see, as shown on this section, that the light blue Valaisan Trilogy is stratigraphically concordant with the underlying Early Cretaceous grey micaschists correctly draping the rift allochthons. An important pre-Alpine Cretaceous compressional event has occurred in the period 110 - 94 Ma, corresponding to the closure of the Valaisan ocean. The yellow meta-sedimentary breccia represented here, apart from Collet des Rousses one (truly sedimentary in origin), are deeper tectonic breccias and associated mylonites related to compressional accretionary prism tectonics.

to preserve in the field a rifted margin with a low-angle detachment fault, following a Cretaceous subduction compression (before theValais Trilogy deposition), followed by a Tertiary Alpine continental subduction to some 40km depth and followed by exhumation. Searching for pre-Alpine rifted margin is a fair topic (e.g. Beltrando et al., 2014b and, more recently, Ribes et al. 2020 for the eastern end of the Valaisan ocean, but in our opinion, we should not forget the clear field evidence related to the closing of the ocean, imbricating in a present-day tectonic mélange the former and initial rifted margin.

Review of other interpretations

Interpretation proposed by Masson et al. (2008)

Beltrando et al. (2012) agreed with Masson et al. (2008) by considering that the wildflysch exposed in the Miravidi cliff ("Méchandeur Wildflysch") is *"separated from the overlying Versoyen Complex by an Alpine thrust… which separates the Hermite unit from the Punta Rossa unit"*.

We have shown (see main text) that the Tertiary Alpine thrusts (marked by cargneules) are located at the base of the Arguerey and PSB calcschists, and that no major Tertiary Alpine thrust is present between the four Versoyen structural units (never cargneule found). All Versoyen units were structured in Cretaceous times, before the Valaisan Trilogy deposition. Masson et al. (2008) describe a nappe tectonic contact (with a significant metamorphic discontinuity) at the base of the Versoyen Complex just below the serpentinite of the Miravidi cliff (Fig. 15a). The Versoyen overlies a newly interpreted "Wildflysch de la Méchandeur" deposited in front of the nappe tectonic contact, on top of the Aroley, considered by Masson et al., 2008) as the top of the normal sequence of the Valaisan Trilogy, starting at its base with the Saint-Christophe Flysch. As indicated in Fig. 15a, this postulated thrust contact would cross the cliff in the middle of the severely sheared "schistes à blocs" of Unit 2a). The aerial photo of Fig. 15b, clearly shows that above the Aroley only one single sheared unit is present. No lithological difference is visible between the so-called "Wildflysch de la Méchandeur" and the basal unit referred to as the "Nappe Versoyen - Petit-Saint-Bernard" by Masson et al. (2008). This photo shows the overturned Aroley pebbly marbles below, and a clear stratigraphic unconformity contact with the tectonic mélange above. The Aroley lithology is nether involved in the "schistes à blocs" sheared fabric characteristic of Versoyen. The same Basal Aroley unconformity contact can be traced and followed regionally on the entire area (Figs. 3 and 4); it is localized on the inverse limb of a regional syncline overturned towards the NW. The stratigraphic nature of this unconformity contact is further indicated by the occurrence near the base of the overturned Aroley cliff of mariposite (chromiferous mineral) clasts (Fudral and Guillot, 1988; Fudral, 1998), most likely derived from the reworking and re-sedimentation of serpentinite slivers from the underlying Versoyen Complex. In our opinion, the Miravidi cliff exposes a sheared tectonic mélange fabric, just similar to that observed in the nearby Bassa Serra - Vallon du Breuil area. We do not recognize any tectono-sedimentary features characteristic of a chaotic flysch.

