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The Palaeozoic metamorphic evolution of the Alpine External Massifs

by Jürgen von Raumer¹, Jürgen Abrecht², François Bussy³, Bruno Lombardo⁴, René-Pierre Ménot⁵ and Urs Schaltegger⁶

Abstract

The pre-Mesozoic metamorphic pattern of the External Massifs, composed of subunits of different metamorphic histories, resulted from the telescoping of Variscan, Ordovician and older metamorphic and structural textures and formations. During an early period, the future External Massifs were part of a peri-Gondwanian microplate evolving as an active margin. Precambrian to lower Palaeozoic igneous and sedimentary protoliths were reworked during an Ordovician subduction cycle (eclogites, granulites) preceding Ordovician anatexis and intrusion of Ordovician granitoids. Little is known about the time period when the microcontinent containing the future External Massifs followed a migration path leading to collision with Laurussia. Corresponding rock-series have not been identified. This might be because they have been eroded or transformed by migmatization or because they remain hidden in the monocyclic areas.

Besides the transformations which originated during the Ordovician subduction cycle, strong metamorphic transformations resulted from Variscan collision when many areas underwent amphibolite facies transformations and migmatization. The different subunits composing the External Massifs and their corresponding P-T evolution are the expression of different levels in a nappe pile, which may have formed before Viséan erosion and cooling. The presence of durbachitic magmatic rocks may be the expression of a large scale Early Variscan upwelling line which formed after Variscan lithospheric subduction. Late Variscan wrench fault tectonics and crustal thinning accompanied by high thermal gradients triggered several pulses of granite intrusions.

Keywords: Palaeozoic, Ordovician, metamorphic evolution, subduction, External Massifs, Alps.

1. Introduction

The pre-Mesozoic basement areas of the External Massifs (Argentera, Pelvoux/Haut-Dauphiné, Belledonne-Grandes Rousses, Mont Blanc-Aiguilles Rouges, Aar-Tavetsch-Gotthard) are window-like structures appearing in the geological map (Fig. 1) among their Mesozoic cover and, in geophysical cross-sections (PFIFFNER et al.,

1996), they represent updomed basement nappes or slices separated by their sedimentary cover. As Mesozoic-Tertiary transformations will be discussed in other papers, we will assume only the pre-Permian evolution of these units. Despite Alpine transformations, the pre-Mesozoic basement areas preserve enough relics to allow their Palaeozoic metamorphic evolution to be deciphered.

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All massifs have in common that they have been lying, at least since the Stephanian, at erosion level and this implies that a minimum of 10 km had already been eroded from the poly-metamorphic domains at that time. However, Lower Carboniferous detrital sediments indicate, that local erosion must have started earlier. Our considerations will be guided by the present-day configuration of the basement areas, but we make the point that, despite the apparent homogeneity of the metamorphic basement suggested in classical geological maps (metamorphic basement, granitoids, Carboniferous cover), it is by no means homogeneous.

Behind the apparent simplicity of the massifs a lengthy geological evolution becomes visible. In the following sections we present the data and observations (2, 3, 4), and in section 5 we offer a more interpretative explanation of the metamorphic evolution than can be deduced from the geological map.

2. Timing of events

During the last five years a wealth of precise information has been added to the metamorphic history. For ease of understanding, we subdivide the metamorphic evolution of the External Massifs into different periods. Obviously, the main overprint comprises pre-Stephanian processes leading to the formation of the Variscan mountain chain and its destruction. At the same time, many relics testify to an earlier evolution comprising late Precambrian rifting (sedimentation, formation of oceanic crust), early Palaeozoic arc forma-

tion and subduction, accompanied by intrusion of Ordovician granitoids. We have therefore a poly-orogenic evolution, comprising Variscan, Ordovician and late Precambrian events, all which are partly confirmed by age data (Tab. 1).

2.1. PALAEOONTOLOGICAL EVIDENCES

Few palaeontological remains are known from the external domain. A possible Visean age is discussed, based on fossil traces, from the Taillefer detrital series (Tab. 2; Ta, Fig. 2C) of the Belle-donne-area (GIBERGY, 1968), and a comparable age is given to low-grade metapelitic series of the Servoz-Les Houches domain in the SW edge of the Aiguilles Rouges massif (SGH, Fig. 2D; BELLIERE and STREEL, 1980). A Cambrian to Ordovician age is based on Reitlingerellides from black and green schists in the Grandes Rousses massif (Huez formation, Hu, Fig. 2C; GIORGI et al., 1979).

2.2. ISOTOPIC AGES

Information about the oldest events is based on Archean and Proterozoic (Pan-African) cores of detrital zircons (GEBAUER et al., 1988, 1989; SCHALTEGGER, 1993, 1994; ABRECHT et al., 1995; SCHALTEGGER and GEBAUER, 1999), and that for the three main groups of Palaeozoic events is summarised in table 1. These groups cover the early Palaeozoic (500–420 Ma), a Devonian evolution, and the period of Variscan collision (340–295 Ma), subdivided into different age groups (magmatic evolution, thermal peak, cool-

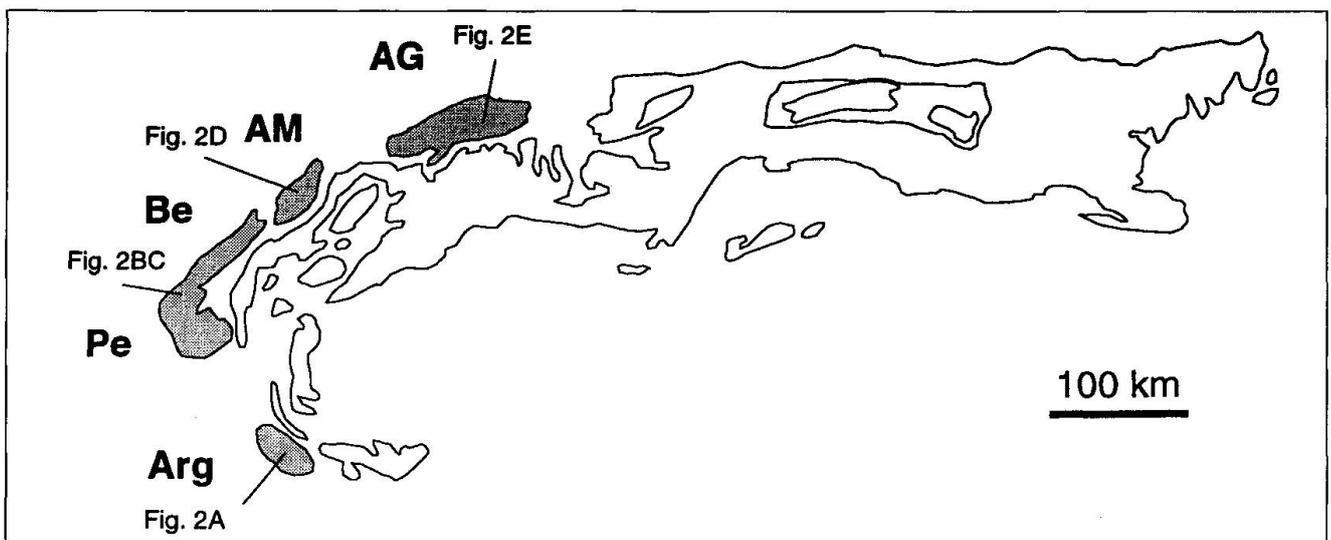


Fig.1 Distribution of pre-Mesozoic basement in the Alps. Hatched areas: External Massifs. **AG**: Aar-Tavetsch-Gotthard massifs; **AM**: Aiguilles Rouges / Mont Blanc massifs; **Arg**: Argentera massif; **Bel**: Belledonne massif; **Pe**: Pelvoux massif.

Tab. 1 Isotopic age determinations from the External Massifs.

