- PART II : FIELD TRIP 1 -

Mont Blanc – Aiguilles Rouges Massifs – (External Massifs)

AN EXAMPLE OF POLYOROGENIC EVOLUTION

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I: INTRODUCTION

1 - Pre-Mesozoic basement in Central Europe

The Pre-Mesozoic basement of Central Europe (Alps included) mostly appears as polymetamorphic domains juxtaposed through Variscan and/or Alpine tectonics (*e.g.* in Iberia, Armorica, Moesia, French Massif Central, Saxothuringian and Moldanubian Domains, External Massifs, Penninic Domain, parts of the southern Alps and the Austroalpine basement). Consequently, Variscan/Alpine structures prevail in most of these basement areas and relicts of former geological events from the Precambrian to the Ordovician are difficult to unravel and to correlate (*e.g.* von Raumer and Neubauer 1993).

The distribution of Cadomian-type basement units and their associated granitoids, detrital sediments, volcanites and Cambrian oceanic crust, as well as provenance studies of detrital zircons and Sm-Nd data (Nance & Murphy, 1994, 1996) all point to a common, Gondwana-derived origin for these relict basement pieces, including the Avalonia microcontinent (fig.16). Identification of subsequent sequences reminiscent of plate-tectonics *i.e.* successive stages of oceanic crust, volcanic arcs, active margin settings and collision zones during the Early Paleozoic led to the geodynamic model proposed in the main introduction of this guide book. This model postulates a rather continuous Gondwana-directed subduction since the Late Proterozoic (von Raumer et al., 2001), and can be summarized as follows (fig.16):

a) a Late Proterozoic active margin setting with formation of volcanic arcs is observed in the entire length of the future microcontinents at the Gondwanan border, and granites of Late Cadomian age (± 550 Ma) are common in many of the Gondwana-derived basement blocks. Detrital sediments of Late Proterozoic to Early Cambrian age carry the fingerprints of Cadomian/peri-Gondwanan origin. The corresponding sedimentary troughs prepared the future location of the Rheic ocean, which resulted from continuing oblique subduction and rifting in a back-arc situation accompanied by strike-slip movements.
b) Drift of Avalonia and opening of the Rheic ocean were enhanced after subduction of an oceanic ridge, whereas in the eastern continuation of Avalonia only early stages of the Rheic ocean may have existed.
c) Drift may have been delayed in the eastern continuation, and the oceanic ridge may have triggered the consumption of the Rheic ocean and the amalgamation of volcanic arcs and continental ribbons with Gondwana in a rather short-lived orogenic event, before the opening of Palaeotethys during the Ordovician, preparing the drift of the composite Hun-superterrane (Stampfli 2000).

Depending on their former location, preVariscan basement areas hidden in the Variscan belt (Alps included) may thus contain Cadomian elements, Late Proterozoic detrital sediments and volcanic arcs, relicts of the Rheic ocean, Cambro-Ordovician accretionary wedges, relicts of an Ordovician orogenic event and its related granites, as well as volcanites and sediments linked to the opening of the Palaeotethys.

In: G.M. Stampfli (ed.), Geology of the Western Swiss Alps – a Guide Book. Mémoires de Géologie (Lausanne), No. 36.

2 - Timing of events in the External Alpine Realm

The so-called "External Crystalline Massifs" of the French and Swiss Alps (*i.e.* Argentera, Pelvoux/Haut-Dauphiné, Belledonne-Grandes Rousses, Mont Blanc-Aiguilles Rouges, Aar-Tavetsch-Gotthard) represent pre-Mesozoic basement nappes or slices appearing as Alpine antiform cores among their Mesozoic covers (fig.2). They are located in the Helvetic realm, the external domain of the Alps. As a consequence, they were moderately affected by the Tertiary Alpine metamorphism and preserved most of their Paleozoic features. In particular, the Aiguilles Rouges Massif is known as the first place in the world where superimposed orogeneses (*i.e.* Alpine and Variscan) were clearly identified (Oulianoff 1953, in Ramsay 1967 p.519).

Apart from the low-grade Alpine overprint, the External Massifs recorded several pre-Mesozoic metamorphic episodes (von Raumer et al., 1999a). The main one resulted from the Variscan orogeny, when nappe stacking brought many units to high-amphibolite facies conditions and local anatexis. Despite this major imprint, many relicts testify to an earlier evolution comprising Late Precambrian rifting (sedimentation, formation of oceanic crust), Early Palaeozoic arc formation and subduction, and intrusion of Ordovician granitoids. We are thus dealing with a poly-orogenic evolution, comprising Alpine, Variscan, Ordovician and Neoproterozoic events. It is substantiated by isotopic ages (Tab. 1) and synthetic data from all External Massifs, which can be summarized as follows:

- Late-Proterozoic to Cambrian rifting and oceanization are inferred from paragneisses (metagrauwackes, marbles, metavolcaniclastic horizons, quartzites) hosting detrital zircons older than 600 Ma (Gebauer, 1993), deposited on a slowly subsiding continental shelf, as well as from the 496 Ma old Chanrousse ophiolite (Ménot et al., 1988b).

-An Ordovician subduction cycle is documented by relicts of MORB eclogites found in all massifs, in particular in the Aar and Gotthard, where eclogitization is bracketed by 467-475 Ma old island-arc type gabbros and the 440 Ma post-HP intrusion of granitoids (Abrecht, 1994; Abrecht et al., 1991, 1995; Abrecht and Biino, 1994; Biino, 1994, 1995; Oberli et al., 1994). Large volumes of S- and I-type granitoids (the so-called younger orthogneisses) intruded between ca. 460 and 440 Ma.

-The Devonian evolution is geochronologically poorly recorded so far (Tab. 1), with the notable exception of trondhjemitic intrusions at 365±17 Ma in Belledonne (Ménot et al., 1988a), suggesting continental rifting. Traces of Early Devonian nappe tectonics might be locally preserved in Belledonne and Aiguilles Rouges.

-The subsequent Carboniferous evolution is recorded at different levels of a supposedly large nappe pile. Wrench tectonic seems to be active during all this period, either in transpressive or transtensive mode. It is accompanied by (and possibly triggering?) important exhumation processes coupled to vigorous erosion. By Stephanian times, more than 10 km were stripped off all massifs. Very coarse to fine-grained sedimentation mixed with volcaniclastic material is recorded in intramountain basins of Early- and Late-Carboniferous age, respectively. Deep-seated units were affected by a Barrowian-type metamorphism of high amphibolite grade and locally by decompression melting (ca. 320 Ma in Aiguilles Rouges, Bussy et al., 2000). Several short-lived pulses of granitic magmatism are recorded, whose typology reflects progressive readjustment of the Variscan lithosphere (Bussy et al., 2000). Plutons are essentially syntectonic and intruded along transcurrent fault zones. A first pulse of high-K monzonitic to shoshonitic magmas (340-330 Ma) originated in a metasomatized lithospheric mantle

age, methode	rocks	reference
A Early Palaeozoic events		
496±6 Ma U/Pb Zrn	plagiogranite	Ménot et al., 1988a
497±27 Ma Sm/Nd	Chamrousse ophiolite	Pin and Carme ,1987
489±22 Ma U/Pb Zrn	granite, Belledonne	Barféty et al., 1997
461 Ma Sm/Nd grt wr	eclogite, Gotthard massif	Gebauer et al., 1988
468 Ma U/Pb Zrn	eclogite, Gotthard massif	
467-475 Ma U/Pb Zrn	island arc gabbro, Gotthard + eclogite facies	Oberli et al., 1994
479±3 Ma U/Pb Zrn	island arc gabbro	Abrecht et al., 1995
475-450 Ma U/Pb Zrn	Ext. M., metabasic protoliths	Paquette et al., 1989
445±2 Ma U/Pb Zrn 456±2 Ma U/Pb Zrn	migmatites, Aar massif	Schaltegger, 1992, 1993
485±50 Ma SHRIMP	Peclet orthogneiss	Bertrand et al. 2000
458±41 Ma, SHRIMP	Modane granite	Bertrand et al. 2000
436±17 Ma Rb/Sr wr	granitoids, Gotthard	Arnold, 1970a,b
>440 Ma U/Pb Zrn	granitoids, Gotthard	Bossart et al., 1986
439±5 Ma U/Pb Zrn	granitoids, Gotthard	Sergeev and Steiger, 1993
453±3 Ma U/Pb Zrn	granitoids, Mt. Blanc	Bussy and von Raumer ,1994
438±5 Ma U/Pb SHRIMP	meta-dacite, Argentera	Lombardo et al., 1997a
424 Ma U/Pb Zrn	eclogite, Argentera	Paquette et al., 1989
B Devonian		
395 Ma U/Pb Zrn	eclogite, Belledonne	Paquette et al., 1989
370 Rb/Sr thin slab	mylonites, Aiguilles-Rouges	Thöni,1989
352±56, 365±17 Ma U/Pb Zrn	Trondhjemite, Belledonne	Ménot et al., 1988b
350-373 Ma Ar/Ar Ms	Argentera	Monié and Maluski, 1983
356±3 Ma SHRIMP	Cogne granodiorite	Bertrand et al. 2000
C Late Variscan evolution		
	shoshonitic-ultrapotasssic-monzonitic rocks	
332-334 Ma, U/Pb Zrn	Aar massif	Schaltegger, 1994
333 Ma U/Pb Zrn	Tödi granite, Aarmassif	Schaltegger & Corfu,1995
332±2 Ma U/Pb Zrn	Pormenaz, Aig. Rouges	Bussy et al., 1997
337±8 Ma U/Pb SHRIMP	Argentera	Lombardo et al., 1997b
332±13 Ma Zrn Pb ev	Sept Laux granite, Belledonne	Debon et al., 1998
315-330±7 Ma Ar/Ar Bt	Argentera, Tinee	Monié and Maluski, 1983
324±12 Ma K/Ar Am	Belledonne	Ménot et al., 1987
324±22 Ma K/Ar Am, Bt	Pelvoux	Vittoz et al., 1987
337-331 Ma Ar/Ar Am	Western Gneiss Unit, w.Aig.R.	Dobmeier, 1998
334 Ma Ar/Ar Am	iron-skarns; Mont-Blanc area	Marshall et al., 1997
330±3 Ma U/Pb Zrn	Aar massif, greenschist to low amphibolite facies	Abrecht et al., 1995
327 U/Pb Mnz	metapelite, therm. peak, Aig. R.	Bussy and Hernandez, 1997
317 Ma; U/Pb Mnz	migmatite Mt. Blanc	Bussy and von Raumer,1994
321 Ma, U/Pb Mnz	migmatite Aig. Rouges	Bussy and Hernandez, 1997
308-310 Ma, U/Pb Zrn	diorites, granitoids, Aar massif	Schaltegger, 1994
307 Ma, U/Pb Zrn	gabbros, granitoids; Aig. R.	Bussy and Hernandez, 1997
303±3 Ma U/Pb Zrn	Mt. Blanc granite	Bussy et al., 1989
308 Ma U/Pb Zrn	acidic volcanics, Aig. Rouges	Capuzzo and Bussy, 1998, 2000
±300 Ma, U/Pb Zrn	partial melting Aar massif	Olsen et al., 1997, 2000
299-303 Ma U/Pb Zrn	pyroclastic deposits, Aar massif	Schaltegger & Corfu,1995
298 Ma, U/Pb Zrn	younger granitoids, Aar massif	Schaltegger, 1994
294, 299 Ma U/Pb Zrn	younger granitoids, Gotthard massif	Bossart et al., 1986 Guerrot and Steiger, 1991 Sergeev et al., 1995
295±3 Ma U/Pb Zrn	acidic volcanics, Aig. Rouges	Capuzzo and Bussy, 1998, 2000b

Tab.1 - Isotopic ages from the External Massifs (wr = whole- rock age; ev = Zrn evaporation age).

with variable lower crustal contamination. A second pulse (310-306 Ma) mainly consists of peraluminous crustal-derived granitoids associated to non-shoshonitic gabbros and diorites, whereas a third pulse (303-295 Ma) includes alkali-calcic (sub-alkaline) granites of mixed mantellic-crustal origin.

