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Paleo-European crust of the Italian Western Alps: Geological history of the Argentera Massif and comparison with Mont Blanc-Aiguilles Rouges and Maures-Tanneron Massifs

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Abstract

The “External Crystalline Massifs” of the Western Alps (Mont Blanc, Aiguilles Rouges, Grandes Rousses, Belledonne, Pelvoux, and Argentera) consist of a polymetamorphic Variscan basement, which was only marginally reworked during the Alpine tectonometamorphic cycle. These massifs experienced an early subduction event at peak metamorphic conditions of ~700°C and 1.5 GPa, followed by continental collision coupled with amphibolite-facies metamorphism, anatexis and exhumation to shallow crustal levels in the Carboniferous (see von Raumer et al., 1999 for a review).

This contribution focuses on the magmatic and metamorphic history of the Argentera Massif, the southernmost and largest of the External Crystalline Massifs exposed in Italy. Its evolution from Ordovician to Early Permian is compared to that recorded in the Mont Blanc-Aiguilles Rouges Massif, the other External Crystalline Massif extensively exposed in the Italian Alps. Further comparison is drawn between these large massifs and the Maures-Tanneron Massif of Provence, France, the area of Variscan Europe nearest to Argentera.

Keywords: Variscan crust, External Crystalline Massifs, H*P* granulite, migmatite, geochronology.

Introduction

The Variscan orogeny (~ 380–300 Ma) is the geological event most largely represented in the basement of the European continent. It was assembled between Ordovician and Carboniferous from the larger collision of Gondwana with the northern plate of Laurentia–Baltica, which involved the microplates of Avalonia and Armorica (Matte, 2001). Variscan units (Fig. 1) extend from the Ibero-Armorican block of southern Spain to the Bohemian Massif of Poland. Large remnants of Variscan basement are preserved in the southern Variscides, within the Alpine chain, where they are located in external positions (Fig. 1). In the Western Alps, such remnants are identified as External Crystalline Massifs (Mont Blanc, Aiguilles Rouges, Grandes Rousses, Belledonne, Pelvoux, and Argentera), which record the general evolution common to all Pangean Europe (von Raumer et al., 2009). They are generally composed of a complex metamorphic basement intruded by Permo-Carboniferous granitoids. In these Massifs, the Alpine metamorphic overprint is weak and commonly limited to shear zones. The exhumation of the External Crystalline Massifs from below their sedimentary cover units and the Alpine nappes initiated in the Miocene (Argentera: Bigot-Cormier et al., 2006), i.e. at the end of the Alpine orogeny
< Figure 1>

Argentera Massif

The Argentera Massif, the southernmost of the External Crystalline Massifs, straddles the boundary between Italy and France in the Maritime Alps of NW Italy and is largely composed of Variscan migmatites with abundant relicts of pre-anatectic rock types. It is an elliptical area of 60x30 km, trending WNW-ESE, with rugged relief and mountain tops of 2800-3000 m in the NW and 3100-3300 m in the centre (Figs. 2a and b). The Argentera Massif consists of the Gesso-Stura-Vésubie (GSV) Terrane to the NE and of the Tinée Terrane to the SW, which are separated by the Ferriere-Mollières shear zone (Fig. 3). The two terranes are characterized by distinct lithological associations and metamorphic evolutions, but both contain rare relicts of high-pressure (H*P*) and/or high-temperature (H*T*) mineral assemblages, which are commonly preserved within mafic rocks and exceptionally within metapelites.

Modern geological maps of the Argentera Massif (Faure-Muret, 1955; Malaroda et al., 1970; Malaroda, 1999) provide accurate lithological information, but fail to describe a coherent lithostratigraphy for the GSV Terrane. Such maps still use the now abandoned terminology of metamorphic rocks and migmatites of the French metasomatic school (Jung & Roques, 1952).

< Figure 2>

Gesso-Stura-Vésubie Terrane

This part of the Massif corresponds to the Malinvern-Argentera Complex of Malaroda et al. (1970) and comprises the Malinvern-Argentera and Chastillon-Valmasque complexes of Faure-Muret (1955).

< Figure 3>

The GSV Terrane (Fig. 3) mainly consists of migmatitic granitic gneiss—the “anatexites” of Malaroda & Schiavinato (1958) and Malaroda et al. (1970)—and of migmatitic paragneisses. Field relationships at the outcrop scale (Figs. 4a and b) suggest that at least a part of the “anatexites” were intrusive into the paragneiss sequence. The metasediments now appear as km-long bands in the granite gneiss, for example in the Rio Freddo valley (Bortolami & Sacchi,1968), but the intrusive contacts have been transposed by the Variscan foliation. Small bodies and boudins of mafic (amphibolite, eclogite, granulite) and ultramafic rocks are common in the “anatexites”, and are more rarely exposed in the paragneisses of the GSV Terrane. Intercalations of marble and calc-silicate rocks are rare, and may contain wollastonite in addition to diopside and grossular (Calisesi, 1971). Dacitic to rhyodacitic metavolcanic rocks with transitional contacts to the surrounding “granitoid” migmatites have been locally recognized in the central and southern GSV Terrane (e.g., Rubatto et al., 2001). The eastern GSV Terrane is characterized by the Bousset-Valmasque Complex (Rubatto et al., 2001), which consists of a close association of amphibolites, agmatites with amphibolite fragments, and migmatites with amphibole-bearing anatectic granite.

Carboniferous to Permian granitoids are present in the GSV Terrane, the largest pluton being the Central Granite (Fig. 3).

In the following, we briefly describe, from the oldest to the youngest, the most significant lithologies of the GSV Terrane, and summarize the information available on its geological history.

< Figure 4>

Relicts of H*P* mafic rocks

The most significant mafic bodies of the GSV Terrane are exposed in three localities (Fig. 3): 1) Laghi del Frisson, where a varied mafic sequence mainly consists of HP granulites (Figs. 5a and b); 2) Val Meris, where a large body of eclogite and retrogressed eclogite is surrounded by “anatexites” (Colombo, 1996; Rubatto et al., 2001); 3) Lago di Nasta, where amphibolitized eclogite and possibly HP granulite are both exposed (Fig. 5c). U-Pb dating on zircons suggests protolith ages for the mafic intrusions ranging between 459 ± 4 Ma (Meris eclogite, Rubatto et al., 2001) and 486 ± 7 Ma (Laghi del Frisson, Rubatto et al., 2010). Ordovician (480-460 Ma) mafic rocks, usually overprinted by low-P metamorphism, are disseminated within the External Crystalline Massifs (Ménot & Paquette, 1993; Rubatto et al., 2001; Guillot & Ménot, 2009) and, as in the Argentera, occur as relatively small bodies within the migmatitic basement.

The Laghi del Frisson mafic sequence (Fig. 5a), exposed in a tectonic window within the Helvetic-Dauphinois sedimentary cover (Fig. 3), forms a lens-shaped body, about 200 m thick and 500 m long, surrounded bybiotite-bearing migmatites of broadly granitic composition (‘‘biotite anatexite’’of Malaroda et al., 1970). First mapped and described as ‘‘garnet–pyroxene gneiss’’ byCampanino (1962 in Malaroda et al., 1970), the sequence is characterized by a compositional layering that mainly consists of alternating mm- to dm-thick mafic layers of green-brownish Pl-poor and gray-whitish Pl-rich H*P* granulite. The rocks of the sequence are medium- to fine-grained, do not show evidence of partial melting, and are characterized by a pervasive mylonitic foliation parallel to the compositional layering (Colombo et al., 1994; Ferrando et al., 2008; Fig. 5b). The sequence shows a high degree of crustal contamination (Rubatto et al., 2010). This chemical signature is common to other Ordovician mafic rocks exposed in the other External Crystalline Massifs, though these are often associated with Si-rich magmas, which are lacking in the Laghi del Frisson sequence. The systematic and repeated interlayering of the two main compositional types and their geochemical characteristics are inherited from a magmatic protolith, most likely a mafic layered intrusion. The original igneous layers were strongly reworked and folded by a pervasive mylonitic deformation, locally observed all through the GSV Terrane and predating widespread migmatization in the Late Carboniferous (see below). Lack of migmatisation of the mafic sequence is attributed to its more refractory composition when compared to the surrounding migmatites (Ferrando et al., 2008).

< Figure 5>

Both the Pl-poor and Pl-rich H*P* granulites contain several generations of minerals which, coupled with thermobarometric data, define four metamorphic stages (Fig. 6; Ferrando et al., 2008). The H*P* granulite-facies peak (stage A: 735 ± 15 °C, ~ 1.38 GPa) is recorded in the core of porphyroclastic garnet and omphacite in association with plagioclase, rutile ± amphibole ± quartz. The first decompression (stage B: ~ 710 °C and 1.10 GPa) corresponds to the rim of porphyroclastic garnet and omphacite in equilibrium with a second generation of plagioclase, rutile ± amphibole ± quartz. Mylonitization (stage C) is marked by neoblastic garnet, diopside, plagioclase, titanite ± amphibole ± quartz, and occurred at amphibolite-facies conditions, i.e. pressures of 0.85 GPa and still relatively H*T* (665±15 °C). Finally, during stage D ($500 < T < 625$ °C; $P < 0.59$ GPa) plagioclase + amphibole symplectites replaced the rim of garnet and clinopyroxene. The evolution and peak metamorphic conditions recorded by the Laghi del Frisson mafic sequence are similar to those recorded by the Meris eclogite (T ~ 750°C and P ~ 1.5 GPa; Colombo, 1996; Rubatto et al., 2001). Based on the common metamorphic conditions, Ferrando et al. (2008) concluded that the Laghi del Frisson H*P* granulites and the Meris eclogite underwent the same metamorphic cycle and that the two rock types preserve different peak assemblages only because of their different bulk chemical composition.

< Figure 6>

Geochronology of H*P* rocks from the Argentera was first attempted by Paquette et al. (1989) using the zircon isotope-dilution TIMS technique on garnet amphibolites with relict eclogitic garnet from the Argentera Massif and eclogites from the Belledonne and Aiguilles Rouges Massifs. They obtained mainly discordant data, whose upper and lower intercepts are of difficult interpretation. In most samples, no age constraints on the HP metamorphism were obtained, but for the Argentera Massif a lower intercept of 424±4 Ma from an amphibolite was proposed as the age of H*P* metamorphism. Notably, a second mafic rock from the same area returned an upper intercept at ~350 Ma with a meaningless lower intercept. More recently, Carboniferous ages at ~340 Ma were obtained for zircon rims in the Frisson Pl-rich H*P* granulite and sector zoned zircons of the Pl-poor H*P* granulite (340.7 ± 4.2 and 336.3 ± 4.1 Ma, respectively: Rubatto et al., 2010). Several lines of evidence constrain the formation of the Carboniferous zircon rims to before mylonitization stage C and, possibly, during stage A: 1) the HREE depletion in the zircon rims is in line with formation, before or during zircon crystallization, of metamorphic garnet that sequestrated HREE from the reactive bulk rock (Rubatto, 2002); 2) the zircon rims lack a significant negative Eu anomaly, which is also absent in the other peak metamorphic minerals such as omphacite, garnet and plagioclase; 3) Ti-in-zircon thermometry indicates temperatures of at least 700–770 °C, which are within that reported for the H*P* peak of stage A, but generally higher than those of the first retrogression of stage B; 4) the Carboniferous zircon domains show evidence of intense deformation, likely related to the mylonitic stage.

Metavolcanic rocks

The presence of dacitic to rhyodacitic metavolcanic rocks at Cima Ghiliè-Testa della Rovina and in Val Meris (Fig. 3) is reported by Romain (1982, p.30), Ghiglione (1990), Bierbrauer (1995), Colombo (1996) and Rubatto et al. (2001). The Cima Ghiliè metadacite is undeformed, preserves a porphyritic structure and contains granulite-facies xenoliths. This rock type shows progressive deformation to foliated metadacite (Fig. 7), and transitional contacts to the surrounding migmatites. The undeformed metadacite preserves phenocrysts of quartz, plagioclase, K-feldspar, biotite and altered cordierite (Colombo et al., 1993). The microcrystalline matrix consists of quartz, feldspars and aggregates of biotite + quartz that probably derived from former xenocrysts of granulite-facies orthopyroxene. The metadacite contains pink, euhedral zircons with composite cores, with variable zoning, and oscillatory-zoned overgrowths. The cores yielded concordant U-Pb ages at 560 Ma, 600 Ma and 700 Ma, respectively. The SHRIMP analyses of the oscillatory-zoned overgrowths yielded a mean $^{206}Pb/^{238}U$ age of 443 ± 3 Ma (Rubatto et al., 2001).

< Figure 7>

The rocks described in the SE GSV Terrane as “pseudoporphyric gneisses” by Malaroda (1991; 1999), though more deformed and recrystallized, appear to be similar to the Ghiliè metadacite both in structure and composition, and are indicated with the same symbol in Fig. 3. Part of the “leptynites”, reported especially in the NW of the GSV Terrane in the map of Malaroda et al. (1970), are possibly also derived from recrystallized acid metavolcanics.

