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PILLOWED METABASALTS AND METABRECCIAS FROM THE VALAISAN OCEAN-CONTINENT TRANSITION PRESERVED IN THE BREUIL VALLEY, AOSTA (ITALIAN WESTERN ALPS)

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ABSTRACT

Subduction plate margins have an intrinsically poor preservation potential for pre-subduction settings because most rocks sink and disappear into Earth's mantle. However, a preserved pre-subduction setting has been reported in the Lower Penninic Units (Valaisan Basin) of the Italian Western Alps (Beltrando et al., 2012). Here, we review two main aspects of the Valaisan Basin cropping out in Italy: the nature of the syn-rift detrital sediments and the characteristics of the metabasalts in proximity to the continental crust metagranitoid. New fossil findings are reported, which confirm a Mesozoic age for the Valaisan rifting. Field and petrographic data from metabreccias and pillowed metabasalts near the fossil-rich high-pressure metasediments support the interpretation of the Valaisan Domain in the Breuil valley (Aosta) as a fossil ocean-continent transition zone.

INTRODUCTION

Ophiolites are portions of oceanic lithosphere now exposed at Earth's surface in mountain belts. High-pressure ophiolites bear important information on the composition of the subducted material, now exposed in fossil subduction wedges (Agard et al., 2021; Vitale Brovarone et al., 2021). The study of high-pressure ophiolites thus appears to be essential to the understanding of the mechanical properties and thickness of the subducted materials, as well as the elucidation of the tectonic behaviour of subduction wedges and the rheology of the subduction interface via comparisons with numerical models (e.g., Dielforder et al., 2019; Vannucchi et al., 2020).

Two separate ophiolite belts are exposed in the Tertiary subduction wedge of the Western Alps, known as the Lower Penninic and Upper Penninic ophiolite belts, respectively (Favre, 1862; Haug, 1909; Argand, 1911; Sturani, 1973; Trümpy, 1980; Beltrando et al., 2010a; Malusà et al., 2015; Schmid et al., 2017). Here we use the term Penninic, usually adopted in the Central Alps, in order to discriminate tectonic units (Penninic) from paleogeographic domains (Valaisan/Piemonte). The two ophiolite belts derive from the Valaisan and Piemonte oceanic or transitional basins separated from each other by the Briançonnais continental domain (e.g., Trümpy, 1980; Stampfli, 1993; Froitzheim and Manatschal, 1996; Liati et al., 2003; 2005; Schmid et al., 2004; Liati and Froitzheim, 2006; Beltrando et al., 2015). During the last 30 years, local discussions have occurred on the transitional nature of part of the ophiolite basins preserved in the Alps (Florineth and Froitzheim, 1994; Pastorelli et al., 1995; Dal Piaz, 1999; Bernoulli and Jenkyns, 2009; Manatschal and Müntener, 2009; Beltrando et al., 2010b; Vitale Brovarone et al., 2011). In particular, the high-pressure rocks of the Valaisan Basin, exposed south of La Thuile, Italy, bear well-preserved features of an ocean-continent transition zone (Figs. 1 and 3; Beltrando et al., 2012). The Valaisan Basin was emplaced as a thrust sheet during the latest Tertiary tectonic phases, which controlled the final architecture of the orogen (Mugnier et al., 1993; Cannic et al., 1995b; Freeman et al., 1998; Fügenschuh et al. 1999; Schmid et al., 2017).

Valaisan rocks with a higher metamorphic grade are metabasalts (spatially associated with carbonaceous schists of an uncertain age), metagranitoids, serpentinites, detrital and carbonate sediments, the "Versoyen" (Kilian and Térmier, 1895; Hermann, 1930; Elter G. and Elter P., 1965), and metasediments divided into three formations, i.e., the "Tarentaise Trilogy" (Barbier and Trümpy, 1955; Elter G., 1960). We focus here on two lithotypes of the "Versoyen" *sensu* Elter G. and Elter P., (1965), i.e., the pillowed metabasalts and metabreccias, which are in contact with the metagranitoid-serpentinite pair that characterizes the ocean-continent transition zone in the Valaisan Domain (Beltrando et al., 2012). As metabreccias and pillowed metabasalts mainly crop out in Italy, we focus here exclusively on the Breuil valley (Aosta). In this study, we describe new outcrops of metabreccias, pillowed metabasalts, and new fossil findings in the tectonic units that sample different portions of the Valaisan Basin. We report new data with the aim of stimulating further research in the region. Based on the structural restoration proposed by Beltrando et al. (2012), we briefly discuss the implications of the new findings that confirm the ocean-continent transition zone setting for this sector of the Italian Western Alps.

GEOLOGICAL SETTING

External Western Alps and the Lower Penninic Units

"Versoyen" rocks and nearby "Tarentaise" metasediments crop out at the northwestern end of the Alpine wedge. Fig. 1 shows, from bottom to top, five different tectonic unit

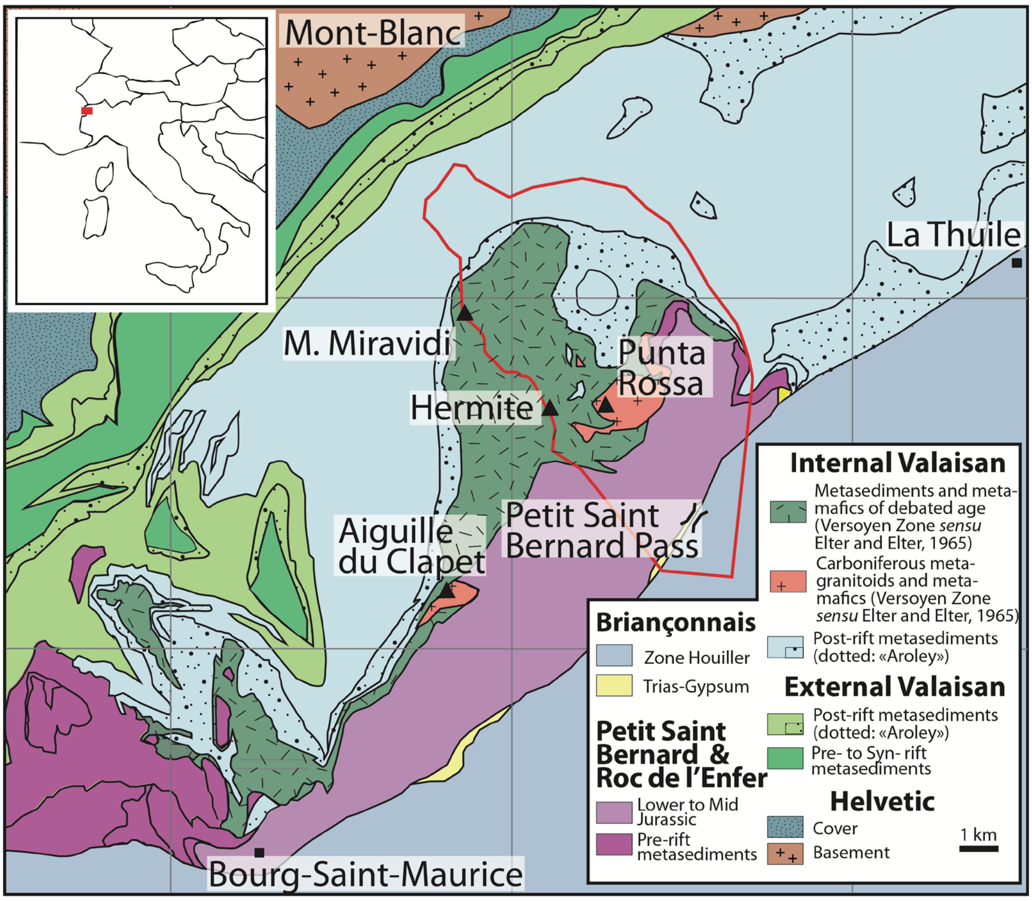


Fig. 1 - Lithotectonic map of the Petit Saint Bernard region (modified after Loprieno et al., 2011 and Carraro et al., 2011). Thin red line delimits the study area (Fig. 3). The inset reports the geographical location in Northern Italy.

groups referred to here as Helvetic, External Valaisan, Internal Valaisan, Petit Saint Bernard-Roc de l'Enfer, and Houiller (Niggli et al., 1978; Loprieno et al., 2011).

The *Helvetic*, which is part of the European proximal margin, is composed of pre-rift sediments, crystalline basement rocks (e.g., Mont Blanc Carboniferous granitoids), and autochthonous to allochthonous pre-to-post-rift Mesozoic and Cenozoic sediments (Cita et al., 1953; Elter G. and Elter P., 1965; Antoine, 1971; Ribes et al., 2020). During the Alpine orogeny, Mont Blanc rocks experienced a lower greenschist facies metamorphic overprint at temperatures slightly higher than 300°C (Boutoux et al., 2016).

The *External Valaisan* consists of Mesozoic carbonate rocks including the syn-rift sediments of the Brèches du Grand Fond Group (mid-Jurassic to Early Cretaceous syn-rift sediments), pre-rift sediments (Carboniferous to Early Jurassic), and post-rift sediments, known as the "Tarentaise trilogy," with mega-breccias, contourites, and turbiditic deposits, mainly of Cretaceous age (Baretti, 1879; 1893; Zaccagna, 1888; Schoeller, 1927; Barbier, 1948; Burri, 1958; Antoine, 1972; Antoine et al., 1992b; Jeanbourquin, 1995; Loprieno et al., 2011).

The *Internal Valaisan* consists of both "Versoyen" and post-rift "Tarentaise trilogy" (Hermann, 1937; Barbier et al., 1963; Fügenschuh et al., 1999; Loprieno et al., 2011). In the Italian part of the Internal Valaisan, two units have been distinguished, i.e., the *Punta Rossa Unit*, characterized by an Ocean-Continent Transition (OCT) zone, and the *Hermite Unit*, as defined by Beltrando et al. (2012), mainly consisting of a "metamafics-carbonaceous schists sequence." Both have a similar metamorphic evolution from blueschist to greenschist facies, with T lower than 420ºC, as determined by Raman spectroscopy of carbonaceous material (Antoine, 1972; Bocquet, 1974; Frey et al., 1974; Saliot, 1978; Antoine et al., 1992a; Oberhänsli et al., 1996; Goffé and Bousquet, 1997; Oberhänsli et al., 2003; Beltrando et al., 2012).

The *Petit Saint Bernard - Roc de l'Enfer* Units have a debated paleogeographic original location, either External Valaisan or Subbriançonnais; they are composed of Carboniferous to Mesozoic pre-rift metasediments (Schoeller, 1928; Termier, 1928; Barbier, 1951; Nabholz and Trümpy, 1954; Ellenberger, 1958; Staub, 1958; Masson et al., 2008; Loprieno et al., 2011). In the study area, the Petit-Saint Bernard Unit is composed of Triassic dolostones and Early-Middle Jurassic carbonate schists, whose metamorphic temperatures were higher than 450ºC, as estimated by Raman spectroscopy (Beyssac et al., 2002; Beltrando et al., 2012).

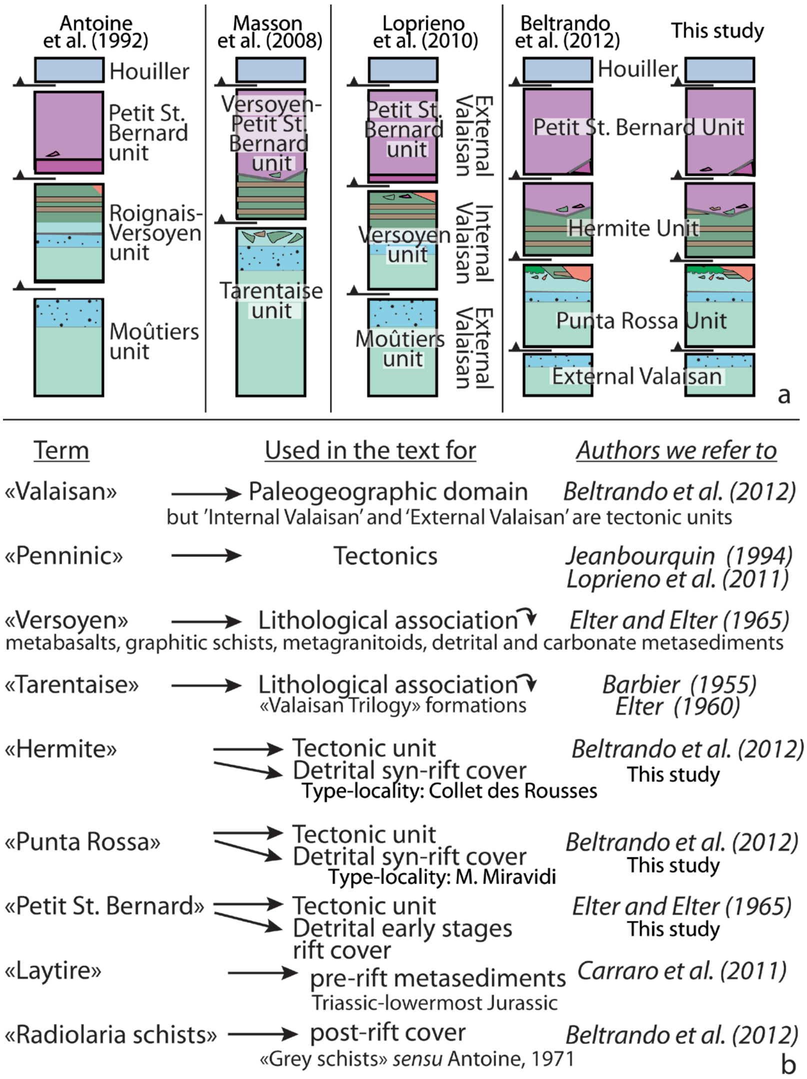
The *Houiller* domain, which is part of the Briançonnais paleogeographic domain (and mid-Penninic tectonic unit), mainly consists of Carboniferous and Permian metamorphic sandstones, conglomerates, and shales- of continental origin, re-equilibrated at metamorphic temperatures lower than 250ºC (Baretti, 1880; Franchi and Stella, 1912; Elter G., 1960; Debelmas et al., 1991; Bucher and Bousquet, 2007; Villa et al., 2014; Ballèvre et al., 2018). Subordinate granitoids, Triassic quartzites, limestones/dolostones, shales, and gypsum characterize the outcrops in the Breuil valley (Peola, 1903; Possenot, 1912; Elter G., 1953; 1954; 1987; Elter G. and Elter P., 1965; Freeman et al., 1998).