-Permian events are hardly recorded in the External Massifs, where Mesozoic sediments rest directly on any kind of pre-Permian lithology. Late Carboniferous erosion and peneplanation carried on in an extensional tectonic regime up to the transgression of the Mesozoic sea.

3 - Geological outline of the Mont Blanc / Aiguilles Rouges massifs

The present-day Aiguilles Rouges-Mont Blanc massifs consist of a complex assemblage of tectonic units with contrasting maximum P-T metamorphic conditions, separated by major, steeply dipping NE-SW faults and/or mylonitic zones (see fig. 18). Most of these tectonic contacts probably formed during the late Variscan strike-slip regime and were reactivated during the Alpine orogeny. These two massifs are essentially composed of polymetamorphic, amphibolite-facies grade rocks and granitic plutons. Low-grade monometamorphic detrital sediments with interlayered volcanites record an Early Carboniferous basin development at the southern end of the Aiguilles Rouges massif (Dobmeier 1996). On the other hand, unmetamorphosed continental, coal-bearing deposits of Late Carboniferous age (308-297 Ma, Capuzzo & Bussy 2000a,b) are preserved in the Salvan-Dorénaz Alpine syncline (northern part of the Aiguilles Rouges massif) and Saint Gervais – Les Houches area (southern part of the Aiguilles Rouges massif).

Age determinations in the polymetamorphic units of the Aiguilles Rouges – Mont Blanc area (Tab. 1) demonstrate a polyorogenic evolution, comprising Variscan, Ordovician and Late Precambrian events (Von Raumer et al. 1999a). Magmatic ages on zircon of c. 450 Ma have been obtained both for eclogitized MORB-like basic rocks (Paquette et al., 1989) and for S-type and I-type calc-alkaline non-eclogitized metagranites ("Ordovician granitoids" in fig.23) (Bussy & Von Raumer 1994). The latter intruded detrital sequences (now paragneisses) of supposedly Late Precambrian to Ordovician age, composed of sandstones and graywackes, with minor carbonate intercalations and tholeiitic basaltic layers. Flysch-type sediments enriched in Cr and Ni, together with eclogites and ultrabasic rocks (Aiguilles Rouges, von Raumer and Fracheboud, unpublished data) might represent deposits in a former accretionary prism (Von Raumer 1998). These lithologies have been interpreted as evidence for a Late Precambrian to Cambrian rifting/drifting episode with opening of an oceanic domain, followed by an Ordovician subduction, either in an island-arc, or an active continental margin environment, linked to the southward subduction of the Rheic oceanic lithosphere underneath Gondwana (see geodynamic model above). The subsequent high P event (700°C/ >14kbar) recorded by eclogites of the Lake Cornu area (Aiguilles Rouges) is not precisely dated. Paragneisses display a succession of deformation events attributed to the Variscan orogeny, with thrust tectonics (Dobmeier 1998) and nappe stacking, leading to the development of a Barrowian-type metamorphism (Von Raumer et al. 1999a). Metapelites record a typical clockwise P-T path, as commonly found in the internal parts of the Variscides, with a peak T at about 327 Ma (Bussy et al., 2000). Rocks of suitable composition experienced decompression melting during exhumation at c. 320 Ma (Bussy et al., 2000).

Magmatic rocks are widespread; as pre-Carboniferous (450-460 Ma) medium- to high-grade metamorphosed granites (*e.g.* Bussy & Von

Raumer, 1993; Wirsing 1997; Paquette et al. 1989; Von Raumer et al. 1990; Dobmeier et al. 1999) or as Carboniferous, essentially non- to weakly metamorphosed intrusions. Subvolcanic facies are associated to some of the intrusions, whereas volcanic horizons are interlayered in the Early- (Dobmeier 1996) and Late Carboniferous (Capuzzo & Bussy 2000a,b) detrital basins, respectively.

4 - The sedimentary record

Pre-Carboniferous sediments in the External Crystalline Massifs experienced a strong metamorphic overprint and are only crudely datable on the basis of their inherited zircon content (*e.g.* Gebauer, 1993) or crosscutting relationships with dated magmatic intrusions. A notable exception is the Cambrian - Ordovician age of black schists in the Grandes Rousses massif (Huez Formation, Giorgi et al., 1979), based on the discovery of Reitlingerellides fossils. On the other hand, Visean detrital deposits are better preserved and have been identified by fossils in the Taillefer detrital series of the Belledonne-massif (crinoids, Gibergy, 1968), and in the low-grade metapelitic series of the Aiguilles Rouges massif (acritarchs, Bellière and Streel, 1980). UpperCarboniferous sediments are only affected by Alpine metamorphism and host both datable volcanic layers and abundant plant fossils. In this chapter, we will focus on the Carboniferous sedimentary record of the Aiguilles Rouges/Mont Blanc area, the best preserved of all External Massifs.

4.1 Lower Carboniferous deposits

They outcrop in Servoz-Les Houches, at the southwestern end of the Aiguilles Rouges massif (fig.23) in two bands on either side of the Montées Pélissier granite. This is where Bellière & Streel (1980) dated Lower Carboniferous sedimentary rocks for the first time using palynology (Late Visean acritarchs), thus allowing a clear separation from the nearby upper Carboniferous deposits. These detrital rocks consist of metamorphozed and variably deformed phyllites, graywackes and sandstones, which recrystallized in greenschist facies conditions [chlorite zone, qtz + Chl + Ser + Pyr] (Dobmeier, 1996, 1998). Deformation is penetrative, although original sedimentary features are still recognizable. Several fold phases and associated structures (including mylonites) developed during a long-lasting transpressive regime (Dobmeier, 1998).

Interlayered with the metagraywackes are found meter-thick bands of green metavolcanites (*e.g.* at the train station of Les Houches) of basaltic to andesitic composition (SiO_2 = 49-60 wt%), consisting of Plg + Chl ± Amp ± Qtz. Trace-element chemistry points to Fe-basalts of E-MORB affinity (Dobmeier, 1996), possibly recording Early Carboniferous transtension linked to the opening of the sedimentary basin and to the 330-340 Ma high-K magmatic pulse.

4.2 Upper Carboniferous deposits (the Salvan-Dorénaz basin)

They are remarquably exposed in the so-called Salvan-Dorénaz Alpine syncline (northern part of the Aiguilles Rouges massif), one of the best preserved example of intramountain sedimentary basins of the Variscan Alps (Capuzzo 2000, unpub. thesis; Capuzzo and Wetzel 2000). This structure has an asymmetric, half-graben geometry, up to about 4 km wide, filled along its northwestern side with up to 1.7 km of sediments that thin to the southeast (fig. 24). Sediments are exposed for 25 km in a NNE-SSW direction along the eastern margin of the Aiguilles-Rouges massif, and are separated from the Aiguilles Rouges basement units, and from the Vallorcine granite, by a steep SE dipping mylonite zone, which may have been active during the Late Carboniferous as a right-lateral strike-slip, transtensive fault (Brändlein et al., 1994). Other steeply dipping N-S to NE-SW

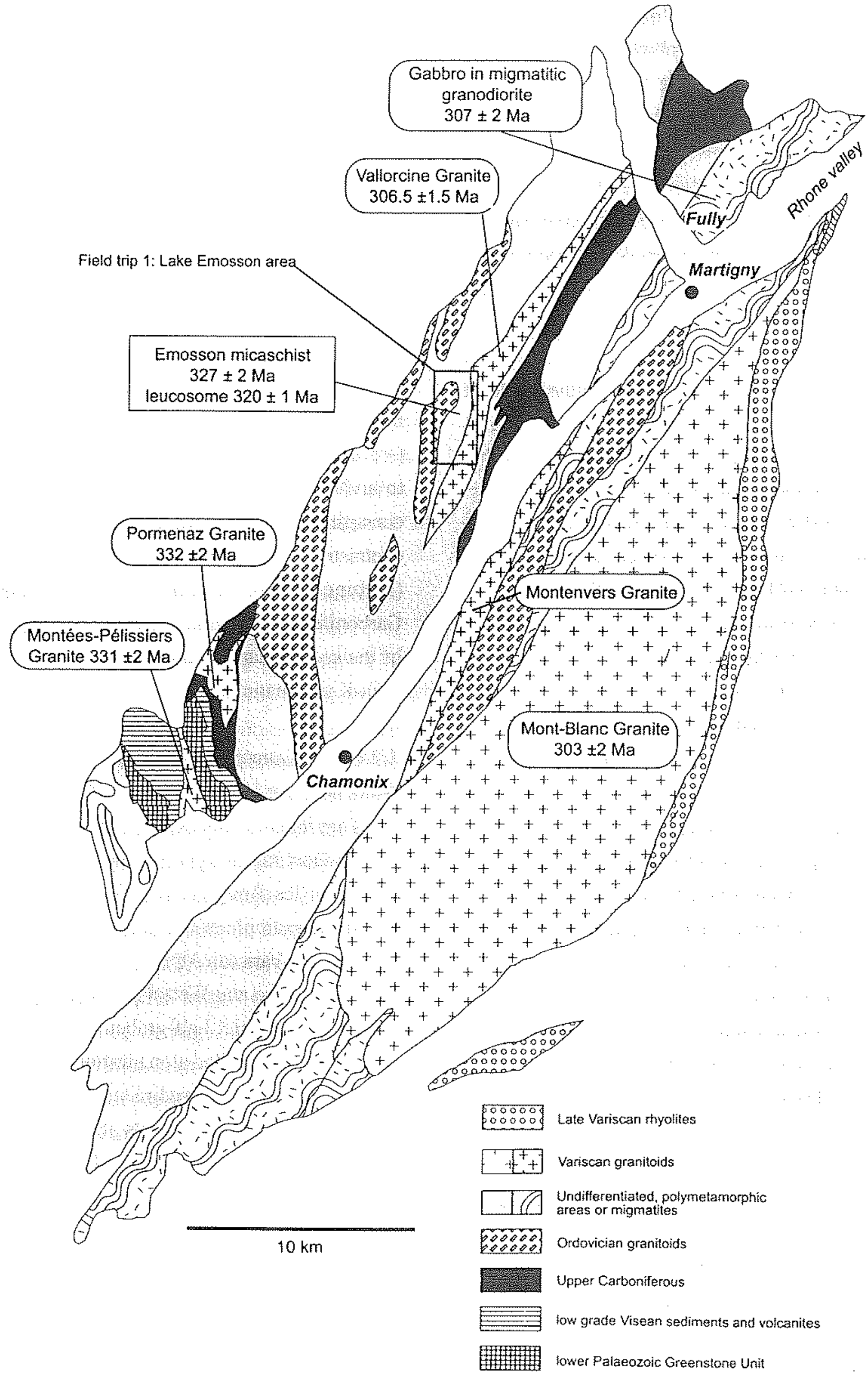


Fig. 23 - Simplified geological map of the Aiguilles Rouges-Mont Blanc massifs, after von Raumer et al.(1999).

oriented faults located near the basin margins seem to have affected the structural evolution of, and the sedimentary facies within, this basin (Pilloud, 1991; Niklaus and Wetzel, 1996). Two Alpine deformations in the brittle-ductile field, resulted in the complex synclinal structure of the basin with fold axes generally dipping 15°-20° toward the northeast (Pilloud 1991; Badertscher and Burkhard 1998). Consequently, increasingly deeper parts of the basin are exposed to the southwest. Illite-crystallinity of upper Carboniferous sediments indicate that Alpine metamorphism attained anchimetamorphic grades (Pilloud, 1991; Frey et al., 1999). A low-angle regional unconformity between the upper Carboniferous and onlapping shallow marine Triassic deposits indicates Permian erosion, probably related to moderate inversion of the basin along its flanks (Pilloud, 1991;