Migmatitic paragneisses and migmatitic granitic gneiss

A striking feature of the GSV Terrane is the abundance and variety of migmatites (Malaroda, 1968), formed from granitic (“anatexites” Auct.), pelitic (Fig. 8a) and mafic protoliths. The bulk composition of the “anatexites” is homogeneously granitic (Faure-Muret, 1955; Malaroda & Schiavinato, 1957a; De Pol, 1966; Blasi & Schiavinato 1968). These rocks generally lack structural relicts of the igneous protolith. A notable exception are the “augen anatexite” and “augen embrechite” (Fig. 8b; Malaroda et al., 1970), which are likely derived from the Late Ordovician porphyritic granitoids that have been extensively documented in the pre-Variscan basement of the External Crystalline Massifs (e.g. Aiguilles Rouges: Bussy & von Raumer, 1993).

< Figure 8>

Although a discussion on the protoliths and genesis of the GSV migmatites is outside the scope of this review, we note that leucosomes in the migmatitic paragneiss and migmatitic granitic gneiss have mineral assemblages compatible with the main amphibolite-facies metamorphic stage recorded in the whole GSV Terrane. Specifically, the mineral assemblage observed in metapelites of the upper Val Gesso (Compagnoni et al., 1974; Bierbrauer, 1995; Prever, 1997)—i.e. quartz-plagioclase (An_{20-30})-biotite-fibrolitic sillimanite-cordierite with scarce K-feldspar and muscovite—and the relict kyanite and garnet rarely included in plagioclase suggest P-T conditions of the upper amphibolite-facies (650–700°C; 0.4–0.6 GPa) and decompression from higher P, respectively. In the migmatitic granitic gneiss, more rarely in migmatitic paragneisses, the end products of partial melting are pockets and larger bodies of a fine-grained muscovite-biotite granite [“granito aplitico microgranulare di anatessi” (fine grained aplitic anatectic granite) of Malaroda et al. (1970)] and quartzo-feldspathic pods and dykes that commonly contain large crystals of pinitized cordierite (Fig. 9).

The L*P* metamorphism and partial melting in the GSV Terrane are not directly dated, but a Late- to Mid-Carboniferous age for migmatization (≤ 323 ± 12 Ma) has been proposed on the basis of a zircon lower intercept age obtained from the Meris eclogite (Rubatto et al., 2001).

< Figure 9>

The Bousset-Valmasque Complex

The Bousset-Valmasque Complex was named “Entracque-Tenda Granite” by Roccati (1925) and “Granite à enclaves de la Valmasque” by Faure-Muret (1955). It consists of amphibole migmatite and amphibole-bearing anatectic granite that contains enclaves of amphibolite and ultramafics of angular or rounded shape, with size from a few cm to a few meters (Fig. 10). The Complex comprises two E-W directed subvertical bands separated by the Alpine Fremamorta-Colle del Sabbione shear zone (Fig. 3). The N band extends to a maximum thickness of ~ 5 km between Lago Brocan and the Bousset valley, whereas the S band extends to a maximum thickness of 1 km in the Gelas-Clapier ridge between the Gesso della Barra valley and the upper Valmasque. As noted by Roccati (1925) and Faure-Muret (1955), a noteworthy feature of the Bousset-Valmasque Complex is the great variety of mafic-ultramafic enclaves (including rare eclogite and metagabbro) (Fig. 10a), some of which were studied by Faure-Muret (1955) and Boucarut (1969). The igneous appearance and the lack of deformation of the Valmasque granite suggest either a peak anatectic origin linked to the Late Carboniferous metamorphic event or a post-metamorphic emplacement. However, no geochronological or modern petrological data exist to constrain the age and igneous/metamorphic history of the Bousset-Valmasque Complex.

< Figure 10>

Carboniferous-Permian magmatic rocks

Late Variscan plutonic bodies are widespread in the External Crystalline Massifs of the Alps. The age of emplacement, Mg/(Fe + Mg) ratio, and mafic mineral content allow to recognise two plutonic suites: an earlier, Visean (~ 330–340 Ma) and Mg-rich suite, and a later suite, mainly Stephanian (~ 295–305 Ma) and richer in Fe (Debon & Lemmet, 1999).

In the Argentera Massif, rocks belonging to the Visean plutonic suite occur as small bodies and dykes of metamonzonite in the central part of the GSV Terrane, e.g. on the N slope of the Cima dei Gélas and in the upper Valmasque (Figs. 3 and 11). Such rocks were first reported by Roccati (1925) as "pyroxene-bearing porphyritic gneiss" and were later mapped as "biotite-amphibole embrechites" by Malaroda et al. (1970). One of the largest metamonzonite outcrops is exposed near the Muraion glacier, N of Cima dei Gelas. Here the plutonic rock, though showing evidence of incipient migmatization, well preserves the original igneous fabric and mineralogy. The magmatic assemblage consists of cm-sized euhedral crystals of K-feldspar and minor plagioclase in a medium-grained mineral aggregate, which contains relicts of magmatic clinopyroxene that are partly replaced by amphibole and biotite. U-Pb SHRIMP analyses of zircons from this rock yielded a concordant age of 332 ± 3 Ma (Rubatto et al., 2001).

< Figure 11>

The Stephanian magmatic suite is represented in the GSV Terrane by the Central Granite, a large pluton straddling the boundary between Italy and France in the upper Gesso and Vésubie valleys, and by a minor leucogranite body in the upper Valle Stura (Brondi, 1958; Malaroda et al., 1970, and references therein). The Central Granite is a shallow pluton cutting across the regional metamorphic foliation of country rocks. It was emplaced through magmatic stoping at shallow crustal levels after the Variscan amphibolite-facies metamorphism and anatexis (Boucarut, 1967). Contact metamorphism of the surrounding rocks produced both andalusite and sillimanite (Compagnoni et al., 1974). The Valle Stura leucogranite, on the other hand, is parallel to the regional foliation trend of country rocks, though probably discordant at the outcrop scale.

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al., 1974). The Valle Stura leucogranite, on the other hand, is parallel to the regional foliation trend of country rocks, though probably discordant at the outcrop scale.

The emplacement age of the Central Granite is constrained by Rb-Sr ages on magmatic muscovites (Ferrara & Malaroda, 1969) at 292 ± 10 Ma (av. of 4 analyses), whereas a cooling age at ca 296-299 Ma was proposed on the basis of ^{40}Ar/^{39}Ar single grains muscovite analyses from the granite (Corsini et al., 2004). The emplacement age of the Valle Stura leucogranite is only constrained by a single Rb/Sr muscovite age from a dyke from Bagni di Vinadio at 299 ± 10 Ma (Ferrara & Malaroda, 1969).

A probably younger suite of intrusive rocks is represented by quartz-porphyry dykes with large crystals of Kfeldspar exposed on the W ridge of Cima del Dragonet, E of Terme di Valdieri (Franchi 1894; Malaroda et al., 1970). Early Permian-Late Carboniferous basalt-andesite pyroclastics and lava flows are reported from the SE of the GSV Terrane (Romain, 1978), in particular from the Vallon de Figuière Unit (Malaroda ,1999). The widespread swarms of basalt-andesite rocks [“porfiriti anfibolico-plagioclasiche, talora quarzifere” (locally quartzbearing plagioclase-amphibole porphyrites) of Malaroda et al. (1970)] that cut across the Central Granite and its country rocks are possibly related to this young volcanism.

Carboniferous sedimentary sequences

Late Carboniferous sediments (conglomerates, sandstones, fossiliferous black schists) are reported from synforms in the GSV gneisses of the upper Vésubie valley (Fig. 3) by Faure-Muret (1955, and references therein) and Haudour et al. (1958). Plant fossils indicate a Westphalian D-Stephanian A age (Faure-Muret, 1955; Haudour et al., 1958). Deposition of these sediments marks the final exhumation of the GSV Terrane after the Variscan orogeny.

Unfossiliferous metasediments of presumed Late Carboniferous age (mollieresite Auct.) are described in the area between the Mollières valley and Saint Martin Vésubie (Faure-Muret, 1955; Malaroda et al., 1970). The mollieresite is lithologically similar to the fossiliferous Late Carboniferous—as it consists of conglomerates, sandstones and graphitic schists—but is affected by low-grade metamorphism (Bortolami et al., 1974).

Ferriere–Mollières shear zone

The Ferriere–Mollières shear zone represents the main shear zone cutting the Paleozoic basement in the western portion of the Argentera Massif. It strikes NW–SE and extends from Ferriere (Valle Stura) to the northwest, to Mollières to the southeast. Mylonitic rocks, which are unconformably covered by the Triassic sediments in the Ferriere area, almost continuously crop out along the Ferriere–Mollières shear zone with a thickness ranging from 100 to 1000 m (Fig. 3). These mylonites have been interpreted by Bogdanoff (1986) as a sequence including both metasedimentary rocks ("Micaschistes de La Valetta") and mylonites derived from high-grade metamorphic rocks of both the Tinée and GSV terranes.

In a typical section of the Ferriere–Mollières shear zone between Colle di Stau and Rocco Verde (Valle Stura), mylonites reach a thickness of nearly 1 km (Musumeci & Colombo, 2002). Foliations strike N140–150E and show upright attitude or dip strongly toward northeast or southwest. Mineral lineations are defined by elongated grains of quartz or feldspar, which have a dominant subhorizontal trend, or gently plunge (20°) toward northwest. The mylonites include small bodies of foliated, mica-rich quartzites ["Quarziti del Pebrun" ("Pebrun quartzites") of Malaroda et al., 1970], amphibolites and marbles. In the Rocco Verde section, the Ferriere–Mollières mylonites are interleaved with dm- to m-thick ultramylonitic and phyllonitic layers. In mylonites and phyllonites, foliations dip strongly toward southwest and mineral lineations or slickenside striae are subhorizontal or gently dipping toward northwest. Mylonitic mineral assemblages are indicative of low- to very low-grade metamorphic conditions, whereas the porphyroclasts are derived from high-grade gneiss.

Mylonitic muscovite-bearing leucogranites crop out as subvertical northwest-trending intrusions in the northern portion of the Ferriere–Mollières shear zone. A Rb/Sr muscovite – whole rock age of 327±3 Ma on foliated leucogranite gives a lower limit for the age of mylonitic deformation for which kinematic indicators indicate a dextral sense of shear. This strike-slip tectonics is compatible with the extensional regime that occurred during Carboniferous across western Europe (Musumeci & Colombo, 2002).

Tinée Terrane

The Tinée terrane has been subdivided by Faure-Muret (1955) into three metamorphic formations (Fig. 3): the metasedimentary Varélios-Fougieret, the Anelle-Valabres (see also: Prunac, 1976) and the Rabuons lithological Formations. Part of the Rabuons Formation is exposed on the Italian side of the Argentera Massif in the upper part of side valleys joining the Stura River from Ferriere to Bagni di Vinadio (Malaroda et al., 1970). Lithologies in this area were grouped into two sequences, the Corborant - and Laroussa Series (Sacchi, 1961; De Pol ,1963), equivalent to the Rabuons and Anelle Formations of the French side, respectively.

< Figure 12>

The Anelle-Valabres and Rabuons Formations are less migmatitic than the GSV terrane (Fig. 12). The Rabuons migmatites (Fig. 12c) in particular contain a significantly smaller volume of neosome than the migmatites of the GSV. This neosome forms "augen" or ribbons of K-feldspar and plagioclase or muscovite-bearing granite (Sacchi, 1961; Malaroda, 1968, Tables I, II, III). Both Formations have relicts of more or less retrogressed eclogite (Faure-Muret, 1955; Malaroda et al., 1970). The Anelle-Valabres Formation also includes mafic granulites, coronitic metagabbros (Latouche & Bogdanoff, 1987; Fig. 3) and marbles (Prunac, 1976; Bogdanoff, 1980). In addition to muscovite related to regional metamorphism, the Anelle-Valabres Formation also contains sillimanite and late kyanite (Fig. 12a). The Rabuons Formation contains muscovite and sillimanite, with scarce kyanite present as relicts in gneisses (Faure-Muret, 1955; Bogdanoff, 1980, 1986) and in quartz veins (Pierrot et al., 1974).

Peculiar amphibole migmatites [amphibole-bearing gneiss and dioritic gneiss ("gneiss anfibolici" and "gneiss dioritici") of Malaroda et al., 1970] that are somewhat similar to the Valmasque Granite, were reported by Franchi (1894, 1933) and Franchi & Stella (1930) in the Ferriere valley, at the NW tip of the Tinée Terrane. Similar migmatites also crop out further to the SE in the upper Bagni di Vinadio valley (Sacchi,1961).

The Tinée terrane is generally lacking large intrusive bodies. Minor intrusions are 1) the Iglière metagranodiorite (Fig. 12b), which was emplaced into the Anelle-Valabres Formation before the Variscan metamorphism and deformations (Bogdanoff & Ploquin 1980), and 2) a small body of aplitic granite and some discordant garnet-tourmaline-muscovite pegmatite dykes within the Rabuons Formation (Piccoli, 2002).