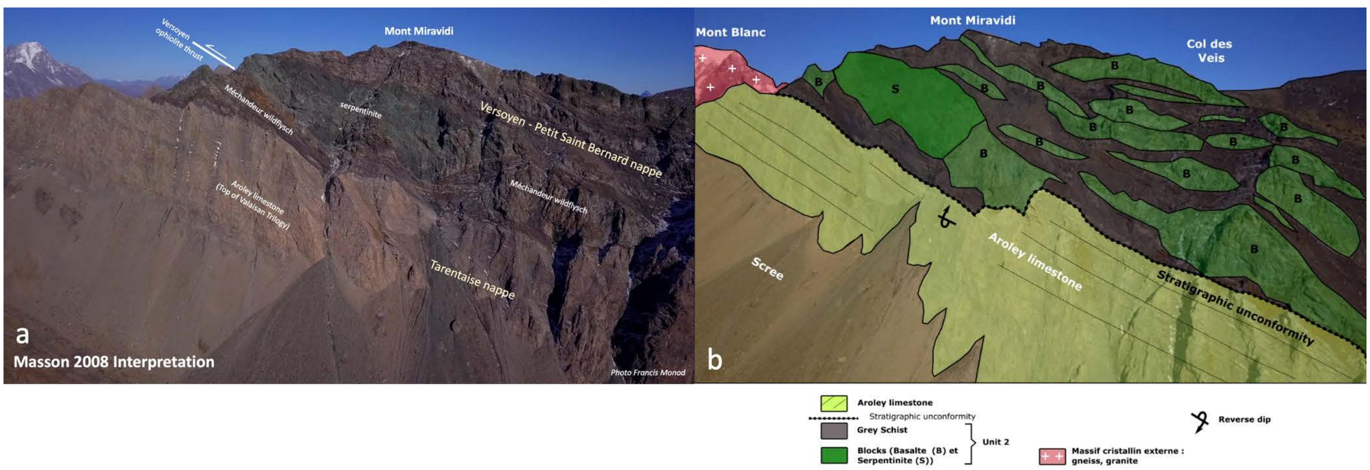

Fig. 15 - **(a)** Detail on our drone aerial photo of the interpretation of the Miravidi cliff by Masson et al. (2008). According to them, the base of the Versoyen ophiolite is a thrust. It overlies the Méchandeur wildflysch with blocks of Versoyen rocks, at the top of the Valaisan Trilogy in normal stratigraphic position (Aroley on top). The Versoyen ophiolite has no link with the Valaisan basin. This thrust corresponds to an abrupt change in tectonic style. The Versoyen complex and the overlying Petit-Saint-Bernard series are in stratigraphic contact and constitute a single tectonic unit named the Versoyen - Petit-Saint-Bernard nappe. PSB series is younger than the Versoyen, consequently, the Versoyen ophiolitic complex is Paleozoic and forms the basement of the PSB Mesozoic sediments. **(b)** Geological photo interpretation of Mont Miravidi cliff, this paper. The whole section here (Versoyen schistes à blocs and Aroley limestone) is clearly overturned, as interpreted by Antoine (1971). Early Cretaceous radiolarian-bearing sandy grey micaschist with oceanic blocks of serpentinite and basalt (on top, our Unit 2a) are overlain unconformably by the Turonian Aroley pebbly limestone (below on the photo). The Valaisan Trilogy and Versoyen are therefore stratigraphically closely linked. The stratigraphic unconformity is clearly mapped regionally (Fig. 3) and never any Aroley block can be found within the Versoyen schistes à blocks. Within the entire section of the Versoyen schistes à blocs section shown on this cliff, no clear ophiolite thrust can be placed, we see no structural difference above and below the serpentinite block-sliver, and certainly no abrupt change in tectonic style. The complete Versoyen section here is intensely sheared (tectonic mélange), everywhere, and much more than the overlying Aroley section. We do not see any sign of sedimentary chaotic process (wildflysch) below the serpentinite sliver and more than above the serpentinite… The schistes à blocs tectonic fabric is again the same all the way through this Versoyen Miravidi cliff section. The Valaisan trilogy is mapped as a regional overturned structure (Fig. 4) with a normal flank to the northwest, resting on the Pyramides Calcaires (Fig. 16a) and a reverse flank here at Mont Miravidi (entire overturned Trilogy, Fig. 16b). This reverse flank is regionally extending towards the Swiss Valais at the Briançonnais Front. The Versoyen complex and the overlying Petit-Saint-Bernard series are in clear tectonic thrust contact with occasional cargneule at the contact interpreted by Masson as a reduced stratigraphic Triassic section under the Liassic PSBA section. Difficult to explain then the PSBA basal contact with cargneule at Tête du Chargeur (Fig. 3) over a tightly folded Valaisan Trilogy section.

