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Tectonics

Paleozoic evolution of the External Crystalline Massifs of the Western Alps

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Abstract

The External Crystalline Massifs (ECMs) of the Alps record, during the Paleozoic, the progressive closure of oceanic domains between Gondwana, Armorica and Avalonia in three contrasting tectonic domains. The eastern one shows the Early Devonian closure of the Central-European Ocean between Armorica and Gondwana along a northwest dipping subduction zone. The western domain is marked by Lower Ordovician rifting followed by Mid-Devonian obduction of the back-arc Chamrousse ophiolite. The central domain underwent Late Devonian to Dinantian extension in a back arc setting associated with southeast dipping subduction of the Saxo-Thuringian Ocean. Based on tectonostratigraphic correlations, we propose that the western domain shows an affinity to the Barrandian domain while the eastern and central domains correspond to the north-eastward extension of the Moldanubian zone, to the south of the present-day Bohemian Massif. From Mid-Carboniferous to Permian, the eastern and central domains of the ECMs, including the internal parts of the Maures Massif, Sardinia and Corsica were stretched towards the south-west along the ca. 1500 km long dextral ECMs shear zone preceding the opening of the Palaeo-Tethys ocean. ***To cite this article: S. Guillot, R.-P. Ménot, C. R. Geoscience 341 (2009).***

Résumé

Évolution Paléozoïque des Massifs Cristallins Externes des Alpes occidentales. Les Massifs Cristallins Externes (MCE) ont enregistré l'histoire orogénique Paléozoïque liée à la convergence entre Gondwana, Armorica et Avalonia. Le domaine est a enregistré la subduction vers le nord-ouest de l'Océan Central Européen au cours du Siluro-Dévonien, donnant naissance à la suture éo-Varisque. Le domaine ouest a enregistré le *rifting* continental Cambro-Ordovicien, la fermeture du domaine arrière-arc de Chamrousse au cours du Dévonien moyen, puis la collision Viséenne. Le domaine central a enregistré une longue histoire orogénique entre le Dévonien et le Carbonifère, marquée par un magmatisme d'arc et d'arrière-arc, la mise en place de plutons granitiques Mg-K et une sédimentation syncollision d'âge Viséen. Cet épisode orogénique marque la fermeture de l'Océan Saxo-Thuringien. La forte analogie sédimentaire, magmatique et tectono-métamorphique des domaines est et central avec la zone Moldanubienne permet de proposer que les MCE, incluant les Maures, la partie interne de la Corse et de la Sardaigne, furent initialement situés dans la prolongation est du Massif de Bohème. Dès le Carbonifère Moyen, ces massifs ont été dilacérés sur plus

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de 1000 km, selon une direction NE-SW, le long de la zone de cisaillement dextre des MCE, précédent l'ouverture de la Paléo-Téthys. ***Pour citer cet article : S. Guillot, R.-P. Ménot, C. R. Geoscience 341 (2009).***

Keywords: Variscan belt; Subduction; Collision; Suture zone; Strike-slip fault; External Crystalline Massifs; Alps

Mots clés : Chaîne Varisque ; Subduction ; Collision ; Décrochement ; Massifs Cristallins Externes ; Alpes

1. Introduction

The Variscan belt of Europe resulted from two successive orogenic events characterized by the Late Ordovician – Early Devonian eo-Variscan suturing between Armorica and Gondwana and the Late Devonian to Early Carboniferous suturing between Laurussia and Gondwana [30]. Although, these two suture zones are clearly recognized from southern Spain to the Bohemian Massif (Fig. 2 in [30]), their occurrence within the External Crystalline Massifs (ECMs) of the western Alps is more problematic. Ménot [31] ascribed the Chamrousse ophiolite in SW Belledonne and the retrogressed eclogites found in the Aiguilles Rouges, NE Belledonne and Argentera to the eo-Variscan suture zone and proposed that the Belledonne Massif comprises a tectonic ‘‘collage’’ related to late-orogenic strike-slip faulting. On the other hand, Von Raumer [47] and Von Raumer et al. [50] recognized the Saxo-Thuringian domain, but do not clearly identify the eo-Variscan suture. In this paper, we will summarize our present-day knowledge of the tectono-metamorphic evolution of the ECMs and demonstrate that the two main Variscan suture zones are partly preserved, from Aar-Gotthard to Sardinia, within the dextral ECMs shear zone. This paper will be focused on the central part of the ECMs (Belledonne-Grandes Rousses and Oisans massifs) as these massifs record the entire Paleozoic evolution, and then these conclusions will be extended to the overall ECMs.

2. Geological setting

The Paleozoic metamorphic basement of the ECMs is composed of various Early to Mid-Paleozoic metamorphic units and non-metamorphic Late Paleozoic cover unconformably covered by Mesozoic sediments [27] (Fig. 1). The highest Alpine metamorphic imprint is due to greenschist facies conditions along localized thrusts and strike-slip faults [26,40]. In order to reconstruct the pre-Mesozoic relationship between the ECMs, we regroup here the different units, according to their lithological affinities, age, deformation and metamorphic conditions in three geographical domains (Fig. 1).

2.1. The western domain

The external part of the Belledonne Massif, east of the Synclinal Median (SM) fault (Fig. 2) is composed of a flysch series, with rare intercalations of basic layers [31]. Similar metasedimentary formations are observed in the Aiguilles Rouges (St Gervais schists) in the Argentera (Valetta unit) [35] and in the Barrandian domain of the Bohemian massif [12]. The absolute age of these sediments is unknown, but a Late Neoproterozoic to Early Palaeozoic age is commonly proposed [12,31].

2.2. The central domain

In SW Belledonne, the ophiolitic complex of Chamrousse is a well-preserved kilometer-scale slab of oceanic lithosphere [20]. It is usually considered as overturned and lies over the Devono-Dinantian formations (Fig. 2). The plutonic sequence overlies a leptyno-amphibolitic complex, interpreted as the volcanic and volcaniclastic member of a back-arc related ophiolitic suite dated at 497 ± 24 and 496 ± 6 Ma [34,38]. The Chamrousse ophiolite shows well-preserved magmatic textures and high-temperature low-pressure ridge axis deformations [20]. The Aar-Gotthard ultramafics are also considered as ophiolitic remnants [37].

