Bull. Soc. géol. Fr., 2009, t. 180, n° 6, pp. 483-500

Suture zones and importance of strike-slip faulting for Variscan geodynamic reconstructions of the External Crystalline Massifs of the western Alps

STÉPHANE GUILLOT[1], SILVIA di PAOLA[2], RENÉ-PIERRE MÉNOT[3], PATRICK LEDRU[4], MARIA IOLE SPALLA[2], GUIDO GOSSO[2] and STÉPHANE SCHWARTZ[1]

Key-words. – Paleozoic belt, Subduction, Collision, Suture zone, Strike-slip fault, External Crystalline Massifs (ECM), Western Alps.

Abstract. – This paper reviews the geodynamic evolution of the Belledonne, Grandes Rousses and Oisans massifs in the western Alps from Early Ordovician to Permian times. Three domains are distinguished. The eastern domain, which includes the NE Belledonne massif and the inner Oisans massif, records the subduction of the Central-European ocean along a NW dipping subduction zone. The western domain is marked by Cambro-Ordovician back-arc rifting (Chamrousse ophiolite) initiating the opening of the Rheic ocean. It was followed by Mid-Devonian obduction of the back-arc Chamrousse ophiolite, towards the NW in relation with the SE dipping subduction of the Saxo-Thuringian ocean. The central domain, including the SW part of the Belledonne massif, the Grandes Rousses massif and the outer Oisans massif, records the Devonian to Carboniferous orogenic activity that produced calc-alkaline magmatism, Mg-K granite intrusions and syn-collisional sedimentation related to Visean nappe stacking that we relate to the closure of the Saxo-Thuringian ocean. Based on tectonostratigraphic correlations we propose that these domains initially correspond to the northeastward extension of the Bohemian massif. During the late Carboniferous, the External Crystalline Massifs including Sardinia and Corsica were stretched towards the SW along the > 600 km long dextral External Crystalline Massifs shear zone. Offset of the Saxo-Thuringian and eo-Variscan suture zones from the Bohemian massif to the ECM suggests a possible dextral displacement of about 300 km along the ECM shear zone.

Zones de suture et importance des décrochements tardi-varisques pour la reconstruction géodynamique des Massifs Cristallins externes des Alpes occidentales

Mots-clés. – Chaîne Paléozoïque, Subduction, Collision, Zone de suture, Décrochement, Massifs Cristallins Externes, Alpes Occidentales.

Résumé. – Ce papier résume l'histoire géodynamique des massifs de Belledonne, des Grandes Rousses et de l'Oisans (Alpes occidentales) de l'Ordovicien au Permien. Trois domaines ont été identifiés et connus sur l'ensemble de l'Europe. Le domaine E est formé par le massif de Belledonne NE et la zone interne de l'Oisans a enregistré la fermeture de l'océan central européen au Dévonien inférieur, entre Gondwana et la zone Moldanubienne, le long d'une zone de subduction pentée vers le NW. Le domaine W a enregistré le rifting Cambro-Ordovicien donnant naissance à l'océan Rhéic, puis l'obduction au Dévonien inférieur de l'ophiolite de Chamrousse, située en domaine arrière-arc. Le domaine central inclus la partie SW de Belledonne, le massif des Grandes Rousses et la zone externe de l'Oisans. Ce domaine a enregistré au cours du Dévonien et au Carbonifère la fermeture de l'océan Saxo-Thuringien le long d'une subduction pentée vers le SE, associée à la mise en place de granites syntectoniques magnésio-potassique, puis la collision viséenne. Nous proposons que le domaine central corresponde à la zone Moldanubienne, dans la prolongation est du massif de Bohème. A la fin du Carbonifère, les Massifs Cristallins Externes incluant la Corse et la Sardaigne ont été entrainés le long d'une grande zone de cisaillement dextre (> 600 km) orientée NE-SW dans sa branche nord associée à des conjugués senestres de direction NW-SE dans la branche sud. Le décalage des sutures saxo-thuringienne et éo-varisque depuis le massif de Bohème et au travers des Massifs Cristallins Externes suggère un possible déplacement dextre de l'ordre de 300 km le long la zone de cisaillement des Massifs Cristallins Externes.

INTRODUCTION

The Variscan belt of Europe formed during the convergence of Laurussia with Gondwana by closure of different oceans and produced several suture zones; the Rheno-Hercynian, the Saxo-Thuringian and the eo-Variscan suture zones [Arthaud et Matte, 1977; Matte, 1986; 2001; Franke, 1989; Faure *et al.*, 2005]. Although these three suture zones are

1. Université Joseph Fourier – Grenoble1, CNRS, OSUG, BP 53, F38041 Grenoble cedex, France. e-mail : sguillot@ujf-grenoble.fr
2. Dipartimento di Scienze della Terra, Università di Milano and CNR-IDPA, via Mangiagalli 34, 20133 Milano, Italy
3. Université Jean Monnet, UMR-CNRS « Magmas et Volcans », F42023 St-Etienne cedex2, France
4. AREVA Business Unit Mines, Département Géosciences, 1 place Jean Millier, BAL 0515A, 92084 Paris La Défense
Manuscrit déposé le 15 janvier 2009; accepté après révision le 26 juin 2009.

well recognized from southern Spain to the Bohemian Massif (fig. 1) their presence in the External Crystalline Massifs (ECM) of western Alps is not certain. Ménot [1987; 1988a, b] ascribed the Chamrousse ophiolite in SW Belledonne and the retrogressed mafic eclogites in the Aiguilles Rouges, NE Belledonne and Argentera Massifs [Ménot and Paquette, 1993] (fig. 2), to the eo-Variscan suture zone and proposed that the Belledonne Massif results from a tectonic "collage" related to late orogenic Mid-Carboniferous strike-slip faulting. Matte [2001] proposed that the eo-Variscan suture zone was sheared during Permian times, from the Bohemian Massif to Sardinia (including the External Crystalline Massifs), along a N030° strike-slip fault. Finally, von Raumer *et al.* [2003; 2009] distinguished two episodes of subduction in the ECM. The aim of this paper is to take stock of the suture zones in the ECM of Belledonne, Grandes Rousses and Oisans and their relationships with major suture zones in the Paleozoic belts of western Europe. We first summarize the regional geology of these massifs based on many new data emerged during recent 1/50,000 scale mapping and we discuss the geological evolution of the area in the framework of the Paleozoic orogenic belts.

GEOLOGICAL SETTING

The Paleozoic basement of the ECM is composed of various metamorphic rocks with ages spanning from Cambrian to Carboniferous, and their non-metamorphic covers with ages ranging from Late Carboniferous to Permian. They are unconformably overlain by Mesozoic sedimentary rocks. The highest grade of Alpine metamorphic imprint reaches low greenschist facies conditions [Gratier *et al.*, 1973], which ensures that they retain the pre-Alpine tectono-metamorphic history.

The Belledonne Massif has been divided into three major tectonic zones, separated by Late Paleozoic strike-slip faults (fig. 3). The external zone of Belledonne is composed of a weakly metamorphosed flysch series, the "Série Satinée" (fig. 3). The internal zone of Belledonne is divided into two parts; the NE and SW areas, separated by the Rivier-Belle Etoile fault (RBE, fig. 3) [Ménot, 1988b]. The NE area consists of gneissic and amphibolitic rocks intruded by Visean granites and overlain by volcanoclastic rocks. The SW area consists of three nappes: Lower Paleozoic Chamrousse ophiolitic complex, which overlies Devonian-Dinantian igneous rocks, and Lower Paleozoic micaschists slices [Ménot, 1988a].

To the East, the Grandes Rousses Massif, separated from the Belledonne Massif by the Liassic Bourg d'Oisans sedimentary basin (fig. 3), is composed of N-S elongated Devono-Dinantian volcano-sedimentary units. Farther east, the crystalline basement of the Oisans Massif has been divided into an inner and outer zone [Le Fort, 1973]. The inner zone is composed of high grade metabasic and metapelitic units intruded by Carboniferous granites (fig. 3) [Debon and Lemmet, 1999]. The outer zone is mainly composed of micaschist and low grade or unmetamorphosed volcanic and clastic sedimentary rocks of Devonian-Dinantian age [Le Fort, 1973], free of Late Carboniferous magmatic rocks (fig. 3).

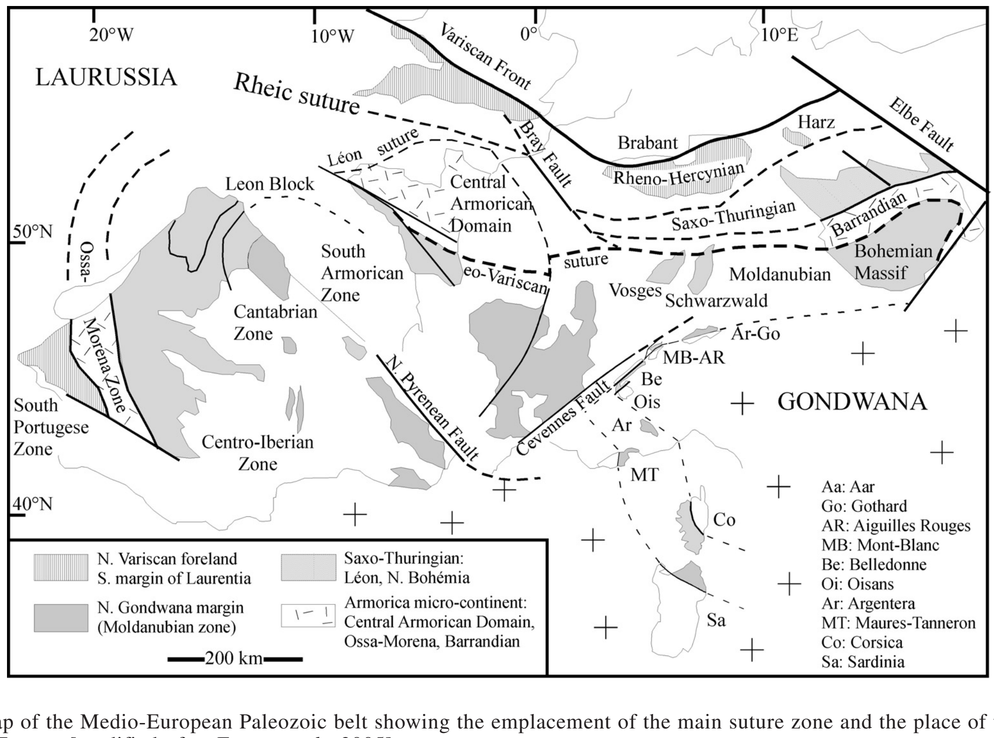

FIG. 1. – General map of the Medio-European Paleozoic belt showing the emplacement of the main suture zone and the place of the External Crystalline Massifs in western Europe [modified after Faure *et al.*, 2005].

FIG. 1. – *Carte générale de la chaîne paléozoïque médio-européenne avec ses principales zones de suture et figurant l'emplacement des Massifs Cristallins Externes [modifié d'après Faure* et al.*, 2005].*

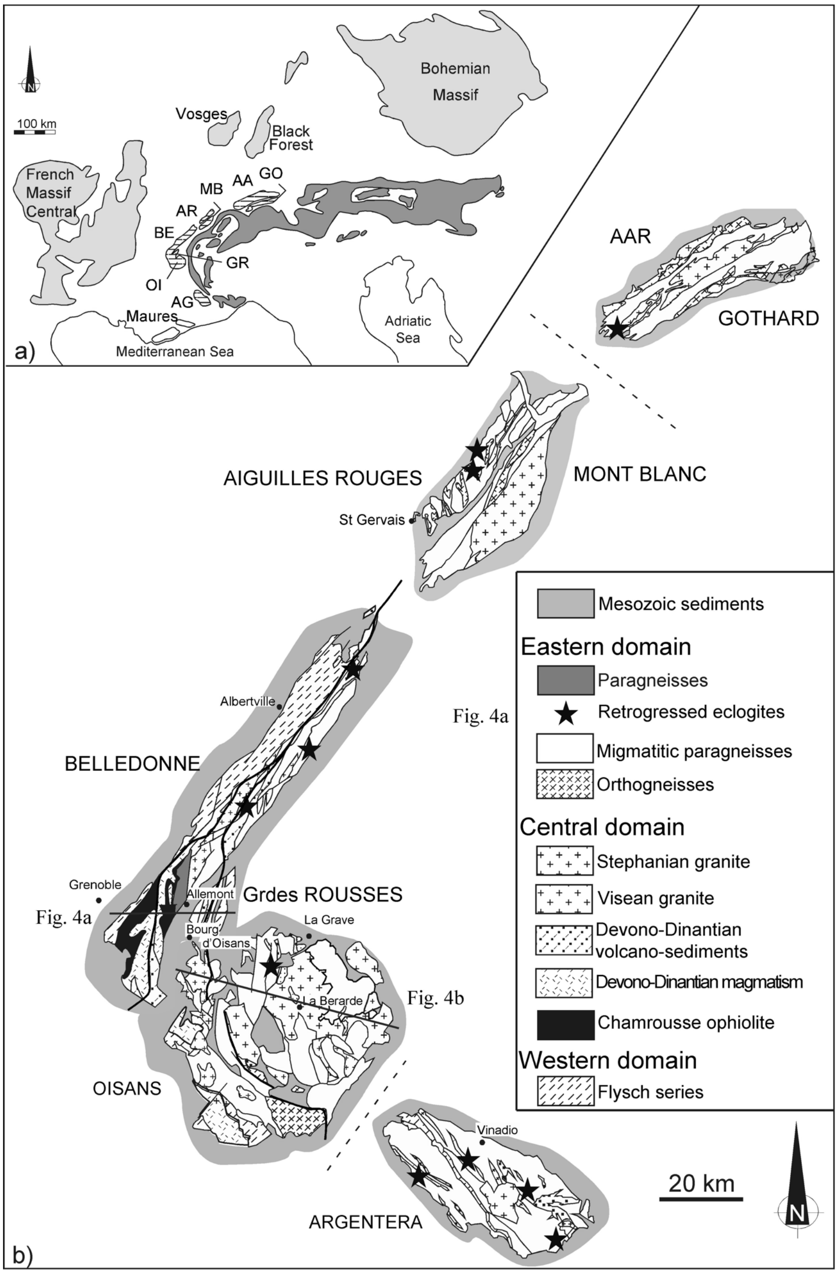

FIG. 2. – Structural domains of the External Crystalline Massifs [modified after Vivier *et al.*, 1987].
FIG. 2. – *Principaux domains structuraux des Massifs Cristallins Externes [modifié d'après Vivier* et al., *1987].*

Based on their lithologies and tectono-metamorphic evolutions, we propose a subdivision of the ECM into three domains (figs. 2 and 4). The western domain corresponds to the external zone of the Belledonne Massif, west of the Synclinal Median (SM) fault. The central domain corresponds to SW Belledonne and the Grandes Rousses Massif, and the outer zone of the Oisans Massif. The central domain is separated from the eastern domain by the Rivier-Belle Etoile fault (RBE, fig. 3) [Ménot, 1988b]. The eastern domain includes NE Belledonne and the inner zone of the Oisans Massif. In this new frame, the Aar-Gothard, The Mont Blanc and the Argentera Massifs belong to the eastern domain (fig. 2).