The five frontal tectonic unit groups of the Western Alps agglomerated during the Cenozoic (Bigi et al., 1990). In this contribution, we focus on the uppermost tectonic units, characterized by higher metamorphic grades. Loprieno et al. (2011) and Beltrando et al. (2012) favour large-scale overturning in this uppermost part. Conversely, Masson et al. (2008) separate the "Tarentaise Trilogy" metasediments from the metamafics with an Alpine thrust contact marked by metabreccias and blocks, suggesting an analogy with that observed further north in Switzerland (Bagnoud et al., 1998; Fudral, 1998; Masson, 2002).

Metamafics and metabreccias occur in the uppermost part of the frontal units (Fig. 2a). Available geochronological data support a Paleozoic age for the metamafics and metagranitoids that crop out in the innermost part of the Internal Valaisan (Schärer et al., 2000; Beltrando et al., 2007; Masson et al., 2008). Loprieno et al. (2011) reported a Mesozoic age for the other metamafics in the Internal Valaisan. Metabreccias occur at different positions in the lithostratigraphic column (Bertrand, 1896; Trümpy, 1980; Loprieno et al., 2011) (Fig. 2a). In the Breuil valley, to the north of Petit Saint Bernard Pass, three units are exposed (from bottom to top): the Punta Rossa and Hermite units, both ascribed to the Internal Valaisan, and the Petit-Saint Bernard Unit (Fig. 2a, column for "this study"). Fig. 2b shows the nomenclature used in this study for the lithotypes observed in the Breuil valley.

Punta Rossa Unit lithostratigraphy: Remnants of an ocean-continent transition

The Punta Rossa Unit consists of extensively serpentinized sub-continental mantle ultramafics, juxtaposed against a Paleozoic basement and metasediments of uncertain age (Figs. 2 and 3). This lithostratigraphy largely formed during rift-related extensional tectonics, when mantle peridotites were exhumed at the bottom of the Valaisan Basin (Loubat, 1975; 1984; Kelts, 1981; Einsele, 1985; Beltrando et al., 2012). The extensional tectonics resulted in the widespread faulting of continental basement rocks, whose fragments rested above the exhumed serpentinized mantle as isolated blocks, known as extensional allochthones. Tectonic breccias, gouges, and ophicalcites provide evidence of this rifting event, as observed in the Central Alps (Manatschal, 1999; 2004). The serpentinite-continental basement pair was covered by polymictic breccias from a local source prior to being sealed by the deposition of post-rift sediments, defined as "Radiolaria schists" (Beltrando et al., 2012). "Tarentaise Trilogy" basinal metasediments, including impure marbles and metabreccias,



Term	Used in the text for	Authors we refer to
«Valaisan»	→ Paleogeographic domain but 'Internal Valaisan' and 'External Valaisan' are tectonic units	*Beltrando et al. (2012)*
«Penninic»	→ Tectonics	*Jeanbourquin (1994)* *Loprieno et al. (2011)*
«Versoyen»	→ Lithological association metabasalts, graphitic schists, metagranitoids, detrital and carbonate metasediments	*Elter and Elter (1965)*
«Tarentaise»	→ Lithological association «Valaisan Trilogy» formations	*Barbier (1955)* *Elter (1960)*
«Hermite»	→ Tectonic unit → Detrital syn-rift cover Type-locality: Collet des Rousses	*Beltrando et al. (2012)* This study
«Punta Rossa»	→ Tectonic unit → Detrital syn-rift cover Type-locality: M. Miravidi	*Beltrando et al. (2012)* This study
«Petit St. Bernard»	→ Tectonic unit → Detrital early stages rift cover	*Elter and Elter (1965)* This study
«Laytire»	→ pre-rift metasediments Triassic-lowermost Jurassic	*Carraro et al. (2011)*
«Radiolaria schists»	→ post-rift cover «Grey schists» *sensu* Antoine, 1971	*Beltrando et al. (2012)*

Fig. 2 - Previous literature and results from this study on the Valaisan Basin and Breuil valley. a) Log with the tectonic units proposed in the area according to different studies. b) Terms used in this study and those from previous studies, which we refer to for definitions. The sedimentary cover in this study is denoted as the name of the tectonic unit.

followed as post-Jurassic cover (Beltrando et al., 2012). The rift-related rock association has been preserved at several localities along the Valaisan ocean-continent transition, despite multi-stage shearing, and high-*P* and low-*T* metamorphic overprinting (Beltrando et al., 2012). Fig. 3 shows the significant parageneses of the samples examined here from all three units.

Punta Rossa basement: serpentinite and metagranitoid at the OCT

Both serpentinite and peraluminous metagranitoid are highly affected by cataclastic deformation and locally separated by tectonic breccias with an Alpine metamorphic overprint (Hermann, 1930; Antoine, 1971; Beltrando et al., 2007; 2012). Outcrops of the *antigorite-serpentinite* (Hassenfratz,

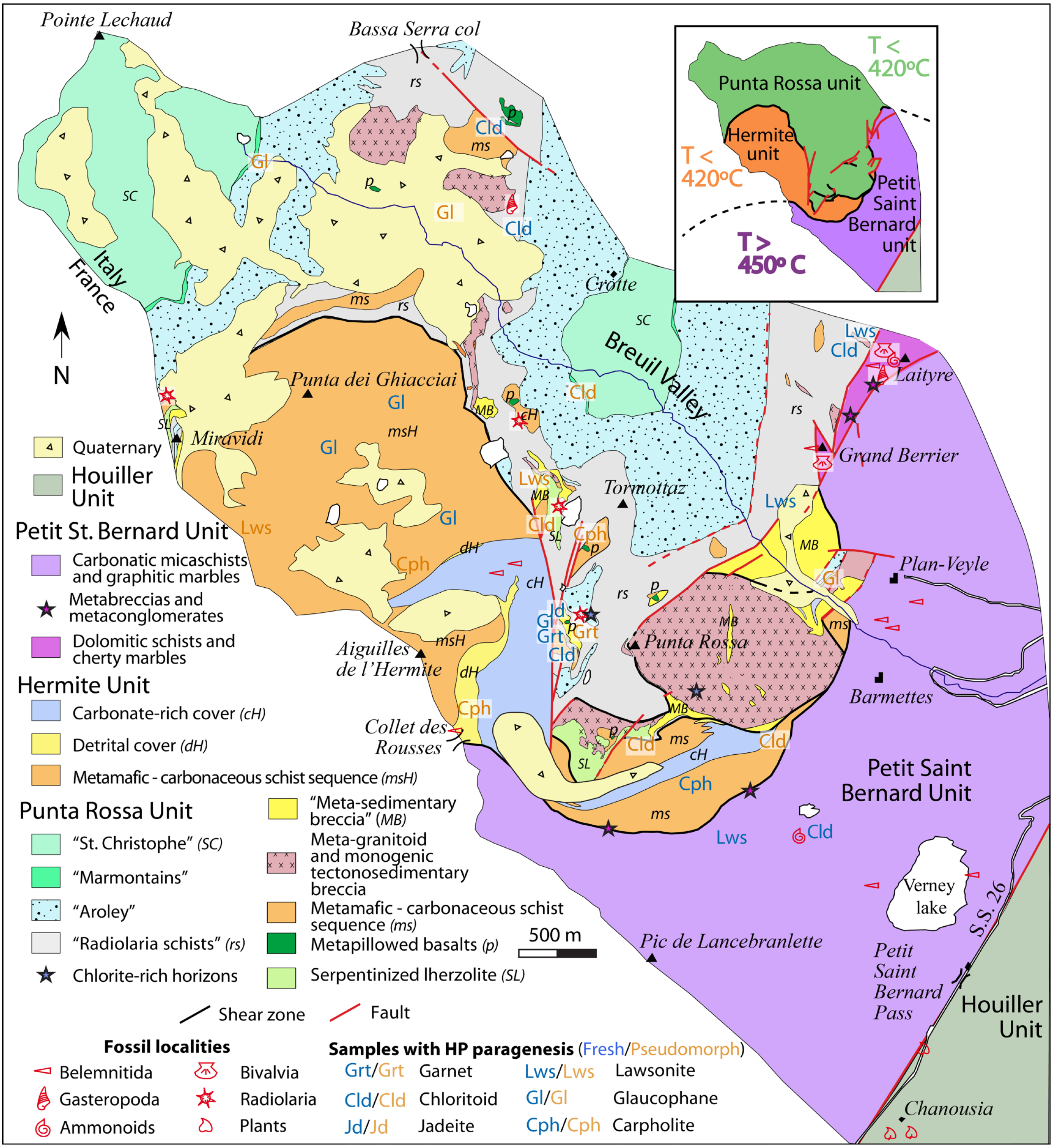


Fig. 3 - Simplified geological map of the Valaisan and Sub-briançonnais Domains in the Breuil valley [modified after Beltrando et al. (2012)]. Tectonostratigraphic units defined in Beltrando et al. (2012) in the inset. Fossil remnants and HP metamorphic minerals from new findings and data from the literature are reported (Antoine, 1971; Bousquet et al., 2002; Frasca, 2011).

1805; Kilian and Revil, 1904, page 285; Franchi and Stella, 1912) rarely preserve the original peridotite fabric, characterized by alignments of high-T spinel and clinopyroxene (Fig. 4a). Clinopyroxenes are completely replaced by tremolite and rare titanite, suggesting an original Ti-bearing composition. Skeletal structures, composed of chlorite, antigorite, and tremolite, can be interpreted as the product of plagioclase destabilization (Fig. 4b; cf. Piccardo, 2011). This is consistent with an abyssal origin from an ocean-continent transition setting with minor melt depletion, or refertilization (see Barnes et al., 2014). Chrysotile and calcite veins are widespread (Fig. 4c).

The Punta Rossa *metagranitoids* preserve remnants of the original igneous microstructure, except at the albite-rich contacts with other lithotypes (Hermann, 1928; 1930). The original K-feldspar is completely replaced by albite and fine-grained white mica (Fig. 4d). Muscovite flakes, several mm in size, suggest a peraluminous composition (Beltrando et al., 2007). High-pressure mineral relicts do not occur here; a previous report of jadeite most likely originated from the Punta Rossa region and not from the Punta Rossa granitoid itself [Bocquet (1974); Saliot (1979); see Schürch (1987) for jadeite location].

Mesozoic cover:
Syn-rift pillowed metabasalt and metabreccia

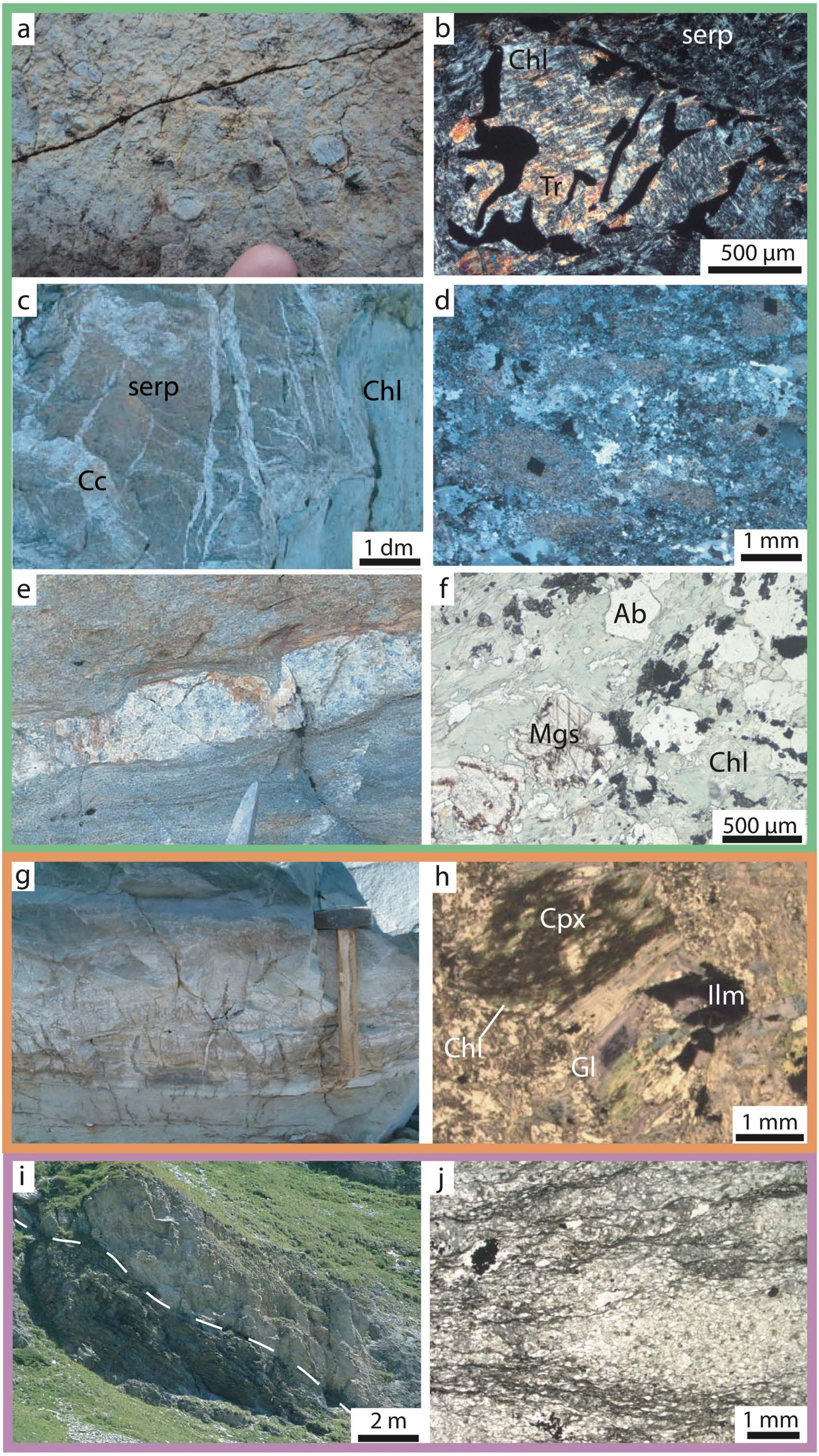
The detrital cover of the Punta Rossa Unit occurs near the basement rocks described above (Fig. 3; Antoine, 1971; Beltrando et al., 2012). The clast composition is laterally variable, but always consistent with the adjacent basement. The metabreccia thickness is highly variable, which is likely for the case for both the original pre-Alpine geometry and the effects of alpine deformation. The thickness ranges from a few meters (on the western side of Tormottaz Lake, where ultramafics and "Radiolaria schists" formations are separated by less than 5 m of polymictic breccias and meta-arkoses) to approximately 20 m (on the ridge to the south-west of Punta Rossa). On the ridge to the SW of Punta Rossa, the matrix-supported breccia consists of ultramafic clasts, ranging in size from 10 to > 40 cm, which are embedded in a serpentinite matrix. Detrital rocks, with clasts of mafic composition and typically spatially associated with pillowed metabasalts, have been described from several localities in the Breuil and Versoyen valleys (Loubat and Antoine, 1965; Loubat, 1965; Schürch, 1987). Such pillows have been advocated as evidence of Mesozoic rift-related mafic magmatism in the Valaisan Basin (e.g., Antoine et al., 1973; Loubat, 1975; Loprieno et al., 2011). We focus on the breccias and pillows at the interface between the basement rocks and carbonate-rich metasediments to strengthen the OCT interpretation and obtain information on the polarity and age of the metasediments.