The Devono-Dinantian magmatism has only been described and dated in the southwestern part of the Belledonne Massif (Riouperoux–Livet complex) (Fig. 1). It consists of bimodal suites of volcanic and plutonic rocks. The upper part consists of metamorphic felsic and basic volcanic, volcaniclastic and plutonic rocks; the lower part consists of leptynites and amphibolites intruded by trondhjemitic sills and stocks [31]. A U/Pb zircon age of 352 ± 56 Ma has been obtained for the trondhjemitic intrusions of the lower part of the complex, whereas the trondhjemites of the upper part yielded a U/Pb zircon age of 367 ± 17 Ma [33]. P-T conditions for the early deformation phase have been calculated at 8 ± 2 kbar and 590 ± 60 °C, while syn-stacking assemblages have yielded slightly lower P-T conditions at 7 ± 2 kbar and 590 ± 60 °C. K/Ar ages of

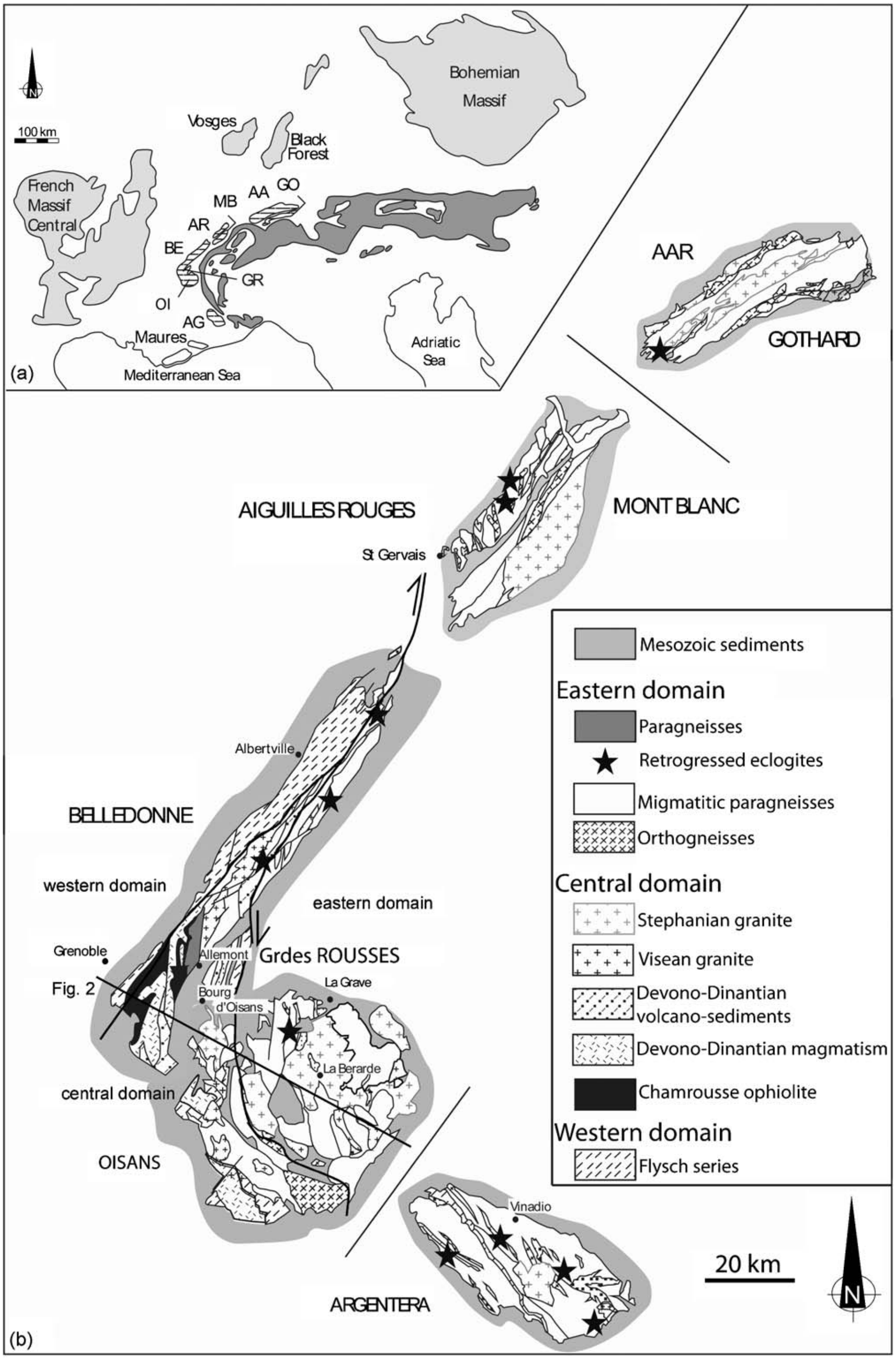

Fig. 1. **a**: the Paleozoic basement in Central Europe and the External Crystalline Massifs – AA: Aar; AG: Argentera; AR: Aiguilles Rouges; BE: Belledonne; GO: Gotthard; GR: Grandes Rousses; MB: Mont Blanc; OI: Oisans (modified after [47]); **b**: simplified geological maps of the ECMs (modified after [35]).

Fig. 1. **a** : le socle paléozoïque en Europe centrale incluant les Massifs Cristallins Externes. Massifs – AA : Aar ; AG : Argentera ; AR : Aiguilles Rouges ; BE : Belledonne ; GO : Gotthard ; GR : Grandes Rousses ; MB : Mont Blanc ; OI : Oisans (modifié d'après[47]) ; **b** : cartes géologiques simplifiées des MCE (modifié d'après[35]).