Age, method	Rocks	Reference
A Early Palaeozoic events		
496 ± 6 Ma U/Pb Zrn	plagiogranite, dating	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	migmatites, Aar massif	SCHALTEGGER, 1992, 1993
456 ± 2 Ma U/Pb Zrn		
436 ± 17 Ma Rb/Sr wr	granitoids, Gotthard	ARNOLD, 1970 a, 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	Trondhemite, Belledonne	MÉNOT et al., 1988b
350–373 Ma Ar/Ar Ms	Argentera	MONIÉ and MALUSKI, 1983
C Late Variscan evolution		
	<i>shoshonitic-ultrapotassic- monzonitic rocks</i>	
332–334 Ma, U/Pb Zrn	Aar massif	SCHALTEGGER, 1994
333 Ma U/Pb Zrn	Tödi granite, Aarmassif	SCHALTEGGER and CORFU, 1995
333 ± 2 Ma U/Pb Zrn	Aiguilles 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., 1994, 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
325–335 Ma Ar/Ar Am	greenstone unit, w. Aiguilles 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	Metapelit, 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 Aiguilles Rouges	BUSSY and HERNANDEZ, 1997
308–310 Ma, U/Pb Zrn	diorites, granitoids, Aar massif	SCHALTEGGER, 1994
307 Ma, U/Pb Zrn	gabbros, granitoids; Aiguilles R.	BUSSY and HERNANDEZ, 1997
304 ± 3 Ma U/Pb Zrn	Mt. Blanc granite	BUSSY et al., 1989
308 Ma U/Pb Zrn	acidic volcanics, Aiguilles Rouges	CAPUZZO and BUSSY, 1998
± 300 Ma, U/Pb Zrn	partial melting Aar massif	OLSEN et al., 1997
299–303 Ma U/Pb Zrn	pyroclastic deposits, Aar massif	SCHALTEGGER and 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 Ma U/Pb Zrn	acidic volcanics, Aiguilles Rouges	CAPUZZO and BUSSY, 1998

(wr = whole rock age; ev = Zrn evaporation age)

ing ages). The age data indicate Cambrian intrusion of mafic and ultramafic rocks in the western domain. In the eastern domain, a Cambro-Ordovician orogenic evolution is characterized by island arc gabbros and their eclogitization (OBERLI et al., 1994; ABRECHT et al., 1995), followed by anatexis and granitoid intrusion. Ordovician anatexis and intrusion of granitoids also appear in the data from the western areas. Late Silurian-Early Devonian eclogite-ages should be interpreted cautiously as they may represent influences of early Variscan metamorphic events. The Devonian intrusion of trondhjemitites in the SW Belledonne massif (MÉNOT et al., 1994) indicates continental rifting, whereas traces of Early Devonian tectonics seem to be preserved in the polymetamorphic domains of Belledonne and Aiguilles Rouges. After the general collision during the Early Carboniferous, several magmatic pulses and ongoing tectonic evolution considerably modified earlier assemblages and structures.

Complementary to the fossil findings of the other massifs, the Visean age of the Tödi granite in the Aar massif (SCHALTEGGER and CORFU, 1995) confirms the presence of Visean clastic rocks which the granite is crosscutting. The late Variscan, mainly magmatic evolution (SCHALTEGGER, 1994; BUSSY and HERNANDEZ, 1997), may be subdivided into rather short-lived magmatic pulses and comprises: (i) a Visean assemblage of shoshonitic-ultrapotassic-monzonitic rocks (340–330 Ma) and a general Visean cooling (\pm 333 Ma), followed by (ii) a thermal pulse including the formation of migmatites (320 Ma), a pulse around 310–306 Ma with gabbros, diorites and granitoids, and (iii) a still younger pulse characterized by granitoids and pyroclastic deposits at around 300 Ma.

This preliminary review of the main age groups serves to show, that the geological evolution of the External Massifs is not straight forward. For a better understanding of the complex, long-lasting evolution, we must consider the lithologic units (section 3) and their metamorphic evolution (section 4), before presenting the complex geological history of the External Massifs.

3. Lithologic units

Many units have been partly transformed into migmatites, or into amphibolite facies rocks (metapelites, metagreywackes, amphibolites, retrograded eclogites, serpentinites, granitoid orthogneisses, calcisilicate-marbles) where relics of older mineral parageneses indicate a complex geologic evolution. When discussing the metamor-

phic evolution (see below), special care must be taken to differentiate between a Cambro-Ordovician plate tectonic event and the Variscan collisional history. Where evidence such as granitoids or migmatites of Ordovician age is lacking, the attribution to a former Precambrian to lower Palaeozoic sedimentary series is questionable, as sediments of Ordovician to Devonian origin may also be found in the so-called polymetamorphic areas. An example of such a difficulty is the controversial interpretation of metasediments from the "cortex Chaillol series" (Tab. 2; Ch, Fig. 2B) and from the "noyau" (core) of the Pelvoux area (LE FORT, 1973). Metasediments from the "cortex" can be interpreted as forming the cover of the polymetamorphic "noyau"; however, the latter could also represent metasediments comparable to the "cortex" but with a higher-grade metamorphic imprint. The age of the metasediments encountered in the "cortex" and in the "noyau" of the Pelvoux area is still a matter of debate as, besides Precambrian to lower Palaeozoic sediments, sequences of Middle Palaeozoic age could also be encountered (see below). A further matter of debate is the Tremola series of the Gotthard area (Tab. 2; Tr, Fig. 2E), which may represent Devonian or Lower Carboniferous units (MERCOLLI et al., 1994). Despite such considerations, several main lithological age groups may be distinguished.

3.1. PRECAMBRIAN TO SILURIAN UNITS

The occurrence of dated Ordovician acidic volcanics or granitoids (Tab. 1, "pre-Variscan granitoids" in the metamorphic map) is evidence for the existence of pre-Late Ordovician sedimentary series serving as country-rocks for these intrusions. Comparing such lithologies in the different outcrop areas, we have to keep in mind that relics of former lithologies observed in the polymetamorphic units, undifferentiated pre-Variscan basement on compilatory maps (VON RAUMER et al., 1993), migmatitic or undifferentiated, polymetamorphic domains (Fig. 2), may have their counterparts in less metamorphic subunits.

The former sediments, encountered in the External Massifs, were composed of detrital sequences with some minor carbonate intercalations and containing layers of basic volcanic rocks. ABRECHT et al. (1991) suggested the existence of Ordovician olistostromes in the Aar massif, while former detrital sediments enriched in Cr and Ni, together with eclogites and ultrabasic rocks (Aiguilles Rouges, VON RAUMER and FRACHEBOUD, unpublished data) may represent compara-