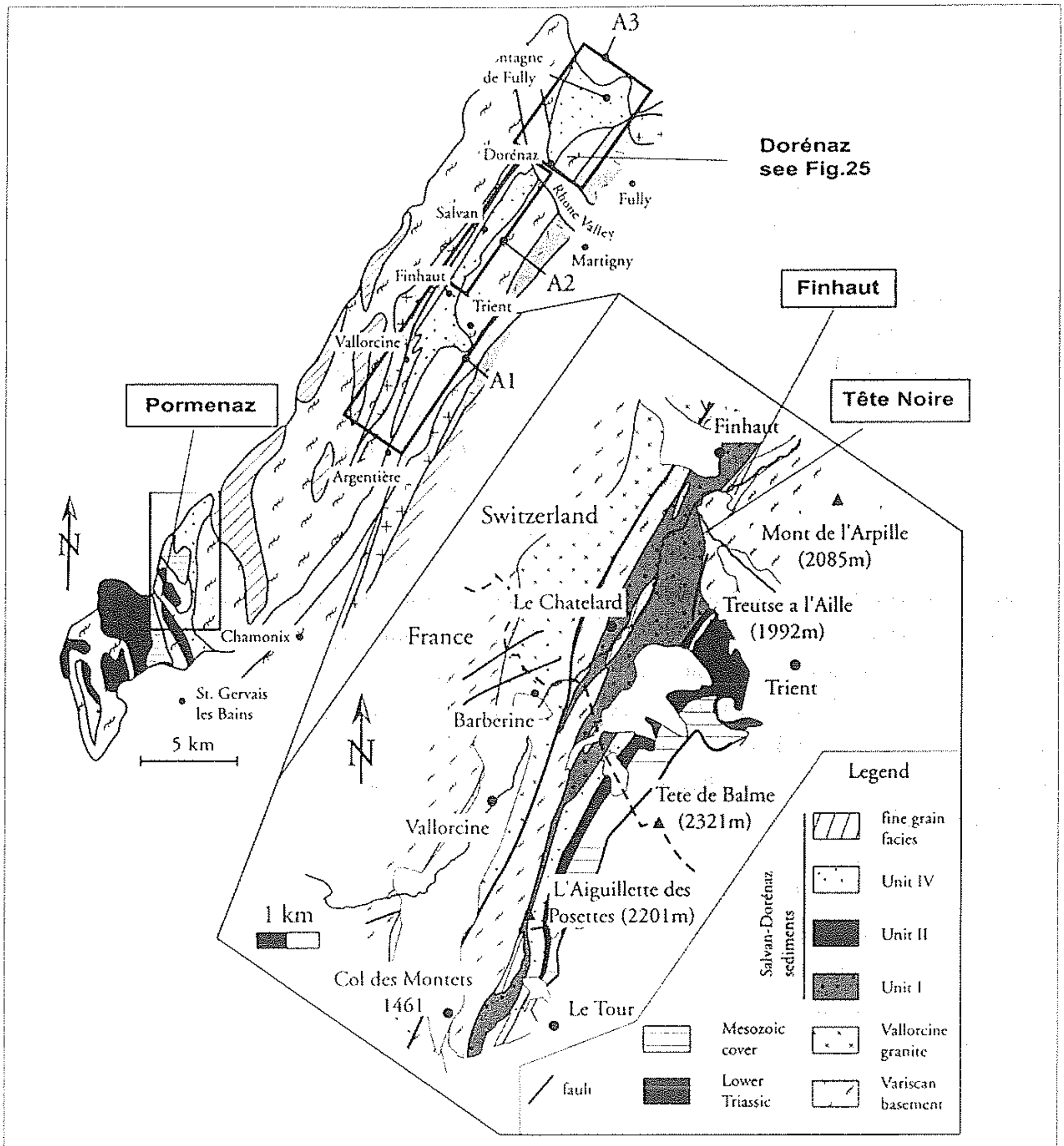


Fig. 24 - (from Capuzzo 2000, Fig. 13) Schematic map of the Aiguilles-Rouges massif (modified after Brändlein et al., 1994). and distribution of sedimentary facies in Late Carboniferous sediments. (with indication of localities).

Badertscher and Burkhard, 1998).

The age of the basin fill was first determined from palaeofloral associations, and later from isotopic dating. Macrofloral determinations indicate Late Westphalian (C-D) at the base of the succession and Stephanian ages further up (Jongmans, 1960; Weil, 1999, unpubl. data). Recent radiometric age determinations on synsedimentary volcanic deposits constrain the basin fill to the Late Carboniferous (Capuzzo and Bussy, 2000a), with ages of 308 ± 3 Ma for basal dacitic flows, and of 295 ± 3 Ma for a tuff layer from the upper levels of the basin.

4.2.1 Evolution of the Salvan-Dorenaz basin

Based on the structural analysis of Pilloud (1991), Niklaus and Wetzel (1996) and Capuzzo (2000), four lithologic units can be distinguished (alluvial fans and braided, anastomosed and meandering river deposits), which record a sedimentary evolution in a strike-slip tectonic regime (fig.25).

Unit I: The evolution of the Salvan-Dorénaz basin started at the end of the Westphalian (308 ± 3 Ma) with mainly coarse-grained clastics forming an alluvial fan system from the western margin, an overall wedge-shaped body thinning to the SE. Intense weathering produced abundant clastic material mainly derived from metamorphic and igneous rocks (Sublet, 1969; Niklaus and Wetzel, 1996). Granitoid boulders of Late Carboniferous age imply rapid uplift and denudation in the source areas. The sediments suggest deposition in an intramountain setting affected by active faulting and probably rapid uplift in the catchment areas. Mass flows and debris flows dominate the proximal areas of the alluvial fan systems close to the footwall slope, whereas the distal parts are characterised by braided distributary channels (figs 25 and 26). All climate indicators, especially a rich flora, point to a humid, seasonal climate. The groundwater table was probably close to the land surface, as dark coloured, hydromorphic paleosols dominate.

Unit II: A drastic change in facies association occurred as braided river deposits (Unit I) were overlain by mud-dominated floodplain deposits. The fine-grained alluvial plain sediments accumulated in a swampy environment with anastomosed, sand-filled channels (fig.26). They display palaeoflow to the NE and document an axial drainage. Rapid subsidence led to the reduction of valley slope, and preservation of palaeosols and primary-structured volcaniclastic deposits suggest a rapidly subsiding setting. Asymmetric subsidence is indicated by shallow-lacustrine and peat-swamp deposits along the western side of the basin. The spatial association of localised "black shales" and coals deposits with fault zones is ascribed to differential subsidence leading to the formation of shallow, temporary lakes. In the upper part of Unit II laterally persistent, thick, caliche-bearing palaeosols can be considered as evidence for low aggradation rates, during periods of tectonic quiescence under semiarid, seasonal climate. The matrix of the conglomerates and breccias deposited on the alluvial fan at the northwestern side, however, document the onset of climatic changes during early Unit II, when the hydromorphic conditions prevailing during Unit I changed to well drained conditions producing red soils indicating a warm, at least seasonally dry climate which corresponds to the Late Carboniferous-Early Permian climate scenario in the European Variscides, located within the equatorial belt (see fig.14) (Ziegler, 1990; Scotese and McKerrow, 1990).

Unit III: The anastomosed river deposits of Unit II gradually change to meandering river deposits, which reflect the readjustment of the fluvial system to an increasing valley gradient and decreasing accommodation rate. The reversal in paleoflow from NE (Unit II) to SW (Unit III) may be attributed either to drainage reversals during a

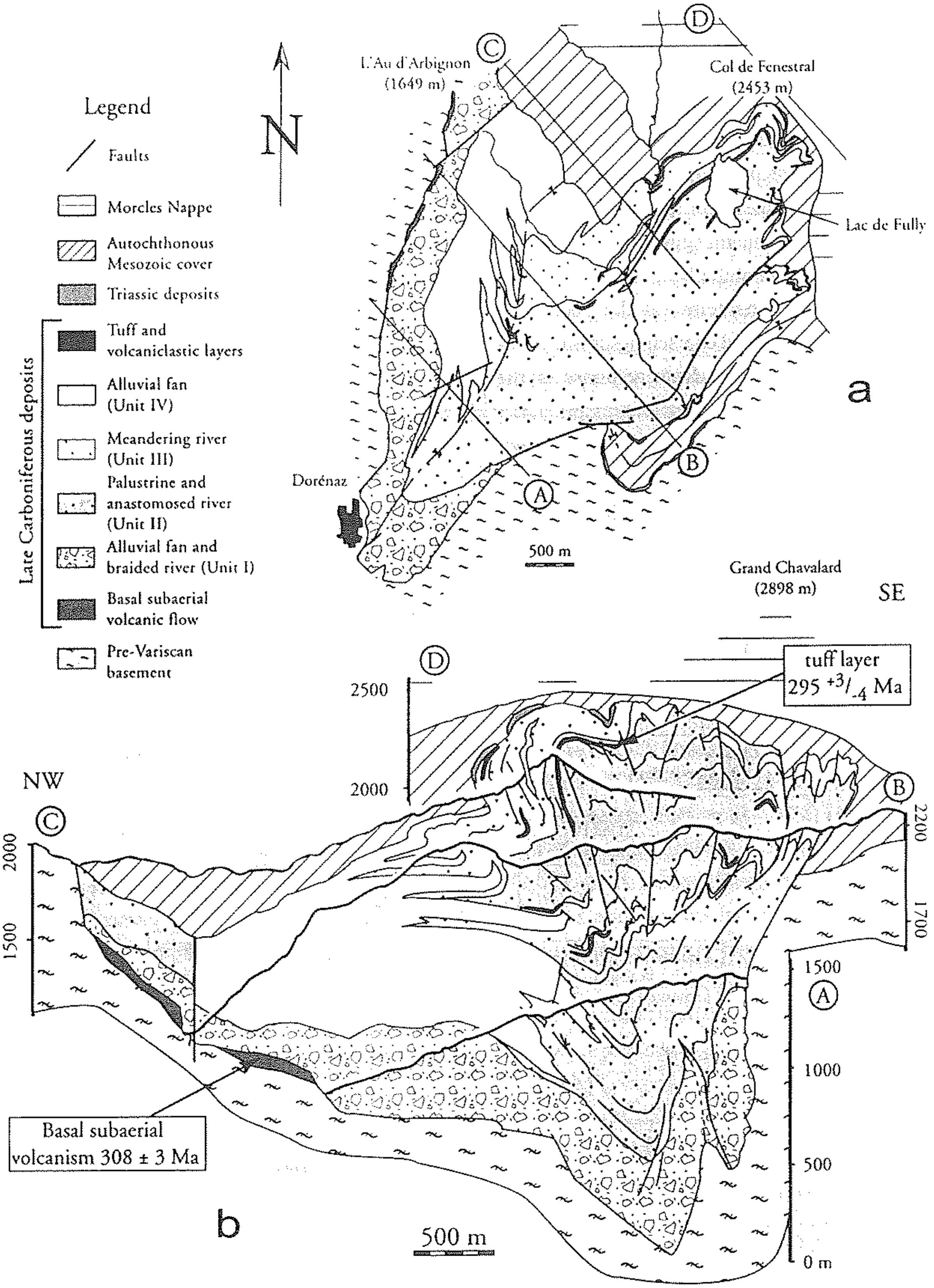
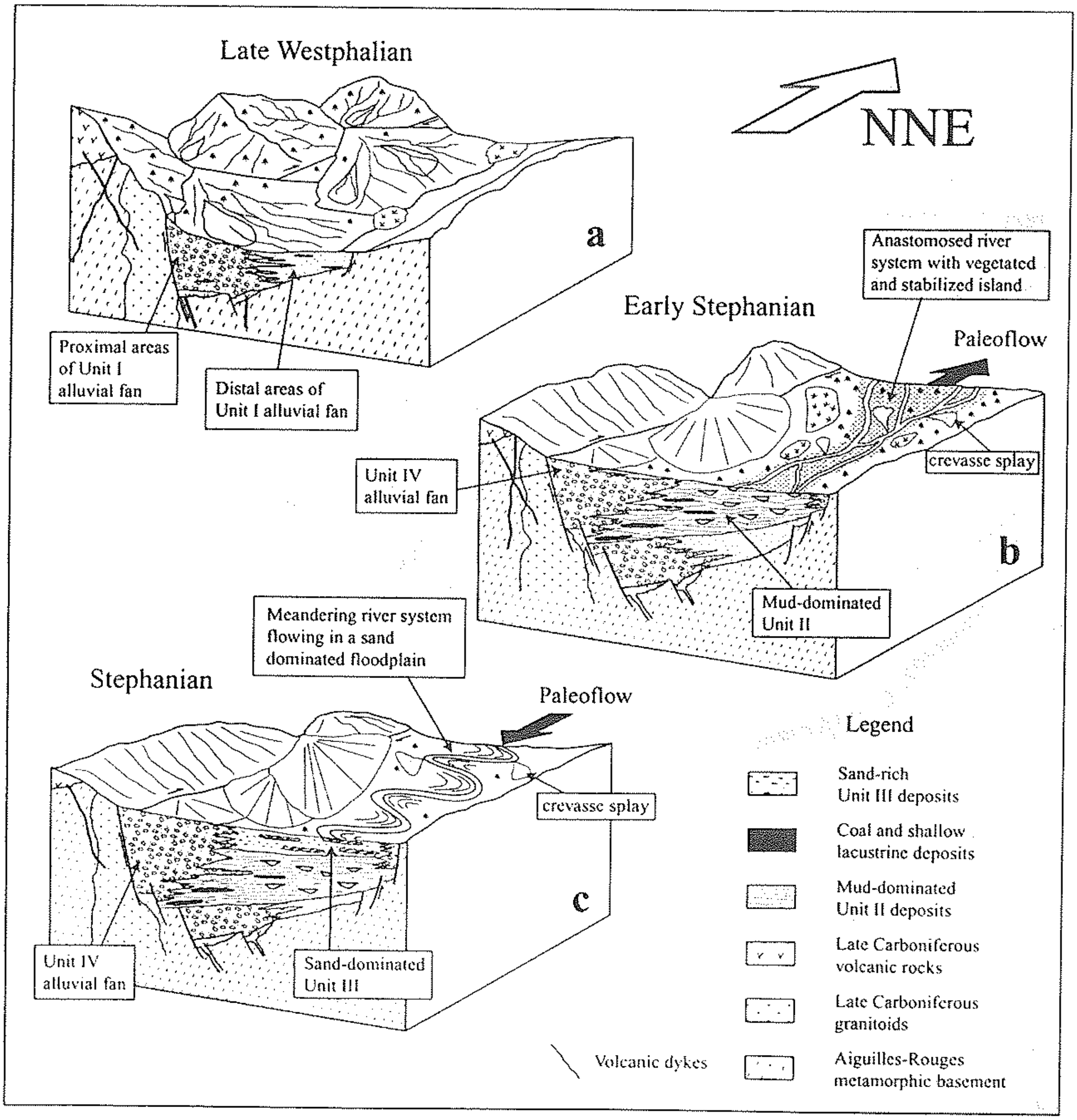