Mesozoic cover: Post-rift metasediments

A thick succession of fine-grained metasediments crops out near metabreccias and pillowed metabasalts (Antoine, 1971). These micaschists become progressively richer in carbonates away from the continental basement (Zulauf, 1963; Antoine, 1972). This formation is defined as "Radiolaria schists" (Beltrando et al., 2012). Actual carbonate sedimentation is evident only in the metasedimentary succession extensively exposed in the Breuil valley, which is generally compared to the "Valaisan Trilogy" (Baretti, 1893; Franchi, 1907; Trümpy, 1955; Elter G., 1987). These metasediments are subdivided into the "Aroley," "Marmontains," and "St. Christophe" formations (Trümpy, 1954; Burri, 1958). The *"Aroley" formation* consists of pure to impure marbles, carbonate schists, conglomeratic beds, and megabreccias (Elter G., 1987; Lomas, 1992; Ribes et al., 2020). The *"Marmontains" formation* is characterized by alternating beds of carbonate-free black schists and quartzarenites while the *"St. Christophe" formation* consists of calcareous-arenaceous strata and black marls and schists (Burri, 1979). The age of the carbonate sedimentation in the "Tarentaise Trilogy," which is poorly constrained due to the rarity of fossils, has been interpreted as different stages of the Cretaceous, either the Barremian-Aptian (Schoeller, 1947; Trümpy, 1954; Elter P., 1954; Sodero, 1968) or Turonian-Santonian (Antoine, 1965; 1971; Burri, 1967; Jeanbourquin and Burri, 1991). The "Aroley" formation, closest to the pillowed metabasalt and metabreccia, is characterized by minor volumes of detrital rocks with rounded, cm-sized, and mainly carbonate clasts (dotted in Figs. 1, 2a, and 3; Elter G. and Elter P., 1965; Fudral and Guillot, 1988). Megablocks are absent here, unlike in the External Valaisan (Antoine, 1971; Ribes et al., 2020). Rare relicts of high-pressure minerals have been reported in these metasediments (Fe-Mg-carpholite and chloritoid, XMg = 0.10-0.17; Bousquet et al., 2002; Loprieno et al., 2011; see also glaucophane in Fig. 3).

Lithostratigraphy of the Hermite Unit

The Hermite Unit is composed of alternating carbonaceous schists and metamafic sills, referred to as a "metamafics-carbonaceous schists sequence" (Hassenfratz, 1805; Franchi, 1899; Loubat, 1973; Mugnier et al., 2008), and by a Mesozoic detrital to carbonate-rich cover (Schoeller, 1929; Elter G. and Elter P., 1965; Antoine, 1968; Loubat, 1968). The mafic sills have a variable thickness from 0.5 to 40 m (Cannic, 1995; 1996) and now consist of albite-chlorite-actinolite bearing metamicrogabbros, albite-chlorite-epidote bearing metadolerites and greenstones. A magmatic gabbroic texture is preserved in larger intrusions, where magmatic relicts of clinopyroxene and brown hornblende have been reported (Elter G. and Elter P., 1965; Debelmas et al., 1991). The contact between the carbonaceous schists and metamafics is locally metasomatized ("spilitized"), as indicated by an increase in SiO_2, Na_2O, and H_2O (Franchi, 1903; Loubat and Delaloye, 1984; Mugnier et al., 2008). Albite, clinozoisite, actinolite, chlorite with minor titanite, phengite, ilmenite and quartz, and rare tourmaline and apatite characterize the Alpine paragenesis in the "metamafics-carbonaceous schists sequence" (Vuagnat, 1956; Loubat, 1968; Antoine, 1971). Hydrothermal concentrations of tourmaline and axinite have also been reported (Schürch et al., 1986b). A high-pressure eclogitic assemblage has been reported (garnet-omphacite in Cannic et al., 1995a; omphacite in Schürch et al., 1986a; Bousquet et al. 2002). The Mesozoic cover of the Hermite Unit is characterized by syn-rift metasediments with paragreenstone matrix and impure marble clast laterally changing to carbonaceous matrix with metamafic clasts. The carbonate-rich cover, with common detrital layers, has a debated age, Cretaceous (Lomas et al., 1992) or Early-Mid Jurassic (Debelmas et al., 1991) and is composed by chlorite-white mica graphitic marbles, phengitic micaschists, graphitic-carbonate paragreenstones, graphitic marbles interlayered with chloritic marbles and carbonate schists. Relicts and pseudomorphs of high-pressure minerals, such as glaucophane, and Fe-Mg carpholite, are common in both the basement and cover rocks (Figs. 3 and 4h; Goffé and Bousquet, 1997; Bousquet et al., 2002; Frasca, 2011; Beltrando et al., 2014a).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Lithostratigraphy of the Petit Saint Bernard Unit: Pre-rift metasediments

The entire Petit Saint Bernard Unit consists of carbonate-rich metasediments, possibly Triassic to Middle Jurassic in age (De Saussure, 1803; Franchi, 1899; 1929; Elter G. and Elter P., 1965; Debelmas et al., 1991). The pre-rift metasediments, which crop out exclusively in the northeastern part of the mapped area, are hereafter referred to as the *"Laytire" formation* (Carraro et al., 2011; Laytire and Grand Berrier peak, Fig. 3). At the base of the pre-rift succession, Late Triassic yellowish dolomitic schists, and Rhaetian black carbonate schists crop out on the western side of the Grand Berrier peak (Fig. 4i; see Elter G. and Elter P., 1965). Scattered outcrops of possibly Late Triassic phyllites with a preserved sedimentary layering occur at the base of the succession on the eastern side of the Grand Berrier peak (Frasca, 2011). Gray and massive marbles follow upward the Triassic metamorphic rocks, which have been interpreted as lowermost Early Jurassic in age (Franchi and Stella, 1912; Antoine, 1971). This part of the "Laytire" formation contains orange quartzitic (cherty) layers (mainly in the Laytire area north of Grand Berrier, Fig. 3) and a several-meters-thick belemnite-bearing dark layer of carbonate schists (Elter G. and Elter P., 1965). Above the "Laytire" formation, carbonate-rich metasediments are mainly from the Early Jurassic in the Breuil valley (Elter G. and Elter P., 1965; Debelmas et al., 1991). Raman geothermometry estimates have yielded *T* higher than that in the underlying units, but HP minerals are rarely observed on the Italian side of the Petit St. Bernard Unit (Fig. 4j; Frasca, 2011; Beltrando et al., 2012).

Revision of the tectonostratigraphic setting

In this study, special attention was given to identify the nature of the contacts between the basement rocks and metasediments of the deformed fossil OCT (Frasca, 2011). Taking the restoration of the multistage deformation performed by Beltrando et al. (2012), we mainly examined the contacts, focusing on the type and distribution of the rocks. Deformation of the OCT is fully documented by photographs (folds and shear zones) and structural data (detailed maps, cross-sections, and statistics) in Beltrando et al. (2012). We discovered new outcrops of breccias and pillows, sandwiched between the basement rocks and post-rift sediments, possibly filling paleotopographical lows. Petrography and SEM-EDS mineral chemistry were performed on samples from both old and newly discovered outcrops.

RESULTS

Contacts between basement rocks of the OCT: Metasomatism and intrusions

Serpentinite boundaries

Metasomatic rocks mark the boundaries of serpentinites and have different compositions depending on the neighboring rock-types (Fig. 4c). Chloritites or ovardites (albite-chlorite rocks with minor carbonate and titanite), separate serpentinites from metagranitoids (see chemical gradient in Barnes et al., 2014); these rocks were quarried to build baking stones (Baretti, 1893, pag. 241). Carbonate (mainly magnesite), tremolite (both mm-long euhedral crystals and fibers) and talc occur at the boundary with the metasediments. The amount of talc increases when the juxtaposed material is the tectonosedimentary breccia. Locally, a dm-thick magnetite rim grows over "acicular" antigorite and talc, separating serpentinites from metamafics.

Metamafics-carbonaceous schists contacts

Metamafics alternate with carbonaceous schists, which alternatively bear a mafic or quartzitic composition, in the "metamafics-carbonaceous schists sequence." At the contact, the intrusion breccia is missing, suggesting emplacement into unconsolidated sediments. Metasomatic albitite rims, from 20 cm to 1 meter thick, occur, which are always parallel to the basalt-carbonaceous schist contact. Albitite rims usually exhibit sharp sides (Fig. 4g) and locally show carbonate- dissolution cavities. Metasomatism was previously ascribed to an oceanic environment (Loubat, 1968). However, an albitite rim at the clast-matrix boundary in a breccia dismantling mafic rocks (400 m W of Punta Rossa peak) and albite pseudomorphs after HP Fe-Mg carpholite in the albitite rims indicate that some hydrous fluid-phase circulation occurred after both the dismantling of mafic rocks and the Alpine HP peak.

Metagranitoid intrusive contacts

Intrusions of granitoid dykes is observable at several outcrops W of Punta Rossa peak in the carbonaceous gneisses, which we consider of a comparable composition (Fig. 4e) to the carbonaceous schists of the "metamafics-carbonaceous schists sequence." Conversely, leucocratic metagranitoids intrude the metamafics in a single locality near Tormottaz. Metamafics do not intrude the leucocratic granitoids. Mafic layers exposed to the south of Punta Rossa (see Fig. 3) are different from the other metamafics owing to their exclusive chlorite and carbonate compositions (Fig. 4f). Therefore, the

Fig. 4 - Basement rocks of the three tectonic units (cf. inset in Fig. 3). Outcrop pictures on the left and photomicrographs on the right. Coloured borders (online version) refer to the units in Fig. 3. a) Serpentinized ultramafic rock with textural relicts of peridotitic clinopyroxene (whitish) and spinel (black). Finger for scale; ~ 800 m SSW of Punta Rossa. b) Photomicrograph of skeletal spinel in a matrix of mesh serpentine (Srp), chlorite (Chl) and tremolite (Tr). Crossed polarizers (XP). c) Network of carbonate veins (Cc) in an ophicalcite (Srp) with chlorite rim (chl) on the right side, juxtaposed against the Punta Rossa metagranitoid. 600 m S of Punta Rossa. d) Photomicrograph of the Punta Rossa metagranitoid with sericitized plagioclase laths in a groundmass of albite and quartz. XP. Sample collected ~ 400 m SSE of Punta Rossa. e) Boudinaged leucocratic metagranitoid dyke intruding a carbon-rich matrix (with different degrees of weathering), which is interpreted here as part of the "metamafic-carbonaceous schist sequence" (see also Debelmas et al., 1991). Hammer tip for scale; ~ 500 m SSW of Punta Rossa. Plane polarized light (PPL). f) Photomicrograph of the metamafic volcanoclastic intercalation in the Punta Rossa sedimentary cover. Note the presence of carbonate and the absence of a relict texture as in h); Ab = albite, Mgs = magnesite, Chl = chlorite. g) Whitish albite metasomatic rim at the contact between the carbonaceous schist (above) and metamafic (below). Hammer for scale; ~ 1 km E of Mt. Miravidi peak. h) Photomicrograph of the glaucophane (Gl)-bearing metagabbro with relict igneous pyroxene (Cpx) and a chlorite rim (Chl). Zoned blue amphiboles suggest three growth stages. Ilm = ilmenite PPL. i) Panoramic view of the stratigraphic unconformity (dashed line) between the "Laytire" Rhaetian carbonate schists and marbles (see Elter G. and Elter P., 1965) in the Petit-Saint Bernard Unit. W of Grand Berrier summit. j) Photomicrograph of the Petit-Saint Bernard Mesozoic cover showing an isoclinal fold with the development of axial plane foliation (left side). The darker layers are enriched in carbonaceous material (T = 469 °C; Beltrando et al., 2012). PPL.

mafic layers here are not interpreted as dykes, but rather as volcanoclastic horizons interleaved in the metasedimentary cover of the Punta Rossa metagranitoids.