Tab. 2 Monocyclic and low grade metamorphic units in the External Massifs

Unit	Authors	Characteristics
ARGENTERA (Fig. 2A) Valetta unit (Va)	BOGDANOFF, 1986	black micaschists (relics of Ky, St, Sill) with amphibolites, marbles, and quartzites, supposed Cambrian or Upper Silurian age.
PELVOUX / HAUT DAUPHINÉ (Fig. 2B) Chaillol series (Ch)	LE FORT, 1973	"cortex"; composed of amphibolites, black micaschists (Ky, St, Grt), marbles, and conglomerates of unknown age. Supposed pre-Visean age.
Olan series (Ol)	LE FORT, 1973	Composed of amphibolites, amphibole augengneisses, chlorite-biotite-gneisses, originally representing latitic volcanics. Possible time-equivalent of Visean durbachitic-vaugneritic volcanics of the other external Massifs (Tab. 1).
BELLEDONNE / GRANDES ROUSSES (Fig. 2C, 3B) Série satinée (SS)	MÉNOT, 1987b	Low-grade metasediments, mainly micaschists and chlorite-schists with few intercalations of quartzites and carbonates. Of special interest are horizons with albite blasts. Unknown age, perhaps Precambrian or Cambro-Ordovician age, but also an upper Ordovician age might be probable (former tillite?).
Chamrousse-Séchilienne	MÉNOT, 1987b, 1988	Cambro-Ordovician inverted ophiolite complex, with ultrabasic, basic, volcanic and volcano-sedimentary sequences. Metamorphic evolution comprises early, intra-oceanic extensional tectonics and Devonian to Early Carboniferous low-grade overprint.
Allemont gneiss (Al)	MÉNOT, 1987a	Micaschists, marbles, metavolcanics, supposed early Palaeozoic age, relics of Ky, St, Sil, Grt, followed by greenschist facies overprint.
Rioupérroux-Livet (RL)	MÉNOT, 1986	Devonian rift situation, mainly bimodal volcanic evolution, followed by intrusion of granitoids and acidic volcanics; relics of Ky, St, Grt, followed by greenschist facies parageneses.
Taillefer series (Ta)	MÉNOT, 1987a	detrital series with conglomerates, few carbonates, metavolcanics, probably Devonian to Late Visean age, low grade greenschist facies of Late Visean age.
Huez schists (Hu)	GIORGI et al., 1979	low-grade micaschists, quartz-schists, chlorite-schists, with amphibolites, marbles, quartzites; higher greenschist facies, Cambrian fossils.
MONT BLANC / AIGUILLES ROUGES (Fig. 2D, 3C) including St-Gervais-Les Houches (SG) Greenstone unit (GSU)	DOBMEIER, 1996	Pre-Carboniferous (Cambro-Ordovician?, Devonian?) unit composed by a variety of calc-alkaline volcanics, indicating a supposed volcanic arc situation.
Visean sediments	DOBMEIER, 1996	Low-grade detrital sediments with andesitic and Fe-basaltic volcanics of Visean age (BELLIERE and STREEL, 1980).
GOTTHARD (Fig. 2E) Tremola series (Tr)	MERCOLLI et al., 1994	Composed of marine metasediments (shales, carbonates, sandstones), supposed middle Palaeozoic age.

(Abbreviations: see Fig. 2)

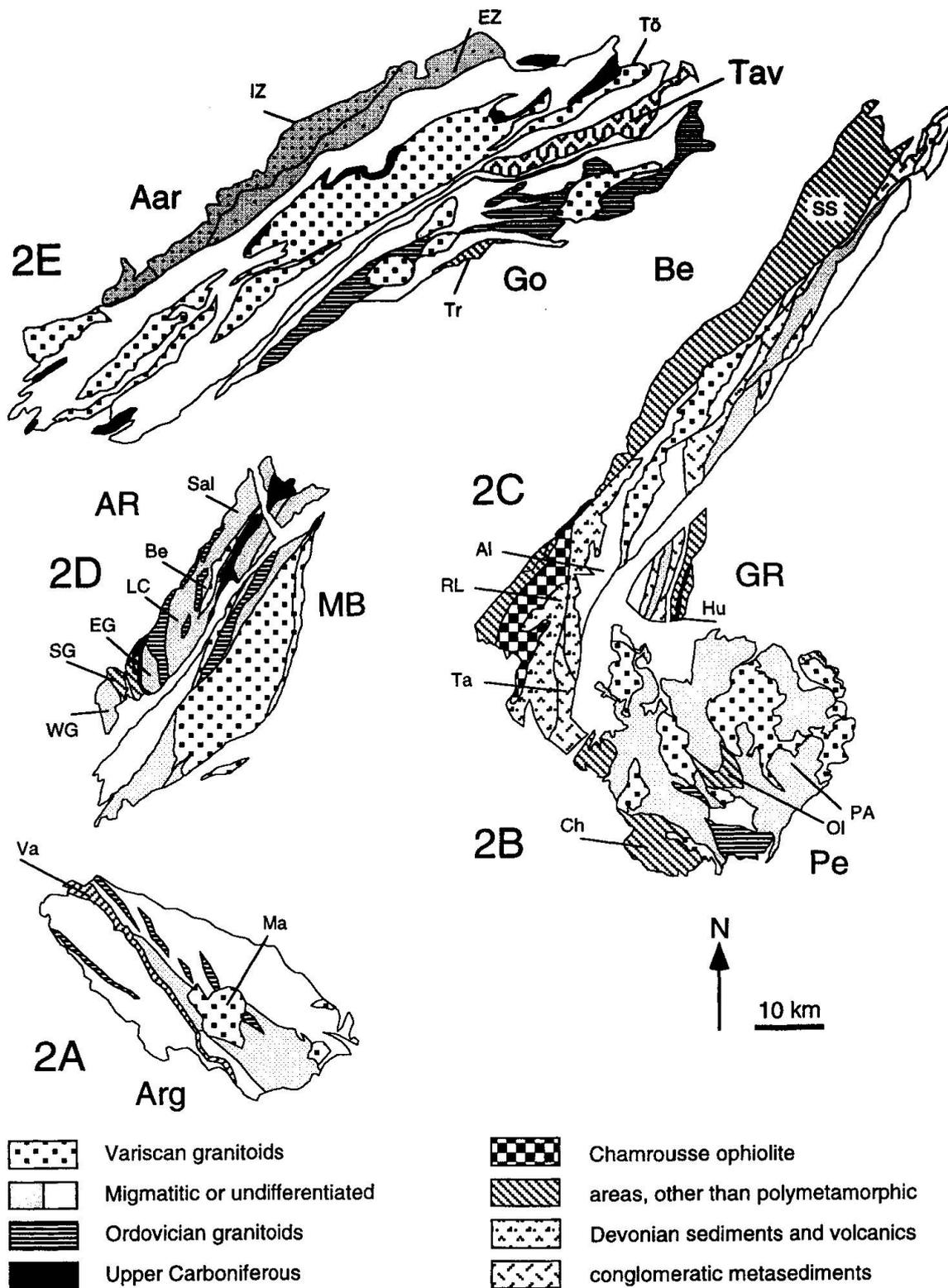


Fig. 2 Geological information about the External Massifs (see also Tab. 2). The areas "other than polymetamorphic" comprise: Argentera **Va** – Valetta unit; Pelvoux **Ch** – Chaillol series; **Ol** – Olan gneisses; Belledonne **Hu** – Huez series, **SS** – Série satinée; Aiguilles Rouges **SG** – St-Gervais – Les Houches area, comprising the Greenstone unit (GSU) and Viséan sediments.; Gotthard **Tr** – Tremola series.

Aar: Aar massif; **Al**: Allemont unit; **AR**: Aiguilles Rouges; **Arg**: Argentera; **Be**: Val Bérard; **Bel**: Belledonne; **Ch**: Chaillol unit; **EG**: Eastern gneiss unit; **EZ**: Erstfeld gneiss zone; **Go**: Gotthard; **GR**: Grandes Rousses; **Hu**: Huez region; **IZ**: Innertkirchen gneiss zone; **LC**: Lac Cornu; **Ma**: Malinvern granite; **MB**: Mont Blanc; **Ol**: Olan gneisses; **PA**: Peyre-Arguet area; **RL**: Riouxpérour – Livet; **Sal**: Salanfè area; **SG**: St-Gervais – les Houches area; **Ta**: Taillefer area.; **Tav**: Tavetsch; **Tö**: Tödi area; **Tr**: Tremola; **Va**: Valetta unit; **WG**: Western gneiss unit.

