ABSTRACTS

Tectonic-metamorphic evolution of the migmatites from the Central area of the Roc de Frausa Massif (Eastern Pyrenees)

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The Roc de Frausa is a dome shaped massif formed by pre-Variscan metasedimentary and metaigneous rocks. It is surrounded by the Variscan La Jonquera - Sant Llorenç plutonic complex, which is emplaced on top of the Upper Proterozoic - Lower Cambrian series, and intruded by Ceret stock in deeper levels. Petrological study and pseudosection modelling have been used to establish the P-T paths of the migmatites in the central area of the massif. The studied samples belong to the intermediate series from the Ceret stock contact aureole and to the lower series located far from the contact aureole. The goal is to correlate the P-T path with the structural record and to understand which parts of the P-T paths are common, which parts of the P-T path can be correlated with the regional metamorphism and what is the effect of contact metamorphism.

Macroscopically, the main foliation is shallow-dipping (D2) and is folded by subvertical tight to isoclinal folds (D3), and by open folds (D4). Under the microscope, an earlier foliation (D1) is locally distinguished. In the migmatites from the contact aureole of the intermediate series the crystallization - deformation relationships show the following metamorphic assemblages: fibrolite (D1), fibrolite-biotite-ilmenite (D2) and prismatic sillimanite-garnet-biotite-cordierite (D3); and in the migmatites from the lower series, far from the contact aureole: biotite- muscovite- garnet (D2) and locally, biotite-muscovite-cordierite (D3). D4 is retrograde in all rocks of the massif and it is defined by chlorite and muscovite. In the migmatites from the contact aureole, garnet has a flat compositional profile in the core (alm 0.77-0.78, sps 0.03, prp 0.15-0.16, grs 0.04 and X_{Fe}= 0.83-0.84) with slight decrease of almandine (0.76) and pyrope (0.09-0.10) and increase of spessartine (0.10) and X_{Fe} (0.90) near the rim. In contrast, in the lowermost migmatites scarce garnet is present as isolated crystals embedded in plagiclase. It is very small, with a size of x mm, and is not zoned, showing a chemical value of alm 0.60, sps 0.17-0.19, prp 0.18-0.17, grs 0.03 and X_{Fe}= 0. 76-0.77.

Pseudosection modelling of migmatites is not straightforward; it is necessary to trace the P-T path backwards. Last major equilibration is usually interpreted as the point on the P-T path where last melt (or fluid) was consumed by continuous reactions. Then observed succession of crystallization and preserved zoning of minerals is interpreted tracing the P-T path backwards on the diagram, taking into account to eventual melt loss (or gains). Preservation of the typical assemblage of the migmatites from the intermediate series (g-sill-crd-bi-kfs) on retrograde P-T path is possible only for a restricted amount of H_2O in the whole rock composition (c. 4.2 mol%), deduced from P-MH_2O pseudosections. Higher or lower amount of H_2O leads to loss of sillimanite or cordierite, but K-feldspar and garnet are lost at higher amount of H_2O, remaining stable at large field of the lower amount of H_2O. The assemblage and garnet chemistry around the liq-out line in a P-T pseudosection constructed for this amount of H_2O can be compared to the observed assemblage at 3.1-6 kbar and 610-750°C. Garnet core composition is close to the compositional isopleths in the g-sill-bi-kfs-liq field at 4.8-6 kbar and 690-725°C. For the Migmatites from the lower series, a restricted amount of H_2O in the whole rock composition (c. 4.0 mol%) was also deduced from P-MH_2O pseudosections for preservation of the typical assemblage (g-mt-bi-kfs) on P-T path. Higher or lower amount of H_2O leads to loss of magnetite, garnet or cordierite, but K-feldspar is lost at higher amount of H2O, remaining sufficiently stable at lower amount of one. The assemblage and garnet chemistry in a P-T pseudosection constructed for this amount of H_2O can be compared to the observed assemblage at 6-8 kbar and 765-800°C. Garnet composition is close to the compositional isopleths in the g-mt-bi-kfs-liq field at 6.3-7 kbar and 780-800°C.

Therefore, garnet zoning is interpreted as diffusionally equilibrated core at “peak” P-T conditions, where the rock spend long time enough to flatten completely its compositional profile, with partial reequilibration of the garnet rim on

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decompression in the migmatites of the intermediate series. In the studied samples it is not possible to trace the P-T path further backwards, because there are not preserved prograde features, as for example remnants of prograde garnet zoning or other inclusions in garnet. However, the rocks from different structural levels record different PT histories. Rocks from higher levels and affected by contact metamorphism record minor PT conditions than rocks from lower levels and only affected by regional metamorphism. In the lower structural levels the main foliation is synchronous to D2 and D3 is not clearly prograde, whereas in the migmatites from the contact aureole D2 can be almost completely obliterated by the subsequent deformation D3 at prograde conditions. These facts indicate that during the last stages of the Variscan orogeny the intrusion of igneous bodies constituted a way to transfer heat from the core of the orogen to the higher parts of it.

Thrust geometry and the location of gneiss domes: implications of thermal models of the Central Iberian crustal domain during the Variscan

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England and Thompson (1984) and Peacock (1989) developed a method to produce thermal models of the pressure-temperature-time (P-T-t) paths of regional metamorphism in thickened continental crust. Their models place the physical conditions undergone by rocks initially at different depths in a temporal frame and permit a better understanding of the orogenic processes involved. One common response to thickening that is observed in orogenic belts is the formation of gneiss domes (Whitney *et al.*, 2004). Gneiss domes are an important feature of the Iberian crust affected by the Variscan orogeny and are abundant in the core of the Central Iberian arc (Martínez Catalán, 2011). Recent investigations (Rubio Pascua,l 2012) in the Central Iberian zone (CIZ) provide data that can be used to constrain thermal models and to evaluate the model response to changes in basic parameters and in the geometry of structural evolution.

We have used finite difference models to investigate possible causes of gneiss dome formation in the CIZ. The thermal models are constructed in two dimensions to include two compressional events: homogeneous thickening of the crust and movement of an allochthon as it ramps upward and emplaces upon the original surface of the autochthon. Both are consistent with regional structural data. Compressional events are followed by two periods of extension: first homogeneous thinning over 15 Ma to return the crust to a thickness of 45 km and then 5 Ma of top-down thinning (erosion or near surface detachment) removing 10 additional km. With each stepwise vertical and (or) horizontal motion and with the passage of time, changes in the thermal structure of the crust and upper mantle are determined using finite difference calculations that consider movement of heat along thermal gradients and the addition of heat from radiogenic elements in the crust. Key parameters in the model are the amount and extent of homogeneous thickening in the crust prior to thrusting, the size of the thrust sheet, the initial thickness of the radiogenic crust and the heat generated within it.

Results from multiple runs confirm that the thrust loading produces a consistent thermal path for a given depth within the crust at different locations beneath the thrust sheet. Initial depression of cold, upper-crustal rocks produces a lower temperature geotherm. However, the addition of the radiogenic material in the thrust sheet and the blanketing effect of the thrust act to increase temperatures in the mid to lower crust. Thinning moves the warming crust to higher levels and so also produces a higher temperature geotherm. P-T-t paths produced by the models are comparable to those inferred for the CIZ from thermo-barometric analysis (Díez Montes, 2007; Rubio Pascual, 2012) and so are considered reasonable.

Of more interest to the problem of cause and location of the gneiss domes in the orogen, is the development of a distinct thermal dome centered just behind the location where the thrust changes from ramping upwards to moving horizontally across the original surface (Fig. 1). We propose that the location of this strong thermal dome acts through positive feedback to focus gneiss dome growth in this area. Higher temperatures act to reduce the density of the crust relative to its surroundings and to initiate partial melting of crustal rocks that are rich in mica. Combined, these factors lead to uplift of the thermal dome and to deeper crustal flow into the area of more rapid uplift. Upward movement facilitates decompression melting that in turn eases additional uplift. The model results are interpreted to indicate that thrust geometry may play a significant role in determining the location of gneiss domes within an orogen.

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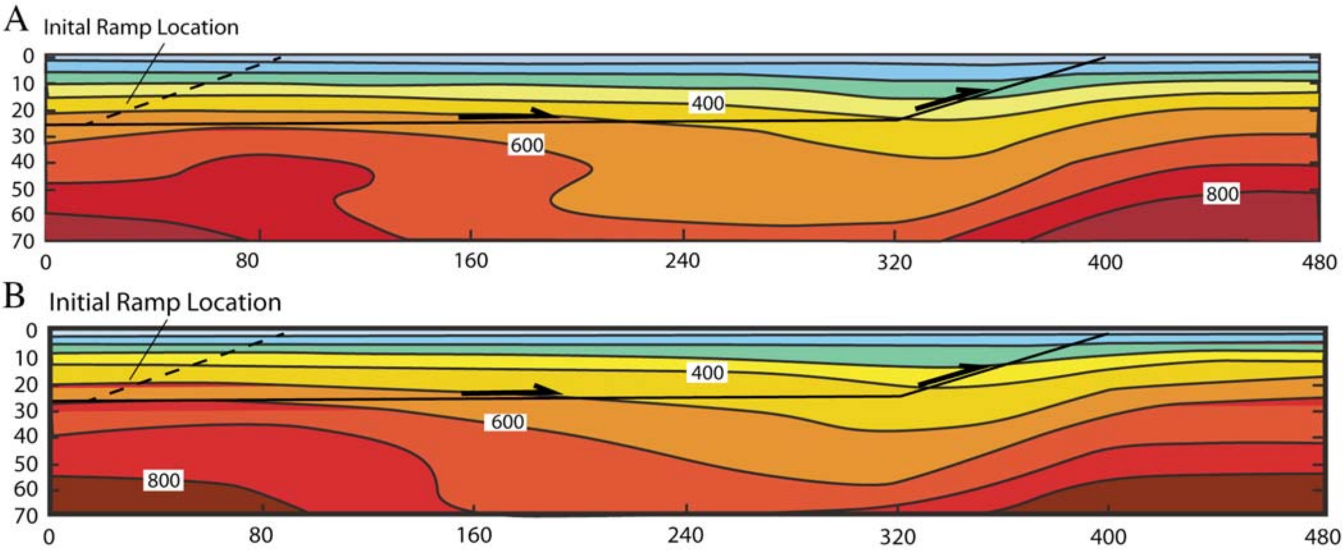

Fig.- 1A and 1B compare two models using different thicknesses of radiogenic crust. In A the radiogenic material is initially limited to 16 km of the upper crust. In B the radiogenic material is initially spread through the upper 20 km. Both contribute 40 mW to the surface heat flux. The degree of concentration of radiogenic elements affects the thermal relaxation process and the horizontal temperature gradients. However, a distinct thermal dome is visible in both figures. Distances are in km with no vertical exaggeration.

Allochthonous terranes involved in the Variscan suture from NW Iberia: A review of their origin and tectonothermal evolution

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NW Iberia includes a rather complete section of the Variscan suture, where different terranes with continental or oceanic affinities appear with clear structural relationships. Three groups of terranes, namely upper, ophiolitic and basal units and a frontal tectonic mélange appear in Galicia, in Cabo Ortegal, Órdenes and Malpica-Tui complexes. They constitute a huge allochthonous pile thrust over the Iberian parautochthonous and autochthonous domains, which represent the section of the Gondwanan margin that escaped continental subduction during the Variscan cycle (Schistose Domain of Galicia-Trás-os-Montes and Central Iberian Zone).

In the upper units, ca. 10000 m of terrigenous sediments (Órdenes Series) intruded by large massifs of Cambrian (ca. 500 Ma) I-type calc-alkaline granitoids (Corredoiras orthogneisses) and tholeiitic gabbros (Monte Castelo gabbro), are considered to represent a section of a magmatic arc built up in the periphery of Gondwana during Neoproterozoic-Cambrian times. Nd model ages from the Cambrian topmost turbiditic series (Ares-Sada greywackes) are relatively young (720-1215 Ma) and suggest relative proximity to some Avalonian terranes. The uppermost part of this terrane was affected by metamorphism ranging between the greenschist facies and the intermediate pressure granulite facies conditions (IP upper units), dated at 496-484 Ma. The IP upper units can be considered a relic section preserving the Cambrian tectonothermal activity that took place in the peri-Gondwanan arc almost intact. That activity was caused by magmatic underplating followed by accretion of arc slices, which developed counter-clockwise P-T paths evolution. However, the lower part of this terrane shows a completely different tectonothermal activity, because it was affected by a generalized high-P and high-T metamorphic event (HP-HT upper units; Cedeira and Capelada units in the Cabo Ortegal Complex, Sobrado Unit in the Órdenes Complex). This event developed extensive recrystallization under eclogite and granulite facies conditions, the peak pressures being in the range of ultra-high-P metamorphism (proved minimum pressure at 22 Kb, with some indications of higher values). The high/ultra-high-P metamorphism (ca. 400 Ma) was followed by drastic and fast exhumation coeval with partial melting (ca. 390 Ma). The development of extensional detachments (ca. 375 Ma), recumbent folds and thrusts drove the exhumation of this high-P complex later on.

True MORB ophiolites derived from typical oceanic lithosphere are unknown in the Variscan suture of Galicia. On the contrary, the mafic-ultramafic sequences preserved in NW Iberia were generated in supra-subduction settings, their mafic rocks showing island-arc tholeiitic composition. There exist two critical oceanic to transitional crust-forming events: a Middle-Late Cambrian phase (ca. 500 Ma, lower ophiolitic units, Vila de Cruces Unit), and a Middle Devonian phase (ca. 395 Ma, upper ophiolites, Careón and Purrido units). Both types of mafic units were accreted beneath the upper units during Variscan convergence, the upper ophiolites first (ca. 391-377 Ma), and then the lower ophiolites (ca. 367 Ma). Due to their buoyant nature, many Devonian ophiolites escaped from early-Variscan subduction, so they are the most common ophiolites preserved in the Variscan suture across Europe. The mafic-ultramafic sequence of the Bazar Unit has been interpreted as peri-Gondwanan oceanic lithosphere accreted beneath the magmatic arc system at 480 Ma. This unit is the only one in NW Iberia showing low-P granulite facies conditions, which has been linked to mid-ocean ridge subduction under Gondwana and the opening of an asthenospheric window.

The basal units consist of a thick sequence of Ediacaran-Early Ordovician terrigenous metasedimentary rocks intruded by Cambrian to Ordovician granitoids (calc-alkaline to peralkaline) and minor mafic igneous rocks. These

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units are considered to outline the most external part of the Gondwanan paleomargin. However, detrital zircon age populations along with (very old) Nd model ages obtained from well-preserved turbiditic series (ranging between 1782 and 2223 Ma) indicate a paleoposition further to the East than the arc-related section preserved in the upper units. The basal units also represent a continental paleosubduction zone affecting a wide and continuous section of the margin at the onset of the Variscan collision (ca. 370-360 Ma). Subduction polarity was to the W (present-day coordinates) and included right-lateral components. Continental layers were imbricated below previously accreted ophiolites, while a variety of C-type eclogites, blueschists and lawsonite bearing metabasites developed. The basal units can be subdivided in two main groups according to their tectonothermal evolution: an upper group with high-P and medium-high-T metamorphism (Agualada and Espasante units); and a lower group with high-P and low-medium-T metamorphism (Ceán, Malpica-Tui, Lamas de Abad, Santiago, Cercio, Lalín and Forcarei units). The upper group is considered the closest section to the overlying mantle wedge during Variscan subduction, whereas the lower group accounts for the cooler sections of the subduction wedge. The arrival of thicker, more buoyant continental crust blocked the subduction, leading to several thrusting events that transported the subduction complex onto the adjacent, inner sections of the margin, represented by the parautochthonous sequences of the Schistose Domain.

The Somozas mélange is a piece of the Variscan continental subduction channel developed between the section of the Gondwanan margin represented by the basal units and their respective overlying mantle wedge. The subducted continental margin was exhumed later on and emplaced over the mélange zone. The mélange appears as a unique element at the easternmost contact between the allochthonous terranes and their relative autochthon. The mélange unit consists of ca. 500 m of serpentinite showing block-in-matrix texture. The blocks are variable in size and include metasedimentary rocks, volcanics, gabbros, granitoids and high-P rocks. As a major plate boundary, and given the nature and sensitive structural position of this unit, multiple tectonic events have left strong imprint on it.

Continental convergence did not decline after Variscan subduction and early Variscan nappe tectonics. The allochthonous pile and the suture zone were transferred onto the Gondwana mainland, thus triggering the thermal and gravitational collapse of the collisional wedge. The convergence continued during the Pennsylvanian, when the entire allochthonous pile was subjected to heterogeneous reworking in strike-slip systems.

Considering the allochthonous character of the nappe pile and the strong deformation associated to the Variscan collision, there are problems to identify the original tectonic setting of some terranes and thence, it is almost impossible to reconstruct the paleogeographic setting during the Variscan and pre-Variscan times in detail. Key features to perform any evolving model for the Variscan convergence should consider the existence of two different high-P metamorphic events, both of them affecting continental or transitional crustal sections that belonged to the margin of Gondwana. On the other hand, the ophiolitic units provide evidence for two stages of generation of oceanic or transitional crust precisely within the paleogeographic domain that separated the two sections recording the high-P events. Previous models developed in NW Iberia suggested that the upper units represent a peri-Gondwanan terrane drifted away from the main continent during the opening of the Rheic Ocean. The lower and upper ophiolitic units would be generated respectively during the opening (rifting) and the beginning of the closure (by intraoceanic subduction) of this Paleozoic ocean. In those models, the two high-P metamorphic events would be related first to the accretion of the drifted terrane to the southern margin of Laurussia (upper units), and then to the subduction of the thinned Gondwanan margin after complete closure of the Rheic Ocean (basal units).

The previous models have important problems to explain the high/ultra-high-P metamorphic event and the exhumation of deeply subducted transitional-type sections. On the other hand, the recently discovered participation of an older continental crust in the generation of some protoliths belonging to both types of ophiolitic units (Purrido and Vila de Cruces units), along with their highly depleted Sm-Nd isotopic signature, make difficult their relationship to open wide oceanic domains. A two-stages collisional model affecting a wide Gondwanan platform may explain most of the evidences in NW Iberia. This platform would contain Cambrian back-arc sections with transitional crust (ca. 500 Ma) filled by siliciclastic material, and also the remnants of a previous Ediacaran-Cambrian magmatic arc. Collision of this platform with the southern margin of Laurussia, in a dextral convergence setting, would have caused imbrication and subduction of transitional crustal sections to high/ultra-high-P depths (ca. 400 Ma), followed by exhumation and subsequent generation of ephemeral supra-subduction or pull-apart oceanic basins (ca. 395 Ma), finally closed during the second event of collision and restarted subduction of the Gondwana margin to the North (ca. 370 Ma). According to this model the upper units of NW Iberia would represent the lower plate to the Rheic Ocean suture.

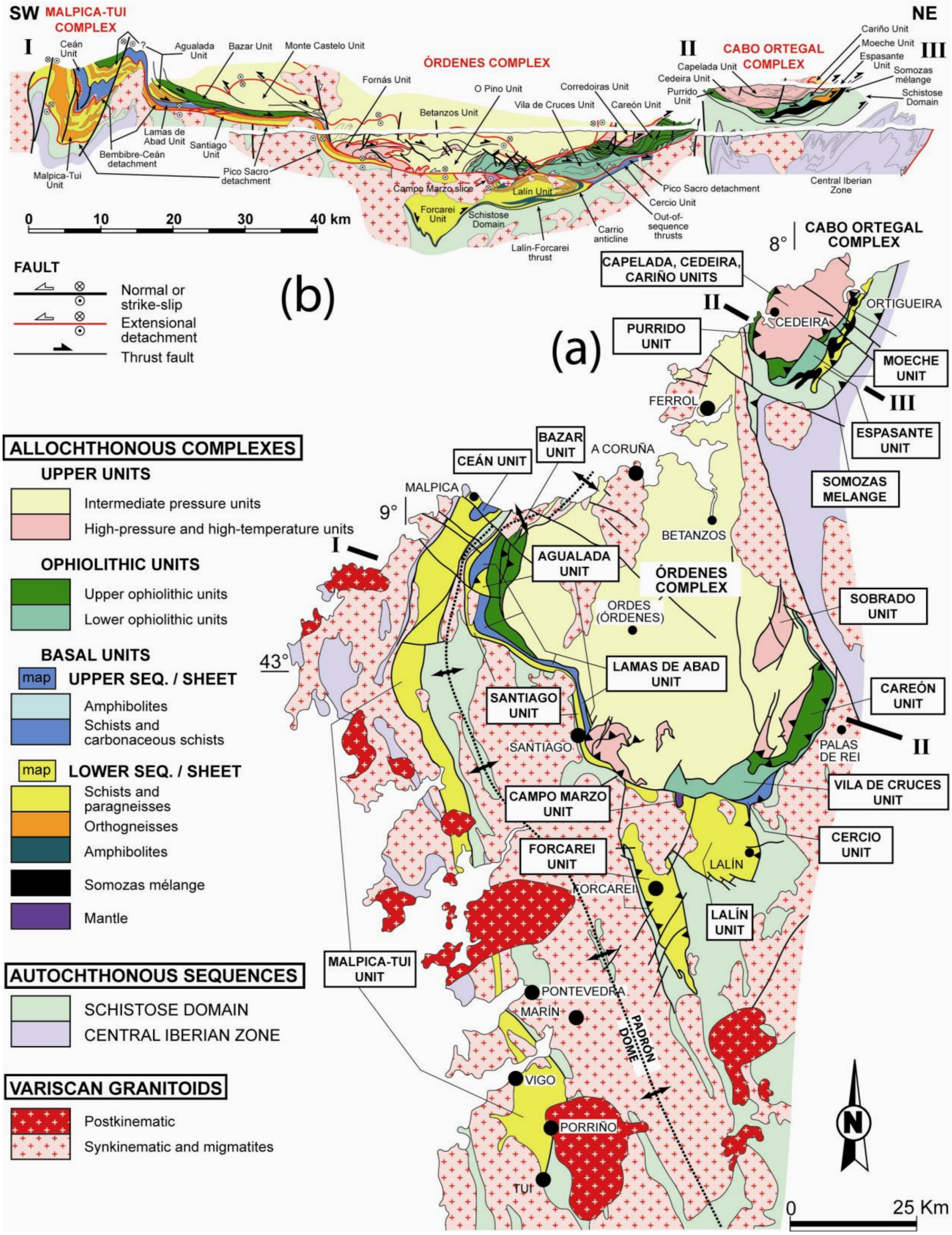

Fig. 1.- (a) Map showing the allochthonous complexes of Órdenes, Cabo Ortegal and Malpica-Tui in NW Spain. (b) Composite cross section showing the general structure of the allochthonous complexes. For the basal units, the section includes further details than the map (see legend).

A model of heterogeneous delamination of the Variscan lithospheric roots in Northern France by Late Carboniferous-Early Permian times: implications for the Late Variscan orogenic collapse and the Paris basin development

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The Paris basin (northern France) is a Late Paleozoic-Mesozoic intracratonic basin that settled upon the collapsed Variscan collisional belt. More precisely, subsidence patterns within the basin suggest that it results from a long-term thermal cooling of the lithosphere subsequent to a Stephanian-Early Permian (generally referred to as Late Variscan) rifting event. The latter is responsible for the individualization of deep but highly localized intramontaneous troughs that can be now observed at the base of the basin. A very significant point is that these troughs are localized along the Northern Variscan Suture Zone (NVZS) *i.e.* the Lorraine-Sarre-Nahe (LSN) trough along the Rhenohercynian segment of the NVSZ and the Central Channel trough along the Lizard segment of the NVSZ. Seismic profiles across these basins suggest that they correspond to deep hemi-graben structures, filled up by very thick fluvio-lacustrine continental deposits (up to about 4 kms in the LSN trough), and controlled by large normal faults reactivating at depth the main thrust structures active along the NVSZ during the Namurian-Westphalian Variscan orogenic phase. This structural pattern observed at the base of the Paris basin characterizes a general mechanism of negative tectonic inversion, mainly localized, along the Northern Variscan Suture Zone. Such inversion event is coeval with a well-defined large-scale lithospheric thermal anomaly within the internal zones of the Variscan belt (*i.e.* South of the NVSZ) responsible for an extensive magmatic and hydrothermal activity. We suggest that this extensive late-orogenic lithospheric thermal event, coupled to the negative inversion of the NVSZ, can be interpreted as the result of the delamination of the Variscan lithospheric mantle roots along the Carboniferous Northern Variscan Suture Zone *i.e.* the detachment of the south-directed Lizard-Rhenohercynian slab and the associated rise of the asthenospheric mantle below the suture zone.

To precise this model and investigate in more detail the mantle roots of the Variscan orogenic system, we present here the results of a European-scale P-wave velocity tomographic model below the Paris basin (the model PM0.5). This intermediate-scale mantle tomography model (nodes interspacing is 55 km in horizontal and 50 km in vertical direction) points out the existence of a significant high velocity anomaly in the upper mantle below the western part of the basin. At depths between 100-200 km (*i.e.* at the base of a standard continental lithosphere), the anomaly extends with a NW-SE trend along the buried Northern France trace of the Northern Variscan Suture Zone *i.e.* the Bray segment. As a matter of fact, the main high-velocity anomaly is spatially correlated with the prominent Paris Basin Magnetic Anomaly (though slightly shifted to the SW) and spatially anti-correlated with the location of Stephanian-Early Permian rifted troughs at the base of the Paris basin (the Lorraine-Sarre-Nahe and Central Channel troughs). Its vertical extent reaches depths greater than 200 km below the southern border of the Paris basin. As suggested in other tomographic studies below ancient suture zones, these data argue for such anomaly being the remnant of the NVSZ subducted slab that locally escaped the late orogenic delamination process affecting the Variscan root zones by Late Carboniferous-Early Permian times and that was partially preserved over 300 Ma at the base of the lithosphere. It is worth to note that the postulated remnant slab along the Bray segment of the Lizard-Rhenohercynian suture corresponds to a specific transverse zone along the NVSZ submitted to a significant oblique convergence during the orogenic Variscan development that, in turn, may have had a direct impact upon its subsequent detachment from the Variscan lithospheric root.

These results provide a new insight into the mechanisms that controlled the late orogenic collapse of the Variscan belt. We suggest here that the delamination of the Variscan root zones in Northern France was a strongly heterogeneous process, controlled by the 3D dynamics of the subduction-collision system along the Northern Variscan Suture Zone, resulting finally in different patterns of asthenopheric rise below the suture zone *i.e.* different amount along strike of Late Paleozoic extension and subsequent thermal subsidence in the Paris basin.

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Cambrian sandstones from Morocco and SW Sardinia: Coupled U-Pb-Hf of detrital zircons with implications for provenance and crustal evolution

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U-Pb-Hf of detrital zircons from diverse Cambrian units in Morocco and Sardinia were investigated in order to clarify the sandstone provenance and how it evolved with time, to assess whether the detrital spectra mirror basement crustal composition and whether it is a reliable pointer on the ancestry of peri-Gondwana terranes. Coupled with Hf isotopes, the detrital spectra allow a unique perspective on crustal growth and recycling in North Africa, much of which is concealed below Phanerozoic sediments. In Morocco, the detrital signal of Lower Cambrian arkose archives local crustal evolution dominated by Ediacaran (0.54-0.63 Ga) and Late-Paleoproterozoic (1.9-2.2 Ga; Eburnian) igneous activity. A preponderance of the Neoproterozoic detrital zircons possesses positive $\varepsilon Hf_{(t)}$ values and their respective Hf-TDM ages concentrate at 1.15 Ga. In contrast, rather than by Ediacaran, the Neoproterozoic detrital signal from Middle Cambrian quartz-rich sandstone is dominated by Cryogenian-aged detrital zircons alongside a noteworthy early Tonian (0.95 Ga) peak; a few Stenian-aged (1.0-1.1 Ga) detrital zircons are also distinguished. The majority of the Neoproterozoic zircons display negative $\varepsilon Hf_{(t)}$, indicating the provenance migrated onto distal Pan-African terranes dominated by crustal reworking. Terranes such as the Tuareg Shield were a likely provenance. The detrital signal of quartz-arenites from the Lower and Middle Cambrian of SW Sardinia resembles the Moroccan Middle Cambrian, but 1.0-1.1 Ga as well as ~2.5 Ga detrital zircons are more common there. Cambrian Sardinia may have been fed from sources located farther to the east along the north Gondwana margin, perhaps in front of Arabia. 1.0-1.1 Ga detrital zircons abundant in Sardinia generally display negative $\varepsilon Hf_{(t)}$ values, while 0.99-0.95 Ga detrital zircons (abundant in Morocco) possess positive $\varepsilon Hf_{(t)}$, attesting for two petrologically-different Grenvillian sources in North Africa. An Andean-type Stenian source appears to have been more prominent in the east. A paucity of detrital zircons younger than 0.6 Ga is a remarkable feature of the detrital spectra of the Moroccan and Sardinian quartz-rich sandstones, indicating that sandstone production involved dispersal of earlier molasse sediments that did not contain detrital zircons younger than 0.6 Ga in the first place.