Metabreccias

In the *Punta Rossa Unit*, metabreccias occur in three different positions at the base of the "Radiolaria schists" formation, namely (1) at the top of the OCT metagranitoid basement, (2) at the top of the metamafics, and (3) at the top of the serpentinites [see Beltrando et al. (2012) for a detailed description of the fault rocks]. We stress the difficulty in recognizing the nature, i.e., tectonic vs. sedimentary, of the breccias, in part because of later metamorphic overprint and shearing, in part because of rift-related deformation history prior to Alpine metamorphism (Fig. 5a). Fault breccias are usually monogenic (Fig. 5a), while undisputable sedimentary breccias are characterized by an abundant matrix, which does not show evidence of foliation (Figs. 5c and 5e). When the original nature is not recognized we use the term tectonosedimentary breccia as defined in Beltrando et al. (2012) and Manatschal et al. (2006). The post-rift "Aroley" metabreccias cannot be confused with syn-rift metabreccias. Their composition is mainly carbonate-rich both in the clasts and matrix, whereas the syn-rift metabreccias are often metamafic-rich both in the clasts and matrix (Fig. 5d-f).

In the *Hermite Unit*, the detrital cover contains mafic and marble clasts, as previously described by Beltrando et al (2012). We report only the presence, at the cliff 500 m east of Aiguilles de l'Hermite Peak, of rounded clasts of carbonaceous schists embedded in a carbonate-rich matrix (Fig. 5i), adding a greater lateral variability to the mixed composition of the detrital cover of the Hermite Unit. Clasts of lithotypes comparable to those in the Punta Rossa Unit basement were not observed. The age is considered Mesozoic based on the presence of belemnites, as reported by Schoeller (1929), at the Collet des Rousses (Fig. 3).

In the *Petit Saint Bernard Unit*, metabreccias crop out in two positions (Fig. 3): (1) below the Petit Saint Bernard Unit cover and above the metamafics of the Hermite Unit and (2) below the Petit Saint Bernard Unit cover and above the "Laytire" pre-rift (see violet stars in Fig. 3). Metabreccias do not occur at the contact between the Petit Saint Bernard metasediments and the overlying Houiller rocks. Clasts are angular to locally rounded and their composition varies strongly from Triassic dolostones to Early Jurassic pre-rift "Laytire" marbles (Fig. 5j-l). We note that despite its proximity with a "metamafics-carbonaceous schists sequence" basement, clasts from this rock sequence are absent. Alpine deformation and metamorphism strongly affect the "facies" of the metabreccias and thus we cannot rule out completely a tectonic origin for these breccias.

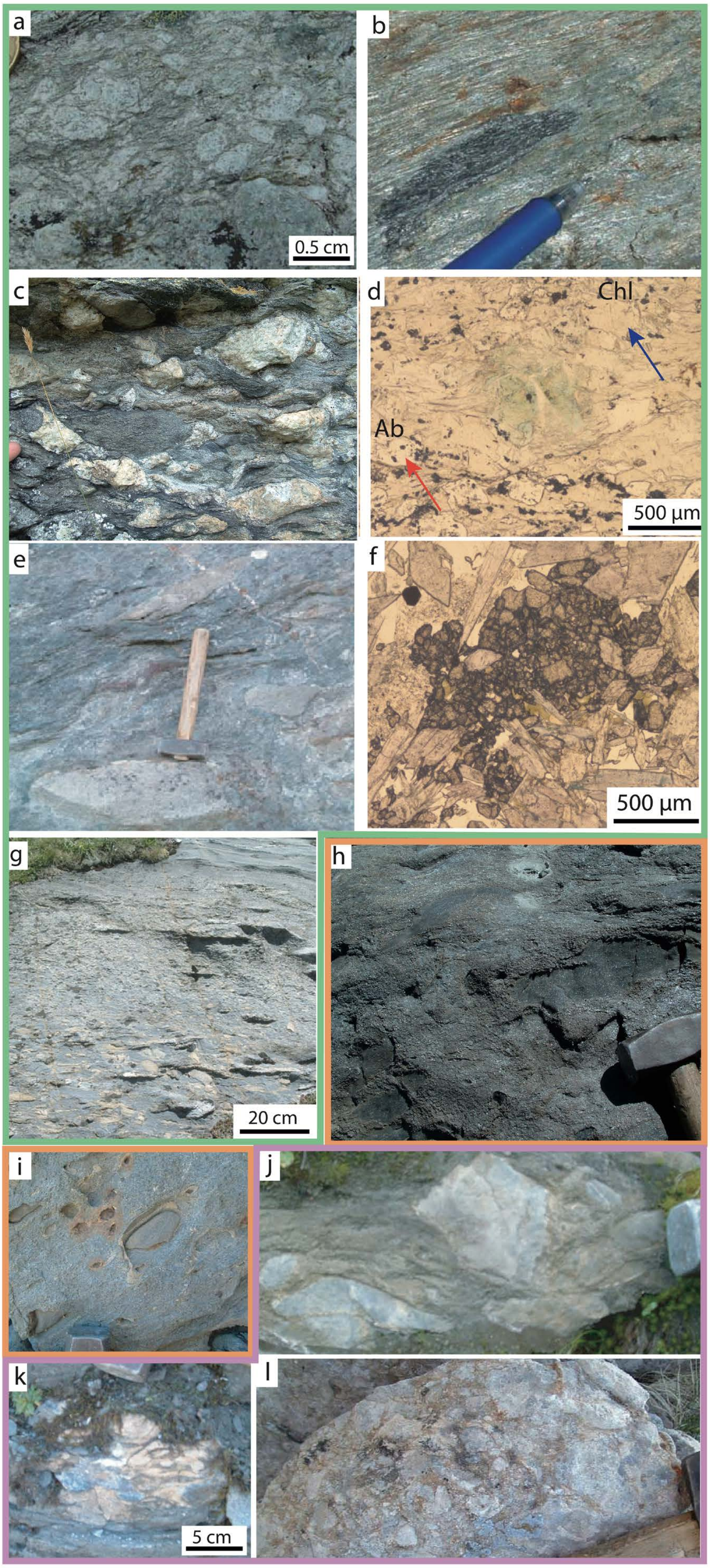
Pillowed metabasalts

Fig. 3 unequivocally shows that the pillowed lava outcrops are scattered along the contact between the basement rocks and the "Radiolaria schists." In the best pillow outcrop, which is exposed 500 m SE of the Bassa Serra Col, pillows are only slightly deformed. Fig. 6a shows pillowed basalts similar to what has been described in the Chenaillet ophiolite (Chalot-Prat, 2005; Manatschal et al., 2011). No dykes feeding the lava flows were observed, and the pillow shape varies from spherical to elongated to defined lava tubes (Fig. 6b). Rare prismatic aggregates of chlorite are interpreted as pseudomorphs after igneous pyroxene phenocrysts. In the chlorite-rich pillow-rims, rare albite and titanite appear to derive from primary varioles. Minor actinolite-tremolite amphibole, stilpnomelane, and calcite are also observed. At the top of the cliff, pillows grade into a metaconglomerate with a dark chlorite matrix.

The Mesozoic age of the lava flow emplacement at the seafloor can be derived only indirectly by the presence of interlayered metasediments, such as marbles (Fig. 6c) or quartzites (Fig. 6d), which are typical of Mesozoic pillowed metabasalts in the Chenaillet ophiolite. We note that a tectonic monogenic breccia developed to the west at the expense of the Punta Rossa granitoid (Fig. 6h), suggesting an original proximity between these strongly weathered faulted rocks and the pillow lavas. The proximity is also testified by foliated metapillowed breccias (Fig. 6d).

Pillowed metabasalts are missing from the Italian side of the Hermite Unit. On the French side, pillowed rocks have been reported to become progressively massive near Mt. Miravidi peak (Antoine, 1971; Mugnier, 2008), but an attribution to the Hermite Unit, as defined on the Italian side, is doubtful. In the Punta Rossa Unit, ~ 200 m to the south of Tormottaz, pillows are observed inside massive metamafics (Debelmas et al., 1991; VV. AA., 1992). Metaconglomerates with rounded clasts in a chlorite-matrix, such as those exposed ~ 500 m to the south of Tormottaz, are likely pillowed breccias owing to the preservation relict of a ghost rounded shape in the preserved pillows, as suggested by Loubat and Antoine (1965). In some localities, the chlorite-rich portions are ambiguous and could derive from deformed veins (e.g., ~ 500 m N of Punta Rossa or ~ 400 m W of Mt. Laytire). However, ~ 600 m NW of Tormottaz, a well-preserved pillow shape clearly occurs (Fig. 6i), suggesting the occurrence

Fig. 5 - Examples of metabreccias from the Punta Rossa Unit (a,b,c,d,e,f), Hermite Unit (g), and Petit-Saint-Bernard Unit (h,i,l). Coloured borders (online version) refer to the units in Fig. 3. a) Metamorphic fault breccia developed at the expense of a Paleozoic granitoid. Lacs de la Tormottaz. b) Metasedimentary breccia. Clasts of carbonaceous schists and micaschists indicate provenance from a "Versoyen" *sensu* Elter G. and Elter P. (1965) basement type. Lacs de la Tormottaz. c) Metasedimentary breccia. Clasts of carbonaceous gneisses and granitoids indicate provenance from a "Versoyen" *sensu* Elter G. and Elter P. (1965) basement type. 300 m S of Punta Rossa. d) Photomicrograph of the detrital cover of the Punta Rossa Unit A lithic clast with a greenish Cr-rich white mica wrapped by a colorless white mica-chlorite foliation. Post-tectonic albite (Ab) and chlorite (Chl) porphyroblasts are evident. PPL. 600 m SSW of Punta Rossa. e) dm-sized clasts of a carbonate-bearing greenstone in a carbonate schist matrix rich in carbonaceous material. Hammer for scale. f) Photomicrograph of a mafic breccia matrix, where titanite, glaucophane, and greenish biotite aggregates are evident in the albite groundmass. PPL. Sample from ~400 m W of Punta Rossa. g) cm-long clasts of carbonate-free carbonaceous schists in a carbonate-rich matrix. 500 m E of Aiguilles de l'Hermite. h) Metasedimentary breccia from the "Aroley" formation with fining upward grading. i) Metasedimentary breccia from the post-rift carbonate-rich cover of the Hermite Unit with impure marble clasts and mica-rich carbonate matrix. Arguerey Glacier. j) Angular clasts of light-grey marbles in a carbonate-rich matrix. W of Lac de Verney dessus. k) dm-long clast of a yellowish metadolostone in a matrix of carbonate-rich micaschist. Outcrop near the hump to the N of Pic de Lancebranlette at ~2,470 m a.s.l. l) Clasts of Jurassic marbles in a yellow-orange matrix. Base of the Petit-Saint-Bernard Unit cover. 200 m SW of Laytire.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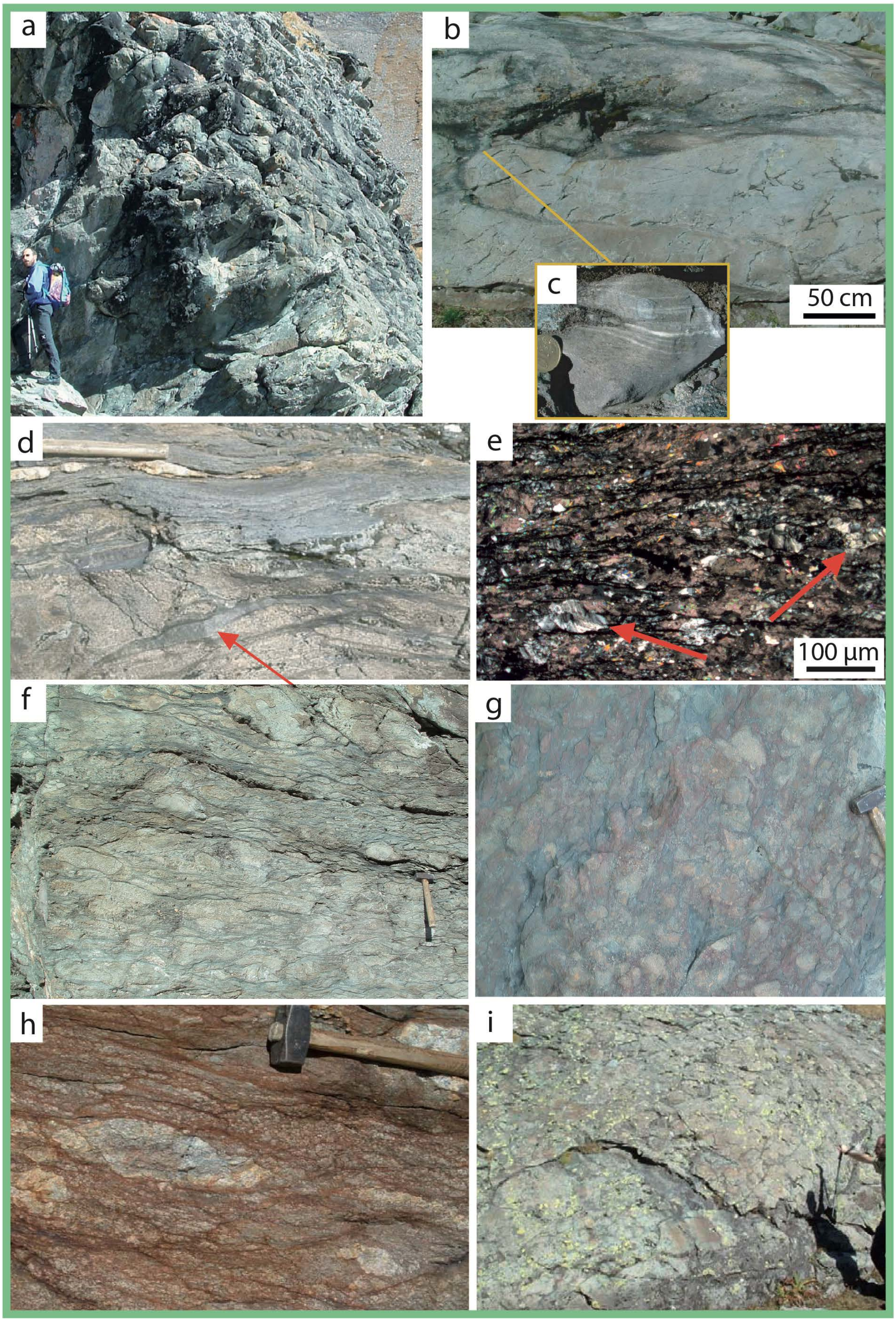


Fig. 6 - Pillowed metabasalts and associated metasediments and meta fault rocks in the Punta Rossa Unit (green colored border indicates the Punta Rossa Unit). a) Cliff entirely composed of pillowed metabasalts. SE of Bassa Serra Col. b) Lava tube cut parallel to the flow direction. From the base of cliff (a). c) Grey marble intercalation in the pillow lavas, detailed view of b). Coin for scale. d) Metamorphosed pillow breccia grading upward to carbonaceous micaschists in the "Radiolaria schists." Hammer handle for scale. Note the light-grey lens of quartzite (red arrow). e) Photomicrograph of "Radiolaria schists" when rich in carbonate. Main foliation wrapping around albite pseudomorphs after likely lawsonite (red arrows). f) Foliated pillow breccia. Hammer for scale. SE of Bassa Serra Col. g) Pillow breccia undeformed. Hammer handle for scale. 300 m S of Tormottaz. h) Metamorphosed granitoid fault-breccia in a weathered and foliated matrix. i) Slightly deformed pillowed metabasalts with chlorite rims. 700 m NW of Tormottaz.

of subaqueous lavas (i.e., *"Metapillowed basalts"* in Fig. 3); therefore, the quantity of these rocks is larger than previously known.