From his structural work in the upper Tinée valley, Bogdanoff (1980,1986) concluded that the Tinée Terrane records a long deformation history, with complex deformation in Late Proterozoic-Early Paleozoic times (D1). This phase was followed early in the Variscan cycle by H*P* metamorphism responsible for the formation of H*P* granulites and eclogites at the expense of basic rocks. A second deformation phase (D2) developed the regional foliation S2. The metamorphic overprint at amphibolite-facies conditions was accompanied by migmatisation. This metamorphism was synchronous with two deformation events at the megascopic scale: nappe stacking and recumbent folding of the Anelle and Rabuons Formations (D3), followed by verticalization of the earlier structures and upright folding at the hectometric scale (D4). A final deformation (D5) consisted of folds of variable style from metric to decametric scale and vertical shear zones, and did not modify significantly the earlier structures.

Time constraints on the evolution of the Tinée terrane are limited to $^{40}Ar/^{39}Ar$ data (Monié & Maluski 1983): muscovites from the Rabuons Formation yielded and age of 342 ± 7 Ma, the biotites from the Iglière metagranodiorite are as old as ~ 312-316 Ma, and amphiboles and biotites from the Rabuons gneiss were dated at ~ 299 and 283 Ma, respectively.

Mont Blanc – Aiguilles Rouges Massifs

The Mont Blanc, as the Argentera Massif, straddles the boundary between Italy and France in the NW Alps. Elevations in the Mont Blanc Massif are much higher than in the Argentera, culminating at 4810 m in Mont Blanc itself, the highest point in the European continent. This summary is largely based on an extensive compilation of previous works that can be found in von Raumer & Bussy (2004), in Bussy et al. (2001), and in the web site at:
http://www.unil.ch/webdav/site/igp/shared/stampfli_research/field_trips/field_trip1.pdf

The Mont Blanc Massif (Fig. 13) consists of a complex pile of tectonic units with contrasting peak P-T metamorphic conditions. These units are separated by major, steeply dipping NNE-SSW faults and/or mylonitic zones. Most of these tectonic contacts probably formed during the late Variscan strike-slip regime and were reactivated during the Alpine orogeny. One such fault is the faille de l'Angle ("Angle fault"; Fig. 13) that separates the Massif in two portions, each one with its sedimentary cover: an internal portion, essentially granitic, to the E, and a more composite external portion to the NW (Epard, 1990).

Unlike the Argentera, the Mont Blanc Massif mainly consists of Variscan granitic rocks, with only minor paragneiss sequences and Ordovician metagranitoids. Its pregranitic history may be better understood in the nearby Aiguilles Rouges Massif, where a polymetamorphic basement is extensively exposed (Fig. 13).

Like the Argentera, the Mont Blanc Massif was only marginally reworked during the Alpine tectonometamorphic cycle, developing low-T greenschist-facies mineral assemblages (albite, stilpnomelane, green biotite, epidote, actinolite: von Raumer & Bussy, 2004)

< Figure 13>

Polymetamorphic basement and Ordovician metagranitoids

According to the geochronology of its polymetamorphic basement, the Mont Blanc Massif underwent at least three orogenic cycles: Late Precambrian, Ordovician and Variscan (von Raumer et al., 1999).

Magmatic ages of ~ 450 Ma have been obtained from zircons of MORB-like H*P* mafic rocks (Paquette et al., 1989), and from S-type and I-type calc-alkaline metagranitoids ("Ordovician granitoids": Bussy & von Raumer, 1994). The "Ordovician granitoids" intruded detrital sequences (now paragneisses) of supposedly Late Precambrian to Ordovician age and mainly consisting of sandstones and graywackes, with minor carbonate intercalations and tholeiitic basaltic layers (von Raumer & Bussy, 2004). It has been suggested that flysch-type sediments enriched in Cr and Ni, which are associated to mafic rocks (now eclogites) and ultramafic rocks (Aiguilles Rouges), represent a former accretionary prism (von Raumer, 1998).

The subsequent H*P* event has not been precisely dated. Although observed in metapelites and paragneisses as relicts of staurolite and kyanite (the latter being sometimes rimmed with reaction coronas of cordierite and spinel), the H*P* assemblage (1.4 GPa and 700°C) is better preserved in the retrogressed eclogites of Lac Cornu (Aiguilles Rouges, Fig. 13; Liégeois & Duchesne, 1981). An isothermal decompression to ~700 °C and 0.8 GPa and a later amphibolite-facies overprint is preserved in retrogressed eclogites from Val Bérard, Aiguilles Rouges (Fig. 13; Schulz & von Raumer, 1993). Leucocratic rocks associated with some eclogitic boudins have been interpreted as early decompression melting products linked to the exhumation from HP conditions (von Raumer et al., 1996). A preliminary dating of zircons from one of these leucosome yielded an age of ~340 Ma (Bussy & Schaltegger, quoted by Bussy et al., 2001).

The paragneisses display a succession of deformation events attributed to the Variscan orogeny, with thrust tectonics (Dobmeier, 1998) and nappe stacking, which led to the development of Barrovian metamorphism (von Raumer et al. 1999). Metapelites of the Aiguilles Rouges experienced a typical Barrovian evolution, recording a clockwise P-T path characterized by sillimanite-bearing assemblages (biotite + plagioclase + quartz +sillimanite ± garnet ± cordierite ± muscovite ± K-feldspar) and by late stage andalusite found in quartz ± K-feldspar tension gashes (von Raumer, 1984). Metagraywackes and metagranites show evidence of partial melting of variable degree, ascribed to isothermal decompression during exhumation processes. Typical mineral assemblage of these migmatites is plagioclase + quartz + K-feldspar + biotite ± sillimanite ± muscovite ± garnet ± cordierite. A decompressional event is also documented in polymetamorphic paragneiss collected in the French part of the Mont Blanc Tunnel (Borghi et al., 1987), where an earlier amphibolite-facies mineral assemblage with garnet I, oligoclase, white mica I, is formed before the development of the Variscan regional foliation defined by biotite, white mica II, K-feldspar and garnet II. The thermal peak has been dated at 327 ± 2 Ma by U-Pb analyses on monazites from Lake Emosson micaschists (Fig. 13; Bussy et al., 2000). Monazite from a leucosome vein of a migmatitic greywacke at Lake Emosson yielded a crystallization age of 320 ± 1 Ma, whereas monazite from a migmatitic granite from the Mont Blanc Massif yielded 317 ± 2 Ma (Bussy et al., 2000). These ages are similar to that suggested by Rubatto et al. (2001) for migmatization of the Argentera GSV Terrane (≤ 323 ± 12 Ma) on the basis of a zircon lower intercept age obtained for the Meris eclogite.

Greenstone Unit and Visean volcano-sedimentary sequence

The SW part of the Aiguilles Rouges Massif (Fig. 13) is characterized by the presence of the so-called "Greenstone Unit" and of low grade metamorphic sediments and volcanics (Dobmeier, 1996; Dobmeier et al., 1999). The Greenstone Unit is composed of greenish, calc-alkaline volcanic rocks of rather low metamorphic grade (von Raumer & Bussy (2004), presumably representing an Early Paleozoic arc environment (Dobmeier et al., 1999), though a Devonian or Silurian age cannot be excluded (von Raumer & Bussy (2004). The low grade metasediments consist of variably deformed pelites, graywackes and sandstones (Bussy et al., 2001), which were metamorphosed at greenschist-facies conditions [chlorite zone, Dobmeier, 1996, 1998)] An Early Carboniferous deposition age was obtained using palynological data (Late Visean acritarchs, Bellière & Streel (1980). Meterthick bands of green metabasalts (Fe-basalts of E-MORB affinity; Dobmeier, 1996) and meta-andesite are found interlayered with the metagraywackes. These rocks possibly record Early Carboniferous transtension linked to the opening of the sedimentary basin and to the 330-340 Ma high-K magmatic pulse.

Carboniferous magmatism

Carboniferous magmatic rocks mainly consist of non-to weakly-metamorphosed intrusions, locally associated to subvolcanic rocks (Fig. 13). Three magmatic pulses are recognized in the Mont Blanc – Aiguilles Rouges area: a) high-K calc-alkaline to shoshonitic, b) peraluminous, and c) metaluminous, ferro-potassic and alkali-calcic (Bussy et al., 2001).

The high-K calc-alkaline to shoshonitic magmatism

The 330-340 Ma high-K calc-alkaline to shoshonitic event that is well known throughout the European Variscan belt is documented by the Pormenaz monzonite (333 ± 2 Ma; Bussy et al., 2000) and the Montées-Pélissier granite (331 ± 2 Ma; Bussy et al., 2000), both in the southwestern Aiguilles Rouges.

The Pormenaz monzonite was emplaced at shallow depth, along the transpressive border fault of the Visean volcano-sedimentary basin. The main facies is porphyritic to equigranular with pink or white cm-sized K-feldspar megacrysts in a dark grey-green amphibole-rich matrix. Euhedral crystals of brown titanite are clearly visible in hand specimen. Metre-sized bodies of durbachite are found as dark-green microgranular magmatic enclaves (von Raumer & Bussy, 2004).

Like the Pormenaz monzonite, the Montées-Pélissier granite was emplaced syntectonically along ductile shear zones during the transcurrent stage, and recorded the subsequent vertical movements during cooling (Dobmeier, 1996). It is a foliated fine-grained two-mica monzogranite, which hosts rare biotite-rich restites, mafic microgranular enclaves and biotite-bearing lamprophyres (von Raumer & Bussy, 2004). The lamprophyre-type mafic magmatism is systematically associated to the Mg-K granitoids: the isotopic composition of Sr, Nd and Hf, and the episodic zircon inheritance all point to an essentially high-K lithospheric mantle source, metasomatized during an earlier subduction event, mixed with variable amounts of lower crust material (von Raumer & Bussy, 2004).

The peraluminous magmatism

The second magmatic pulse is represented by peraluminous granites intruded simultaneously into the Aiguilles Rouges and Mont Blanc Massifs at ~ 307 Ma: the Vallorcine and Montenvers granites, and the Fully granodiorite, respectively (Fig. 13).

The Vallorcine granite (Aiguilles-Rouges Massif) is a syntectonic pluton, which intruded at 306.5 ± 1.5 Ma (Bussy et al., 2000) along a steeply dipping, NE-SW trending, dextral strike-slip shear zone. During Late Variscan, the Vallorcine granite was affected along its SE contact by intense low-T ductile shearing subsequently reworked during the Alpine orogeny. The Vallorcine intrusion is a typical S-type granite with Al-rich minerals, such as cordierite, muscovite and andalusite, abundant zircon inheritance and a crustal stable isotope signature (Brändlein et al., 1994). Two facies have been differentiated in the Vallorcine granite (Brändlein et al., 1994): 1) the topographically lower facies is a biotite-rich monzogranite hosting numerous enclaves (up to 30 cm in size), including xenoliths of country gneiss, hornfelses, micaceous restites with sillimanite and hercynite, cordierite-bearing leucogranites, and mafic microgranular enclaves; 2) the upper facies is finer grained, with less biotite and almost devoid of enclaves. Aplites and other types of dykes are concentrated within the wall rocks of the upper contact.

The peraluminous Montenvers granite (Mont Blanc Massif) was emplaced syntectonically at 307 ± 3 Ma (Bussy & von Raumer, 1994) as a sheet-like intrusion, similarly to the Vallorcine granite. It is a S-type granite now strongly deformed and often converted to a mylonitic leucocratic orthogneiss hosting both microgranular and restitic enclaves.

The Fully granodiorite (Aiguilles-Rouges Massif; Krummenacher, 1959) is a highly heterogeneous, coarse-grained granodiorite of migmatitic appearance (presence of Schlieren and nebulitic structures) and characterized by clots of pinitized cordierite, scattered K-feldspar megacrysts, and numerous small biotite-rich restitic enclaves. Cordierite-bearing leucogranitic dykes and stocks crosscut the main plutonic facies. The Fully granodiorite is a typical peraluminous, anatectic granitoid with a significant restitic component and abundant Al-rich minerals (garnet, cordierite, muscovite, hercynite). It might represent a deeper and less evolved equivalent of the Vallorcine granite. Micaschists, gneisses, marbles and amphibolites are found as dm-long xenoliths. Enclaves of magmatic rocks include microgranular quartz-diorite to granodiorite and angular to rounded pieces of fine- to coarse-grained gabbros up to one meter in size (Bussy et al., 2000). Zircon and monazite, extracted from granodiorite, leucogranite and gabbro, yielded ages of 307 ± 2 Ma for all these rock types (Bussy et al., 2000). Although solid at time of its incorporation into the anatectic mass, the gabbro enclaves are coeval with the acid magmatism, suggesting large-scale dehydration melting of crustal units in close association with mantellic magmas (von Raumer & Bussy, 2004). These field relations have been related to mantellic basic magmatism that was active at the time of crustal anatexis (bimodal magmatism: Bussy et al., 2001).