GEOLOGICAL UNITS

The Liassic rifting that affected the Alpine domain, separated the Variscan basement into three tilted blocks; Belledone, Grandes Rousses and Oisans [Lemoine *et al.,* 1986]. We evaluated the pre-Mesozoic relationship of these massifs based on their lithologies, deformation and metamorphic histories.

The western domain

The external zone of the Belledonne Massif, east of the Synclinal Médian (SM) fault, comprises metasedimentary rocks [the "Série Satinée", Bordet and Bordet, 1963; Figs. 4

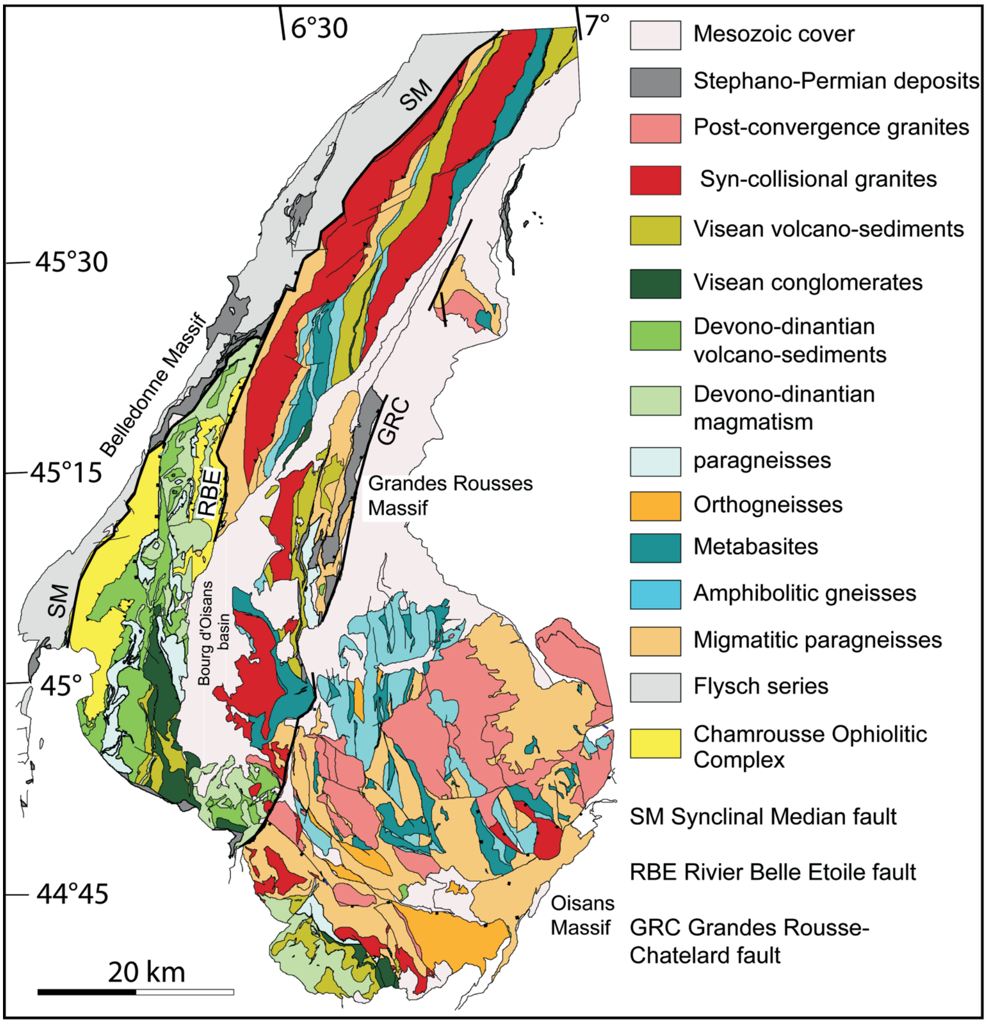

FIG. 3. – Geological map of the Belledonne, Grandes Rousses and Oisans Massifs based on the synthesis of 1/50,000 scale geologic maps. SM : Synclinal Median fault ; RBE : Rivier-Belle Etoile fault and GRC : Grandes Rousses-Chatelard fault.

FIG. 3. – *Carte géologique des massifs de Belledonne, Grandes Rousses et Oisans réalisée à partir des levés au 1/50 000^{e}.* SM *: synclinal Médian ;* RBE *: faille de Rivier-Belle Etoile et* GRC *: faille des Grandes Rousses-Chatelard.*

and 5] with rare intercalations of basic layers. This unit is interpreted as a terrigenous sequence [Ménot, 1988a and ref. therein]. Their age is estimated to be Late Neoproterozoic to Early Palaeozoic based on their similarities with the Cévennes metapelitic series of the Massif Central [Ménot, 1988 a,b]. Similar metasedimentary rocks are observed in the Aiguilles Rouges, in the Argentera [Ménot *et al.,* 1994] and in the Barrandian domain of the Bohemian Massif [Drost *et al*., 2004].

The central domain

The central domain consists of a nappe pile including the Cambro-Ordovician ophiolitic complex of Chamrousse, the Devono-Dinantian plutonic and volcanic series and Visean metasediments and volcanics. The ophiolitic complex of Chamrousse in the SW area of Belledonne is a well preserved kilometre-scale slab of oceanic lithosphere. It is overturned and lies on younger plutonic and volcanic units (figs. 3 and 4). The eastward extension of the complex has been recognised east of the La Pra fault [Barféty *et al.,* 2001].

The plutonic sequence overlies a leptyno-amphibolitic complex, interpreted as the volcanic and volcanoclastic member of the ophiolitic suite [Carme, 1970; Ménot, 1979; 1988a]. The ophiolitic complex yielded Cambro-Ordovician ages for protoliths: an U/Pb zircon age of 496 ± 6 Ma [Ménot *et al.,* 1988] and Sm/Nd isochron age of 497 ± 24 Ma [Pin and Carme, 1987]. Bodinier *et al.* [1981] and Pin and Carme [1987] recognized three magmatic components: E-MORB, N-MORB and a subduction-related component. Ménot [1988a] found a progressive decrease in continental contribution in parental magmas and suggested that the magmatism took place near an active continental margin and evolved to an open oceanic domain. The Chamrousse ophiolite preserves magmatic textures and high temperature low-pressure (T = 600-800°C, P = 0.3-0.4 GPa) ridge axis-related deformations [Guillot *et al*., 1992].

The ***Devonian-Dinantian magmatism*** has been described and dated in the SW part of the Belledonne Massif (Riouperoux-Livet plutonic-volcanic complex, fig. 6). It consists of bimodal suites of igneous rocks. The upper part consists of metamorphosed felsic and basic volcanic, volcanoclastic and plutonic rocks. The lower part comprises leptynites and amphibolites intruded by trondhjemitic sills and stocks [Ménot, 1986]. A U/Pb zircon age of 352 ± 56 Ma has been obtained for the trondhjemitic intrusions of the lower part of the complex [Ménot *et al.,* 1985], and the trondhjemites of the upper part yielded a U/Pb zircon age of 362 ± 4 Ma and 367 ± 17 Ma [Ménot *et al.,* 1987]. These series underwent a series of deformations and metamorphism starting with the early deformation at 0.8 ± 0.2 GPa and 590 ± 60ºC, followed by a deformation at slightly lower P-T conditions (0.7 ± 0.2 GPa and 590 ± 60ºC). K/Ar ages of hornblende bracket the earlier metamorphism between 352 ± 55 Ma and 324 ± 12 Ma [Ménot *et al.,* 1987]. Finally, Westphalian normal faults developed under greenschist facies conditions [Guillot and Ménot, 1999].

In the SW part of the Oisans Massif the protoliths of massive amphibolites with interlayered quartzites, leptynites and Chl-bearing micaschists [Le Fort, 1973] (fig.6) are related to the same Devono-Dinantian magmatism. This might be also the case for the amphibolitic gneisses from the southwestern part of the Grandes Rousses Massif showing similar lithology and mineral assemblages. Based on its calc-alkaline character, Carme and Pin [1987] proposed an active margin setting for the Devono-Dinantian magmatism. On the other hand, Ménot [1988a] favors a continental extensional setting as it shows a progressive change from a mantle to a crustal source. The transition from an extensional to a compressional regime [Ménot, 1988 a,b] is also observed in the French Massif Central [Faure *et al.*, 2005].

Metavolcanic and sedimentary rocks of Visean age are common in the three massifs (fig. 6). Their common occurrences suggest that they likely formed in the central domain. They are quartzites and Qtz- or Chl-rich schists, with minor amphibolites, graphitic and marble beds and locally associated with metaconglomerates (Taillefer Massif, NE Belledonne, NW Grandes Rousses). The suite of clastic rocks includes tuffs and volcanic breccias [Gibergy, 1968], which are intruded by Visean Alpetta granites in the Grandes Rousses Massif [Debon and Lemmet, 1999]. In NE Belledonne, the Visean granites intrude the amphibolitic basement, but not the volcano-sedimentary rocks, which always remain in an upper structural position [Vivier *et al.*, 1987]. This suggests that the Visean magmatism occurred during the opening of local extensional basins in the NE Belledonne domain, whereas in SW Belledonne and in the Grandes Rousses Massif, this volcanism extends the Devonian calc-alkaline magmatism. The Early Visean magmatism displays an arc-related tholeiitic signature [Carme and Pin, 1987] with crustal contamination [Ménot, 1987; Vivier *et al.*, 1987] that we interpret as a back-arc basin developed on a thinned continental crust. On the map of figure 6, the schists of volcano-sedimentary origin are distinguished from the Visean conglomerates.

The syn-collisional plutonism postdates the early tectonic and metamorphic evolution of the gneissic basement. In the Belledonne Massif, syn-collisional Mg-K granites constitute three plutons elongated parallel to the main regional structures trending N030. They have calc-alkaline to alkaline affinities. The Sept Laux granite is concentrically zoned, varying from granodioritic to monzogranitic in composition, with locally abundant enclaves of lamprophyre. Its outer parts show a striking synmagmatic foliation nearly parallel to the margins. An age of 335 ± 13 Ma has been obtained by single-zircon Pb evaporation [Debon *et al.*, 1998]. In the St. Colomban pluton (343 ± 16 Ma) [Debon *et al.*, 1998] the main rock type is a medium-grained, often strongly foliated monzogranite. Mafic enclaves are abundant in the southern part of the intrusion. The La Lauziére pluton (341 ± 13 Ma) [Debon *et al.*, 1998] is heterogeneous in composition, but mainly consisting of syenogranites with minor quartz-syenites.

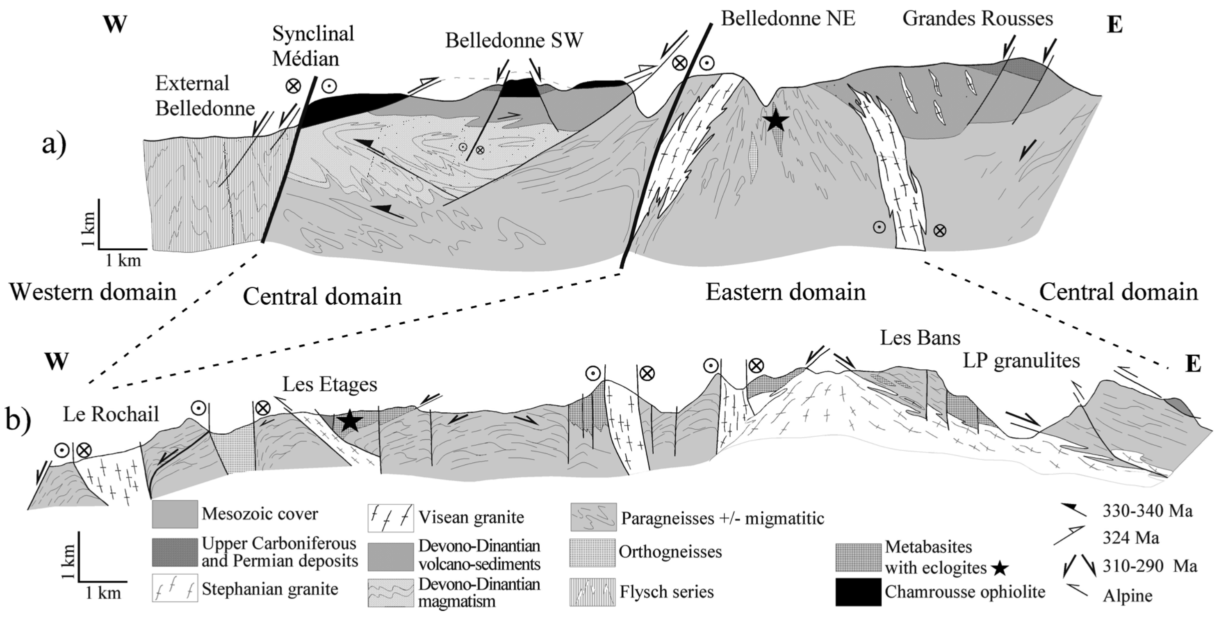

FIG. 4. – (a) Schematic cross section showing the structural relationships in the Belledonne and Grandes Rousses Massifs. (b) Cross section of the Oisans Massif [modified after Barféty and Pêcher, 1982].