Metasediments and fossils

In the Punta Rossa Unit, microfossils are commonly found within the carbonate-free part of the so-called "Radiolaria schists," which are characterized at the meso- and microscale by a foliation defined by white mica (Si = 3.3 a.p.f.u.) and chloritoid (Fig. 7a; Beltrando et al., 2012). The microfossils observed under an optical polarizing microscope exhibit a circular cross-section of 20 to 150 μm long, composed of opaque matter including regularly distributed holes ~ 5 μm long (Figs. 7a-e). The SEM data (Al_2O_3 = 3.1, SiO_2 = 2.37, P_2O_5 = 1.06, S = 0.89, FeO = 69.1) for the opaque matter indicate mainly Fe-hydroxides (Fig. 7f-h) while the holes correspond to the original organic portions. These data suggest that the microfossils were Radiolaria, whose original siliceous skeleton was replaced by Fe-hydroxides.

In the carbonate-rich part of the "Radiolaria schists" formation, larger fossil shells of Gasteropoda are completely replaced by Fe-hydroxide and calcite (Fig. 7i). In the post-rift marbles of the Punta Rossa Unit cover ("Aroley" formation), chlorite-rich layers can be interpreted as volcanoclastic layers (see Fig. 3; Frasca, 2011).

Similarly, in the Petit Saint Bernard Unit, ammonite remnants in the chloritoid-bearing micaschist intercalations of the Petit-Saint-Bernard cover are recognizable (Fig. 7j*). Bivalves* were discovered in the "Laytire" formation (Fig. 7k) and belemnites in the Petit Saint Bernard Unit have reported (Frasca, 2018; originally reported by Franchi, 1899; Fig. 7m, n; Fig. 3).

DISCUSSION

Significance of the detrital metasediments: Age, polarity, and source

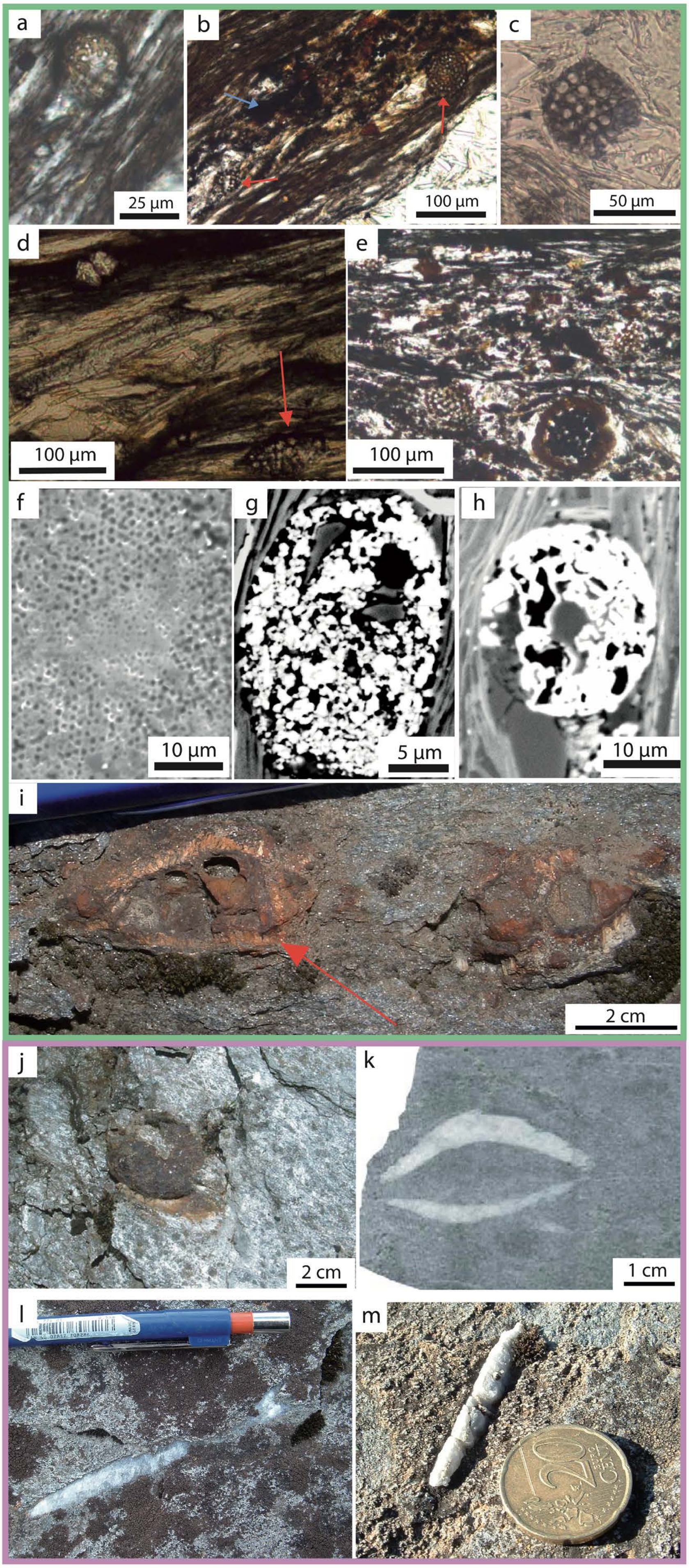
In the *Punta Rossa Unit*, the basement, composed of serpentinites, metagranitoids, metabasalts, and carbonaceous schists, was the source of the overlying clastic syn-rift sediments. The clast size and shape, combined with the observation that the clast composition is strongly dependent on the type of underlying basement rock, indicate transport over a short distance. The composition of the metabreccia clasts alone does not provide an indication of polarity, but the local derivation of the clast from the basement sliver is not compatible with chaotic mixing in a tectonic or sedimentary setting. Beltrando et al. (2012) interpreted the thrust north of the Mt. Miravidi (Masson et al., 2008) as the tectonic contact separating the Hermite and Punta Rossa Units and the "Radiolaria schists" formation and the "Tarentaise trilogy" formations as the overturned interior of the Punta Rossa tectonic Unit (Loprieno et al., 2011). However, the poor preservation of Radiolaria and Gasteropoda does not allow a precise age determination. Furthermore, the presence of fossils in fine-grained detrital sediments may also suggest a possible original reworking. Metabreccias in the post-rift "Aroley" formation contain almost exclusively rounded Mesozoic carbonate clasts from a far, possibly Helvetic, source, which agrees with the suggested paleo-OCT paleogeographic position of the Punta Rossa Unit. The composition of clasts from the "Aroley" formation further suggests that sediments were deposited at the very tip of the "mega-scarps" debris at the boundary between the necking domain and hyperextended domain during the post-rift stage (Fig. 8b; Ribes et al., 2019b).

In the *Hermite Unit*, the discontinuous nature of the breccia outcrops also suggests a local infill of topographic lows. The composition of the breccia matrix suggests mainly local reworking of metamafics. However, marble clasts are observed in the Hermite detrital cover even if marbles are not a component in the basement of the Hermite Unit, suggesting that pre-rift material was derived from sources other than the Hermite Unit. Large meter-sized angular and rounded blocks of impure marbles and cm-thick detrital layers in the carbonate-rich part of the Hermite Unit cover suggest a post-rift input of detritus, such as that observed in the "Aroley" formation in the Punta Rossa Unit.

In summary, we can envisage a continuous evolution from syn-rift (~ 170 Ma; Ribes et al., 2019a) to post-rift (~ 135 Ma) deposition of the "Aroley" formation (Loprieno et al., 2011), as proposed in the Valaisan Basin further to the east (Fig. 8a). The composition of the metabreccia clasts in both the Punta Rossa and Hermite cover is changing in a similar manner from syn- to post-rift. Basement rocks are eroded mainly in the early syn-rift; however, in the Hermite Unit cover, the pre-rift sediment component of the clast is more significant (Fig. 8a). The size of the clasts in the Punta Rossa cover shows larger cobbles in the syn-rift deposits and finer grained sediments in the post-rift. Conversely, sparse large boulders occur in the carbonate post-rift cover in the Hermite Unit, suggesting possibly a more proximal position with respect to the Punta Rossa Unit (Fig. 8b).

In the *Petit Saint Bernard Unit*, on both sides of the Breuil valley, the discontinuous detrital metasediment outcrops occur in the same structural position, i.e., below its Early Jurassic cover. Triassic metadolostone and Early Jurassic marble clasts indicate erosion from different stratigraphic horizons. The presence of cherty marble clasts, exclusively near the cherty outcrops of the "Laytire" formation, suggests a local source. However, the proximity cannot be estimated on the western side of the Breuil valley because the Petit Saint Bernard cover was likely excised at the underlying tectonic contact. A Raman T estimate of the metabreccia matrix could better constrain the tectonic unit of this detrital rock. However, the carbonate-rich composition of the matrix and the widespread preservation of belemnite and ammonite in the overlying metasediments clearly indicate a Mesozoic age.

Debelmas et al. (1991) proposed a younger mid Jurassic age for the overlying carbonate metasediments. The Petit-Saint Bernard breccias could have thus been deposited during the latest Early Jurassic, possibly coeval with the deposition of the "*Grès Singulier*" in the Helvetic realm (Ribes et al., 2020). This observation allows a definition of the very early stages of rifting in the Petit Saint Bernard Unit. We tentatively propose that the paleogeographic position of the Petit Saint Bernard Unit was on the Briançonnais side of the Valaisan Basin, based on the Subbriançonnais stratigraphy proposed by Elter G. and Elter P. (1965) and Debelmas et al. (1991) (Fig. 8b). The detrital cover of the Petit St Bernard Unit does not show variability in both the matrix and clast compositions, as well as the clast size (Fig. 8a). This detrital cover, sealed by Early Jurassic metasediments, should be older than that inferred for the breccias in the Punta Rossa and Hermite Units (see above). We recall here that all of the ages proposed in the Breuil valley are mainly based on a facies analogy with less or non-metamorphic sedimentary successions.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Significance of pillowed metabasalts at the Valaisan Ocean-Continent Transition

Volcanic edifices are commonly recognized by seismic data at present-day magma-poor rifted margins (e.g., Gailler et al., 2009). For example, along magma-poor margin OCT cross-sections in the North Atlantic, lavas can easily cover areas on the order of 20 km^2 over a total area of 260 km^2 in the hyper-extend domain margin (e.g., Péron-Pinvidic and Manatschal, 2009; Tugend et al., 2020). Furthermore, in the NW Mediterranean Sea between Nice and Cap Corse, lavas cover an area of 400 km^2 over a total area of 2,700 km^2 in the hyperextend margin (Rollet et al., 2002). Moreover, massive basalts, pillow lavas, pillow breccias, and hyaloclastites are commonly found in ophiolites exposed in mountain belts, which have been interpreted as analogues of magma-poor rifted margins, such as in the Central Alps (Manatschal et al., 2006; Epin et al., 2019). There, the basalts are highly variable in thickness and size; their abundance usually increases ocean-ward, where the lavas appear to be controlled by late syn-magmatic high-angle faults (Epin et al., 2019; Ribes et al., 2019c).

In the *Punta Rossa Unit*, new outcrops of metabreccias and pillowed metabasalts have been reported, which, as documented in this study, are sealed by fossil-bearing metasediments and alternate with discontinuous "extensional allochthons" composed of metagranitoids and "metamafic-carbonaceous schist sequences" rocks (Beltrando et al., 2014b). The Mesozoic age of the pillows is inferred thanks to the presence of quartzite and carbonate intercalations (Fig. 6). Fossils (mainly Gasteropoda or Radiolaria), preserved despite the high-pressure metamorphism (Fig. 6e), do not allow for a reliable age determination. The position of the pillows adjacent to the granitoid tectonic breccias (Fig. 6f) may indicate a link between faulting in the basement rocks and the location of submarine basalt lava flows.

In summary, pillowed metabasalts systematically separate "metagranitoid-serpentinite pairs," "metamafic-carbonaceous schist sequences," and "extensional allochthons," but they are never faulted (Fig. 8c). This observation indicates that faulting pre-dates the deposition of lavas without any further segmentation via Alpine faulting. The same absence of brittle faulting has been reported in the metabreccias described above. Moreover, the volume of Mesozoic lava flows appears to be larger than previously thought in the Punta Rossa Unit, in agreement with the large amount of lavas described in OCT settings worldwide. Moreover, we interpreted the metamafics observed to the south of Punta Rossa peak as a volcanoclastic intercalation in the metasedimentary Punta Rossa cover (blue star in Fig. 3), instead of a dyke intrusion in the metagranitoids. Granitoid dykes are common in carbonaceous metasediments, but rare in metamafics (only near Tormottaz peak), suggesting that part of the metamafic rocks in the Punta Rossa Unit may be older than the metagranitoids, in agreement with previous geochronological data (Permian and Carboniferous: Beltrando et al., 2007).