The metaluminous, ferro-potassic, alkali-calcic magmatism

The last magmatic pulse within the Mont Blanc – Aiguilles Rouges area is represented by the voluminous 303 ± 2 Ma Mont Blanc granite (Fig. 13), a foliated, porphyritic monzo- to syenogranite with K-feldspar megacrysts and Fe-rich biotite (Marro, 1988; Bussy, 1990). It hosts numerous mafic microgranular enclaves, calc-alkaline micro-monzodioritic stocks and syn-plutonic dykes of mantellic origin, which record magma mingling processes (Bussy, 1990). The Mont Blanc granite is a metaluminous, ferro-potassic, alkali-calcic intrusion characterized by high K, Y, Zr contents and Fe/Mg ratios, and a low $^{87}Sr/^{86}Sr$ initial isotopic ratio of about 0.706 (Bussy et al., 1989). Emplacement of the Mont Blanc granite is the last major magmatic event recorded in the area. However, ash-fall deposits, embedded at different levels of the Salvan Dorénaz basin of the Aiguilles Rouges Massif, have been dated at 295 + 3-4 Ma (Capuzzo & Bussy, 2000). Such ash deposits probably derive from volcanic centers located in the Aar-Gotthard Massifs of Central Alps (Capuzzo & Bussy 2000).

Carboniferous sedimentation

Upper Carboniferous sedimentation is best documented in the Salvan-Dorénaz basin of the Aiguilles Rouges (Fig. 13) where it started at the end of the Westphalian. These coarse-grained clastic sediments formed an alluvial fan system and were deposited on top of the exhumed polymetamorphic basement intruded by Variscan granitoids (Capuzzo, 2000, quoted by Bussy et al., 2001). Subsequent sedimentation of braided, anastomozed and meandering river deposits records a sedimentary evolution in a strike-slip tectonic regime. Volcanic layers within the sediments are dated to the Late Carboniferous (Capuzzo & Bussy, 2000), with an age of 308 ± 3 Ma for basal dacitic flows and of 295 ± 3 Ma for a tuff layer from the upper levels of the basin sequence.

Maures-Tanneron Massifs

Also known as "Provence Crystalline", the Maures (to the SW) and Tanneron (to the NE) Massifs (Fig. 14) were not involved in the Alpine orogeny and preserve a fine example of the South Variscan crust as exposed at the end of the Variscan orogeny. They have been the focus of numerous studies in recent times. Only a brief summary of their geological history is given here to put the geological record preserved in the Argentera and Mont-Blanc-Aiguilles Rouges Massifs in a broader Variscan framework. This summary is based on Toutin-Morin et al. (1994) and on the papers by Crévola & Pupin (1994), Elter et al. (2004), Bellot (2005), Demoux et al. (2008) and Rolland et al. (2009), in which the reader will find references to earlier papers.

< Figure 14>

Maures Massif

The Maures Massif comprises two main tectono-metamorphic blocks, the Western Block and the Eastern Block, which are in tectonic contact along the Grimaud Fault (Fig. 14). The two blocks together display a complete metamorphic zoning, ranging from low greenschist-facies to upper amphibolites-facies conditions and including in the Western Block, from W to E, a chlorite zone, a garnet-chlorite zone, a biotite-staurolite zone, a biotite-kyanite zone, a biotite-muscovite-sillimanite zone, and in the Eastern Block a biotite-sillimanite zone characterized by partial melting (Fig. 14).

The Western Block

The Western Block consists of three metamorphic units: the Western metamorphic Unit, the middle Bormes Unit, and the eastern La Garde-Freinet Unit (Fig. 14).

The Western metamorphic Unit is mainly composed of phyllite and quartzite. Intercalated beds of black schist preserve the well known Llandovery graptolite fauna of Mont Fenouillet, near Hyères (Gueirard et al., 1970), discovered by Schoeller (1938).

The Bormes Unit consists of staurolite-kyanite-garnet two-mica micaschist and two-mica paragneiss, and of the Bormes granitic orthogneiss. Relicts of an aluminous porphyritic granite ("Barral granite"), which was metamorphosed under LP granulite-facies conditions (P = 0.67 GPa and T >850°C; Gueirard, 1976), are found in the Bormes orthogneiss. Geochronological data summarized by Bellot (2005) indicate a Precambrian age (~ 550-600 Ma) for the emplacement of the Barral granite. U-Pb dating of monazite from the Bormes orthogneiss yielded an age of 345 ± 3 Ma, interpreted as dating the regional intermediate P metamorphism (Moussavou, 1998). ^{40}Ar/^{39}Ar dating of biotite from a sheared orthogneiss yielded ages of 323-328 Ma, that have been interpreted to date the top-to-the NW shear deformation and retrograde low-P metamorphism (Gaubert, 1994, quoted by Bellot, 2005). Metapelites included in the Bormes orthogneiss preserve pre-D1 whiteschist assemblages (1.2-1.6 GPa and 480-550°C) retrogressed to 0.4-0.6 GPa and 600-650°C during shear deformation of the Bormes orthogneiss (Leyreloup et al., 1996, quoted by Bellot, 2005).

The La Garde-Freinet Unit ("Cavalaire Unit" of Bellot, 2005) consists of a wide range of rock types, including acid, mafic, and ultramafic igneous rocks hosted by two mica-garnet-sillimanite micaschist and migmatitic paragneiss. In addition to migmatitic orthogneiss this unit is characterized by an association of amphibolites and "leptynites" (Seyler, 1986) and by the local presence of cordierite in the migmatitic paragneiss. Emplacement of the felsic volcanic protoliths of the "leptynites" is constrained at 548 +15/-7 Ma by U-Pb zircon ages (Innocent et al., 2003). A recent study of the ultramafic rocks (Bellot et al., 2010) shows that they are spinel peridotites and minor garnet–spinel peridotites. In particular, spinel peridotites represent both residual dunites and harzburgites typical of fore-arc upper mantle, and ultramafic cumulates, i.e. dunite adcumulates, harzburgite heteradcumulates and mesocumulates, melagabbro heteradcumulates and amphibole peridotites. The Maures spinel peridotites and melagabbros are interpreted as the lowermost parts of a crustal sequence and minor residual mantle of lithosphere generated in a supra-subduction zone during the Early Paleozoic (Bellot et al., 2010).

The Eastern Block

The Eastern Block ("Cavalières Unit" of Bellot, 2005) is mainly made up of migmatites derived from orthogneiss and biotite-sillimanite paragneiss containing amphibolitized eclogite lenses recording an early HP metamorphism (Fig. 14). Small bodies of biotite- and amphibole-rich orthogneisses are interpreted as primary calc-alkaline granodiorite and diorite, emplaced during the Precambrian (U-Pb zircon ages of 612-630 Ma; Lancelot et al., 1998, quoted by Bellot, 2005). A detailed study of eclogites (Caruba, 1983, Chapt. IX) shows that, even in the best preserved varieties ("amphibolites à grenats auréolés") such as at Cap du Pinet, garnet is the only pristine eclogite phase that survived the subsequent retrogression. A notable exception is the Cavalières eclogite, in which kyanite also survived with garnet, and is surrounded by spectacular corona textures of sapphirine-anorthite symplectite (Bard & Caruba, 1982). The Cavalières kyanite eclogites are inferred to be derived from calc-alkaline gabbro emplaced in a back-arc setting (Buscail et al., 1999 quoted by Bellot, 2005) during Upper Ordovician (zircon U-Pb 452 ± 8 Ma; Lancelot et al., 1998, quoted by Bellot, 2005) and transformed into eclogite during the Lower Silurian (zircon U-Pb 431 ± 4 Ma; Lancelot et al., 1998, quoted by Bellot, 2005).

Four generations of synkinematic to postkinematic plutons intruded the central and eastern Maures from 336 to 297 Ma. The oldest intrusions are the Hermitan Granite in Central Maures emplaced at 338 ± 6 Ma and the Reverdit Tonalite in Eastern Maures emplaced at 334 ± 3 Ma (Moussavou, 1998). The largest granite body is represented by the Plan de la Tour Granite of Central Maures, 19 km-long and 5 km-wide (in its northern part), elongated N-S (Fig. 14). The granite is porphyritic—with K-feldspar phenocrysts up to a few cm-long—and hosts dark microgranular "enclaves" or mica-rich inclusions ("enclaves surmicacées") with diffuse rims. Local varieties also contain cordierite crystals a few mm to 1-2 cm of size. The emplacement of the Plan de la Tour Granite is constrained by an U-Pb age of 324 ± 5 Ma (Moussavou, 1998) and by a Rb-Sr age of 313 ± 10 Ma (Maluski, 1971). The youngest granite intrusion is that of Cap Camarat which was emplaced at c. 300 Ma (Morillon et al., 2000).

The exhumation of the Maures Massif

A detailed $^{40}Ar/^{39}Ar$ geochronological study (22 plateau ages on single grains and bulk samples of amphibole, muscovite and biotite) of metamorphic and magmatic rocks from both sides of the Grimaud Fault (Morillon et al., 2000), shows that migmatites, micaschists, gneisses, pegmatites and granites display muscovite and biotite plateau ages which range from 317.2 ± 1.0 to 322.9 ± 1.7 Ma on the western side of the Grimaud fault, and from 300.2 ± 0.6 to 306.0 ± 2.4 Ma on the eastern side, respectively. In the Western Block, amphiboles yielded plateau ages of 328.1 ± 2.8 and 329.9 ± 2.1 Ma for amphibolites, whereas in the Eastern Block, amphibolite and magmatic bodies contain amphibole that yielded ages ranging from 307.9 ± 1.2 to 317.4 ± 2.4 Ma. These data demonstrate distinct cooling histories in the eastern and western side of the Grimaud Fault. Two distinct periods of fast cooling were recognized, at 320 Ma to the west and at 305–300 Ma to the east of the Grimaud fault, which is identified as a major crustal discontinuity during the late Variscan orogeny.

Post-metamorphic exhumation of the Maures Massif is also constrained by the Late Carboniferous sedimentation in the Plan de la Tour basin. This 16 km-long and 1 km-wide basin is located in the central Maures along the Grimaud fault (Bellot, 2005, and references therein) and is filled with a 400 m thick sequence of conglomerates and arkoses. The base of the sedimentary sequence is dated as Early Stephanian, whereas microgranite dykes emplaced within the basin are of Late Stephanian age (295.4 ± 2.4 Ma, $^{40}Ar/^{39}Ar$ on biotite: Morillon, 1997, quoted by Bellot, 20 05).

Tanneron Massif

The Tanneron Massif is the 40 x 15 km area of metamorphic rocks and granites sited NE of the Maures Massif, from which it is separated by a belt of Permian sedimentary and volcanic deposits (Fig. 14). The Tanneron Massif is divided by the N-S-trending Joyeuse (to the W) and La Moure (to the E) faults into three domains: the Western, the Central and the Eastern domain.

To the W of the Joyeuse fault (Fig. 14), the Western domain comprises a narrow band of sillimanite-rich migmatitic paragneiss and micaschist forming the basement of the small Late Carboniferous Pennafort basin (G. Crévola in Toutin-Morin et al., 1994; Demoux et al., 2008, and references therein).

To the E of the Joyeuse fault (Fig. 14), the Central domain comprises sillimanite-rich migmatitic gneiss intruded by the granite and tonalite of the Rouet-Prignonet magmatic complex. The Rouet granite, an aluminous porphyritic biotite granite with large crystals of altered cordierite, is comparable to the Plan de la Tour granite of the Maures Massif (Crévola & Pupin, 1994; Onezime et al., 1999). The migmatitic gneisses are sillimanite-rich, occasionally with cordierite, and are intruded by an E-W trending tourmaline-bearing leucogranite body (Grime leucogranite) associated with a swarm of leucogranite dykes. More to the E, a thick sequence of orthogneisses and paragneisses, showing increasing partial melting from E to W, and a wide band of blastomylonitic orthogneiss of granodiorite composition (Bois de Bagnols orthogneiss) is found (G. Crévola in Toutin-Morin et al., 1994). The Bois de Bagnols orthogneiss is the basement of the Reyran Late

Carboniferous basin, which is filled with 1000 m of sandstone, coal, pelite, and conglomerate dated as Upper Westphalian to Lower Stephanian and hosts intercalations of pyroclastic rhyolite (Basso, 1985, quoted by Bellot, 2005).

The Eastern domain, E of the La Moure fault (Fig. 14), is composed of a thick sequence of migmatitic gneiss and of biotite-muscovite-sillimanite-kyanite-garnet micaschist. A migmatitic orthogneiss (Tanneron orthogneiss), intercalated in this series as a N-S-trending bands, locally preserves granitic structure with garnet and cordierite, in spite of widespread transformation into blastomylonitic orthogneiss (Crevola & Pupin, 1994). Amphibolites lenses with eclogite relicts are found in all three domains (Fig. 14). However, even in the best preserved variety ("kelyphitoid eclogite") omphacite is completely replaced by a plagioclase + diopside symplectite (G. Crévola in Toutin-Morin et al., 1994).