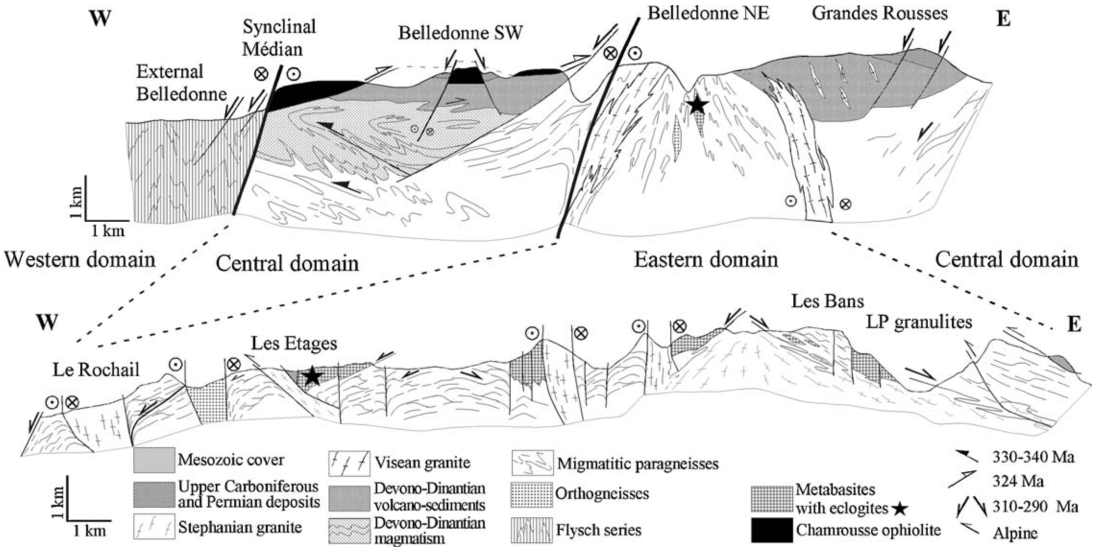

Fig. 2. **a**: schematic cross section showing the structural relationships in the Belledonne and Grandes Rousses Massifs. **b**: cross section of the Oisans Massif.

Fig. 2. **a** : coupe schématique montrent les relations structurales entre les massifs de Belledonne et des Grandes Rousses. **b** : coupe du massif de l'Oisans.

hornblende constrain the earlier metamorphic history between 352 ± 55 Ma and 324 ± 12 Ma [33].

In the south-western part of the Oisans Massif, massive amphibolites with interlayered quartzites, leptynites and chlorite-bearing micaschist [24] are related to the same Devono-Dinantian magmatism. This might be also assumed for amphibolitic gneisses from the south-western part of the Grandes Rousses Massif that show similar lithologies and petrology. Based on its calc-alkaline character, Carme and Pin [11] proposed an active margin setting for the Devonian-Dinantian magmatism. Alternatively, Ménot [31] attributed this magmatism to a continental extensional setting, based on the change in igneous rocks from bimodal (mantle origin) to felsic (crustal origin). The evolution of the magmatism suggests a transition from an extensional to a compressional regime [31] as observed in the French Massif Central [15] or in the Bohemian massif [44].

Quartzites and quartz- or chlorite-rich schist, with minor amphibolite, graphitic schist and marble beds, are widespread all over the ECMs [35]. These fine-grained rocks are locally associated with spectacular metaconglomerates (Taillefer, NE Belledonne and NW Grandes Rousses). They are mainly of clastic origin including Visean tuffs and interlayered volcanic breccias [18]. In the Grandes Rousses Massif, the Visean Alpetta granite [13] intruded the volcano-sedimentary unit. In NE Belledonne, Visean granites intrude paragneisses and metabasics, but not the volcano-sedimentary unit, which is always in an upper position [46]. This evidence suggests that different parts of this Visean unit overlie different basement rocks. The Early Visean volcanism presents an arc-related tholeiitic geochemical signature [11] with continental crust contamination [31,45] that we have interpreted as a continental margin environment.

In SW Belledonne and in the Aiguilles Rouges massifs, slices of alumosilicate-bearing paragneisses are tectonically intercalated with Devono-Dinantian volcanic rocks [22,46]. Two sub-units are distinguished: the upper sub-unit is mostly composed of kyanite-staurolite-bearing micaschists, whereas the lower sub-unit is mainly made up of migmatitic gneisses and granitoids The rocks of the lower sub-unit preserve relics of an early intermediate P metamorphic assemblage (P = 10 ± 1 kbar, T = 550 ± 50 °C). Both the lower and upper sub-units recorded the same metamorphic conditions during their subsequent evolution. Thermobarometric estimates for syn-stacking mineral assemblages yield P = 8 ± 2 kbar and T = 610 ± 80 °C. Late deformation phase develops extensional shear bands at P = 5 ± 2 kbar and T = 630 ± 100 °C. The early metamorphic evolution took place during the Devonian, whereas the late syn-extensional metamorphism is Westphalian in age [16]. In the eastern part of the Grandes Rousses massif, chlorite-bearing micaschists of the Grandes Rousses massif, unlike the previously described Belledonne paragneisses, do not show evidence of amphibolite facies metamorphism. The most prominent fabric is a greenschist facies penetrative foliation.

From Aar-Gotthard to Argentera, circa 340–330 Ma Mg-K granites constitute a suite of elongated plutons parallel to the main regional NNE-SSW structures (Fig. 1) [13]. They have calc-alkaline to alkaline affinities with locally abundant mafic enclaves (Mg-K metasyenites). In the western part of the Grandes Rousses Massif, the Alpetta granite is a deformed magnesian sub-alkaline intrusion. Although not dated, the Alpetta granite most likely represents the southern extension of the St. Colomban pluton [5]. Syn-magmatic C-S fabric in the NE Belledonne plutons and in the Alpetta granite indicates their emplacement during the development of a N20°E-trending transpressive sinistral shear zone [3].

In the Oisans Massif, Mg-K granites are restricted to the outer part of the Massif. The 343 ± 11 Ma Rochail monzogranite includes minor granite and syenite bodies, and locally mafic enclaves [13]. The Combeynot syenogranite, also shows high Mg and K, but with alkaline affinities, and has yielded an age of 312 ± 7 Ma (U-Pb zircon [9]) about 20 Ma younger than the ages of other Mg-K granitoids. The Mg-K granitoids are considered to have derived from enriched sub-continental lithospheric mantle, contaminated by continental crust [13].

Late Carboniferous and Permian sedimentary rocks include black schists, sandstones and conglomerates with economic coal seams. Volcanic rocks, including rhyolites, dacites andesites pyroclastics are commonly intercalated with the sedimentary rocks and abundant in the northern part of the Grandes Rousses Massif [1] and in the Aiguilles Rouges [10].