In the Italian side of the *Hermite Unit*, pillows are not observed at the contact with the Mesozoic cover and fault rocks do not directly juxtapose the microgabbros to the sedimentary breccias, which is typically observed in Mesozoic gabbros from other OCT fossil remnants in the Alps (Epin et al., 2019). Moreover, the Hermite Mesozoic syn-rift cover contains fragments of lithified carbonaceous schists (Fig. 5g) and commonly clasts of metamafics and of the "Laytire" marble. The carbonate cover is then considered as Early Jurassic (Debelmas et al., 1992). These characteristics could support a Paleozoic age for the 4 km^3 "metamafic-carbonaceous schist sequence" in the Hermite Unit. Future geochronological studies of the metadolerite, metamicrogabbro, and metagabbro should focus on lithotypes north of Hermite peak, not only in the Aiguille de Clapet and Punta Rossa regions. The published geochemistry of tholeiitic magmas shows similar composition for sills and pillow and cannot thus be used to discriminate between possible Paleozoic metamafics and Mesozoic pillowed metabasalts (Mugnier et al., 2008). Furthermore, identifying the tectonic unit of the metamafics and defining their metamorphic grade and age [i.e., either blueschist-facies (Fig. 4f) or eclogite facies (Cannic, 1996), Tertiary or Paleozoic] require further petrologic investigations.

CONCLUSIONS

The new outcrops of pillowed metabasalts, the reported variability in the clast composition of the Mesozoic metabreccias (i.e., greater than previously thought), and the new observation on the relationships between the syn-rift cover and basement lithotypes support the interpretation of the Punta Rossa Unit as a former ocean-continent transition zone, as proposed by Beltrando et al. (2012). We propose a Mesozoic age for the syn-rift pillowed basalts, which have a volume larger than previously thought in the ocean-continent transition zone. Likewise, we validated previous Paleozoic geochronological data using the relative chronology of the mafic and leucocratic granitoid intrusions in the Punta Rossa Unit (Beltrando et al., 2007). New metabreccias and Mesozoic fossils in the Petit St. Bernard Unit better constrain the early stages of the Valaisan rifting record. The new lithostratigraphic observations should be combined with future petrological, geochronological, and tectonic investigations, and paleogeographic reconstruction, to improve our comprehension of the role that Paleozoic or Mesozoic inheritance had on the structural evolution of the Lower Penninic in the Western Alps.

Fig. 7 - Fossil remnants in the metasediments of the Punta Rossa and Petit-Saint-Bernard units. Coloured borders (online version) refer to units in Fig. 3. a,b,c,d,e) Photomicrograph of "Radiolaria schists" preserving Radiolaria and other microfossil remnants (see also Beltrando et al., 2012). 400 m W of Punta Rossa and north of M. Miravidi (see Fig. 3). PPL. f) BSE images of the opaque minerals in (e). Note the μm-sized hole related to the biogenic origin of sulfur. g,h) BSE images of a 5 and 10 μm-sized Radiolarian replaced by iron hydroxide ore (white). Note the perfect preservation of the fossil shape, and the central hole (black) corresponding to the original organic portions. See text for further explanation. i) Two cm-long gastropods replaced by brownish iron hydroxide and calcite in the carbonaceous carbonate-rich micaschists of the "Radiolaria schists" formation. j) 4-cm-wide ammonite embedded in a chloritoid-rich silvery matrix of the micaschists in the Petit-Saint-Bernard Unit. 600 m W of Verney lake. k) Bivalve (white) in the pre-rift "Laytire" (grey) in the Petit-Saint Bernard Unit. l,m) Belemnites (white) in the carbonate schist (grey) cover of the Petit-Saint Bernard Unit.

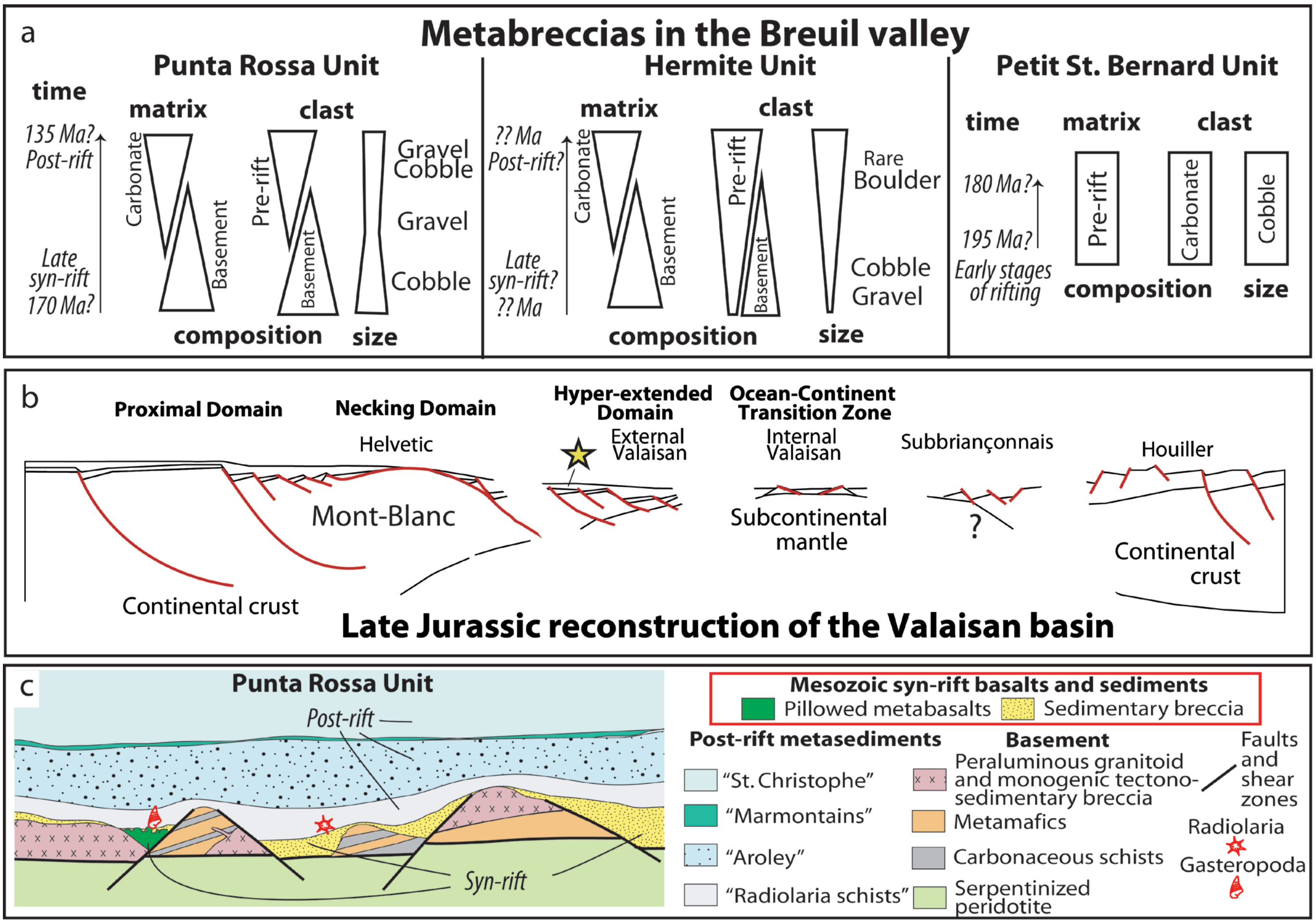

Fig. 8 - a) Diagram of the variation inside the metabreccias in the Breuil valley. The left shows the breccias in the Punta Rossa and Hermite Units; the right shows the older breccias from the Subbriançonnais rifted margin (Petit Saint Bernard Unit). b) Tentative Late Jurassic reconstruction of the tectonic domains in the Valaisan Basin (modified after Ribes et al., 2020, 2019c). Star indicates the possible position of the main post-rift "Aroley" detrital deposits (Ribes e al., 2019b). c) Idealized reconstruction of the pre-alpine geologic setting of the Punta Rossa Unit. Syn-rift pillowed basalts and sedimentary breccias occur in a similar position in-between the faulted blocks of various basement rocks (modified after Beltrando et al., 2012). Note that the brittle faults that bound the basement blocks do not affect the post-rift sediments but partly affect the breccias (tectono-sedimentary breccias).

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REFERENCES

Agard P., 2021. Subduction of oceanic lithosphere in the Alps: Selective and archetypal from (slow-spreading) oceans. Earth Sci. Rev., 214: 103517. https://doi.org/10.1016/j.earscirev.2021.103517.

Amann M., Ulrich M., Manatschal G., Pelt E., Epin M.-E., Autin J. and Sauter D., 2020. Geochemical characteristics of basalts related to incipient oceanization: The example from the Alpine-Tethys OCTs. Terra Nova, 32: 75-88. https://doi.org/10.1111/ter.12438.

Antoine P., 1965. Sur l'existence du Crétacé supérieur daté dans la nappe des Brèches de Tarentaise au Nord des Chapieux (Savoie). C.R. Acad. Sci. Paris, 261: 3640-3642.

Antoine P., 1968. Sur la position structurale de la «Zone du Versoyen» (Nappe des Brèches de Tarentaise sur les confins franco-italiens). Géol. Alpine, 44: 5-26.

Antoine P., 1971. La Zone des Brèches de Tarentaise entre Bourg-St-Maurice (Vallée d'Isère) et la frontière italo-suisse. Trav. Lab. Géol. Univ. Grenoble, Mém., 9: 1-367.

Antoine P., 1972. Le domaine pennique externe entre Bourg-St-Maurice (Savoie) et la frontière italo-suisse. Géol. Alpine, 48: 5-40.

Antoine P., Barféty J.C., Vivier G., Debelmas J., Desmons J., Fabre J., Loubat H. and Vautrelle C., 1992a. Notice explicative de la Carte géologique de France 1/50 000. Feuille Bourg-Saint-Maurice, 727: 110 pp.

Antoine P., Féraud J. and Poulain P.A., 1992b. Notice explicative de la Carte géologique de France 1/50 000. Feuille Mont Blanc, 704: 1-22.

Antoine P., Loubat H. and Vatin-Perignon N., 1973. Hypothèses nouvelles sur la signification des "ophiolites" du domaine pennique externe (Savoie-Valais). Géol. Alpine, 49: 21-39.

Argand E., 1911. Les nappes de recouvrement des Alpes pennines et leurs prolongements structuraux. Matér. Carte Géol. Suisse, 31: 1-26.

Bagnoud D.A., Wernli R. and Sartori M., 1998. Découverte de foraminifères planctoniques dans la zone de Sion-Courmayeur à Sion. Ecl. Geol. Helv., 91: 421-429.

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

Barbier R., 1948. Les Zones ultradauphinoise et subbriançonnaise entre l'Arc et l'Isère. Mem. Expl. Carte Géol. France, 1-45.

Barbier R., 1951. La prolongation de la zone subbriançonnaise de France en Italie et en Suisse. Les conséquences pour une corrélation d'ensemble des zones penniques de ces trois pays. Trav. Lab. Géol. Grenoble, 29: 3-46.

Barbier R., Bloch J.P., Debelmas J., Ellenberger F., Fabre J., Feys R., Gidon M., Goguel J., Gubler Y., Lanteaume M., Latreille M. and Lemoine M., 1963. Zones Internes des Alpes Occidentales. Mém. Soc. Géol. Fr.. Extrait du livre a la mémoire du professeur Paul Fallot, 2: 334-350.

Barbier R. and Trümpy R., 1955. Sur l'âge du flysch de la zone des Brèches de Tarentaise. Bull. Soc. Géol. France, 5: 207-216.

Baretti M., 1879. Studi geologici sulle Alpi Graie Settentrionali. Mem. R. Acc. Lincei, 5: 407- 508.

Baretti M., 1880. I giacimenti antracitiferi della Valle d'Aosta. Ann. R. Ist. industriale e professionale Torino, 8: 1-23.

Baretti M., 1893. Geologia della Provincia di Torino. Casanova, Torino, p. 1-732.

Barnes J.D., Beltrando M., Lee C.-T.A., Cisneros M., Loewy S. and Chin E., 2014. Geochemistry of Alpine serpentinites from rifting to subduction: A view across paleogeographic domains and metamorphic grade. Chem. Geol., 389: 29-47. https://doi.org/10.1016/j.chemgeo.2014.09.012

Beltrando M., Compagnoni R. and Lombardo B., 2010. (Ultra-) High-pressure metamorphism and orogenesis: An Alpine perspective. Gondw. Res., 18 (1): 147-166.

Beltrando M., Compagnoni R., Barnes J., Frezzotti M.L., Regis D., Frasca G., Forster M., and Lister G., 2014. From passive margins to orogens: The link between zones of Exhumed Subcontinental Mantle and (U)HP metamorphism. Day 2 - The UHP Lago di Cignana Unit, Zermatt-Saas Zone.10th Int. Eclogite Conf., Pre-Conf. Excursion, September 2013, GFT - Geol. Field Trips, 6 (1.1): 1-61. ISSN: 2038-4947, doi: 10.3301/GFT.2014.01.

Beltrando M., Compagnoni R., Ferrando S., Mohn G., Frasca G., Odasso N., Vukmanovič Z., and Masini E., 2015. Crustal thinning and mantle exhumation in the Levone area (southern Canavese zone, Western Alps). In: G. Manatschal et al. (Eds.), A field guide across the margins of Alpine Tethys. J. Virt. Expl., 48, doi: 10.3809/jvirtex.2013.00326.

Beltrando M., Frasca G., Compagnoni R. and Vitale Brovarone A., 2012. The Valaisan controversy revisited: Multi-stage folding of a Mesozoic hyper-extended margin in the Petit St. Bernard pass area (Western Alps). Tectonophysics, 579: 17-36.