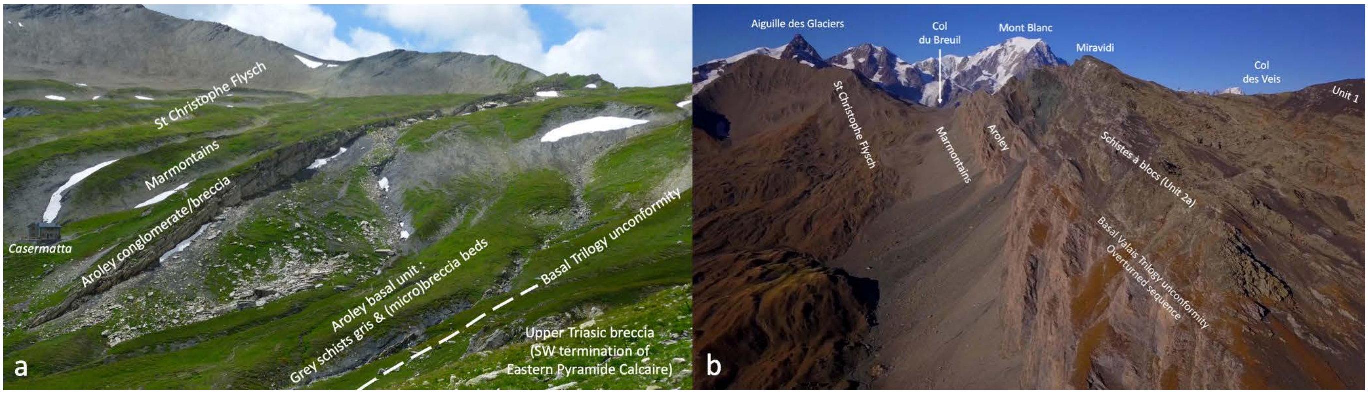

Fig. 16 - **(a)** The Valaisan Trilogy normal stratigraphic section (Aroley-Marmontains-Flysch), near the Col de la Seigne (top right on the photo 16a), is resting unconformably on the Subbriançonnais massif of the Pyramides Calcaires, flanked structurally against the Mont-Blanc massif. We are situated here on the normal flank of the overturned regional fold shown on the cross-section of Fig. 4. This photo is taken only 3km to the NW of the Bassa Serra Pass with the first Versoyen schistes à blocs outcrops. A very similar normal stratigraphic section of the Valaisan Trilogy is largely developed to the South-West in the Beaufortain massif (Combe de la Neuva, near Cormet de Roselend and Lac de l'Arcachat Anticline, to the west of Aime). Note: we proposed to extend the existing Subbriançonnais domain to the pre-Aroley passive margin sediments of Unité de Moûtiers (Antoine 1971) in Combe de la Neuva and Pyramides Calcaires. This new Subbriançonnais extension corresponds within the passive margin to a series of horst and graben deposits between the present Dauphinois and the Briançonnais domains**.** **(b)** Interpreted aerial geophoto landscape from Col du Breuil to Col des Veis, showing an overturned stratigraphic section of the Valaisan Trilogy (Flysch-Marmontains-Aroley) and Miravidi schistes à blocs (Unit 2a). The base of the Aroley (Turonian) can be mapped regionally resting unconformably over the Early Cretaceous Versoyen schistes à blocs (Fig. 3 and 4). Never can we observe any of the Aroley rocks involved within the schistes à blocs structural fabric, proving that the angular unconformity postdates the formation of the schistes à blocs. Additionally, in this section, the base Aroley contains mariposite clasts attesting of the erosional reworking of the Versoyen serpentinite slivers (Fudral and Guillot, 1988).

In contrast to Masson et al. (2008) interpretation, Bousquet et al. (2002) and Loprieno et al. (2011) did not recognize any significant metamorphic discontinuity between the Versoyen Complex and the overlying Trilogy, considering both units linked stratigraphically since 90-65 Ma and buried together during the Tertiary Alpine collision with the HP metamorphism peaking at around 40 Ma (Bousquet et al., 2002).

Considering the Valaisan Trilogy as a normal sequence including - from bottom to top - St Christophe – Marmontains – Aroley (Masson et al., 2008) would imply unrealistically that: (1) the Marmontains and the St Christophe are older than Turonian (basal Aroley dated Turonian by Antoine, 1971, and Fudral, 1973), and (2) the Valaisan Trilogy (Aroley at the base, Marmontains and St Christophe at the top) observed 3km to the West (Chapieux Valley and Pyramides Calcaires area, Fig. 16a) would lie unconformably (in overturned position) on top of Triassic and Liassic marine deposits from the Subbriançonnais continental margin. So, it is well established, based on geological mapping in France, Italy and Switzerland, that the Trilogy correct succession is from base to top: Aroley - Marmontains - St Christophe, as proposed originally by Trümpy, (1954). It is also well established that along the Briançonnais front in France and Valais, the Trilogy is always found in an overturned structural position, as shown on the Miravidi area (Fig. 16b). The overlying grey micaschists with slivers and blocks are therefore older, as indicated by the presence of Early Cretaceous radiolarians (Fig. 1S). At the French-Italian border (Col de la Seigne) the Trilogy can however be observed in normal position (Fig. 16a). This part corresponds to the normal flank of the reverse syncline of the Pointe Rousse sector (Fig. 4).