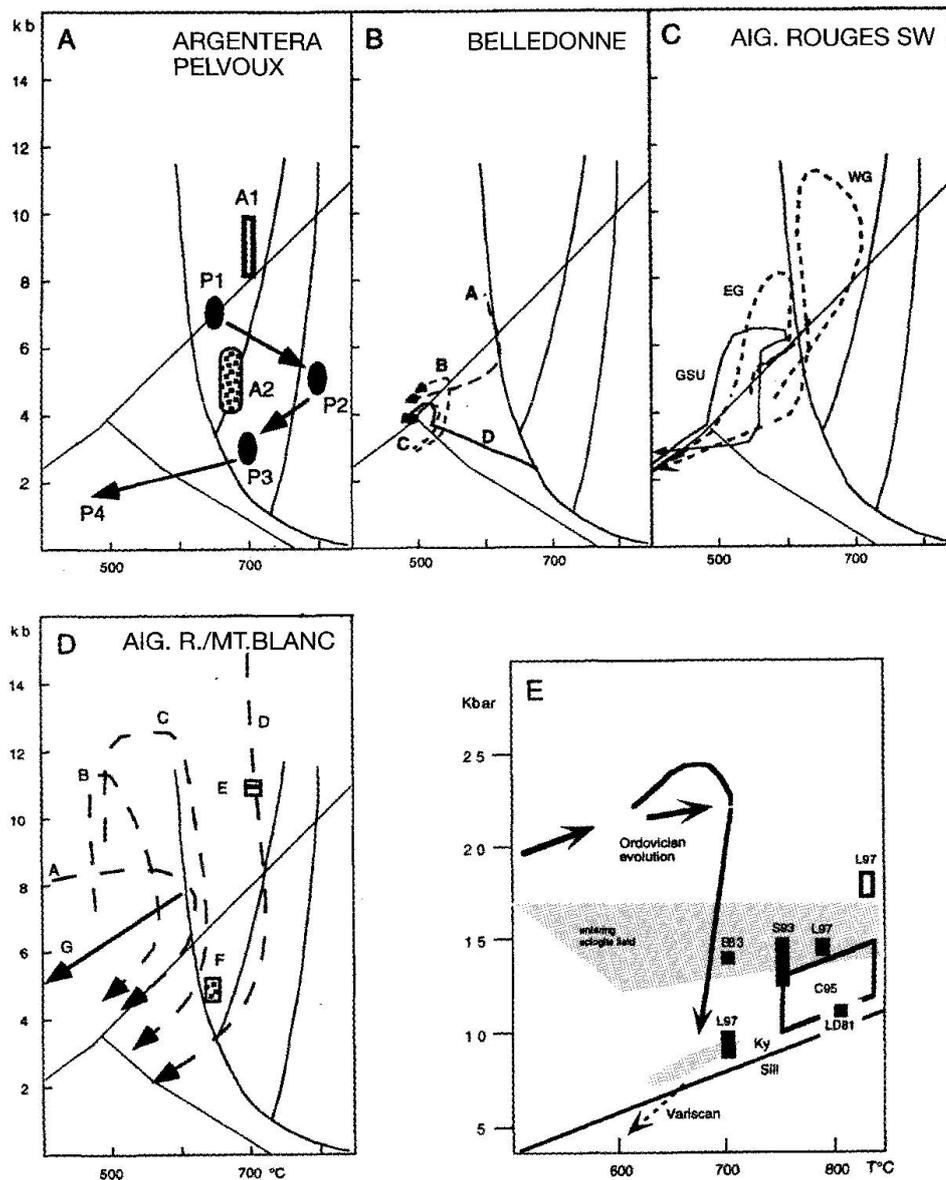


Fig. 3 Pressure-temperature evolution in distinct areas of the External Massifs during Ordovician and Variscan orogenic events. Although state of knowledge and of data is different for the massifs, the diagrams show evolution paths, which are either based on sound petrographic and field observations, or on petrologic data (see text and references therein). Reaction curves: Al-silicate stability fields after HOLDAWAY (1971); solidus of granites and corresponding dehydration melting curves after THOMPSON (1990).

3A: Argentera: **A1** – Amphibolite facies of retrograded eclogites (BIERBRAUER, 1995); **A2:** Formation of migmatites (BIERBRAUER, 1995). Pre-Variscan retro-eclogite or granulite data: see Fig 3E. **Pelvoux:** Supposed Variscan evolution (P1–P4, see text) of granulites from the Peyre-Arguet area (PA, Fig. 2B; GRANDJEAN et al., 1996).

3B: Estimated Variscan evolution of different nappe units in the Belledonne area (MÉNOT, 1987 a, b): **A** – evolution of Allemont gneiss formation (Al, Fig. 2C); **B** – Devonian-Dinantian orogenic evolution of the Chamrousse ophiolite; **C** – evolution of Devonian Livet metasediments (Li, Fig. 2C); **D** – Trondhjemites of the Livet formation.

3C: Variscan P-T evolution in the southwestern parts of the Aiguilles Rouges massif (St-Gervais – Les Houches area, SG, Fig. 2D; DOBMEIER, 1996, 1998); EG, WG (see text); GSU: Greenstone unit (comprised in SG, Fig. 2D).

3D: Variscan P-T evolution of the central part of the Aiguilles Rouges massif and the northeastern Mont Blanc massif (Val Bérard area; Be, Fig. 2D, SCHULZ and VON RAUMER, 1993): **A, B, C:** Grt-bearing gneisses; **D:** Retrograded eclogites; **E:** Ky-bearing tonalitic melts from the Lac Cornu area (LC, Fig. 2D, VON RAUMER et al., 1996); **F:** formation of W-Au-skarns, 317 Ma (Salanfe area; Sa, Fig. 2D, CHIARADIA, 1993). **G:** Late Variscan P-T-path after MARSHALL et al. (1997) in the north-eastern Mont-Blanc area.

3E: Pre-Late Ordovician and Variscan P-T path (arrows) after BIINO (1995); and P-T estimations for retro-eclogites (black boxes) and granulites (white boxes) found in the External domain: Argentera: **B83** – LATOUCHE and BOGDANOFF (1987); **C96** – COLOMBO (1996); **L97** – LOMBARDO et al. (1997 a, b); Aiguilles Rouges: **LD81** – LIÉGOIS et DUCHESNE (1981); **S93:** SCHULZ and VON RAUMER (1993).

ble deposits, although their age has to be confirmed. Banded amphibolites occurring locally are interpreted as former basaltic lavas of lower Palaeozoic age (VON RAUMER et al., 1990; MÉNOT and PAQUETTE, 1993). The presence of oceanic crust is demonstrated by the Cambro-Ordovician Chamrousse ophiolite body in the Belledonne massif (Fig. 2C; MÉNOT, 1987b). Its layered gabbros and peridotites have been affected by intra-oceanic extensional tectonics (MÉNOT, 1987; GUILLOT et al., 1992). Although relics of serpentinites are observed in all massifs, they do not necessarily represent the same generation of oceanic crust, as older rock suites may have also been preserved (PFEIFER et al., 1993).

These lithologic units must be interpreted in a global sedimentary and tectonic framework involving the peri-Gondwanian origin of the basement units hidden in the Alps (VON RAUMER et al., 1998 a, b; VON RAUMER, 1998). On this global interpretation, the External Massifs had their origin at the Gondwana margin which was surrounded, during the Cambrian and Ordovician, by extended areas of the same sedimentary facies (NOBLET and LEFORT 1990, PARIS and ROBARDET 1990, COURJAULT-RADÉ et al., 1992). Consequently, the pre-Late Ordovician sedimentary development preserved in the metasediments of the External Massifs, may be seen to represent the evolution through plate tectonic processes from an upper Precambrian platform and rifting situation to an Ordovician accretionary wedge situation at the Gondwana margin, thus explaining the similarity of protoliths of metamorphic rock series observed in the polymetamorphic domains of the different massifs.

In the external domain appear metasedimentary sequences of unknown age which may represent less metamorphosed time-equivalents of the above mentioned polymetamorphic domains. The Allemont unit from the internal part of the Belledonne area (Al, Fig. 2C; Tab. 2), which attained amphibolite facies grade, may serve as an example of this. Additionally, the flysch-type low-grade micaschists ("série satinée"; Tab. 2; SS, Fig. 2C), appearing in the external part of the Belledonne massif, may correspond to a comparable plate-tectonic situation, although an origin as former Ordovician tillite might also be possible. The "Chaillol-series" from the Pelvoux "cortex" (Fig. 2B, Tab. 2; LE FORT, 1973) should also be considered under this heading. The well established lithological sequence comprises, at the base, amphibolites, followed by pink marbles and black micaschists, the latter overlain by conglomerates (containing marble pebbles). It is difficult to determine whether this series represents, at its base, Cambro-

Ordovician metabasic series, overlain by lower Palaeozoic metasediments and even younger conglomerates, or if it should be classified under the Devonian-Carboniferous lithologic units.