Recent isotope dilution U–Pb monazite dating (Demoux et al., 2008) indicates a pre-Variscan history in the Bois de Bagnols orthogneiss of the Central domain, with monazite ages from ~ 440 to 410 Ma. Monazites from a migmatitic paragneiss of the Central domain record a Late Carboniferous HT event at 317 ± 1 Ma (Demoux et al., 2008) In the eastern part, a migmatization event is recorded by monazites from a synkinematic leucogranite body and the Tanneron mylonitic orthogneiss, which yielded ages of 309 ± 5 and 310 ± 2 Ma, respectively (Demoux et al., 2008)

Later post-collisional magmatism is recorded by the intrusion of the post-tectonic Rouet granite at 302 ± 4 Ma (Demoux et al., 2008) and of undeformed leucogranite dykes in the Eastern domain, which mark the final stage of the Variscan evolution at 297 ± 5 Ma (Demoux et al., 2008)

Thirty-two ^{40}Ar/^{39}Ar plateau ages on single grains of muscovite from metamorphic and magmatic rocks sampled along an east-west transect through the Massif range from 302 ± 2 to 321 ± 2 Ma, and reveal a heterogeneous exhumation that lasted about 20 Ma during the Late Carboniferous (Corsini et al., 2010). In the Eastern Domain, closure of the K-Ar isotopic system is at ~ 311-315 Ma (Corsini et al., 2010). whereas in the Central Domain the K-Ar system closed earlier (~ 317-321 Ma, (Corsini et al., 2010). These cooling paths are interpreted as resulting from differential exhumation processes of distinct crustal blocks controlled by the La Moure fault that separates the two domains (Corsini et al., 2010). In the Western Domain, the ages decrease from ~ 318 to 304 Ma approaching the Rouet granite, which provided the youngest age at 303.6 ± 1.2 Ma (Corsini et al., 2010).

Discussion

The recent geochronological-geochemical studies of Rubatto et al. (2001, 2010) and the petrological study of Ferrando et al. (2008), combined with previous data, well constrain the evolution of the GSV Terrane of the Argentera massif before and during the Variscan orogeny (Fig. 15). On the contrary, the geological history of the Tinée Terrane is less documented, but the presence of eclogites and HP granulites suggests it may have been similar to that of the GSV Terrane. A major difference between the two terranes is that in the Tinée muscovite was stable during the Carboniferous amphibolite-facies event (see below) and the P-T path ended in the kyanite stability field, not in the cordierite stability field as in the GSV Terrane. Though each massif has its peculiarities and has been studied from somewhat different perspectives, the main geological events recorded in the GSV Terrane of Argentera are also recorded in the Mont Blanc-Aiguilles Rouges and Maures-Tanneron (Table 1).

< Figure 15>

The GSV Terrane of the Argentera Massif underwent in the Paleozoic a complex magmatic and metamorphic evolution beginning in the Early Paleozoic (or possibly still in the Late Proterozoic) with the intrusion of large granitoid bodies into a (meta-) sedimentary sequence of graywackes, pelites and rare limestones. In the Maures-Tanneron Massifs, this event is documented by the emplacement of the Barral granite (550-600 Ma) and of the felsic volcanic protoliths of the "leptynites" (~ 548 Ma). However, evidence of this event appears to be lacking in the Mont Blanc-Aiguilles Rouges Massifs (Table 1).

These early granitic intrusions were followed in the Early Ordovician by the emplacement of mafic magmas (now represented by eclogites and H*P* granulites) in the Argentera (at 480-460 Ma; Fig. 15), in the Maures-Tanneron (at 452 ± 8 Ma), and in the Mont Blanc-Aiguilles Rouges Massifs (at ~ 450 Ma). In the Argentera Massif the crustal contamination shown by the Laghi del Frisson mafic sequence supports an extensional setting, in agreement with what proposed for other External Crystalline Massifs (Ménot & Paquette, 1993; Guillot & Ménot, 2009).

A new magmatic cycle, at the Ordovician – Silurian boundary is documented by shallow sheet-like intrusions of dacite with granulitic xenoliths at 443 ± 3 Ma in the GSV Terrane (Fig. 15), by the emplacement of both the S-type and I-type calc-alkaline "Ordovician granitoids" at ~ 440 Ma in the Mont Blanc-Aiguilles Rouges Massifs, and of the granodioritic protolith of the Bois de Bagnols orthogneiss at 440-410 Ma in the Tanneron Massif (Table 1). Granulite xenoliths in the GSV Terrane metadacite are the only preserved evidence of a high-grade metamorphic basement already present in the area during Late Ordovician. Another relic of a LP granulite-facies metamorphism (P

= 0.67 GPa and T >850°C;) is reported from the “Barral granite”, an aluminous porphyritic metagranite preserved in the “Bormes orthogneiss” (Gueirard, 1976).

These crystalline basements were later subjected to H*P*–H*T* metamorphism with formation, depending from the protolith bulk chemical composition, of either eclogites or H*P*-granulites. *P-T-t* conditions of this event are well constrained at ~ 1.38 GPa, 735 ± 15 °C and 340 ± 4 Ma in the GSV Terrane (Fig. 15). Similar peak metamorphic conditions (1.4 GPa and 700°C) are recorded in the Aiguilles Rouges Massif.

Peak conditions reached by the Laghi del Frisson mafic sequence indicate a geothermal gradient of ~ 16 °C/ km, compatible with subduction zone environments and, in particular, with the conditions reported by O'Brien (2000) for subduction during continental collision. Relatively high exhumation rates can be inferred for the GSV Terrane from the preservation of peak mineral compositions and the recording of an almost isothermal decompression in the Laghi del Frisson mafic sequence. It is noteworthy that a similar P-T evolution has been reported from the Aiguilles Rouges Massif, where the decompression melting observed around eclogite boudins has been dated at ~ 340 Ma (Table 1). Also the Barrovian amphibolite-facies metamorphism of the Maures “leptynites” at 348 Ma possibly represents decompression following a HP metamorphic event, but this speculation awaits to be confirmed by further studies.

< Table 1>

Exhumation of the H*P* rocks was followed—after a few million years—by the emplacement of characteristic Mg-K monzonite and granite. In particular, a limited magmatism of likely extensional nature is represented in the GSV Terrane by the intrusion of small dykes and bodies of K-rich monzonite dated at 332 ± 3 Ma (Fig. 15). A more extensive syn-tectonic magmatism is represented in the Mont Blanc-Aiguilles Rouges Massifs by the Pormenaz monzonite (332 ± 2 Ma) and Montées-Pélissier granite (331 ± 2 Ma), and in the Maures Massif by the the Hermitan granite (338 ± 6 Ma) and Reverdit tonalite (334 ± 3 Ma) (Table 1).

Only some 10–20 Ma after the Carboniferous H*P* metamorphism, an amphibolite-facies metamorphism with extensive development of migmatites occurred not only in the Argentera Massif (323 ± 12 Ma; Fig. 15) but elsewhere in the External Crystalline Massifs (Mont Blanc-Aiguilles Rouges: 327-317 Ma) and Variscan Provence (Maures-Tanneron: 317-310 Ma) (Table 1). The tight succession of HP metamorphism and amphibolite-facies anatexis suggests that, at least in the Argentera Massif, the two stages are part of the same metamorphic cycle, where intense melting occurred upon decompression and advective heat transfer. However, further research is needed to better establish the *P-T* path followed by the GSV and Tinée Terranes during the Carboniferous amphibolite-facies event and its timing.

The Variscan igneous cycle is closed by the emplacement at shallow crustal levels of syntectonic peraluminous granites (Table 1)—the Valle Stura leucogranite (299 ± 10 Ma) in the GSV Terrane (Fig. 15), the Vallorcine and Montenvers granites (~ 307 Ma) in the Mont Blanc-Aiguilles Rouges Massifs, possibly the Plan de la Tour granite of the Maures massif, which however seems to be older (324 ± 5 Ma), and of post-tectonic, granites (Table 1), i.e. the Central Granite (cooling ages at 299-292 Ma) in the GSV Terrane (Fig. 15), the Mont Blanc granite (303 ± 2 Ma) in the Mont Blanc Massif, the Camarat and Rouet granites (~ 300 Ma) in the Maures-Tanneron.

The final exhumation of the Massifs is marked by the deposition on the crystalline basements of Westphalian D-Stephanian A (306-303 Ma, according to the geological time scale of Gradstein & Ogg, 2004) continental sediments (Fig. 15 and Table 1). Currently available geochronological data seem to suggest that in Argentera the Tinée Terrane may have been exhumed a few My earlier than the GSV Terrane, but this has to be corroborated by further investigations.

Conclusions

Though the main geological events recorded by these Massifs are similar, a few of the events documented in the Mont Blanc-Aiguilles Rouges and Maures-Tanneron have not yet been documented in the Argentera Massif. In particular, the Late Proterozoic emplacement of granitoids in a (meta-) sedimentary sequence documented in the Maures and the Late Ordovician granite plutonism documented in the Mont Blanc Massif, still await to be confirmed by geochronological data. Field observations generally support the occurrence of these magmatic events in the Argentera. On the other hand, the age of the HP metamorphic event documented by eclogites and HP granulites found in all the massifs is well constrained so far only in the GSV Terrane of the Argentera Massif.

A discussion of tectonic models for the Variscan belt of the Western Alps and Provence is outside the scope of this review. However, the recent geochronological data from the Argentera Massif (Rubatto et al., 2010) link together in a single orogenic cycle the H*P* and amphibolite-facies metamorphisms and suggest that the evolution of the Variscan belt may resemble that of presentday collisional settings, such as the Himalayan belt. Similarities between the Variscan and the Himalayan orogenies include the conditions of H*P* granulite-facies metamorphism, and the rapid (within 20 Ma) succession of H*P* peak metamorphism, fast exhumation and widespread late anatexis. Further petrological, structural and geochronological investigations, however, are needed to explore this hypothesis and properly place the Argentera Massif in the framework of the South Variscan belt.

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Figures and Tables

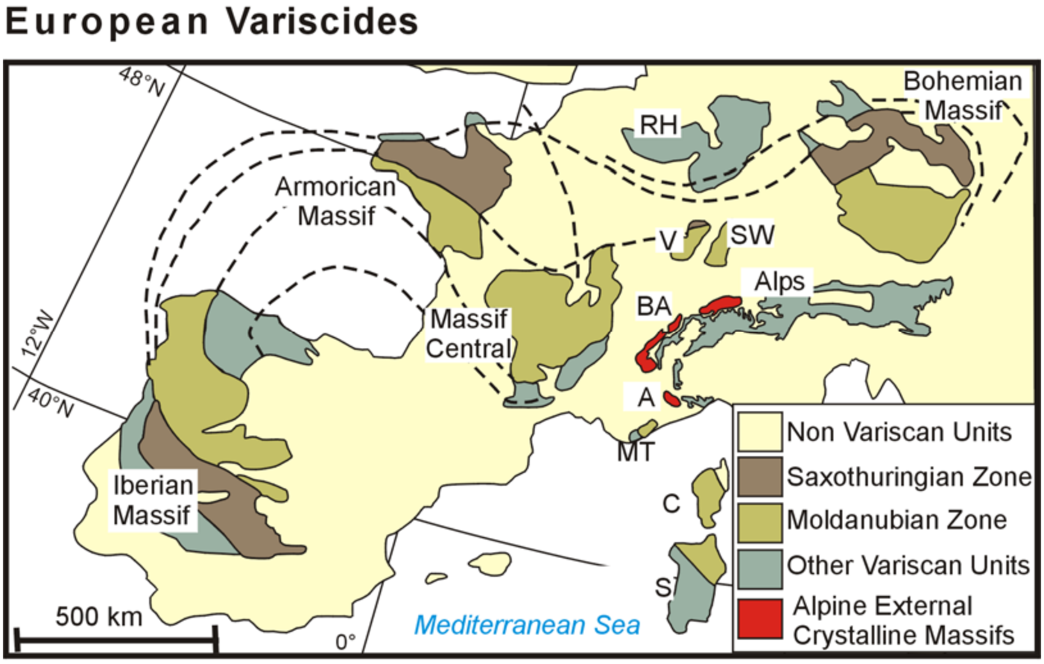


Fig. 1 Distribution of the European Variscan massifs and units (modified from O'Brien, 2000; Stampfli et al., 2002; von Raumer and Bussy, 2004). A: Argentera; BA: Mont Blanc – Aiguilles Rouges; C: Corsica; MT: Maures-Tanneron; RH: Rheno-Hercynian; S: Sardinia; SW: Schwarzwald; V: Vosges.

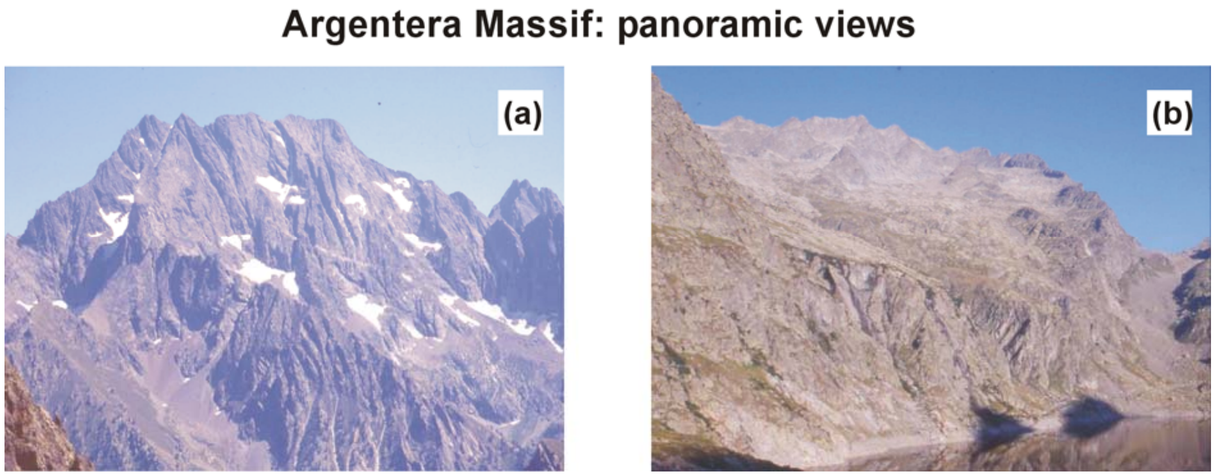


Fig. 2 Examples of young morphology on old rocks of the GSV Terrane. **(a)** The W face of the Argentera ridge, looking SE from the path to Colle di Valmiana, upper Gesso della Valletta valley. **(b)** The E side of the Argentera ridge and the Chiotas Reservoir from the path to Rifugio Genova, looking W. Upper Valle della Rovina.