About a quarter of the Neoproterozoic-age detrital zircons in the quartz-rich sandstones of Morocco (and a double proportion in Sardinia) display positive $\varepsilon Hf_{(t)}$ values indicating considerable juvenile crust addition in North Africa, likely via island arc magmatism. A substantial fraction of the remaining Neoproterozoic zircons which possess negative $\varepsilon Hf_{(t)}$ values bears evidence for mixing of old crust with juvenile magmas, implying that crustal growth in an Andean-type setting was also abundant in this region.

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Geometry and correlation of the nappe stack in the Ibero-Armorican arc across the Bay of Biscay: a joint French-Spanish project Part 1: the data

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Since its early recognition and widespread acceptance following the birth of plate tectonics, the Ibero-Armorican arc has been acknowledged as a first-order structure of the Variscan belt. Palaeomagnetic and structural data indicate that the arc dates from the latest Carboniferous (Stephanian, c.a. 305-295 Ma) and that it bends structures that were previously essentially linear. The latter include a huge nappe stack that was built during the early phases of the Variscan orogeny.

Our primary aim was to establish the geometry of the nappe stack on both sides of the Bay of Biscay, and therefore to unify the terminology used by both teams when describing it (see figure). Field excursions have been made in common for checking whether or not both lithologies and structures were similar. The following account relies on detailed mapping made by both teams, the two sections having weaknesses as well as strengths. The section along the NW coast of Spain is of exceptional quality because of the high relief, but presents a “rootless suture”. On the French side, adding to the relatively poor quality of most outcrops, one has to take into account that the South-Armorican shear zone cuts across significant portions of the nappe stack, and therefore displaces the suture zone.

The **Autochthon** and **Parautochthon** are made of a thick sequence of dominantly terrigenous sediments laid down in the continental platform of northern Gondwana, including a few key lithological markers, namely (i) shallow-water carbonates of proved or presumed Early Cambrian age, (ii) a huge amount of felsic volcanics (“Ollo de Sapo” in Spain, “porphyroïdes” in France), both dated at about 490-470 Ma and derived from partial melting of a source that includes a significant Cadomian component, (iii) Early Ordovician quartzites frequently referred to as the Armorican Quartzite, and (iv) black shales and cherts of Silurian age.

The **Lower Allochthon** includes a terrigenous sequence of latest Proterozoic age intruded by Cambrian and Early Ordovician plutons (500-470 Ma), displaying a wide range of chemistries, including metaluminous, calc-alkaline rocks largely predominating over peralkaline bodies. These are recognized from Portugal to the Massif Central. A coeval or younger set of mafic bodies (mainly doleritic dykes) cuts across the granitoids and their country rocks. A younger terrigenous sequence of early Paleozoic age intercalates igneous mafic rocks both in France (Groix: 490-480 Ma, Bois de Cené: 490 Ma) and Spain (Ceán, Lamas de Abad, and Cercio units). This series represents the farther sections of a continent facing the Cambro-Ordovician Ocean that was involved in accretionary prisms at the onset of the Variscan cycle.

The **Middle Allochthon** consists of dismembered ophiolitic slices that locally display a blueschist-to eclogite-facies overprint during the Variscan orogeny. These include in NW Portugal and Spain a diverse array of well-characterized oceanic complexes, in many cases of Devonian age (Careón and Morais-Talhinhas: 400-395 Ma, Drain: 380 Ma). Other record Late Cambrian, Early Ordovician and younger Palaeozoic ages. Some are true ophiolitic bodies (Audierne: 480 Ma, Izeda-Remondes in Morais: ca. 450 Ma), others are better interpreted as accretionnary prisms derived from an Early Ordovician ocean (Groix: 490-480 Ma, Bois de Cené: 490 Ma), or display a transitional ocean-continent domain (Vila de Cruces: 500Ma) related to the upper sequence of the Lower Allochthon.

The **Upper Allochthon** derives from a Late Cambrian, continental (ensialic) arc developed at the northern margin of Gondwana, and comprises two groups of units. Occupying the lower structural position, the first group preserves evidence of a high-pressure, granulite to eclogite-facies event (Bragança; Fornás, Belmil, Melide, and Sobrado in Órdenes; Cedeira, and A Capelada in Cabo Ortegal; upper slice of the Essarts Complex in Vendée). The eclogitic event was followed by partial melting and exhumation to amphibolite-facies conditions in the interval of 410-380 Ma. The upper group displays granulite (Monte

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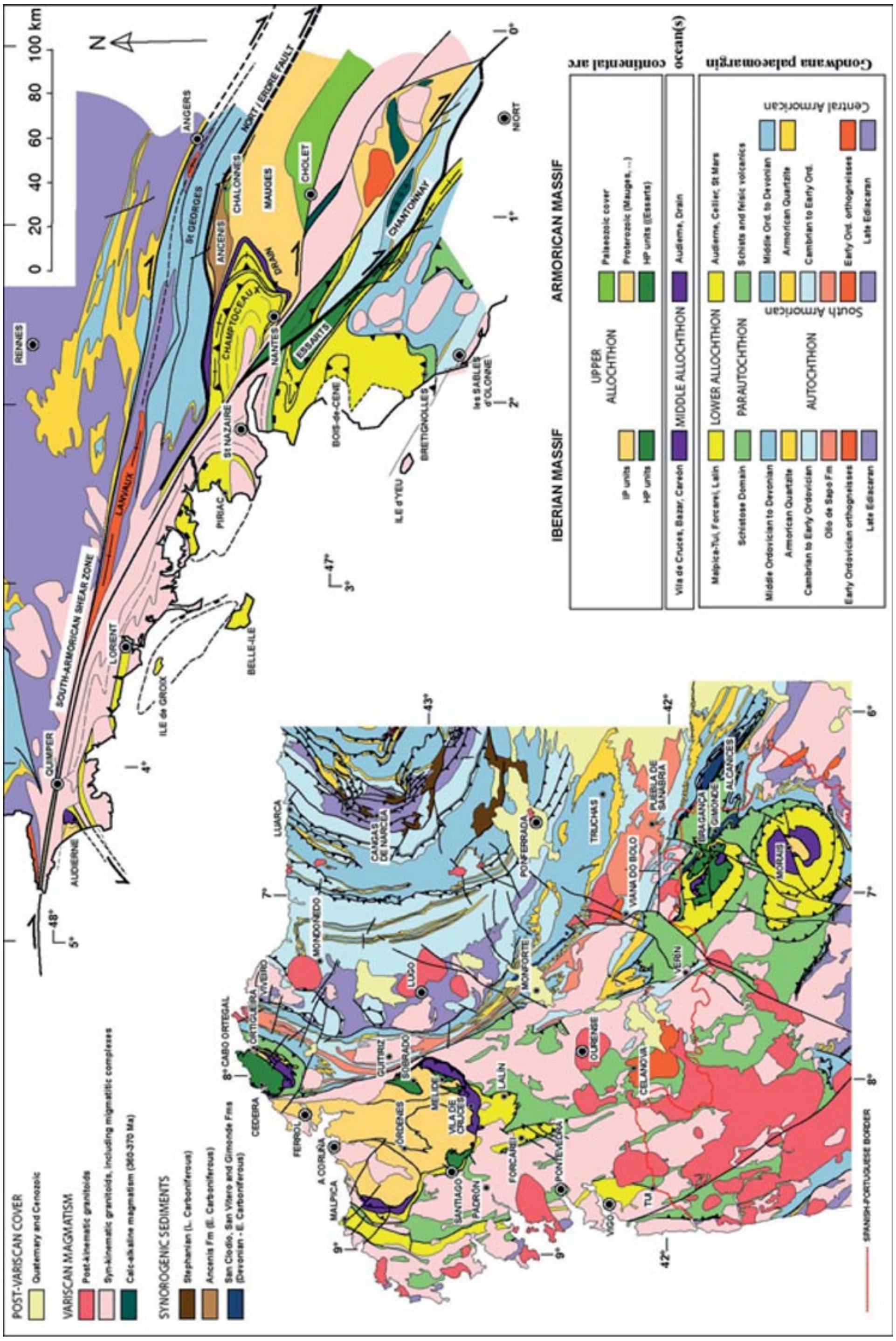
Castelo and Corredoiras in Órdenes), amphibolite or greenschist facies metamorphism of Late Cambrian age, which closely followed arc formation. Amongst the low-grade units, that of Mauges in the SW Armorican Massif is unique because it preserves Cambrian or Early Ordovician sediments unconformably overlying a low-grade basement, followed by a discontinuous sedimentation recording the Hirnantian glaciation, then the Silurian anoxic event, and finally, the establishment of a carbonate platform close to an emerged land during the Early Devonian.



New geo-petrographical data on pelitic rocks at the Sardic unconformity, SW Sardinia, Italy

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A geological, petrographic and geochemical survey was carried out in the key locality (near Nebida, SW Sardinia) for the study of the "Sardic Phase" (Stille, 1939), on rocks below and above the "Sardic Unconformity" (Teichmüller, 1931). The studied rocks belong to the metamorphic basement of Iglesiente-Sulcis located in the External zone, the southernmost segment of the Variscan chain in Sardinia (review in Franceschelli et al., 2005). The pre-Sardic unconformity succession includes the Nebida, Gonnesa, Campo Pisano and Cabitza Formations from bottom to the top. The post-Sardic unconformity succession comprises the Monte Argentu, Monte Orri, Portixeddu, Domusnovas, Rio San Marco, Genna Muxerru, Fluminimaggiore and Pala Manna Formations from bottom to the top.

Four deformation phases, the first one considered of Eo-Caledonian age ("Sardic Phase") whereas the following of Variscan age, were distinguished by several authors in SW Sardinia (see review in Carmignani *et al.*, 2001; Franceschelli *et al.*, 2005). The Eo-Caledonian Sardic Phase was hypothesized by Stille (1939) on the basis of an angular unconformity, the Sardic unconformity, described by Teichmüller (1931), separating the underlying Cambro-Ordovician sequence from the overlying middle-upper Ordovician transgressive metaconglomerates. Some authors do not accept the existence of this Eo-Caledonian deformation phase and consider of Variscan age some tectonic contacts in the key areas of the Sardic Phase. However, new field geological surveys and a more detailed cartography in several localities of the Iglesiente-Sulcis, led to recognize that, in many cases, brittle structures (reverse faults and overthrusts) and ductile structures (km-sized folds) were generated during a tectonic phase that took place between lower Ordovician and middle-upper Ordovician. These pre-Variscan structures are still recognizable in spite of the overwhelming Variscan imprint, in some important key areas (near Gonnesa, Monte S. Giovanni area, Pertunto etc.).

The first Variscan Phase produced gentle discontinuous E-W trending folds accentuating the previous structures but unable to generate a new schistosity. In spite of the similar orientation, these first Variscan deformations are remarkably weaker than the Eo-Caledonian ones, as suggested by folds more open, more discontinuous and less extended than the previous ones.

The second Variscan Phase, to which the main schistosity S2 is referred, generated N-S trending faults, overthrusts and folds showing a very inclined axial plane. To this phase may be attributed W-verging, N-S trending asymmetric folds, W-verging reverse faults, generally associated with broad cataclastic bands and E-verging overthrusts. The NNE-SSE-trending reverse faults are steeply inclined towards ENE and show a WSW direction of tectonic transport. The third Variscan phase is characterized by minor structures with variable axial directions deforming the previous structures.

More than 40 pelitic samples from the Cabitza and Monte Argentu Formations were studied.

As to the clay mineralogy, the two groups of samples corresponding to Cabitza Fm and Monte Argentu Fm show only minor differences. The mineral assemblages in both groups always include quartz, illite and chlorite with occurrence of paragonite in about 50% of the Cabitza Fm and in the 75% of the Monte Argentu Fm samples. Kaolinite, frequently observed in the Cabitza Fm samples (30% of samples) was found only in one sample of the Monte Argentu Fm. Pyrophyllite occurs in 6 out of 20 samples of the Monte Argentu Fm and only in one sample of the Cabitza Fm. Mixed-layer illite/smectite were found only in two samples of the Cabitza Group.

In some samples we have found together with the paragonite also a Na/K mica phase. The weak peaks at d = 9.6 Å and 4.81 Å and 3.21 Å resolved from K-micas reflections, reveal the occurrence of small amount of paragonite and

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small peaks intensity at d = 4.94 Å and 4.88 Å indicate the presence of K/Na micas with composition intermediate between muscovite and paragonite. The Cabitza Fm samples yielded IC values in the range °Δ 2θ = 0.25-0.34 with 20 samples out of 26 falling in the range °Δ2θ = 25-31 and an average value of 0.29; the Monte Argentu Fm samples are characterized by IC values in the range °Δ2θ = 0.28-0.42 with 15 samples out of 20 plotting in the range 0.33-0.38 with an average value of 0.36.

The values obtained emphasize the difference of metamorphic grade between the underlying, more metamorphic Cabitza Fm and the overlying, less metamorphic, Monte Argentu Fm.

The b_0 spacing of white mica from the Cabitza samples (23 samples) ranges from 8.976 to 9.042 with a cluster of values between 8.99 and 9.00 and between 9.01 and 9.03. The b_0 spacing of white mica from the Monte Argentu samples (20 samples) ranges between 8.988 and 9.018, one sample gave 9.036. Cumulative frequency curves concerning the b0 spacing of white mica from Cabitza and M Argentu Fm are comparable to those obtained for the white mica of the Bosost, New Hampshire and Ryoke belts reported as typical of low pressure metamorphism by Sassi and Scolari (1974). However, several samples studied contain paragonite or pyrophillite, and therefore further data should be acquired in order to confirm the low pressure regime of metamorphism.

In the K_2O/Na_2O *vs.* SiO_2/Al_2O_3 (Wimmenauer, 1984) all the samples plot in the pelite field. There is no significant difference among the two groups of rocks.

In the diagram $Al_2O_3/(Al_2O_3 + MnO + Fe_2O_2)$ *vs.* Fe_2O_3/TiO_2 all the Iglesiente samples plot in the continental margin setting of Murray (1994) and more precisely in the old upper continent crust provenance subfield. The samples of the Cabitza and Monte Argentu Formations show very similar, parallel trends with the Cabitza Fm samples shifted upwards owing to Fe_2O_3/TiO_2 values generally higher than those of the Monte Argentu Fm.

In the studied samples SiO_2 content ranges between 53.04 and 62.77 wt % while Al_2O_3 content is mostly between 20 and 23 wt%. The high K_2O content (3.12-6.77%) and the low Na_2O content almost always lower than 1 wt % indicate a prevalence of K-bearing minerals such as illite, pyrophyllite, muscovite and K-feldspar on the Na-bearing ones, i.e. paragonite and plagioclase.

Extremely high Ba contents higher than 1000 ppm up to 4363 ppm were found in samples very near to the Sardic unconformity in the uppermost part of the Cabitza Fm and in the lowermost part of the Monte Argentu Fm. This suggests the presence of abundant barite or celsian component of the K-feldspar (the highest Ba contents in samples with very high K contents) presumably deposited by hydrothermal fluids running along the tectonic plane of the Sardic unconformity. Owing to the fact that these high Ba contents are an intrinsic chemical feature of the pre- and post–Sardic unconformity metasediments, we can hypothesize that hydrothermal circulation of Ba-rich fluids was contemporary with the Sardic Phase, then older than the late- to post-Variscan circulation of similar Ba-rich fluids discussed by Fedele *et al.* (2003).

The chemical index of alteration (CIA) values for the Iglesiente samples are always higher than 70. The whole range is 71-81 with 32 samples out of 46 falling in the range 78-80. Values higher than 70 indicate intensive alteration (CIA > 70). The chemical index of weathering (CIW) mainly varies in the range 91-100. Most values (36 samples) fall in the range 95-100. These data confirm the large prevalence of clay minerals and the remarkable intensity of alteration. A confirmation of the great abundance of clay minerals is given by the A-CN-K diagram. This diagram shows that the Iglesiente samples partially fall on an estimated average shale field and cluster in a restricted area between the average shale field and the A-K side with a few samples plotting just on the illite point.

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Carboniferous Foreland-Basin Deposits, Interbedded Magmatism and Kinematic Evolution of the Mesetan Fold-Thrust Belt of Morocco

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Reconsideration of Carboniferous tectono-sedimentary data from northern/central Morocco suggests a new model for the Mesetan Hercynian orogeny. This hypothesis implies a series of orogenic processes associated with plate convergence.

The progression of the deformation has been controlled by two "piggy back" thrust-sequences. The first one, ranging in age from the Famenno-Tournaisian to the upper Visean, determines a prism with two deformation fronts located respectively in the Middle-Atlas- eastern High-Atlas arc (the inflected alignment of Tazzeka-Azrou-Aït/Tamlil-Tamlelt) and the Khouribga-Oulmès ridge. This type of deformation triggers antiformal culminations in the Ordovician to Devonian pre-tectonic series with duplexes and antiformal stacks characterized by: a basal level of detachment following the basis of the Ordovician slates , and, an uppermost level of detachment within the Silurian shales which typically have a weak efficient viscosity. This propagation of the deformation controls the transgressive carboniferous sedimentation. The mainly catastrophic sedimentation of the Tournaisian (or Famenno-Tournaisian) and early Visean is represented by conglomerates, gravity flows and turbidites, and it is followed by a transgressive peak with carbonate sedimentation that became generalized during the upper Visean.The second one (late Visean-to terminal-Westphalian in age) is characterized by second-order-type depocentres associated with thrust-and-fold propagation systems. The anticline uplifting related to stages of thrust-propagation controls the sedimentation which is organized into tectonogenetic sequence deposits.

The retrograde geometry of the synorogenic sedimentation sequences is catastrophic (breccias/turbidites and debris/turbidity flow deposits) and records the successive uplifting of anticlines controlled by second-order overstepping thrust branches. These deposits are interdigitated towards the northwestern passive border of the sub-basin with a normal-type sedimentation with proximal tempestites. Thrusts of this second sequence are branching into the upper décollement within Silurian black shales and evolving on the basis of the carboniferous series. When compared to the model of DeCelles and Giles (1996), the foreland basin system of the Moroccan Meseta is characterized by the predominance of wedge-top-depozones over other types of deposits, thus corresponding to underfilled foreland basins marking the early stages of development of these systems. The interbedded basic magmatism of the Namuro-Westphalian orogenic series belonging to the Fourhal depocenters (differentiated sills, dolerites and basalts pillows), display a calc-alkaline geochemical signature with cogenetic facies, being the melting product of a hydrated metasomatized lithospheric mantle. As this retro-foreland basin magmatism is located more than 500 km away from the suture, we suggest that it was either the result of dehydration of a shallow-dipping foregoing oceanic slab, or underplating of a continental lithosphere ending with slab break-off beneath the foreland basin.

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Ophiolite and eclogites from Limousin (French Massif Central): keys to Variscan subduction processes

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The structural boundary between the two major allocthonous lithotectonic units of the French Massif central (FMC) is underlined in central Limousin by a nearly continuous nappe of ultramafic-mafic complexes associated with metapelites and scarce eclogites. The ultramafic-mafic complexes have been recognized as ophiolites on the basis of peridotite fabric analysis, geophysical-structural investigations and of the geochemistry of mafic rocks (Dubuisson *et al.*, 1988, 1989). However: i. some amphibolites within these complexes present locally corundum-kyanite-sapphirine-gedrite assemblages that are apparently not compatible with an ophiolitic origin (Maillet *et al.*, 1984; Santallier, 1994); ii. Nd isotopic analysis on a gabbro gave an εNd value of +2.6 (while ultramafic rocks range between +5.7 and +6.5 for; Pin, 1989), which is quite low for an oceanic origin. The eclogites at the structural boundary between the ophiolitic unit and the lower allochthon have not been investigated before our studies. As most eclogites from the FMC are from the upper allochthon leptyno-amphibolitic complex, those situated below the ophiolitic nappe probably bears new information on the pre-collisional Variscan events in the FMC. Here we present a review of field, petrographic, thermobarometric and geochemical investigations performed by our research group on Limousin ophiolite and eclogites.

The most complete ophiolitic bodies are composed from bottom to top of mantle diopside-bearing porphyroclastic harzburgites, mantle dunites with podiform chromitites, werhlites and troctolites, magnesian gabbros, Fe-Ti oxide gabbros and a few meta-dolerites. Some outcrops are composed only of mantle rocks while others show only the igneous section of the complete ophiolitic log. The crystallization sequence, characterized by the presence of cotectic olivine-plagioclase-spinel assemblages is compatible with a low pressure crystallisation (< 5 kbar). Compositional variations in preserved igneous minerals argue for crystallization from an anhydrous N-MORB tholeiitic magma. In particular, the absence of igneous highly calcic plagioclase contrasts with what is observed in worldwide supra-subduction zone ophiolites and modern back-arc basins (see Berger *et al.*, 2006).

Most of the ophiolitic sequence has been subject to pervasive hydration and metamorphism with the presence of epidosites, rodingites formed by hydrous Ca-Al silicates assemblages (prehnite, pumpellyite, hydrogarnet, epidote), low pressure Mg-hornblende pseudomorphosing igneous clinopyroxenes that share many equivalent in the modern, hydrothermally altered oceanic crust (see Berger *et al.*, 2005). We interpret all these features as the result of ocean-floor metamorphism at a slow-spreading ridge.

Two-pyroxene and spinel coronas between olivine and plagioclase and anorthite-pargasite-spinel-corundum-kyanite-sapphirine-gedrite assemblages in meta-troctolites obviously did not form during ocean-floor metamorphism. Because anorthite-pagasite associations develop around low-pressure hornblende in amphibolitized Mg-gabbros, this HT event post-dates the oceanic metamorphism. Precise PT calculations and thermodynamic modeling argue for a counter clockwise PT path with a peak at 800°C, 10 kbar. At variance the conclusions of Maillet *et al.* (1984) and Santallier (1994), these metamorphic conditions, PT path and kind of rocks are not rare in ophiolitic sequences: they have been found in the sole or within the crustal sequence of various ophiolites from Oman, Spain, the Appalachian, the Balkan, the Dinarides….(see Berger *et al.*, 2010a). Such a metamorphic imprint is classically interpreted as a result of partial subduction of the still hot oceanic lithosphere.

The trace-element geochemistry of the 33 crustal igneous rocks from the ophiolite gave no evidences for crustal contamination. Both N-MORB and back-arc basin geochemical fingerprints have been observed in melt-like fine-grained amphibolites, the initial tectonic setting of the genesis of this oceanic crust is thus difficult to resolve. It could have been a small oceanic basin subject to intra-oceanic subduction or a back-arc basin system.

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The eclogites, lying structurally below the ophiolitic unit, are kyanite-bearing or zoisite-bearing or both. PT calculations gave equilibration conditions in the range 600-700°C at 2.5-3.0 GPa while fixed composition phase diagram argue for slightly lower P: 2.2 GPa at 620°C. U-Pb dating by LA-ICP-MS performed on zircons from the zoisite-eclogites exhibit cores with igneous oscillatory zoning that gave concordant ages between 475 and 489 Ma and metamorphic unzoned rims giving two age clusters: 412 Ma and 382 Ma. The youngest age is well known in the Limousin and represents a local anatectic event in surrounding orthogneisses (Lafon, 1986; Faure *et al.*, 2008). Accordingly, the 412 Ma age is interpreted as the high-pressure metamorphic event (Berger *et al.*, 2010b). Zoisite eclogites have abnormal bulk composition due to segregation of zoisite during fluid-rock exchange at high-pressure. Kyanite eclogites show positive initial εNd values (+5 to +9), LREE-depleted signatures with pronounced negative Nb-Ta anomalies. Their composition is strikingly similar to those of Izu-Bonin-Mariana back-arc basin basalts; the eclogites thus represent a portion of SSZ oceanic lithosphere that has been subducted down to ~100 km depth.

Both eclogites and ophiolite are marker of intra-oceanic settings, the igneous precursor of the eclogites have been emplaced around 480 Ma in an intra-oceanic back-arc basin and subducted at 412 Ma to UHP or near UHP conditions. The ophiolitic bodies are not dated but they have been built both with MORB-type magmas and back-arc basin basalts. Our preferred interpretation is that it was initially a small oceanic basin that was then subject to intra-oceanic subduction. The local development of HT metamorphic assemblages in the ophiolitic complexes can be explained by ridge subduction and exhumation, this portion of the oceanic lithosphere is characterized by strong temperature variations with depth.

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Late Neoproterozoic - Early Paleozoic accretion of the Southalpine and Austroalpine basements of Central Alps (Italy)

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The study that we have conducted on the Variscan basement of Southern Alps and of a section of the Austroalpine nappes is essentially geochemical and isotopic, and therefore it is based on the assumption that the regional metamorphism did not significantly change the chemical composition of the sedimentary and igneous protoliths.

It is well known that the accretion of the continental crust occurs in the accretionary orogens where material from oceanic plates and from the erosion of overriding continent is added to subducting margins. The two domains are separated by a suture. Sutures may be marked by ophiolitic belts and/or high pressure rocks. Amalgamation of existing terranes gives rise to composite terrane or superterranes. The emplacement of the Ordovician igneous complexes 'stitched' all the amalgamated terranes.

The geochemistry of the metasedimentary rocks of the basement revealed that we are dealing with a superterrane that was mostly assembled probably before the collisional Variscan orogeny. Each of the studied units was accreted in different times and in a peculiar environment. Judging from the ages of the inherited igneous zircons, the oldest sediments are those of the Serie dei Laghi. The Scisti dei Laghi sedimentary protoliths were eroded from a granite-granodiorite rich and deposited in an active margin depositional environment, while the Strona Ceneri Zone shows more affinity with a marginal basin environment in which there was also supply also of sediments derived from mafic rocks. The Strona Ceneri Border Zone, may well represent the reworked products of a pre-Hercynian suture, in which ophiolitic remnants, with U/Pb zircon ages of about 555 Ma, that underwent HP metamorphism in a subduction zone, have been incorporated in turbiditic sediments derived from back-arc bimodal volcanites. The Ordovician I-granites (U-Pb SHRIMP II zircon age results 478 + 6 Ma), which originated on a convergent margin, are present in all three units (but are not present in the adjacent Kinzigitic Formation of the Ivrea-Verbano Zone).

In the Orobic basement the arenaceous-pelitic protoliths of the Morbegno Gneiss and Edolo Schists seem to be a bit younger. They derived from the erosion of source rocks of prevailing intermediate-acidic composition of Neoproterozoic to Lower Cambrian age. Both element and isotope geochemistry suggest for these protoliths a depositional environment of passive or cratonic margin. The development of an intracontinental basin, also reflected by the presence of rare occurrences of metamorphic rocks derived from alcaline metabasalts, allowed the emplacement in the Lower Ordovician of the protolith of Gneiss Chiari, and in the Middle Ordovician that of the Monte Fioraro Complex.

The protoliths of the basement rocks of the Austroalpine Nappes of lower Valtellina have about the same age of sedimentation, but were accreted on an active margin. In particular, in the Monte Tonale Series (Upper Austroalpine) the protolith of the kinzigites derived from the erosion of both Proterozoic and Ordovician source rocks. This protolith can be interpreted as original pre-Varisican *flysch* with carbonatic and mafic olistoliths that seem to have been deposited in back-arc marginal basin. The sedimentary protolith is younger than the Ordovician and could well represent a relic of the closure of another oceanic basin (Silurian?).

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Evidence of two distinct Paleozoic magmatic events in the Lower Penninic units (Ossola Valley, N-Italy): geochemical and SHRIMP U/Pb data

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Protoliths of Lower Penninic basement units in the Ossola-Vigezzo area (Lepontine Alps, N-Italy) mainly consist of Late Paleozoic granitoids, which underwent a pervasive Alpine polyphase deformation and metamorphism. These units, separated by “synclines” mainly filled with Mesozoic sediments, comprise, from the deepest to the highest, the Verampio, Antigorio, Pioda di Crana and Monte Leone Nappes. Even though their Alpine evolution has been investigated for more than 150 years, the pre-Alpine history of these rocks is still poorly understood. Based on a careful structural and petrographic mapping and geochemical and geochronological study, the present contribution focuses on the Paleozoic evolution of these units.