Fig. 25 (Fig 4.3 in Capuzzo 2000) : a) Geological map of the northern areas of the Salvan-Dorénaz syncline. The four lithological units that fill the basin are schematically reported, as the location of the volcanic and volcanigenic layers; b) Multiple cross-sections of the northern areas of the Salvan-Dorénaz syncline. Section lines are reported in the geological map and indicated by capital letters (modified after Pilloud, 1991).

stress field change or to uplift and subsidence of a wide area inducing backward incision of valleys and the capturing of the catchment areas of rivers draining to the opposite direction.

Unit IV: From the western margin of the basin an alluvial fan system repeatedly prograded into and retreated from the basin floor as documented by the migrating fan margin and coarsening-upward cycles. Mud at the base of a cycle documents enhanced subsidence of the basin, the overlying prograding and coarsening-upward alluvial fan sediments result from response of the catchment area to relief generation. Additionally, the alluvial fan sediments at the western side of the basin document a gradual right-lateral displacement of the fan depositional area relative to the elevated sediment source areas.

Synsedimentary volcanism: The strike-slip movements favoured synsedimentary magmatism. Basal rhyodacitic flows and autobrecciated products, localized along the north-western margin of the basin, were deposited at 308 ± 3 Ma during its initial stage of development. This lower volcanism is probably associated with the



syntectonic intrusion of the nearby Vallorcine granite dated at 307 ± 1.5 Ma. On the other hand, ash-fall and volcaniclastic layers found within sediments of Unit II and III testify for high-explosive volcanic eruptions from distant volcanic centers at 295 +4/-3 Ma (Capuzzo and Bussy, 2000). Their zircon typology presents a bimodal distribution, which suggests derivation from alkaline magma series contaminated by crustal material. Coeval, highly explosive volcanism is known from the Aar massif in the Central Alpine basement (Schaltegger and Corfu, 1995), and tuff layers associated with this magmatic event have already been described in a Permo-Carboniferous basin located in northern Switzerland (Schaltegger, 1997).

5 - Mineral assemblages and metamorphic evolution

As mentioned above, the Aiguilles Rouges–Mont Blanc massifs consist of a complex assemblage of lithological units with contrasting metamorphic histories, including non-, mono- and polymetamorphic units. Such associations might represent former basement-cover relationships or the tectonic juxtaposition of slices, which experienced different metamorphic paths. Among the polymetamorphic units, most contain mineral assemblages of amphibolite, granulite or eclogite facies grade. Although successive parageneses are observed, a clear attribution to specific orogenic events is difficult. For convenience, Alpine mineral parageneses will be distinguished from late Variscan and earlier relict assemblages, sometimes overinterpreted in the past (von Raumer 1976, 1981), but re-evaluated by von Raumer et al. (1999).

5.1 Alpine mineral assemblages

One of the main effects of the Tertiary Alpine orogenic phase in the Aiguilles Rouges – Mont Blanc area is the formation of large-scale basement folds (see general cross-section) with a locally well developed schistosity (*e.g.* in the Mont Blanc granite), as well as major fault zones, locally of mylonitic type. Alpine structures are often at angle with older ones (*e.g.* they often display a N45° orientation in the Aiguilles Rouges - Mont Blanc area against N10° for Variscan structures), but not always, as pre-existing (especially brittle) structures might be reworked, making interpretation ambiguous. As a consequence of the Alpine compression, the original distance between the Aiguilles Rouges and the Mont-Blanc massif was probably in the order of 20 km, instead of 1 km now. Metamorphic conditions reached only the lowermost greenschist facies in the Aiguilles-Rouges and a slightly higher grade in the nearby Mont-Blanc massif (400°C and 0.25 GPa for fluid inclusions in quartz, Poty et al., 1974) (von Raumer, 1971; Frey et al.; 1999).

In the Aiguilles-Rouges area, pumpellyite, prehnite and laumontite are found in weakly retrograded amphibolites; stilpnomelane is observed in the matrix of nearly undeformed Late Carboniferous rhyolites; orthogneisses yield chlorite-albite mineral assemblages, and quartz shows the first stages of undulation and low angle boundary crystallisation (polygonisation) (von Raumer 1974, 1984). Characteristic healed frac-

Fig. 26 - (from Capuzzo 2000, Fig. 2.10) Schematic block diagrams representing various depositional environments during the evolution of the Late Carboniferous Salvan-Dorénaz basin. a) formation of the basin induced by asymmetric subsidence along western bounding faults, which also favoured the emplacement of basal dacitic flows and controlled the deposition of Unit I alluvial fans derived from western source areas. Sediment production by weathering exceeded fan transport capacity. b) Deposition of the mud-dominated Unit II and establishment of an anastomosed river system with axial drainage to the NE; this change was possibly induced by increased differential tectonic subsidence within the basin; c) Deposition of the sand-dominated Unit III by a meandering river system formed in a relatively steeper fluvial valley presenting a reversal of its axial drainage towards the SW. Schematically, in figures b and c are illustrated prograding and retreating cycles of alluvial fans (Unit IV), and their right lateral displacement through time.

ture patterns appear in specific lithologies and Alpine foliation is expressed as a faint neoformation of white mica of lowest greenschist facies grade, accompanied by pressure solution of quartz grains in black shales of Late Carboniferous age. In the Mont Blanc granite, a penetrative foliation developed (leading to the so-called protogine of early authors). The mineral paragenesis [green biotite–chlorite–epidote-albite] indicates lower greenschist facies conditions (von Raumer 1963, 1971), stilpnomelane is omnipresent (von Raumer 1968) and neoformation of chlorite, garnet and/or epidote is observed along joint surfaces.

5.2 Variscan mineral assemblages

The strongest metamorphic imprint of polymetamorphic units in the Aiguilles Rouges and Mont Blanc massifs reached high amphibolite facies grade and locally anatectic conditions. The few available isotopic ages all point to a late Variscan age of 327-317 Ma (Bussy et al., 2000); but as lower Paleozoic migmatites are documented in other External Massifs, it is suspected that some high grade rocks in the Aiguilles Rouges-Mont Blanc area are pre-late Variscan in age as well. So far, only high pressure rocks (*e.g.* eclogites) can be safely related to a pre-Late Carboniferous metamorphic phase.

The high-T/anatectic late Variscan event is recorded in most lithologies of the Aiguilles Rouges massif **(Stop 1G)**, whereas the Alpine overprint destroyed all index minerals in the Mont Blanc area.

(a) Metapelites are characterized by sillimanite-bearing assemblages [Bt + Pl + Qtz + Sil ± Grt ± Crd ± Ms ± Kfs] and by late stage andalusite found in quartz ± Kfs tension gashes (Von Raumer, 1984), pointing to a clockwise decompression path typical of a Barrowian metamorphic evolution (fig. 27). Monazites from such micaschists yielded a U-Pb isotopic age of 327 ± 2 Ma at Emosson (fig. 23 and Tab. 1), interpreted as the peak temperature age (Bussy et al. 2000).

(b) Metagraywackes and metagranites experienced partial melting of variable intensity, ascribed to isothermal decompression during exhumation processes. Typical mineral assemblages of these migmatites are [Pl + Qtz + Kfs + Bt ± Sil ± Ms ± Grt ± Crd]. Monazite from a leucosome vein of a migmatitic graywacke at Emosson yielded a crystallization age of 320 ± 1 Ma, whereas monazite from a migmatitic granite in the Mont Blanc massif yielded 317 ± 2 Ma.

(c) Paragneisses of various compositions display monotonous assemblages [Qtz + Bt + Pl(olig) ± Ms ± Grt ± Sil ± Kfs] (Schulz & Von Raumer, 1993, Dobmeier, 1998).

(d) Metabasites of basaltic or gabbroic origin found as boudins of variable size record amphibolite facies conditions with mineral assemblages [Pl + Am + Ilm ± Grt ± Ca-cpx ± Zo]. Relicts of earlier high-P events are often preserved.

5.3 Pre-late Variscan mineral assemblages

As stated above, high-pressure relicts are the only mineral assemblages indisputably older than the Late Carboniferous high-T event, although none of them has been dated so far. Such relicts are found in metapelites and paragneisses as remnants of staurolite and kyanite, the latter being sometimes rimmed with reaction coronas of cordierite and spinel. High-P assemblages are better preserved in the retrograded eclogites of Lac Cornu (Liégeois & Duchesne, 1981) and Val Bérard (Schulz & Von Raumer, 1993), where [Grt + symplCpx + Am + Pl] parageneses are found. Relict omphacite Jd26 within garnet or associated with plagioclase yield T-P estimates of 700°C/0.14 Gpa and 700°C/0.08 Gpa, respectively. Leucocratic, equigranular rocks associated with some eclogitic boudins have been interpreted as early decompression melting products linked to the exhumation of high-pressure units (Von Raumer et al., 1996). A preliminary dating of zircons from one of these leucosomes

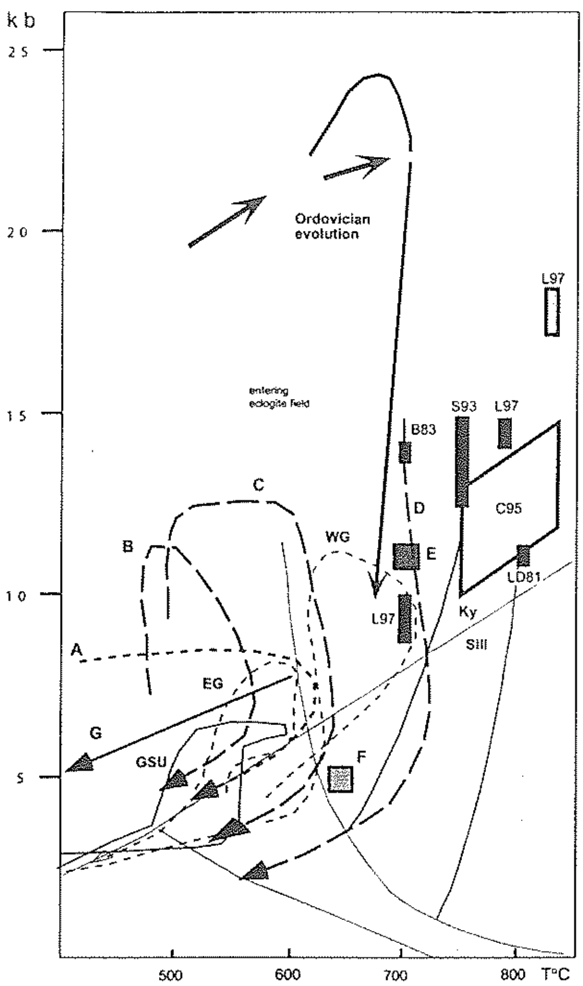


Fig. 27 - Pressure (P) – Temperature (T) evolution discussed for the External Massifs (from von Raumer et al. 1999). Reaction curves: Al-silicate stability fields after Holdaway (1971), granite solidus and corresponding dehydration melting curves after Thompson (1990).