Interpretations proposed by Cannic (1996), Fudral (1998) and Loprieno (2001)

The Cannic (1996) conclusion is in stark contrast to that of Jeanbourquin, (1994) who considers the Versoyen as a tectonic mélange. In this paper, we clearly support Jeanbourquin, who has been the first one to draw the consequence of the basal Aroley stratigraphic unconformity on the Versoyen, established by Antoine (1971). According to Cannic (1996), the blocks or slivers in the mélange have different stratigraphic, metamorphic and/or structural characteristics. In our opinion, the metamorphism could not be an argument, as the HP metamorphism occurred at around 40 Ma, i.e., after the mélange formation. Furthermore, the Versoyen Complex is considered structurally homogeneous and isoclinally folded, similar to the PSBA and Valaisan flysch Trilogy, without a chaotic structure. On the contrary, our fieldwork and structural mapping demonstrate three "schistes à blocs" units, with numerous blocks of both oceanic and continental origin, and tectonic stacks of slivers (Punta Rossa massif). The last argument against a tectonic mélange put forward by Cannic (1996) – we consider meaningless - is that the Versoyen and Visp basalts have the same tholeiitic composition.

Beltrando et al. (2007; 2012), Fudral, (1998, Fig. 145) and Loprieno, (2001) do not close the Valaisan ocean before the Valaisan Trilogy deposition, despite the clear Turonian unconformity sealing a pre-existing "schistes à blocs" structuration. Loprieno et al. (2011) consider the Aroley deposition in the context of a "rift induced flank uplift", while in our opinion, it is associated to the closure of the Valaisan ocean. Fudral (1998) and Loprieno (2001) consider the Arguerey calcschists with the Brèche du Collet des Rousses as part of the Versoyen because in stratigraphic contact with the overlying basalts and black schists of the Aiguille de l'Hermite. From our observations, a fault is present there (Fig. 12), which separates the Arguerey Unit from the Versoyen Complex. Furthermore, The Arguerey calcschists are part of the Petit-Saint-Bernard calcschists Unit, also in clear fault contact with the Versoyen.

Valaisan ocean closing and subduction: our model

The closure of the Valaisan ocean connected to the subduction and collision of the Tertiary Alpine continental plates, mentioned in several papers (Schürch, 1987; Stampfli, 1993; Jeanbourquin et al., 1991; Jeanbourquin, 1994; Marthaler, 2001; Bousquet, 2002; Stampfli et al., 2002; Stampfli and Hochard, 2009), seems to be a common missing step in some recent publications (Loprieno et al., 2011; Beltrando, 2012). Beltrando et al. (2007) described on Permian zircons, mainly from the Clapet leucogabbro, clear thermal overgrowths dated at 110-100 Ma. Having in mind the rifting (155-125 Ma) and oceanisation (125-110 Ma) periods for the Valaisan ocean, Stampfli and Hochard (2009) suggest that this thermal event could mark the onset of subduction and intense basement deformation process against the Briançonnais basement backstop (110-90 Ma) that gave rise to the Versoyen accretionary prism. Associated with white metagranitoid and green gneiss basement blocks, black mylonites are often observed, sometimes a few meters thick, with mineral lineation and C/S criteria indicating under-thrust kinematics and intense basement rocks shearing (see later section), most likely linked to a thermal event. The subduction would have started around the plate margin (mid-ocean ridge/transform faults), producing a hot hydrothermal up-welling when pull-down into the subduction zone.

Our interpretation, that the pre-Aroley Versoyen Complex in the Petit-Saint-Bernard pass area displays an imbricated "schistes à blocs" tectonic mélange fabric, is consistent with its formation in an accretionary subduction complex, which is related to the closing of the Valaisan Ocean over the period 110-90 Ma (Fig. 17) but postdating the 110-100 Ma thermal event envisaged by Beltrando et al. (2007).

Our main conclusion is that the Aroley and Valaisan Trilogy unconformably overlie an already structured, imbricated and sheared Versoyen tectonic mélange. The grey micaschists mapped by Beltrando et al. (2012), originally deposited over the rifted NW Briançonnais margin, became the sedimentary matrix of the tectonic mélange, were sheared in the accretionary complex, and incorporated the rifted mar-