The dominant lithology in the investigated units is represented by medium to fine-grained orthogneisses deriving from Late Variscan protoliths, granitic to granodioritic in composition (with very subordinate tonalities). Their typical mineralogical assemblage is Qtz + Kfs + Pl + Bt ± Ms ± Ap ± Zr ± Ttn ± Op. Grt and Hbl are locally found in the Pioda di Crana gneisses, whereas in the Antigorio rock-types Aln is the main accessory mineral. Geochemical and isotopic patterns of orthogneisses from different Alpine tectonic units almost perfectly overlap, making them indistinguishable. Minor differences can be found only in REE patterns. The Antigorio and Pioda di Crana orthogneisses are smooth and moderately enriched in LREE with $(La/Yb)_n$ = 9-30, and show a slight Eu anomaly (Eu/Eu* = 0.6-1), whereas the Monte Leone and Verampio orthogneisses show a less pronounced REE fractionation pattern ($(La/Yb)_n$ = 5-9) and a more pronounced Eu anomaly (Eu/Eu* = 0.2-0.9). The crystallization ages of the protoliths are scantily reported in the literature (Allegre *et al.*, 1974; Streckeisen *et al.*, 1978; Koppel *et al.*, 1980, Romer *et al.*, 1996) and generally summarized as Hercynian ages by Koppel *et al.* (1980). Our SHRIMP U-Pb analyses performed on magmatic Zrn textures provided Late Carboniferous to Early Permian ages, interpreted as the emplacement time of the protoliths. In detail, the Verampio metagranite is dated at 289 ± 3 Ma. Four samples from the Antigorio Nappe have yielded emplacement ages of 296 ± 2 Ma (metatonalite), 294 ± 5 and 290 ± 3 Ma (metagranodiorites) and 289 ± 4 Ma (metagranite). Ages of 301 ± 4 and 302 ± 4 Ma have been obtained for the Pioda di Crana and Monte Leone orthogneisses, respectively. These ages are in agreement with those determined by Bussien *et al.* (2011) for orthogneisses from the Sambuco and Cocco Nappes.

A distinct set of metagranitoids have been mapped in the Monte Leone Nappe. Here we have discriminated leucocratic and coarse-grained orthogneiss lenses, mainly granitic in composition, consisting of Qtz + Pl + Kfs + WM ± Bt ± Ttn ± Zrn ± Ap ± Tur ± Op. Despite they are strongly transposed during the Alpine polyphasic deformations, in the field they can be readily distinguished from the Late Variscan granitoids by the presence of abundant and large WM flakes. Moreover, they are always spatially associated with paragneisses (Pl + Qtz + WM + Bt ± Grt ± Ep ± Op), micaschists (WM + Bt + Qtz + Pl ± Ap ± Op) and minor amphibolite lenses (Hbl + Pl + Bt ± Qtz ± Rt). Zircons from a nearly undeformed metagranitoid present both typical concentric and oscillatory zoning and inherited cores surrounded by magmatic overgrowths. The age of the inherited cores ranges from 563 to 962 Ma, recalling Panafrican ages. Magmatic rims give a concordant age of 456 ± 4 Ma. According to zircon textures and U-Th geochemistry (Th/U = 0.1-0.4), this age could be interpreted as the emplacement age of the magmatic protolith, indicating that also an Ordovician magmatic cycle could be found in these areas. Emplacement ages older than Late Variscan have been sporadically reported in literature for the Ossola-Vigezzo area (Allegre *et al.*, 1974; Koppel *et al.*, 1980). More recently, Bussien *et al.* (2011) have determined Ordovician emplacement ages for orthogneisses from the Sambuco Nappe. The geochemical data also highlight the differences between Late Variscan and Ordovician granitoids. The latter clearly show distinct evolutionary trends

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with respect to the Late Carboniferous/Early Permian suite. The Ordovician granitoids are mainly granitic in composition, follow a typical AFM calcalkaline trend, and plot in the high-K calcalkaline field. They differ from the Late Variscan granitoids in having higher K_2O, TiO_2, Zr, Hf, V, Zr and Sc, contents, lower Al_2O_3, Fe_2O_3, CaO, Na_2O and P_2O_5 contents, and lower Al2O3/TiO2 and Rb/Zr ratios. On the PM-normalized spider diagram, the Ordovician granitoids are enriched in LILE with respect to the HFSE and show negative P, Ba, Nb and Ti, and positive Pb and Zr spikes. Although the Late Variscan metagranitoids are also characterized by LILE enrichment, those from the Monte Leone Nappe differ from the Ordovician ones in very sharp negative Ba, Sr, Zr and Ti spikes, whereas those from the Antigorio in negative Pb and Ti anomalies.

From our study we can infer that: 1) geochronological data confirm Late Carboniferous/Early Permian magmatic emplacement age for a large volume of the granitoid protoliths of the Lower Penninic basement units; 2) the Late Variscan metagranitoids show mineralogical assemblage, chemical composition and zircon features which suggest a common magmatic source and evolution; 3) the Ordovician metagranitoids + paragneiss + micaschist + amphibolite lenses represent the remnants of a Variscan basement, which could be interpreted as the host rock of the Late Carboniferous/Early Permian granitoids; 4) the Panafrican inherited core ages from the Ordovician granitoids suggest a Gondwana-derived terranes affiliation for this pre-Variscan basement, in agreement with current paleogeographic reconstruction (Von Raumer *et al.*,2003).

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The post-orogenic disruption of the Southern Alp basement: emplacement, petrology and stratigraphy of the Permian volcanic-dominated series in the Valganna basin

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In the Southern Alps, during the Permian, the post-Variscan extensional phase is commonly associated with widespread plutonic and volcanic activity (Cassinis *et al.*, 2007; Schaltegger and Brack, 2007).

Between Lugano and Maggiore lakes the almost unknown Valganna area represents an almost tectonically undisturbed sequence of Permian volcanic to subvolcanic rocks (Bakos *et al.*, 1990, Schaltegger and Brack, 2007), that we addressed for field, petrographic, geochemical and geochronological insights.

In the area three volcanic series (Riccardi M.P., 1988; Bakos *et al.*, 1990; Schaltegger and Brack, 2007) were investigated and our field and petrographic observations recognized that the series emplaced in different environments from subaqueous lacustrine to subaerial. From the bottom to the top:

Series I (basal series): this extrusive sequence (150-350 m in thickness) rests in non-conformity over the Variscan basement (Scisti dei Laghi, Boriani et al., 1990). The series consists of a few meters thick volcaniclastic mass-flow (fining - upwards, layered, volcaniclastic sediment with grain-supported texture of abundant basement lithics, porphyric volcanic fragments and quartz phenoclasts) followed by lithic-crystal tuffs (matrix-supported texture, with cineritic matrix and prevailing quartz phenoclasts) interbedded with thin cinerite levels. In the M. Piambello area a sequence of rhyolithic ignimbrites and lava flows (porphyric texture with microcrystalline matrix and quartz, plagioclase, alkali feldspar, biotite, and rare pyroxene phenocrysts) ends this series. Towards the top of the series, the lithic-crystal tuffs are interbedded with thin levels of fine-grained black sandstones, suggesting a decrease of volcanic activity.

Series II: it starts with andesitic to dacitic agglomerates (porphyric texture with phenocrysts of plagioclase, pyroxene, amphibole and biotite embedded in a microcrystalline matrix, with scant quartz phenoclasts) followed upward by tuff and cinerite levels, identified as the Alpe Tedesco rhyolitic lava flow. The rhyolites display a porphyric texture with quartz, alkali feldspar, plagioclase and biotite phenocrysts embedded in a microcrystalline matrix. Lithic fragments made of metamorphic polycrystalline quartz and quartz phenoclasts are common. The Series II ends with a final ignimbrite (Poncione di Ganna Ignimbrite - welded texture with glassy, locally flow-oriented, matrix and quartz, alkali feldspar, plagioclase and biotite phenocrysts). Lithic fragments with myrmekitic texture are quite common and have been interpreted as derived from the Valganna granophyre. On the base of this assumption the Poncione di Ganna Ignimbrite is interpreted to have postdated the emplacement of the granophyre (Bakos *et al.*, 1990; Schaltegger and Brack, 2007).

Series III: it starts with the M. Piambello dacite lava flow (porphyric texture with microcrystalline matrix and plagioclase, alkali feldspar, biotite and minor pyroxene phenocrysts) followed by lithic-crystal and crystal tuffs (matrix-supported texture with glassy, locally flow-aligned, matrix; basement and porphyric volcanic fragments, cinerite lithics and quartz phenoclasts are included) and a rhyolitic ignimbrite (with eutaxitic texture with glassy and/or welded glass shards and plagioclase, alkali feldspar and biotite phenocrysts; polycrystalline quartz and quartz phenoclasts also occur).

The whole of volcanic products from the three series show high-K calc-alkaline geochemical affinity, with a composition from dacitic to rhyolitic for the Series I and from andesitic to rhyolitic for the Series II and III. The well-known Valganna granophyre, as well as the acidic products from series II, presents a general enrichment in K_2O leading to a transitional signature.

In andesites and dacites of Series II and III, Al_2O_3, CaO, Fe_2O_3, TiO_2, P_2O_5 and Sr contents decrease with MgO decreasing, whereas Rb and Ba increase. They have similar REE (Rare Earth Elements) patterns, with LREE (Light

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Rare Earth Elements) enrichment relative to HREE (Heavy Rare Earth Elements) and a negligible Eu anomaly. In the PM (Primitive Mantle) normalized spider diagram, they show LILE (Large Ion Lithophile Elements) enrichment relative to HFSE (High Field Strength Elements), with positive Pb and Nd and negative Nb, P and Ti spikes.

Whereas the andesitic to dacitic extrusive products show very similar geochemical behavior, the most significant differences are among the acidic volcanic products of the three series. Lithic-crystal and crystal tuffs from the Series I negatively correlate with Sr and positively with Rb and Y. The rhyolitic tuffs, ignimbrites and the compositionally homogeneous rhyolite lava flows from the Series II mainly differ from those of the Series I and III in higher K_2O and Rb and lower MgO, Al_2O_3, CaO, TiO_2, P_2O_5 and Sr contents. The Valganna granophyre displays a geochemical composition close to the extrusive products of the Series II. Both lithic-crystal and crystal tuffs from the Series I and III have similar REE patterns, characterized by LREE enrichment over HREE and negative Eu anomaly. In the primitive mantle normalized spiderdiagram all samples present similar patterns, with LILE enrichment with respect to HFSE. The extrusive products of the Series II generally show more pronounced negative Ba, Nb, Sr, P, Zr and Ti and positive Th, K and Pb spikes.

The Valganna granophyre shows a flat REE pattern with a very pronounced negative Eu anomaly. It presents the highest HREE and HFSE contents.

The geochemical features of the Valganna volcanic complex (*e.g.*, high-K calc-alkaline affinity) well fit other Permian magmatic provinces occurring in the western Southern Alps (e.g., Collio basin, Biella area and Graniti dei Laghi). In particular, the acidic extrusive products of Series II overlap in composition those from the Collio basin (Cortesogno *et al.*, 1998). The Valganna granophyre shows a composition similar to that of the Graniti dei Laghi, whose emplacement is linked to the Cossato-Mergozzo-Brissago transtensional fault, active in Permian times (Boriani *et al.*, 1992 and reference therein).

Field and petrographic data suggest that the Valganna volcanic-sedimentary succession was emplaced in a dynamic depositional environment. The basal extrusive series was probably emplaced in a shallow lacustrine environment, as reported for the basal part of the Collio basin in the Caffaro valley area (Breitkreuz *et al.*, 2001; Cassinis *et al.*, 2008), whereas the Series II could reflect a subaerial apron of intermediate composition. The Series III was emplaced along an active fault probably located at the boundary of the basin (Series I) and its shoulders (Series II). Several ignimbrites (as the Poncione di Ganna, including granophyre clasts) then covered and sutured the succession. U-Pb geochronology by SHRIMP is then addressed at deciphering the timing of emplacement of the volcanic series and of the latest pyroclastic episodes.

Petrographic and geochemical data reveal an igneous evolution dominated by fractional crystallization within each series, together with density selection during the emplacement. The enrichments in LILE and LREE observed could origin in the different abundance of the crustal component or in different source levels in magma genesis. Moreover, the association of high-K-calcalkaline (Series I and III) with K-rich transitional Series II is consistent with a transtensional setting, probably driven by Permian strike-slip faults at regional scale, as already reported for the Collio and Orobic basins (Cassinis *et al.*, 2007; Cassinis and Perotti, 2007).

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Original position of the Western Carpathian crystalline basement in the frame of the European Hercynides

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Crystalline massifs of the Western Carpathians have been formed and integrated to the European Hercynian orogenic belt during the Paleozoic. These massifs were reworked and gradually re-positioned as result of Alpine geotectonic processes from the place of their origin to the present position in the Carpathian arc. The traces of original Hercynian structure were identified in contemporary Alpine structure of the Western Carpathians. The main goal of this work is an attempt to assess a feasible primary position of the Western Carpathian Hercynian complexes in the European Hercynian belt basically by analogy of tectonic structure, lithological and metamorphic signs, as well as by knowledge of tectonic movements during the Alpine orogen.

Recent division of the Western Carpathians is based on the Neoalpine tectonic processes, which resulted in accretion of flysch nappes of the Outer Carpathians as a consequence of the oblique collision of the Inner Carpathian block with the European platform. The Inner Carpathians consist of incorporated tectonic units of Palaeoalpine and Hercynian stages of tectonic development.

The oldest tectonic elements of the Western Carpathians are Hercynian tectonic units of the crystalline basement and fragments of Cadomian blocks in their substratum. They form the fundamental structural units of the Western Carpathians crust. The Hercynian units represent middle crustal nappe system composed of metamorphosed rocks differing in the metamorphic grade and lithology. The four main Hercynian lithotectonic units were identified in the former structure of the basement, which were thrust to the South. The final stage of their development was represented by intrusions of granites. During later tectonic events the Hercynian structure was disintegrated, fragmented and incorporated within Alpine tectonic units and reworked structurally. In the present structure of the Western Carpathians the crystalline complexes crop out in isolated mountain ranges (horsts) separated by Neogene grabens.

Disintegration of the Hercynian-formed continental crust started already in the Late Paleozoic and continued in the Mesozoic, when fundamental Paleoalpine tectonic units of the Western Carpathians (Tatricum, Veporicum, Gemericum and superficial nappes) were formed.

The crystalline complexes in the Tatricum and Veporicum units show similar lithological, structural, metamorphic, geochronological and magmatic signs and history as the crystalline massifs in the southern branch of the European Hercynides, mainly the Massif Central and the External Massifs of the Western Alps. These are:

- analogical rock types (*e.g.* Ordovician orthogneisses, leptyno-amphibolite complexes),
- similar tectono-metamorphic evolution (high pressure Silurian metamorphism connected with the subduction, followed by the Devonian collision with the development of middle-crustal tectonic units and, finally the Late Palaeozoic tectonic stage with evolution of transpressional shear zones, low grade metamorphism and rifting),
- south vergent thrusting of Hercynian nappes,
- supposed Cadomian basement below subautochthonous Lower Hercynian lithotectonic unit (low-grade continental mica-schists).

Existing data point to a former location of the Western Carpathian crystalline massifs in the south-eastern part of the European Hercynian belt, most probably in a space southeast of the Massif Central and External massifs of the Western Alps. This space is now occupied by the Alpine orogen. This interpretation supposes wedging out the Cadomian terrane of Brunia to the southwest.

The Carpathian massifs were in later stages of the tectonic development gradually transported from the place of their origin along huge strike-slip zones towards northeast.

The displacement began already in the Late Paleozoic and continued during the Mesozoic. The final emplacement of the massifs to the present position within Neoalpine arc occurred in the Neogene.

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Coupled Variscan continental crust slices in the Western Alps: a case history in the Ambin Massif

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In the chain of the Western Alps large volumes of pre-Alpine continental crust, which often represent the bulk of some palaeogeographic domains, are involved. The intense Alpine deformation has pervasively obliterated the pre-Alpine structural imprinting sometimes even almost completely erasing the original lithostratigraphic characteristics. This is particularly true in the Penninic domain, where only rare rock volumes were preserved from the Alpine tectono-metamorphic overprinting. Historically, the recognition of pre-Alpine units in the Penninic basement has always been restricted to the discovery of mineralogical relics not congruent with the low thermal gradients characteristic of the Alpine metamorphism.

With the development of radiometric dating and in particular with the method U/Pb on zircon different rock volumes considered mono-metamorphic have provided pre-Variscan age as in the complex system of the Grand Saint Bernard nappe (Bertrand *et al.*, 2000), then stimulating the development of new research on the pre-Alpine basements.

In this respect, an example is represented by the Ambin Massif that consists of a continental crust unit outcropping in the central sector of the western Alps under different units of the Piedmont-ligurian ocean. Classically it is attributed to the system of the Gran San Bernardo and consists of a pre-Triassic crystalline basement on which unconformably lies a succession of Mesozoic age and Brianconnais affinity.

In this work new geological, structural and petrological data have been collected to elucidate the pre-Alpine tectono-metamorphic evolution of this unit. The Ambin Nappe forms a large antiform in the Cottian Alps and consists of two pre-Mesozoic litho-stratigraphic complexes (Gay, 1972): the lower Clarea Complex and the upper Ambin Complex, both showing clear evidences of blueschist-greenschist facies conditions during the Alpine orogeny (Borghi & Gattiglio, 1997).

The Clarea Complex mainly consists of paragneiss and micaschists, with minor metabasites and meta-intrusives. Primary compositional alternations are recognizable at the mesoscale (quartz mica schist and chloritoid - amphibole bearing micaschist) suggesting an original succession of arenaceous-pelitic type. The Clarea Complex shows a polymetamorphic history and a polyphase pre-Alpine evolution, well preserved in the lowermost part of the complex (Borghi *et al.*, 1999). Only in the upper structural levels of the Complex, the rocks are syn-kinematically recrystallized under blueschist conditions.

In the Clarea Complex the pre-Alpine foliation of metapelites and metabasites developed under epidote-amphibolite facies conditions. In additions also pre-Variscan orthogneiss occurred. They are marked by a main foliation defined by the preferential orientation of muscovite overprinted on the magmatic biotite. The first pre-Alpine stage occurred under H-P medium-grade conditions defined only by mineralogical relics as garnet porphyroclasts in the metabasites and Rt in the metapelites. The second and dominant metamorphic stage developed under epidote-amphibolite-facies conditions (Ms-Bt-Grt-St-Al_2SiO_5 assemblage in the metapelites and Hbl-Pl-Ep-Ttn assemblage in the metabasites). Temperatures between 570 and 660°C at pressures of 4-6 kbar can be supposed for this pre-Alpine event.

Based on Ar^{40}/Ar^{39} ages (340-360 Ma, *i.e.* Late Devonian-Early Carboniferous) on muscovite and biotite (Monié, 1990), this foliation would be ascribed to the Variscan orogeny. The general attitude of the pre-Alpine foliation is sub-horizontal and only close to the contact with the Ambin Complex it is increasingly folded and transposed during the first Alpine deformation phase.

The overlain Ambin Complex is marked by a complex lithostratigraphic setting. Quartz-micaschists with discontinuous levels of metaconglomerates predominate in the lower part. Upward, and laterally, they pass to albite and

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chlorite-rich gneisses, interpreted as a former volcaniclastic sequence (Gay, 1972; Borghi & Gattiglio, 1997), which are intruded by aplitic gneiss of rhyolitic composition (Callegari *et al.*, 1980). The upper levels of the Complex mainly consist of micaschists. Recent geochronological data (U/Pb on zircons) constrain a Cambrian age of 500 ± 7 Ma for the emplacement of the aplitic gneisses (Bertrand *et al.*, 2000). This pre-Variscan age points to an older age also for the other rocks of the Ambin Complex and implies that also this Complex may have suffered the Variscan orogeny. Therefore, the contact between Clarea and Ambin Complexes, originally interpreted of stratigraphic nature in the literature, must be considered of tectonic origin. Consistently with this interpretation, structural and petrographic observations show the occurrence of a mylonitic zone along the Clarea-Ambin contact, defined by quartz-rich micaschists and phyllites recrystallized under Alpine blueschist-facies conditions. On top of this contact, the Ambin Complex presents variable ratios of opposite polarity between ortogneisses and para-derivates.

Clarea and Ambin Complexes, therefore, represent two distinct continental crust units of pre-Alpine age, showing a common Alpine evolution, but a highly different pre-Alpine history. In Variscan age, the Clarea Complex suffered amphibolite facies condition, while the lack of pre-Alpine relicts suggests that the Ambin Complex remained at shallow crustal levels. In this sense, the contact between Clarea and Ambin Complexes can be interpreted as a low angle normal fault that juxtaposed two different crustal units.

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The Carboniferous evolution of high-pressure metapelites from the Spessart Crystalline Complex, Germany, and the Ulten Zone, Italian Alps

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The Carboniferous history of the Variscan chain, exposed in several basement units throughout western and central Europe, is related to the evolution of the Gondwana and Laurussia continental margins after their collision in Devonian times. One of the geodynamic scenarios that seem to acquire a growing consensus implies the south-eastward thrusting of the Laurussia continental margin under Gondwana, a geodynamic model also referred to as Himalayan-style collision. The Himalayan model implies the subduction of oceanic crust and subsequent continent-continent collision accompanied by underthrusting leading to Barrovian metamorphism and crustal anatexis. This is the preferred model for different sectors of the Variscides such as the Argentera Massif, (Rubatto *et al.*, 2010) and the Bohemian Massif (Massonne and O'Brien, 2003, but for an alternative view see also Schulmann *et al.*, 2009). Here we present petrologic and geochronologic data on high-pressure metapelites occurring in two different sectors of the eastern Variscan chain: the Mid-German Crystalline High, a metamorphic region adjacent to the southern margin of Laurussia, and the Ulten Zone, a crystalline basement unit with Gondwanan affinity enclosed in the Eastern Alps. The study of these two units highlights the similar evolution of different sectors of the Variscan chain and provides important data for the Early Carboniferous evolution of the Variscan orogen.

The Spessart Crystalline Complex of the Mid-German Crystalline High is composed of several medium-grade metamorphic units comprising orthogneisses, several kinds of metasediments and small intrusive bodies. These units extend in NE-SW directions and seem to have formed a nappe stack. The detailed petrological investigation of garnet-bearing mica-schists from the northern part of the Spessart Crystalline Complex (Geiselbach and Mömbris Formations) yielded pressure(P)-temperature(T) paths characterised by a pressure peak of 1.2-1.5 GPa at 500-540°C that was followed by a thermal maximum at 560-620°C at 1.1-0.9 GPa. The early retrograde metamorphism resulted, for instance, in the formation of staurolite and plagioclase porphyroblasts in mica-schists from the Mömbris Formation at P ≤ 0.7 GPa. Monazite ages, determined with the electron microprobe, range from early Carboniferous to early Permian and provide the timing of the studied mica-schists from the Spessart Crystalline Complex. Geochronologic results on different monazite domains allowed us to identify the following age peaks and relate them to specific events: (1) high-pressure metamorphism occurred at 346 Ma; (2) the thermal peak and the retrograde event under amphibolite-facies conditions (staurolite-grade) was at 329 and 316 Ma; (3) a late metamorphic event accompanied by infiltration of hydrous fluids into the broadly exhumed metapelitic Geiselbach Formation occurred at 295 Ma.

In the Austroalpine region of the Italian Eastern Alps, the Ulten Zone represents a basement unit of Variscan continental crust that survived the Late Cretaceous-Paleogene Alpine metamorphic overprint. The Ulten Zone is generally correlated to the Moldanubian region on the basis of similar rock assemblage (Godard *et al.*, 1996). For instance, both in the Ulten Zone and in the Gföhl Unit in the southern Bohemian Massif garnet peridotites and pyroxenites are enclosed in high-pressure migmatitic gneisses. The Ulten Zone is a deep-seated continental crust that comprises kyanite-grade metapelitic gneisses with a metamorphic evolution similar to the mica-schists of the Spessart Crystalline Complex, i.e. the peak pressure of 1.0-1.8 GPa at 600-650°C (Braga *et al.*, 2007) occurred before the temperature climax around 750°C between 0.9-1.3 GPa (Braga and Massonne, 2008). The late metamorphic stage is marked by the onset of small staurolite idioblasts. U-Th-Pb isotopic ages recently acquired on large matrix monazite from unmelted metapelitic gneiss of the Ulten Zone indicate that the metamorphic peak occurred at about 347 Ma followed by decompression heating at 328 Ma as recorded by fine-grained matrix monazite and rims of the coarse monazite (Langone *et al.*, 2011).

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In spite of the difference in metamorphic grade between the Spessart Crystalline Complex and the Ulten Zone, which experienced ca. 150°C higher peak T (see above), the evolution of the two Variscan regions is comparable in terms of lithology, P-T path and monazite geochronology. This is surprising as both regions show a significant difference in regard to the distance to the northern Variscan front. We explain this as follows: the Devonian underthrusting resulted in a thickened orogenic root that extended over many hundreds of kilometre perpendicular to this front. According to Shelley and Bossiére (2000), this thickened and afterwards partially denuded orogen was squeezed between the (proto)Asia and the North American plates. Dextral transpressive megashear zones developed and large basins opened and were closed again. During this closure in Early Carboniferous times, according to our geochronologic constraints, the sediments of these basins were thrust under the crust of a basin flank and experienced high-pressure metamorphism and heating, which could have even resulted in the onset of partial melting during the subsequent decompression, as in the case of the Ulten Zone. The time span between this thermal-peak event and the previous pressure peak was about 20 Ma, which points to erosion as the major mechanism for the partial exhumation of middle to lower portions of crust, thickened by basin-closure, to upper crustal levels in Early Carboniferous times.

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Tectonic regime in the NE-Iberian Variscides: significance for orogenic zonation

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The basic trends of the Variscan zonation are well established across central and Western Europe. However the setting of some massifs where Variscan rocks are exposed are often excluded or vaguely located from maps correlating different major areas. There are three main reasons for this: 1) some massifs are located in Alpine belts (*e.g.* Pyrenees, Alps and Betics) where the effects of reworking make difficult the reconstruction of pre-Alpine (mainly Variscan and pre-Variscan) geology. 2) Some segments or massifs were subjected to rotation and translation in eo-Alpine (e.g. Iberia) or late- to post-Alpine (e.g. Sardinia) times, their correlation with the Variscan of the European plate becoming complex. 3) The existing correlations are based on the main structures of present in the major Variscan massifs, while the geological features of the minor massifs are often not sufficiently taken into account. These three circumstances apply with different degrees to the Variscan massifs of NE-Iberia (Pyrenees, Catalonian Coastal Ranges, Iberian Chain and Minorca). This study focuses on the Eastern Pyrenees and the Catalonian Coastal Ranges, where the three circumstances above mentioned apply.

Some tectonic features are presented that are relevant for these massifs to be coherently placed. Among them, (i) the transpressional character of main and late deformations and the association of these tectonic events with HT/LP metamorphism and related calc-alkaline magmatism, and (ii) the presence in some Pyrenean massifs of these high-grade rocks and structures prevent them from being tied to an external position in the belt, indicating the necessity for slight changes in the interpretation of the Variscan belt zonation.

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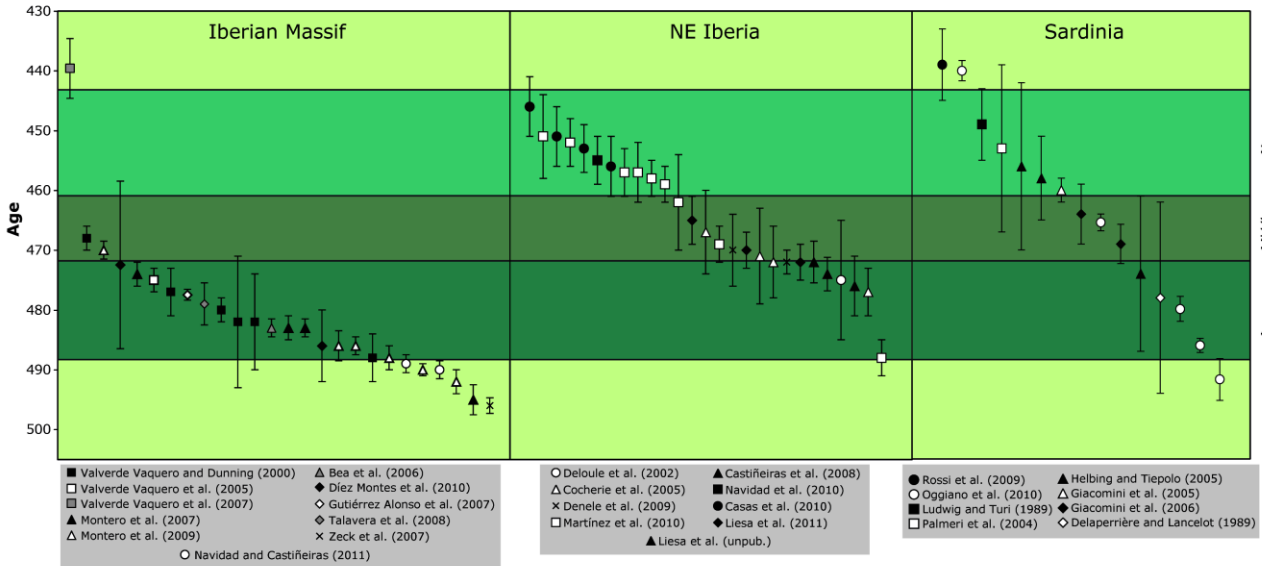

Fig. 1.- Summary of the U-Pb geochronology data of the Ordovician magmatism of the Iberian Massif, NE Iberia and Sardinia.