3.2. DEVONIAN UNITS

In the southwestern part of the Belledonne area, the Rioupéroux-Livet lithologic unit has been described and dated (Tab. 2, Fig. 2C; MÉNOT et al., 1988a; MÉNOT and PAQUETTE, 1993). Trondhjemitic intrusives (see Tab. 1) and time-related bimodal volcanic rock series may represent a stage of aborted Devonian rifting, which may have a continuation in the Grandes Rousses massif (Fig. 2C) and in the Chaillol series of the Pelvoux area (Ch, Fig. 2B, Tab. 2; MÉNOT et al., 1994).

3.3. LOWER CARBONIFEROUS UNITS

Lower Carboniferous tectonics, volcanic activity and sedimentary products are closely related. In the Aar Massif, FRANKS (1968), SCHENKER (1987), BÖHM (1988), and OBERHÄNSLI et al. (1988) observed a detrital series containing subaerial pyroclastic deposits formed in a rifting environment which, on the basis of the age of the Tödi granite, is attributed to the Visean (see Tab. 1). In the Western Alps, comparable clastic, fossil-bearing deposits (see above) accumulated during an extensional regime, accompanied by bimodal volcanism, before the Stephanian fluvialite sediments were deposited (MÉNOT, 1986, 1987b; DOBMEIER, 1996). Comparable units may be part of the "Taillefer series" (Ta, Fig. 2C) in the Belledonne area. All External massifs have a Visean magmatic event in common (Tab. 1) characterized by durbachitic-monzonitic-Mg-potassic magmas. Although not dated, the amphibolitic "gneiss d'Olan" (Ol, Fig. 2B, Tab. 2; LE FORT, 1973) may represent the time-equivalent in the central part of the Pelvoux area.

4. Mineral assemblages and metamorphic evolution

In a first approach the External Massifs have to be subdivided into slices of lithological subunits (Fig. 2; locally the so-called mono- and polymetamorphic subunits), which may represent a former basement-cover relationship or, before stacking, tectonic slices of one lithological unit with different metamorphic histories. Such subunits have

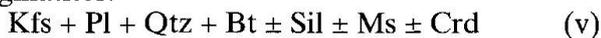
been discussed extensively for each area (Tab. 2, Fig. 2; Argentera: BOGDANOFF, 1986; Pelvoux: LE FORT, 1973; Belledonne: MÉNOT et al., 1994; Aiguilles Rouges-Mont Blanc: VON RAUMER et al., 1993; Aar: ABRECHT, 1994; Gotthard: MERCOLLI et al., 1994).

Most parts of the External Massifs are underlain by polymetamorphic basement containing mineral assemblages of amphibolite, granulite or eclogite facies grade. Although a succession of parageneses is observed, the late Variscan amphibolite facies or Alpine greenschist facies transformations do not enable the recognition of older metamorphic events. In the domains, where Alpine metamorphism was only of very low grade, it is convenient to differentiate late Variscan mineral parageneses from relic assemblages. Such assemblages had been interpreted optimistically (VON RAUMER 1976, 1981) and require careful re-evaluation on the basis of new observations and age data.

4.1. LATE VARISCAN MINERAL ASSEMBLAGES

Parts of the high-grade metamorphic basement areas received their polymetamorphic character through a late Variscan overprint, attaining amphibolite facies and migmatite conditions. It is therefore convenient to begin with the characteristics of this late Variscan evolution. Although migmatites of Early Palaeozoic age have been proved to exist in the External Massifs, late Variscan anatexis has also been observed in several polymetamorphic areas. The late Variscan metamorphic evolution had its thermal peak during the Viséan and was accompanied or followed by the intrusion of granitoids (see Tab. 1). Former greywackes and granitoids, transformed into migmatites, display the assemblages (for all assemblages of this text; v: Variscan, c: pre-Variscan; mineral abbreviation after BUCHER and FREY, 1994):

migmatites:



and metapelites:



Such mineral assemblages are observed in the Argentera, Pelvoux, Belledonne, Aiguilles Rouges, and Mont Blanc massifs (BORTOLAMI and SACCHI, 1968; LE FORT, 1973; CARME, 1974; VON RAUMER, 1983; BOGDANOFF, 1986; BIERBRAUER, 1995; COLOMBO, 1995; BARFETY et al., 1997; GUILLOT and MÉNOT, in press). Rocks in the Gotthard area reached amphibolite facies conditions (ARNOLD, 1970a). In the Aar massif, greenschist to lower amphibolite facies conditions have been at-

tained (ABRECHT et al., 1995), and OLSEN et al. (1997) proved the formation of Late Carboniferous partial melts (Tab. 1).

In several areas, andalusite formed during a late stage. In the Aiguilles Rouges, the assemblage Qtz + And \pm Kfs is found in mineral clefts, and undeformed andalusite appears as nodules on tension gashes (VON RAUMER, 1984). Locally, contact metamorphism around the late Variscan granitoids led to newly-formed biotite flakes (Mont-Blanc granite, VON RAUMER, 1984), and to recrystallized quartz (Vallorcine granite, JOYE, 1989). In the Aar massif, SCHENKER and ABRECHT (1987) observed andalusite, garnet, muscovite, and biotite in the contact aureole of the Central Aar granite, and andalusite at the contact of the Tödi Granite indicates (EUGSTER, 1951), that after contact metamorphism no further overprint by higher pressure has affected this area. COMPAGNONI et al. (1974) described biotite, andalusite, and sillimanite in the contact aureole of the central Argentera granite.

4.2. PRE-LATE VARISCAN ASSEMBLAGES

In many localities isotopic age information is lacking for mineral assemblages characteristic of amphibolite facies preceding the Late Carboniferous thermal peak but a pre-Late Variscan or an Ordovician age may be deduced from other informations (see annotations). They appear as relics in the polymetamorphic domains, but are also found in those domains that have not been affected by late Variscan anatexis. In a later section we will discuss mineral parageneses from metapelites and from retrograded eclogites, and related rocks. Meta-carbonates also attained amphibolite facies conditions but we do not propose to consider them further, as information on the fluid composition, and thus on their P-T evolution, is lacking.

In metapelites, relics of kyanite, staurolite and garnet were found in many regions where the Alpine overprint remained weak. Such parageneses, which testify to a medium-grade metamorphic evolution, will be presented. Metabasic rocks and retrograded eclogites, either of basaltic or gabbroic origin, are well known from all polymetamorphic areas in the external massifs. In general they attained amphibolite facies conditions (Pl + Am + Ilm \pm Grt \pm Ca-Cpx \pm Zo) during their late Variscan metamorphic overprint. In many places, relics give additional information on earlier events (numbers indicate localities in figure 2; again for all parageneses: v – Variscan, c – pre-Variscan paragenesis):

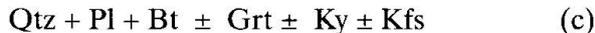
4.2.1. Argentera massif

The metamorphic map indicates a mainly Variscan amphibolite facies evolution with formation of migmatites. Orthogneisses of Ordovician age and late Variscan granites appear locally. Pre-Variscan relics of granulite- and eclogite-facies and local findings of sillimanite and kyanite are evident. Besides polymetamorphic evolution of all domains, a late-stage regional anatexis was reached only in the eastern part (Fig. 2A). In metapelites, the general presence of kyanite is mentioned in the western parts of the massif, where it is also found as large crystals in late-metamorphic veins (PIERROT et al., 1974).

– In the contact area around the central Argentera granite, COMPAGNONI et al. (1974) mentioned relics of kyanite preserved in plagioclase belonging to a contact metamorphic paragenesis.

– In the eastern part, in St. Anna and Rio Freddo regions, BORTOLAMI and SACCHI (1968) observed relics of garnet, staurolite and probably also kyanite, in metapelites containing biotite, cordierite and sillimanite.