FIG. 4. – (a) *Coupe schématique montant les relations structurales entre les massifs de Belledonne et des Grandes Rousses.* (b) *Coupe schématique du massif de l'Oisans [modifié d'après Barféty et Pêcher, 1982].*

In the western part of the Grandes Rousses Massif, the Alpetta Granite (fig. 6) is a deformed magnesian sub-alkaline intrusion, composed of augen-gneisses including lenses of amphibole-bearing gneiss and cut by a later, syn-tectonic monzonitic intrusion [Roche Noire Granite; Giorgi, 1979; Bogdanoff *et al.*, 1991]. The Alpetta granite likely represents the southern extension of the St. Colomban pluton judging from the distribution and similar geochemical characteristics [Bogdanoff *et al.,* 1991]. As revealed by syn-magmatic S-C fabric in the NE Belledonne plutons and in the Alpetta granite their emplacement occurred during the development of a N000º to N020ºE transpressive shear zone [Barféty *et al.*, 2001].

Mg-K granites intrude the outer zone of the Oisans Massif (fig. 6). The Rochail intrusion is mainly monzogranitic in composition, with minor granite and syenite and locally mafic enclaves [Debon and Lemmet, 1999]. It was dated at 343 ± 11 Ma by U-Pb zircon [Guerrot, 1998]. The Combeynot alkaline syenogranite, also shows high Mg and K contents, and gives an U-Pb zircon age of 312 ± 7 Ma [Cannic *et al.*, 1998], about 20 Ma younger than the ages of other Mg-K granitoids. The Mg-K granitoids are considered to derive from enriched subcontinental lithospheric mantle contaminated by continental crust [Debon and Lemmet, 1999].

The eastern domain

The eastern domain is mainly built by a polymetamorphic gneissic basement including retrogressed eclogites and mafic granulites and intruded by plutons of intermediate to silicic composition. This basement is overlain by younger Visean metasediments and volcanics (see above) and by Permo-Carboniferous deposits (see below).

The polymetamorphic basement is dominantly made up of biotite- and amphibole-rich migmatitic gneisses with subordinate metabasites in the NE area of Belledonne. The protoliths are mainly graywackes including minor mafic volcanic layers and intruded by granitic bodies aged 489 ± 22 Ma (single zircon Pb evaporation) [Barféty *et al.*, 2001]. The metamorphism is polyphased [von Raumer et Ménot, 1989; Guillot *et al.*, 1998; von Raumer *et al.*, 1999]: (1) a Lower Paleozoic high-P event recorded in the metabasites is followed by (2) intermediate-P amphibolite facies metamorphism with the development of Ky-St assemblages in the metasediments and by (3) a regional anatexis associated with Crd-bearing assemblages during Devonian time. Finally, the retrogression of the rocks under greenschist facies conditions was accompanied by the development of a subvertical foliation related to dextral

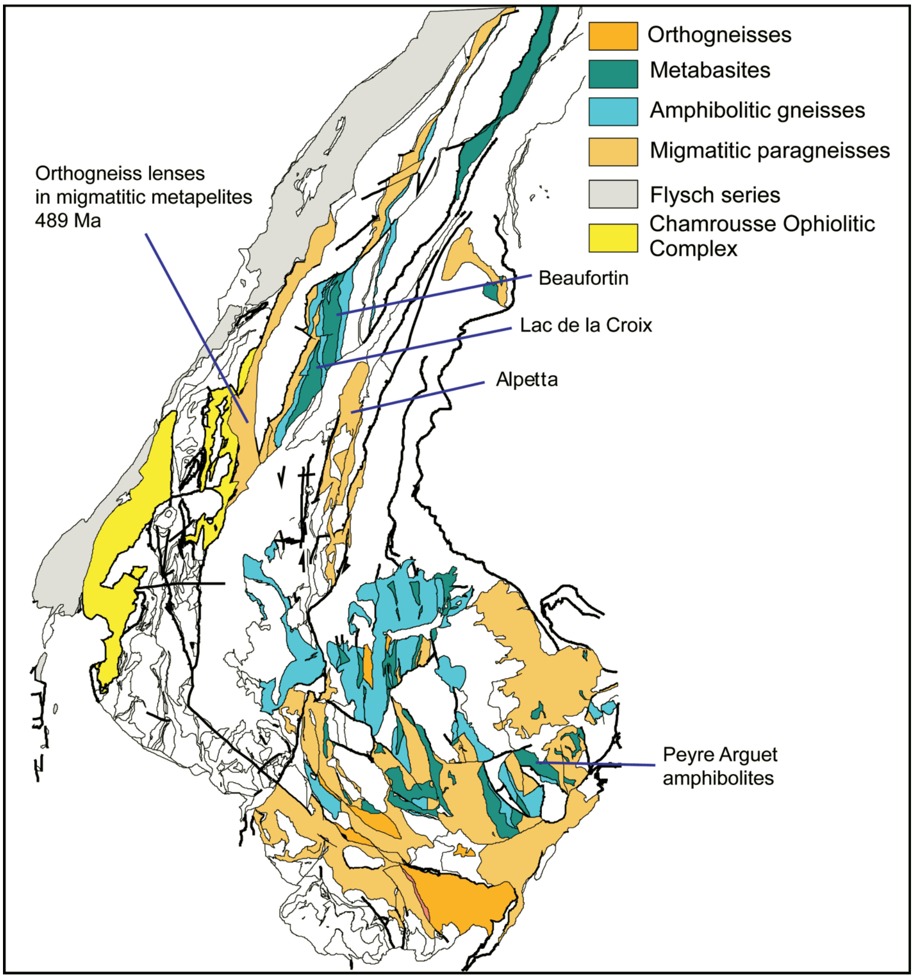

FIG. 5. – Geological map of rocks with pre-Devonian protoliths.
FIG. 5. – *Carte géologique des formations pré-Dévoniennes.*

shearing and coeval with intrusion of granitoids (at 335 ± 13 Ma) [Debon *et al.*, 1998; Barféty *et al.*, 2001].

In SW Belledonne, slices of Ky-St bearing metapelites are tectonically interlayered with Devono-Dinantian volcanics. Two sub-units are distinguished; the upper sub-unit is mostly composed of Ky-St bearing micaschists, whereas the lower sub-unit ("Allemont Fm.") is mainly made up of migmatitic gneisses and granitoids [Guillot and Ménot, 1999]. The rocks of the lower sub-unit preserve relics of an early intermediate-P metamorphic assemblage (P = 1.0 ± 0.1 GPa, T = 550 ± 50°C). Subsequently, both the lower and upper sub-units underwent similar metamorphic conditions; P = 0.8 ± 0.2 GPa and T = 610 ± 80°C. A late deformation phase develops extensional shear bands at P = 0.5 ± 0.2 GPa and T = 630 ± 100°C. The earlier metamorphism takes place during Devonian, whereas the late syn-extensional metamorphism is Westphalian in age [Fernandez *et al.*, 2002].

The core of the Oisans Massif (fig. 3) is mainly composed of garnet-bearing gneisses and rare Ky- and Crd-bearing metasediments. They locally record two episodes of migmatisation: (1) synkinematic Devonian leucosome veins, (2) postkinematic Crd-bearing assemblages related to the Upper Carboniferous deformation [Bogdanoff *et al.*, 1991].

Several orthogneiss bodies occur with the paragneisses of the eastern domain. One has been dated at 489 ± 22 Ma (single-zircon Pb evaporation, Barféty *et al.*, 2001; fig.5) in the NE Belledonne Massif. Other alkaline to calc-alkaline metagranitoids from the Oisans Massif, ("Gneiss d'Olan") (fig. 5) are considered to be Visean in age [von Raumer, 1998].

The retrogressed eclogites and granulites are interlayered within the paragneisses in NE Belledonne (Beaufortin region, fig. 5) [Vivier *et al.*, 1987 and ref. therein]. Relicts of retrogressed eclogites are also recognized in the southernmost sector of NE Belledonne (Lac de la Croix, fig. 5) [Vivier *et al.*, 1987 and ref. therein]. Thermobarometric estimates show P greater than 1.2 ± 0.1 GPa and T higher than 640 ± 30°C [Guillot *et al.*, 1998]. The age of the protolith and eclogite facies metamorphism have been dated at 473 ± 21 Ma, and 390 ± 8 Ma respectively [U-Pb on zircon, Paquette *et al.,* 1989]. The retrogression under amphibolite facies conditions is dated at 373 Ma [Demeulemeester, 1982]. These metabasites have a N- to E-MORB geochemical signature [Ménot et Paquette, 1993].

In the Oisans Massif, amphibolitic lenses in migmatites [Le Fort, 1973] show N- to T-MORB geochemical signatures and considered to have formed during Lower Paleozoic continental rifting [Ménot and Paquette, 1993]. Among these metabasites, garnet bearing granulites in the northwestern part of the massif contain relics of rutile and symplectites of clinopyroxene + plagioclase suggesting that they are retrogressed eclogites and the peak condition greater than 1.4 ± 0.1 GPa and 850 ± 50°C [Guillot *et al.*, 1998]. These retrogressed eclogites may be comparable to those of NE Belledonne, indicating the evidence for an early Paleozoic subduction.

In the SE part of the Oisans Massif, Grt-bearing granulitic lenses contain orthopyroxene symptomatic of LP granulite facies (Peyre Arguet metabasites, fig. 5). Their protoliths are probably the same as the eclogites described above, but their metamorphic evolution is different with a temperature increase up to 800°C during decompression from 0.7 to 0.3 GPa, and is likely related to the Late Paleozoic orogenic evolution [Grandjean *et al.*, 1996].

The post-convergence magmatic events are represented by several granitic stocks in the Oisans Massif and by the single Grand Chatelard Granite in the Belledonne Massif (fig. 7). The younger granitic plutons display high Al and Fe contents [Debon and Lemmet, 1999]. Some stocks display a monzogranitic and syenogranitic composition, but the most striking difference with the Mg-K granites is the absence of mafic enclaves. In the ECM, the Al-Fe magmatism is well defined in age, between 305 and 295 Ma [Debon and Lemmet, 1999], and all granites with high Al and Fe have been interpreted to be emplaced during the Stephanian transtension regime [Strzerzynski *et al.*, 2005]. Granites are abundant in the Oisans Massif and associated with Upper Carboniferous Crd-bearing migmatites [Le Fort and Ehstrom, 1969]. Sources appear to be similar to those of the Mg-K granites: continental crust and subordinate enriched subcontinental lithospheric mantle [Debon and Lemmet, 1999].

The Stephano-Permian sedimentary rocks are recorded in both the central and eastern domains and are comprised of black schists, sandstones and conglomerates with economic coal seams (fig. 7). They are commonly associated with rhyolitic, dacitic to andesitic volcanic and pyroclastic rocks in the northern part of the Grandes Rousses Massif [Banzet *et al.*, 1985] and in the Aiguilles Rouges [Capuzzo and Bussy, 2001]. Carboniferous sedimentary rocks are in places pinched within the basement along major NNE-SSW dextral faults during Permian time [Barféty *et al.,* 2001].

STRUCTURAL EVOLUTION

Early Devonian nappe emplacement (D1)

The oldest structure (D1) is identified in the inner zone of the Oisans Massif and corresponds to the emplacement of the eclogitic unit onto the metasedimentary unit (fig. 4). The age and direction of thrusting are unknown but nappe emplacement occurred after the eclogitization of this unit (ca. 395 Ma) and prior to its Devonian migmatisation (< 355 Ma). As the root of the eclogitic unit is observed in NE Belledonne [Paquette *et al.*, 1989] a SE direction of thrusting may be inferred. Southward thrusting of the eclogitic nappe (Upper Gneissic Unit) onto a metasedimentary unit (Lower Gneissic Unit) is also known in the French Massif Central and dated at ca. 380 Ma [e.g. Lardeaux *et al.*, 2001 and Faure *et al.*, 2005].

The amphibolitic sole of the Chamrousse ophiolite (fig. 8a) preserved a Mid-Devonian foliation dated at 376 ± 7 Ma (unpublished ^{40}Ar-^{49}Ar dating on amphiboles by Monié and Ménot). This S1 foliation is oriented 70°E 27°S bearing a N097° 10°ESE amphibole lineation. Shear criteria indicate top-to-the-WNW thrusting, probably related to the early obduction of the Chamrousse ophiolitic complex. Moreover, we recently observed that the primary contact between the serpentinites and the gabbros is locally preserved in normal position defining the petrological Moho at the top of the ophiolitic complex (fig. 8b). This normal sequence (serpentinites + gabbros) is overlying the

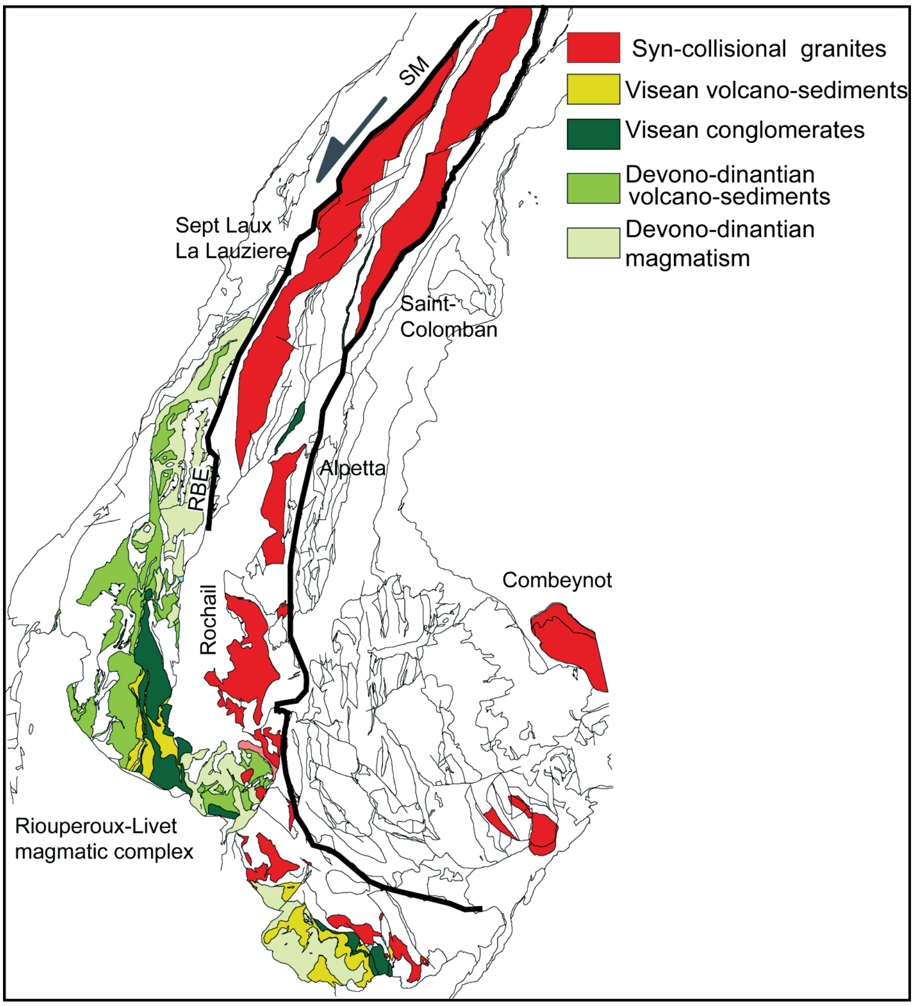

FIG. 6. – Geological map of the Devonian-Dinantian magmatic and metasedimentary rocks, which developed in a back-arc basin on a thinned continental crust. Visean magmatic and sedimentary rocks are related to syn- to post-collision basins.
FIG. 6. – *Carte géologique des formations Dévono-Dinantiennes formant un domaine d'arrière arc. Les formations viséennes sont syn à post collision.*

gabbros along an intra-ophiolitic ductile thrust that developped under amphibolite facies conditions; it also shows top to-the-NW thrusting (fig. 8a). The lower contact between the gabbros and the Sechilienne amphibolites (equivalent of the layer 1 in Alpine ophiolite) is still not clearly identified all along the Chamrousse ophiolite; a 10 meters thick mylonite oriented N005^o 20^{o}W bearing a N100 15^{o}WNW stretching lineation also indicates top to the NW thrusting just above the Chamrousse skiing station (fig. 8c). This suggests that the contact between the Sechilienne amphibolites and the gabbros is also a tectonic contact with the same thrusting vergency [Guillot and Ménot, 2009]. We conclude that the apparent inversion of the whole ophiolitic nappe pile may not be related to its passive rollover (inverted limb of a decakilometric fold) but it may result to nappe stacking during Mid-Devonian times.