2.3. The eastern domain

From Aar-Gotthard to Argentera, retrogressed eclogites are recognized (Fig. 1), having a north to east-MORB geochemical signature [32], with a protolith age ranging between 473 and 453 Ma [36]. Thermobarometric estimates for these eclogitic relics display minimum P-T conditions of 11–14 kbar and ca. 700 °C [21]. The age of the eclogitic facies metamorphism is indicated between 425 and 395 Ma [36]; retrogression under amphibolite facies conditions is Devonian in age (375–350 Ma) in NE Belledonne and in Argentera [35]. In the Oisans massif, amphibolic lenses are preserved within migmatites [24]. Ménot and Paquette [32] show that their protoliths originated as N- to T-MORBs and were emplaced during Lower Paleozoic continental rifting. Among these metabasites, HP granulites interpreted as eclogitic relics, are only preserved in the north-western part of the Massif: P-T estimates of the earlier metamorphic stage in a metabasic rock yielded Pmin = 12 ± 1 kbar and T = 850 ± 50 °C [21]. With regards to their chemistry and metamorphic history, these HP granulites may be compared to those of the NE Belledonne domain, indicating early Paleozoic subduction. In the SE part of the Oisans Massif (Fig. 2), different garnet-bearing amphibolitic lenses display LP granulitic facies relics. Their protoliths are probably the same as described above, but their metamorphic evolution is different, with a temperature increase up to 800 °C during decompression from 7 to 3 kbar, and this is likely to have been related to the Late Paleozoic orogenic evolution [19].

In the northeastern domain of Belledonne, paragneisses are dominantly biotite- and amphibole-rich. The protoliths are mainly greywackes including minor volcanic layers and intruded by granitic bodies of age 489 ± 22 Ma (single zircon Pb evaporation [3]). The metamorphism is polyphase [21,46], with an initial Lower Paleozoic high-P event recorded in the metabasics, followed by intermediate-P amphibolite facies metamorphism, with the development of Ky-St assemblages in the metasediments and then by a regional anatexis event, associated with cordierite-bearing assemblages, during Devonian time. Finally, retrogression under greenschist facies condition was associated with the development of a pervasive subvertical foliation, related to dextral shear and coeval with the intrusion of granitoids. Also in the NE Belledonne Massif, orthogneiss in the migmatitic paragneisses has been dated at 489 ± 22 Ma [3]. With respect to their lithological, structural and chemical similarities with other units, undated alkaline to calc-alkaline orthogneisses from the Oisans massif, (''Gneiss d'Olan'') are considered to be Ordovician or Silurian in age (e.g. Streifengneisses in the Gotthard Massif, 421 Ma [46]. The youngest granitic plutons crop out in the eastern domain: they contain high Al and Fe [13]. Several elongated Stephanian granitic plutons are recognized in the ECMs (Fig. 1). They are also monzogranitic and syenogranitic in composition but the most notable difference from the Mg-K granites is the absence of mafic enclaves. This Al-Fe magmatism is well-defined in age between 305 and 295 Ma [13] and was emplaced during the Stephanian transtensional regime [8,43]. Sources are similar to those for the Mg-K granites: continental crust and subordinate enriched, subcontinental lithospheric mantle [13]. The inner part of the Oisans Massif is mainly composed of garnet-bearing gneisses and rare kyanite- and cordierite-bearing metasediments. Locally, two episodes of migmatization have been recorded all along the ECMs: synkinematic Devonian leucosome dykes and post-kinematic cordierite-bearing assemblages related to the Late Carboniferous tectonic evolution [5,46].

3. Structural evolution

3.1. Early Devonian nappe emplacement (D0)

The oldest structure (D0) is identified in the internal part of the Oisans Massif: it corresponds to the nappe emplacement of the retrogressed eclogitic unit over the paragneissic unit (Fig. 2). The exact age and direction of thrusting is unknown, but it occurred after the eclogite formation in this unit (ca. 395 Ma) and prior to the Devonian migmatization (< 355 Ma) that affected the entire nappe pile. The direction for this earlier thrusting event is not preserved. However, as the root of the eclogitic unit is observed in the NE Belledonne domain [36] a south-east direction of thrusting is inferred here. Southward thrusting of the eclogitic nappe is also well know in the French Massif Central as an Upper Gneissic Unit and is dated at ca. 380 Ma [15,23]. In contrast, the amphibolitic sole of the Chamrousse ophiolite preserved a Mid-Devonian age of 376 $\pm$ 7 Ma (unpublished ^{40}Ar-^{49}Ar dating on amphiboles by Monié and Ménot) for top-to-the-northwest thrusting, probably related to its early obduction. Moreover, we recently observed intra-ophiolitic top-to-the-northwest ductile thrusts suggesting that the apparent inversion of the whole ophiolite is probably related to this major tectonic event.

3.2. Visean nappe stacking (D1 and D2)

In the NE Belledonne domain and in the Grandes Rousses Massifs, the major deformation is dominated by the emplacement of Mg-K granites during Visean times along a north-N20°E trending transpressive shear zone. In the Belledonne domain it leads to D1 thrusting of the internal high-pressure unit towards the north-west [21]. This 10 km long ductile shear zone can be traced southward up to the external part of the Oisans Massif. Considering the contribution of the mantle in the generation of the Mg-K granite, this transpressive shear zone was probably rooted within the upper mantle.

In the SW Belledonne domain, the nappe pile, including the Devono-Dinantian bimodal magmatic complex and the Chamrousse ophiolite, (Fig. 2), record two stages of Visean deformation [16,22]. In the felsic gneisses and amphibolites of the Devono-Dinantian magmatic complex, the D1 tectonic event generated km-scale folds and a regional S1 foliation dipping to the east. Shear criteria and fold asymmetry indicate top-to-the-west or north-west thrusting during D1.