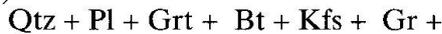
– In the migmatitic domain, mainly in the southeast and east of the Malinvern granite body, assemblages of different metasedimentary gneisses (COLOMBO, 1995; BIERBRAUER, 1995) can be summarized as:



– In the same area, COLOMBO et al. (1993) reported the granulite facies assemblage from highly aluminous xenoliths in the Late Ordovician metadacite body:



– whereas felsic granulites from several localities (COLOMBO et al., 1995; LOMBARDO et al., 1997a) preserve the high grade assemblage (Fig. 3E):



Retrograded eclogites and granulites have been described from different localities. In the north-western part, LATOUCHE and BOGDANOFF (1987) described kelyphitic garnet amphibolites, coronitic gabbros, and retrograded granulites. They also calculated pressure and temperature values corresponding to conditions intermediate between high-grade amphibolite and granulite facies.

In the southwestern domain, two unretrograded eclogitic parageneses were described by LOMBARDO et al. (1997b). A body of omphacite granulite interlayered with eclogite yielded the paragenesis $\text{Pl} + \text{Grt} + \text{Omp}$ ($\text{Jd}_{30}\text{Aug}_{70}$). Geothermobarometry (Fig. 3E) suggests equilibrium conditions of about 18 kbar / 830 °C. Such estimates are

consistent with values obtained for relic $\text{Pl} + \text{Ky} + \text{Grt}$ parageneses of felsic granulites (18 kbar / 830 °C). In a second eclogite, hosted in a granitic orthogneiss, omphacite ($\text{Aug}_{77}\text{Jd}_{23}$) occurs as armoured relics within garnet porphyroblasts. Minimum pressures of 14–15 kbar and equilibrium temperatures of about 780 °C were estimated on the base of the jadeite content in omphacite and Fe/Mg partition coefficients between omphacite and host garnet.

New age measurements and observations (LOMBARDO et al., 1997a) suggest a need for a new pressure-temperature loop since the Silurian (early Variscan docking) followed by late Variscan anatexis (4–6 kbar / 650–700 °C; BIERBRAUER, 1995). Deeper seated units underwent melting with formation of migmatites during their uprise to higher crustal levels, before the intrusion of Late Variscan granitoids.

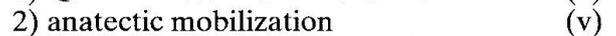
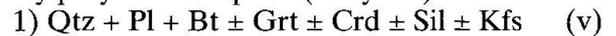
4.2.2. Pelvoux or Haut Dauphiné massif

In the metamorphic map, rock series of Variscan amphibolite facies grade with formation of migmatites contain small bodies of undated orthogneisses ("gneiss de Crupillouse", LE FORT 1973; probably Ordovician) and many Variscan granites. Local occurrences of kyanite, staurolite and sillimanite and a relic of granulite are mentioned. The following parageneses are present in metapelitic rocks (LE FORT, 1973):

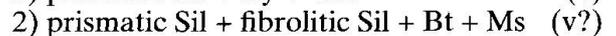
Chaillol monometamorphic "cortex":



Lavey polymetamorphic ("noyau"):

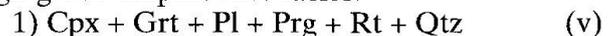


In the Peyre-Arguet area (PA, Fig. 2B), PÉCHER and VIALON (1970) observed the following mineral sequences in meta-greywackes:

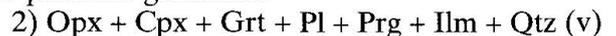


Paragenesis 1 is interpreted to represent granulite-facies conditions, and these rocks are accompanied by meta-gabbros (metabasic granulites). Granoblastic amphibolites ($\text{Am} + \text{Pl}_{\text{II An}_{38-45}}$) contain relics of $\text{Grt} + \text{Pl}_{\text{I An}_{45}} + \text{Cpx}$, Pl_{II} forming coronitic structures around garnet. Comparing formation of these H-T-granulites with thermal events of the French Central Massif, GRANDJEAN et al. (1996) propose a late Variscan evolution and mention the following parageneses (Fig. 3A):

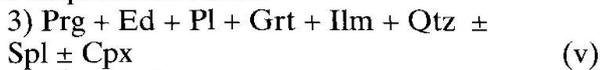
high-grade amphibolite facies:



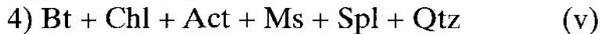
low-pressure granulite:



H-T amphibolite facies:



greenschist facies:



In the "cortex" area, metasediments attained amphibolite facies grade with St + Ky, whereas in the core area ("noyau") Sil + Crd parageneses and anatexis support a H-T evolution. Both domains may represent two parts of a truncated field gradient.

4.2.3. Belledonne and Grandes Rousses massifs

Both areas are subdivided into longitudinal metasedimentary units of Variscan amphibolite or greenschist facies grade with few occurrences of eclogite relics. One subunit is occupied by the Cambrian Chamrousse ophiolite. Variscan granitoids occur at many places, and Late Carboniferous molasse appears locally.

In metapelites of the Allemont region (Al, Fig. 2C), CLAVEL (1963) observed assemblages containing St, Ky and And, and Qtz + Pl + Bt + Ms + Grt + And. In the same region CARME (1970, 1973, 1974) mentioned the assemblage Qtz + Pl + Grt + St + Ky + Sil + Kfs and discussed metamorphic zones with St + Alm, Ky + Alm and Sil + Alm ± Kfs. In comparable metasediments, TOBI (1959) mentioned St- and Ky-bearing Grt-Bt-Pl (An₃₅) micaschists. Recent studies (BARFÉTY et al., 1997; GUILLOT and MÉNOT, in press) define the following Variscan evolution (Fig. 3B):

- 1) Grt + St + Bt + Ms + Qtz (v)
- 2) Grt + Ky + Bt + Qtz (v)
- 3) Crd + Sil + Bt + Kfs (v)

the latter being associated with local melting.

Strongly retrograded eclogites found among the metabasic rocks of the polymetamorphic domain (BARFÉTY et al., 1997) indicate, that this domain should have followed an evolution comparable to that of the neighbouring areas. The retroeclogites have been the subject of geochemical research and isotopic dating (see above, Tab. 1; PAQUETTE, 1987), but ages (Tab. 1) should be checked, as Variscan collision may have strongly influenced former Ordovician rocks. Distinct *P-T* evolutions (Fig. 3B) have been proposed by MÉNOT (1987 a, b) for the different subunits composing the complex Belledonne area. Besides the subunits mentioned above, the Chamrousse ophiolite and the Devonian Rioupérroux-Livet subunits had a more external origin, and all subunits are part of a Visean nappe pile. In the southern region, such loops may be completed by a late

Variscan stage under relatively low-*P* conditions (630 ± 50 °C/c. ± 1 kbar; GUILLOT and MÉNOT, submitted).

4.2.4. Mont Blanc and Aiguilles Rouges massifs

In the metamorphic map, both areas are characterized by meta-sediments with Variscan amphibolite facies and migmatites. Retro-eclogites are observed in both massifs, and in the Aiguilles Rouges many relics of kyanite, staurolite, sillimanite and andalusite are found. Pre-Variscan (Ordovician) orthogneisses are common. Late Variscan granitoids and Late Carboniferous molasse are well known.