Pre-Late Ordovician evolution in the Gotthard area (Biino 1995), P-T estimations for retro-eclogites (black boxes) and granulites (white boxes) found in the External Massifs: Argentera – B83 Latouche & Bogdanoff (1987); C96 Colombo (1995); L97 Lombardo et al (1997a,b); Aiguilles Rouges – LD81 Liégois & Duchesne (1981); S93 Schulz & von Raumer (1993).

Variscan evolution in the central Aiguilles Rouges area (from Schulz & von Raumer 1993): A, B, C - garnet bearing gneisses; D – retrograded eclogites; E - kyanite-bearing tonalitic melts from the Lake Cornu area (von Raumer et al. 1996); F – Formation of W-Au skarns, 317 Ma, Salanfe area, Chiaradia 1993); Southwestern part of the Aiguilles Rouges (St. Gervais – Les Houches area) from Dobmeier (1996, 1998): Eg – Eastern gneiss unit; WG – Western gneiss unit; GSU – Greenstone unit; North-Eastern Mont Blanc area: G – Late Variscan P-T path after Marshall et al. (1997).

yielded an age of c. 340 Ma (Bussy & Schaltegger, work in progress).

Assuming that the high-pressure episode preceded the high-temperature phase without major cooling in-between, P-T paths have been established from mineral assemblages of various lithologies (Fig.27). They point to contrasting metamorphic histories, with both counterclockwise (south of the Aiguilles Rouges, Dobmeier, 1998) and clockwise (central part of the Aiguilles Rouges, Schulz & Von Raumer, 1993) paths. The position of the early leucosomes associated with the Lake Cornu eclogites is reported on the isothermal decompression path of the latter. Marshall et al. (1997) proposed a Variscan P-T-t path for the northeastern part of the Mont Blanc massif, which is comparable to those of the Aiguilles Rouges.

6 - Magmatic evolution

Two main groups of magmatic rocks are isotopically dated in the Aiguilles Rouges-Mont Blanc massifs, an Ordovician group at 450-460 Ma and a Carboniferous group at 330-300 Ma. The existence of older intrusive or sub-aerial rocks is suspected on the basis of indirect stratigraphic and/ or lithologic arguments, but has not yet been demonstrated.

6.1 Ordovician magmatic activity

(Retro-)eclogitized pyroxenites, lherzolites and N-MORB-type basalts are outcropping in the Lake Cornu area (Aiguilles Rouges). Paquette et al. (1989) interpreted an upper intercept U-Pb zircon age of 453 +2/-3 Ma as a magmatic crystallization age. These rocks were derived from a depleted mantle source (initial $\varepsilon_{Nd} = +6$).

They have been originally thought to be emplaced in a thinned continental crust associated with the initial stages of oceanic rifting (Paquette et al., 1989) and more recently to be emplaced in a back-arc setting associated with an active continental margin (Dobmeier et al., 1999). The latter interpretation is supported by the contemporaneous intrusion of several granites of calc-alkaline (I-type) or peraluminous (S-type) character, as expected in an active continental (or island-arc) margin. Dated intrusions include the I-type Luisin granodiorite (457 ± 2 Ma, Bussy, unpublished data) in the Aiguilles Rouges and the Lognan S-type orthogneiss (453 ± 3 Ma, Bussy & Von Raumer, 1993) in the Mont Blanc massif. Other I- and S-type orthogneisses in the Aiguilles Rouges (Val Bérard, Wirsing, 1997) are presumably of similar age. **(stop 1G6)**.

Among the still undated, and possibly older magmatic rocks, are strings of amphibolite (+ retro-eclogites) boudins interlayered with metasediments, which can be followed over distances of several kilometers in the Aiguilles Rouges massif, and locally in the Mont-Blanc as well. They have been interpreted as sills or dykes of continental tholeiites (Von Raumer et al., 1990) intruded in pre-Ordovician sedimentary units, either linked to the Lac Cornu metabasites or to the Late Proterozoic / Cambrian rifting episode mentioned in the geodynamic reconstructions. Another metavolcanic sequence defined as the "Greenstone Unit" (Dobmeier et al., 1999) in the southwestern part of the Aiguilles Rouges Massif consists of an association of basalt to andesite and basalt to rhyolite lava flows of continental tholeiitic and calc-alkaline affinity, respectively. These rocks have been interpreted as additional remnants of the above-mentioned Ordovician active continental margin (Dobmeier et al. 1999).

6.2 Carboniferous magmatic activity

The Carboniferous magmatic rocks consist of syntectonic intrusive granites, locally associated with subvolcanic facies, acidic sub-aerial lava flows and volcanic/volcaniclastic ash-fall deposits. High-precision U-Pb dating evidences three short-lived pulses at 330 Ma, 307 Ma and 303 Ma (Bussy & Von Raumer, 1993; Bussy et al., 2000).

6.2.1 The 330 Ma magmatic pulse

The 330-340 Ma event is well known throughout the European Variscan belt and is characterized by high-K calc-alkaline to shoshonitic plutons. In the southwestern part of the Aiguilles Rouges massif, it is documented by the Pormenaz monzonite (332 ± 2 Ma) and the Montées-Pélissier granite (331 ± 2 Ma). **The Pormenaz monzonite** is a 1.4 by 2.5 km porphyritic funnel-shaped mass in vertical cross section, which intruded amphibolite-facies metamorphic rocks and lower Carboniferous metagraywackes (Délitroz & Fellay 1997). The shape and internal structures of the intrusion suggest a syntectonic emplacement of the magma and post-crystallization mylonitic deformations along a long-lasting dextral transpressive fault. The main facies is a porphyritic to equigranular monzonite with large pink or white K-feldspar megacrysts (up to 4 cm) in a dark gray-green amphibole-rich matrix. Euhedral crystals of brown sphene are clearly visible on hand specimen. Plurimetric bodies of durbachites (Holub 1977; Rock 1991) are found as dark green, equigranular, magmatic enclaves. The Pormenaz monzonite is characterized by high to very high concentrations in LILE like K, Rb, Ba, Sr, in Mg and transition elements like Cr, Ni, and V, and in incompatible elements like LREE, Zr and Th. Conversely, Ca is relatively low in this range of SiO_2 content. REE are strongly fractionated without substantial Eu anomaly. The durbachitic enclaves have the same chemical characteristics as the monzonites, reminiscent of lamprophyres.

The Montées-Pélissier granite is a vertical 3 km-long by 500 m-wide sheet-like pluton in tectonic contact with its country-rocks. A transpressive regime induced subhorizontal movements with extreme elongation, subsequently reoriented into subvertical displacements (Dobmeier 1998). The granite intruded syntectonically along ductile shear-zones during the transcurrent stage and recorded the subsequent vertical movements during cooling (Dobmeier 1996). Primary magmatic flow fabrics are mostly superimposed by low-T ductile to brittle deformation. The Montées-Pélissier granite is a fine-grained foliated two-mica monzogranite, which hosts rare biotite-rich restites, mafic microgranular enclaves and biotite-bearing lamprophyres. It is peraluminous with A/CNK values between 1.17 and 1.27; but primary muscovite is scarce and the mean representative point of its zircon morphological population plots at the limit between peraluminous and calc-alkaline granite fields in the typological grid of Pupin (1988).

6.2.2 The 307 magmatic pulse

Three peraluminous granites intruded simultaneously in the Aiguilles Rouges-Mont Blanc area. Located in the northern part of the Aiguilles-Rouges massif **(stop 1A and 1G1)**, the **Vallorcine granite** is a 15-km-long by 1-km thick sheet-like pluton (see fig. 23), which intruded at 306.5 ± 1.5 Ma along a steeply dipping, NE-SW trending, dextral strike-slip shear zone (Brändlein 1991; Brändlein et al. 1994). Syntectonic intrusion is inferred on the basis of structural analysis, which documents long-lasting strike-slip shearing both in the country rocks (pre- and post-intrusion fabrics) and in the granite. The latter developed an early NE-SW trending magmatic flow structure, evolving locally into a post-solidus foliation. The Vallorcine granite was subsequently affected along its SE contact by an intense low-T ductile shearing leading to the well-known "Miéville ultramylonite" (Kerrich et al. 1980) of Late Variscan age (but reworked during the Alpine orogeny). Alpine relief provides a 2000 m-high natural cross-section through the pluton. The lowermost facies is a biotite-rich monzogranite hosting numerous enclaves up to 30 cm in size: including gneiss xenoliths from the country rocks, hornfelses, micaceous restites with sillimanite and hercynite, early cordierite-bearing leucogranite blocks and mafic microgranular enclaves. The upper facies is finer-grained with less biotite and almost no enclaves, pointing to an enclave unmixing process during upward motion of the magma. Aplitic and subvolcanic dykes are concentrated within the wall rocks of the upper contact. The Vallorcine intrusion is a typical S-type granite, as confirmed by zircon typology, stable isotopes (Brändlein et al. 1994) and the presence of Al-rich minerals (cordierite, muscovite, andalusite, etc.).

The **Fully granodiorite (stop 1B)** is located in the vineyards of the northern end of the Aiguilles-Rouges massif (Krummenacher 1959). It is a highly heterogeneous, coarse-grained granodiorite of migmatitic aspect with cordierite clots (up to 10 vol.% now greenish pinite), dispersed K-feldspar megacrysts and numerous small biotite-rich restitic enclaves. Schlieren and nebulitic structures are common. Micaschists, gneisses, marbles and amphibolites are found as dm-long xenoliths, whereas mafic magmatic enclaves can reach one meter in diameter. Cordierite-bearing leucogranitic dykes and stocks crosscut the main facies. No systematic internal structure is observed. Despite the migmatitic structure, the whole mass has a clear intrusive character. It is a typical peraluminous, anatectic granitoid with a large restitic component and abundant Al-rich minerals (garnet, cordierite, muscovite, hercynite). Zircons preferentially develop the {211} crystallographic form (low A index) and plot in the expected field of intrusive aluminous granites in the typological grid of Pupin (1988). The mafic magmatic enclaves include typical mafic microgranular enclaves of intermediate composition (quartz-dioritic to granodioritic), as well as angular to rounded pieces of fine- to coarse-grained gabbros, up to one meter in size (Bovay 1988). The latter preserve clear, locally pegmatitic, undeformed igneous textures, but experienced hydrothermal alteration. Pyroxene recrystallized into Mg-hornblende + minor Mg-biotite and plagioclase (An60) is strongly sericitized.

The angular shape and absence of chilled margins indicate that these gabbro enclaves are pieces of a larger mafic body, that were incorporated as solid-state fragments into the mobile migmatitic mass. They have chemical characteristics of calc-alkaline type similar to those found in other Variscan acid-basic associations (*e.g.* Corsica, Pyrenees). Interactions with crustal material, possibly during hydrothermal retrogression, are evidenced by high contents in LILE like K, Ba and Rb. Zircon and monazite, extracted from granodioritic, leucogranitic and gabbro samples, yielded ages of 307 ± 2 Ma for all rock types. Although solid at time of incorporation into the anatectic mass, the gabbro enclaves are thus contemporaneous with the acid magmatism within errors. In other words, a mantellic basic magmatism was active at the time of enhanced crustal anatexis.