Visean nappe stacking (D2 and D3)

The major deformation in the NE Belledonne area and in the Grandes Rousses Massifs is dominated by the emplacement of Mg-K granites during Visean times along a N000^o-N020^{o}E transpressive shear zone (fig. 6). In the Belledonne Massif, the deformation resulted in the thrusting of the internal HP unit towards the NW [Guillot *et al.*, 1998]. This 10 km large shear zone can be traced southward by the distribution of granites to the outer part of the Oisans Massif (fig. 6). Considering the high Mg content of the granites, this transpressive shear zone likely rooted within the upper mantle.

In the SW Belledonne area, the nappe pile including the Devonian-Dinantian magmatic complex and the Chamrousse ophiolite, records two stages of Visean deformations [Guillot and Ménot, 1999; Fernandez *et al.*, 2002]. In the felsic gneisses and amphibolites of the Devonian-Dinantian magmatic complex, the D2 tectonic event generated km-scale folds and a regional foliation dipping to the east. This foliation is associated with an early mineral lineation (N090^o 130^{o}E) defined by the orientation of plagioclase and amphibole. This lineation is locally realigned close to late N030 dextral strike-slip faults. In mylonitic metasediments, the lineation is marked by the preferred orientation of staurolite (N090^{o}E). Shear criteria, asymmetry of the folds and geometry of S-C structures indicate top to the west or northwest thrusting during D2.

D3 deformation enhanced the NE back-thrusting of the Chamrousse ophiolitic complex over the Devono-Dinantian magmatic complex. The tectonic sole of the Chamrousse ophiolitic complex shows a pervasive S3 foliation oriented approximately N095°E and dipping 25°N, which clearly overprinted the S1 foliation. All along the southwestern part of the Belledonne Massif, the amphibolitic lineation L3 is oriented N030°E dipping 25° towards the NE. The sole of the Chamrousse ophiolite shows D3 microdrag folds oriented N130°E and locally indicating top to the NE sense of shear. Below the Chamrousse ophiolitic complex, in the bimodal magmatic complex, the S3 cleavage is parallel to the mean axial plane orientation of D3 folds with an average direction of N000° dipping 40°W. Hinge lines of these folds strike parallel to the S2-S3 intersection lineation with a N175°E orientation and dipping 25° north. Guillot and Ménot [1999] suggested a local shearing as the cause of reorientation of the S2 surfaces into that of S3, indicating a top to the east motion. Scattered shear criteria in the paragneisses also indicate a thrusting towards the NE [Fernandez *et al.*, 2002]. In the southern flank of the Romanche River in the Taillefer Massif, the dominant planar structure in the Visean volcano-sediments appears as a composite S2-S3 crenulation schistosity. In these schists, the intersection lineation between S2 and S3 is parallel to the microfold axes of the crenulation with a N140° 10°SE trending direction. The microfolds show a northeastern vergence similar to that observed in the amphibolites at the sole of the ophiolitic unit. The axial planes of D3 microfolds are parallel to those of mesoscopic folds. Thus, the geometry of D3 microfolds is consistent with the major fold structures, suggesting both took place during the D3 event. K/Ar ages of hornblende and granites bracket the D2-D3 event between 341 ± 13 Ma and 324 ± 12 Ma [Ménot *et al.*, 1987; Debon *et al.*, 1998].

Westphalian-Middle Stephanian extensional tectonics (D4)

From Late Carboniferous to Permian times, the External Crystalline Massifs belt records a complicate tectonic history dominated by extensional and strike-slip tectonics. The SW Belledonne area records two phases of extension (D4 and D5). Both these deformation phases took place during Late Carboniferous, as inferred from structural relationships with Westphalian and Stephano-Permian sedimentary basins. D4 occurs under low pressure anatectic conditions in lower structural rocks and under greenschist facies conditions in higher nappes [Guillot and Ménot, 1999; Fernandez *et al.*, 2002]. Kinematic indicators mark a SW-NE directed extension, roughly parallel to the strike of the massif, with collapse of the SW part and exhumation of the NE part of this domain. This extensional event is responsible for the opening of the Westphalian basins [Fernandez *et al.,* 2002]. Eastwards, a N-S to N160°E ductile/brittle normal fault dipping 65° to 80° towards the west is located at the transition from the Grandes Rousses Massif to the western boundary of the Oisans Massif (fig. 7). The D4 ductile normal fault bears a N030°E 40°SW muscovite lineation indicating top to the SW extension. This ductile extension is contemporaneous with a local migmatization of the staurolite-bearing schists in the Romanche Valley, as observed in the lower part of the SW Belledonne area. At shallower structural levels, the brittle faulting related to this extensional tectonics post-dated the deposition of Westphalian sediments, as observed in the SW Belledonne area, suggesting a possible Middle Stephanian age for the D4 extensional tectonics [e.g. Basile, 2006].

Stephanian-Permian extension and strike-slip faulting (D5)

The late Variscan structures of the External Crystalline Massifs are dominated by localized metric to hectometric ductile to brittle dextral strike slip faults oriented NE-SW in the Belledonne (fig. 8d) and Grandes Rousses Massifs and a NNW-SSE ductile sinistral slip fault in the inner zone of the Oisans Massif in which granite emplaced [Strzerzynski *et al.*, 2005]. The close association between strike-slip faulting and normal faulting along a lithospheric shear zone is very common as observed in the Tertiary Ailo Shan shear zone in Indochina [Leloup *et al.*, 1995] or the Karakorum fault in western Tibet [Lacassin *et al.*, 2004]. Similar directions of strike-slip faulting and of opening of the Late Stephanian coal basins are observed in the French Massif Central [e.g. Basile, 2006].

In the Oisans Massif, the Devonian nappe pile is crosscut by the intrusion of Stephanian granites along a N160°E sinistral ductile strike-slip fault [Strzerzynski *et al.*, 2005]. A ductile normal fault outcrops on the western flank of the Oisans Massif where syn-migmatization extensional structures oriented N160°E to N010°E and dipping 50°W are observed. These structures are locally associated with conjugated extensional S-C structures oriented N005°E to N020°E and dipping 50°E. In the migmatites surrounding the low-pressure-high temperature mafic granulites, syn-migmatization extensional S-C structures, oriented N140°E dipping 20°W, are interpreted as Stephanian extensional structures [Grandjean *et al.*, 1996].

The External zone of the Belledonne Massif is entirely composed of a sub-vertical metasedimentary unit (Série Satinée). This unit recorded three deformation phases. The first phase of deformation is represented by 10 cm-scale isoclinal folds with vertical axial surfaces and N-dipping axes and reflects earlier dextral wrenching (Visean?). The second phase generated metre-scale folds with horizontal axial surfaces and sense of asymmetry indicating top to the SE displacement compatible with the D5 event. The youngest deformation overprinted the previous structures and generated 10 - to 100 m -scale folds with vertical axial planes and axes oriented N000° 20°N related to the Alpine deformation along the Synclinal Median strike slip-fault.

This Stephano-Permian tectonics resulted in the separation of NNE-SSW trending blocks (fig. 7). Three major normal/strike-slip faults are recognized: the Synclinal Median fault (fig. 4) is a typical Stephanian-Permian dextral strike slip fault reactivated during Alpine convergence [Fernandez *et al.*, 2002]. It marks the juxtaposition of the external and internal zones of Belledonne. The dextral Rivier-Belle Etoile fault marks the boundary between the SW and the NE Belledonne areas (fig. 8d). A third boundary between Devono-Dinantian and older basement rocks has also been traced between the outer and inner parts of the Oisans Massif. Le Fort and Ehstrom [1969] described this boundary as

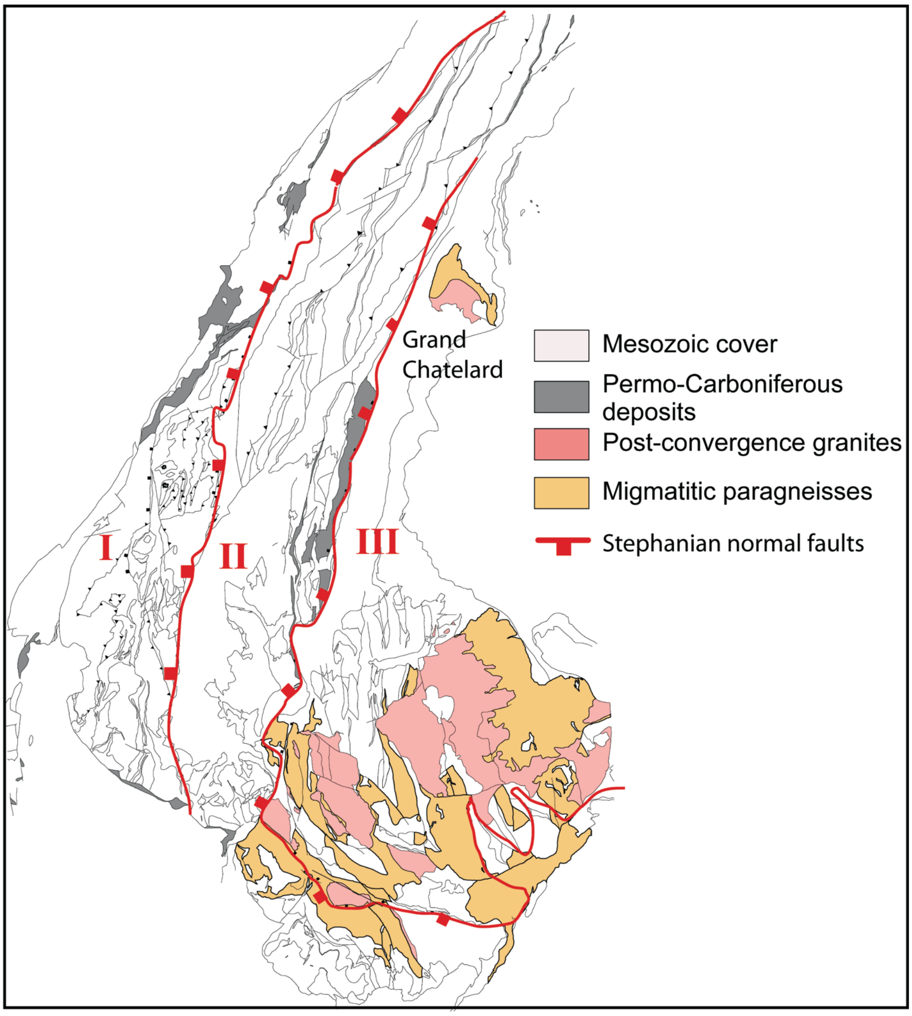

FIG. 7. – Geological map of the Late Carboniferous event. Domain I corresponds to the upper crustal level dominated by brittle extensional tectonics ; domain III corresponds to the deeper crustal level dominated by ductile extensional tectonics associated with widespread magmatism ; domain II is intermediate with both brittle and ductile tectonics and local anatexis.

FIG. 7. – *Carte géologique du Carbonifère inférieur. Le domaine I correspond à la croûte supérieure dominée par l'extension fragile ; le domaine III correspond à la croûte profonde dominée par l'extension ductile et le magmatisme. Le domaine II est intermédiaire, à la transition ductile-fragile avec une anatexie très localisée.*

a major fault and recent structural investigations suggest that it is a Stephanian normal fault [Guillot et Ménot, 1999] with a sinistral component along an initial NW-SE direction [Strzerzynski *et al*., 2005]. The prolongation of this normal fault corresponds northwards to the conjugated Grandes-Rousses-Chatelard dextral-strike slip fault (fig. 7). The emplacement of the Al-Fe granites resulting from melting of continental crust and subordinate enriched subcontinental lithospheric mantle [Debon and Lemmet, 1999] within D5 strike-slip faults, suggests that these faults cross-cut the entire continental crust and were rooted in the lithospheric mantle. The importance of these Stephanian-Permian strike slip fault zones for tectonic reconstruction will be further discussed.

THE EXTERNAL CRYSTALLINE MASSIFS IN THE PALEOZOIC FRAMEWORK

On the basis of the geological data presented above and previous reconstructions [von Raumer et Ménot, 1989; Ménot *et al*., 1994; von Raumer *et al*., 1999; 2002; 2003; 2009; Stampfli and Borel, 2002], we propose here to integrate these three domains within the tectonic evolution of the European Paleozoic orogenic belt. In comparison with the rest of the Variscan belt, in terms of lithology, tectonic evolution and associated metamorphism and magmatism, the External Crystalline Massifs record the complete evolution of the collision zone, comprised between Laurussia and Gondwana, including Armorica. Considering that the Chamrousse ophiolitic complex represents a witness of the Late Cambrian back-arc rifting and a subsequent general extension leading to the opening of the Rheic Ocean [Guillot and Ménot, 2009; Von Raumer *et al*., 2009] and the rest of the External Crystalline Massifs including Sardinia and Corsica represent the southeastward prolongation of the eo-Variscan suture zone [Matte, 2001; Corsini and Rolland, 2009; Rossi *et al*., 2009], we will demonstrate that the central domain represents the Moldanubian zone, initially located northward in the prolongation of the present-day Bohemian Massif (fig. 9) in accordance with the interpretation of von Raumer *et al.* [2003].