Ordovician Magmatism in NE Iberia, Comparison with the Iberian Massif and Sardinia

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An Ordovician magmatic event that lasted about 30 Ma is recorded in the pre-Variscan rocks cropping out in the NE of Iberia. In this contribution we summarize their characteristics together with a comparison with the Ordovician magmatic episodes developed in the Iberian Massif and Sardinia (Fig. 1).

In the NE of Iberia (the Pyrenees and the Catalan Coastal Ranges) the Ordovician magmatic activity is relevant from the Early Ordovician to the Mid Ordovician (in a time span of 15 Ma, 480-465 Ma) and during the early Late Ordovician (460-455 Ma). A period of minor activity between the 465 to 460 Ma can be envisaged. The Early to Mid Ordovician magmatic activity gave rise to large bodies of aluminous granites ranging in thickness from 500 to 3000 m emplaced into the pre-Upper Ordovician metasedimentary sequence. They constitute the protoliths of the large orthogneissic bodies with laccolithic morphology that crop out at the core of dome-like massifs in the backbone of the Pyrenees (Aston-Ospitalet, Canigó, Roc de Frausa and Albera gneisses) and the Catalan Coastal Ranges (Guilleries gneiss). It should be noted that intermediate to basic coeval magmatic rocks have not been described and that no volcanic equivalents have been reported, except some subvolcanic rhyolitic rocks yielded similar ages than those of the main gneissic bodies. Granites exhibit calc-alkaline chemistry and volcanic arc affinity. The early Late Ordovician magmatic pulse originated a more varied suite of magmatic rocks. Small bodies of aluminous granites are emplaced in the pre-Upper Ordovician metasedimentary sequence of the Canigó and Guilleries massif, whereas coeval calk-alkaline volcanic rocks (ignimbrites, andesites, volcaniclastic rocks) are interbedded in the Upper Ordovician sequence in the Catalan Coastal Ranges (the Les Gavarres and Guilleries massifs) and in the Pyrenees (Canigó massif). Their isotopic signature indicates a crustal origin. Moreover, more basic terms (metaluminous bitotite and amphibolte granites and diorite bodies) originated from a mixture of juvenile and crustal melts are emplaced in the lower part of the pre-Upper Ordovician metasedimentary sequence. This early Late Ordovician magmatic event is coeval with normal fault development affecting the Upper Ordovician series, the basal unconformity, and the underlying pre-Upper Ordovician sediments. In the Pyrenees, an angular unconformity exists between the Upper Ordovician sediments and the underlying Early Paleozoic series, recently dated as Late Cambrian (Furongian) to Early Ordovician on the basis of acritarchs. This indicates the absence of Middle Ordovician strata and lends support to the Middle Ordovician age assigned to the deformation that could be responsible for the formation of this unconformity. The development of this Mid Ordovician deformation would be compatible with the period of lesser magmatic activity (465 to 460 Ma).

In the Iberian Massif, an important magmatic event took place over a comparable time span, 25 Ma. Main magmatic activity was concentrated in the Late Cambrian-Early Ordovician, from 495 to 483 Ma, and gave rise to voluminous calk-alkaline felsic volcanic rocks (Ollo de Sapo formation) and subsidiary aluminous granites. Magmatic activity can reach 475-470 Ma (San Sebastián and Antoñita granites) contemporaneously with the sedimentation of the Armorican quartzite over large areas of the Iberian Massif. No metamorphic or tectonic event has been described connected to this magmatic activity.

In Sardinia Ordovician magmatism extends from the Early to the Late Ordovician (485 to 455 Ma). Felsic calk-alkaline granites and volcanic rocks are abundant in the External Zone, the Nappe Zone and the Inner Zone. In the Inner Zone metabasites display Late Ordovician ages for their protoliths, slightly younger than most of the ages of the protoliths of the felsic magmatic rocks. In the External and the

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Nappe zones, magmatic rocks are located below and above the Sardic unconformity.

As a summary, the widespread Ordovician magmatic event exhibits similar characteristics in the three areas: 1) extends over a similar period (25 to 30 Ma), 2) originates voluminous felsic calk-alkaline aluminous magmatic rocks and 3) basic and alkaline terms are subordinate and younger than the main calk-alkaline felsic ones. However, some marked differences exist, namely the older age of the magmatism in the Iberian Massif. Following the interpretation proposed for this area, we suggest that this magmatism results from the melting of the Northern Gondwana continental crust. Melting was triggered by the break-up of the Northern Gondwana passive margin reflecting the opening of the Rheic Ocean and affected a recycled Neoproterozoic-Early Paleozoic continental crust with an important imprint of the Cadomian magmatism. Basic and alkaline terms would indicate the melting of a thinned crust or major mantle involvement at the later stages of the process. Older ages for the magmatism in the Iberian Massif suggest a diachronic, eastward directed, migration of the breaking-up process of this segment of Northern Gondwana. We discuss the role of the Middle Ordovician deformation in this extensional dominated setting and we also suggest that the boundary with the Ordovician active continental margin, documented by the intra-Alpine basement terrains, will be located further east.

Emplacement of the Barrabisa pluton (Corsica-Sardinia Batholith): What drives melting?

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The growth of the Corsica-Sardinia batholith (C-SB; 340-280 Ma, Cocherie *et al.*, 2005) overlaps most of the Variscan deformations and represents a key structure to unravel the feedbacks between partial melting, rheology and tectonics.

The beginning of anatexis in the Variscan crust of Sardinia has been precisely constrained at c.a. 345 Ma from the age of trondhjemitic leucosomes in metatexites (layered migmatites, Ferrara *et al.*, 1978). Structural and geochronologic evidences indicate that these early melts formed during the main phase of N-S shortening (Gerrei - Meana phase, Conti *et al.*, 2001) by muscovite dehydration melting of metatexites at low melting rates (5-15 % melt fraction). Subsequent anatexis at c.a. 320 Ma involved extensive biotite dehydration melting of an heterogeneous crust composed of metatexites and lower-middle Ordovician orthogneisses (Cruciani *et al.*, 2008). These younger melts, mostly coeval with the phase of regional transpression (Di Vincenzo *et al.*, 2004), sourced diatexites (melt fraction between 25-90 %) and narrow, dyke-shaped, peraluminous plutons emplaced within orogen-parallel shear zones such as Barrabisa and S. Maria (Fig. 1a). Late-Carboniferous anatexis involves therefore higher melt production rates, that can be explained in terms of: i) fats, nearly isothermal exhumation, or ii) increasing temperature during decompression. These two end-member models are discussed in relation with numerical experiments and petrologic constraints.

Barrabisa (320 ± 10 Ma, LA ICP-MS zircon age) is a strongly peraluminous granodiorite (Al_2O_3 > 13 wt.%, A/CNK ratio up to 1.12), with distinctive assemblages cordierite + biotite + k-feldspar ± garnet; andalusite is rarely present (Folco, 1991). Fragments of plastically deformed hornblende + plagioclase + quartz amphibolites are relatively common in the peripheral part of the pluton. Overall, the composition is intermediate between that of typical S- and I-type granitic melts. The Na_2O content in fact is slightly above 3.2 wt.% and FeO/(FeO + MgO) ratios vary between 0.50-0.65 wt.%. The trace elements composition decreases with decreasing maficity, and REE patterns are fractionated [$(Gd/Yb)_N$ = 3.84-2.53, $(La/Sm)_N$ = 4.80-4.23]. Emplacement pressures and temperature have been constrained from hornblende-plagioclase thermobarometry (Anderson and Smith 1995) and GASP barometry (calibration of Newton and Haselton. 1985). Results (Fig. 1b) suggest that andalusite-free assemblages formed around 0.37 ± 0.07 GPa; somewhat lower pressures (0.3 ± 0.06 GPa) have been calculated in presence of andalusite. The fabric seen in the field is characterized by a steep WNW-ESE foliation defined by preferred orientation of biotite ± muscovite. A sub-horizontal W-E or NW-SE stretching lineation is marked by incipient quartz ribbons. In thin section, both quartz and feldspars are plastically deformed. High temperature deformation of feldspar involving diffusion creep is indicated by smoothly sutured and indented quartz-feldspar contacts. Solid-state deformation fabrics are common in quartz ribbons, where most crystals display undulose extinction and large, optically visible subgrains, which identify a typical ‘chessboard’ pattern (T > 600°C). Plastic deformation of quartz is confirmed also by its strong crystallographic preferred orientation (CPO), consisting of a load maximum close to the magmatic lineation seen in the field, plus other light maxima widely dispersed within the foliation plane. AMS fabrics in Barrabisa and diatexites (melt fraction > 50 %) are almost flat with k1 direction oriented about W-E, roughly parallel to the elongation of the pluton. Metatexites and orthogneisses show instead a steep N-S fabric, consistent with the orientation of pre-320 Ma quartz and feldspar fabrics.

Origin of melts and emplacement model

Geochemical evidence suggests that layered migmatites, Barrabisa and younger plutons originated by dehydration melting of an heterogeneous crust. The structural record provided by magnetic fabrics and quartz, feldspar deforma-

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tion fabrics suggests that melts underwent horizontal flow. This interpretation is strengthened by the common occurrence of sub-horizontal melt pathways connecting diatexites to Barrabisa. All these observations rule out significant vertical migration of magmas and suggest nearly adiabatic conditions. Given the inferred PT path (Fig. 1b), the abrupt increase of melting rates at c.a. 320 Ma cannot be explained in terms of isothermal decompression alone. A localized temperature increment of 10-50°C is in fact required. The relation between HT-ductile shear zones, Barrabisa and similar plutons suggests that shear heating may be a viable mechanism to explain focused melting. The potential of shear heating is demonstratively evaluated by a simplified one-dimensional numerical model (Fig. 1c). Shear heating is modeled by adding up to 1 μW m^{-3} to the geotherm for depths relevant to ductile deformation (Burg & Gerya, 2005).We used a simplified three-layer crustal section with total thickness of about 50 km and typical heat production rates for the upper crust, middle crust and lower crust. Assuming the ductile shear zone is 1 to 3 km thick, deformation would have raised the temperature of some 40-100°C at a depth of about 16 km. This localized temperature increment can account for the observed increase of the melting rates during the growth of Barrabisa pluton.

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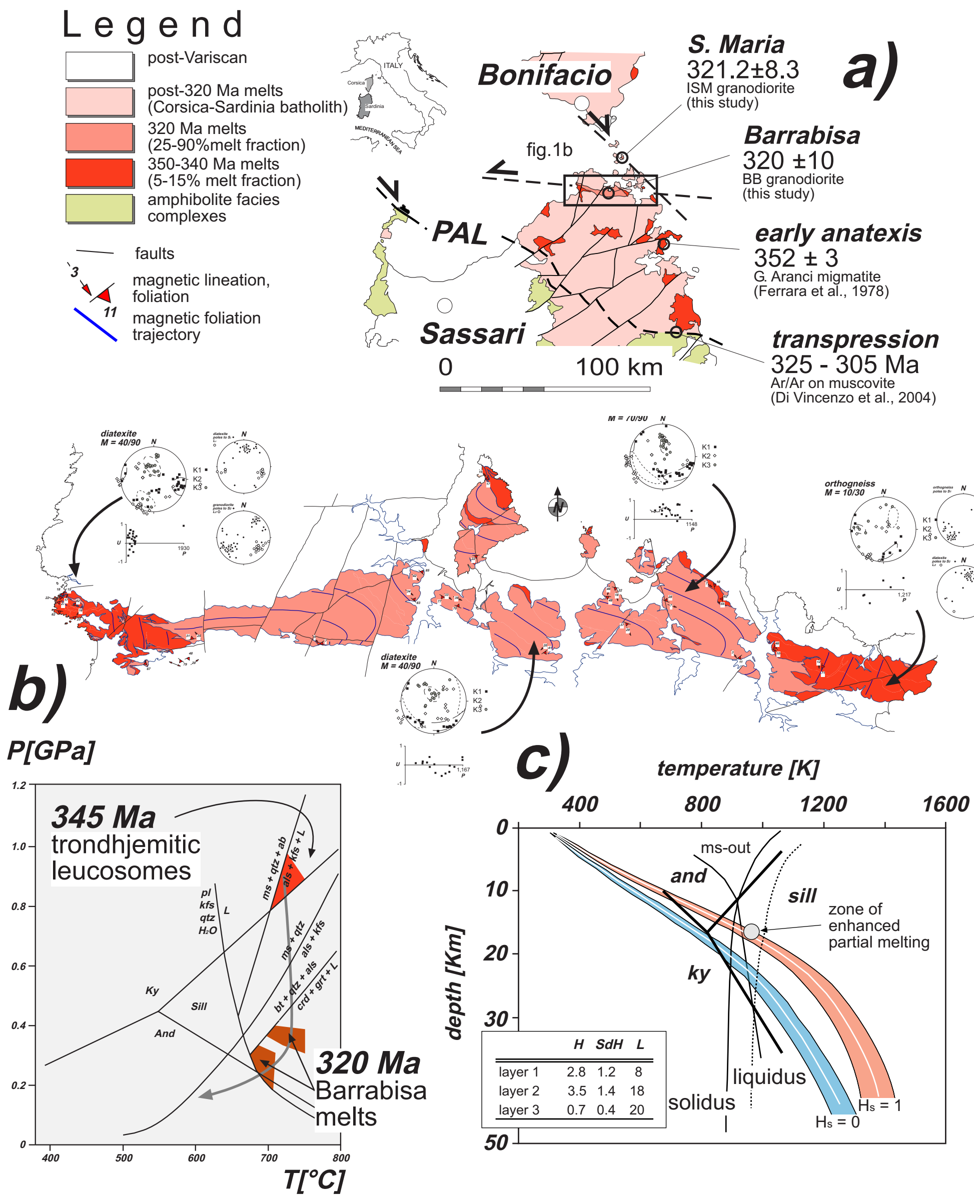

Fig. 1.- a) Geological-structural map of northern Sardinia and the Barrabisa pluton (bottom); the principal geochronologic constraints and major strike-slip shear zones are indicated (PAL refers to the Posada-Asinara Line, Carmignani et al., 1994); b) PT path; c) numerical model of the 320 Ma geotherm, model parameters are indicated in the box. Two different geotherms (white solid lines) along with their error bounds are shown: with contribution of shear heating (Hs = 1, red) and without (Hs = 0, blue).

The Rehamna metamorphic dome in the Morroco Variscide: a structural and $^{40}Ar/^{39}Ar$ geochronological study

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The Rehamna massif is the only place in the Morocco Meseta where the variscan orogenic root is partly exhumed. Its timing and mode of formation remains highly debated. In a form of an intracontinental metamorphic dome surrounded by weakly deformed and unmetamorphosed supracrustal units, its core presents amphibolite facies rocks pervasively deformed. In this study, are presented the structural pattern of the dome and the timing of its growth, in conjunction with syn- to late- variscan magmatism. According to this structural and $^{40}Ar/^{39}Ar$ geochronological study, a new tectonic model is proposed for this part of the orogen. The first tectonometamorphic record is a SSW vergent nappe stacking. In the core of the dome, it is expressed by top-to-the-south intense shearing in subhorizontal fabrics associated with southward increase of the barrowian metamorphism, where it can reach the Std ± Ky stability field within early Cambrian to Devono-Carboniferous metasedimentary rocks (Central and Eastern Rehamna). Dated at 305-295 Ma, the continuous shearing and associated shortening permits the large scale folding of the newly developed S1 metamorphic foliation: an ~ E-W trending elongated domal/anticline structure is progressively developed throughout the whole infrastructure of the massif, even forming subvertical chevron fold in its oriental part (*Lalla Tittaf* fm.). It is probably responsible for the extrusion of the core of the dome against more supracrustal units. Here, this SSW directed shortening is also well visible, developing an originally ~ E-W trending anticline of Lower Palaeozoic sediments (known as the Koudiat el Adam anticline). Then, an WNW-ESE shortening is responsible for heterogeneous deformation orthogonal to the previous metamorphic dome axis. In the Central Rehamna, this superposition is marked by the development of a circular subdome (*Sidi Ali dome*), the folding of isogrades and development of subvertical clivage for which the intensity increases in front of the westward rigid Cambrian coastal block. More easterly, in the deeper part of the Eastern Rehamna, the Devono-Carboniferous metasedimentary rocks (*Lalla Tittaf* and *Ouled Hassine* fm.) experienced heterogeneous reworking marked by localized NNE-SSW subvertical to moderaly dipping clivage. Associated metamorphic fabrics ages range between 280-290 Ma which is similar to syn-tectonic intrusion dated at 285 Ma (Rais el Biod granite). During this event, the supracrustal rocks show important deformation gradient, with only curvature of the Koudiat el Adam anticline and increase of the deformation toward the westward coastal block (Skhour massif). Post-variscan magmatism is finally dated at ~ 275 Ma (*Sebt de Brikiine granite*).

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Structure and development of a mantled gneiss dome within a continental wedge: (Sudetes, European Variscan belt)

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The contribution of lateral forces, vertical load, gravity redistribution and erosion to the origin of mantled gneiss domes in internal zones of orogens remains debated. In the Orlica−Śnieżnik dome (Sudetes, Moldanubian zone of the European Variscan belt), the tectono-metamorphic history is initially characterized by the development of subhorizontal fabrics associated with prograde metamorphism reaching medium- to high-grade conditions in different levels of the crust. It may reflect the eastward downgoing influx and orogenic parallel flow of a Saxothuringian-type passive margin sequence below a basic Teplá-Barrandian upper plate. The ongoing influx of continental crust creates a thick felsic orogenic root with HP rocks and migmatitic orthogneiss. Continuous accumulation of felsic material in the orogenic wedge and its indentation by the eastern Brunia microcontinent produces the growth of the dome and its multiscale folding. The resulting kilometre-scale folding is associated with the variable burial of the middle crust in synforms and the exhumation of the lower crust in antiforms (subdomes) within the infrastructure. These localized vertical exchanges of material and heat are coeval with a larger crustal-scale folding of the whole infrastructure generating a general uplift of the dome. It is exemplified by increasing metamorphic conditions and younging of $^{40}Ar/^{39}Ar$ cooling ages toward the extruded hot migmatitic subdomes cored by HP granulites rocks. The vertical growth of the dome induces exhumation by localized pure shear-dominated ductile thinning laterally evolving to non-coaxial detachment faulting, while erosion feeds the surrounding sedimentary basins (Intra Sudedic basin, Culm). Modelling of the Bouguer anomaly grid is compatible with crustal-scale mass transfers and decoupling between a dense superstructure and a lighter felsic infrastructure. The model implies that the Moldanubian Orlica-Śnieżnik mantled gneiss dome derives from polyphase recycling of Saxothuringian material.

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Metamorphic characteristics in the Eastern part of the Pallaresa massif and their relationships with the variscan deformation events. Axial Zone of the Pyrenees (NW Andorra)

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The Pallaresa massif is a large E-W trend antiformal structure which is included in the metamorphic structural units of the Pyrenean Axial Zone. These units are characterized by metamorphism ranges from low to high grade and different generations of folds and pervasive cleavages accompanied by subordinate thrusting.

Pre-Caradocian rocks outcropping in the eastern part of Pallaresa massif consists of a monotonous alternation of quartzites and slates with some intercalations of limestone or microconglomerate that mainly shows low metamorphic grade. However, close to the Aston and Hospitalet domes, in the vicinity of some igneous intrusions, the metamorphism may reach high grade conditions.

Two variscan deformation events have been recognized in this sector: a) D1 event, which is characterized by E-W trending and north-verging inclined or recumbent folds with an associated foliation (S1) that can be observed at all scales. The S1 foliation has a sub-horizontal orientation, and is the main foliation in the northern and central parts of the study area. b) D2 deformation event, distinguished by the development of E-W trending, upright folds, of centimetric to metric scale. These folds are associated with a steep and rough crenulation cleavage (S2) in the southern part of the study area (Fig. 1).

As regards to metamorphic characteristics, biotite porphyroblasts appears growing coevaly with S1 to southwest of the study area (Fig. 1A). This indicates that the development of S1 ocurred under low metamorphic grade conditions. To the north and to the east, close to Aston and Hospitalet gneiss domes, syn- and post-tectonic growths of andalusite porphyroblasts and syn-tectonic growths of staurolite relatively to S1 are observed (Fig. 1B, C). Therefore, in these points, the S1 cleavage has developed under medium or even in high metamorphic grade conditions. The different variscan structures in the study area and the existing relationships between them suggest that S1 is a tectonic foliation formed in the earlier deformation stages. However, the textural observations allowed us to infer that it continued its development during the last stages of the D1 variscan deformation.

In recent studies carried out in neighbouring areas by other authors, different sequences of tectonic, metamorphic and plutonic events have been proposed: i) the early development during variscan deformation for flat-lying foliations in both schist and orthogneiss. These foliations pre-date the uplift of the gneiss core which began during N-S compression and continued in a dextral transpressional phase. A similar sequence was proposed for the Bossòst dome; ii) the development of flat-lying and steep foliations coevall with the main LP-HT metamorphic event and with the emplacement of peraluminous granites during a syn-convergence extensional phase.

On the basis of the results obtained in this work about the relation of deformational events with metamorphism, we can suggest that S1 could have undergone flattening together with the development of some porphyroblasts growing under high temperature and low to medium pressure metamorphic conditions. This event could be related to a local extensional episode, post-D1 and pre-D2 coeval with the intrusion of igneous rocks. This schema could be similar to the first sequence proposed for this sector and the Bossòst dome by other authors. However, since no evidences of extensional deformation have been found away from the igneous intrusions, an overall extensional phase cannot be evoked at the moment.

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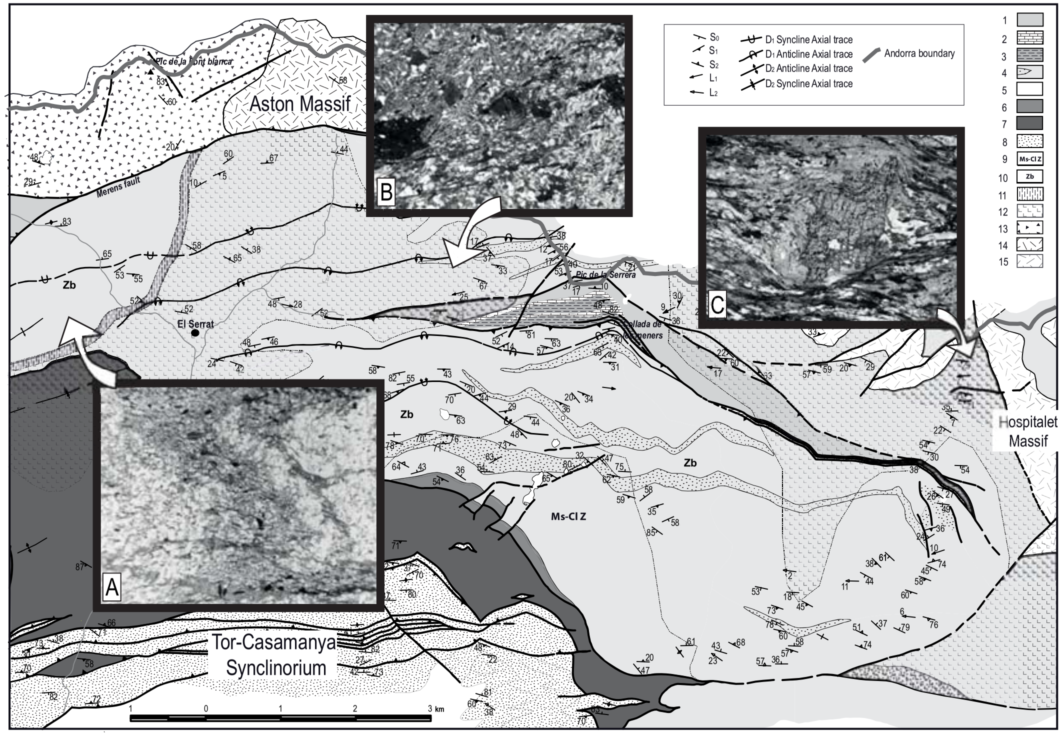

Fig. 1.- Geological map of the eastern part of the Pallaresa massif and location of A, B and C samples. A sample: S1 referred to axial planar foliations defined by preferred orientation of biotite and micas parallel to the axial plane of fold; B sample: post-tectonic andalusite prophyroblast overgrows the previous structure; C sample: staurolite porphyroblast that is syntectonic with respect to D1. Legend: (1) Alos de Isil formation (Lower Cambrian age); (2) white limestone (Lleret - Bayau formation, Lower Cambrian age); (3) black slate (Lleret - Bayau formation, Lower Cambrian age); (4) Alins formation (Lower Cambrian age); (5) undifferentiated Cambro – Ordovician rocks; (6) Upper Ordovician materials; (7) Silurian black slates; (8) Devonian slates and limestone; (9) Muscovite - Chlorite zone; (10) Biotite zone; (11) Garnet zone; (12) Andalucite zone; (13) Sillimanite zone; (14) Aston massif Migmatites; Hospitalet massif gneiss (15).

The Variscan basement of the Riu Ollastu area (Sarrabus, SE Sardinia, Italy)

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Introduction

The studied area is part of the Sarrabus unit (fig. 1A), the shallower tectonic unit of the nappes stack of the Variscan basement of central and southern Sardinia (CARMIGNANI *et al.*, 1994). Up to now, the siliciclastic succession which crops out diffusely in the Riu Ollastu area, has been ascribed to the *Pala Manna fm*, (Lower Carboniferous), interpreted as syn-orogenic foredeep deposit of the Variscan chain (Barca, 1991). The blocks constitued by *Porfidi Grigi del Sarrabus* and *Scisti a Graptoliti*, isolated within the siliciclastic succession, have been interpreted as olistolites. This stratigraphic interpretation has been put into question for paleontological studies which have assigned an Arenigian age to the most part of the siliciclastic succession (Pillola & Leone, 1997; Gnoli & Pillola, 2002; Pillola & Piras, 2003). In this abstract we present new stratigraphic and structural interpretation of the Variscan basement of the *Riu Ollastu* area.

Stratigraphy

The new paleontological ages allow to ascribe the siliciclastic succession of the *Riu Ollastu* area to the *Arenarie di San Vito*, Middle Cambrian-Lower Ordovician in age (Calvino, 1959), constituted by metasandstones, phyllites and quartzites, which we have distinguished in two informal members: *Costa Moddizzi* member, characterized by rare sedimentary structures, and *Riu is Istrias* member (Fig.1 B), characterized by flute-cast, HCS, parallel and cross-bedding structures. The succession continues with the Middle-Upper Ordovician volcano-sedimentary succession, which lies unconformable over the *Arenarie di San Vito* ("Sarrabese unconformity" by Calvino, 1959), constituted by *Metaconglomerati di Muravera* Formation (Fig. 1C) (Carmignani *et al.*, 2001), characterized by metaconglomerates which crop out discontinuously, and *Porfidi Grigi del Sarrabus* (Calvino, 1956), characterized by metarhyolites. Two lithologies, of uncertain ages, have been detected: basaltic rocks showing pillow structures, which can be ascribed to *Monte Santa Vittoria* formation of the Middle Ordovician age (Carmignani *et al.*, 2001), and volcanites, with possible rhyolitic composition, which can be ascribed or to *Monte Santa Vittoria* formation or to *Metavulcaniti del Minderri* of the Arenigian age (Oggiano *et al.*, 2010).

Always in tectonic contact with other formations, the *Scisti a Graptoliti* formation crops out, characterized by black shales and lidites of the Silurian age (Barca & Jäger, 1989).