D2 deformation is related to the northeast thrusting of the Chamrousse ophiolitic complex over the Devono-Dinantian magmatic complex. The tectonic sole of the Chamrousse ophiolitic complex shows a pervasive S2 foliation oriented approximately N95°E and dipping 25°N. The sole of the Chamrousse ophiolite shows D2 microdrag folds oriented N130°E, with shear criteria indicating top-to-the-northeast sense of shear. Scattered shear criteria in the alumosilicate-bearing paragneisses below the Chamrousse ophiolite also indicate thrusting towards the northeast [16]. In the southern flank of the Romanche River, in the Taillefer Massif, the Chamrousse ophiolite is thrust over the Visean volcano-sedimentary rocks involved in kilometer-scale D2 northeast verging folds. K/Ar ages for hornblende timing the granite emplacement in the lower unit and the involvement of Visean sediments, bracket the D1-D2 metamorphic history between 350 and 325 Ma [33].

3.3. Westphalian-Middle Stephanian extensional tectonics (D3)

From Mid-Carboniferous to Permian times, the ECMs record, as for the rest of the Variscan belt, a complicated tectonic story dominated by extensional and strike-slip tectonics [17,28]. The SW Belledonne domain records two phases of extension (D3 and D4). The D3 ductile extension is contemporaneous with local migmatization of the staurolite-bearing schists in the Romanche Valley, and with greenschist facies conditions developed in the higher nappes [15,22]. At shallower structural levels, the brittle faulting related to this extensional tectonic regime post-dated the deposition of Westphalian sediments, suggesting a possible Middle Stephanian age for the D3 extensional tectonics [4]. Kinematic indicators mark a SW-NE directed extension, roughly parallel to the strike of the massif, with collapse of the southwestern part and exhumation of the northeastern part of this domain. This event partly controlled the development of the Westphalian basins [16]. Eastwards, north-south to N160°E ductile/brittle normal faults dipping 65 to 80° towards the west are located at the transition from the Grandes Rousses Massif to the western boundary of the Oisans Massif (Fig. 2). The D3 ductile normal faulting bears a N30°E

40°SW muscovite lineation indicating top-to-the-southwest extension.

3.4. Stephanian-Permian extension and strike-slip faulting (D4)

The late Variscan structures of the ECM are dominated by localized ductile to brittle dextral strike slip faults oriented NE-SW in the Belledonne and Grandes Rousses massifs and NNW-SSE ductile sinistral slip faults in the internal part of the Oisans Massif suggesting an east-west direction of shortening associated with a north-south direction of extension [43]. Although the NE-SW strike-slip faults are reactivated during the Liassic extension and the alpine orogenesis, these structures were clearly active from Stephanian to Permian times: the Al-Fe granites (305–295 Ma) oriented NE-SW in the Belledonne Massif and NNW-SSW in the Oisans Massif are syn-kinematic [13,43]. Also, the NW-SE direction of opening of the Stephanian coal basins is compatible with this fault system and the associated vertical schistosity is in places, unconformably covered by Triassic sediments. It is noticeable that similar directions of strike-slip faulting and opening of the Late Stephanian coal basins are observed in the French Massif Central [4].

In the Oisans Massif, the Devonian nappe pile is cross-cut by the intrusion of Stephanian granites along a N160°E sinistral ductile strike-slip fault [43]. Conversely, the Stephanian tectonics are relatively well preserved. A ductile normal fault outcrops on the western flank of the Oisans Massif where syn-migmatization extensional structures, oriented N160°E to N10°E and dipping 50°W, are observed. These structures are locally associated with extensional C/S structures oriented N5°E to N20°E and dipping 50°E. In the migmatites surrounding the low-pressure high-temperature basic granulites, syn-migmatization extensional C/S structures, oriented N140°E and dipping 20°W, are interpreted as Stephanian extensional structures [19].

Stephanian – Permian tectonics resulted in the separation of NNE-SSW trending domains. Three major normal/strike-slip faults are recognized: the Synclinal Median Fault (Fig. 2) is a typical Stephano-Permian dextral strike slip-fault reactivated during Alpine orogenesis [16]. It marks the juxtaposition of the external domain and internal domains of Belledonne. The dextral Rivier-Belle Etoile fault marks the boundary between the SW Belledonne domain and the NE Belledone domain. At the present day, a tectonic boundary between Devono-Dinantian units and older basement can be traced between the external and internal domains of the Oisans Massif. Le Fort [24] described this boundary as a major fault: recent structural investigations suggest that it is a Stephanian normal fault [22] with a sinistral component [43]. Northward, the prolongation of this normal fault corresponds to the Grandes-Rousses Chatelard dextral-strike slip fault. As the Al-Fe granites resulting from melting of continental crust and subordinate enriched, subcontinental lithospheric mantle [13] emplaced within D4 strike-slip faults suggest that these structures cross-cut the entire continental crust and are rooted in the lithospheric mantle. The importance of these Stephanian-Permian strike-slip fault zones for tectonic reconstruction will be discussed further.

4. The ECMs in the Paleozoic framework

On the basis of the geological data presented above and previous reconstructions [35,42,44,48,50], we propose to integrate the ECMs within the tectonic evolution of the European Paleozoic orogenic belt. Compared to the rest of the Variscan belt, and in terms of lithology, tectonic evolution and associated metamorphism and magmatism, the ECMs record the complete evolution of the collision zone between Avalonia and Gondwana, including Armorica. Considering that the Chamrousse ophiolitic complex represents a record of the Cambro-Ordovician oceanisation and the ECM's including Sardinia and Corsica represent the southeastward prolongation of the eo-Variscan suture zone [30,41], we propose that the core of these massifs (central and western domains) represent the Moldanubian zone, initially located northward in the prolongation of the present-day Bohemian Massif (Fig. 3) in accordance with von Raumer et al. [50].