Lower Paleozoic ocean

The Lower Paleozoic evolution of the External Crystalline Massifs is variably recorded in pre-Devonian units. The ophiolitic complex of Chamrousse in the central domain represents the Cambro-Ordovician oceanic lithosphere. It is characterized by E-MORB signature, relatively large volume of plagiogranites and the presence of volcanoclastic sediments, suggesting that this ophiolite formed in a back-arc continental basin [Guillot and Ménot, 2009]. In the eastern domain, the metabasic rocks from NE Belledonne derive from tholeiitic basalts formed on a thinned continental crust, close to a subduction zone. This continental proximity is also supported by the striking occurence of metasediments surrounding the retrogressed eclogites in NE Belledonne and in the Oisans Massif (fig. 5). The minimum age of sediments is provided by a radiometric age of 489 ± 22 Ma for a metagranite intruding these sediments [Barféty *et al*., 2001].

A continental rifting with a possible subduction influence is also inferred for the geological setting of orthogneisses preserved in the Oisans Massif (fig. 5) that display alkaline compositions [von Raumer *et al*., 1993]. An Ordovician age is inferred since a similar Ordovician magmatic event is well documented in the Paleozoic belt of Europe and similar metagranites are recently reported in NE Belledonne and dated at 489 ± 22 Ma (U/Pb on zircon) [Barféty *et al*., 2001].

In the western domain, there are no relics of ocean ridge or rift related magmatism. The only lithologies are metasediments the protoliths of which are not dated. Their age is supposed to be Late Neoproterozoic to Lower Paleozoic on the basis of lithologic similarities with the metapelitic units of the South Massif Central and Vosges [Ménot, 1988a]. Similar series are observed in the external part of the Maures Massif [Arthaud and Matte, 1977], in Sardinia [Carmignani *et al.,* 1994] and Corsica and are traditionally correlated with the Montagne Noire Massif [von Raumer *et al.,* 1993; Rossi, 2007]. These metasediments probably correspond to a terrigenous series deposited at the northern edge of the Gondwana passive margin during the Cambro-Ordovician rifting.

The Cambrian-Ordovician period of widespread extension and rifting is recorded in some rock sequences from all over the Paleozoic belt, as testified by the protoliths of metabasic rocks with tholeiitic affinities [Paquette *et al.,* 1989; Ménot and Paquette, 1993 and ref. therein]. According to paleomagnetic constraints [Tait *et al*., 1997; Torsvik,

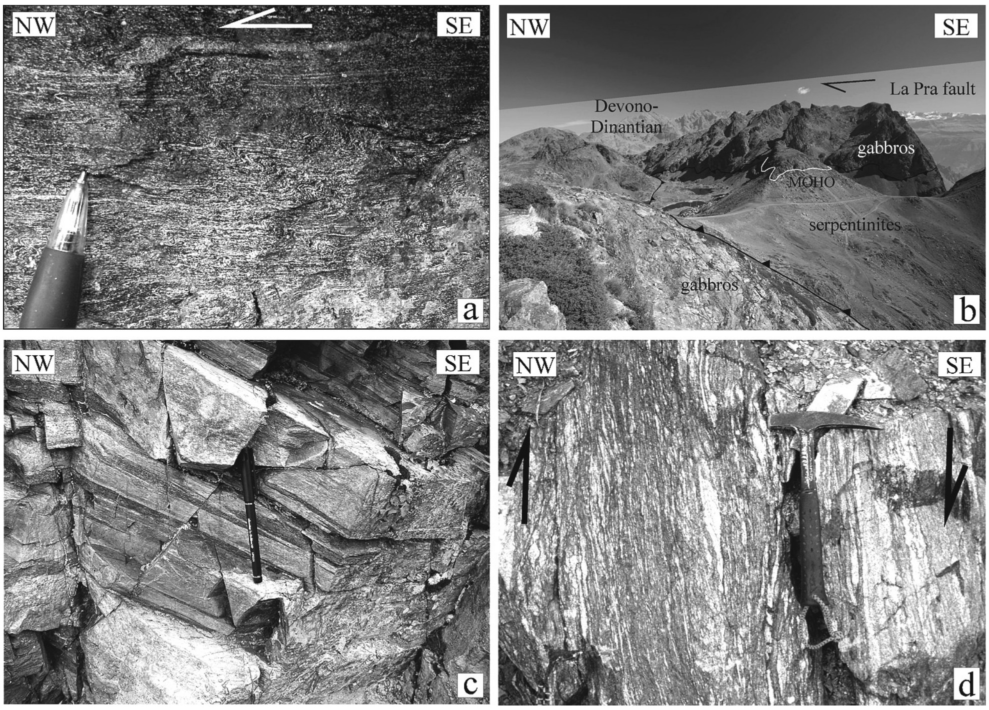

FIG. 8. – a) General view of the upper part of the Chamrousse ophiolitic complex. The N-S dextral strike-slip La Pra fault puts the Devono-Dinantian magmatic rocks in contact with the Chamrousse ophiolitic complex. The petrological Moho (normal contact between the serpentinites and the gabbros) is preserved around the Manqué summit. Front of the photo, a ductile thrust oriented NE-SW puts in contact the normal serie (serpentinites + gabbros) over the gabbros. b) photo of the sole of the Chamrousse ophiolitic complex (Les Puntis, Taillefer Massif) showing the top to the NW vergence folds , dated at 376 ± 7 Ma (unpublished ^{40}Ar-^{49}Ar dating on amphiboles by Monié and Ménot) c) photo of the mylonite oriented N005° 20°W bearing a N100° 15°WNW stretching lineation indicating top to the NW thrusting, putting in contact the gabbro over the amphibolites of Sechilienne (Rocher de la Perche, Chamrousse skiing station). d) Metric dextral shear zone oriented N020° 85°E in the migmatitic paragneisses of NE Belledonne. Notice that shearing is syn to post migmatitic, suggesting that it developed during the Carboniferous.

FIG. 8. – a) *Vue générale de la partie supérieure du complexe ophiolitique de Chamrousse. La faille dextre N-S de La Pra, met en contact les roches magmatiques dévono-dinantienne avec l'ophiolite de Chamrousse. En dessous du Manqué, le Moho pétrologique est observé entre les serpentinites et les gabbros. Au premier plan, un chevauchement ductile orienté NE-SW met en contact la série normale sur les gabbros.* B) *Photo de la semelle ophiolitique de Chamrousse (Les Puntis, Massif du Taillefer) montrant les cisaillements vers le NW daté à 376 ± 7 Ma (datation ^{40}Ar-^{49}Ar sur amphiboles par Monié et Ménot).* C) *Photo de la mylonite (N005° 20°W portant une linéation N100° 15°WNW) correspondant au chevauchement vers le WNW des gabbros sur les amphibolites de Séchilienne (Rocher de la Perche, station de Chamrousse).* d) *Zone de cisaillement métrique orientés N020° 85°E dans les paragneiss migmatiques (NE Belledonne). Noter que la déformation ductile est syn à post migmatisation suggérant que le cisaillement est probablement d'âge carbonifère.*

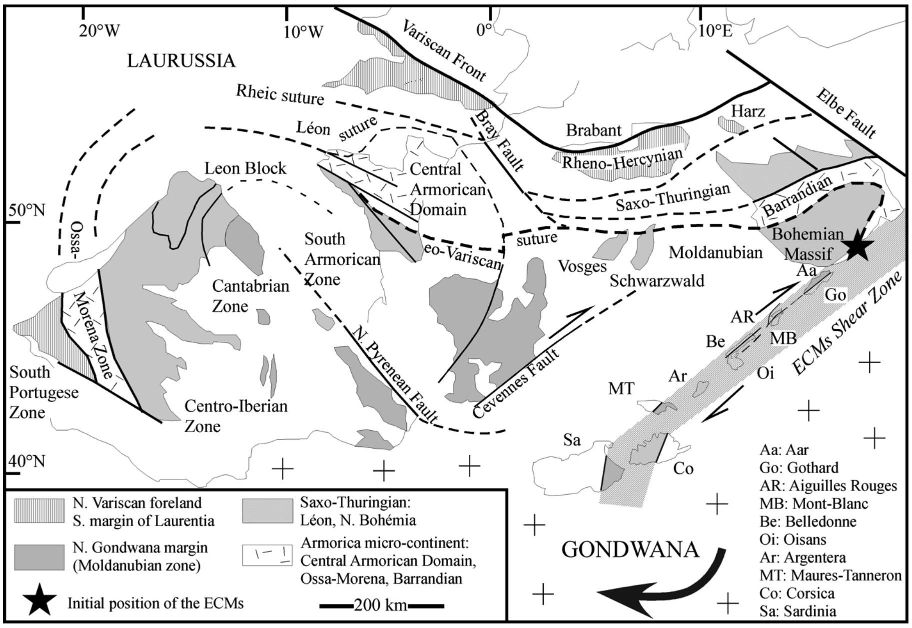

FIG. 9. – Possible configuration of the Variscan belt of western Europe in Late Carboniferous times, showing the main sutures and prolongation of the eo-Variscan suture zone in the External Crystalline massifs but also in Corsica and Sardinia. The southward prolongation of the Saxo-Thuringian suture zone is only observed in the SW Belledonne Massif. The strong shearing of these two main suture zones (reduced at a width of 30 km) from Late Carboniferous to Permian was accommodated by the dextral External Crystalline Massifs shear zone. Correlation of the Chamrousse ophiolite with the Saxo-Thuringian suture zone requires a total offset of a minimum of 300 km. S.A.S.Z.: South Armorican shear zone; C.C.S.Z.: Coïmbra-Cordoba shear zone [after Matte, 2001].

FIG. 9. – *Configuration possible de la chaîne Varisque d'Europe occidentale au Carbonifère supérieur, avec la prolongation de la suture éo-Varisque dans les Massifs Cristallins Externes, en Corse et en Sardaigne. La prolongation vers le sud de la zone de suture saxo-thuringienne n'est observable que dans le massif de Belledonne SW. Le très fort cisaillement subit par les deux zones de suture réduite à une trentaine de kilomètre de large durant que le Permo-Carbonifère est accommodé le long de la zone de cisaillement des Massifs Cristallins Externes. La corrélation de l'ophiolite de Chamrousse avec la zone saxo-thuringienne implique un décalage d'au moins 300 km.* S.A.S.Z. : *zone broyée sud armoricaine ;* C.C.S.Z. : *zone de cisaillement de Coïmbra-Cordoba [d'après Matte, 2001].*

1998], this general extension could be related to the opening of a back-arc basin between the passive north Gondwana margin and the active Armorica domain [Matte, 1986; von Raumer *et al.*, 2002; 2008] (fig. 10a). In this scenario, the ophiolitic complex of Chamrousse is a rare preserved witness of the opening of this oceanic domain initiating the opening of the Rheic Ocean [Guillot and Ménot, 2009].

The age (~ 470 Ma) of the NE Belledonne and Argentera metabasites [Paquette *et al.*, 1989] compared with the Chamrousse ophiolitic complex (~ 495 Ma) may suggest the late opening of the Central-European ocean between the Moldanubian zone and Gondwana (fig. 10b).

Silurian subduction

Convergence and subduction of oceanic crust at the transition from the central domain to the eastern domain, during Silurian-Devonian times, are shown by eclogitic relics in NE Belledonne, which are dated at 390 ± 8 Ma (U-Pb) [Paquette *et al.,* 1989]. Relics of eclogites have been found only in rocks of oceanic origin, and are preserved in the innermost part of the belt. Relics of HP oceanic rocks with similar age (390 – 420 Ma) have been described in other sectors of the External Crystalline Massifs (Argentera, Aiguilles Rouges) [Paquette *et al.*, 1989] but also in the Maures Massif, in Corsica and Sardinia [Palagi *et al.*, 1985; Libourel, 1985; Buscail, 2000; Franceschelli *et al.,* 2007]. In the French Massif Central, the eo-Variscan period, during which subduction of continental and oceanic crusts took place [Matte, 1986], also spanned between 420 and 400 Ma, and corresponds to the closure of the Medio-European ocean (fig. 10c) [Matte, 1986; 2001; Faure *et al.,* 1997, 2009; Torsvik, 1998]. The localized occurrences of eclogitic relics, in the Aiguilles Rouges and NE Belledonne Massifs, and thrusting over the Gondwana basement (eastern domain) towards the SE suggests that the polarity of the subduction zone was initially towards the NW (fig. 10c). This interpretation would be in accordance with the subduction polarity proposed in the French Massif Central [Matte, 1986; 2001]. Subduction was followed by collision marked by the widespread migmatisation and amphibolitisation dated at about 380-360 Ma [Vivier *et al.,* 1987; Paquette *et al.*, 1989; von Raumer *et al.*, 1993]. In contrast with von Raumer and Stampfli [2008] who tentatively proposed that the Chamrousse ophiolite obducted just after its formation in the Early Ordovician, we propose that this major Mid-Devonian collisional event was responsible for the final closure of the back arc Chamrousse basin and its obduction towards the WNW (fig. 10c).

Devonian subduction and Visean collision

Devonian-Dinantian bimodal igneous rocks outcrop in the central domain. It probably corresponds to an arc or a back-arc basin as the Brevenne unit in the French Massif Central [Carme and Pin, 1987; Pin and Paquette, 1997; Faure *et al.*, 1997; 2009] and correlates with the central part of the Moldanubian zone in the Bohemian Massif [Schulmann *et al.*, 2005]. There is no evidence of HP metamorphism associated with this second subduction. The LP eclogites from the Cellier unit and the blueschists from the Groix island in South Brittany are dated between 360 and 370 Ma [Bosse *et al.*, 2000; Ballèvre *et al.*, 2009], but also in the Saxo-Thuringian zone [refs in Ballèvre *et al.*, 2009] confirming the age of this second subduction event. Paquette *et al.* [1989] dated an eclogite in the Argentera Massif at 351 ± 1 Ma that likely corresponds to this second subduction. The subduction plane probably dips towards the SE in the studied area (fig. 10d) because:

– the Devonian-Dinantian volcanism developed within the SW Belledonne-Grandes Rousses and western part of the Oisans Massifs, thus the earlier Gondwana passive margin (eastern domain) was already accreted with Armorica, becoming an active margin; the western part of this second subduction-collision event is only formed by low-grade metasediments, Cambro-Ordovician in age (Série Satinée), thus it corresponds to a passive margin;

– the first compressive phase, recorded in the lower units of the Devonian-Dinantian magmatism, is indicated by a NW direction of shortening (fig 10e).