Structural setting

In the *Riu Ollastu* area crop out isoclinal folds (Fig. 1D) and thrusts, which delimit tectonic slivers formed mainly by *Scisti a Graptoliti*. Isoclinal folds are recognizable in both the Ordovician succession and tectonic slivers, showing W-facing. The development of thrust and isoclinal folds is attributable to E-W shortening deformation phase. The large antiform (Fig. 1E) which refold both the isoclinal folds and thrusts is attributable to later Variscan folding event, also recognizable at the outcrop scale, showing changes in the fold axial directions, roughly oriented NW-SE and NE-SW. A late faulting event, characterized by high-angle normal faults (Fig. 1F) oriented roughly NW-SE and NE-SW, is expression of the post-collisional extensional tectonic. The occurrence of a folding event affecting only the Lower Ordovician succession is suggested by two evidences: i) the *Metaconglomerati di Muravera formation* unconformable lies above the overturned limb of an isoclinal fold that deformed the *Arenarie di San Vito*; ii) the axes in the post-unconformity succession trend roughly N-S, whereas those in the pre-unconfomity succession there are axes trending both E-W and N-S (Cocco & Funedda, 2011). In addition to this, the *Metaconglomerati di Muravera* unconformable rests above both the *Costa Moddizzi* and *Riu is Istrias* members. Thus a pre-Middle Ordovician folding event could be inferred.

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Conclusions

A detailed geological field mapping has allowed obtaining new data on the Variscan basement of the Riu Ollastu area. In the studied area, the absence of *Punta Serpeddì* and *Tuviois* formations of the Upper Ordovician age (Barca & Di Gregorio, 1979), always present in the classic stratigraphic succession of the *Sarrabus* unit, has been explained as stratigraphic gap between Lower-Middle Ordovician and Llandovery (Pillola & Leone, 1997), but, during the field mapping, no stratigraphic contact between *Scisti a Graptoliti* and other formations has been found. The different structures recognized in the studied area can be related to deformation phases described for the Variscan tectonic evolution of central-southern Sardinia (Conti *et al.*, 2001): isoclinal folds and thrusts occurred during the *Sarrabus* phase, large antiform occurred during the *Flumendosa* phase and the system of normal faults occurred during the *Riu Gruppa* phase. The occurrence of a folding event which affects just the pre Middle Ordovician succession is here clearly reported for the first time and it can be responsible, at the regional scale, for the great thickness which this formation presents and for the "*Sarrabese* unconformity".

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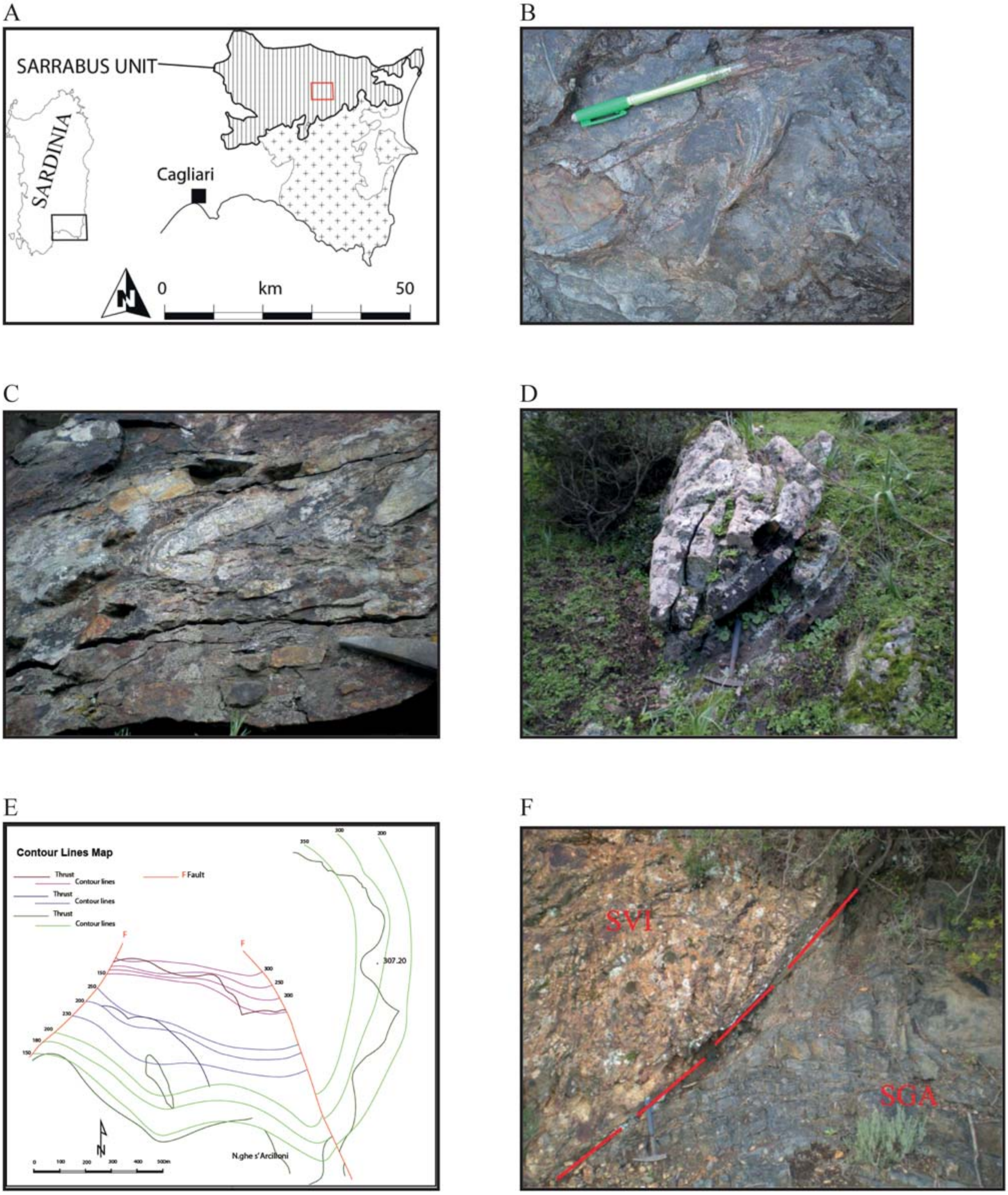

Fig. 1-A.- location of the studied area; B: Phycodes circinatum indicating an overturned limb in the Riu is Istrias member; C: Metaconglomerati di Muravera Formation; D: isoclinal fold in the Scisti a Graptoliti formation; E: contour lines map showing the large antiform which refold the thrusts; F: normal fault between Arenarie di San Vito (SVI) and Scisti a Graptoliti formation.

Global warming of the mantle at the origin of flood basalts over supercontinents: implications from Pangea breakup

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Throughout its history, the Earth has experienced global magmatic events that correlate with the formation of supercontinents. This suggests that the distribution of continents at the Earth's surface is fundamental in regulating mantle temperature. The aggregation of continents impacts on the temperature and flow of the underlying mantle through thermal insulation and enlargement of the convection wavelength. Both processes tend to increase the temperature below the continental lithosphere, eventually triggering melting events without the involvement of hot plumes.

The breakup of Pangea, the last supercontinent, was accompanied by the emplacement of the largest known continental flood basalt, the Central Atlantic Magmatic Province, which caused massive extinctions at the Triassic-Jurassic boundary. Several other massive magmatic events occured during the break up history.

I will present numerical simulations of mantle convection with complex rheologies and continental rafts. They show how the temperature evolves through aggregation and dispersal, and how thermal properties depend on the configuration of continents. I will then discuss the thermal evolution of the continents during the break up of Pangea.

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Late collisional exhumation of the lower crust in a transpressive environment: insight of the Maures-Tanneron massif (SE France)

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The Maures-Tanneron massif (MTM) constitutes one of the southernmost segments of the Variscan belt in France located near the Mediterranean Sea. This segment of Paleozoic crust is mainly composed of highgrade metamorphic rocks intruded by Carboniferous granitoids. Two main domains representing different crustal levels can be distinguished:

- the eastern domain is representative of a deep-crustal level, marked by granulite/amphibolite facies metamorphism, associated with pervasive melting and granitic intrusions;

- the western domain preserves a prograde Barrovian metamorphic sequence, ranging from chlorite-muscovite schists in the west to staurolite, kyanite and sillimanite bearing schists in the east.

The tectono-metamorphic evolution of the MTM can be summarized as follow:

(1) A first phase of subduction (D1) is marked by isoclinal folding and HP–HT metamorphism represented by eclogite relicts [Bard *et al.*, 1981; Bellot, 2005; Schneider *et al.*, in prep.]. Geochronological investigations suggest that the high-pressure metamorphism occurred at ca. 430 Ma (U-Pb zircon in eclogite [Moussavou, 1998]; U-Pb monazite in orthogneiss [Demoux *et al.*, 2008]).

(2) A second phase related to collision (D2) is characterized by SE-directed ductile thrusting and isoclinal folding well preserved in the western domain. MP-MT Barrovian regional metamorphism developed during the nappe-stacking process. This stage probably occurred between 350 and 330 Ma (U-Pb zircon age on intrusives [Moussavou, 1998]; U-Pb monazite in migmatitic orthogneiss [Demoux *et al.*, 2008]).

(3) A third phase of denudation (D3), is marked in the western domain by the development of main normal ductile shear zones that accommodate NW-SE extension [Bellot *et al.*, 2002]. Whereas in the eastern domain orogen-parallel shearing results of crustal-scale ductile dextral strike-slip shear zones and large-scale north-south trending concentric folds [Rolland *et al.*, 2009; Corsini *et al.*, 2010]. Intracontinental Carboniferous basins developed along the major shear zones [Onezime *et al.*, 1999; Morillon *et al.*, 2000] coeval to syn-kinematic granitic intrusion in the core of anticlines [Demoux *et al.*, 2008; Corsini *et al.*, 2010]. LP-HT regional metamorphism is associated with the growth of migmatitic domes. $^{40}Ar/^{39}Ar$ geochronological data revealed a cooling history from 330 to 300 Ma [Buscail, 2000; Morillon *et al.*, 2000; Corsini *et al.*, 2010].

Thus, following crustal thickening, post-collisional exhumation is accommodated in the MTM during late Carboniferous (1) by ductile strike-slip faults associated with regional folding, doming and anatexis in the eastern domain and (2) normal ductile faulting in the western domain. Exhumation of the orogenic lower crust is contemporaneous with E-W shortening in a transpressive context, where dome structures exhume partially-molten crust in a convergent setting.

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Sedimentary structures and geochemistry in low grade sandstones from NE Sardinia: insights into the depositional paleoenvironment

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A detailed geological survey in NE Sardinia led to the discovery of small areas in which the primary sedimentary features of the pre-Variscan sedimentary sequences are still recognizable in spite of the remarkable overprint of the Variscan metamorphism. These features can be observed in a 7.5m-thick yellowish metasandstone sequence outcropping at Sa Parma locality, a few kms south of the Lula village.

The Lula sequence outcrops in the northernmost areas of the Internal Nappe Zone just near the southern border of the Axial Zone of the Variscan Sardinian chain.

The metasandstones underwent the polyphased Variscan metamorphism that characterizes the whole area. Three main deformation phases (D_1, D_2, D_3) were distinguished. The D_1 phase generated isoclinal folds with a penetrative axial plane schistosity S_1. The D_2 phase gave origin to E-W trending open folds and to a strain-slip S_2 schistosity. Moving northwards the D_2 folds change into northwards recumbent tight isoclinal folds whose southwards dipping S_2 schistosity almost completely cancelled the D_1 structural features. The D_3 phase produced N-S trending chevron, box or kink folds locally prsesenting strain-slip or fracture cleavage. The age of the protolith of the Lula metasediments is unknown, but the most probable age is that obtained by Helbing (2005) for the metavolcanics (474 ± 13 Ma) known in literature as “Porphyroids”,often associated or interbedded within metasediments very similar to those of the Lula sequence.

The studied section, well exposed along the SP38 road is cut on a decametric fold hinge. In this section more than 45 sequences were identified. Each sequence represents a single high- to middle-energy depositional event. Each event starts with the deposition of a basal quartz-rich microconglomeratic layer followed by deposition of sands. Fining-upward grading is locally still recognizable. The variable thickness of the sequences (35 to less than 2 cm) may be attributed to both, the extent of the depositional event and the intensity of the tectonic deformation. Different depositional mechanisms could be related to variable fluid characteristics and to changing fluid-sediment mixture rate of flow. The typical depositional sequences that were recognized are: A) sandy massive sequence; B) sandy massive to plane-parallel laminated sequence; C) pebbly to sandy fining-upward sequence with basal lag; D) microconglomeratic sequence without significant gradation. Trend as thinning- and thickening-upwards were also observed. The depositional environment of this prevalently sandy unit could be located in a deeper area flanking a shallower one representing the provenance area of the high- to medium-energy events. The thickening- to thinning-upwards trend of the observed sequences may be tentatively interpreted as a backward to forward migration of the depositional areas with respect to the shoreline reflecting increasing to decreasing mean depositional energy, respectively.

Yellowish metasandstones mainly consisting of quartz, albite, biotite, muscovite, and chlorite. Accessory minerals are epidote, apatite, tourmaline, titanite, ilmenite and Fe-Ti-oxides. Two foliations have been recognized: S_1 is preserved in microlithons whereas S_2, roughly subparallel to the compositional layering, is marked by the alignment of phyllosilicates. Microconglomerates contain rounded or elongated, 2-2.5 mm-sized quartz pebbles embedded in a moderately oriented matrix consisting of quartz, albite, biotite, muscovite, chlorite, and minor epidote and Fe-Ti oxides.

The metapelites, showing a variable amount of a sandy graywacke component, are made up of quartz, albite, muscovite, chlorite, ± biotite oriented as S_1 schistosity. Accessory minerals include epidote, apatite, tourmaline, titanite, ilmenite and Fe-Ti oxides. The distinctive feature of the metapelites is the presence of 1-2 mm-sized flattened albite porphyroblasts showing inclusions of titanite, epidote, apatite, and rare zircon. The albite porphyroblasts predate the S_2 schistosity. Layers with high albite/phyllosilicate ratio

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alternate with layers with lower albite/phyllosilicate ratio. The thickness of these layers is variable from a few millimetres to 1 cm. The layers with high content of albite porphyroblasts resemble an augen-type structure.

In the K_2O/Na_2O *vs.* SiO_2/Al_2O_3 diagram (Wimmenauer, 1984) the yellowish metasandstones plot in the greywacke field, with a few samples in the field of pelitic graywackes.

The metasandstones show LREE enrichment, negative Eu anomalies and flat HREE pattern. These features suggest a derivation of the sedimentary material from an old upper continental crust mainly consisting of felsic rocks.

In the diagram $Al_2O_3/(Al_2O_3 + Fe_2O_3)$ *vs.* Fe_2O_3/TiO_2 all the Lula samples plot in the continental margin setting of Murray (1994) and more precisely in the old upper continental crust provenance subfield The continental margin provenance is corroborated by the Th-Co-Zr/10 diagram (Bathia and Crook, 1986). These results confirms that the sedimentary materials were supplied by dismantling of an older active continental margin or island arc.

The CIA (Chemical Index of Alteration) values for the Lula rocks are intermediate between those typical of no alteration (CIA < 50) and those indicatig intensive alteration (CIA > 70). The higher CIA values of the metapelites (61-76) indicate higher amounts of the clay fraction (higher Al_2O_3, lower SiO_2 contents) and/or a more pronounced alteration of the sedimentary material. The lower CIA values (59-68) of the yellowish metasandstones may be attributed to more frequent sand-rich layers and/or to the supply of less altered sedimentary materials in comparison with the metapelites. A confirmation of the different behaviour of the two lithotypes is given by the A-CN-K diagram (Nesbitt and Young, 1982). This diagram shows a gradual transition of the Lula samples from an area near the feldspar join and the A-CN side, near to or coincident with the average shale field as defined by Rashid (2005) and close to the opposite side A-K. This distribution parallel and similar to the weathering trend as defined by Barbera *et al.* (2006) suggests a growing intensity of weathering of the source rocks or an increasing content of the clay component from the yellowish metasandstones to the metapelites, confirming the information supplied by the CIA values.

Another interesting parameter is the Th/U ratio. An increasing intensity of weathering lead to a gradual increase of the Th/U from values of 4-5 in the fresh samples to values as high as 16-20 in the most altered samples. In the Lula samples 6 out of 7 metapelites have Th/U values in the range 4.95-9.82, 4 out of 8 yellowish metasandstones fall in the range 5.35-7.05.

The different proportion of the sandy and clayey components in metasandstones and metapelites is well highlighted by a geochemical comparison between the two lithotypes. With respect to metapelites the metasandstones reveal slightly higher contents in SiO_2, Zr, Hf, strong enrichment in Na_2O, slightly lower contents in Al_2O_3, Fe_2O_3, Ba, Rb, Cs, and strong depletion in K_2O. Both groups show very similar contents for all other major and trace elements. The above described differences suggest that the metasandstones are characterized by a prevalence of a sandy component rich in detrital heavy minerals. The relatively high Na_2O contents of the metasandstones could be attributed to a possible more or less intense albitization process or alternatively to supply of detrital albitic material produced by the dismantling of the older albitite layers. In this comparison, on the contrary, the metapelites show larger amounts of K- and Al-rich clay minerals.

Several geochemical parameters suggest that the sedimentary environment was characterized by oxidizing conditions for both groups of metasediments and also for the metavolcanics, in the case of reworking. According to Nagarajan *et al.* (2007), U/Th < 1.25, V/Cr < 2, Ni/Co < 5 and Cu/Zn in the range 0.08-0.66 indicate oxidizing conditions. All the Lula rocks have U/Th in the range 0.10-0.28, V/Cr mainly in the range 0.99-1.50, Ni/Co in the range 1.62-3.85, Cu/Zn in the range 0.11-0.66. Oxidizing environment, according to Rashid (2005), produces high SREE and negative Eu anomalies: both these features chracterize the Lula samples. The oxidizing conditions characterize only the yellowish metasandstones, while reducing conditions are clearly recognizable for graphitic metapelites forming sporadic layers interbedded within the sequence.

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Late Ordovician magmatism in the Monte Grighini Unit of the Nappe Zone, central-western Sardinia: insights from U-Pb zircon age

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Southern and central Sardinia corresponds to the External and Nappe Zones of the Variscan Sardinian chain, respectively. The external units of the Nappe Zone are characterized by distinctive volcanic and volcanoclastic successions of Middle Ordovician age representing the witness of Lower Paleozoic calc-alkaline magmatism developed at the northern Gondwana margin. These metavolcanics have been studied in detail in the uppermost external units (*i.e.* Sarrabus Unit and Gerrei Unit) where they are sandwiched between the Sardic unconformity at the base and the Upper Ordovician (Caradocian) transgressive deposits at the top. The Monte Grighini Complex crops out at the northwestern margin of the Flumendosa Antiform and consists, from bottom to top, of the Monte Grighini Unit, the Castello di Medusa Unit and the Gerrei Unit (fig. 1a). The Monte Grighini Unit consists of medium- to high-grade metamorphic rocks that were intruded during late Carboniferous (303-298 Ma) by granitoids spanning in composition from tonalite to leucogranite. The emplacement of the granitoids was synchronous with the activity of a wide dextral strike-slip fault known as the Monte Grighini shear zone. The metamorphic rocks of the Mt. Grighini Unit belong to two main formations, namely the Truzzula Formation (Fm) and the Toccori Fm. The Truzzulla Fm, cropping out in the central part of the Monte Grighini Unit and is a sequence of metavolcanics, metarkoses, metaepiclastite, metapsammopelite, quarzite and minor metapelite. The Toccori Fm manly consists of a sequence of phyllites and schists with intercalated centimeter- to decimeter-thick metasandstone. In the upper portion, thin layers of black graphitic schist and marble occur within the schist. Country rocks of the granitoids show evidence of a thermal metamorphic overprint. Besides, both the granitoids and the adjacent rocks show intense mylonitic deformations. In order to constrain the protolith age of the Monte Grighini Unit, two samples of Truzzulla Fm (G61 and G63) were considered for U-Pb geochronology. Samples G61 and G63 consist of Qtz + Kfs + Pl + Bt + Ms ± Chl. Accessory minerals are: zircon, monazite, apatite and Fe-oxide. Modal amount of K-feldspar is 25-30 vol%, quartz 40-45 vol%, phyllosilicate 15-20 vol% and Plagioclase <5 vol%. Both samples show igneous K-feldspar relicts (up to 1.5 mm in size) surrounded by a fine-grained, schistose matrix made up of phyllosilicates and quartz. Two schistosity (S1 and S2) are well recognisable in the field and at the microscopic scale. Locally, the samples show intense milonytization. K-feldspar is microcline and plagioclase is albite in composition (Ab 92-94). Phyllosilicate mainly consist of celadonite-poor white mica (Si ~ 6.1 a.p.f.u.), biotite (X^{Mg}: 0.36-0.40) and subordinate chlorite (X_{Mg} ~ 0.41). Samples G61 and G63 show the following chemical composition: SiO_2 = 61.43-69.21 (wt%), Al_2O_3 = 16.72-18.12, Fe_2O_{3tot} = 3.33-6.33, K_2O = 7.80-9.07, Na_2O = 0.14-0.43, MgO = 0.34-1.39. Zircons from the two samples were separated with conventional methods, characterized for internal structure by catodoluminescence and dated by laser ablation (LA)-ICP-MS consisting of a sector field ICP-MS coupled with an ArF 193 nm excimer laser microprobe. Zircons, ranging from 50 up to 150 µm in size, are mostly prismatic. Inner inherited cores with very low luminescence and overgrowths with a ghost oscillatory zoning were recognized. Occasionally, a very bright external rim of a few microns in thickness is also observed. Analyses were carried out on the different domains with the exception of the outer rim. A total of 35 analyses were carried out on 29 zircons in samples G63 and 25 data yield concordant ages. They span between 419 ± 5 and 665 ± 8 Ma with two poorly discriminated major clusters at about 430 and 450 Ma. Few zircons yield Neoproterozoic ages with a minor cluster at about 615 Ma. In sample G61, 30 zircons were analyzed for a total of 34 analyses. 28 data yield concordant ages that span between 431 ± 7 and 665 ± 11 Ma with a major cluster in the Late Ordovician at about 450 Ma. Few zircons yield early Ordovician (at about 480 Ma) and Neoproterozoic ages. The clustered ages of 454 Ma indicate that the metaepiclastite of the Truzzulla Formation derive from a sequence of late Ordovician volcanics and volcanoclastic deposits. Alternatively, the clustered ages of 430 Ma might be explained with a lead

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loss during the regional or late Variscan HT/LP contact metamorphism related to the granitoid intrusion. Two major implications arise from these data. Firstly, in the deepest units of the external Nappe Zone the lower Paleozoic magmatism is well recorded by volcanic and volcanoclastic deposits. The majority of radiometric ages are in the late Ordovician (450 Ma; Caradocian) and thus slightly more recent with respect to those (465 Ma) obtained in the volcanic rocks of uppermost units (Porfidi Grigi Fm of Sarrabus Unit; Oggiano *et al.*, 2010). Similar late Ordovician ages are reported for volcanic and intrusive rocks in the Maures-Tanneron Massif and External Crystalline Massifs of Western Alps (Demoux *et al.*, 2008; Rubatto *et al.*, 2001). Secondly, the Late Ordovician age of Truzzulla Fm as well as field evidence that the metapelites of Toccori Fm are the cover sequence of volcanic/volcaniclastic rocks sequence, allow us to definitely disregard the previous suggestion of a Precambrian basement in the Mt. Grighini Unit.

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Emplacement of late-Variscan granitoids and their relationships with post-collisional phases: examples from Arburese igneous complex (SW Sardinia, Italy)

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The Variscan Batholith of Sardinia results from the coalescence of many calc-alkaline plutons dominated by monzogranites, leucogranites, and subordinately granodiorites; both metaluminous and peraluminous rocks coexist in some plutons. Gabbroic rocks and tonalites are very scarce. Cognate dark enclaves are quite common in the granodioritic terms, being rare or absent in the felsic varieties (Ghezzo *et al.*, 1972; Bralia *et al.*, 1982). The Batholith cuts across the whole metamorphic basement, from the high-grade (mainly migmatitic) axial zone to the more external part of the Nappe zone and Foreland (Carmignani *et al.*, 1994 and references therein).

The timing of magmatic activity, recently improved on the basis of U/Pb and Ar/Ar geochronology, is bracketed in the range of 321-285 Ma (Oggiano *et al.*, 2007; Gaggero *et al.*, 2007 and references therein). Despite such improvement, the knowledge of the Sardinia Batholith is still incomplete because of large areas, especially localized in the southern part of Sardinia chain, lack a detailed geological and structural field mapping. At the present time it rise up a different chronological evolution between plutons localized in the different part of Sardinia. In the axial zone, oldest intrusives are represented by small bodies of foliated strongly peraluminous granodiorites and leucogranites, as for example the S. Maria intrusion, in the northernmost side of the Island (Oggiano *et al.*, 2007) dated to 321 ± 8 Ma by U/Pb LA ICP-MS on zircon. Pre-300 Ma calc-alkaline plutons are dominated by monzogranites (Oggiano *et al.*, 2005 and references therein); between 300 and 285 Ma, granodiorites increase. It should be underlined that field relationships coupled to recent geochronological data highlighted that most mafic gabbro-tonalitic sequences, previously inferred to be the earliest intrusions (Bralia *et al.*, 1982 and references), emplaced at about 285 Ma (Gaggero *et al.*, 2007), almost coeval with the end of Batholith assembly and early Permian sedimentation.

Plutons occurring in the Nappe and more external zone show a contrasting geological evolution. In the relatively mafic sequences, gabbroic rocks represent small bodies earlier or contemporaneous with associated rocks (Secchi *et al.*, 1991; Brotzu *et al.*, 1993). Leucogranites instead represent the younger bodies. In addition, the structural and also petrological picture is complicated by the occurrence of monzosyenitic sequences and fayalite-bearing granites documented in the Sarrabus and Ogliastra area (SE Sardinia; Pirinu *et al.*, 1996; Secchi & Lorrai, 2001).

A good example of a composite igneous complex emplaced in the more external zone of Sardinia chain, characterized by continuous and well exposed sharp contacts with the metamorphic basement, is represented by the Arburese pluton (SW Sardinia; Fig. 1). The main geological features and Rb/Sr geochronological data were reported by Secchi *et al.* (1991). According to these authors, the pluton (about 70 km square) emplaced at very shallow crustal levels within a W-directed thrust separating the allochtonous pile of greenschist units from the para-autochtonous Foreland. Shallow crustal levels (in the range of 3-6 km) are constrained by: i) the common occurrence of a quite minute grain size, ii) the development of a narrow contact aureole dominated by andalusite, and iii) by Al-in hornblende barometry (Anderson & Smith, 1995). The architecture of the pluton is schematically drawn by a core of cordierite-bearing leucogranites (LG) and 3 granodioritic terms characterized by different degree of magmatic evolution (named GD1, GD2 and GD3) that represent the outer zone. Field relationships suggest that leucocratic terms post-date the granodiorites. A small monzograbbroic rock-unit (MG) is recognized in the northern border zone. Rb/Sr published isochrones indicate undistinguishable ages of 309 ± 19 Ma and 304 ± 21 Ma for MG-GD rock-sequence and LG respectively. Remarkably, timing based on Rb/Sr has been recently confirmed by an Ar/Ar muscovite age of 308 ± 1 Ma obtained from leucogranites (Boni *et al.*, 2003).

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In order to model the emplacement history of the Arburese pluton and constrain its relationships with the post-collisional phases, we performed a detailed geological-structural survey. Observed basement/intrusive field-relationships show commonly a gently dip; flat contacts are recognized among GD rock units and GD/LG satellite bodies. Size (respectively from 40 to 3 cm) and frequency of cognate dark enclaves of gabbroic and dioritic composition decreases northward, hence dark enclaves are more common in the GD2 granodiorites. Metamorphic xenoliths are particularly frequent in the GD1 granodiorites exposed along the northern sector of the pluton and, in general, are localized within few meters of the contact with the basement. In the field, only xenoliths and dark enclaves are a good marker of the magmatic flow. In detail, data collected in about 100 different localities, reported in stereo-plots, indicate the following: i) the magmatic foliation trends EW and dips quite steep in the southern margin of the pluton (GD2 granodiorites; c and e in Fig. 1), whereas it changes to almost flat in the central and northern parts (GD2 and GD1 granodiorites; d and b in Fig. 1); ii) close to the basement the trajectories of the inferred magmatic flow tend to parallelize the granite-country rock contact, producing a more steep and variably-oriented pattern (b in Fig. 1) and, finally iii) there is no evidence for plastic deformation of primary mineral assemblage.