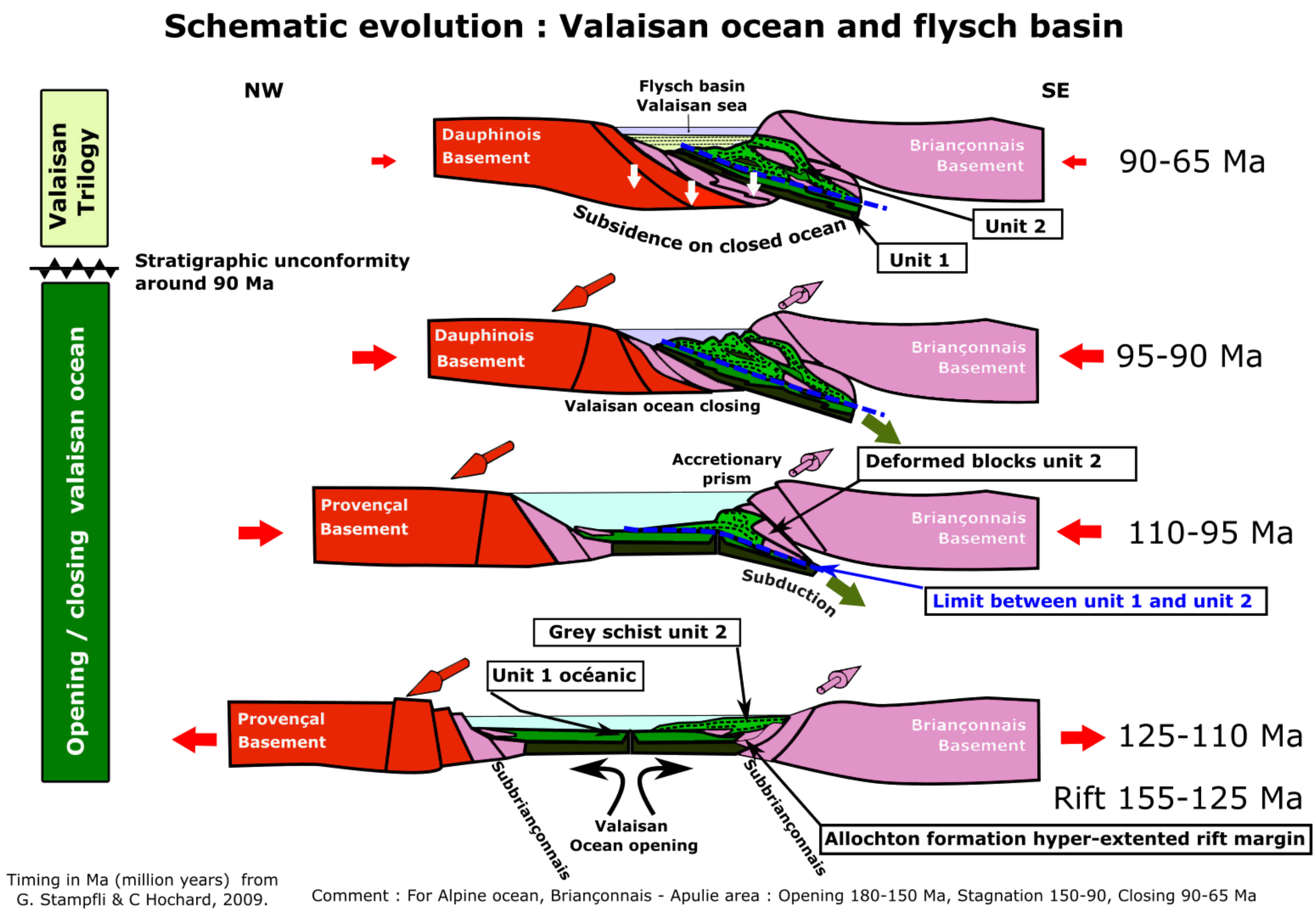

Fig. 17 - Schematic Valaisan ocean geodynamic evolution interpreted from outcrops evidence in the Petit-Saint-Bernard Pass area. The Valaisan rift starts to open 155 Ma ago, within the Subbriançonnais Alpine ocean passive margin, as the consequence of the opening of the Central Atlantic and separation between Newfoundland and Iberia. At the beginning, the Briançonnais basement is opposite the Provençal basement (2 lower pictures). The transcurrent Valaisan oceanic opening occurs over the period 125 – 110 Ma. The Versoyen Unit 1 is formed at that time, and the radiolarian sandy grey schists are deposited on the Briançonnais rifted margin, draping over rift allochthons (Fig. 14, Beltrando et al. 2012). The closing of the Valaisan ocean starts 110 Ma ago developing an accretionary prism against the Subbriançonnais/ Briançonnais Variscan continental basement. This closing continues till around 90 Ma, creating the imbrication/deformation within the accretionary complex (Fig. 5) stacking some slivers of ocean floor (Unit 1) with 3 sub-units of schistes à blocs differentiated by the composition of their blocks (Unit 2a oceanic, Unit 2b mix oceanic and continental, Unit 2c continental). During the period 90-65 Ma the Valaisan Trilogy is deposited unconformably on the Versoyen Complex (representing the Valaisan oceanic suture) and also to the NW on the Subbriançonnais basement and Permian to Liassic section of Pyramides Calcaires (Unité de Moûtiers, Antoine, 1971).

gin blocks of both continental and oceanic origin (Fig. 17). This explains why in their today's structural configuration, the grey micaschists are not only draping over the basement blocks and slivers, but are also forming the mélange matrix. As said above, the possible effects of the Cretaceous thermal metamorphism (if any) could have been lost during the HP Alpine metamorphic overprint.