This is in accordance with the polarity and the timing of subduction of the Saxo-Thuringian ocean in the Bohemian Massif [Schulmann *et al.*, 2005].

Visean rocks are not affected by this second subduction-collision event, suggesting that the volcanism is syn- to post-collisional. During the same period, the central

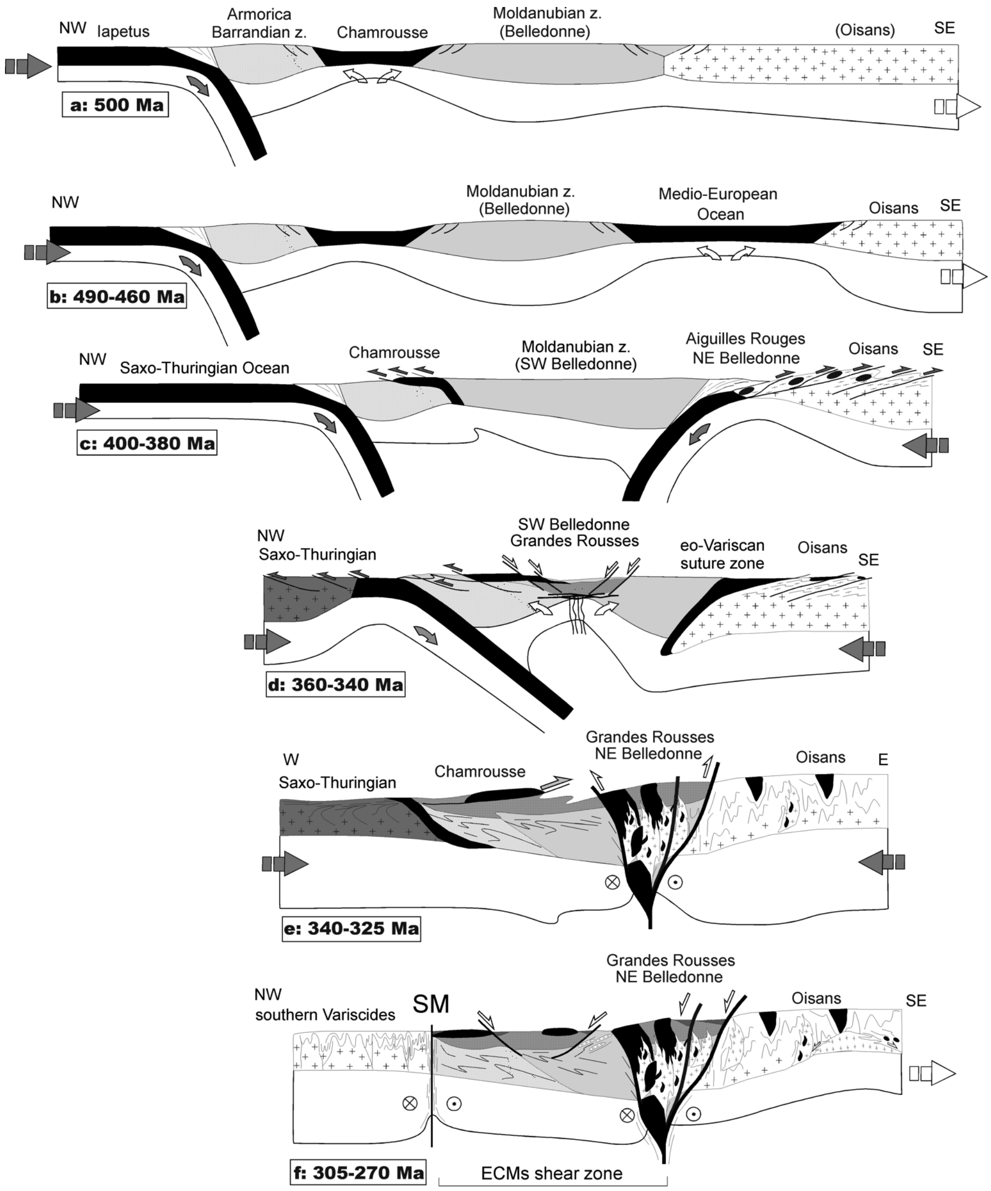

FIG. 10. – Schematic evolution of the Belledonne-Grandes Rousses and Oisans domain in six steps during the Paleozoic Era (see text for explanation). It shows the possible relationships of the Belledonne-Grandes Rousses-Oisans Massifs with the microcontinents Armorica and Gondwana and localizes the two main suture zones : the eo-Variscan suture zone between Gondwana and Moldanubian zone and the Devonian-Dinantian Saxo-Thuringian suture zone between Armorica-Barrandia and Laurusia. In this general scheme, the Chamrousse ophiolite is interpreted as a witness of a back-arc basin, emplaced on the Saxo-Thuringian suture zone. SM: Synclinal Median fault.

FIG. 10. – *Evolution schématique des Massifs Cristallins Externes en six étapes au cours du Paléozoïque. Ces coupes évolutives montrent le lien possible des Massifs Cristallins Externes avec Armorica et Gondwana et identifient les deux zones de suture : la zone de suture éo-Varisque entre Gondwana et la zone moldanubienne et la zone de suture saxo-thuringienne entre Armorica-Barrandia et Laurusia. Dans ce scénario, Chamrousse correspond à un bassin d'arrière-arc obducté sur la zone de suture saxo-thuringienne.* SM : *faille du Synclinal médian.*

domain also recorded a northwestward thrusting with a sinistral component along wrench faults oriented N030°, contemporaneous with the emplacement of Visean Mg-K granites. The simultaneous thrusting and wrenching may suggest a global transpressive regime that is compatible with an oblique collision. The northwestward direction of thrusting in the Belledonne Massif is in good agreement with the common shortening direction and kinematic indicators within the French Central Massif and the Armorican Massif during the same period [Brun and Burg, 1982; Ledru *et al.*, 1989; Faure *et al.*, 1997; Leloix *et al.*, 1999].

A second shortening event, responsible for the overthrusting of the Chamrousse ophiolitic complex onto Devonian-Dinantian units towards the NE (fig. 10e) is dated at 324 ± 12 Ma (K/Ar on amphiboles) [Ménot *et al.*, 1987]. Similar Late Visean deformation is recently recognized as the nappe displacement in the northeastern part of the French Massif Central [Faure *et al.*, 1997; Leloix *et al.*, 1999; Faure *et al.*, 2001, 2002]. During this period, the southern part of the Iberian block records thrusting towards the southwest whereas the northern part of the Ibero-Armorican arc still records NW compression [Brun and Burg, 1982; Matte, 1986]. Thus, the D3 event is likely related to the lateral move of the Paleozoic blocks, located north and south of the Ibero-Armorican arc, during the final collision between Gondwana and Avalonia. This motion is accompanied by the clockwise rotation of the northern branch of the Saxo-Thuringian suture zone [Tait *et al.*, 1996; Edel, 2001].

Late Carboniferous and Permian evolution

Three major NW-SE trending, normal/strike-slip faults rim the Westphalian and Stephanian basins to the east and delineate crustal blocks exhibing different crustal depths, as suggested by their metamorphic evolution and by the location of Late Carboniferous basins (fig. 7).

In the central domain, two phases of Late Carboniferous extension have been recorded, both developed at relatively shallow crustal depths. The geometry of the Westphalian and Stephanian basins and related brittle structures [Fernandez *et al.*, 2002], attests a first Westphalian to Middle Stephanian NE-SW direction of extension followed by a second Late Stephanian NW-SE directed extension (fig. 10f). The development of Westphalian and Stephanian basins over the central domain testifies their shallow crustal level at that time. The eastern domain (fig. 7) displays characteristics of a deeper crustal level. The Al-Fe granitic plutons, emplaced in a N-S extensional regime, are entirely located in this block (fig. 10e). Secondary cordierite bearing migmatites in the inner Oisans Massif are widespread and obliterate quite completely the oldest structures. Moreover, in the SE portion of the Oisans Massif, granulites record a LP-HT late-Paleozoic metamorphism, with a P-T path marked by a strong increase in temperature during decompression [Grandjean *et al.*, 1996], as classically observed in western Europe [e.g. Gardien *et al.*, 1997]. Neither the Westphalian nor the Stephanian basins are presently preserved upon this block, providing another argument for its deeper structural level during the Late Carboniferous.

Mid-Carboniferous to Permian strike-slip faulting plays a major role in the final geometry and emplacement of the External Crystallines Massifs. This fault system is well known northward in the Mont Blanc Massif and was responsible for the emplacement of several granitoids up to the Stephanian [Bussy *et al.*, 2000]. More to the south, in the Argentera Massif, the dextral Ferrière-Mollières shear zone is oriented NW-SE and is dated at 327 ± 3 Ma [Musumeci and Columbo, 2005] while in the Oisans Massif, the NW-SE shear zones are dated by syntectonic granite emplacement at 302 ± 2 Ma [Strzezynski *et al.*, 2005]. This suggest that between the Stephanian and the Tertiary, the southern branch of the External Crystalline Massifs, including the Oisans and the Argentera Massifs recorded important counterclockwise rotation related to a north-south regime of extension and corresponds to the individualization of a conjugated strike-slip fault. This shift in strike is interpreted as anticlockwise tilting of the Argentera massif of ~ 40° during the Early Miocene [Corsini *et al.*, 2004; Corsini and Rolland, 2009]. In the Maure Massif, the Plan de la Tour and the Rouet granites are also emplaced in a NNE-SSW dextral shear zone at ca. 300 Ma [Onezime *et al.*, 1999; Corsini and Rolland, 2009]. Restoring the Oligocene rotation (~30°) of the Corsico-Sardinia block, the foliation strike and the orientation of the main fault aligned along a N-S to a N030° direction and recorded similar evolution from Silurian to Late Carboniferous as described in the rest of the External Crystallines Massifs, in particular the emplacement of Late Carboniferous granites (mostly from 320 to 300 Ma in a transpressive dextral tectonique régime [Corsini and Rolland, 2009; Rossi *et al.*, 2009]. This fault system defines a 30 km wide dextral strike-slip fault system namely the External Crystalline Massifs shear zone (fig. 9).

More to the north of Europe, a similar NW-SE dextral shear zone active all along the Carbonifeous is recognized in the southeastern boundary of the Bohemian Massif, defining the 50 km wide Moravian zone [Suess, 1912; Schulmann *et al.*, 2005]. In accordance with von Raumer [1998], we propose that the Moravian zone is the northward equivalent of the External Crystalline Massifs Shear Zone [Guillot and Ménot, 2009]. The fact that the External Crystalline Massifs show the same lithologies and the same tectono-metamorphic evolution as the eastern part of the Bohemian Massif [e.g. Schulmann *et al.,* 2005 for comparison] suggest that the External Crystalline Massifs were probably in lateral continuity with this massif during the Early Carboniferous (fig. 9) as already suggested [Bard, 1997; Stampfli and Borrel, 2002; von Raumer *et al.*, 2003].

Then, from Late Carboniferous to Permian times, the northern branch was finally stretched and translated towards the SE along the External Crystalline Massifs shear zone. The length of this fault system from the Bohemian Massif to the Maures Massif is of a minimum of 600 km. Moreover, the occurrence of synkinematic granitoids along this shear zone suggests that it represents almost a crustal-scale shear zone similar to the South Armorican shear zone or the Coïmbra-Cordoba shear zone (fig. 9). Correlation of the suture zones (Saxo-Thuringian and eo-Variscan) across the External Crystalline Massifs shear zone requires a possible offset of 300 km. In this general scheme, the external part of the Belledonne Massif, but also the external part of the Maures Massif, Corsica and Sardinia are the only parautochthonous parts of the studied area and belong to the southern Variscides (fig. 9). Such an important offset, equivalent of the offset estimated for example on the Karakorum fault in Tibet [Lacassin *et al.*, 2004], did not result in collision or extrusion processes but was related to the global clockwise rotation of Africa during the Late Paleozoic and the opening of the Paleo-Tethys oceanic domain between Laurussia and Gondwana [Bard, 1997; Edel, 2001; Matte, 2001; Stampfli and Borel, 2002; Nance and Linneman, 2008].

IMPLICATIONS FOR ALPINE RECONSTRUCTION

According to Schmid and Kissling [2000], the northern margin of Apulia (present-day Insubric line) was translated by about 124 km towards the NW during the Alpine collision after the Eocene. Considering that the Bohemian and the Maures Massifs were not affected by Alpine translation and that the External Crystalline Massifs were aligned along the External Crystalline Massifs Shear Zone at the end of the Paleozoic (fig. 9) we estimated by comparing figure 1 and figure 9 that the amount of translation of the ECM along the NW direction is about 110 km after the Paleozoic. Our estimate is similar to Schmid and Kissling's estimates based on Tertiary reconstructions, which suggest that our reconstruction is robust, i.e. that the External Crystalline Massifs were initially aligned along the External Crystalline Massifs shear zone between the Bohemian and the Maures Massifs, prior to the Mesozoic.

CONCLUSION

Reexamination of the 1/50,000 scale geological maps and new structural and metamorphic data allow us to evaluate the Paleozoic evolution of Belledonne, Grandes Rousses and Oisans Massifs. We propose that the eo-Variscan suture zone between the internal part of the Belledonne and the Oisans Massif formed during the Silurian-Devonian subduction-collision when Gondwana (Oisans) subducted beneath and collided with Armorica (Belledonne-Aiguilles Rouges) along a NW dipping subduction zone. The collision was accompanied by the closure of the back arc Chamrousse basin and its obduction toward the WNW over Armorica (or Barrandia).