On the basis of these structural constraints we propose that investigated pluton could be emplaced within a narrow EW shear zone, that reactivate the contact separating the allochtonous Arburese unit from the underlying parautochtonous. Overall, the geometry of the entire pluton resemble an EW trending elliptical body, as previously argued by Cavinato (1930). Magmatic flow trajectories allow to infer the geometry of this shear zone. The steep fabrics observed in the southern margin can be interpreted as the quenched feeder zone, mimicking the roots of shear zone. This interpretation is further supported by the localization of larger cognate dark enclaves along the southern margin of pluton. Given all these evidences, we suggest that growth of the pluton was enhanced by channelized migration of magmas within the shear zone; the general sill-shaped geometry might results from gravity inversion and collapse of the roof, driven by inflation of magma at shallow crustal levels. The proposed emplacement model is quite similar to that inferred for Arzachena pluton (northernmost of Sardinia; Casini *et al.*, unpublished). The emplacement of the Arburese, Arzachena and similar calc-alkaline plutons is fully consistent with the regional phase of strike-slip tectonics constrained between 325 and 305 Ma (Carosi *et al.*, 2011), and indicates an upper bound for post-collisional evolution of Sardinia chain.

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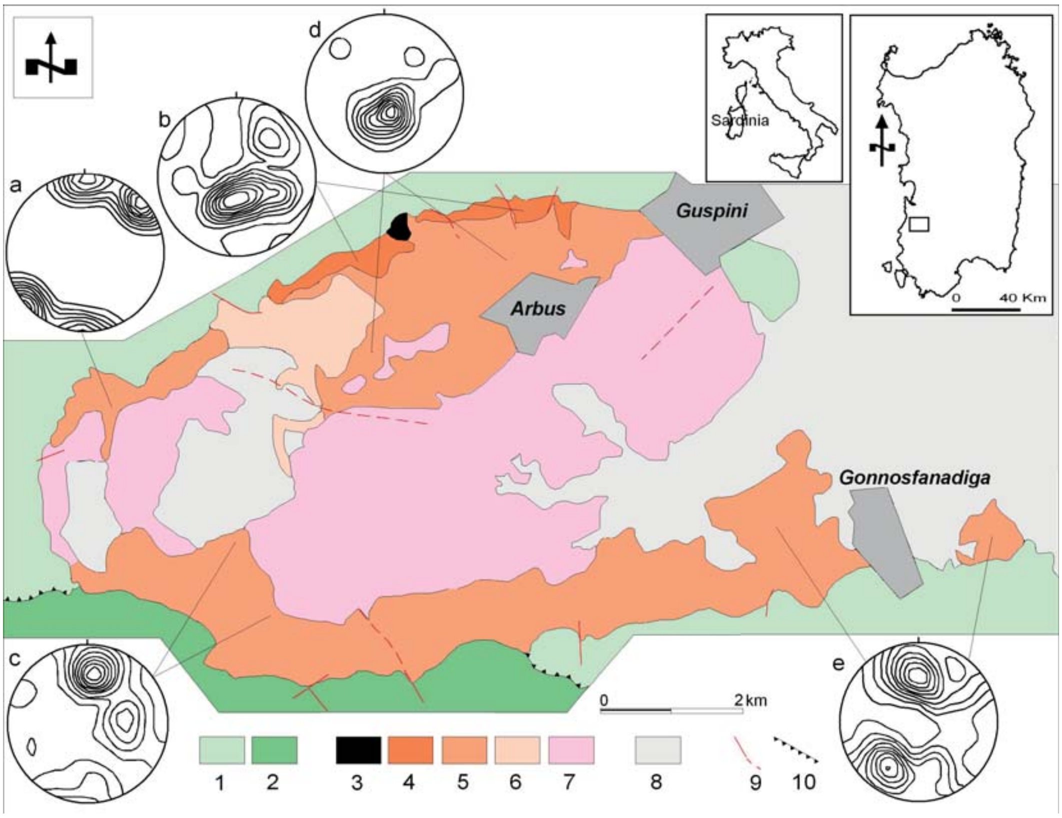

Fig. 1.- Simplified and modified after Secchi et al. *(1991). 1-2: metamorphic basement. 1: Arburese allochtonous Unit (middle Cambrian-lower Ordovician); 2: Parautochtonous Foreland (upper Ordovician). 3-7: Arburese igneous complex. 3: monzogabbronorites (MG); 4: two-pyroxene biotite granodiorites (GD1); 5: two-pyroxene-bearing biotite granodiorites (GD2); 6: biotite granodiorites (GD3); 7: cordierite-bearing leucogranite (LG); 8: Plio-Pleistocene and recent covers (alluvial fan and colluvial deposits). Other symbols: main faults (9); late-Variscan thrust (10). To simplify, dyke swarm was not plotted. a, b, c, d, and e refer to stereo-plots for magmatic foliation measured on dark enclaves and metamorphic xenoliths (see text).*

Portable gamma-ray spectrometer: A practical tool for real-time, field geochemical characterization of magmatic complexes

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A large portion of the Corsica-Sardinia Batholith (C-SB) is well exposed in north Sardinia. The C-SB is composed of several plutons emplaced over about 60 Ma (Paquette et al., 2003; Gaggero et al., 2007), therefore the batholith growth was rather episodic, although the largest magmatic systems might have required 5 to 15 Ma to grow. Accordingly, crosscutting relationships between different plutons are frequent. In spite of such a composite, presumably discontinuous, growth history, most plutons mainly consist of monzogranites and leuco-monzogranitic terms; granodiorites and more basic terms such as quartz-diorite and gabbros are subordinate. This compositional homogeneity is somewhat mirrored by plagioclase-quartz-k-feldspar fabrics seen in the field, therefore plutons of different age, thus unrelated, are often very similar and difficult to distinguish during field mapping.

Actually, the existent maps of the Sardinian part of the batholith are based just on petrographic features and minor outcrop-scale fabric variations. Only very small sectors have been yet studied in details by the means of structural analysis. This approach has led to identification of different intrusions, as well as to characterize their internal structure (Oggiano *et al.*, 2005); however, structural analysis may be not a decisive tool to discriminate among different intrusions generated from a common source during distinct magmatic events. These shortcomings are strikingly apparent where different intrusions of similar composition come into contact. If textural and modal features are indistinguishable in fact, and the contacts are not exposed as frequently is, interpretation may be ambiguous. A more efficient way to discriminate different intrusions would requires to analyze the rock composition in terms of major and trace elements, and REE. Geochronologic and isotopic analyses would provide additional information. This 'laboratory' approach is undoubtedly powerful for recognizing and interpreting plutonic complexes, however all these methods are often very expensive and time consuming. Sample selection is therefore a crucial point as, in general, increasing the number of samples provides more reliable and easy-to-interpret results. On the other hand, too much samples may overcharge the costs of mapping without increasing the accuracy. Thus, a convenient choice would be to keep the number of samples as low as possible but no more.

In order to optimize the phase of sample collection, we developed a portable gamma-ray spectrometer in co-operation with the National Lab of Legnaro (INFN). The device consists of a scintillation detector NaI(Tl) made up of one liter volume crystal coupled with an HV supply, preamplifier, and MultiChannel Analyzer (MCA -digiBASE by ORTEC) governed by a netbook. All collected gamma-ray spectra are processed using the jRadView software, whose algorithms are programmed following the main international guidelines (IAEA TECDOC-1363, 2003). The code allows to determine the activity concentration of ^{40}K, ^{214}Bi (^{238}U decay series), ^{208}Tl (^{232}Th decay series) in Bq kg^{-1} and to calculate their respective abundance expressed in ppm for uranium and thorium, and wt.% for potassium. The uranium and thorium activity concentrations and abundances are calculated assuming that their respective decay series are in secular equilibrium and, therefore, can be indicated as equivalent uranium (eU) and thorium (eTh). Statistical accuracy is ensured by using a method for data analysis that consider the full spectrum analysis with non-negative least square (FSA-NNLS) constraints (Caciolli *et al.*, 2012). According to this method, each measured spectra [N] can be composed by a linear superposition of some characteristic spectra [S] well defined through a rigorous calibration procedure according to:

$$[N] = [C] \times [S] \text{ minimizing } ||[C][S] - [N]||, \text{ when } [S] \geq 0$$

where [C] is the activity concentration matrix. The deduced concentrations are confined in the non negative side of the available space.

This instrument allows to detect in-situ concentrations of U-Th-K by analyzing about 1 m^3 of rock (a much greater

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volume than that routinely used for laboratory chemical analysis). Another important advantage is the fast acquisition rate of the instrument (less than 5 minutes). Preliminary works (Puccini *et al.*, 2010, Puccini, 2011) demonstrated the efficiency and accuracy of the instrument for surveying of high-grade metamorphic and magmatic complexes, where most rocks are characterized by a well distinguishable geochemical signature, that is, consistent U/Th and U/K or Th/K ratios.

In order to draft a geological structural maps of northern Sardinia, the portable gamma-ray spectrometer has been used as a practical tool for improving the robustness of field-survey observations. In this way, similar plutons with different origin and emplacement histories have been discriminated to a first order approximation. Such preliminary results usually cannot describe thoroughly a pluton, however they have been very useful to plan further geochronologic, thermo-chronometric and chemical analyses, reducing the number of samples to be investigated and, thus, the costs.

The data obtained from field survey (position of magmatic contacts, attitude to anisotropies, *in-situ* U-Th-K compositions) were also implemented by LA-ICP-MS zircon dating of selected samples in order to draw a sequence of magmatic events. The results obtained from application of combined field structural survey and gamma-ray spectrometry allowed us to map the northern sector of the Sardinian batholith.

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Time scale of gneiss dome formation and ductile flow: The Mont-Louis, Ax-les-Thermes and La Jonquera plutons and related gneiss domes in the French Pyrenees

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The Variscan segment of the Pyrenees is characterized by migmatitic-granitic-cored gneiss domes and by large calc-alkaline plutons which intruded the upper crust. A new geochronological and structural study was performed on orthogneissic/granitic cores of the domes and their related calc-alkaline plutons on two sectors: the Aston, Hospitalet and Mont-Louis domes in the central Pyrenees and the Roc de France dome in the eastern Pyrenees (Fig. 1). The aim of this study is to characterize the mechanism and timing of gneiss dome formation.

The Aston gneiss dome shows four main Variscan events (Denèle *et al.*, 2009a). (i) D1 deformation appears only as relics in the orthogneisses located above the sillimanite isograd; it shows a NS non coaxial stretch associated to top to-the-south motions, attributed to a NS convergence. (ii) D2-a deformation appears in the orthogneisses and their country-rocks located below the sillimanite isograd, where the D1 structures are transposed, and in the peraluminous granites whatever their structural level; this deformation shows an EW to N120 stretch associated to a top-to-the-east flat shearing attributed to lateral flow in the hot middle crust in a transpressive regime. (iii) D2-b deformation is characterized by EW-trending megafolds with horizontal axes in the middle crust; during this event the calc-alkaline Querigut pluton which located in the vicinity of the Aston dome, emplaced in the upper crust. (iv) Subvertical MT mylonitic bands developed by the end of the transpression.

The orthogneisses and the peraluminous granites of the Hospitalet gneiss dome, systematically located below the sillimanite isograd, are characterized by the same events, with the exception of the D1 structures which have been completely transposed (Denèle *et al.*, 2007).

The Mont-Louis dome is largely overlapped by the Mont-Louis pluton. Structural study shows that emplacement of the various calc-alkaline facies of the pluton occurs earlier than the formation of the dome. The kilometre-scale Bolquère leucogranite dike crosscut both the dome and the pluton.

In situ ion probe U-Pb dating on zircons demonstrates that the orthogneisses belonging to the Aston and Hospitalet dome cores correspond to former Ordovician (469 ± 3 Ma) granitic laccoliths subsequently deformed during the Variscan orogeny (Denèle et al., 2009b). In situ LA-ICPMS U-Pb dating on zircons from the Variscan peraluminous granites of the Ax-les-Thermes pluton located in the core of the Aston gneiss dome and affected by the D2-a deformation gave an age of emplacement at 306.2 ± 2.3 Ma. LA-ICPMS U-Pb dating on zircons from three calc-alkaline granitoïds of the Variscan calc-alkaline Mont-Louis pluton gave an age of emplacement at 301.0 ± 2.1 Ma, 303.3 ± 1.1 Ma and 304.7 ± 1.1 Ma. The later Bolquère leucogranite dike gave an age of emplacement at 302.4 ± 2.9 Ma

These new data show that the Variscan formations of the Central Pyrenees recorded the evolution in transpressive regime from a stage of ductile flow of the middle crust which occurred around 306 Ma to a stage of large scale folding (buckling of the upper crust and dome formation) which occurred between 303 and 301 Ma.

The study of the Canigou area, more to the east, yields to a similar scenario (Laumonier *et al.*, 2010).

In the easternmost Pyrenees, the Roc de France dome is overlapped by the calc-alkaline La Jonquera pluton and the granitoïds have been emplaced earlier than the formation of the dome. Preliminary LA-ICPMS U-Pb dating on zircons from three calc-alkaline granitoïds samples gave an age at 301.0 ± 2.1 Ma, 293.5 ± 2.3 Ma and 293.1 ± 1.3 Ma. New petrostructural data are ongoing to interpret the difference of ages between these three more or less similar facies. These data suggest that formation of gneiss domes is younger in the eastern Pyrenees by comparison to the Central Pyrenees. New datations are necessary to discuss this hypothesis that could imply a progressive widening of

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an EW-trending transpressive zone from west to east in the southern foreland of the variscan chain.

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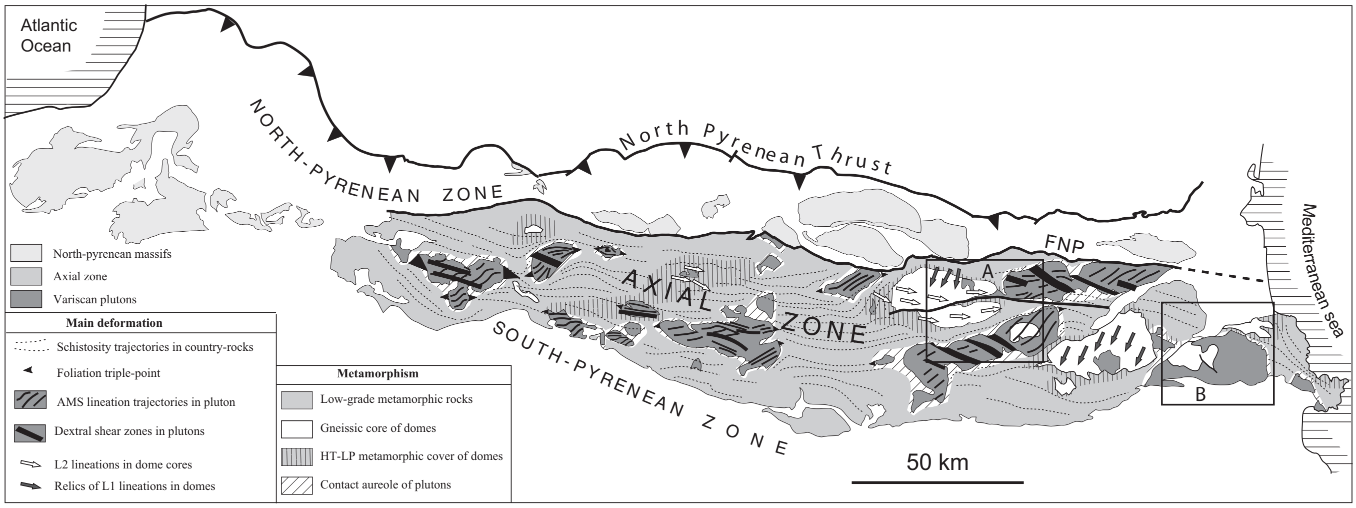

Fig. 1.- Synthetic geological map of the variscan domain of the Pyrenees. The squares delimiting the two areas of study: A) from north to south the Aston, Hospitalet and Mont-Louis domes, B) the Roc de France dome and La Jonquera pluton.

The North-Armorican Shear Zone (Brittany, France) revisited

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The *North-Armorican Shear Zone* (NASZ), exposed in the Armorican Massif in Brittany, France, has always been described as an intracontinental, through-going dextral transcurrent shear zone, active during the late Paleozoic Variscan orogeny. The E-W trending trace of the NASZ is based on scattered observation of mylonites, cataclasites, as well as on the map-based, apparent displacement of late Variscan magmatic complexes. However, taking into account the extremely poor degree of exposure, and thus the scattered occurrences of cataclasites and mylonites, with only limited constraints of their temporal and/or spatial relationship with the surrounding terrains, the overall geodynamic significance of the NASZ should be reassessed.

In the Queffleuth valley, south of Morlaix, the kinematics along the supposed trace of the NASZ have been studied on a well-exposed road cut, oriented perpendicular to the map trace of the NASZ, exposing relatively homogeneous proto- to cataclasites. We name this occurrence of fault rocks the *Queffleuth Cataclastic Zone* (QCZ). Four morphological fault classes, without consideration of orientation or shear sense, were observed. Based on microscopical observations, one morphological fault class can directly be linked to cataclasis. Therefore, the cross-cutting nature of the faults indicates that fault activity must have taken place during and after, the cataclastic deformation. A paleostress analysis enables to distinguish five distinct stress states, in particular dominated by antithetic, oblique to pure strike-slip, N-S trending faults. Both dextral and sinistral kinematics are inferred for the overall NASZ. As the stress states are based on a mixture of faults of all morphological classes, they indicate the presence of both dextral and sinistral kinematics during and after cataclastic flow. Obviously, a recurrence of sinistral and dextral movements is proposed. The recurrence of dextral and sinistral kinematics and the dominance of antithetic faults demonstrates that the NASZ is most probably a fossil immature transcurrent shear zone, comparable to the South Island Seismic Zone.

An integrated study (*i.e.* petrography, fluid inclusion microthermometry, chlorite geothermometry, stable isotope analysis) of quartz vein occurrences along and around the NASZ lead to a better understanding of the fluid systems involved and provided some relative age constraints for the NASZ activity. Three different fluid systems have been distinguished. A first system is the *Plougastel fluid system* for which the fluid source was likely metamorphic formation waters from the Lower Palaeozoic, siliciclastic rocks of the Plougastel Formation. This closed fluid system can be related to the regional folding and cleavage development during the compression-dominated Bretonian stage of the Variscan orogeny, which is related to the earliest stage of the closure of the Rheic ocean. As the veins that precipitated from these fluids occur in a similar structural context on both sides of the NASZ, they indicate (1) that the NASZ was not a major tectonic boundary at the moment of vein formation, or (2) that the NASZ was not present at that time. Probably, the Plougastel fluid system was active until the Late Carboniferous main stage of the Variscan orogeny.

The second *Plouaret-Quintin fluid system* became active along the trace of the NASZ (Guic area). This fluid system is characterised by high temperatures, related to the intrusion of granites in the region, *i.e.* the Plouaret-Commana (329 + 5 Ma) and the Quintin (291 ± 9 Ma) granites. As it is clear that the Commana granite is the protolith of the cataclasites in the Queffleuth valley, the NASZ must have been active during and/or after the emplacement of the granite (*i.e.* 329 ± 5 Ma). An upper age for the NASZ is evidenced by the undeformed nature of the Bas-Léon (292 + 9 Ma) and the Belle-Isle-en-Terre microgranites (292 + 13 Ma).

After the main Variscan deformation, a third NS fluid system, related to fault activity became active. This system is regionally characterised by multiphase N-S trending, complex vein systems, possibly related to cataclasis (*cf.* QCZ). Although there are no indications that the NASZ acted as a major fluid pathway, the massive vein occur-

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rences evidence local overpressured fluid compartments at the end and/or after the main NASZ activity. The fluid inclusion study indicates a changing composition in time, from H_2O-NaCl + CO_2-CH_4-N_2 over H_2O-NaCl towards H_2O-NaCl-$CaCl_2$. Such evolution in fluid source, from a metamorphic fluid and/or fluids related to Paleozoic granites towards a higher saline H_2O-NaCl-$CaCl_2$ fluid, is commonly observed in several parts of the Variscan orogenic belt.

Structural and stratigraphical significance of U-Pb ages from the Saldanha and Mora volcanic complexes (NE Portugal, Iberian Variscides)

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It is generally established that a group of far travelled allochthonous tectonic units override the Variscan Massif in the NW corner of the Iberian Peninsula (Arenas *et al.*, 2004; Martínez Catalán *et al.*, 1997, 2007; Ribeiro *et al.*, 1990, 2006). They are known as the Galicia-Trás-os-Montes Complexes. Between them and the autochthonous Central Iberian Zone (CIZ) there is a thick intermediary unit named Parautochthon or Schistose Domain of the Galicia-Trás-os-Montes Zone (GTMZ) (Farias *et al.*, 1987). It presents Gondwanian sedimentary affinity as its relative autochthonous unit, the Central Iberian Zone (Farias *et al.*, 1987; González Clavijo and Martínez Catalán, 2002). In the south-eastern rim of the Morais Complex, two tectono-stratigraphic sub-domains limited by regional scale Variscan thrust faults were identified: The Lower Parautochthon, which is thrust over the autochtonous unit; and the Upper Parautochthon, thrust over the previous tectono-stratigraphic unit (Rodrigues *et al.*, 2006a, b, c). The Saldanha felsic volcanic rocks belong to the latter sub-domain (Fig. 1). They were formerly considered Middle Ordovician by lithological correlation (Pereira *et al.*, 2006) or even Silurian because they were supposedly concordant with low-grade Silurian metasediments (Ribeiro and Ribeiro, 2004).

New detailed mapping around the Morais Complex allowed the identification of another group of volcanic rocks in the same structural unit, but in a slightly lower tectono-stratigraphic position, the Mora volcanic complex (Fig. 1). Both Saldanha and Mora volcanic complexes are mainly made of rhyolites and rhyodacites, acidic tuffs and ignimbrites. However, Mora presents some basic tuffs and lavas with some interbedded recrystallized limestones. Also in the Mora volcanics, it is possible to identify metallic mineralization, in the form of euhedral magnetite crystals and sulphide-rich stockworks.

Representative felsic rocks from both volcanic complexes were dated using U-Pb CA-ID-TIMS in zircon (IGME Laboratory, Tres Cantos, Madrid). The Saldanha sample is an "Ollo de Sapo" type coarse grain porphyritic acid metatuff that yields an age of 483.76 ± 1.5 Ma. The Mora sample is a fine to medium grain massive metarhyolite with magnetite crystals and brings a 493.7 ± 0.76 Ma age (Fig. 1). These data prove that none of the studied volcanics are Silurian.

Due to the lithological and age differences in both volcanic complexes, we consider that they represent two separate major volcanic pulses, demonstrating a late Cambrian to earliest Ordovician age for the middle-lower part of the Upper Parautochthon in this region. This volcano-sedimentary package is in thrust contact with underlying rocks, revealing the unforeseen structural complexity of the Schistose Domain of the GTMZ under the Morais Complex.

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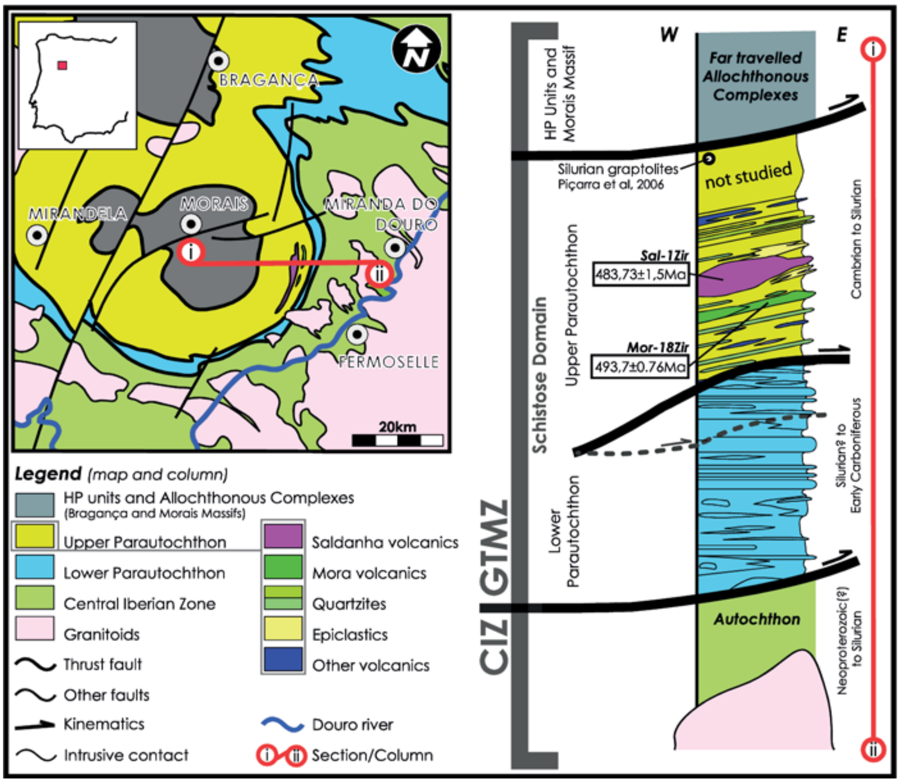

Fig. 1.- Situation map (left) and stratigraphic column (right) of the studied sector. CA-ID-TIMS ages are represented in boxes, with sample name on top (Sal-1Zir and Mor-18Zir, for Saldanha and Mora volcanics, respectively). The Upper Parautochthon represents a duplication of the autochthonous (CIZ) sequence, being limited at its base by a thrust fault. Silurian graptolite fauna in upper parts of this unit is represented with a black circle (Piçarra et al., 2006).

The Late Carboniferous - Early Permian, 90° rotation of the Maures - Estérel - Corsica - Sardinia block confirmed by new paleomagnetic data

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During the Late Carboniferous - Permian, the southern Variscides were affected by large scale dextral wrenching and intense magmatism (Arthaud and Matte, 1977; Bard, 1997, Cortesogno *et al.*, 1998). Since wrenching is generally associated with block rotations (Jackson and McKenzie, 19), paleomagnetism is an appropriate tool for deciphering this Late Variscan tectonic history. The paleomagnetic investigations were facilitated by the occurrence of numerous outcrops of Late Carboniferous volcanic units and associated dykes in Maures, Estérel, Corsica, Sardinia (MECS) and southern Alps (Cortesogno *et al.*, 1998). These investigations showed contrasting results from the north to the south of the Corso-Sardinian batholith (Zijderveld *et al.*, 1970; Westphal *et al.*, 1976; Edel *et al.*, 1981; Vigliotti *et al.*, 1990). For instance, the paleomagnetic directions in volcanites of northwestern Corsica and south-eastern Sardinia differ by about 90°. Two interpretations were proposed for these deviated directions: 1) the Corso-Sardinian block has been strongly deformed and sealed by granites, 2) the directions recorded in the magmatic rocks were not acquired at the same time but represent the different stages of a global rotation. The latter solution was favoured by Edel (1980) who, nevertheless, introduced a relative rotation between northern and southern Corsica, according to the data obtained respectively by Westphal *et al.* (1976) and Vigliotti (1990). Another unclear point is the sense, clockwise or counterclockwise, of the 90° rotation. The clockwise rotation has the advantage to resituate the polarity and the parallelism of the metamorphic zonation of the MECS and the eastern part of the central Variscides (Edel, 2000).

In order to solve these unclear points a new paleomagnetic investigation was carried out in both islands. The 90° rotation being based on results from various volcanic rocks of Late Carboniferous age of central and south-western Sardinia (Edel *et al.*, 1981), sampling was concentrated on Late Carboniferous rocks of north-western Corsica and north-eastern Sardinia, i.e. the Osani andesite (308.1 ± 2.9 Ma) in Corsica, the Isola Rossa diorite, the Trinità d'Agultu granodiorites (300.1 ± 6.1), and the Barrabisa migmatite and granodiorite (313 ± 6 Ma), in Sardinia. In addition, Early Carboniferous granodiorites of the MGK suite of northern Corsica (340-330 Ma), and various generations of dykes were sampled in order to follow the paleomagnetic evolution with time. After thermal demagnetization, all the oldest, Late Carboniferous rocks exhibited easterly and seldom westerly directions similar to those of south-western Sardinia, *i.e.* 107°/13°, α^{95} = 13° VGP = -8°N/82°E for the Osani andesite, 102°/8°,α^{95} = 13°, VGP = -6°N/89°E) for the Isola Rossa -Trinita granodiorites and 111°/15°, α^{95} = 5° VGP = -10°N/79°E for the main components of the Barrabisa granitoids. In north-western Corsica was also obtained a mean direction 96°/7°, α^{95} = 12° VGP = -2°N/92°E very close to the direction from the Osani andesite in the MGK granodiorites, which indicates that the batholith was affected by a pervasive remagnetization during the U2 intrusive and effusive magmatic phase.In addition to these magnetic components which are considered to be the oldest, we obtained components with directions which fall into two groups of directions also measured in the dykes and which correspond respectively to the southerly directions of the U3 magmatic phase of northern Corsica (Westphal *et al.*, 1976) and the south-easterly directions of the Gallura ignimbrites (Zijderveld *et al.*, 1970;Westphal *et al.*, 1976) and dykes of southern Corsica and northern Gallura (Vigliotti *et al.*, 1990). These components are interpreted as overprints in the early granitoids. We also confirm the southerly direction of the Ota gabbro which cooled around 282 Ma. So, in rocks emplaced and cooled prior to 295 Ma in northern Corsica, northern and southern Sardinia, the declinations are E-W, while in volcanites and dykes emplaced around 285-280 Ma, the declinations become N-S. This means that there was no relative rotation between the different parts of the Corsica-Sardinia block and that the whole block has rotated by 90° at the end of the Carboniferous. The sense, clockwise or counterclockwise of the rotation is in discussion.