Although the Alpine greenschist facies overprint destroyed all index minerals in the Mont Blanc massif, large areas are underlain by migmatites with pseudomorphs indicating widely distributed cordierite (pinite). Part of this evolution is certainly of late Variscan age (Tab. 1), and first mobilization steps show relics of muscovite together with K-feldspar and sillimanite. In the Aiguilles Rouges massif, amphibolite facies assemblages are widespread, and kyanite has been found in metapelitic and quartzitic rocks. VON RAUMER (1983, 1984) and SCHULZ and VON RAUMER (1993) reported on a sequence of parageneses in the Val Bérard area (Be, Fig. 2D), where kyanite or andalusite additionally appear in quartz veins:

relic paragenesis:

- 1) Qtz + Bt + oligoclase ± Grt ± St ± Ky (v?)

followed by:

- 2) Qtz + Bi + oligoclase ± Grt ± Sil (v)

late stage:

- 3) formation of andalusite (v)

More recent observations concern rather light-coloured, equigranular rocks with well formed garnets which appear in the neighbourhood of retrograded eclogite bodies of the Lac Cornu area (LC, Fig. 2D). Numbered according to generations, such rocks contain (VON RAUMER et al., 1996; DUPASQUIER, unpubl. data):

included in garnet appear:

- 1) St + intergrowth Bt + Pl (Phe?) (c?v?)

the main paragenesis of:

- 2) Bt + Pl + Grt + Ky ± St (c?v?)

with reaction rims around kyanite:

- 3) Hc + Crd; in biotite: fibrolitic Sil (v)

late stage pods or rock-forming:

- 4) andalusite (v)

In metasedimentary gneisses of the southwestern Aiguilles Rouges (Fig. 2D; SG, St-Gervais-Les Houches area; WG, EG), DOBMEIER (1996, 1998) discovered:

Western gneiss unit (WGU):

in S_1 :
Qtz + Bt + oligoclase + Grt + Ky + Kfs (v)

in S_2 :
Qtz + Bt + Ms + oligoclase + Grt ±
± Sil ± Kfs (v)

Eastern gneiss unit (EGU):

pre- S_2 :
Qtz + Bt + Ms + Pl + Grt + Ky + Sil + Kfs (v)

in S_2 :
Qtz + Bt + Ms + oligoclase + Grt +
+ Sil + Kfs (v)

Cores of retrograded eclogite lenses (Lac Cornu, LC, Fig. 2D, LIÉGOIS and DUCHESNE, 1981; Val Bérard, Be, Fig. 2D, SCHULZ and VON RAUMER, 1993) show the paragenesis:

Grt + symplectitic Cpx + Am + Pl (c?v?)

with relic omphacite Jd_{26} within garnet (700 °C / 14 kbar), and Jd_{22-25} to Jd_{7-15} in symplectitic pyroxenes associated with plagioclase (700 °C / 7–8 kbar). Such eclogitic amphibolites are surrounded by high-grade amphibolite facies metasedimentary units (VON RAUMER et al., 1996, see above). Coronitic metagabbros have been observed in the Val Bérard area (VON RAUMER, unpublished data) and this most probably indicates an evolution comparable to that of the Gotthard area (see below).

Re-interpreting earlier data (VON RAUMER, 1983, 1984), and on the basis of new data, MARSHALL et al. (1997) proposed a Variscan pressure-temperature-time path for the northeastern part of the Mont Blanc area. When comparing with the evolution of the Aiguilles Rouges we may conclude that the different paths depend on individual histories of uplift and erosion, but all end at surface conditions. The neighbourhood of complex counterclockwise paths in the gneiss-units (WGU, EGU, Fig. 3C) and a complex clockwise path in the greenschist unit (GSU) is the mirror of stacking and uplift in the southwestern part of the Aiguilles Rouges massif (DOBMEIER, 1996, 1998), whereas clockwise paths characterize the central part of the Aiguilles Rouges area (JOYE, 1989; SCHULZ and VON RAUMER, 1993; Fig. 3D). In addition, an isothermic decompression path has been presented for the Lac Cornu area from the neighbourhood with former eclogites. Besides the evolution of retrograded eclogites (SCHULZ and VON RAUMER, 1993), formation of H-P/H-T tonalitic melts has been discussed (VON RAUMER et al., 1996). The corresponding point (Fig. 3D) plots on the isothermal decompression path mentioned before, and such evolution could represent either a late Variscan uplift and decompression path or, depending on age determination, a relic consequence of Variscan collision. Late Variscan hy-

drothermal activity produced the W-Au-skarn deposits from the Salanfe area (CHIARADIA, 1993).

4.2.5. Aar, Tavetsch, and Gotthard massifs

Despite Alpine transformations which reached greenschist (Tavetsch) or greenschist to amphibolite facies (Gotthard massif) conditions, older assemblages are found. In the metamorphic map appear large areas of pre-Variscan amphibolite facies with or without migmatites, and pre-Variscan (Ordovician) orthogneisses occupy considerable areas in the Gotthard massif. Relics of eclogite and granulite are observed and kyanite appears in some places. Large areas are occupied by late Variscan granites.

ABRECHT (1994) gives a review of the main lithologic units in this area, where two different melting processes (Ordovician and late Variscan, Tab. 1) strongly transformed older relics. Detailed information comes from the Innertkirchen-Lauterbrunnen region where RUTISHAUSER (1973) reported Qtz + Bt + Pl + Or + Grt + Crd in metasedimentary sequences. From the Susten area, SCHALTEGGER (1986) reports the paragenesis Qtz + Bt + Pl (An₂₀₋₆₀) + Or + Sil ± Grt ± brown Am ± Ttn ± Tur, and ABRECHT (1994) mentions armoured relics of kyanite as a high pressure precursor in migmatitic gneisses containing Qtz + Bt + Pl + Sil + Kfs. In the Gotthard area, ARNOLD (1970a) has given a sequence of mineral parageneses, which have been preserved from Alpine upper greenschist facies overprint and which represent pre-Late Ordovician granulite facies overprinted by late Variscan amphibolite facies mineral associations.

Ky-Sil-gneiss:

1) garnet (c)

2) Qtz + Pl + Bt + Grt + Ky + Sil + Gr (c)

Opx-Grt-Bt-gneiss:

1) Qtz + Bt + Kfs + Grt + Opx + Gr (c)

2) Qtz + Pl + Bt + Grt + Ky + Sil (c)

Relics and mineral assemblages showing the transition from eclogite and subduction stages to granulite and amphibolite facies assemblages point to a pre-Late Ordovician subduction cycle (age constrained by Late Ordovician granitoids) and the following Variscan overprint. ABRECHT et al. (1991), ABRECHT and BIINO (1994), and BIINO (1994, 1995) reported the following parageneses (Fig. 3E):

pre-eclogite prograde:

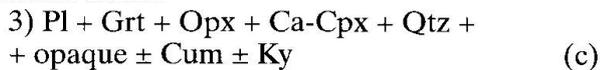
1) metagabbro with lawsonite (c)

eclogite stage:

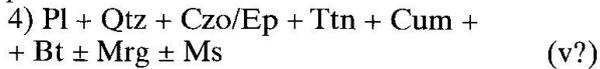
2) Grt + Na-Cpx + brown Am + Qtz +

Rt + Qtz ± Ky ± Zo ± Phe ± opaque (c)

granulite facies:



amphibolite facies:



Considering these observations together with the Ordovician orogenic cycle (Fig. 3E), different types of Variscan pressure-temperature evolutions are proposed (Figs 3A–E). The Allemont gneiss unit (A, Fig. 3B) appears to have a loading-decompression path comparable to that of the gneiss units of the Aiguilles Rouges area (GSU, Fig. 3C; B, C, Fig. 3D), and a similar decompression path is seen in the Western and Eastern Gneiss units of the Aiguilles Rouges (EG, WG, Fig. 3C), although their early history shows a distinct evolution. The complex evolution of the latter may be explained by their thrusting above a cooler unit (DOBMEIER, 1998). A distinct P-T path has been determined for the northeastern Mont Blanc area (G, Fig. 3D), and MARSHALL et al. (1997) concluded that uplift rates and geothermal gradients differed between the Mont Blanc and the Aiguilles Rouges areas. A specific thermal evolution becomes apparent for the supposed late Variscan evolution in the Pelvoux area (P1–P4, Fig. 3A), but needs dating.