This paper does not intend to establish from the restricted Petit Saint Bernard Pass area a final plate tectonic model for the Valaisan ocean. This subject is still a subject of great debate (van Hinsbergen et al., 2019, Ribes et al., 2020; Le Breton et al., 2021). However, the model of Stampfli and Hochard (2009) used here and unlike others, presents a geodynamic scenario consistent with our field data and model.

A simple interpretative scheme, based on detailed regional field observations and assuming a relatively fixist point of view, is shown on Fig. 17. It contributes to set the main stages of the geodynamic evolution. However, using the plate tectonics model of the Alpine area (Stampfli et al., 2002; Stampfli and Hochard, 2009 and references therein), it can be shown that a simple scenario of an oceanic closure around 90 Ma is not enough to explain the whole evolution. Based on the magnetic anomalies from the Atlantic, it is possible to determine the distances separating the continental masses and the displacement of the Iberian plate, of which the Briançonnais was part. The latter was facing the Provençal margin at the time of the closure, with a remnant oceanic basin still around 200 km wide. In this Provençal transect, the late Cretaceous flexural basin implies that the distance from the accretionary wedge was c. 250 km, and that the margin inversion took place in the Late Albian (see La Ciotat conglomerates; Thum et al., 2015 and references therein). A similar northern margin inversion scenario can be established on a western Dauphinois transect for the Piolit-Pelat flysch (Thum et al., 2015). In the Swiss transect, the final closure of the Valaisan Basin is constrained by the deposition of the Maastrichtian Niesen flysch and further east by the Paleocene Sardona flysch (Stampfli et al., 2002, and references therein). These data give a precise time frame for the closure of the Valais oceanic basin between Late Albian and Late Maastrichtian.

A more elaborated scenario

Fig. 18 presents a more elaborated scenario that takes into consideration the geodynamic constraints just exposed. In this scenario, all the Subbriançonnais units associated to the Valaisan domain are part of an extended NW Briançonnais passive margin, starting with a rifting stage in the late Jurassic, which led to an embryonic oceanisation during the Aptian. The basin opened in a strike-slip context, with small *en échelon* spreading centres offset by transform faults. In this context, the sill-lava-sediment sequence of the Versoyen (Unit 1) were emplaced in gaps within the hyper-extended margin on which crustal allochthons of all sizes rested on denuded upper mantle.

Starting in the Albian (110 Ma), the rotation of the Iberian/African plate induced the onset of subduction in the Valaisan ocean, along the spreading centers and associated transform faults. During the following 10-15 Ma, the Briançonnais passive margin became active and incorporated the Subbriançonnais allochthons and the oceanic/mantle material. At that time the accretionary complex appeared, which produced the Versoyen "schistes à blocs" tectonic mélange. Lastly, Aroley-type mass flows and conglomerates unconformably covered this accretionary complex and the "Pyramides Calcaires" Subbriançonnais basement allochthon. The subduction was quite oblique, the northeastward displacement of the Briançonnais landmass being in the order of 500 km, whereas the convergence Europe-Iberia was in the order of 300 km. Around 100-95 Ma, allochthons from the northern margin of the ocean were accreted to the growing accretionary prism, giving birth to a larger backstop structure.

When the subduction was well established, during the Cenomanian-Turonian, perched basins developed on the structured active margin, which on the long term would have given birth to a larger fore-arc type basin. In this basin, the Marmontains and then the St Christophe flysch were most likely deposited (Trilogy shown in yellow) in a relatively calm setting, because much of the deformation took place later in the accretionary prism within the remnant Valaisan basin. The outermost allochthon and accreted material became the backstop of the prism, and more allochthons from the northern margin were accreted and underplated. A few islands might have existed along its strike providing a source of clastics, and recycling the pelagic fauna (radiolarians, foraminifers) of Early Cretaceous age (Burri, 1958; Bagnoud et al., 1998).