4.1. Lower Paleozoic oceanisation

The Lower Paleozoic evolution of the ECMs is variably recorded in pre-Devonian units. The ophiolitic complex of Chamrousse testifies to the existence of a Cambro-Ordovician back-arc domain. The enriched tholeitic oceanic crust records slight continental crust contamination and is associated with volcanoclastic sediments, suggesting that this ophiolite formed in a back-arc continental basin environment. Paragneisses and micaschists with rare volcanic beds embedded the amphibolitic lenses in NE Belledonne and in the Oisans Massif. A radiometric age of 489 ± 22 Ma for a granitic protolith [3] intruding the sediments provide the

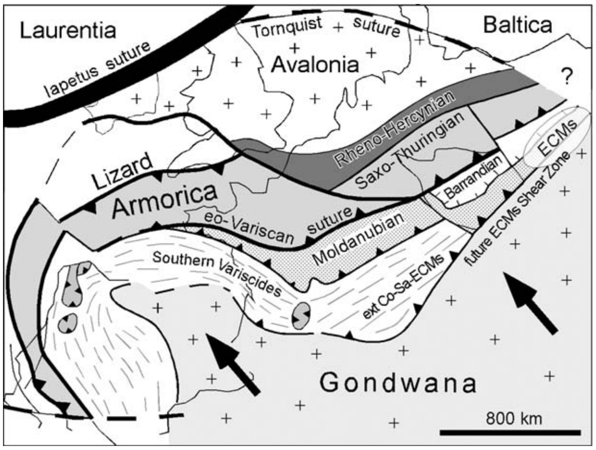

Fig. 3. Early Carboniferous reconstruction of the ECM in the Variscan belt. The Chamrousse ophiolitic complex (ch) provides a record of the Rhenohercynian suture zone. The Moldanubian zone includes the internal parts of the External Crystalline Massifs (ECM), Sardinia (sar) and Corsica (cor) in continuity with the Bohemian Massif (Bo) and the French Massif Central (MCF).

Fig. 3. Reconstruction des MCE au sein de la Chaîne varisque au Carbonifère inférieur. Le complexe ophiolitique de Chamrousse représente un témoin de la suture Rhéno-Hercynienne. La zone Moldanubienne inclut les zones internes des MCE, la Sardaigne (sar) et la Corse (cor) en prolongation du massif de Bohème (Bo) et du Massif central français (MCF).

minimum age of the sedimentation. Orthogneisses preserved in the Oisans Massif display geochemical alkaline characters typical of continental rifting with subduction influence [47]. The age of the paragneisses in the external Belledonne domain is also unknown but is supposed to be Late Neoproterozoic to Lower Paleozoic on the basis of lithological similarities with the flysch series [12,31]. Similar series are also observed in the external part of the Maures Massif, in Sardinia and Corsica and traditionally have been correlated with the Montagne Noire sediments [41]. These metasediments probably correspond to flysch series deposited at the northern edge of the Gondwana passive margin during the Cambro-Ordovician rifting [49].

The Cambro-Ordovician period of widespread extension and rifting is recorded in some rock sequences from all over the Paleozoic belt, as suggested by the protoliths of metabasic rocks with a tholeiitic affinity [32,36]. According to paleomagnetic constraints [45], this general extension could be related to the opening of the Rheic Ocean initiated as a back arc between the passive north Gondwana margin and the active Avalonia domain [29,50] (Fig. 4a).

The younger age ($\sim$ 470 Ma) of the NE Belledonne and Argentera metabasites [36] compares with the Chamrousse ophiolitic complex ($\sim$ 495 Ma) and suggests the later opening of the Medio-European oceanic domain (Fig. 4b). The separation of the Belledonne domain (Moldanubian zone) from the inner Oisans Massif (Gondwana) was also suggested by their contrasted Siluro-Devonian evolution.

4.2. *Silurian subduction*

Convergence and subduction of oceanic crust in the ECMs during Silurian-Devonian times are shown by eclogitic relics, also found in the Maures Massif, in Corsica and Sardinia [41]. In the French Massif Central, the eo-Variscan period, during which subduction of continental and oceanic crust occurred [29], took place between 420 and 400 Ma, and corresponds to the closure of the Medio-European Ocean located between Armorica and Gondwana (Fig. 4c) [30]. The localized occurrences of relict eclogite in the Aiguilles Rouges and NE Belledonne Massifs, thrusting over the Gondwana basement (Oisans Massif), indicate a north-west dipping subduction. This is in accordance with the subduction polarity proposed in the French Massif Central [25]. This subduction event was followed by a collision event marked by widespread migmatization at about 380–360 Ma [36,47]. In contrast with von Raumer and Stampfli [48], who proposed that the Chamrousse ophiolite obducted just after its formation in the Early Ordovician, we relate the Mid-Devonian amphibolitic metamorphism recorded within its metamorphic sole to its top-to-northwest obduction during this first major eo-Variscan subduction-collisional event (Fig. 4c).

4.3. *Devonian subduction and Visean collision*

The Devonian-Dinantian bimodal magmatism and volcanism developed at the western margin of the study area involved the SW Belledonne domain – the Grandes Rousses and the western part of the Oisans Massif. It probably corresponds to a back-arc domain like the Brevenne unit in the French Massif Central [15] or the central part of the Moldanubian zone in the Bohemian Massif [44]. There are *a priori* no HP metamorphic rocks associated with this second subduction event in the ECMs, as in the rest of the western Paleozoic belt. The Champtoceaux Massif in South Brittany, dated at 356 ± 8 Ma [6], testifies to this second subduction event. Moreover, the HP to UHP event in the Bohemian massif is also dated at $\sim$ 340 Ma [44]. Paquette et al. [36] dated an eclogite in the Argentera Massif at 351 ± 1 Ma that we tentatively attributed to this second subduction