A second episode of subduction-collision occurred from Devonian to Visean time. It was characterized by the closure of the Saxo-Thuringian ocean along a SE dipping subduction zone beneath the External Crystalline Massifs and the development of an active margin on the northern part of Moldanubian domain (SW Belledonne, Grandes Rousses and outer Oisans Massifs]. The Visean collision was characterized by intrusions of Mg-K syntectonic granites, nappe stacking towards the NW and Barrovian metamorphism and ended with the back thrusting of the Chamrousse ophiolitic complex towards the NE.

The final tectonic activity was marked by widespread extension and dextral wrenching from Carboniferous to Permian times, along the > 600 km long External Crystalline Massifs shear zone. This strike-slip faulting was responsible for the SW translation of the External Crystalline Massifs from northern Europe (in prolongation with the Bohemian Massif) in response to oblique collision between Laurussia and Gondwana.

Acknowledgements. – We thank M. Brunel, J.-P. Burg, M. Faure, J.-M. Lardeaux, J. von Raumer and K. Schulmann for stimulating discussions and Gabriel Courrioux for his help with MapInfo. We also thank Kéiko Hattori for reading the manuscript. This work was supported by the INSU-BRGM programme "Geo-France 3D – Alpes" and a doctoral grant co-tutored by the Universities of Milano and Lyon I (S.D.P.).

References

ARTHAUD F. & MATTE. P. (1977a). – Late Paleozoic strike-slip faulting in southern Europe and northern Africa result of a right-lateral shear zone between the Appalachians and Urals. – *Geol. Soc. Amer. Bull.*, **88**, 1305-1320.

ARTHAUD F. & MATTE P. (1977b). – Détermination de la position initiale de la Corse et de la Sardaigne à la fin de l'orogenèse hercynienne grâce aux marqueurs géologiques anté-Mésozoïque. – *Bull. Soc. géol. Fr.*, 7, **XVII**, 833-840.

BALLÈVRE M., BOSSE V., DUCASSOU C. & PITRA P. (2009). – Paleozoic history of the Armorican massif: Models for the tectonic evolution of the sutures zones. – *C. R. Géoscience,* Paris, **341**, 174-201.

BANZET G., LAPIERRE H., LE FORT P. & PÊCHER A. (1985). – Le volcanisme Carbonifère supérieur du massif des Grandes Rousses (Zone dauphinoise-Alpes externes françaises). Un exemple de magmatisme à affinité shoshonitiques lié à la fracturation crustale tardi-varisque. – *Géol Alpine*, **61**, 33-60.

BARD J.-P. (1997). – Démembrement anté-mésozoïque de la chaîne varisque d'Europe occidentale et d'Afrique du Nord: rôle essentiel des grands décrochements transpressifs dextres accompagnant la rotation horaire de l'Afrique durant le Stéphanian. – *C. R. Acad. Sci.,* Paris, **324**, 693-704.

BARFÉTY J.-C. & PÊCHER A. (1982). – Notice de la carte géologique de la France au 1: 50 000, feuille de St. Christophe en Oisans.

BARFÉTY J.-C., BARBIER R., BORDET P., MÉLOUX J., MOUTERDE R. & VATIN-PÉRIGNON N. (1977). – Notice de la carte géologique de France à 1: 50 000, feuille St. Jean de Maurienne (774).

BARFÉTY J.-C., BORDET P., CARME F., DEBELMAS J., MELOUX M., MONT-JUVENT G., MOUTERDE R. & SARROT-REYNAULD J. (1972). – Notice de la carte géologique de la France au 1: 50 000, feuille de Vizille (797).

BARFÉTY J.-C., GIDON M., MÉNOT R.-P., DEBON F., PÊCHER A., GUILLOT S., FOURNEAUX J.-C. & GAMOND J.-F. (2001). – Notice de la carte géologique de la France au 1: 50 000, feuille de Domène (773), 2nd edition.

BASILE C. (2006). – A new interpretation of Stephanian deformation in the Decazeville basin (Massif Central, France): consequence on late Variscan tectonism. – *Internat. J. Earth Sci.*, **95**, 791-801.

BODINIER J.-L., DUPUY C., DOSTAL J. & CARME F. (1981). – Geochemistry of ophiolites from the Chamrousse complex (Belledonne Massif, Alps). – *Contrib. Mineral. Petrol.,* **78**, 379-388.

BOGDANOFF S., MÉNOT R.-P. & VIVIER G. (1991). – Les Massifs Cristallins Externes des Alpes occidentales françaises, un segment de la zone interne varisque. – *Bull. Sci Géol., Strasbourg*, **44**, 237-285.

BORDET P. & BORDET C. (1963). – Belledonne-Grandes Rousses et Aiguilles Rouges Mont Blanc: quelques données nouvelles sur leurs rapports structuraux. – Livre à la mémoire du professeur Fallot. – *Mém. h.s., Soc. géol. Fr.*, **1**, 309-316.

BOSSE V., FÉRAUD G., RUFFET G., BALLÈVRE M., PEUCAT J.-J. & DE JONG K. (2000). – Late Devonian subduction and early-orogenic exhumation from the Champtoceaux complex (Variscan belt, France). – *Geol. J.*, **35**, 297-335.

BRUN J.-P. & BURG J.-P. (1982). – Combined thrusting and wrenching in the Ibero-Armorican arc: a corner effect during continental collision. – *Earth Planet. Sci. Lett.*, **61**, 319-332.

BUSCAIL F. (2000). – Contribution à la compréhension du problème géologique et géodynamique du massif des Maures: le métamorphisme régional modélisé dans le système KFMASH: analyse paragénétique, chémiographie, thermobarométrie, géochronologie Ar/Ar. – Thèse de Doctorat, Université de Montpellier, 320 p.

BUSSY F., HERNANDEZ J. & VON RAUMER J. (2000). – Bimodal magmatism as a consequence of the post-collisional readjustment of the thickened Variscan continental lithosphere (Aiguilles Rouges Mont Blanc, western Alps). – *Trans. Royal Soc. Edinburgh*, **91**, 221-233.

CANNIC S., LAPIERRE H., SCHÄRER U., MONIÉ P., BRIQUEU L. & BASILE C. (1998). – Origin of Hercynian magmatism in the French western Alps: geochemical and geochronological constraints. – *Mineral. Mag.*, **62A**, 274-275.

CAPUZZO N. & BUSSY F. (2001). – Syn-sedimentary volcanism in the Late-Caboniferous Salvan-Dorenaz continental basin (western Alps). – *Mem. Sci. Natural. Brescia*, **25**, 203-211.

CARME F. (1970). – Age briovérien de la majeure partie des séries supposées dévono-dinantiennes et existence d'un cycle orogénique anté-Alpin, sans doute Cadomien, dans la chaîne de Belledonne (Alpes françaises). – *C. R. Acad. Sci.,* Paris, **271**, 631-633.

CARME F. & PIN C. (1987). – Vue d'ensemble sur le magmatisme pré-orogénique, l'évolution métamorphique et tectonique varisques dans le sud de la chaîne de Belledonne (Massif Cristallins Externes, Alpes françaises). – *C. R. Acad. Sci.,* Paris, **304**, 1177-1181.

CARMIGNANI L., CAROSI R., DI PISA A., GATTIGLIO M., MUSUMECI G., OGGIANO G. & PERTUSATI P.C. (1994). – The Hercynian chain in Sardinia (Italy). – *Geodin. Acta*, **5**, 217-233.

CORSINI M., RUFFET G. & CABY R. (2004). – Alpine and late-Hercynian geochronological constraints in the Argentera Massif (western alps). – *Eclogae. Geol. Helv.*, **97**, 3-15.

CORSINI M. & ROLLAND Y. (2009). – Late evolution of the southern European Variscan belt: exhumation of the lower crust in a context of oblique convergence. – *C. R. Geoscience,* **341**, 214-233.

DEBON F., GUERROT C., MÉNOT R.-P., VIVIER G. & COCHERIE A. (1998). – Late variscan granites of the Belledonne Massif (French western Alps): an early Visean magnesian plutonism. – *Schweiz. Mineral. Petrogr. Mitt.*, **78**, 68-87.

DEBON F. & LEMMET M. (1999). – Evolution of Mg-K ratios in the Late Variscan plutonic rocks from the External Crystalline Massifs of the Alps (France, Italy, Switzerland). – *J. Petrol.*, **40**, 1151-1185.

DEMEULEMEESTER P. (1982). – Contribution à l'étude radiométrique à l'argon et au strontium des Massifs cristallins externes (Alpes françaises). Distribution cartographique des âges sur biotites et amphiboles. – Thèse de 3ème cycle, Grenoble, 227p.

DI PAOLA S. (2002). – Eredita litostratigrafica, structurale e metamorfica paleozoica nel margine interno europea (Grandes Rousses et Argentera), ristructtturato durante l'orogenesi Alpina. – Thèse Université de Milan et Université de Lyon, 342p.

DROST K., LINNEMANN U., MCNAUGHTON N., FATKA O., KRAFT P., GEHMLICH P. M., TONK Ch. & MAREK J. (2004). – New data on the Neoproterozoic – Cambrian geotectonic setting of the Tepla-Barrandian volcano-sedimentary successions: geochemistry, U-Pb zircon ages, and provenance (Bohemian Massif, Czech Republic). – *Int. J. Earth Sci.,* **93**, 742-757.

EDEL J.B. (2001). – The rotations of the Variscides during the Carboniferous collision: paleomagnetic constraints from the Vosges and the Massif Central (France). – *Tectonophysics*, **332**, 69-92.

ELTER F.M., MUSUMECI G. & PERTUSATI P. (1990). – Late Hercynian shear zones in Sardinia. – *Tectonophysics*, **176**, 387-404.

FAURE M., CHARONNAT X., CHAUVET A., CHEN Y., TALBOT J.-Y., MARTELET G., COURRIOUX G., MONIÉ P. & MILESI J.-P. (2001). – Tectonic evolution and ore bearing fluids circulation in the Cévennes para-autochthonous domain of the Hercynian belt (French Massif Central). – *Bull. Soc. géol. Fr.*, **172**, 687-696.

FAURE M., LARDEAUX J.-M. & LEDRU P. (2009). – A review of the pre-Permian geology of the Variscan French Massif Central. – *C. R. Geoscience,* **341**, 202-213.

FAURE M., LELOIX C. & ROIG J.-Y. (1997). – L'évolution polycyclique de la chaîne hercynienne. – *Bull. Soc. géol. Fr.*, **168**, 695-705.

FAURE M., MONIÉ P., PIN C., MALUSKI H. & LELOIX C. (2002). – Late Visean thermal event in the northern part of the French Massif Central: a new $^{40}Ar/^{39}Ar$ and Rb-Sr isotopic constraints on the Hercynian syn-orogenic extension. – *Int. J. Earth Sciences*, **91**, 53-75.

FAURE M., MÉZÈME E.B., DUGUET M., CARTIER C. & TALBOT J.-Y. (2005). – Paleozoic tectonic evolution of the medio-Europa from the example of the French Massif Central and Massif Armoricain. – *J. Virtual Expl.*, **19**, 1-24.

FERNANDEZ A., GUILLOT S., MÉNOT R.-P. & LEDRU P. (2002). – Late Devonian to Upper Carboniferous tectonic evolution of the SW Belledonne (ECM, French Alps): polyphased nappe stacking and extensional tectonics. – *Geodin. Acta*, **15**, 127-139.

FRANCESCHELLI M., PUXEDDU M., CRUCIANI G. & UTZERI D. (2007). – Metabasites with eclogite facies relics from Variscides in Sardinia, Italy: a review. – *Int. J. Earth Sci.*, **96**, 795-915.

FRANKE W. (1989). – Variscan plate tectonics in Central Europe – current ideas and open questions. – *Tectonophysics*, **169**, 221-228.

GARDIEN V., LARDEAUX J.-M., LEDRU P., ALLEMAND P. & GUILLOT S. (1997). – Metamorphism during late orogenic extension: insights from the French Variscan belt. – *Bull. Soc. géol. Fr.*, **168**, 271-286.

GIBERGY P. (1968). – Découverte de " grès à trous " renfermant des débris d'organismes dans les schistes noirs du Valbonnais (série crystallophyllienne des massifs cristallins externes des Alpes françaises). – *C. R. Acad. Sci.,* Paris, **267**, 1251-1254.

GIORGI L. (1979). – Contribution à l'étude géologique des terrains cristallins du massif des Grandes Rousses, Isère, France. – PhD thesis, University of Grenoble, 184 p.

GRANDJEAN V., GUILLOT S. & PÊCHER A. (1996). – Un nouveau témoin de l'évolution métamorphique BP-HT post-orogénique hercynienne: l'unité de Peyre-Arguet (Haut-Dauphiné). – *C. R. Acad. Sci.,* Paris, **322**, 189-195.

GRATIER J.-P., LEJEUNE B. & VERGNE J.-L. (1973). – Etude des déformations de la couverture des MCE de Belledonne, Grandes Rousses et du Pelvoux. – PhD thesis, University of Grenoble, 289p.

GUERROT C. (1998). – Résultats de datation U-Pb par dissolution sur zircons pour deux échantillons du Pelvoux (Alpes, massif du Rochail (Ro1) – massif de Turbat-Lauranoure (TL 1). – Rapport SMN/PEA/ISO, Orléans, BRGM, 146/98.

GUILLOT P.L. & CLUZEL D. (1986). – A propos de la schistosité (varisque et/ou alpine) dans le socle du domaine subalpin: l'exemple du massif du Grand Châtelard (Savoie). – *C. R. Acad. Sci.,* Paris, **303**, 407-12.

GUILLOT S. & MÉNOT R.-P. (1999). – Nappe stacking and late Variscan extension in the Belledonne Massif (ECM, French Alps). – *Geodin. Acta*, **12**, 97-111.

GUILLOT S. & MÉNOT R.-P. (2009). – Paleozoic evolution of the External Crystalline Massifs of the western Alps. – *C. R. Geoscience*, **341**, 253-265

GUILLOT S., MÉNOT R.P. & FERNANDEZ A. (1998). – Paleozoic evolution of the External Crystalline Massifs along the Belledonne-Oisans transect (western Alps). – *Acta Univ. Carol.*, **42**, 257-259.

GUILLOT S., MÉNOT R.-P. & LARDEAUX J.-M. (1992). – Tectonique intra-océanique distensive dans l'ophiolite paléozoïque de Chamrousse (Alpes occidentales). – *Bull. Soc. géol. Fr.*, **163**, 229-240.