In the Mont Blanc massif, the peraluminous **Montenvers granite** was emplaced syn-tectonically at 307 ± 3 Ma as a sheet-like intrusion, in a similar way and at the same time as the Vallorcine granite. It is now a strongly deformed, often mylonitic leucocratic orthogneiss hosting both microgranular and restitic enclaves (Morard, 1998). Most primary minerals recrystallized in the greenschist facies, but zircon typology and whole-rock chemistry still point to an S-type granite.

Sub-aerial dacitic flows outcropping at the base of the Salvan-Dorénaz sedimentary basin (fig.25, p53) erupted at 308 ± 3 Ma (Capuzzo & Bussy, 2000); they represent the surface equivalent of the nearby Vallorcine granite and associated rhyolitic dykes. They are characterized by variable proportions of coherent and autoclastic scoriaceous volcanic facies interlayered toward the top with upper Carboniferous sediments. They present porphyritic textures with large euhedral and subhedral quartz and plagioclase phenocrysts. These lava flows are presumably related to the emplacement of a rhyodacitic lava dome along the north-western margin of the half-graben sedimentary basin. In the Mont-Blanc massif, calc-alkaline rhyolitic dykes were emplaced simultaneously (307 ± 2 Ma) at shallow crustal levels, but they derive from different, deeper magma sources.

6.2.3 The 303 Ma magmatic pulse

It is represented by the voluminous 303 ± 2 Ma Mont-Blanc granite, located in the Mont-Blanc massif. It is a foliated, porphyritic monzo- to syenogranite with K-feldspar megacrysts and Fe-rich biotite as the only mafic mineral (Marro 1988; Bussy 1990). It hosts numerous mafic microgranular enclaves, calc-alkaline micromonzodioritic stocks and synplutonic 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 0.705 (Bussy et al. 1989). Zircon morphology shows an extreme typology with very high A and T indices, typical of alkaline granites. The Mont Blanc granite is the last magmatic event recorded in the area, apart from ash-fall deposits embedded at different levels of the Salvan Dorénaz basin, which testify a 295 +3/-4 Ma old episode of high-explosive volcanism from distant volcanic centers, possibly located in the Aar-Gotthard massifs (Central Alps).

6.3 Typology, sources and significance of the Carboniferous magmatism

6.3.1 The high-K magmatism

The 332 Ma Pormenaz monzonite has all characteristics of Mg-K-rich magmatic suites as defined for example by Rossi and Cocherie (1995). Typical features are the ubiquity and abundance of sphene, K-feldspar megacrysts, the presence of high-Cr and Ni basic enclaves of lamprophyric affinity, high to very high contents in K, Mg, Rb, Sr, Ba, Cr, Ni, LREE, Th, Zr in all petrographic facies. Mg-K magmatic suites are well represented in the European Variscan belt, including Corsica, the External Crystalline Massifs, the French Massif Central, the Vosges and Bohemian massifs (see review of Debon et al. 1998). All available ages point to almost simultaneous intrusion between 330 and 343 Ma, in keeping with the 332 Ma age of the Pormenaz monzonite. This episode seems to be always short-lived, commonly syntectonic within major shear-zones and early in the local magmatic activity, either accompanied by anatectic peraluminous melts or not. The Pormenaz monzonite intruded at shallow depth along the transpressive border fault of a small Visean volcano-sedimentary basin (fig. 23), a situation identical to that observed in the Vosges (Schaltegger et al. 1996) and the Aar massif (Schaltegger & Corfu 1995). The development of these basins attest for local extensional zones (first extensional event of Burg et al. 1994) within an overall transpressive regime, favoring the high-level emplacement of magmas. The lamprophyre-type mafic magmatism systematically associated to the Mg-K granitoids, Sr, Nd and Hf isotopic data (*e.g.* Schaltegger & Corfu 1992; Cocherie & Rossi 1995; Janousek et al. 1995; Schaltegger et al. 1996; Gerdes et al. 1998a) and 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 crustal material.

6.3.2 The peraluminous magmatism

Peraluminous melts were generated throughout the Late Carboniferous magmatic activity of the Aiguilles-Rouges / Mont Blanc massifs, either as *in situ* or short-range mobilized leucosomes, or as larger, syntectonic intrusions along major dextral strike-slip faults. All these melts have an indisputable crustal origin, documented by their Al-rich mineralogy, high restite content, zircon typology and oxygen isotopes. Cordierite-bearing granites such as the Vallorcine and Fully intrusions, are high temperature melts formed through dehydration melting of biotite. Partial melting would be triggered by the addition of heat supplied by mantle-derived magmas, as documented by the hosted mafic magmatic enclaves (*e.g.* Fully gabbros). The latter evolve from shoshonitic to normal calc-alkaline type with time, *i.e.* from the 332 Ma Pormenaz durbachites and Montées-Pélissiers lamprophyric dykes to the 307 Ma Fully gabbros.

6.3.3 The ferro-potassic magmatism

The Mont-Blanc granite belongs to the so-called ferro-potassic or alkali-calcic or low-mg-number suites (Debon & Lemmet 1999). These suites are characterized by acid-basic bimodal magmas, high-K contents (alkali-calcic suites), Fe/Mg ratios and "A" zircon indices. Using the Fe/Mg ratio as a discriminating factor, Debon and Lemmet (1999) showed that the Variscan Fe-K granites (*e.g.* Aar, Gotthard) emplaced within a well-defined period of time between 295 and 305 Ma, in the same way as Mg-K granites did between 330 and 340 Ma. These authors ascribe the change in the Fe/Mg ratio between the two suites to a combination of several interacting factors, including the evolving nature of the magma sources, the physical and chemical conditions of melting (P, T, PH_2O, fO_2), and the geotectonic settings. According to Bonin et al. (1998), Fe-K suites document the onset of the post-orogenic stage of a Wilson cycle. They would ultimately originate in an astenospheric mantle source, replacing the older orogenic lithospheric mantle. Granitic melts would result from crustal assimilation and contamination of mantle-derived magmas, as well as [biotite + plagioclase] fractionation under relatively high water pressures.

6.3.4 Tectono-magmatic evolution

The Carboniferous tectono-magmatic evolution of the Aiguilles-Rouges/Mont-Blanc area can be synthesized in the following way (Bussy et al. 2000):

(a) Peak T metamorphic conditions are recorded at 327 Ma (peak P is undated, but is probably older) in the Emosson metapelites and isothermal decompression melting at 320 Ma. This relatively short time span requires fast uplift rates, accommodated through active tectonic exhumation. According to Thompson and Connolly (1995), decompression melting within the sillimanite-andalousite metamorphic facies cannot occur through simple erosional uplift. Exhumation was thus active already in the Late Visean, shortly after the transpressive episode recorded by the Montées-Pélissier granite. This is confirmed by $^{39}Ar/^{40}Ar$ cooling ages as old as 331-337 Ma measured on white micas from gneisses adjacent to the Montées-Pélissier granite (Dobmeier 1998). The former nappe stacking which led to crustal thickening is documented by microstructures (Dobmeier 1996), but its timing is unknown. In the adjacent Belledonne massif, nappe stacking did not occur before the Visean (Guillot & Ménot 1999) and decompression melting followed quickly during the Westphalian, a timing very similar to that of the Aiguilles-Rouges massif.

(b) The 332 Ma Pormenaz monzonite intruded along a high-strain, NNE-SSW trending mylonitic transcurrent fault, which also controlled the position of the adjacent Visean detrital basin. Considering the ultimate mantellic origin of these melts, and their usual syntectonic character in the Variscides, it is inferred that this transcurrent fault zone was a major crustal- to lithospheric-scale structure, which tapped deep-seated magma chambers or possibly enhanced melting processes. The nearby and contemporaneous Montées-Pélissier granite intruded in a similar context. Fluids circulating along the transcurrent fault might have favoured melting of crustal lithologies, triggered by heat transfer from the mantellic magmas (presence of lamprophyric dykes).

(c) The next recorded event is the simultaneous formation of the Late Carboniferous detrital basin of Salvan-Dorénaz, starting at 308 Ma (Capuzzo & Bussy 1999), and the 307 Ma magmatic pulse of cordierite-bearing granites. The Vallorcine granite intrudes syntectonically along the border fault of the basin, which is again considered as a major crustal-scale structure. Erosion is very active and thick coarse deposits are accumulating in the basin at least until 295 Ma (Capuzzo & Bussy 1999). This is interpreted as an evidence for continued tectonic exhumation in the latest Carboniferous in an essentially transcurrent to transtensional rather than extensional regime. In that context, the sedimentary trough could have formed as a kind of pull-apart structure or half-graben in case of oblique sliding (intermediate between normal and transcurrent faulting) along the border fault. Granodioritic cordierite-bearing melts require temperatures well above 800°C to form (*e.g.* Patiño-Douce & Harris 1999). Such conditions were not reached through regional metamorphism in the lower-middle crust and required additional heat, most probably supplied by the associated mafic mantellic magmatism. The lower crustal magma sources were tapped by the deep transcurrent faults along which progressive restite unmixing and crystal fractionation occurred.

(d) In the nearby Mont-Blanc massif, the larger post-tectonic 303 Ma Mont-Blanc acid-basic association intrudes within a pull-apart structure in a continued transcurrent to transtensive regime. The inferred mantellic source is different from that of the Pormenaz monzonite.

The Carboniferous tectono-magmatic evolution outlined above is virtually identical to that observed in the other External Crystalline Massifs and adjacent areas, with minor differences in the timing of events (*e.g.* Schaltegger 1997; Debon & Lemmet 1999). More generally, it is in good accordance with the overall Carboniferous evolution of the internal Variscides (*e.g.* Burg et al. 1994; Rey et al. 1997), considered as a period of post-collisional readjustment of a thickened continental crust.