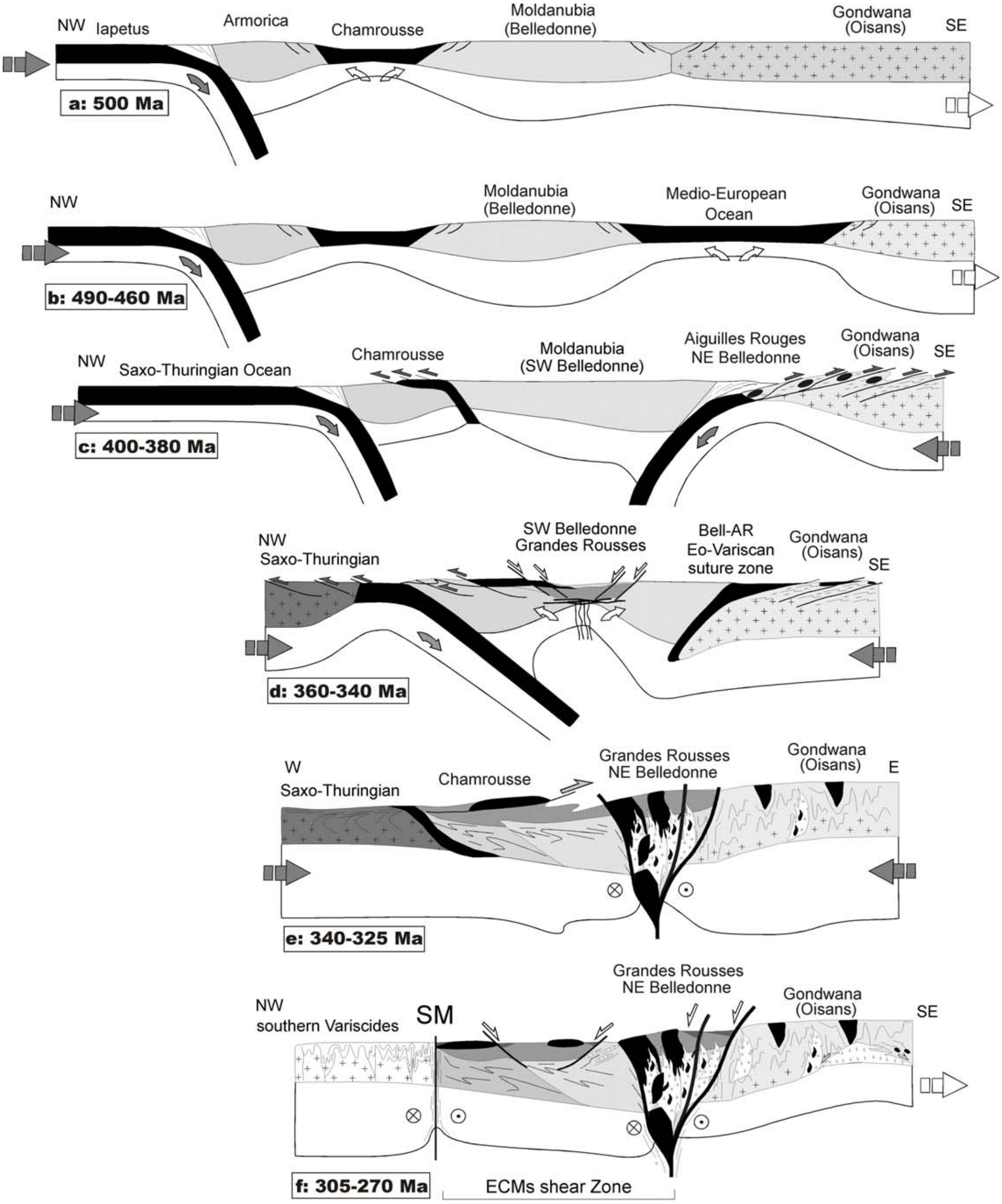

Fig. 4. Schematic evolution of the ECMs in six steps during the Paleozoic orogen (see text for explanation). It shows the possible relationships of the ECMs (Moldanubian zone) with the microcontinents Armorica (Saxo-Thuringian) and Gondwana and localized the two main suture zones: the Silurian eo-Variscan suture zone and the Devono-Dinantian Saxo-Thuringian suture zone.

Fig. 4. Évolution schématique des MCE en six étapes durant l'orogenèse paléozoïque (voir le texte pour les explications). Ces schémas montrent les relations entre les MCE (Zone Moldanubienne) et le microcontinent Armorica-Barrandia et Gondwana. Deux zones de suture sont identifiées : la suture éo-Varisque au Silurien et la suture Saxo-Thuringienne au Dévono-Dinantien.

event. The polarity of the subduction was necessarily towards the southeast as the Moldanubian zone became an active margin at that time (Fig. 4d), also the eastern part of the ECMs is unaffected by Devonian magmatism and finally the associated compressive phase is towards the north-west (Fig. 4e). This is in accordance with the polarity and the timing of subduction of the Saxo-Thuringian Ocean in the Bohemian Massif [44].

The Visean volcanic unit is not affected by this second subduction-collision event, suggesting that the volcanism is syn- to post-collision. During the same period, the northeastern domain of Belledonne, the Grandes-Rousses Massif and the external part of the Oisans Massif also recorded a transpressive regime along N30° wrench faults, contemporaneous with the emplacement of Visean Mg-K granites. The north-west direction of thrusting observed in the Belledonne Massif is also in good agreement with the common shortening direction and kinematic indicators within the French Massif Central and the Armorican Massif during the same period [15].

A second transpressive event, responsible for the overthrusting of the Chamrousse ophiolitic complex onto Devono-Dinantian units towards the northeast (Fig. 4e) is dated at 324 ± 12 Ma (K/Ar on amphiboles [31]). This Late top-to-the-northeast Visean tectonics has also been recently recognized in the north-eastern part of the French Massif Central [15] and in the Moldanubian zone [44], whereas in the southern part of Europe, the nappe displacement is towards the SSW [15]. At the same time, the southern part of the Iberian block records thrusting towards the south-west, whereas the northern part of the Ibero-Armorican arc still continues to record compression towards the northwest [7,29]. The D2 event recorded the lateral escape of the Paleozoic blocks located north and south of the Ibero-Armorican arc during the final collision between Gondwana and Laurussia. It results to the clockwise rotation of the northern branch of the Rheic suture zone [14,45] accommodated by NW-SE dextral wrenching.

4.4. Late Carboniferous and Permian evolution

In SW Belledonne, 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 [16] attests a first Westphalian to Middle Stephanian NE-SW direction of extension, followed by a second Late Stephanian NW-SE directed extension (Fig. 4f). The development of Westphalian and Stephanian basins over these the eastern and central domains testifies to their shallow crustal level during the Late Carboniferous. Moreover, in the eastern domain, cordierite-bearing migmatites and associated LP-HT metamorphic rocks crop out [21] suggesting a global north-west tilting.

The eastern domain displays characteristics of a deeper crustal level. The Al-Fe granitic plutons, emplaced in a north-south extensional regime and still associated with dextral shearing along NE-SW faults (Fig. 4e). Secondary, cordierite-bearing migmates in the eastern domain are widespread and completely obliterate the earlier features. Moreover, in the southeastern part of the Oisans Massif, amphibolic granulites record a LP-HT Late-Paleozoic metamorphism, with a P-T path marked by a strong increase in temperature during decompression [19], as classically observed in western Europe [17]. Neither the Westphalian nor the Stephanian basins are preserved upon this domain, providing another argument for its buried position during the Late Carboniferous. The widespread occurrence of Stephanian granites in the rest of the ECMs suggests that they correlate with the central or the eastern domains.