5. Conclusions and comparative considerations

In the preceding sections we have tried to describe the complex metamorphic evolution of the pre-Mesozoic basement of the External Massifs, and the above mentioned parageneses are the traces of mainly two metamorphic histories, identified as Variscan (v) or pre-Variscan (c). Although there remain many open questions about ages, we will try to establish a metamorphic evolution through time. There is no doubt that events corresponding to an Ordovician orogeny were recorded in the basement of the External Massifs. Ordovician anatexis is dated in the Aar massif (SCHALTEGGER, 1992, 1993) but should be found also in the other external domains. Ordovician granulites serving as upper time limit for the Ordovician metamorphic evolution are known in nearly all External Massifs ("pre-Variscan granulites" in the metamorphic map; Tab. 1, Fig. 2). Relics of pre-Variscan eclogites are found in all massifs (Fig. 2E), and the best information comes from the Aar and Gotthard areas (ABRECHT, 1994; ABRECHT et al., 1991, 1995; ABRECHT and BIINO, 1994; BIINO, 1994, 1995), where a complete subduction cycle is inferred preceding Ordovi-

cian anatexis and the intrusion of Ordovician granulites. In addition the retro-eclogites (Ordovician protoliths, PAQUETTE et al., 1989) and granulites from the Argentera and Aiguilles Rouges massifs (Fig. 2E) testify to an Ordovician evolution.

The following time period is established mainly on the basis of Carboniferous age data points, whereas only few data from the Devonian exist (Tab. 1). A zonal distribution of different mineral parageneses from Ky + Grt + St to Grt + Sil and anatexis mobilization is believed to represent field gradients of Variscan collisional tectonics and uplift (Visean regional cooling, Ar–Ar data Tab. 1). Eclogites underwent re-equilibration (Fig. 3E), probably through thermal relaxation (BIINO, 1994) and through Variscan collisional events, which may explain inconsistent ages (PAQUETTE, 1987). Variscan transformation of Ordovician orthogneisses shows deformation stages under the conditions of amphibolite facies (Argentera, meta-dacite, BIERBRAUER, 1995; orthogneiss Belledonne, BARFÉTY et al., 1997; Streifengneiss, Gotthard area) and/or anatexis (Argentera, Pelvoux, Aiguilles Rouges, Mont Blanc). Such orthogneisses in the Aiguilles Rouges area were involved, together with metasediments, in large-scale folds (VON RAUMER, 1984). The accompanying metasediments display mineral assemblages of amphibolite facies (Bt + Pl + Grt_{II} + Sil), and recorded a thermal pulse about 327 Ma ago (BUSSY and HERNANDEZ, 1997; Tab. 1). Equivalent information comes from the central (Val Bérard area; WIRSING, 1997) and southwestern parts (Servoz-Les Houches area, DOBMEIER, 1996, 1998) of the Aiguilles Rouges, and, in the latter area, are confirmed by the Visean age of the Pormenaz granite (BUSSY et al., 1997; Tab. 1) emplaced parallel to the main foliation. In the Argentera domain the well-preserved relics of acidic, Late Ordovician meta-volcanic rocks (Tab. 1) show that their country rocks were at surface, and COLOMBO et al. (1993) and BIERBRAUER (1995) showed that these metavolcanics were deformed under amphibolite facies conditions before they were gradually involved in regional anatexis of Variscan age. The development of large-scale fold structures and the disruption of an older, strongly foliated metamorphic layering occurred during this migmatization event (BIERBRAUER and ONCKEN, 1996). In the central part of the Pelvoux area, LE FORT (1973) described an older meta-sedimentary series which was intruded by granites (Crupillouze augengneiss, supposed Ordovician age), and underwent regional transformation into migmatites. Many detailed observations resemble those made in the Argentera, Aiguilles Rouges

and Mont Blanc massifs, and a Variscan age should be accepted for migmatization.

The observed, complex, metamorphic pattern visible in the External Massifs resulted from a succession of different orogenic events combined with an evolution in different continental blocks. No doubt, the Ordovician orogenic cycle is well documented in all polymetamorphic basement areas (see above). According to a tentative reconstruction (VON RAUMER, 1998), the External Massifs are part of a post-Ordovician Gondwana-derived microplate which, during the Cambro-Ordovician period, evolved as an active margin (accretionary wedge, volcanic arc; VON RAUMER and SCHALTEGGER, 1998; VON RAUMER et al., 1998 a, b) 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, in common with the other peri-Gondwanan microcontinents, should have followed a migration path comparable to that of the Eastern Alps (TAIT et al., 1998) before Variscan collision with Laurussia (VON RAUMER, 1998). Unfortunately, traces of sedimentary and magmatic evolution during this period of rifting and drifting have only been identified in the Belledonne area (MÉNOT, 1986). Other relics may be hidden in the so-called monocyclic domains (Tab. 2), if they were not lost during tectonic evolution or through erosion. In the External Massifs, no information on Devonian oceanic crust or a Devonian subduction exists, but two distinct situations may be considered during the period:

(i) a period of Devonian extension (Riouperoux-Livet) represents the evolution from a more external domain, which might have parallels in the Rhenohercynian domain of the Variscides, but is also known from the Eastern Alps (LOESCHKE and HEINISCH, 1993; NEUBAUER and SASSI, 1993), where the Gondwana-margin type evolution (rifting, accompanied by sedimentation and magmatic activity) continued until the very late Devonian.

(ii) The question arises as to what has been the Variscan history in the polymetamorphic subunits of the external domain. If it is admitted that the external domain was part of a peri-Gondwanan microcontinent, then parallels of the Variscan evolution should be found in the present day Variscan framework of the Alps. After the rifting and drifting from Gondwana, docking should have occurred during the Devonian to Lower Carboniferous, and the few age indications (Tab. 1) may be traces of such events, but little information is available about this period.

The linear distribution of durbachitic-shoshonitic magmatites of Visean age from the Bohemian massif and across all External massifs and the Tauern region (VON RAUMER, 1998) could be a significant feature for reconstructing a Visean plate configuration. In the core of the Bohemian massif, the narrow relationship between Visean durbachitic rock-series and upwelling of the Variscan orogenic root has been recently demonstrated (SCHULMANN et al., 1998). Consequently, the linear distribution of durbachitic rocks in all External massifs could be interpreted as the relics indicating upwelling of formerly subducted lithospheric crust, a former Variscan suture zone perhaps situated in a former lateral prolongation of the Variscan root zone known in the Bohemian massif.

The formation of H-P/H-T tonalitic melts at the rim of meta-eclogites (see above, VON RAUMER et al., 1996) could be related with these processes. Nappe-stacking resulted in different pressure-temperature paths within the different subunits of the External massifs, and amphibolite facies parageneses were probably formed at that time. The final collision, representing the closure between Gondwana and Laurussia, must have occurred before Late Visean cooling. Complications resulted from migmatization and intrusion of granitoids which transformed, since the Visean, the Variscan pile of nappes. Polymetamorphic domains containing late Variscan migmatites should have occupied lower levels in the nappe pile (GUILLOT and MÉNOT, submitted), whereas slices of higher crustal position escaped migmatization. The latest thermal evolution with intrusion of gabbros and granitoids, and contemporaneous sedimentation and volcanic events, corresponds to a general situation of lithospheric thinning (BUSSY et al., 1998).

Despite parallels with pre-Permian metamorphic development, the evolution of the External Massifs has to be interpreted independently from the present-day Variscan framework. These configurations resulted from the bringing together, by Alpine and Late Variscan tectonics, crustal elements which may have occupied very different original geographical locations (e.g. MERCOLLI and OBERHÄNSLI, 1988). Consequently, parallels of evolution should not be used as a basis for a continuous interpretative cross-section. The External Massifs evolved independently from the Variscan framework, as part of a peri-Gondwanan microcontinent, parallel to Armorica containing the present-day Variscan framework of the External Massifs. The latter arrived at their pre-Permian (Pangea) location through rifting and drifting since the Ordovician. Only since the Visean, the

linear location of the External massifs may coincide with structures found in the present day Variscan framework. All late Variscan phenomena could be accommodated by a large-scale wrench-fault system (VON RAUMER, 1998), corresponding to a large strike-slip corridor situated between Africa and Europe (ARTHAUD and MATTE, 1977; NEUGEBAUER, 1988; BARD, 1997). It is hoped that future comparative work, accompanied by careful structural investigations, geochemical and isotopic research, and high precision dating will lead to the correct explanation.

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