In Fig 18 the positions of the Tertiary Alpine thrusts are shown in green: only very small slivers of this margin and the top layer of the Briançonnais landmass escaped subduction. In this domain (A), the top thrust corresponds to the detachment of the sedimentary cover that will give birth to the Préalpes Médianes tectonic units once detached by the arriving Piedmont accretionary prism (Stampfli et al., 2002). The bottom thrust (B) took place when the underlying continent was already subducted, then upper crustal elements with their cover of Carboniferous and Permian were emplaced in the nappe pile. On the section at bottom of Fig. 18, we tentatively put Permo-Carboniferous grabens within the Subbriançonnais domain, and we consider the grabens as the weak late Variscan structures reactivated during the Late Jurassic rifting.

From the Piedmont sedimentary pile of the Nappes Supérieures of the Préalpes Médianes (see Stampfli et al., 2002 and references therein), it is evident that no compressional / subduction event took place before the arrival of turbidites into the Piedmont oceanic basin in Turonian times (c. 90 Ma); thus, the onset of the pre-Turonian closure of the Valaisan ocean and that of the Piedmont ocean south of the Briançonnais are not coeval, but following each other. During the subduction of the Briançonnais, a few slivers of the former active margins passed in the upper plate (detachment C) and through exhumation were eventually brought up to the surface and severely eroded. Geologists can be thankful that kilometre size fragments of these are still visible nowadays. At the bottom of Fig. 18, we show two different types of preserved Subbriançonnais units corresponding to what is now observed in the field; the external Subbriançonnais corresponding to elements pertaining to the accretionary backstop (e.g., Pyramides Calcaires - Miravidi-Punta Rossa), and the internal Subbriançonnais to the former crustal allochthons (e.g., Petit-Saint-Bernard).

CONCLUSIONS

Beltrando et al. (2007; 2012) show two new major data and a new interpretation that are key to the Valaisan geology. They report a Permian age for the Punta Rossa and Aiguille du Clapet massifs and a superimposed Cretaceous thermal event recorded in the rims of some zircons. Moreover, in the grey micaschists of the Punta Rossa area they discover radiolarian microfossils, which we consider here as likely Early