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

Beltrando M., Rubatto D., Compagnoni R. and Lister G., 2007. Was the Valaisan basin floored by oceanic crust? Evidence of Permian magmatism in the Versoyen Unit (Valaisan domain, NW Alps). Ofioliti, 32: 85-99.

Beltrando M., Rubatto D. and Manatschal G., 2010b. From passive margins to orogens: the link between Ocean-Continent Transition Zones and (Ultra-)High-Pressure Metam. Geology, 38: 559-562.

Bernoulli D. and Jenkyns H.C., 2009. Ophiolites in ocean-continent transitions: From the Steinmann Trinity to sea-floor spreading. C.R. Geosci., 341: 363-381.

Bertrand M., 1896. La Tarentaise au Nord de l'Isère. C. R. Soc. Géol. Fr., 8: 1-220.

Beyssac O., Goffé B., Chopin C. and Rouzaud J.N., 2002. Raman spectra of carbonaceous material from metasediments: a new geothermometer. J. Metam. Geol., 20: 859-871.

Bigi G., Castellarin A., Coli M., Dal Piaz G.V., Sartori R., Scandone P. and Vai G.B., 1990. Structural Model of Italy, sheet 1. C.N.R., Prog. Finalizzato Geodin., SELCA Firenze.

Bocquet J., 1974. Études minéralogiques et pétrologiques sur les métamorphismes d'âge alpin dans les Alpes françaises. PhD. Thesis, Univ. Grenoble, France, p. 1-489.

Bousquet R., Goffé B., Vidal O., Oberhänsli R. and Patriat M., 2002. The tectonometamorphic history of the Valaisan domain from the Western to the Central Alps: new constraints on the evolution of the Alps. Geol. Soc. Am. Bull., 114: 207-225.

Boutoux A., Bellahsen N., Nanni U., Pik R., Verlaguet A., Rolland Y. and Lacombe O., 2016. Thermal and structural evolution of the external Western Alps: Insights from (U-Th-Sm)/He thermochronology and RSCM thermometry in the Aiguilles Rouges/Mont Blanc massifs. Tectonophysics, 683: 109-123. https://doi.org/10.1016/j.tecto.2016.06.010.

Bucher S. and Bousquet R., 2007. Metamorphic evolution of the Briançonnais units along the ECORS-CROP profile (Western Alps): new data on metasedimentary rocks. Swiss J. Geosci., 100: 227-242. https://doi.org/10.1007/s00015-007-1222-4.

Burri M. 1958. La Zone de Sion-Courmayeur au nord du Rhône. Matér. Carte Géol. Suisse, N.S., 105: 1-45.

Burri M., 1967. Prolongation de la zone de Sion dans le Haut-Valais. Ecl. Geol. Helv., 60: 614-617.

Burri M., 1979. Les formations valaisannes dans la région de Visp. Ecl. Geol. Helv., 72: 789-802.

Cannic S., 1995. The Versoyen: an intriguing metamorphic basaltic complex at the boundary between internal and external domains of the western Alps. Terra Abstr., 7: 117.

Cannic S., 1996. L'évolution magmatique et tectono-métamorphique du substratum du Domain Valaisan, complexe du Versoyen (Alpes Occidentales): implications dans l'histoire alpine. PhD. Thesis, Univ. Grenoble, p. 1-142.

Cannic S., Lardeux J.-M., Mugnier J.-L. and Hernandez J., 1995a. Tectono-metamorphic evolution of the Roignais-Versoyen Unit, Valaisan domain, France). Ecl. Geol. Helv., 89: 321-343.

Cannic S., Mugnier J.-L. and Lardeaux J.-M., 1995b. Mise en évidence d'une faille ductile dans l'unité du Roignais-Versoyen, Alpes occidentales, France. C.R. Acad. Sci. Paris, sér. IIa, 321: 513-519.

Carraro F., Fontan D., Gianotti F., Perello P., Schiavo A. and Venturini G., 2011. Geological map of Italy at 1:50,000 scale, sheet 89, "Courmayeur". ISPRA, Serv. Geol. d'It,

Ceriani S., Fügenschuh B. and Schmid S.M., 2001. Late-stage thrusting at the "Penninic Front" in the Western Alps between Mont Blanc and Pelvoux massifs. Int. J. Earth Sci., 90: 685-702.

Chalot-Prat F., 2005. An undeformed ophiolite in the Alps: field and geochemical evidences for a link between volcanism and shallow plate tectonic processes. In: G.R. Foulger, J.H. Natland, D.C. Presnall and D.L. Anderson (Eds.), Plates, plumes and paradigms. Geol. Soc. Am., Spec. Paper, 388: 751-780.

Cita B.M., 1953. Studi geologici sulla Valle Ferret italiana. Boll. Serv. Geol. It., 75: 65-172.

Dal Piaz et al., 1992. Alpi dal Monte Bianco al Lago Maggiore. 97 escursioni a piedi. Guide Geologiche regionali. Soc. Geol. It., BE-MA ed., 2, 1-209.

Dal Piaz G.V., 1999. The Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys. Mem. Sci. Geol., Padova, 51: 155-176.

De Saussure S., 1803. Voyages dans les Alpes, précédés d'un essai sur l'histoire naturelle des environs de Genève. Fauche-Borel L., Neuchâtel, 8: 1-305.

Debelmas J., Desmons J. and Caby R., 1991. Notice explicative de la Carte géologique de France 1/50000. Feuille S.te-Foy-Tarentaise, 728: 1-43.

Dielforder A., Frasca G., Brune S. and Ford M., 2019. Formation of the Iberian-European convergent plate boundary fault and its effect on intraplate deformation in Central Europe. Geochem. Geophys. Geosyst., 20: 2395–2417.

Einsele G., 1985. Basaltic sill-sediment complexes in young spreading centers: Genesis and significance. Geology, 1 (4): 249-252.

Ellenberger F., 1958. Étude géologique du pays de Vanoise. Mém. Carte géol. France, 12: 1-561.

Elter G., 1953. Sul rilevamento geologico di alcune zone dei fogli 27 ("M. Bianco") e 28 ("Aosta"). Boll. Serv. Geol. It., 75: 692-698.

Elter G., 1954. Nuovi risultati del rilevamento dei fogli Monte Bianco e Aosta. Boll. Serv. Geol. It., 76: 477-479.

Elter G., 1960. La zona pennidica dell'alta e media Valle d'Aosta e le unità limitrofe. Mem. Ist. Geol. Miner. Univ. Padova, 22: 1-113.

Elter G., 1987. Carte géologique de la Vallée d'Aoste, échelle 1:100.000. C.N.R. Centro Studi sui Problemi dell'Orogeno delle Alpi Occidentali, Torino. Printed by SELCA, Firenze

Elter G. and Elter P., 1965. Carta geologica della regione del Piccolo San Bernardo (versante italiano). Note illustrative. Mem. Ist. Geol. Miner. Univ. Padova, 25: 1-53.

Elter P., 1954. Etudes géologiques dans la Val Veni et le Vallon du Breuil (Petit St. Bernard). Thèse, Univ. Genève, 1-38.

Epin M.-E., Manatschal G., Amman M., Ribes C., Clausse A., Guffon T. and Lescanne M., 2019. Polyphase tectono-magmatic evolution during mantle exhumation in an ultra-distal, magma-poor rift domain: example of the fossil Platta ophiolite, SE Switzerland. Int. J. Earth Sci., 108: 2443-2467.

Favre A., 1862. Explication de la carte géologique des parties de la Savoie, du Piémont et de la Suisse, voisines du Mont Blanc. Arch. Sci. Genève, 15: 1-39.

Florineth D. and Froitzheim N., 1994. Transition from continental to oceanic basement in the Tasna nappe, Engadine window (Graubünden, Switzerland): Evidence for Early Cretaceous opening of the Valais Ocean. Schweiz. Miner. Petrogr. Mitt., 74: 437-448.

Franchi S., 1899. Nuove località con fossili mesozoici nella zona delle pietre verdi presso il colle del Piccolo San Bernardo (Valle d'Aosta). Boll. R. Com. Geol. It., 10: 303-324.

Franchi S., 1903. Contribuzione allo studio delle roccie a glaucofane e del metamorfismo onde ebbero origine nella regione ligure alpina occidentale. Boll. R. Com. Geol. It., 33: 255-318.

Franchi S., 1907. Escursioni in Valle d'Aosta, 12-13 settembre 1907. Boll. Soc. Geol. It., 26: 165-173 and 183-186.

Franchi S., 1929. Sul confine franco-italiano tra il Colle del Piccolo San Bernardo ed il Colle della Seigne, a sud del Monte Bianco. Rend. Accad. Naz. Lincei, 10: 617-621.

Franchi S. and Stella A., 1912. Carta Geologica d'Italia alla scala 1:100.000. Foglio 12, "M. Bianco". Serv Geol. It., Roma.

Frasca G., 2011. Rilevamento geologico-strutturale delle Unità Vallesane nel vallone del Breuil (La Thuile, AO), Tesi di Laurea, Università di Torino, p. 1-220.

Frasca G., 2018. Fossiliferous high-pressure metasediments from the Western Alps (Petit-Saint-Bernard Pass, Subbriançonnais Unit, Italy). Int. J. Earth Sci., 107: 2635-2637.

Freeman S.R., Butler R.W.H., Cliff R.A., Inger S. and Barnicoat A.C., 1998. Deformation migration in an orogen-scale shear zone array: An example from the Basal Briançonnais Thrust, internal Franco-Italian Alps. Geol. Mag., 135: 349-367.

Frey M., Hunziker J.C., Frank W., Bocquet J., Dal Piaz G.V., Jäger E. and Niggli E., 1974. Alpine metamorphism of the Alps: a review. Schweiz. Miner. Petrogr. Mitt., 54: 247-290.

Froitzheim N. and Manatschal G., 1996. Kinematic model for Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes, Eastern Switzerland). Geol. Soc. Am. Bull., 108: 1120-1133.

Fudral S., 1998. Étude géologique de la suture téthysienne dans les Alpes franco-italiennes nord-occidentales de la Doire Ripaire (Italie) à la région de Bourg-Saint-Maurice (France). Géol. Alpine, Mém., 29: 1-306.

Fudral S. and Gouillot P., 1988. Découverte des clastes à mariposites dans les conglomérats de la base du «flysh de Tarentaise» (zone valaisane), Savoie, France. Conséquences. C.R. Acad. Sci. Paris, série II, 306: 911-914.

Fügenschuh B., Loprieno A., Ceriani S. and Schmi S.M., 1999. Structural analysis of the Subbriançonnais and Valais units in the area of Moûtiers, Savoy (Western Alps): paleogeographic and tectonic consequences. Int. J. Earth Sci., 88: 201–218.

Gailler A., Klingelhoefer F., Olivet J.-L. and Aslanian D., 2009. Crustal structure of a young margin pair: New results across the Liguro-Provençal Basin from wide-angle seismic tomography. Earth Planet. Sci. Lett., 286: 333-345.

Gély J.P., 1989. Stratigraphie, tectonique et métamorphisme comparés de part et d'autre du Front pennique en Tarentaise, Alpes de Savoie, (France). Thèse doct., Chambèry, p. 1-343.

Goffé B. and Bousquet R., 1997. Ferrocarpholite, chloritoïde et lawsonite dans les métapélites des unités du Versoyen et du Petit St Bernard (zone valaisanne, Alpes occidentales). Schweiz. Miner. Petrogr. Mitt., 77: 137-147.

Hassenfratz J., 1805. Lettre à M. Gilles Laumont, conseiller des mines. J. Mines, 99: 235.

Haug E., 1909. Les géosynclinaux de la chaîne des Alpes pendant les temps secondaires. C.R. Acad. Sci. Paris, 148: 1637.

Hermann F., 1928. Les écailles de gneiss de la Pointe Rousse de Verney, aux environs du Petit-Saint-Bernard. Ecl. Geol. Helv., 21 (1): 1-72.

Hermann F., 1930. Studi geologici nelle Alpi Occidentali- La regione del Piccolo San Bernardo. Mem. Ist. Geol. Univ. Padova, 8: 72-80.

Hermann F., 1937. Carta Geologica delle Alpi Nord-Occidentali alla scala 1:200.000, con note illustrative. Tipografia Allegretti di Campi, Milano, 24 p.

Jeanbourquin P., 1995. The lower Penninic nappes in the Western Alps: The link between Helvetic and Penninic. Reply. J. Struct. Geol., 17: 1485-1488.

Jeanbourquin P. and Burri M., 1991. Les métasédiments du Pennique inférieur dans la région de Brigue-Simplon - Lithostratigraphie, structure et contexte géodynamique dans le bassin Valaisan. Ecl. Geol. Helv., 84: 463-481.

Kelts, K., 1981. A comparison of some aspects of sedimentation and translational tectonics from the Gulf of California and the Mesozoic Tethys. Ecl. Geol. Helv., 74, 317-338.

Kilian W. and Révil J., 1904. Description orographique et géologique de quelques parties de la Tarentaise, de la Maurienne et du Briançonnais septentrional. In: Études géologiques dans les Alpes occidentales. Contributions à la Géologie des chaînes intérieures des Alpes françaises. Mém. Expl. Carte géol. détaillée France. Mem. Carte Géol. Fr., 1: 1-369.

Kilian W. and Termier P., 1895. Sur quelques roches éruptives des Alpes françaises. Bull. Soc. Géol. Fr.., 1: 1-35

Liati A. and Froitzheim N., 2006. Assessing the Valais ocean, Western Alps: U-Pb SHRIMP zircon geochronology of eclogite in the Balma unit, on top of the Monte Rosa nappe. Eur. J. Miner., 18: 299-308.

Liati A., Froitzheim N. and Fanning C.M., 2005. Jurassic ophiolites within the Valais domain of the Western and Central Alps: geochronological evidence for re-rifting of oceanic crust. Contrib. Miner. Petrol., 149: 446-461.

Liati A., Gebauer R.D. and Fanning C.M., 2003. The youngest basic oceanic magmatism in the Alps (Late Cretaceous, Chiavenna unit, Central Alps): geochronological constraints and geodynamic significance. Contrib. Miner. Petrol., 146: 144-158.