Argentera Massif: geotectonic map

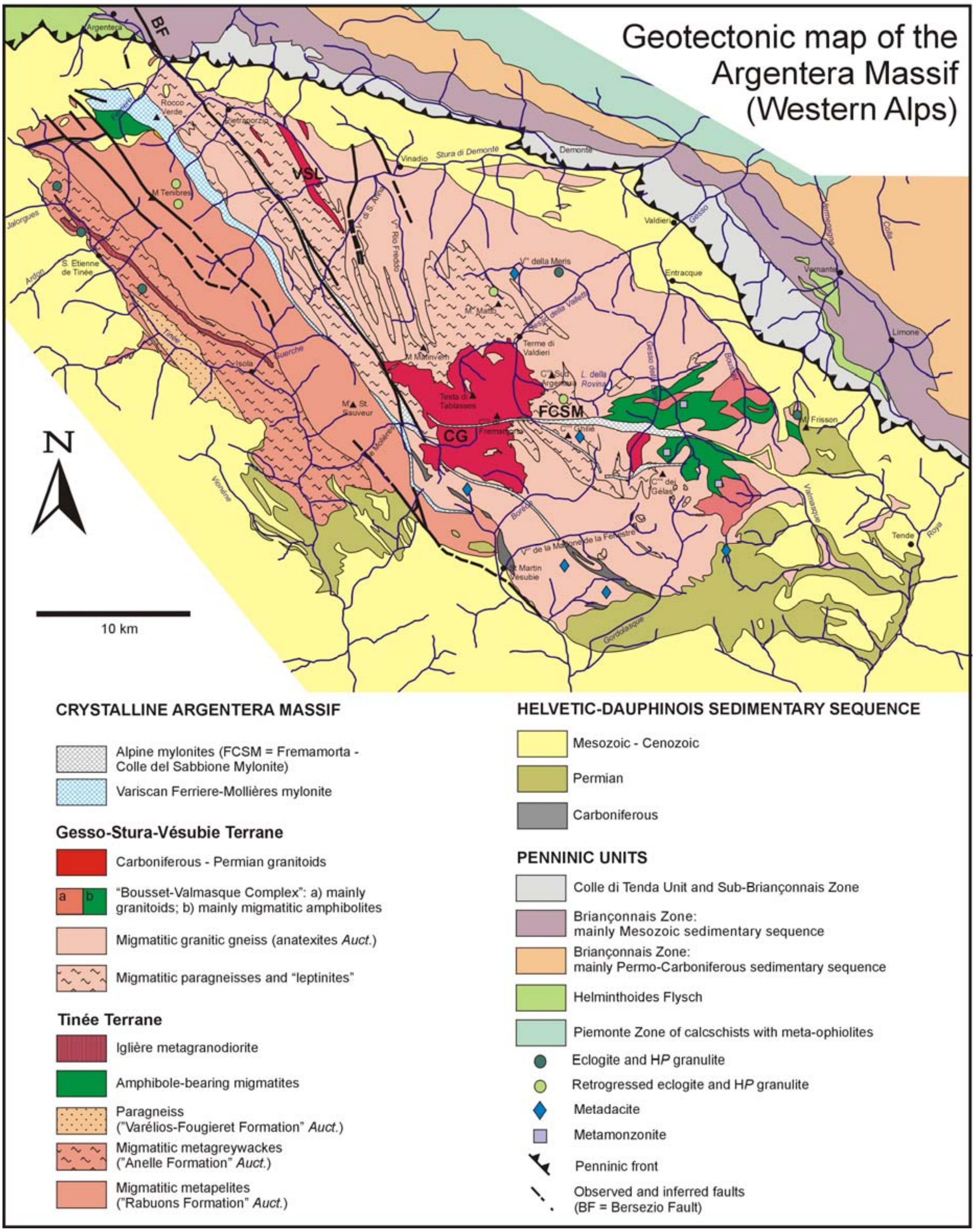


Fig. 3 Geotectonic map of the Argentera Massif. The map is based on those of Faure-Muret (1955), Malaroda et.al. (1970), Malaroda (1999) and on sheet Gap of the 1:250'000 Geological Map of France. CG: Central Granite; VSL: Valle Stura leucogranite; FCSM: Fremamorta-Colle del Sabbione mylonite.

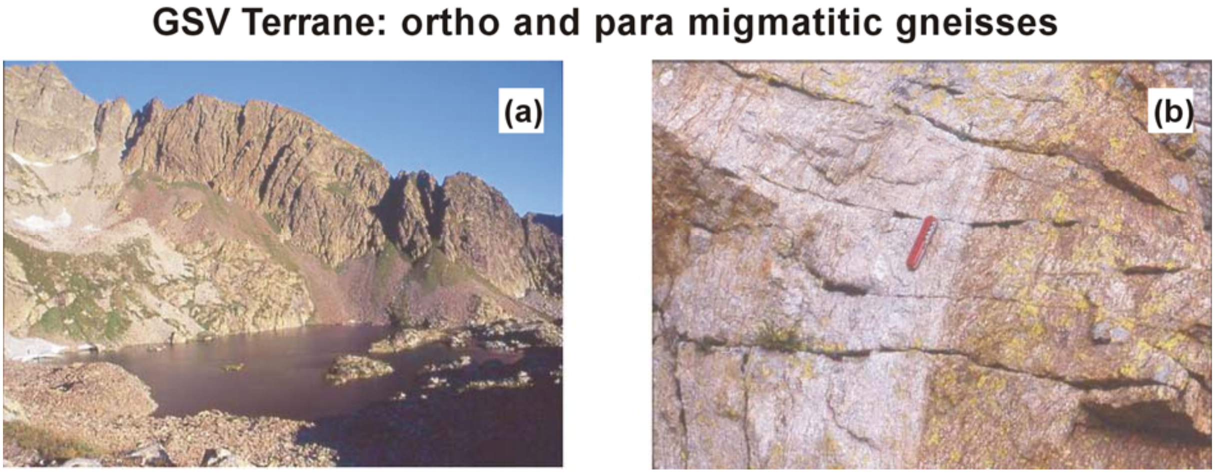


Fig. 4 Migmatitic gneisses. **(a)** Lithologic contact between migmatitic granitic gneiss (lighter rocks and scree on the left) and migmatitic paragneisses (reddish rocks and scree on the right). GSV Terrane. Looking N from Lago del Claus, upper Gesso della Valletta valley. **(b)** Detail of the contact between migmatitic granitic gneiss (on the left) and migmatitic paragneiss (on the right). GSV Terrane. Laghi della Sella, upper Valle della Meris.

Fig. 5 H*P* mafic rocks. **(a)** Lago Frisson and the ridge between the upper Val Grande di Vernante and Val Gesso. The banded H*P* granulites are exposed in the small hill by the lake and in the ridge to the right of the saddle (Passo della Mena). **(b)** Lago Frisson H*P* granulites. Typical compositional banding parallel to a pervasive mylonitic foliation. Banding consists of grey-whitish Pl-rich H*P* granulite and reddish Pl-poor H*P* granulite. **(c)** Banded amphibolite with portions containing remnants of eclogitic garnet. GSV Terrane. Lago di Nasta, upper Gesso della Valletta valley.

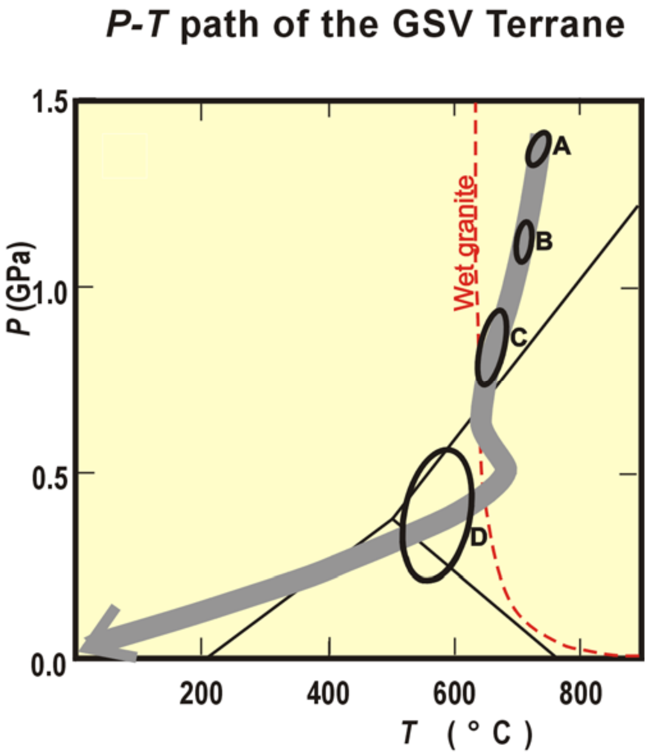


Fig. 6 *P*–*T* path of the GSV Terrane and metamorphic stages A to D of the Lago Frisson H*P* granulites, from Ferrando et al. (2008). Phase relations for Al_2SiO_5 are after Holdaway and Mukhopadhyay (1993) and the wet granite *solidus* is after Aranovich and Newton (1996).

GSV Terrane: metadacite

Fig. 7 Slightly foliated metadacite with xenoliths of metamorphic rocks including Grt-Opx granulite. GSV Terrane. Cima Ghilié, upper Gesso della Valletta valley.

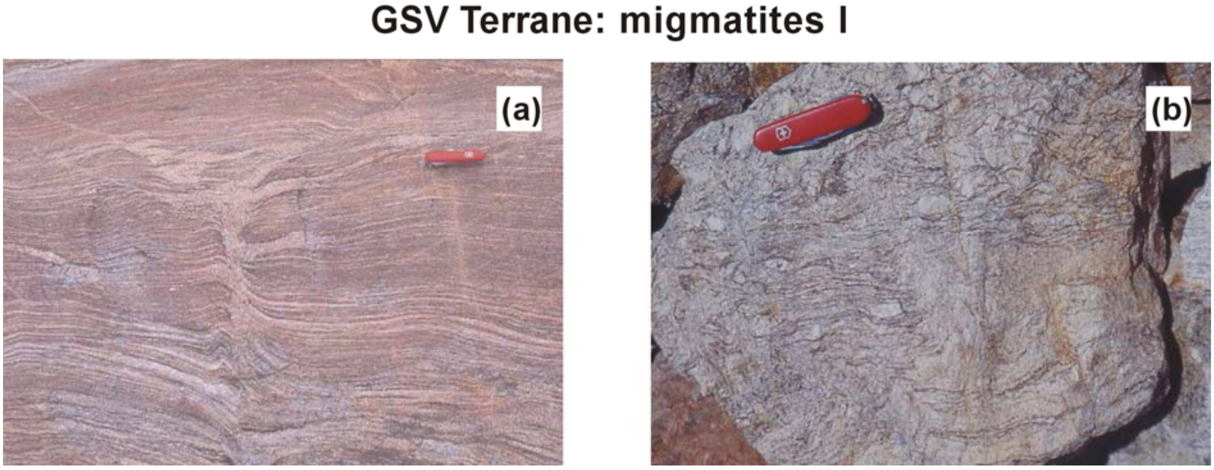

GSV Terrane: migmatites I

Fig. 8 Migmatites. **(a)** Thinly banded paragneiss showing a discordant leucosome with concordant branches developed along an incipient dextral shear zone. GSV Terrane, Laghi della Sella, upper Valle della Meris. **(b)** Migmatite with K-feldspar porphyroclasts derived from a granitoid of probable Ordovician age. GSV Terrane. Ridge between Valrossa and Valmiana, Valle di Valasco, upper Gesso della Valletta valley.