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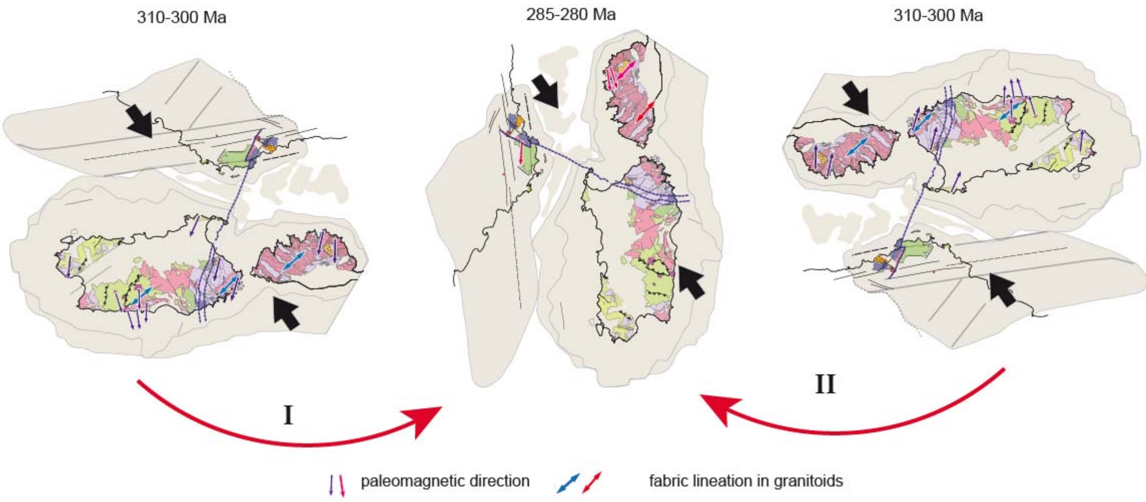
Structural geology shows also a great difference between the older and younger plutonic units. In granitoids emplaced in the time range 320-295 Ma the fabric is generally striking NW-SE. In contrast, the U3 granitoids show a NE-SW trending fabric. Reconstructions of the MECS bloc respectively around 305 Ma and 280 Ma indicate that the direction of principal stress remained NW-SE during the Late Carboniferous - Early Permian rotation.



Crustal melting and tectonic setting of plutonism in the Variscan French Massif Central and Massif Armoricain

FAURE Michel

Conversely to the Alpine collisional belt, crustal melting is widespread in the Variscan belt. In the French Massif Central (MC) and Massif Armoricain (MA), the Variscan orogeny developed through a polyorogenic evolution is subdivided into i) an Eo-Variscan cycle from Cambrian to Early Devonian, and ii) a Variscan *stricto sensu* cycle from Late Devonian to Late Carboniferous (*e.g.* Faure *et al.*, 2005). The intermediate period, during the Middle Devonian, corresponds to a south-directed oceanic subduction stage (in the present coordinates) coeval with the formation of a magmatic arc and back-arc basins in the upper plate. All the stages of the Variscan orogeny are characterized by peculiar magmatic activities.

The Eo-Variscan cycle corresponds to the rifting-drifting-rewelding of micro-continental ribbons, such as Avalonia, Mid-German Crystalline Rise (MGCR), and Armorica detached from the northern margin of Gondwana in Early Ordovician and re-attached to Gondwana in the Late Silurian-Early Devonian. The Early Ordovician alkaline magmatism, mainly plutonism and rare volcanism, developed during the pre-orogenic rifting stage. During the Silurian, the convergence between Armorica and Gondwana was accommodated by the north-directed subduction of the Medio-European Ocean, followed by the continental subduction of the north Gondwana margin. This convergence was coeval with a high pressure (HP) and locally ultra-high pressure (UHP) metamorphism dated between 420 and 400 Ma (Late Silurian-Early Devonian). The exhumation of the HP-UHP metamorphic rocks was accommodated by crustal melting responsible for the first generation of migmatites (MI migmatites) well observed in the southern part of the MA (or Champtoceaux Complex), and the westrn part of the MC (or Limousin area). Zircon U-Pb and monazite U-Th-Pb_{tot} datings of the Eo-Variscan MI migmatite indicate Eifelian to Frasnian ages (390 Ma to 375 Ma). The HP rocks form and allochthonous unit (the Upper Gneiss Unit) emplaced to the SW. The mechanism of exhumation of the HP unit and MI crustal melting is discussed in terms of transition from high compression to low compression regimes of continental subduction (Faure *et al.*, 2008).

The Variscan cycle corresponds to the closure of the Rheic Ocean, and the collision of Laurussia, Gondwana, and intervening microcontinents such as the MGCR (or the Léon Block in MA). The convergence was accommodated by two south-directed subductions. The southward subduction of the Rheic Ocean gave rise to a magmatic arc, the superficial and deep parts of which are preserved in NE MC (Morvan) and western MC (Limousin), respectively. Furthermore, the opening of several back-arc basins (*e.g.* the Brévenne unit in MC) is coeval with the southward subduction (Pin, 1990).

At the end of the collision, at ca 360-350 Ma, crustal melting gave rise to the formation of per-aluminous granitoids, collectively known as the “Guéret-type” massifs in the North Limousin or in the Tulle antiform of South Limousin. The Guéret-type granites are laccoliths structurally characterized by a flat-lying foliation and a NW-SE mineral lineation, also documented by AMS studies (Roig *et al.*, 1998; Cartannaz, 2006).

The main magmatic period of the MA-MC segment started in the Late Visean (ca 335 Ma). This period that extended from the syn-orogenic to the late-orogenic stages of the Variscan evolution can be subdivided, at least, into four stages, each one characterized by a typical magmatism.

1. The Late Visean syn-orogenic crustal melting

The Late Visean period is characterized by crustal melting in the central part of the orogens (*i.e.* in the northern part of the Massif Central and in Massif Armoricain). The superficial term of this magmatism is known for a long time as the “Tufs anthracifères” series event. Various rock types are encountered in this magmatic stage: acidic and intermediate lava flows; dykes, hypovolcanic plutons, and microgranites. This Late Visean magmatism develops in the internal part of the orogen coevally with the onset of the syn-orogenic extensional tectonics. Conversely, in the outer part of the orogen

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(*i.e.* Ardennes, Montagne Noire) compression is still going on. It is shown that NW-SE stretching characterizes the crustal deformation during the emplacement of the magma.

2. The MII migmatite

Around 330-325 Ma, migmatites and anatectic granites (MII migmatites) are recognized in many places, such as North Brittany, Vendée, Millevaches, Morvan, Northern Cévennes, Montagne Noire (*e.g.* Faure *et al.*, 2010). Except in this last area, the limited surface of outcrop does not allow us to settle the tectonic context of the MII migmatite. The Montagne Noire Axial zone is a highly controversial granite-migmatite dome. Recent petro-structural and AMS studies argue for a combination of diapirism and compressional and extensional shearing on the southern and northern flanks, respectively (Charles *et al.*, 2009). Considering that the crustal melting took place in the upper plate, the heat flow cannot be the product of radiogenic heating due to the thickenend crust in the lower subducting plate, but requires the participation of the upper plate mantle. A model involving lithosphere mantle delamination has been proposed (Faure *et al.*, 2009).

3. The Namurian-Westphalian late-orogenic plutonism

It is well acknowledged that the Late Carboniferous magmatism in the Massif Central, dated around 325-315 Ma, is represented by per-aluminous leucogranites and porphyritic monzogranites, exposed in the NW and SE parts of the MC, respectively. Whatever their lithology, the granitic plutons are characterized by a NW-SE maximum stretching direction observed by various markers (preferred MFK orientation, xenoliths, enclaves, joints), and AMS measurements (*e.g.* Faure, 1995). The Namurian-Westphalian plutons are syn-kinematic bodies that recorded the stress and strain fields active during their emplacement. Some of these plutons exhibit mylonitized margins with normal kinematics (country rocks moving down with respect to the granite). The contact metamorphic minerals also record the same kinematics. Several examples in the MC such as the North Limousin leucogranites, the Cévennes monzogranites, and the Carnac and Quiberon leucogranites (MA) document the structural features of this late orogenic plutonism (*e.g.* Talbot *et al.*, 2005a,b; Gébelin *et al.*, 2006; Joly *et al.*, 2009; Turrillot *et al.*, 2011).

4. The post orogenic Late Carboniferous-Early Permian magmatism

This last stage of the Variscan evolution in the MA-MC area is characterized by N-S to NNE-SSW maximum stretching direction. In the MC, plutonism is rare during this stage. The Velay granite-migmatite dome (MIII migmatite) is the most significant area for this stage. The Velay dome is bounded to the North by the Pilat detachment fault (Malavieille *et al.*, 1993). During the Late Carboniferous, the high thermal input from the mantle gave rise to high temperature granulite facies metamorphism similar to that observed in the Ivrea zone in the Alps. However, in the MC, the HT granulites are found only as xenoliths in the Cenozoic volcanic rocks. Conversely to the eastern branch of the Variscan Belt, the Permian anorogenic alkaline or per-alkaline magmatism is absent in the MCF and MA. Nevertheless, this intraplate anorogenic magmatism is unrelated to the Variscan orogeny.

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P-T estimates for the metamorphic rocks of the Stilo Unit (Aspromonte Massif, Calabria) and correlations with analogue Sardinian Variscan crystalline complexes

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The Variscan continental belt fragmented during Alpine tectonic phases is currently dispersed in the whole circum-Mediterranean area. The Sardinia-Corsica block (SCB) and Calabria-Peloritani Orogen (CPO) represent remnants of this chain. Although there is an agreement in the literature that they have been strictly connected for most of their tectonic evolution before the opening of the Tyrrhenian Sea, the corresponding arguments seem to be poor (Alvarez & Shimabukuro, 2009).

The PT path here presented is a contribution to the knowledge of the Variscan Orogeny in the southern part of the belt, which has been intensely reworked by Alpine tectonics in the Calabrian region. The metapelitic sequence of the intermediate/upper crust of the Stilo Unit (SU) exposed in the Aspromonte Massif (southern Calabria) is weakly affected by Alpine deformation (Fazio *et al.*, 2008) and well preserves the earlier Variscan tectono-metamorphic evolution. Moreover, the inferred PT path allows us to establish possible correlations with similar rocks exposed at different places of the southern European Variscides. In particular, a comparison has been made with similar metapelites in Calabria along the eastern and southern borders of the Serre Massif (Stilo Unit *s.s.*), as well as in northern Sardinia (Nurra and Baronie areas). Indeed, a similar metamorphic zonation in both crystalline basements of Calabria (Aspromonte and Serre massifs) and northern Sardinia (Franceschelli *et al.*, 1982), showing a complete prograde sequence from the chlorite to sillimanite zone, has been recognised.

The SU is the uppermost nappe of the Alpine edifice forming the Aspromonte Massif (Pezzino *et al.*, 2008, Heymes *et al.*, 2010) consisting of phyllites grading downwards (*i.e.*, northward due to the southward tilting of the whole tectonic pile) to amphibolite-facies schists (Graeßner & Schenk, 1999). Occasionally, Cambrian to Carboniferous protolith ages have been documented (Bouillin *et al.*, 1984).

PT estimates of principal metamorphic episodes of the SU (Aspromonte Massif), inferred by means of PT pseudosections, suggest a steep clockwise loop (Fig. 1a). The path consists of an initial syn-D1 episode (M1: 360-600°C at 0.35-0.6 GPa depending on the metamorphic zone, varying from Chl to St+And zone) linked to a thickening phase producing folds associated to a pervasive axial plane foliation (Fig. 1b, S1); these early structures are successively affected by crenulations (M2: syn-D2s blastesis of Qtz, Wm, Chl, Bt). A syn-D3 shear phase (M3: 450-550°C - 0.5-0.9 GPa) probably coeval with the emplacement of granitoid bodies along extensional shear zones followed. A final (M4) static crystallization episode (Wm, Bt, sporadic Crd, and overgrowth of And on St) produces a clear metamorphic aureole in the host rocks testified by the widespread occurrence of spotted schists close to the intrusive bodies. According to the tectonic model proposed by Angì *et al.* (2010), this PT path shows strong similarity with the trajectory reconstructed for analogous crystalline rocks of the Serre Massif (central Calabria, Fig. 1a).

Similar clockwise PT paths, typical of collisional belts, have been also depicted for the Variscan metamorphism of Sardinia. They have been attributed to late thermal relaxation following the initial thickening stage (Franceschelli *et al.*, 2005), advising a rough correspondence with Calabrian metamorphic rocks. Focusing our attention on metapelitic sequences that show a strict compositional and metamorphic similarity with those of Calabria, we believe that the greenschist to amphibolite facies units exposed in north Sardinia (Nurra and Baronie areas) could be analogue candidates of the Calabrian SU rocks. The PT trajectories reconstructed for the Nurra area show very similar peak pressure conditions and a temperature range, from Chl- to And-zone, overlapping the SU thermal estimates; this suggests a possible correlation between them. In the Baronie area, except for higher pressure estimates (about 0.9-1.1 GPa), again the thermal range (420-580°C) is comparable with that of the SU (550°C ca.), supporting the

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hypothesis of a potential continuum between metamorphic zonation of the north-eastern Sardinia coast to that occurring in the southern Calabria Aspromonte region.

Aiming at solving the question of the match between the Variscan geological history of Sardinia and Calabria, we attempted to compare existing PT paths (*e.g.*, Carmignani *et al.*, 2001; Carosi *et al.*, 2004; Franceschelli *et al.*, 2005, and references therein) for the SCB, as well as for the CPO (*e.g.*, Graeßner & Schenk, 1999). Nevertheless, caution should be taken when such correlations are attempted, because of PT estimates obtained by means of different techniques based on different thermodynamic datasets can be rather different, definitely weakening their consistency. In order to do this evaluation, we propose to carry out similar investigations on the Sardinian side using the PT pseudosection approach. PT estimates obtained with the same technique, based on the same thermodynamic database, will improve the accuracy of such regional PT database.

Several further correlations based on different aspects (petrographic, mineralogical, structural, geological, geochemical and geochronological features) between the Calabrian and Sardinian sides can be made. In this view, regional scale shear zones of Sardinia (*e.g.* Posada-Asinara Line, PAL) should have their continuation on the Calabrian side. One of such shear zones has been partially studied (Fazio, 2005) in the metapelite sequence of the SU in the Aspromonte Massif, and future investigations could allow us to better compare it with Sardinian shear zones. The occurrence of HP key minerals could also give additional evidence of a similarity between the two exposed crystalline basements: Ky relics containing fibrolitic sillimanite in the Asinara migmatites (Oggiano & Di Pisa, 1998) have been also found near Palizzi village (southern Calabria, Grande, 2008). Other analogies have been observed between structural features of Sardinian and Calabrian basement rocks. Three main Variscan deformation phases have been recognized in Sardinia (Conti *et al.*, 1999), the principal ones are: D1a, b, which is a composite compressional phase, with early SW and later W-verging folds and associated S1a, b schistosity; D2, strike slip, either transpression and transtension, with S2 schistosity transposing S1 within NW-SE shear zones. Later, D3 produced kilometre-long antiformal structures with an axis roughly parallel to the orogenic trend; the very late stage of deformation (D4, extensional) was coeval with thermal doming and denudation of metamorphic core-complexes (Casini & Oggiano, 2008). The main deformational events recorded in the SU of the Aspromonte Massif (Fig. 1b) roughly resemble those observed within the Sardinian metamorphic rocks: compressional (D1) and shear (D3) events appear comparable to D1a, b and D2 Sardinian phases. A further folding episode (D4) possibly related to the late D3 Sardinian phase produces metre- to decametre-sized chevron folds.

Further evidence for validating the supposed match between the two crystalline basements of northern Sardinia and southern Calabria could arise from a detailed study evaluating the petrological signatures of granitoid bodies outcropping in the north-eastern Sardinian (Giacomini *et al.*, 2006) and western Calabrian coast (Rottura *et al.*, 1993, Fiannacca *et al.*, 2008). Moreover, a comparison between migmatitic complexes widely occurring north of the PAL (Posada-Asinara Line) in Sardinia and similar rocks outcropping near the village of Scilla (at the Calabrian Tyrrhenian coast) could furthermore support the hypothesis of a continuous Variscan metamorphic chain presently exposed in Sardinia and Calabria.

In this contribution we presented only preliminary data and further studies and useful constraints, such as geochronological ones, are needed to prove such hypothesis making more forceful correlations between the margins of Sardinia and Calabria. Nevertheless, the PT estimates of a small portion of the Variscan belt presented here are a useful contribution to the reconstruction of its tectono-thermal evolution.

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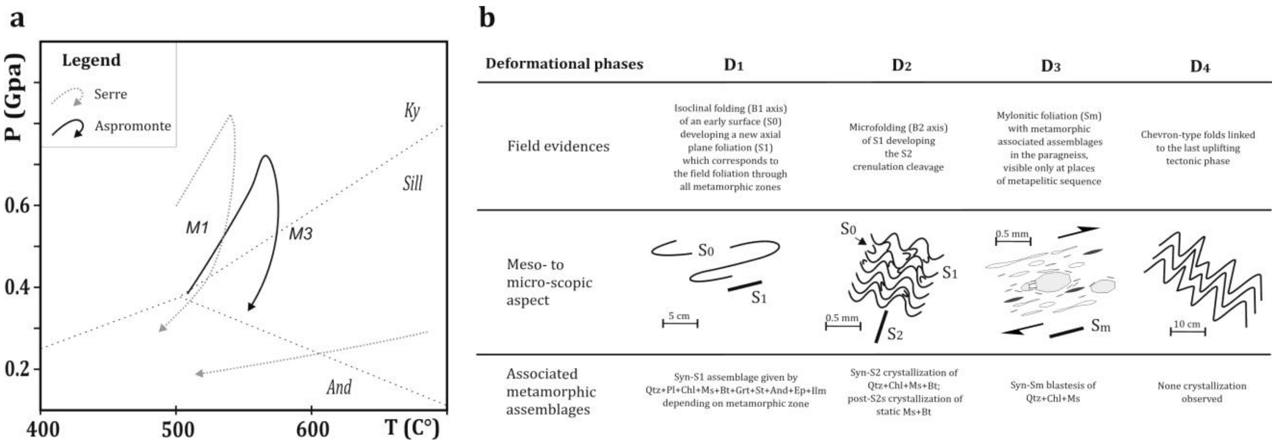

Fig. 1.- a) P-T paths of the Stilo Unit (SU) outcropping in the Aspromonte Massif (southern Calabria) and Serre Massif (central Calabria, after Angì et al.*, 2010); b) deformational phases recognized within SU rocks.*

The Late Paleozoic Geodynamic Evolution of North Africa and Arabia: Evidence for Late Devonian major uplift and diffuse extensional deformation

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The Upper Paleozoic geodynamic evolution is discussed at the scale of a wide part of Gondwana from North Africa to Arabia (Fig. 1). With the aim of giving an integrated tectonic scenario for the study domain, we revisit six key areas namely the Anti-Atlas Belt (Morocco), the Béchar Basin (west Algeria), the Hassi R'Mel High (Central Algeria), the Talemezane Arch (south Tunisia), the Western Desert (Egypt) and finally the High Zagros Belt (Iran). Below the so-called "Hercynian unconformity" (Fig. 2), which is in reality a highly composite discontinuity, surface and subsurface data display a well-known Arch-and-Basin geometry, with basement highs and intervening Paleozoic basins (figure). We show that this major feature results primarily from a Late Devonian event and can no longer be interpreted as a far effect of the Variscan Orogeny. This event is characterized by a more or less diffuse extensional deformation and accompanied either by subsidence, in the western part of the system, or by an important uplift of probable thermal origin followed by erosion and peneplanation. By the end of the Devonian, the whole region suffered a general subsidence governed by the progressive cooling of the lithosphere. Such a primary configuration is preserved in Arabia with typical sag geometry of the Carboniferous and Permian deposits but strongly disturbed elsewhere by the conjugated effects of the Variscan Orogeny during the Carboniferous and/or by subsequent uplifts linked to the Central Atlantic and Neo-Tethys rifting episodes. In conclusion, we try to integrate this new understanding in the geodynamics of the Late Devonian, which, at world scale is characterized by the onset of the Variscan orogeny on the one hand and by magmatism, rifting and basement uplift on the other hand.

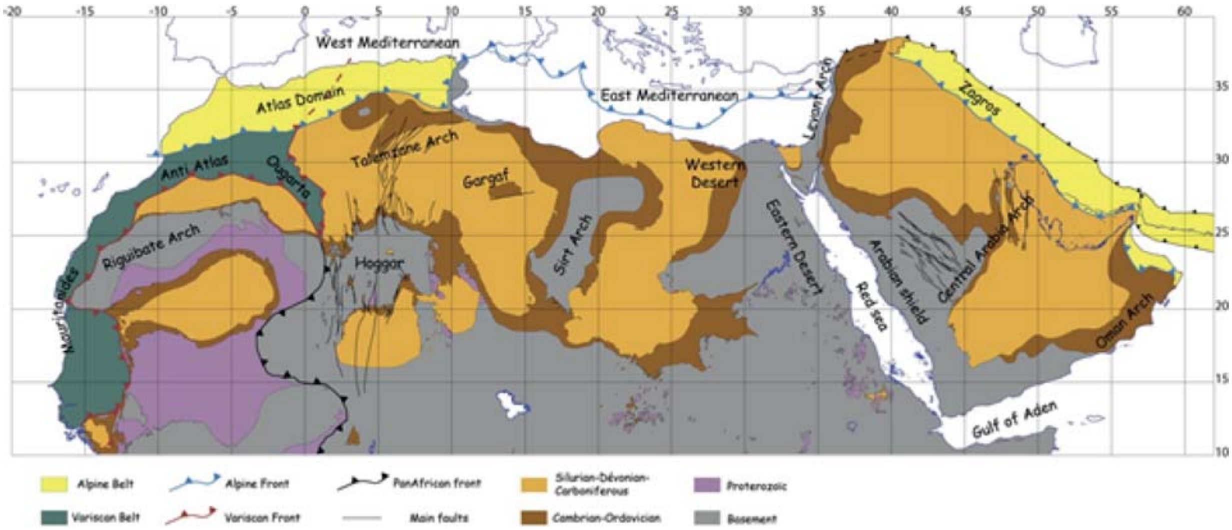

Fig. 1.- Simplified subcrop map beneath the "Hercynian" unconformity showing the major arches and intervening basins as well as the Variscan and Alpine tectonic fronts. Note that the « Hercynian » unconformity is a composite discontinuity having different significances

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Fig. 2.- A helicopter view of the so-called "Hercynian Unconformity" in the Central High Zagros Belt (Iran). The cliff is made up of a thick Permian to Cenomanian carbonate platform resting on Lw Paleozoic rocks (Cambrian & Ordovician). Both together are thrusted over the Cretaeous beds exposed in the foreground.

The geological map of Brecca area (Sardinia SE, Italy)

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A detailed field survey has addressed to the mine district of Brecca in south eastern Sardinia (external nappe zone). Aim of this work is to constrain the geometry of recognized Variscan structures and to provide insights on their timing.

Introduction

The study area is located in the Nappe zone of the Variscan metamorphic basement of Sardinia which is a part of the Southern Variscan chain. The Variscan basement that crops out in the study area is metamorphosed in lower greenschist facies conditions. In the study area two tectonic units are mapped (from the bottom): Gerrei Unit (with the Monte Lora sub-unit) and Meana Sardo Unit.

Stratigrafy

The succession of Gerrei Unit outcropping in this area is characterized by:

- silici-clastic and volcano- sedimentari succesion of Middle Cambrian - Lower Ordovician age: San Vito formation (SVI), Metagonglomerati di Muravera formation (MRV) and Monte Santa Vitoria Formation (MSV) all these formations outcropping close the study area;

- silici-clastic succession of Middle Ordovician (Muzzioni formation, MUZ)

- meta-rhyolithic rocks, with a porphiric texture and phenocrysts

of quartz and feldspar (Porfiroidi, PRF);

- a silici-clastic to carbonate succession of Upper Ordovician - Lower Carboniferous age, with metaarkose (Metarcose di Genna Mesa formation, MGM), metasiltstones and marl of Riu Canoni formation (ACN), marls, black shales and metalimestones of Scisti neri a Graptoliti formation (SGA);

while the “klippe” of Meana Sardo Unit is characterized by:

- a volcano-sedimentary succession of Middle Ordovician age, with metatuffites, metavolcanoclastites with interlayered metaepiclastites (Monte Santa Vitoria Formation, MSV);

- a volcanic metabasic rock belonging to the upper part of the the Orroeleddu formation).

Structural setting

The Variscan tectonic evolution of the study area is characterized by a shortening phase (D1) related to the continent-continent collisional stage, that produced the nappe stack, and by a later phase related to post-collisional extension (D2).

The main D1 structures are kilometric recumbent isoclinal folds (Brecca Sinclinal - SB and Gibixedda Anticlinal - GA) facing to SSW and plunging to NE, with a well developed axial plane foliation (S1) associated to a low-grade blastesis, and the overthrust of the Meana Sardo Units (with top-to-south transport direction). Geological cross sections C-C’ across the Gibixedda area and B-B’ acrosse the Bruncu Nieddu zone show some of these folds and the main thrust. The S1 axial plane foliation, depending on the lithotype, could be a slaty cleavage in phyllites or a non-continuous cleavage in quartzites. It is the main planar surface at outcrop scale and usually transposes the original bedding. Between the Meana Sardo Unit and the underlying Gerrei Unit a thin mylonite zone developed during D1 deformation crops out.

In the study area all of the D1 structures are affected by late shortening events (Late D1) that produced upright antiforms and synform, with a wavelength of about 800 m, amplitude around 100m and trending E-W. During the post-collisional D2 phase all of the nappe stack described above was uplifted and extended and the antiformal structures were enhanced by low-angle ductile normal shear zones. Inside the normal shear zone, asymmetric folds developed, and they overturned away from the hinge zone of the antiforms (Funedda et al, 2011) these folds outcropping close to Masala zone, in the same time high angle normal

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fault (Antoni Santu Fault -ASF) have been activated. The D1 Meana Sardo Thrust (MST) then had been reactivated as a low angle normal faults. Also related to post collisional evolution are D3 upright folds, trending NNW-SSE. These are best exposed in the Bruncu Nieddu zone.

Conclusions

A detailed geological field mapping has allowed obtaining new data on:

- minor structures of the D1 stage, which allowed to determine the real thickness of the formations involved;

- the real thickness of Porfiroidi due to discovery of Su Muzzioni formation in the valley of the Riu Brecca ;

- the overturned folds that post-date D1 structures are joined with fault zones related to ANF and antiformal culmination of D2 phase.

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The "Leptyno-Amphibolite" Complexe in the asirana Island (Sardinia): insights into a long-lived peri-Gondwanan basement by U-Pb geochronology and geochemistry

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In northern Sardinia, the inner complexes of the Southern Variscan belt comprise the Medium Grade (MGMC) and the migmatitic High Grade Metamorphic Complexes (HGMC - Carmignani *et al.*, 1992; 1994). Both derived from eo-Variscan metamorphism of Ordovician igneous protoliths emplaced within undated sedimentary successions (Cortesogno *et al.*, 2004; Palmeri et al. 2004; Giacomini *et al.*, 2006, Oggiano *et al.*, 2010). The metamorphic evolution of these rocks roughly records the continental collision and the exhumation of Variscan continental roots.

Along the Posada – Asinara tectonic line, the occurrence of eclogitic relicts with N-MORB affinity provides evidence for a small oceanic basin developed between Gondwana and Armorica (Cappelli *et al.*, 1992; Carmignani *et al.*, 1992, 1994), or between Gondwana and a ribbon-like terrane detached from the northern margin of Gondwanaland (Stampfli *et al.* (2002) ;von Raumer *et al.* (2002, 2003)

Recent papers based on structural, geochronological (Frassi 2006; Giacomini *et al.*, 2006) and geochemical (Giacomini *et al.*, 2006) data discussed the presence of an oceanic suture in Sardinia. In addition, Giacomini *et al.* (2006) have suggested a possible ensialic evolution between the Hun terrane and the northern margin of Gondwana as a consequence of the early closure of Palaeotethys before spreading.