Lomas S., 1992. Submarine mass-flow conglomerates of the Tarentaise zone, Western Alps: Sedimentation processes and depositional setting. Sedim. Geol., 81: 269-287.

Loprieno A., Bousquet R., Bucher S., Ceriani S., Dalla Torre F.H., Fügenschuh B. and Schimd S.M., 2011. The Valais units in Savoy (France): A key area for understanding the palaeogeography and the tectonic evolution of the Western Alps. Int. J. Earth Sci., 100: 963-992.

Loubat H., 1965. Sur la présence de laves en coussins dans les ophiolites du Versoyen (Savoie). Arch. Sci. Genève, 18: 131-133.

Loubat H., 1968. Étude pétrografique des ophiolites de la « zone du Versoyen » (Savoie, France), Province d'Aoste, Italie). Arch. Sci. et C.R. Séances Soc. Phys. et Hist. Nat. Genève, 2: 265-457.

Loubat H., 1973. Soubassement des dorsales volcaniques océanique : modèle de réseau magmatique composite. Schweiz. Miner. Petrogr. Mitt., 53: 337-353.

Loubat H., 1975. La zone du Versoyen: témoin possible d'une intersection entre dorsale océanique et marge continentale. Arch. Sci. Genève, 28: 101-116.

Loubat H., 1984. Considération préliminaires sur la configuration horizontale de l'édifice subvolcanique du Versoyen, Alpes franco-italiennes) analogue aux bassins du type golfe de Californie. Géol. Alpine, 60: 37-44.

Loubat H. and Antoine P., 1965. Sur l'extension des laves en coussins dans la région du Petit-Saint-Bernard, frontière franco-italienne). Arch. Sci. et C. R. Séances Soc. Phys. et Hist. Nat. Genève, 18: 689-692.

Loubat H. and Delaloye M., 1984. La zone du Versoyen, Alpes franco-italiennes : le témoin d'une océanisation mésozoique circonscrite constituant un milieu hybride, subvolcanosedimentaire avec mobilisats et adinoles. Géol. Alpine, 60: 45-76.

Malusà M.G., Faccenna C., Baldwin S.L., Fitzgerald P.G., Rossetti F., Balestrieri M.L., Danišík M., Ellero A., Ottria G. and Piromallo C., 2015. Contrasting styles of (U) HP rock exhumation along the Cenozoic Adria-Europe plate boundary (Western Alps, Calabria, Corsica). Geochem. Geophys. Geosyst., 16: 1786-1824.

Manatschal G., 1999. Fluid- and reaction- assisted low-angle normal faulting: evidence from rift- related brittle fault rocks in the Alps, Err Nappe (eastern Switzerland). J. Struct. Geol., 21: 777-793.

Manatschal G., 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. Int. J. Earth Sci., 93: 432-466.

Manatschal G., Engström A., Desmurs L., Schaltegger U., Cosca M., Müntener O. and Bernoulli D., 2006. What is the tectono-metamorphic evolution of continental break-up: the example of the Tasna Ocean-Continent Transition. J. Struct. Geol., 28: 1849-1869.

Manatschal G. and Müntener O., 2009. A type sequence across an ancient magma-poor ocean-continent transition: the example of the western Alpine Tethys ophiolites. Tectonophysics, 473: 4-19.

Manatschal G., Sauter D., Karpoff A.M., Masini E., Mohn G. and Lagabrielle Y., 2011. The Chenaillet Ophiolite in the French/Italian Alps: An ancient analogue for an Oceanic Core Complex? Lithos, 124: 169-184.

Masson H., 2002. Ophiolites and other, ultra-basic rocks from the West-Central Alps: new data for a puzzle. Bull. Soc. Vaudoise Sci. Nat., 88: 263-276.

Masson H., Bussy F., Eichenberger M., Giroud N., Meilhac C. and Preisniakov S., 2008. Early Carboniferous age of the Versoyen ophiolites and consequences: nonexistence of a "Valais ocean" (Lower Penninic, Western Alps). Bull. Soc. Géol. Fr., 4: 337-355.

Mugnier J.L., Cannic S. and Lapierre H., 2008. The tholeiites of the Valaisan domain (Versoyen, western Alps): A Carboniferous magma emplaced in a small oceanic basin. Bull. Soc. Géol. France, 179: 357-368.

Mugnier J.L., Loubat H. and Cannic S., 1993. Correlation of seismic and geology at the boundary between internal and external domains of the western Alps. Bull. Soc. Géol. France, 16: 607-708.

Nabholz W. and Trümpy R., 1954. Sur le lambeau du Versoyen - Petit Saint Bernard. C. R. Soc. Géol. Fr., 16: 1-481

Niggli E. and Coworkers, 1978. Metamorphic map of the Alps 1:1.000.000 and explanatory text. Subcomm. Carthography metam. Belts of the World, Unesco, Leiden, p. 181-242.

Oberhänsli R., Bousquet R. and Goffé B., 2003. Comment to "Chloritoid composition and formation in the eastern central Alps: a comparison between Penninic and Helvetic occurrences". Schweiz. Miner. Petrogr. Mitt., 83: 341-344.

Oberhänsli R., Goffé B. and Bousquet R., 1996. Record of a HP-LT metamorphic evolution in the Valais zone: geodynamic implications. Boll. Mus. Reg. Sci. Nat. (Torino), 12: 221-239.

Pastorelli S., Martinotti G., Piccardo G.B., Rampone E. and Scambelluri M., 1995. The Geisspfad complex and its relationship with the Monte Leone nappe (Lower Pennine, Western Alps). In: R. Polino and R. Sacchi (Eds.), Atti Conv. Rapporti Alpi-Appennino. Accad. Naz. Sci., Scritti e Docum., 14: 349-358.

Peola P., 1903. Appendice paleontologica sulla flora del Piccolo San Bernardo. Mem. Descr. Carta Geol. It., 12: 207-226.

Péron-Pinvidic G. and Manatschal G., 2009. The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: a new point of view. Int. J. Earth Sci., 98: 1581-1597.

Piccardo G.B., 2011. The evolution of the lithospheric mantle during Mesozoic rifting in the Ligure-Piedmontese Domain. In: M. Beltrando, A. Peccerillo, M. Mattei, S. Conticelli and C. Doglioni (Eds.), The Geology of Italy. J. Virt. Expl., 36 (7), doi: 10.3809/jvirtex.2009.00219.

Possenot C., 1912. Le Westphalien moyen dans la zone axiale alpine. C.R. Acad. Sci., 155: 1564-1567.

Ribes C., Ghienne J.-F., Manatschal G., Dall'Asta N., Stockli D.F., Galster F., Gillard M. and Karner G.D., 2020. The Grès Singuliers of the Mont Blanc region (France and Switzerland): stratigraphic response to rifting and crustal necking in the Alpine Tethys. Int. J. Earth Sci., 109: 2325-2352. https://doi.org/10.1007/s00531-020-01902-z.

Ribes C., Ghienne J.-F., Manatschal G., Decarlis A., Karner G.D., Figueredo P.H. and Johnson C.A., 2019a. Long-lived mega fault-scarps and related breccias at distal rifted margins: insights from present-day and fossil analogues. J. Geol. Soc., 176: 801. https://doi.org/10.1144/jgs2018-181.

Ribes C., Manatschal G., Ghienne J.-F., Karner G.D., Johnson C.A., Figueredo P.H., Incerpi N. and Epin M.-E., 2019b. The syn-rift stratigraphic record across a fossil hyper-extended rifted margin: the example of the northwestern Adriatic margin exposed in the Central Alps. Int. J. Earth Sci., 108: 2071-2095. https://doi.org/10.1007/s00531-019-01750-6.

Ribes C., Petri, B., Ghienne J.-F., Manatschal G., Galster F., Karner G.D., Figueredo P.H., Johnson C.A. and Karpoff A.-M., 2019c. Tectono-sedimentary evolution of a fossil ocean-continent transition: Tasna nappe, central Alps (SE Switzerland). GSA Bull., 132: 1427-1446. https://doi.org/10.1130/B35310.1.

Rollet N., Déverchère J., Beslier M.-O., Guennoc P., Réhault J.-P., Sosson M. and Truffert C., 2002. Back arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, Western Mediterranean. Tectonics, 21: 1-23. 10.1029/2001TC900027

Saliot P., 1978. Le métamorphisme dans les Alpes françaises. PhD. Thesis, Univ. Paris-Sud, p. 1-183.

Saliot P., 1979. La jadéite dans les Alpes françaises. Bull. Soc. Fr. Min. Crist., 102: 391-401.

Schärer U., Cannic S. and Lapierre H., 2000. Preliminary evidence for a Hercynian age of the Versoyen complex, Western Alps. C.R. Acad. Sci. Paris, 330: 325-332.

Schmid S.M., Fügenschuh B., Kissling E. and Schuster R., 2004. Tectonic map and overall architecture of the Alpine orogen. Ecl. Geol. Helv. 97: 93-117. https://doi.org/10.1007/s00015-004-1113-x.

Schmid S.M., Kissling E., Diehl T., van Hinsbergen D.J.J. and Molli G., 2017. Ivrea mantle wedge, arc of the Western Alps, and kinematic evolution of the Alps-Apennines orogenic system. Swiss J. Geosci., 110: 581-612. https://doi.org/10.1007/s00015-016-0237-0.

Schoeller H., 1927. La nappe de l'Embrunais en Tarentaise, au nord de l'Isère et son prolongement en Italie et en Suisse (note préliminaire). Bull. Soc. Géol. Fr., C.R., 27: 77-88.

Schoeller H., 1928. La Zone du Petit Saint Bernard en France. Bull. Soc. Géol. Fr., C.R., 28 (5): 62-64.

Schoeller H., 1929. La nappe de l'Embrunais au Nord de l'Isère. Bull. Carte Géol. Fr., 33: 1-422.

Schoeller H., 1947. Sur la présence de Crétacé supérieur dans la zone des conglomérats de Tarentaise, au Nord de l'Isère. C.R. Soc. Géol. Fr., 6: 1-123.

Schürch M.L., 1987. Les ophiolites de la Zone du Versoyen: témoin d'un bassin à évolution métamorphique complexe. Thèse doct., Univ. Genève, p. 1-157.

Schürch M.L., Bertrand J., Chessex R. and Loubat H., 1986a. Présence de l'omphacite dans la zone du Versoyen (Alpes franco-italiennes): implications structurales. 4^{e} réunion groupe tect. Suisse, Genève, déc. 1986, Abstr.

Schürch M.L., Bertrand J. and Loubat H., 1986b. Présence de ferroaxinite dans la série volcano-sédimentaire de la Zone du Versoyen (Savoie, France, et province d'Aoste, Italie). Schweiz. Miner. Petrogr. Mitt., 66: 267-280.

Sodero D., 1968. Sull'età Barremiano-Aptiana delle formazioni basali del "Flysch" della Zona delle Brecce di Tarantasia in Valle d'Aosta. Boll. Soc. Geol. It., 87: 223-231.

Stampfli, G.M., 1993. Le Briançonnais, terrain exotique dans les Alpes? Ecl. Geol. Helv., 86: 1-45.

Staub R., 1958. Klippendecke und Zentralalpenbau, Beziehungen und Probleme. Beitr. Geol. Karte Schweiz, 103: 1-184.

Sturani C., 1973. Considerazioni sui rapporti tra Appennino settentrionale ed Alpi Occidentali. In: Atti Convegno "Moderne vedute sulla Geologia dell'Appennino", Acc. Naz. Lincei, 183: 119-142.

Termier P., 1928. Le pays de nappes des Alpes françaises. C.R. Acad. Sci. Paris, 186: 1-113.

Trümpy R., 1954. La zone de Sion-Courmayeur dans la haut Val Ferret valaisan. Ecl. Geol. Helv., 47: 315-359.

Trümpy R., 1955. Remarques sur la corrélation des unités penniques externes entre la Savoie et le Valais et sur l'origine de la nappe des Préalpes. Bull. Soc. Géol. Fr., 6: 217-231.

Trümpy R., 1980. Geology of Switzerland: a guide book. Part A. An outline of the Geology of Switzerland, with contrib. by D. Bernoulli, M. Grünenfelder, V. Köppel, S. Müller and V. Tromsdorff. Wepf and Co. Ed., Basel, p. 1-104.

Tugend J., Gillard M., Manatschal G., Nirrengarten M., Harki, C., Epin M.-E., Sauter D., Autin J., Kusznir N. and McDermott K., 2020. Reappraisal of the magma-rich versus magma-poor rifted margin archetypes. Geol. Soc. London Spec. Publ., 476: 23. https://doi.org/10.1144/SP476.9.

Vannucchi P., Morgan J.P., Polonia A. and Molli G., 2020. The life cycle of subcontinental peridotites: From rifted continental margins to mountains via subduction processes. Geology, 48: 1154-1158. https://doi.org/10.1130/G47717.1.

Villa I.M., Bucher S., Bousquet R., Kleinhanns I.C. and Schmid S.M., 2014. Dating polygenetic metamorphic assemblages along a transect across the Western Alps. J. Petr., 55: 803-830.

Vitale Brovarone A., Beltrando M., Malavieille J., Giuntoli F., Tondella E., Beyssac O., Groppo C. and Compagnoni R., 2011. Inherited ocean-continent transition zones in deeply subducted terranes: insights from Alpine Corsica. Lithos, 124: 273-290.

Vitale Brovarone A., Piccoli F., Frasca G. and Giuntoli F., 2021. Fresh mantle peridotites from the lawsonite eclogite-facies San Petrone unit, Alpine Corsica. Ofioliti, this volume.

Vuagnat M., 1956. Sur les roches à stilpnomélane du Versoyen, Savoie. Arch. Sci. (Genève), 9: 321-325.

Zaccagna D., 1888. Sulla geologia delle Alpi Occidentali. Boll. R. Com. Geol. It., 11-12,

Zulauf R., 1963. Zur Geologie der tiefpenninischen Zonen nördlich der Dora Baltea im oberen Val d'Aosta (Italien). Promotionsarbeit ETH Zürich, p. 1-151.

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