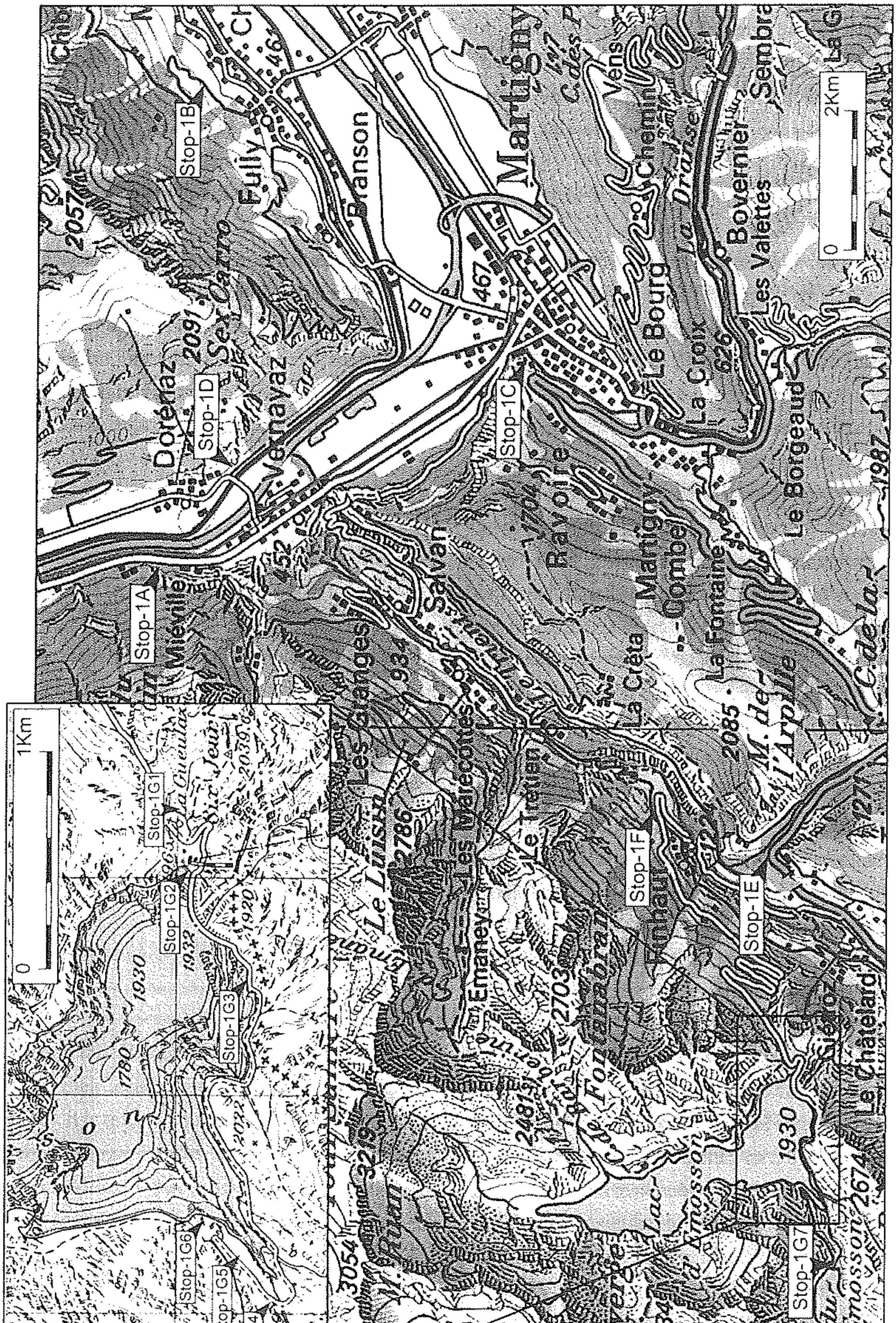
7 - Conclusions

The complex metamorphic pattern observed in the External Alpine Massifs resulted from the succession of several orogenic events combined with an early evolution in different continental blocks. Among them, the last two, *i.e.* the Alpine and the Variscan cycles, are easily recognized as they left contrasting imprints in the lithologies. Earlier events are more difficult to unravel, although an Ordovician cycle is definitely documented in all polymetamorphic basement areas (*e.g.* by the "pre-Variscan" granitoids), probably hiding relicts of an even older evolution. According to tentative reconstructions, the External Massifs were part of a post-Ordovician Gondwana-derived microplate, which evolved as an active margin (accretionary wedge, volcanic arc) during the Cambro-Ordovician period at the border of Gondwana.

The time period between the Late Ordovician intrusion of granitoids and the Variscan collision is badly constrained. The microcontinent containing the future External Massifs, like the other peri-Gondwanan microcontinents, should have followed a migration path comparable to that of the Eastern Alps before Variscan collision with Laurussia. Traces of sedimentary and magmatic evolution, during this period of rifting and drifting, were only identified in the Belledonne area. Other relicts may be hidden in the so-called monocyclic domains, if not lost during tectonic evolution or through erosion. The subsequent period is documented mostly by Variscan age information. The zonal distribution of different mineral parageneses from Ky + Grt + St to Grt + Sil, eclogite retrogression, large-scale folding and decompression melting at c. 320 Ma are ascribed to Variscan nappe tectonics and deformation of a cordillera followed by exhumation/erosion in an essentially transcurrent tectonic regime. Short-lived and bimodal magmatic pulses reflect successive stages of post-collisional restoration to normal size of a thickened continental lithosphere, in a geodynamic setting of the Variscan cordillera collapse.

Alpine orogenic events in the External Massifs induced brittle to ductile to mylonitic deformation in anchizonal to greenschist facies metamorphic conditions, as well as a late doming, which brought the massifs to their present-day high topographic position.

MAP FIELD TRIP 1



II: EXCURSION OUTCROPS

Stops are located on the topographic map on the opposite page, a structural map corresponding to the same area is found in annex (MAP 1).

STOP 1A - MIEVILLE QUARRY [568300/111000]: VALLORCINE GRANITE

Topic: Late Variscan magmatism, vertical magmatic differentiation in a syntectonic sheet-like intrusion and ultramylonitisation.
Outline: The Vallorcine granite is part of the 307 Ma magmatic pulse characterized by the syntectonic intrusion of S-type granites along major transcurrent faults. These high temperature melts result from large-scale dehydration melting of biotite in deep-seated crustal levels, probably triggered by a contemporaneous mantellic magmatic activity. Post-solidus ultramylonitisation of the Vallorcine granite testify for long-lasting transcurrent movements at the largest scale at the end of the Variscan orogeny (see details in §6.2.2).

The outcrop is located in an old quarry at the lowermost level of the vertical sheet-like intrusion of the 307 Ma old Vallorcine granite. The dominant facies is a biotite-rich monzogranite hosting numerous enclaves up to 30 cm in size; including gneiss xenoliths from the country rocks, hornfelses, micaceous restites with sillimanite and hercynite, early cordierite-bearing leucogranite blocks and mafic microgranular enclaves. The upper facies of the Vallorcine granite is visible 1600 m above at Emosson **(Stop 1G1)**, it is finer-grained with less biotite and almost no enclaves, pointing to an enclave unmixing process during upward motion of the magma. The Vallorcine intrusion is a typical S-type granite, as confirmed by zircon typology, high $\delta^{18}O$ values 9-10‰, Brändlein et al. 1994) and the presence of Al-rich minerals (cordierite, muscovite, andalusite, etc.).

Walking along the path in the small forest towards the eastern margin of the intrusion, the granite is increasingly and heterogeneously deformed with the occurrence of black stringlets of mylonite (fig. ft1-A1). About 10 meters from the contact with the upper Carboniferous host rocks, the original granitic texture is hardly recognizable, except a few K-feldspar porphyroclasts. The ultramylonite, looking like a silicified black shale at the contact, undistinguishable from a phyllite, has been carefully described by Meyer (1916); Reinhard and Preiswerk (1927) discussed its tectonic significance during the late Variscan period and its reactivation during the Alpine events. Mylonitisation resulted in a strong grain size reduction (<5 µm) without substantial mineralogical and chemical changes (see fig. ft1-A1, Steck & Vocat, 1973). Temperature during translation (superplastic flow) is estimated at 250 ± 30 °C (Kerrich et al., 1980), whereas the timing of event is not directly dated, but a Late Carboniferous age is inferred (with Alpine reworking) on the basis of Rb-Sr thin slab dating of neighboring mylonitic bands (Thöni, 1989).

STOP 1B - FULLY VINEYARDS [575460/110830]: MIGMATITIC GRANODIORITE OF FULLY

Topic: bimodal late Variscan magmatism, crustal-derived migmatitic granite and coeval gabbro enclaves (see in §6.2.2).
Outline: The Fully migmatitic intrusion is another example of the large-scale dehydration melting of crustal units in close association with mantellic magmas. It might be considered as a deeper and less evolved equivalent of the Vallorcine granite (see details in §6.2.2).

The Fully vineyard is growing on the granodioritic intrusion of Fully. The latter is best outcropping on both sides of a small road cutting along the road to the village of Eule. It is a highly

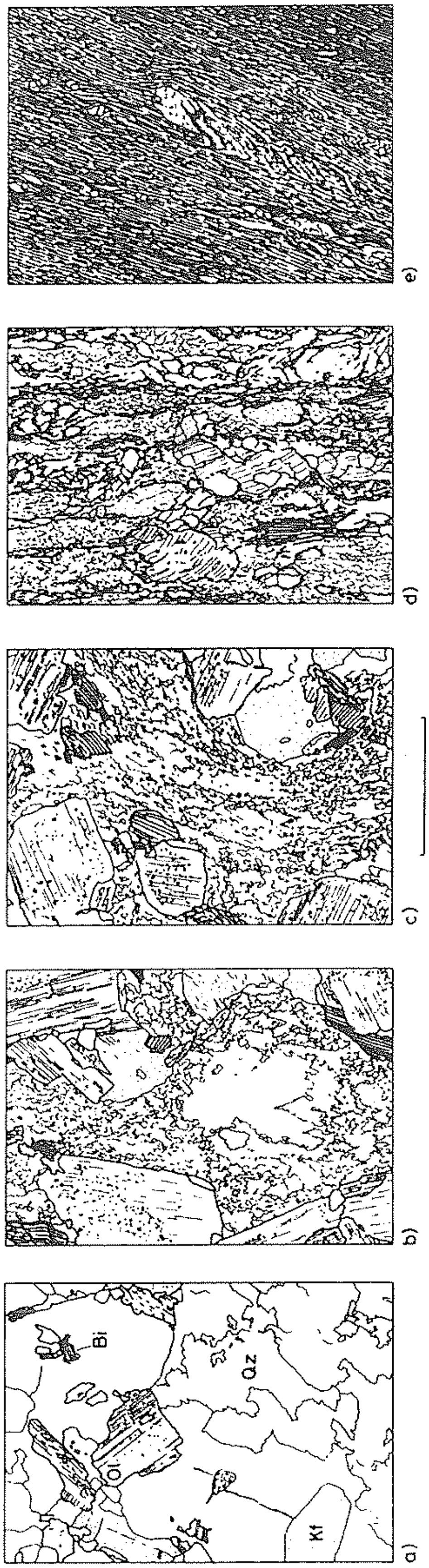


Fig. ft1-A - Progressive transform of the Vallorcine granite into an ultramylonite. Drawn by A. Steck in Masson et al. 1980.

heterogeneous, coarse-grained rock of migmatitic aspect with cordierite clots (up to 10 vol.%, now greenish pinite), dispersed K-feldspar megacrysts and numerous small biotite-rich restitic enclaves. Schlieren and nebulitic structures are common. Dm-long xenoliths are abundant as well as mafic magmatic enclaves, which can reach one meter in diameter. Cordierite-bearing leucogranitic dykes and stocks crosscut the main facies. No systematic internal structure is observed. Despite the migmatitic structures, the whole mass has a clear intrusive character. It is a typical peraluminous, crustal-derived granitoid with a large restitic component.

The mafic magmatic enclaves include typical microgranular enclaves of intermediate composition (quartz-dioritic to granodioritic), as well as pieces of fine- to coarse-grained gabbros (Bovay 1988). The latter preserve clear, locally pegmatitic, undeformed igneous textures, but experienced hydrothermal alteration. The angular shape and absence of chilled margins indicate that these gabbro enclaves are pieces of a larger mafic body, that were incorporated as solid-state fragments into the mobile migmatitic mass. They have chemical characteristics of calc-alkaline type similar to those found in other Variscan acid-basic associations (*e.g.* Corsica, Pyrenees). Zircon and monazite, extracted from granodioritic, leucogranitic and gabbro samples, yielded ages of 307 ± 2 Ma for all rock types. Although solid at time of incorporation into the anatectic mass, the gabbro enclaves are thus contemporaneous with the acid magmatism within errors.

Stop 1C - Martigny Batiaz [571400/105950]: Mesozoic metasediments (Chamonix zone)

Topic: Multiple deformation in between basement bloks.

Outline: The outcrop area is situated in the Chamonix zone, containing the Mesozoic cover (middle Jurassic to lower Cretaceous) of the adjacent basement areas. First mentionned by Oulinaoff (1924), the entire zone has been characterized by Ayrton (1980), giving details on stratigraphy and the extreme deformation. In the outcrop area, parautochthonous marly metasediments of Middle Jurassic age suffered high plastic deformation between approaching basement blocks. The main visible structures are intersection lineations l_1 between axial cleavage planes and D_1-fold-axes with strong changes from vertical to horizontal dip, representing highly plastic creep in such environment. Additionally, vertical D_3-folds are superposed on the complex structures.

Stop 1D - Dorénaz quarry [569630/110330]: Salvan-Dorénaz Late Carboniferous sedimentary basin

Topic: sedimentary structures in coarse-grained detrital deposits
Outline: The Salvan-Dorénaz basin is the best preserved of the transtensional grabens formed during the Late Carboniferous dismembering of the Variscan belt. It caught huge volumes of detritus from the neighboring eroding relief. Three stops, *i.e.* at Dorénaz, Tête Noire and Finhaut, provide typical lithologic sections in the alluvial fan system of Unit I (fig. 24), (see details in §4.2.1).

The old quarry at Dorénaz shows typical coarse-grained sediments in overturned position as a consequence of the Alpine deformation. The large size of the clasts points to a proximal position in the fan structure. Conglomerates are interlayered with coarse sandstones (fig. 26), and crossbedding as well as channel-structures are visible. A horizon with organic débris is visible in the southernmost section, where Burri (1969) discovered large coalified trunks.