LARDEAUX J.-M., LEDRU P., DANIEL I. & DUCHÊNE S. (2001). – The Variscan French Massif Central – a new addition to the Ultra-high pressure 'club': exhumation and geodynamic consequences. – *Tectonophysics*, **332**, 143-167.

LE FORT P. (1973). – Géologie du Haut-Dauphiné cristallin (Alpes françaises). Etude pétrologique et structurale de la partie occidentale. – PhD. Thesis, University of Grenoble, 373 p.

LE FORT P., BARBIERI A., GILOT C., LACOMBE J.-C., PÊCHER A. & VIALON P. (1969). – Existence d'un socle précambrien dans le massif des Ecrins-Pelvoux (Alpes du Dauphiné, France). – *C. R. Acad. Sci.,* Paris, **20**, 2392-2395.

LE FORT P. & EHSTROM C.E. (1969). – Caractères géochimiques et origine des formations métamorphiques des massifs du Chaillol et de Belledonne. Volcanisme et sédimentation dans l'orogène hercynien des Alpes françaises. – *Sciences de la Terre, Nancy*, **3**, 215-238.

LEDRU P., LARDEAUX J.-M., SANTALLIER D., AUTRAN A., QUENARDEL J.-M., FLOC'H J.-P., LEROUGE G., MAILLET N., MARCHAND J. & PLOQUIN A. (1989). – Où sont les nappes dans le Massif central français? – *Bull. Soc. géol., Fr.*, 8, **V**, 3, 605-618.

LELOIX C., FAURE M. & FEYBESSE J.-L. (1999). – Hercynian polyphase tectonics in the northeast French Massif Central: the closure of the Brévenne Devonian-Dinantian rift. – *Int. Journ. Earth Sci.*, **88**, 409-421.

LELOUP P.H., LACASSIN R., TAPPONNIER P., SCHÄRER U., DALAI Z., XIAOHAN L., LIANGSHANG Z., SHAOCHENG J. & TRONG TRINH P. (1995). – The Ailo Shan-Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina. – *Tectonophysics*, **251**, 3-84.

LEMOINE M., BAS T., ARNAUD-VANNEAU A., ARNAUD H., DUMONT T., GIDON M., BOURBON M., GRACIANSKY DE P.-C., RUDKIEWCZ J.-L., MÉGARD-GALLI J. & TRICART P. (1986). – The continental margin of the Mesozoic Tethys in the western Alps. – *Mar. Petrol. Geol.*, **3**, 179-199.

LACASSIN R., VALLI F., ARNAUD N., LELOUP H., PAQUETTE J.-L., TAPPONNIER P., LI HAIBING, CHEVALIER M.-L., GUILLOT S., MAHÉO G., DELOULE E. & XU ZHIQUIN (2004). – Large scale geometry, offset and kinematic evolution of the Karakorum fault. – *Earth Planet. Sci. Lett.*, **219**, 255-269.

LIBOUREL G. (1985). – Le complexe de Santa Lucia di Mercurio (Corse), ultramafites mantelliques, intrusion basique stratifiée, paragneiss granulitiques. Un équivalent possible des complexes de la zone d'Ivrée. – Thèse doct. Géologie, Université Paul Sabatier, Toulouse, 461 p.

MARQUER D., CALCAGNO P., BARFETY J.-C. & BAUDIN T. (2006). – 3D modeling and kinenatics of the external zone of the French western Alps (Belledonne and Grand Châtelard Massifs, Maurienne Valley, Savoie). – *Eclogae Geol. Helv.*, **99**, 211-22.

MATTE P. (1986). – La chaîne varisque parmi les chaînes paléozoïques peri-atlantique, modèle d'évolution et position des grands blocs continentaux au Permo-Carbonifère. – *Bull. Soc. géol. Fr.*, 8, **II**, 1, 4-24.

MATTE P. (1998). – Continental subduction and exhumation of HP rocks in Paleozoic orogenic belts: Uralides and Variscides. – *GFF*, **120**, 209-222.

MATTE P. (2001). – The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. – *Terra Nova*, **13**, 122-128.

MÉNOT R.P. (1979). – Lithostratigraphie et pétrographie du groupe amphibolitique de Séchilienne et du massif ultrabasique de Chamrousse (massif de Belledonne, Alpes Occidentales). – *Géol. Alp.*, **55**, 93-110.

MÉNOT R.P. (1986). – Les formations plutono-volcaniques dévoniennes de Rioupéroux-Livet (Massifs Cristallins externes des Alpes françaises). – *Schweiz. Minéral. Petrogr. Mitt.*, **66**, 227-256.

MÉNOT R.-P. (1987). – Magmatismes et structuration orogénique paléozoïques de la chaîne de Belledonne: le domaine SW. – *Géol. Alp.*, **63**, 55-93.

MÉNOT R.P. (1988a). – Magmatisme paléozoïque et structuration carbonifère du massif de Belledonne (Alpes françaises). Contraintes nouvelles pour les schémas d'évolution de la chaîne varisque Ouest-Européenne. – *Mém Doc. C. Armor Etudes Struct. Socles,* Rennes, **21**, 465p.

MÉNOT R.-P. (1988b). – An overview of the geology of the Belledonne Massif (External Crystalline Massifs of western Alps). – *Schweiz. Mineral. Petrogr. Mitt.*, **70**, 33-53.

MÉNOT R.-P., PEUCAT J.-J., SCARENZI D. & PIBOULE M. (1985). – A (continental?) volcanic arc of devono-carboniferous age in the French Alpine External Massifs: The Rioupéroux and Livet formations (Romanche valley, Belledonne Massif). – *Ofioliti*, **10**, 2/3, 528.

MÉNOT R.-P., BONHOMME M. & VIVIER G. (1987). – Structuration tecto-métamorphique carbonifère dans le massif de Belledonne (Alpes occidentales françaises). Apport de la geochronologie K/Ar des amphiboles. – *Schweiz. Mineral. Petrogr. Mitt.*, **67**, 273-284.

MÉNOT R.-P., PEUCAT J.-J., SCARENZI D. & PIBOULE M. (1988). – 496 Ma age of plagiogranites in the Chamrousse ophiolite complex (External Crystalline Massifs in the French Alps): evidence of a Lower Paleozoic oceanization. – *Earth Planet. Sci. Lett.,* **88**, 82-92.

MÉNOT R.-P. & PAQUETTE J.-L. (1993). – Geodynamic significance of basic and bimodal magmatism in the External domain. *In*: J.F. von RAUMER & F. NEUBAUER, Eds, The pre-Mesozoic geology in the Alps. – Springer-Verlag, Heidelberg, 241-254.

MÉNOT R.-P., VON RAUMER J.F., BOGDANOF S. & VIVIER G. (1994). – Variscan basement of the western Alps: the External Crystalline Massifs. *In*: J.D. KEPPIE, Ed., Pre-Mesozoic geology in France and related areas. – Springer-Verlag, Heidelberg, 458-466.

MUSUMECI G. & COLOMBO F. (2002). – Late Visean mylonitic granitoids in the Argentera Massif (western Alps, Italy): age and kinematic constraints on the Ferrière–Mollières shear zone. – *C. R. Géosciences*, **334**, 213-220.

NANCE R. D. & LINNEMANN U. (2008). – The Rheic ocean: origin, evolution, and significance. – *GSA Today,* **18**, doi: 10.1130/GSATG24A.1.

ONEZIME J., FAURE M. & CREVOLA G. (1999). – Étude pétro-structurale du complexe granitique Rouet – Plan-de-la-Tour (massifs des Maures et du Tanneron occidental, Var). – *C. R. Acad. Sci.,* Paris, **328**, 773-9.

PALAGI P., LAPORTE D., LARDEAUX M., MÉNOT R.-P. & ORSINI J.-B. (1985). – Identification d'un complexe leptyno-amphibolique au sein des " gneiss de Belgodère " (Corse occidentale). – *C.R. Acad. Sci.,* Paris, **301**, II, 14, 1047-1052.

PAQUETTE J.-L., MÉNOT R.-P. & PEUCAT J.-J. (1989). – REE, SM-Nd and U-Pb zircon study of eclogites from the Alpine External Massifs (western Alps): evidence for crustal contamination. – *Earth Planet. Sci. Lett.*, **96**, 181-189.

PIN C. & VIELZEUF D. (1983). – Granulites and related rocks in Variscan median Europe: a dualistic interpretation. – *Tectonophysics*, **93**, 47-74

PIN C. & PEUCAT J.-J. (1986). – Ages des épisodes de métamorphisme paléozoïque dans le Massif central français et le Massif armoricain. – *Bull. Soc. géol., Fr.*, 8, **II**, 3, 461-469

PIN C. & CARME F. (1987). – A Sm-Nd isotopic study of a 500 Ma old oceanic crust in the Variscan belt of Europe: the Chamrousse ophiolite complex, western Alps (France). – *Contrib. Mineral. Petrol.*, **96**, 406-413.

PIN C. & PAQUETTE J.-C. (1997). – A mantle-derived bimodal suite in the Hercynian belt: Nd isotope and trace element evidence for a subduction-related rift origin of the Late Devonian Brevenne metavolcanics, Massif Central (France). – *Contrib. Mineral. Petrol.,* **129**, 222-238.

RAMSAY J.G. & GRAHAM R.H. (1970). – Strain variation in shear belts. – *Can. J. Earth Sci.*, **7**, 786-813.

ROSSI P. (2007). – Evidence of Panafrican and Variscan basements in the Maures and Corsica Massifs (France). Comparisons and connections with Middle Europe. – *Géol. France*, **2**, 154.

ROSSI P., OGGIANO G. & COCHERIE A. (2009). – A restored section of the "southern Variscan realm" across the Corsica-Sardinia microcontinent. – *C. R. Geoscience,* **341**, 224-238.

SCHALTEGGER U. (1997). – Magma pulses in the Central Variscan Belt: episodic melt generation and emplacement during lithospheric thinning. – *Terra Nova*, **9**, 242-245.

SCHMID S.M. & KISSLING E. (2000). – The arc of the western Alps in the light of geophysical data on deep crustal structure. – *Tectonics*, **19**, 62-85.

SCHULMANN K., KRÖNER A., HEGNER E., WENDT I., KONOPASEK J., LEXA O. & STIPSKA P. (2005). – Chronological constraints on the pre-orogenic history, burial and exhumation of the deep-seated rocks along the eastern margin of the Variscan orogen, Bohemian Massif, Czech Republic. – *Am. J. Sci.*, **305**, 407-448.

STAMPFLI G.M. & BOREL G.D. (2002). – A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. – *Earth Planet. Sci. Lett.*, **196**, 17-33.

STRZERZYNSKI P., GUILLOT S., LEDRU P. & COURRIOUX G. (2005). – Modélisation géométrique 3D des granites stéphaniens du massif du Pelvoux (Alpes, France). – *C. R. Acad. Sci.,* Paris, **337**, 1284-1292.

SUESS F.E. (1912). – Die moravischen Fenster und ihre Beziehung zum Grundgebirge des Hohen Gesenke. – Denkschrichte des Koeniglischen Akademie der Wissenscahft, Mathematik. – Naturwissenschaft **12**, 541-631.

TAIT J.A., BACHTADSE V. & SOFFEL H.C. (1996). – Eastern Variscan fold belt: paleomagnetic evidence for oroclinal bending. – *Geology*, **24**, 871-4.

TAIT J.A., BACHTADSE V., FRANKE W. & SOFFEL H.C. (1997). – Geodynamic evolution of the Euroepan fold belt: paleomagnetic and geological constraints. – *Geol. Rundsch.*, **86**, 585-598.

THOMPSON A.B. & ENGLAND P.C. (1984). – Pressure-temperature-time paths of regional metamorphism II. Their inference and interpretation using mineral assemblages in metamorphic rocks. – *J. Petrol.,* **25**, 929-955.

THOUVENOT F., FRÉCHET J., JENATTON L. & GAMOND J.-F. (2003). – The Belledonne border fault: identification of an active seismic strike-slip fault in the western alps. – *Geophys. J. Int.*, **155**, 174-92.

TORSVIK T.H. (1998). – Paleozoic paleogeography: a North Atlantic viewpoint. – *GFF*, **120**, 109-118.

VIVIER G., MÉNOT R.-P. & GIRAUD P. (1987). – Magmatismes et structuration orogénique paleozoiques de la chaîne de Belledonne (Massif Cristallins Externes): le domaine NE. – *Géol. Alpine*, **63**, 25-53.

VANOSSI M., PEROTTI C.R. & SENO S. (1994). – The Maritime Alps arc in the Ligurian and Tyrrhenian systems. – *Tectonophysics*, **230**, 75-89.

VON RAUMER J.F. (1998). – The Paleozoic evolution in the Alps: from Gondwana to Pangea. – *Geol. Rundsch.*, **87**, 407-435.

VON RAUMER J.F. & MÉNOT R.-P. (1989). – Evolution paléozoïque du socle ouest-alpin et place des Massifs Cristallins Externes dans l'orogène Varisque. – *C. R. Acad. Sci.,* Paris, **309**, 397-402.

VON RAUMER J.F., MÉNOT R.-P., ABRECHT J. & BIINO G. (1993). – The Pre-Alpine evolution of the external massifs. In: J.F. von RAUMER & F. NEUBAUER, Eds, Pre-Mesozoic geology in the Alps. – Springer-Verlag, Heidelberg, 221-240.

VON RAUMER J.F., ALBRECHT J., BUSSY F., LOMBARDO B., MÉNOT R.-P. & SCHALTEGGER U. (1999). – The Palaeozoic metamorphic evolution of the Alpine External Massifs – *Schweiz. Mineral. Petrog. Mitt.*, **79**, 5, 5-22.

VON RAUMER J.F. & STAMPFLI G.M. (2008). – The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. – *Tectonophysics*, **461**, 9-20.

VON RAUMER J.F., STAMPFLI G.M., BOREL G. & BUSSY F. (2002). – Organization of the pre-Variscan basement areas at the north-Gondwana margin. – *Int J. Earth Sciences*, **91**, 35-52.

VON RAUMER J.F., STAMPFLI G.M. & BUSSY F. (2003). – Gondwana-derived microcontinents, the constituents of the Variscan and Alpine collisional orogens. – *Tectonophysics*, **365**, 7-22.

VON RAUMER J.F., BUSSY F. & STAMPFLI G.M. (2009). – The Variscan evolution in the External massifs of the Alps and place in their Variscan framework. – *C. R. Geoscience*, **341**, 239-252.