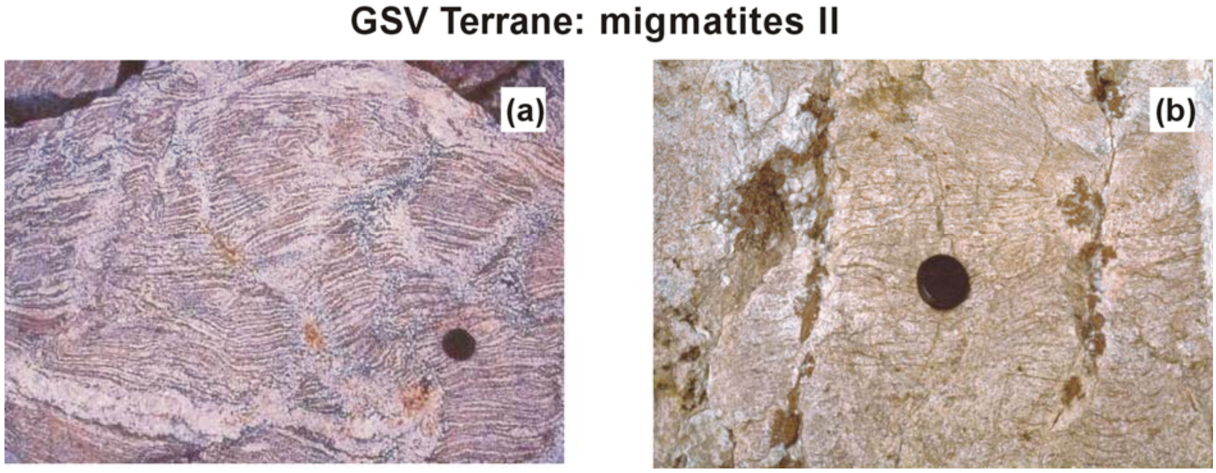


Fig. 9 Migmatites. **(a)** Thinly banded “anatexite” with both concordant and discordant granitoid leucosomes. GSV Terrane. Path from Rifugio Genova to Colle Fenestrelle, upper Valle della Rovina. **(b)** “Anatexite” showing cm-thick veins of pinitized cordierite ± quartz corresponding to the latest stages of the anatectic melt crystallisation. GSV Terrane. Upper Valle della Meris.

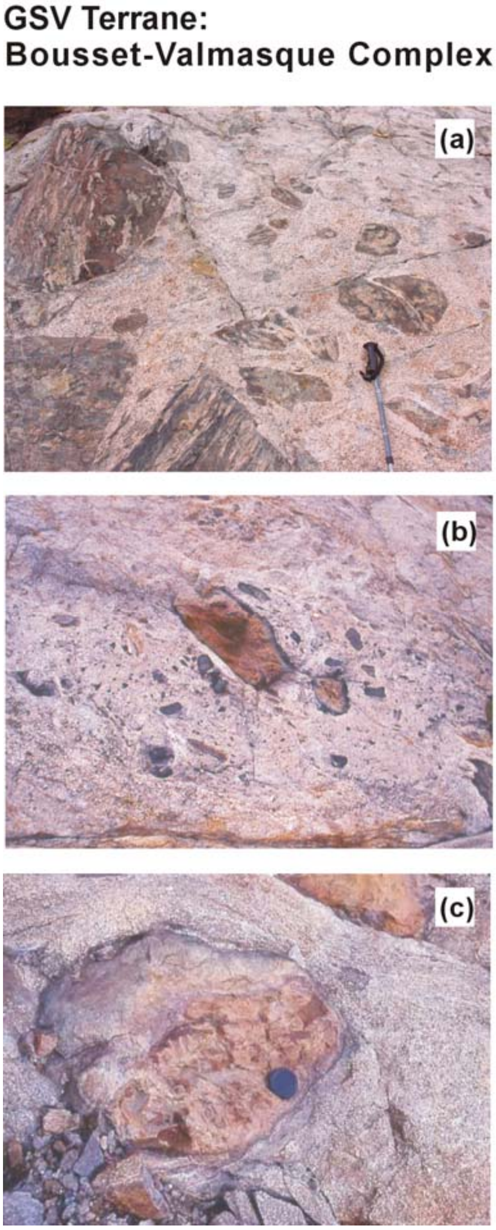
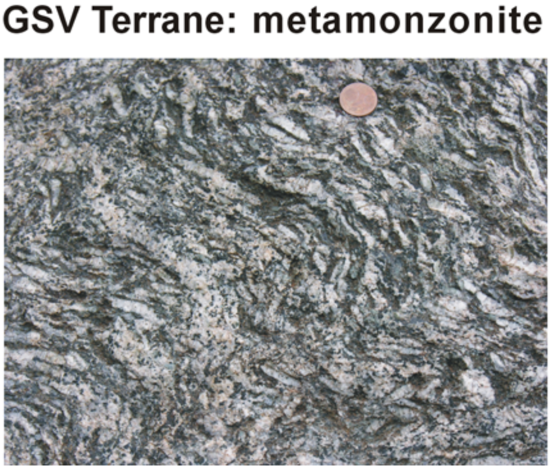


Fig. 10 Bousset-Valmasque Complex **(a)** “Granite de la Valmasque”. “Agmatite” with angular melanocratic fragments (“enclaves”) of hornblendite in a leucogranite matrix. The white patches in the hornblendite are plagioclase-diopside aggregates. GSV Terrane. Upper Valmasque, Pas de la Fous. This outcrop is the same as that described by Faure-Muret (1955, p.100 and Fig.1, Plate XI). **(b)** Ultramafic fragments are enclosed in an anatectic matrix of granitoid composition. The ultramafite-matrix contact is marked by a continuous rim of radially arranged amphibole, whereas the larger ones still have a serpentinized core. The smaller fragments are completely replaced by amphibole. GSV Terrane. Path between Rifugio Genova and Colle Fenestrelle,upper Valle della Rovina. **(c)** A larger ultramafic block in a granitoid matrix with sub-idioblastic plagioclase crystals (“perlgneiss”). Path between Rifugio Genova and Colle Fenestrelle, upper Valle della Rovina.



GSV Terrane: metamonzonite

Fig. 11 Deformed metamonzonite where are evident porphyroclasts of the relict igneous K-feldspar and an anatectic dykelet of granitoid composition (centre left), which is cutting across the pre-migmatitic metamorphic foliation . GSV Terrane. Upper Valmasque, just below the Pas de la Fous.

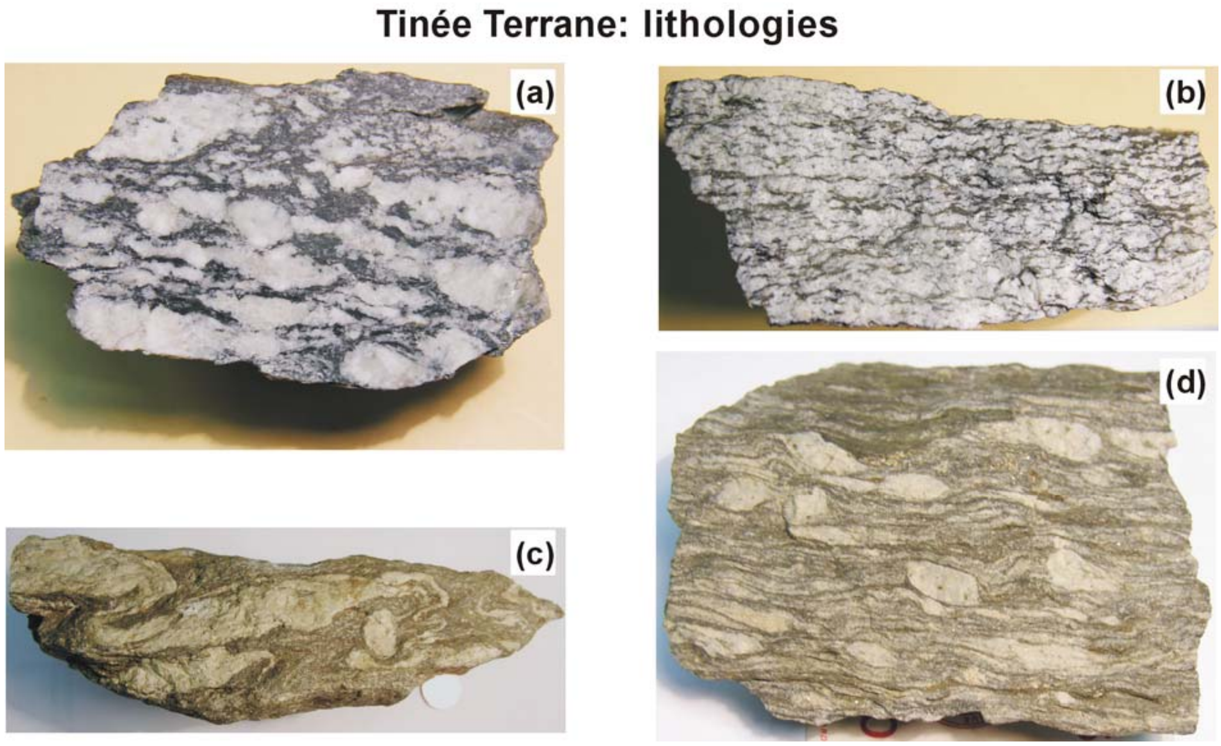


Fig. 12 Lithologies from Tinée Terrane. **(a)** Two-micas plagioclase gneiss typical of the Anelle Formation. A biotite-rich foliation with quartz, plagioclase and minor muscovite, sillimanite and garnet wraps around elongated quartz-plagioclase aggregates. Saint Etienne de Tinée, Vallon d'Assuéros, c. 1200 m a.s.l. Faure-Muret collection. Musée d' Histoire Naturelle de Nice, France. Sample 139/46 and Plate II, Fig. 3 of Faure-Muret (1955). **(b)** Iglière granodioritic to tonalitic gneiss with a biotite foliation wrapping around quartz and feldspar aggregates. Road from Tinée Valley to Roya. Sample 289/45: Faure-Muret collection. Musée d'Histoire Naturelle de Nice , France. **(c)** Typical Rabuons gneiss, characterized by folded quartz-plagioclase-K-feldspar leucosomes in a quartz-oligoclase-K-feldspar-two micas-sillimanite matrix. Saint Etienne de Tinée, Route de l'Energie, Vallon du Lusernier, 2440 m a.s.l. Faure-Muret collection. Musée d'Histoire Naturelle de Nice, France. Sample 222/45 and Plate IV, Fig. 3 of Faure-Muret (1955). d) Augen gneiss of the Rabuons Formation with a mylonitic foliation. Porphyroclasts of K-feldspar and plagioclase and quartz-feldspar augen enclosed in a closely spaced foliation defined by biotite-rich layers and discontinuous quartz-feldspars layers. Saint Etienne de Tinée, Route de l'Energie, S of Mont Garnet, 2420 m a.s.l. Faure-Muret collection. Musée d'Histoire Naturelle de Nice, France. Sample 348/45 and Plate IV, Fig. 1 of Faure-Muret (1955).

Mont Blanc - Aiguilles Rouges Massifs: geotectonic map

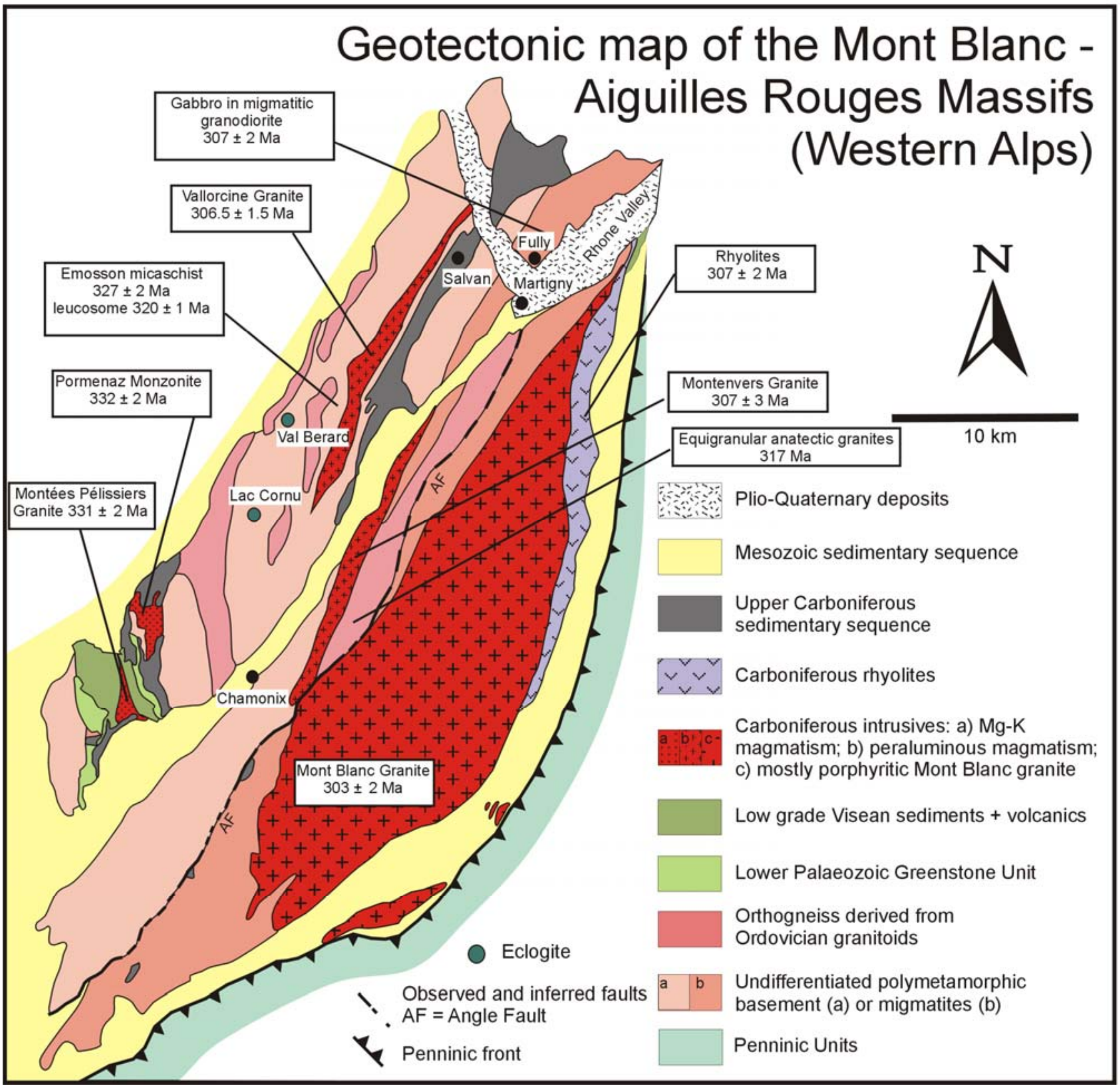


Fig. 13 Geotectonic map of the Mont Blanc Massif, from Bussy et al. (2001) and von Raumer & Bussy (2004), modified. Distribution of Carboniferous sedimentary rocks in the Mont Blanc Massif after Gidon (1976).