Stop 1E, Tête Noire [564180/102300]: Salvan-Dorénaz Late Carboniferous sedimentary basin

Topic: original contact between the detrital sediments and the metamorphic basement
Outline: see previous stop.

The Tête Noire road cut is the nicest place to observe the original, but tilted (by Alpine compression) contact between upper Carboniferous sediments and the underlying basement. Pinpointing this contact requires careful observation, as basement rocks underwent *in situ* disintegration prior to deposition of the first sediments. The latter are black and fine-grained, but evolve westward to very coarse-grained conglomerate beds of Unit I, interlayered with finer-grained shales hosting plant debris.

Basement rocks are highly micaceous paragneisses, whose sedimentary origin is established by a finely banded layer of calcsilicate marbles, mainly composed of calcite and diopside, visible about 20 meters uproad (east) of the contact. Pegmatitic veins might be related to the 320 Ma anatectic event or to the 307 Ma peraluminous magmatism. The age of the metacarbonates is unknown, they might be of Cambrian age, as inferred for other marble lenses in the area, but a Devonian age is also possible.

Stop 1F - Finhaut [565000/103860]: Salvan-Dorénaz Late Carboniferous sedimentary basin

Topic: mass flow deposits (boulders)
Outline: see stop 1D.

Along the road-cut leading to the village of Finhaut very coarse conglomerates of Unit I can be seen, where large boulders of migmatites represent the proximal situation at the shoulder of the fan system. The dark couloured fine grained channels underline the quickly changing situation between the deposits in the channel and the very coarse-grained boulder beds.

Stop 1G - Lake Emosson [561250/101840]: Polymetamorphic basement of the Aiguilles Rouges massif.

Topic: Variscan metamorphism/anatexis and Alpine overprint of sedimentary and igneous lithologies.

Outline: The Lake Emosson area is one of the best sites to observe the polymetamorphic basement of the Alpine External Massifs. The oldest lithologies are upper Proterozoic to lower Palaeozoic sediments and volcanites, which were intruded by Ordovician granitoids (orthogneisses), before all rocks underwent Variscan metamorphism. The latter was of high amphibolite facies grade and locally induced partial melting (see field-trip introduction). Metamorphism was accompanied by long-lasting deformation with superposition of at least three fold generations, the last one being of kilometer scale. The latter is identified by ubiquitous Z-, S- and M-shaped parasitic folds, which allow distinction between adjacent anti- and synforms. Alpine metamorphism reached low greenschist facies grade. All units are unconformably overlain by sandstones of Triassic age, hosting the famous saurian footprints (Demathieu and Weidmann 1982) in the Vieux Emosson Lake area. The Alpine dome-like structure of the massif is underlined by the position of the Mesozoic sediments, which rest horizontally on top of the basement rocks in the middle of the massif (Aiguille de Belvédere, 2600 m), whereas they are steeply dipping on both margins of the latter in the Rhone valley (400 m above sea-level).

A walk around the lake from east to west will give the opportunity to recognize the main lithologies of the polymetamorphic basement. The lakeshore is a continuous outcrop, but only a limited number of topics have been selected.

Vallorcine granite (stop 1G1)

The upper facies of the Vallorcine granite is outcropping right after the car park, along the small road to the dam. Compared to the lower facies of Miéville **(stop 1A)**, it is finer-grained with less biotite and almost no enclaves, which is thought to result from an enclave unmixing process during upward motion of the magma. The intrusive contact of the granite with its gneissic host rocks is visible behind the small chapel facing the restaurant (coord. 561310/102000). It is characterized by a 1 m thick brecciated and silicified band, with fibrous quartz crystallized radially all around the clasts. This spectacular texture has been interpreted as a result of hydraulic brecciation during the shallow level intrusion of a fluid-saturated granitic magma (Genier, 2000).

Mylonite-Zone (stop 1G2)

At the eastern dam edge, a nearly 500 m large mylonite zone separates the Vallorcine granite from the polymetamorphic metasediments located further to the northwest. Despite the very strong deformation, former orthogneisses (Ordovician granitoids) and metasediments, like calc-silicate lenses (former calcsilicate marbles) can be recognized. The strike-slip tectonics producing the mylonites probably facilitated intrusion of the Vallorcine granite. The Rb-Sr-thin-slab method of dating (Thöni 1989) produced an age of 300±20 Ma for the general deformation (± 500°C), which corresponds to the age of the Vallorcine granite, 307 Ma (Bussy et al. 2000). Microstructural observations (Joye 1989) show that the entire zone is dominated by dextral shearing with formation of a subhorizontal stretching lineation (dip 20° NE) produced through a SSW/NNE tangential compression of pre-existing, more horizontal structures (S_2). Joye (1989) interpreted narrow, very fine-grained, dark veinlets of glassy constitution as probable pseudotachylites.

Metasedimentary units (stop 1G3)

Complex and superimposed tectonic structures exclude any lithostratigraphic reconstruction in the Aiguilles Rouges massif. Only major sequences or units can be crudely identified at the map scale. They consist of:

(I) a unit of graywackes with metapelitic interlayers;

(II) a mixed unit composed mainly by metapelites with some thin metagraywacke layers, one quartzite horizon, one layer of carbonates (appearing mostly as large boudins), and hosting one or two amphibolite layers;

(III) a third unit characterized by finely banded metagraywackes and metapelites with a rusty patina.

Many detailed observations are found in von Raumer (1983), von Raumer and Schwander (1985), Schulz & von Raumer (1993), Dupasquier (1996), Schmocker (1996), Fracheboud (1997), and Marquis (1997). A comparison with other European lithostratigraphic sections brings convincing evidence that these lithologies have a Late Proterozoic to Early Palaeozoic age (see field-trip introduction).

Metaquartzites (stop 1G4) form a recognizable white horizon, which can be followed in the field when mapping strongly boudinized pieces preserved in the highly plastic micaschists. They are rather coarse-grained quartzitic sandstones with tiny garnets and a faint layering underlined by biotite.

Metapelites and metagraywackes (stop 1G5) record a Barrowian-type of metamorphism with early [biotite-staurolite-kyanite-garnet] assemblages evolving towards [biotite-garnet-sillimanite] parageneses. Joye (1989) locally observed sillimanite and cordierite in strongly sheared rocks among the mylonites. The thermal peak has been dated at 327 ± 2 Ma (U/Pb on monazite, Bussy et al. 2000). Late stages are quartz segregation lenses with K-feldspar and andalusite. Such a sequence of parageneses does not necessarily represent a continuous PT-path, but could reflect two distinct events, *i.e.* an early-Variscan high pressure phase and a late-Variscan, more temperature dominated phase. Geochemical data from different localities indicate that metagraywackes carry the fingerprints of an active margin setting (Bhatia 1983), resulting from the erosion of quartzitic lithologies or acidic volcanites (Roser and Korsch 1988). This agrees well with our general interpretation of shelf sediments located at the Gondwana active margin (see introduction).

Marbles are rare, strongly sheared and completely smeared out among the hosting rock series. Larger lenses are locally preserved as banded calcite-diopside rocks. This lens shape is either the result of boudinage during stretching of the hosting micaschists, or might represent former patch-reefs, a well-known lithology in the Cambrian. These calcsilicate lenses are often hosting scheelite ore deposits, which most probably resulted from metasomatic transfer during late Variscan granite intrusions (Chiaradia 1993).

Metabasites (stop 1G6) appear as boudin-shaped amphibolites, mainly concentrated in the micaschist-series, but also as eclogite bodies, as in the Lake Cornu area, situated a few kilometers to the southwest. Distribution of amphibolites in km-long strings of boudins point to the former existence of one or two relatively thin layers, best preserved in the fold-hinges. They mainly consist of amphibole – plagioclase ± diopside ± garnet, and pseudomorphs of former zoisite needles. Von Raumer et al. (1990) distinguished two main groups of amphibolites: plagioclase amphibolites (former spinel-olivine-tholeiites with relatively higher contents in Cr and Ni) and garnet-plagioclase amphibolites (former hypersthene- or quartz-tholeiites with enriched values of V and P), which were considered to represent a magmatic differentiation series. The fine grain size of the amphibolites and high TiO_2 and V-contents (>0.5% and > 100 ppm, respectively) suggests a volcanic or subvolcanic origin (Pfeifer et al. 1989). The original rocks were interpreted (von Raumer et al. 1990) as transitional MORB volcanites typical for continental rift zones at the onset of ocean floor spreading. Their age could be either Cambrian or Ordovician. Some of the largest amphibolite bodies are accompanied by leucocratic garnet-bearing gneisses, containing large crystals of staurolite and kyanite, the latter with reaction rims of cordierite and hercynite, interpreted as a HT-decompression reaction (Dupasquier, 1996). The origin of these leucocratic rocks remains unexplained, but they could result from dehydration melting of amphibolites comparable to those observed in the Lake Cornu area (von Raumer et al. 1996).

Orthogneisses (stop 1G7) occupy large areas in the Emosson region, as large dike-like bodies, which record two phases of folding, as illustrated by the huge, steeply dipping fold structure adjacent to the former Barberine dam site (now flooded by the Emosson lake) (von Raumer 1984). This fold is clearly visible in the landscape and helped to understand the complexity of the regional structures during mapping of the area. Both I-type (hornblende-biotite-bearing granodiorites) and S-type (biotite-bearing porphyritic granites) intrusions were identified (Wirsing, 1997). The Luisin granodiorite has been dated at 457 ± 2 Ma (U-Pb on zircon, Bussy, unpubl. data), whereas an S-type augengneiss from the nearby Mont Blanc massif intruded at 453 ± 3 Ma (Bussy and Von Raumer, 1994). This magmatic event is ascribed to an active margin context, as also documented by the MORB-type mafic rocks of the Lake Cornu area (von Raumer et al. 2001). The late Variscan metamorphism is well documented in the orthogneisses, which experienced partial melting. Late Variscan strike-slip deformation is also documented through C-S tectonites.

Migmatites (stop 1G3)

Partial melting affected several of the above-cited lithologies, in particular muscovite-bearing metagraywackes and the orthogneisses. Migmatitic structures are beautifully outcropping along the road west of the dam. Besides local structures due to Alpine metamorphism and deformation, the leucosomes clearly record syn- to post-anatexis dextral shearing. Monazites from one of the thickest leucosome lens yielded an age of 320 ± 1 Ma (Bussy et al. 2000). The leucosomes mainly consist of K-feldspar (50-60 vol%), quartz (30%) and plagioclase (5-30%) ± muscovite ± biotite (Genier, 2000). These are mostly local melts, which did not substantially migrate. Anatexis is ascribed to the dehydration melting of muscovite during the high-T isothermal decompression of the rocks. Adjacent metapelites host abundant folded quartz veinlets of metamorphic origin, but no leucosomes at all. Considering that pelites usually melt more readily and at lower temperatures than graywackes, a major tectonic contact is inferred between the migmatitic metagraywackes unit and the non-migmatitic metapelites, for which a lower peak metamorphic temperature is postulated.

Alpine deformation

Alpine metamorphism increases from northwest to southeast throughout the orogen; it is of lowest greenschist facies grade in the Aiguilles-Rouges area (estimated at c. 275°C, on the basis of mineral textures and stability). Most rocks at the dam site show traces of Alpine deformation, where every rock type carries its own characteristics (von Raumer 1974, 1984). Pumpellyite, prehnite and laumontite are found in weakly transformed amphibolites, and stilpmnomelane is observed in the matrix of almost undeformed rhyolites of

Permian age. Granitoid orthogneisses yield chlorite-albite mineral assemblages when approaching higher levels to the overlying nappes, where also small drag-folds appear. Quartz shows the first stages of undulation and low angle boundary crystallisation (polygonisation). Depending on the lithology, conjugated shear systems with corresponding tension gashes developed at different scales. Orthogneisses developed a general, closely spaced fracture cleavage with tiny chlorite-filled tension gashes, whereas micaschists show two sets of larger shearing planes with growth of fiber quartz crystals parallel to the stretching direction. In the slightly deformed overlying Triassic sandstones, tension gashes are up to 10 cm long. All three types of brittle shear probably represent one answer to the same Alpine deformation in the vicinity of the basal Alpine nappe thrust plane.

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