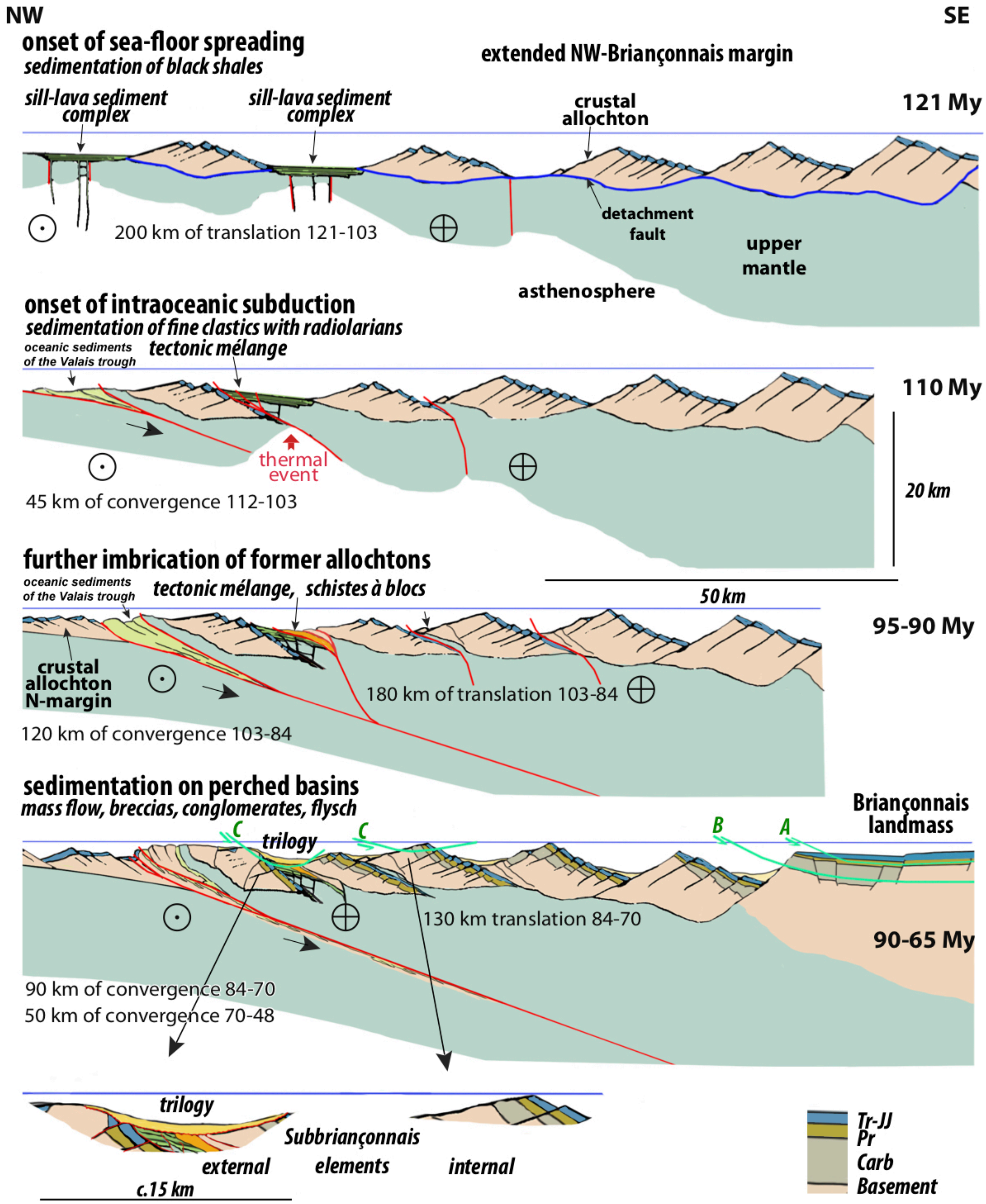

Fig. 18 - Geodynamic evolution of the Valaisan ocean and its Briançonnais margin. During the Aptian (121 My), after 200 km of translation, the separation of the Iberian-Briançonnais landmass from Europe led to the opening of small basins were oceanisation started to take place. During the Albian (110 My), the highly extended northern Briançonnais passive margin started being imbricated due to a convergence between the two plates. The oceanised basins became the site of subduction and formation of mélanges (Versoyen), still in a dominant strike-slip displacement where the Briançonnais margin became an upper plate element (95-90 My). The more external allochthons became the tectonised substratum of a perched basin (Trilogy), sealing the previous deformation during the Turonian (90-65 My). The perched basin remained an active site of sedimentation until the end of the Cretaceous, when the distal European margin started to collide with the Briançonnais subduction zone. During the Alpine collision and subduction of the Briançonnais landmass, only very small slivers of the former margin escaped subduction (detachment C), and only a thin sliver of the Briançonnais was detached from its substratum (detachment B, detachment A corresponding to the obduction of the Préalpes Médianes).

Cretaceous. The hyper-extended rift margin interpretation is also a step forward in the comprehension of the Valaisan geology. In this work we report in addition the occurrence of a Cretaceous (pre-Turonian) shortening event linked to a subduction process associated to the closure of the Valaisan Ocean and preceding the Tertiary Alpine continental collision and associated HP metamorphism. From our field investigations, we redefine the Versoyen Complex as an imbrication of four structural units, interpreted as a pre-Alpine Cretaceous tectonic mélange formed in an accretionary prism.

A new U/Pb zircon age of 310 ± 4 Ma is obtained on a Versoyen layered diorite from the Tormottaz area. The calc-alkaline signature of this rock is similar to other plutonic rocks included in the tectonic mélange, such as the Punta Rossa and Aiguille du Clapet massifs. We consider the calc-alkaline rocks as former rift allochthons, derived from the Briançonnais continental basement, which would represent a late Variscan back-arc environment. Based on a Western Alps late Variscan geochemical review, we also propose that the Valaisan rift opened within the Subbriançonnais domain by reactivating deep Variscan fault systems located along the Briançonnais Zone Houillère domain, in agreement with Ballévre et al. (2018). The geology of the Petit-Saint-Bernard Pass remains a key area to unravel the geodynamic evolution of the Western Alps.

ACKNOWLEDGEMENTS

This article is intended to be the continuation of the pleasant and constructive debate with Marco that began more than 10 years ago, when, after reading its article (Beltrando et al., 2007), GDB contacted him asking if “the Punta Rossa granitoid and Clapet Gabbro could be considered as old large blocks, derived from the Briançonnais margin, in a younger Cretaceous mélange unit?”. The opportunity to discuss the two geological models with Marco and Michel Marthaler took place in 2015 at the 12th Alpine Workshop in Briançon - Montgenèvre: Unfortunately, the joint field trip planned for 2016 could not be carried out.

This work has benefited from the financial support of the “Alpes and peripheral basins” project as part of the French national RGF program. We are very grateful to all reviewers for their advices and constructive comments that improved the manuscript. We are also sincerely grateful to Pierre Antoine, author of a thesis on the Valaisan Trilogy and the Versoyen published in 1971, for sharing his deep regional knowledge and for the many field excursions and fruitful discussions over the last 12 years, contributing to build and comfort our model. Finally, we would like to thank the editor, Alessandra Montanini, who made possible our contribution to this special issue in memory of Marco Beltrando.

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Received, January 14, 2021
Accepted, July 16, 2021