Maures - Tanneron Massif: geotectonic map

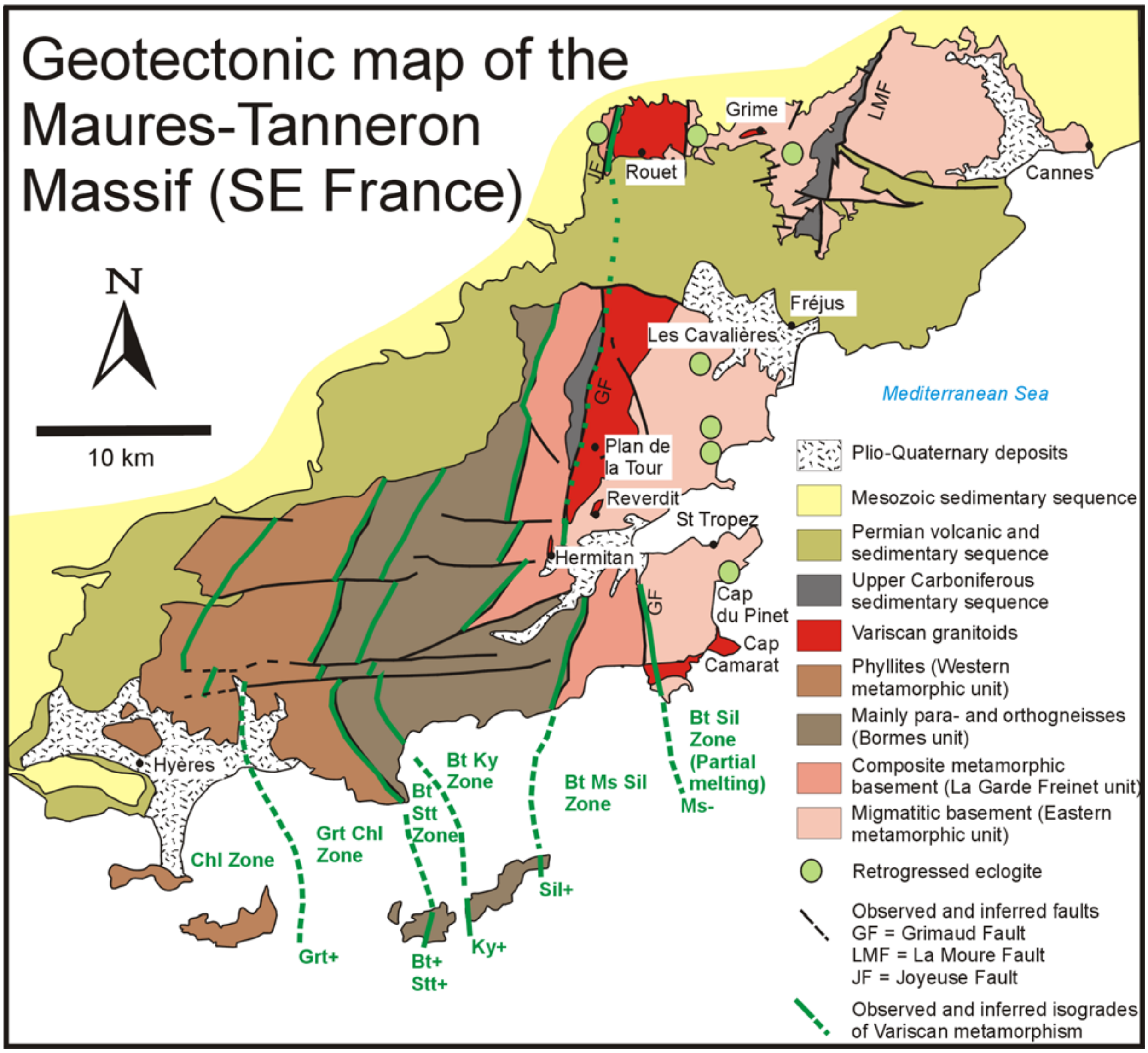


Fig. 14 Geotectonic map of the Maures and Tanneron Massifs [from Elter et al. (2004) and Rolland et al. (2009), Crévola & Pupin (1994), modified].

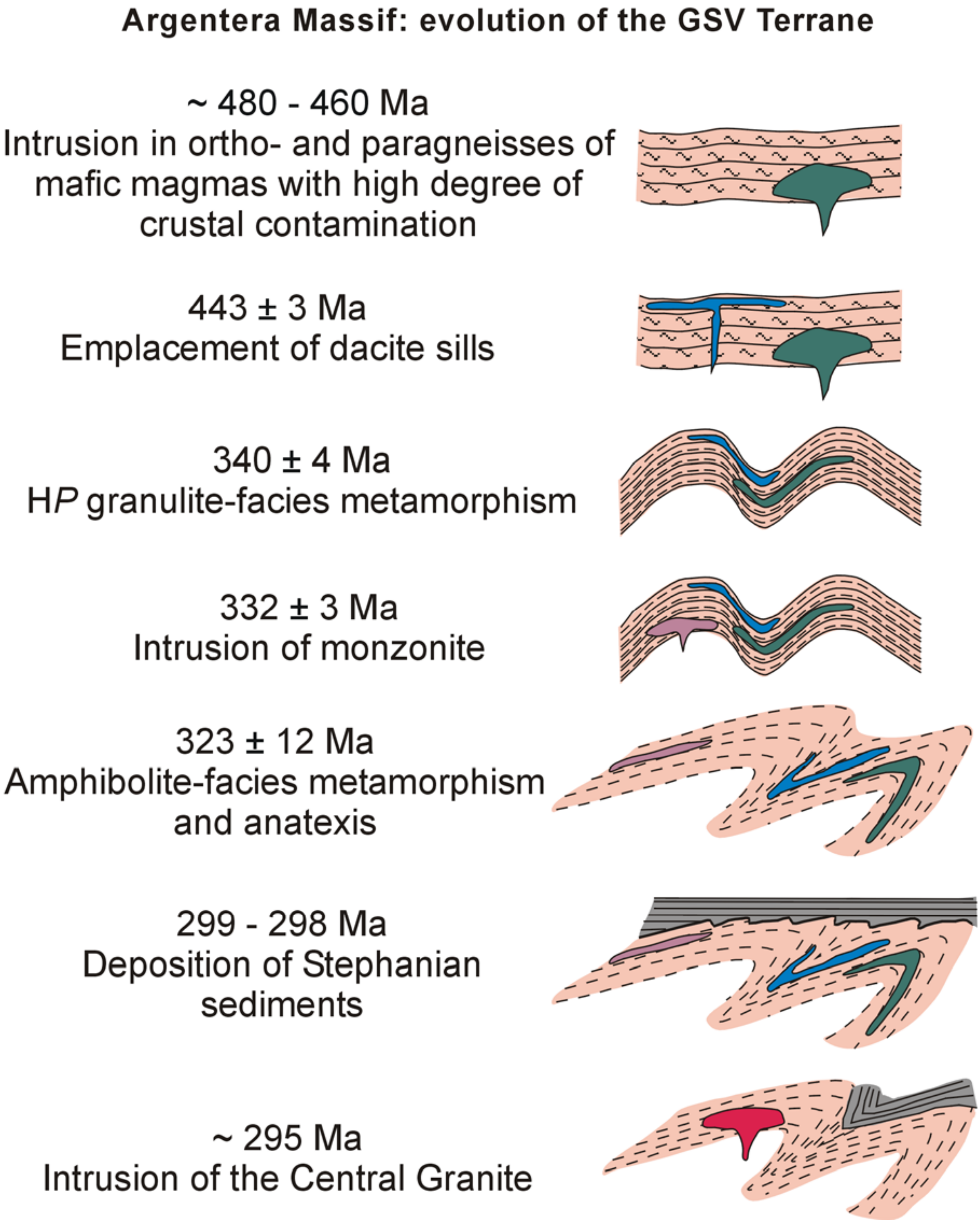


Fig. 15 Evolution of the GSV Terrane before and during the Variscan orogeny [from Rubatto et al. (2001), modified].

Argentera (GSV Terrane)	Mont Blanc – Aiguilles Rouges	Maures -Tanneron
Early Paleozoic (possibly Late Proterozoic) intrusion of granitoids into a (meta-) sedimentary sequence		Precambrian (600-550 Ma) emplacement of the Barral granite. Emplacement at ~ 548 Ma of the felsic volcanic protoliths of the Maures “leptynites”.
Early Ordovician (480-460 Ma) emplacement of the gabbro protoliths of eclogites and H*P* granulites	Magmatic zircons ages of ~ 450 Ma from eclogitized mafic rocks	Late Ordovician (452 ± 8 Ma) emplacement of the calc-alkaline gabbro protolith of the Cavalières kyanite eclogite.
Late Ordovician (443 ± 3 Ma) shallow sheet-like intrusions of dacite with granulite xenoliths	~ 440 Ma S-type and I-type calc-alkaline granitoids (“Ordovician granitoids”)	Emplacement of the granodioritic protolith of the Bois de Bagnols orthogneiss from Central Tanneron (~ 440-410 Ma).
Carboniferous (340 ± 4 Ma) metamorphism at the transition between H*P* granulite- and eclogite-facies.	Decompression melting, observed around eclogite boudins, at ~ 340 Ma	Barrovian amphibolite-facies metamorphism of the Maures “leptynites” (~ 348 Ma).
Intrusion of dykes and small bodies of monzonite (332 ± 3 Ma).	Mg-K plutonism: Pormenaz monzonite (332 ± 2 Ma) and Montées-Pélissier granite (331 ± 2 Ma)	Syn-kinematic intrusions of: - Hermitan granite (338 ± 6 Ma), Central Maures; - Reverdit tonalite (334 ± 3 Ma), Eastern Maures; - Plan de la Tour granite (324 ± 5 Ma), Central Maures.
L*P* upper amphibolite-facies metamorphism and anatexis (323 ± 12 Ma)	Amphibolite-facies metamorphism: - 327 ± 2 Ma from Lake Emosson micaschists (peak-T age); - 320 ± 1 Ma from a Lake Emosson leucosome (crystallization age); - 317 ± 2 Ma from a Mont Blanc massif migmatitic orthogneiss.	Migmatization in Eastern Maures between 325 ± 8 Ma and 334 ± 3 Ma. Late Carboniferous HT metamorphism: - 317 ± 1 Ma in migmatitic paragneiss of the Central Tanneron; - 310 ± 2 Ma in the Tanneron mylonitic orthogneiss.
Emplacement of the Valle Stura leucogranite (299 ± 10 Ma)	~ 307 Ma emplacement of syntectonic peraluminous granites (Vallorcine and Montenvers granites), and Fully granodiorite. Calc-alkaline rhyolitic dykes in the Mont Blanc massif	K-Ar cooling ages: - 321-317 Ma, Central Tanneron; - 315-311 Ma, Eastern Tanneron; - 323- 317 Ma, Maures W of the Grimaud fault; - 306-300 E of the Grimaud fault.
Emplacement of post-tectonic Central Granite (299-292 Ma)	Emplacement of post-tectonic metaluminous, ferro-potassic granitoids (303 ± 2 Ma, Mont Blanc granite).	Post-tectonic intrusion of: - 302 ± 4 Ma Rouet granite, Western Tanneron; - 297 ± 5 Ma leucogranite dykes, Eastern Tanneron; - ~ 300 Ma post-kinematic Camarat granite, Eastern Maures.
Deposition on the exhumed migmatites of Westphalian D-Stephanian A continental sediments.	Deposition of Westphalian D-Stephanian A continental sediments in the Salvan-Dorénaz basin, with sub-aerial dacitic flows at 308 ± 3 Ma and ash-fall deposits at 295 ± 3 Ma.	Deposition in the Plan de la Tour basin (Maures) of Late Carboniferous sediments cut across by microgranite dykes of Late Stephanian age (295 ± 2 Ma). Deposition in the Reyran basin (Tanneron) of Late Westphalian to Early Stephanian sandstone, coal, pelites, and conglomerate.

Table 1 Geological evolution of the Argentera, Mont Blanc-Aiguilles Rouges and Maures-Tanneron massifs. References of age data are reported in the text.