The NS to N30°E Late Stephanian to Permian dextral strike-slip faults play a major role in the final geometry and emplacement of the ECMs. This fault system is well known to the north in the Mont Blanc Massif and was responsible for the emplacement of several granitoids during the Stephanian. These were associated with a strong ductile vertical schistosity with a shallow dipping stretching lineation [8,26] Southward in the Argentera Massif, Late Stephanian dextral strike-slip faulting is also responsible for the emplacement of the Argentera granite. This important fault system can be also followed in the Maures Massif, in Corsica and Sardinia separating the already recognized eo-Variscan suture zone marked by the occurrence of eclogites in the eastern part and schistose rocks in the western part [41]. Northwards in Europe, a similar N30° dextral shear zone is recognized in the south-eastern boundary of the Bohemian Massif, defining the 300 km long and 50 km wide Moravian zone [39,44]. We propose that this Moravian zone is the northward equivalent of the ECM Shear zone, as the ECMs were probably in lateral continuity with the Moldanubian zone during the Early Carboniferous (Fig. 3) [2,42,49]. The length of this fault system from the Bohemian Massif to Sardinia is about 1500 km (Fig. 5). The occurrence of synkinematic Carboniferous granitoids along this shear zone suggests that it represents a near crustal-scale shear zone similar to the South Armorican Shear Zone or the Coïmbra-Cordoba Shear Zone (Fig. 5). Correlation of the suture zones across the ECMs Shear Zone requires a total offset of ca. 500 km. In this general scheme, the external part of the Belledonne Massif, comparable with the external parts of the Maures Massif, Corsica and Sardinia, is the only parautochnous part of the study area (Fig. 5). Such an important offset, equivalent or superior to the offset estimated, for example, on the Tertiary Ailo Shan Red River Shear zone in Indochina [26] did not simply result in collision or extrusion

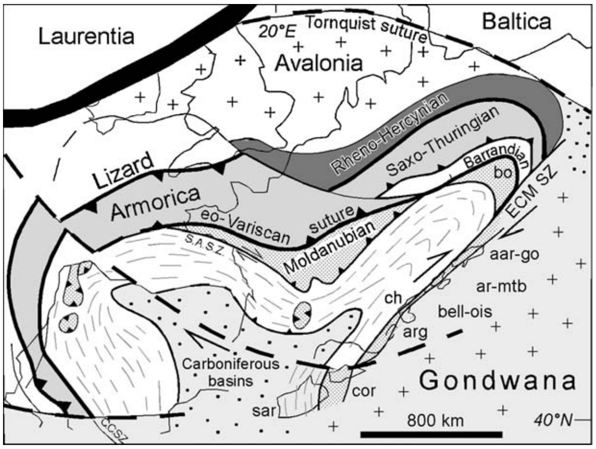

Fig. 5. Possible configuration of the Variscan belt of western Europe in Permian times, showing the main sutures and prolongation of the eo-Variscan suture zone in the External Crystalline massifs and also in Corsica and Sardinia. The southward prolongation of the Saxo-Thuringian suture zone is only observed in the SW Belledonne Massif. The strong shearing of these two main suture zone (reduced at a width of 30 km) from Late Carboniferous to Permian was accommodated by the dextral ECM Shear Zone. Correlation of the Chamrousse ophiolite with the Saxo-Thuringian suture zone in northern Europe requires a total offset of a minimum of 500 km. SASZ: South Armorican Shear Zone; CCSZ: Coimbra-Cordoba Shear Zone (after [30]).

Fig. 5. Configuration possible de la Chaîne varisque d'Europe de l'Ouest au Permien. Cette carte montre la prolongation des zones de suture au sein des MCE, ainsi qu'en Corse et en Sardaigne. La prolongation vers le sud-ouest de la suture Saxo-Thuringienne n'est observée que dans le massif de Belledonne. Le cisaillement important des zones de suture du Carbonifère au Permien est accommodé le long de la zone de cisaillement dextre des MCE. La corrélation de l'ophiolite de Chamrousse avec la suture Saxo-Thuringienne en Europe du Nord impose un déplacement d'au moins 500 km. SASZ : zone broyée Sud-Armoricaine ; CCSZ : zone de cisaillement de Coimbra-Cordoba (d'après [30]).

processes but is also related to the global clockwise rotation of Africa during Late Paleozoic and opening of the Paleo-Tethys oceanic domain between Laurussia and Gondwana (Fig. 5) [2,14,30,42].

5. Conclusions

Re-examination of the ECMs allows a better integration of these massifs in the European Paleozoic framework. We propose that the eo-Variscan suture zone marked by the occurrence of eclogites from the Gotthard to the Sardinia massifs corresponds to the Siluro-Devonian subduction-collision zone, during which time Gondwana (Gotthard-Mt Blanc-Oisans-eastern Argentera) subducted and collided beneath Armorica (Aar-Belledonne-Aiguilles Rouges-western Argentera) along a north-west dipping subduction zone. This first Paleozoic subduction-collision event was also responsible for the closure and obduction of the Chamrousse back-arc domain and its tectonic inversion along top-to-the north-west intra-ophiolitic ductile thrusts.

A second episode of subduction-collision occurred from Devonian to Visean times. It was characterized by the closure of the Saxo-Thuringian oceanic domain along a south-east dipping subduction zone beneath the ECMs and was marked by the development of an active margin on the northwestern margin of Moldanubian zone. The Visean collision is characterized by intrusions of Mg-K syntectonic granites, nappe stacking towards the north-west and Barrovian metamorphism. It ended with the north-east backthrusting of the Chamrousse ophiolitic complex in a global dextral transpressive regime. The final collision was marked by widespread extension during Stephanian-Permian times related to major N30° dextral wrenching along the ca. 1500 km long ECM Shear Zone. This strike-slip faulting was responsible for the souhwest migration of the ECMs from northern Europe (in prolongation of the Bohemian Massif) to its present day location.

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