Therefore, addressing the metamorphic evolution and its timing within the Posada Asinara line may get useful information on the collisional history.

The kilometre-thick mylonitic mélange zone developed along the Posada Asinara line shows ductile to brittle deformation structures. Two main deformation phases related to crustal thickening in compressional (D1) or partitioned oblique (D2a, b) tectonic regime, followed by a later extensional event (D3), have been recognized. In spite of a general HT/LP metamorphic overprint linked to D3, a relic Barrowian zoneography is still detectable (Carosi *et al.*, 2004). The Barrowian assemblages are pre- to syn-kinematic with respect to the D2 deformation phase, and predate both the late post-nappe shortening (D2b) and the post-collisional extension D3.

In the Asinara Island, juxtaposed tectono-metamorphic units represent an intermediate to high-grade granulite crustal section (Oggiano and Di Pisa, 1988). The deeper level is exposed at Punta Scorno, where a basic complex made of amphibolites (Ca-amphibole + plagioclase + garnet) interleaved by cm to meters thick leucocratic (quartz + plagioclase + garnet) layers occurs. The more mafic part of the complex includes also sparse amphibole-dominated ultrabasic and meta-gabbro layers with relic coarse-grained hypidiomorphic textures.

Peak metamorphic conditions in the mafic terms were estimated under granulite facies (≈740°C and P exceeding 0.8 GPa); peak assemblages are frequently re-equilibrated at amphibolite facies conditions (500-600°C and P 0.3-0.4 GPa; Di Pisa *et al.*, 1993). The Punta Scorno complex is associated with a high-strained orthogneiss deformed under high-grade metamorphic conditions (Sillimanite + K-feldspar ± garnet). The contact between the orthogneiss and the mafic/felsic layered complex is parallel to the main schistosity.

The leucocratic layers of the basic complex and the associated orthogneiss were selected for U-Pb dating on zircons separates by ELA-ICP-MS (excimer laser ablation Inductively coupled plasma mass spectrometry) carried out at CNR – IGG Pavia.

The preliminary results highlighted several populations of U-Pb Concordia ages: in the orthogneiss, an early Palaeoproterozoic event at 2006 ± 25 Ma and a younger Neoproterozoic (Pan African?) between 623 ± 13 and 579 ± 12 Ma can be inferred. A subsequent early-Ordovician interval is recorded between 478 ± 11 and 437 ± 11 Ma, followed by a Devonian event at 413 ± 11 and 403 ± 7.4 Ma.

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In the amphibolite complex with granulite relics, each leucocratic layer yielded different ranges of Concordia ages, starting from Neoproterozoic (stepped between 672 ± 12 and 588 ± 16 Ma) until a Cambrian system closure (514 ± 22 to 506 ± 15 Ma). An Early Ordovician group of Concordia ages spans between 491 ± 13 and 474 ± 12 Ma. Late Ordovician - Early Silurian ages fall in the 461 ± 10 to 435 ± 12 Ma time interval. Some Devonian and Carboniferous age values are also recorded.

Preliminary Sm-Nd data (Castorina *et al.*, 1996) consistently suggest fractionation from a DM source, with possible metasedimentary contamination.

Based on these preliminary results, some considerations can be drawn: i) the orthogneiss recycles an ancient basement, older than Neoproterozoic, ii) the U-Pb system of the orthogneiss records a different sequence of events than the basic complex, iii) within the basic complex, each felsic layer shows different populations of ages. This points to a complex, long-lasting, sequence of metamorphic events involving several episodes of partial melting. This could occur for instance by several steps of partial melting within a deep crust; iv) the orthogneiss and the amphibolite shared a common evolution since the Devonian-early Carboniferous.

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Geodynamic regimes of post-subduction collision: numerical modeling and implications for the origin of ultrahigh-temperature metamorphic complexes

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Using two-dimensional thermomechanical models with spontaneously moving plates we obtained and investigated a number of major geodynamic regimes of oceanic-continental subduction culminated by continental collision. Obtained self-consistent geodynamic scenarios reproduce a number of realistic tectonic and magmatic events characteristic for this geodynamic setting: backarc and intraarc extension, ultrahigh-pressure sedimentary plumes, batholithic intrusion emplacement into the crust, magmatic arc accretion, continental subduction, oceanic slab breakoff and continental mantle delamination. Results of our models have several important implications for the origin of ultrahigh-temperature metamorphic complexes that allways postdate major ultrahigh-pressure events taking place in the early stages of collision. Ultrahigh-temperature metamorphism typically associates with opening of various size asthenospheric windows under continental collision zones and is especially common in case of continental mantle delamination. Several geodynamic modes of this process are identified in which narrow and wide orogens undergo mantle delamination at different time scales in relation to the initial collision. Delamination propagates along the Moho of the subducted plate together with the retreating trench, provided that slab pull is sufficient, and that the meta-stability of the crust-lithospheric mantle joint is initially overcome. Topography is an instantaneous response to delamination and migrates with the singularity point. Early surface exposure of high-pressure rocks is followed by exhumation of high-temperature, partially molten rocks. Convective stabilization of delamination outlasts slab break-offs and impedes renewed build-up of mechanically strong lithospheric mantle by cooling, on time-scales of tens to hundreds million years that are thus significantly larger than conductive cooling would predict. Results of numerical models compare well with a number of modern and ancient collisional orogens.

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The Bazar shear zone (NW Spain): Microstructural and Time-of-Flight neutron diffraction analysis

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Unraveling the kinematic evolution of tectonic contacts it is crucial to understand mass distributions across an orogen. Reactivation of structures is common and might lead to the misunderstanding of the geodynamic context. As a consequence, unequivocal determination of the shear sense is required in major contacts (Gómez Barreiro *et al.*, 2010). The Bazar Shear Zone (BSZ) represents a major regional contact between two allochthonous units in the Ordenes Complex (NW Spain), the metagabbroic Monte Castelo Unit, with magmatic arc affinities above, and the Bazar ophiolite, below (Martínez Catalán *et al.*, 2009; Gómez Barreiro *et al.*, 2007). Previous regional works interpreted the contact as a top-to-the E thrust related to the formation of the Variscan tectonic pile. New crystallographic preferred orientation or texture (TOF-neutron diffraction) and shape fabric data in mylonitic amphibolites suggest that the BSZ recorded a different flow direction, with a top-to-the S shearing. Microstructural analysis suggests a complex interaction of frictional and viscous mechanisms within the shear zone. Mechanical and regional implications are discussed.

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Detrital Zircon U/Pb ages in synorogenic deposits of the Internal Zones of the Iberian Variscan Massif and their significance in the orogenic evolution

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The Variscan synorogenic rocks present extensive exposures in the external parts of the Iberian Variscan massif, namely the Cantabrian and South Portuguese Zones. Nevertheless, in the internal part of the chain this type of sedimentary bodies was preserved exclusively in the nucleus of the main synformal structures. A total of 13 samples were gathered for study of the U-Pb ages in sedimentary zircons belonging to the internal part of the Iberian Variscan Massif: 7 samples collected and analyzed in this research are considered together to previous 6 samples analysis results which are now reinterpreted. Six of them belong to the autochthonous Central Iberian Zone, whereas the rest were collected in one structural unit intermediary between the autochthonous Central Iberian Zone and the far travelled allochthonous domain of the Galicia Trás-os-Montes Zone named Parautochthonous. This intervening unit displays pre-orogenic sedimentary characteristics similar to the Central Iberian Zone, but some authors considered it as the lowermost part of the Galicia Trás-os-Montes Zone by it allochthonous nature. All the zircons have been dated by laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) at MacQuarie University, in Sidney.

Results support the following points: 1) the youngest sedimentary zircon age found in each spot is lower towards the most external syncline, supporting a space-time evolution of the synorogenic groove towards the external areas of the Variscan Belt; 2) the presence of Variscan zircons in the Parautochthonous Unit corroborates the existence of synorogenic deposits in this allochthonous slice; 3) some samples in the Parautochthonous do not produce any Variscan zircon. This could be explained by the scarcity of zircons in the selected samples or because they are pre-orogenic sedimentary units not completely identified yet due to the Parautochthonous structural complexity.

The existence of synorogenic stratigraphic sequences in both, the autochthonous Central Iberian Zone and the Parautochthonous structural unit is more one sedimentary resemblance between the autochthonous and allochthonous units. This similitude supports the previously stated proposal that both structural units belongs to the same continental margin: Gondwana.

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Late-Post Variscan buckling of the Ibero-Armorican Arc: The lithospheric scale tale

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The kinematic evolution and the timeframe for the development of the Ibero-Armorican Arc (West European Variscan Belt), as a bend of a previously more linear orogenic belt, has recently been constrained structurally and paleomagnetically as an orocline in the Cantabrian Zone, northern Iberia (the core of the arc) (Pastor-Galán *et al.*, 2011; Weil *et al.*, 2002, 2010). According to recent evidence, oroclinal generation took place in the uppermost Carboniferous-lowermost Permian, between about 310 and 295 Ma, and, among other interpretations (*i.e.* Martínez-Catalán, 2011), it is considered to have been ultimately caused by the self-subduction of the Pangean global Plate (Gutiérrez-Alonso *et al.*, 2008). Given the large scale of this plate-scale structure, it is bound to have had a profound effect on the lithosphere and consequently the effects of the involvement of the lithosphere should be recognized in structures and geological features of different nature and at different scales developed coevally with the orocline.

One of the most striking features found in the West European Variscan Belt is a large strike-slip shear zone/fault system, characterized as “Late-Variscan”, that runs parallel to the broad structural trends around the Iberian Armorican Arc. ^{40}Ar*-^{39}Ar ages of micas grown during fabric development in five shear zones of this system, both dextral and sinestral, have yielded ages that, within error, cluster at 307 Ma, suggesting that their development took place within the time frame of oroclinal bending constrained by paleomagnetism, that is to say, coeval with the formation of the Ibero-Armorican Arc.

In addition, new U-Pb zircon ages for 19 granitoid intrusions of western Iberia, which have also been classically considered as “Late Variscan”, have yielded crystallyzation ages that significantly cluster around 307 Ma (ranging from ca. 309 to 297 Ma) in the outer arc of the orocline, whereas younger granitoid crystallization ages (ca 303-290 Ma) are found in the core of the orocline.

According to our new data and other data from the literature, we interpret the development of the strike-slip shear zone system and the origin of the magmatic pulse at ca 307 Ma as being related to the initiation of the orocline development. These new ages constrain deformation in the outer arc to be penecontemporaneous with thrust-sheet rotations in the Cantabrian Zone as determined with paleomagnetic and structural data. The 307 Ma strike-slip shear-zones are inferred to have accommodated the vertical axis crustal-block rotations needed to accommodate oroclinal bending, while the 307 Ma granitoids in the outer arc represent decompressive melting during the mechanical thinning of the mantle lithosphere below the outer arc during bending. Younger granitoid ages in the inner arc are interpreted to represent orocline triggered lithospheric delamination in the tectonically-thickened inner part of the orocline (Fernández-Suárez *et al.*, 2000; Gutiérrez-Alonso *et al.*, 2004; Gutiérrez-Alonso *et al.*, 2011a).

This process is bound to replaced old mantle with new mantle and therefore to be capable of substantially modifying the isotopic signature of the SCLM. In the West European Variscan Belt (WEVB), Phanerozoic (500 to 10 Ma) mantle-derived rocks of different ages are abundant and Sm-Nd isotopic data from these rocks can be used as tracers to compare the composition of the sub continental lithospheric mantle before and after the Late Paleozoic Variscan orogeny. The contrasting Sm-Nd isotopic signature between pre-285 Ma and post-285 Ma mantle-derived mafic rocks suggests that the sub-continental lithospheric mantle (SCLM) under the Iberian Massif was extensively replaced in Early Permian times coevally with the aftermath of the Ibero-Armorican Arc generation (Gutiérrez-Alonso *et al.*, 2011b).

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Paramagnetic metamorphic mineral assemblages controlling AMS in low-grade metasediments deformed by the 'Bretonian event' in Central Armorica

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The Armorican Massif in western France exposes a particular segment of the late-Palaeozoic, Pan-European Variscan orogen, that is commonly considered to be dominated by regional wrench tectonics. Between the two major, late-Variscan, transcurrent shear zones, the South-Armorican Shear Zone (SASZ) and the North-Armorican Shear Zone (NASZ), the Central Armorican Domain (CAD) is located. This domain is composed of a Cadomian basement and its Neoproterozoic and Palaeozoic metasedimentary cover (Fig. 1c). Linear belts (Elorn, Monts d'Arrée, Montagnes Noires) within the CAD are commonly considered as reflecting this wrench-dominated deformation. An extensive structural analysis of the Monts d'Arrée Slate Belt (MASB) demonstrates, however, that this belt primarily reflects coaxial, contraction-dominated deformation, resulting from a top-to-the-NW shearing on top of a weakly dipping décollement (Van Noorden *et al.*, 2007). The deformation resulted in NW-verging folds and a pervasive cleavage development and largely occurred prior to the emplacement of the Carboniferous granitoid complexes of Commana and Huelgoat. Therefore, the deformation of the MASB can be related to the late Devonian-early Carboniferous 'Bretonian' orogenic event (*cf.* Rolet, 1982). In fact, a regional study of the deformation in the Palaeozoic metasediments, indicates that the 'Bretonian' event affects the entire northwestern part of the CAD. Moreover, the inferred kinematics are consistent with the top-to-the-NW thrusting and nappe stacking as inferred in the Léon Domain, situated to the northwest of the CAD (*cf.* Rolet *et al.*, 1994, Fig. 1d). Therefore, the 'Bretonian' event can be linked to the closure of the Rheic Ocean and the continental collision of the Léon Domain with the CAD (Sintubin *et al.*, 2008).

A regional analysis of the rock magnetic properties is performed, in order to the test the validity of the contraction-dominated model for the CAD. Due to crystallographic and/or grain-shape dependent anisotropy of the constituent grains, natural rocks are usually magnetically anisotropic. Measuring the anisotropy of the magnetic susceptibility (AMS) allows the quantification of the anisotropy of the internal rock fabric. For the present work, the AMS of a specific lithology within the Lower Palaeozoic Plougastel Formation (i.e. homogeneous siltstone beds) is determined in samples from five different sites that represent the different tectonometamorphic contexts of the CAD (Fig. 1c). Two of these sites are located in the fold-and-thrust belt of the Crozon peninsula (upper-crustal setting, sites 1 & 2) and three sites are located in the high-strain slate belts of the inland CAD (middle-crustal setting, sites 3, 4 & 5).

Despite the fact that we always sampled the same characteristic homogeneous siltstone beds on the various sites, different paramagnetic mineral assemblages control the AMS on the Crozon peninsula sites (sites 1 & 2), compared to inland sites (sites 3, 4 & 5). The Crozon sites predominantly show white mica and chlorite, whereas the inland samples contain white mica, chloritoid and a minor amount of chlorite. These different assemblages can be explained by the difference in the grade of regional metamorphism, i.e. an anchizonal grade for the Crozon peninsula and an epizonal grade for the inland area of the CAD. As the AMS magnitude depends on the intrinsic AMS of the different mineral assemblages, the AMS evolution of the Crozon peninsula and inland sites cannot be compared directly.

The present work demonstrates that the AMS of homogeneous siltstone beds in the various sites can be attributed to differently oriented mineral populations: some which may be oriented along the cleavage, some along the bedding and possibly some oblique to both cleavage and bedding. We propose that these composite fabrics results from the progressive superposition of a cleavage-parallel fabric on a pre-existing bedding-parallel compaction fabric. A particular fabric in site 4 is the only one, in which the initial compaction fabric is seemingly preserved. Examples from the Appalachian fold belt (Graham, 1966) and the Alpes Maritimes (Kligfield *et al.*, 1983; Siddans *et al.*, 1984) have

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shown that this evolution can be tracked, quantitatively, by changes in the shape parameter (T) and the corrected degree of anisotropy (PJ), *i.e.* an initial oblate, bedding-parallel compaction fabric evolves to a prolate, intermediate fabric with low PJ and subsequently towards a triaxial to oblate, cleavage-parallel tectonic fabric with a gradually increasing PJ. Our data show a hockey-stick/boomerang shaped pattern on a plot of T versus PJ for both sites 1 & 2 and sites 3, 4 (partly) & 5 (Fig. 1e). We assume that sites 1 & 5 correspond to the intermediate fabric stage and that sites 2, 3 & 4 (partly) reflect more the tectonic fabric stage. Based on this conceptual model, we argue that, for the Crozon peninsula site 2 has a higher strain compared to site 1, and that, for the inland CAD, sites 3 & 4 (partly) have a higher strain compared to site 5. For both the Crozon peninsula and the inland CAD, this would mean an increase in strain from south to north.

However, the analysis has further shown that for each site the composition of the samples has an influence on the AMS parameters. Firstly, a comparison of the (low-field) AMS with the computed paramagnetic component of high-field AMS shows that the AMS magnitude in the specimens of site 3 and those of site 5 with a relatively high PJ, is altered by a small ferromagnetic (*s.l.*) contribution. Secondly, an influence of the quartz/white mica ratio can be suggested from the observed relationship between white mica content and PJ and T for sites 2, 3 & 5, and from the inverse relationship between quartz content and PJ and T for sites 1, 2, 3 & 5. We attribute these relationship to non-platy quartz that produces areas sheltered from effective stress and acts as a matrix support and thus, disrupts the fabric intensity.

In summary, a regional study of the composite magnetic fabric of homogeneous siltstone beds of the Plougastel Formation in the Central Armorican Domain shows a prolate, intermediate fabric in the southern sites, i.e. site 1 on the Crozon peninsula and site 5 in the inland CAD, and a triaxial to slightly oblate tectonic fabric in the more northern sites, i.e. site 2 on the Crozon peninsula and sites 3 & 4 (partly) in the inland CAD. This suggests a northward-increasing strain gradient for the CAD, in line with the overall geodynamic model of the ‘Bretonian’ convergence of the CAD with the Léon Domain. However, the observed differences in AMS parameters cannot be compared quantitatively in terms of tectonic strain due to (1) differences in the controlling mineral assemblage, (2) an influence of the quartz/white mica ratio on the AMS parameters and (3) a ferromagnetic (*s.l.*) influence on the AMS parameters of site 3 and partially site 5.

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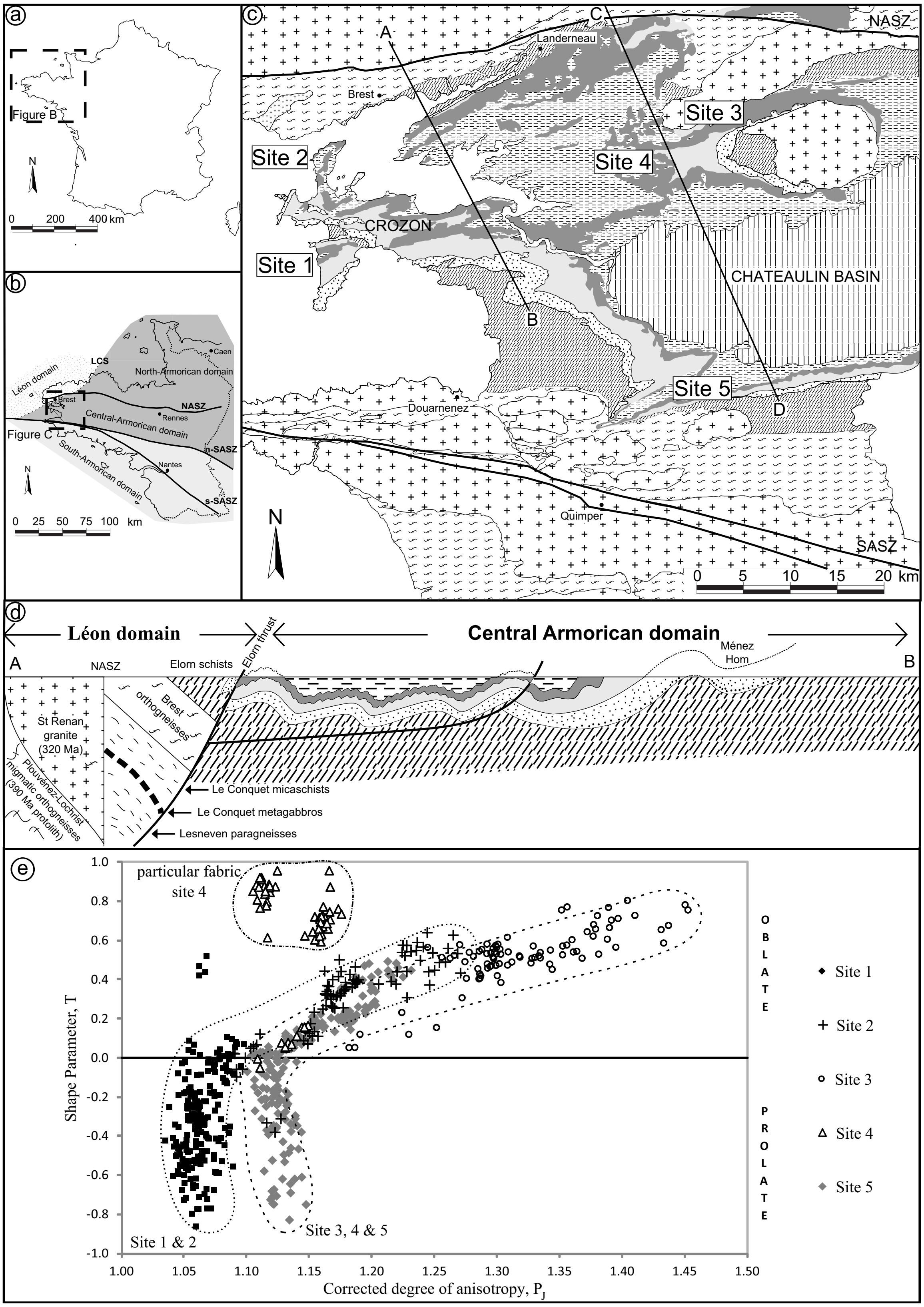

Fig. 1.- (a) Location of study area in France. (b) Schematic map showing the subdivision of the Armorican Massif into the North Armorican Domain, the Léon Domain, the Central Armorican Domain and the South Armorican Domain. (c) Geological map of the Central Armorican Domain with indication of the five investigated sites: site 1- Lostmarc'h, site 2 - Capucins, site 3 - Roc'h Trévezel, Monts d'Arrées, site 4 - Saint Rivoal and site 5 - Roche du Feu, Montagnes Noires. (d) Schematic structural cross-section of the Léon Domain and the Central Armorican Domain in the inland area (after Rolet et al. 1994 and Sintubin et al. 2008). (e) Plot of T versus PJ, showing a hockey-stick/boomerang shaped pattern both for site 1 & 2 (controlled by an anchizonal mineral assemblage) and for site 3, 4 & 5 (controlled by an epizonal mineral assemblage). Abbrevations: LCS - Le Conquet Suture; NASZ - North Armorican shear zone; n/s-SASZ - northern/southern branch of the South Armorican shear zone.

What drives remelting of thickened continental crust in the Bohemian Massif?

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Deep subduction of the Earth's crust and attendant (ultra-) high-pressure metamorphism have far reaching consequences for fractionation of many elements and stable isotopic systems. It may lead to metasomatism, or direct contamination of the adjacent mantle, as the specific (U-HP) metamorphic reactions can release supercritical, ultrapotassic fluids (*e.g.*, Schreyer, 1999). Moreover, it may introduce large amounts of LILE to the lithospheric mantle, including K, U and Th, which can produce, over time, much thermal energy by radioactive heating.

The Variscan orogen in the Bohemian Massif has been recently interpreted as having been driven by Andean-type subduction of the Saxothuringian Ocean (Schulmann *et al.*, 2009). The magmatic arc produced normal to high-K calc-alkaline magmas over the period of c. 375 to 346 Ma (Žák *et al.*, 2011 for overview). The oceanic subduction passed into deep underplating of the mature continental crust under the Teplá-Barrandian and Moldanubian autochthon (O'Brien, 2000; Konopásek and Schulmann, 2005). This refractory material dominated by Ordovician rift-related, mostly felsic metaigneous lithologies is thought to have been relaminated to the base of the Moldanubian crust (Janoušek *et al*., 2004; Janoušek and Holub, 2007; Lexa *et al.*, 2011). Its arrival to the root of the continental arc is bracketed at ~346 Ma by the high-K calc-alkaline syn-tectonic plutons of the Central Bohemian Plutonic Complex showing conspicuous evidence of magma mixing with monzonitic magmas derived from enriched mantle source (Janoušek *et al.*, 2010b; Žák *et al.*, 2012).

Over the time, granulite/eclogite-facies metamorphism of the subducted continental rocks produced felsic garnet-kyanite-mesoperthite granulites, forming, along with anatectic orthogneisses, the bulk of the high-grade Gföhl Unit in the Moldanubian Domain (Janoušek *et al.*, 2004b; O'Brien, 2008). The metamorphic climax took place at ~340 Ma (Janoušek and Holub, 2007; Friedl *et al.*, 2011 for review). The mostly undepleted LILE inventory (except for U, Th, Cs, Pb and Li) of the HP felsic granulites documents that the metamorphic fluid/melts loss was severely limited. This, in accord with uniformly low Zrn and Mnz saturation temperatures (~750°C), supports the thermodynamic models assuming the presence of < c. 10-15 vol. % melt only (Janoušek *et al.*, 2004; Lexa *et al.*, 2011; *cf.* Jakeš, 1997; Kotková and Harley, 1999, 2010).

Lexa *et al.* (2011) modeled the fate of felsic radioactive layer with a heat production corresponding to that in the Saxothuringian felsic metaigneous rocks located at the double-thickened Moho depth. After thermal incubation of 10-15 Ma it would yield heat sufficient to convert the underplated felsic metaigneous crust into granulites via dehydration melting and melt segregation. The (limited) Viséan melt loss is thought to have been responsible for eventual expulsion of radioactive elements, switching off the internal heat source. Appearance of weak and light material within lower crust would trigger gravitational instability and lead eventually to mid-crustal emplacement of the orogenic lower crust.

Soon thereafter, the metasomatised/contaminated lithospheric mantle produced characteristic ultrapotassic magmas (late-syntectonic durbachite series (~342-339 Ma) and less deformed, or even post-tectonic, two-pyroxene syenitoids (~336-335 Ma) - Holub, 1997; Janoušek *et al.*, 2010a and references therein). As a consequence, they not only share with the granulites mutually complementary depletions/enrichments in some trace elements (Cs, Th, U, Pb and Li) and have crustal-like Sr-Nd isotopic signatures, but are also closely related in space and time (Janoušek and Holub, 2007).

Following the crustal collision and the thermal peak of the regional metamorphism, the Moldanubian Zone was penetrated by voluminous anatectic plutons of the Moldanubian Plutonic Complex (MPC). The precise U-Pb Zrn and Mnz geochronology indicates that over its 80 % was constructed during the narrow time period of ~331-323 Ma (Gerdes *et al.*, 2003), forming coarse-grained, Kfs-phyric

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Weinsberg granitoids (331-323 Ma) and porphyritic two-mica Eisgarn granites (328-326 Ma). Finally, small volumes of fine-grained I-type granites-granodiorites intruded at 319-300 Ma.

Thus there seems to be a significant time gap between the mid-crustal emplacement of the hot granulite bodies with ultrapotassic plutons on the one hand, and widespread partial melting of the Moldanubian middle crust, in particular the Monotonous Group paragneisses, on the other. As the amount of basic magmas spatially associated with the Weinsberg and Eisgarn granitic suites is severely limited, ruled out is not only advection of heat by mantle-derived magmas, but also the mantle processes such as slab break off and lithospheric delamination (Henk *et al.*, 2000). The preferred scenario remains internal heating by radioactive decay (Gerdes *et al.*, 2000) associated with horizontal conductive heat transfer resulting from equilibration of perturbed thermal field. We suggest that the advection-dominated vertical material transfers driven by gravity redistribution operated along two major diapir-like megastructures and caused burial of colder and fertile metapelitic rocks in marginal synforms (Warren and Ellis, 1996). These metasediments may have become partially molten during the thermal relaxation, producing typical crustally-derived (S-type) granitoids. In this contribution, we test various length and time scales of gravity overturn processes and the influence of heat redistribution within thickened root along with mantle-hosted thermal anomaly.

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The Cambrian/Ordovician, Devonian/Carboniferous and Permian magmatic rocks - indicators of crust evolution in the Variscan basement of the Western Carpathians

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The Western Carpathians as a part of Stille's (1924) Neo-Europa form a piece of an extensive, equatorial, orogenic belt extending from the Atlas Mountains in Morocco, through the Alps, Dinarides, Pontides, Zagros, and Hindukush to the Himalayas and to China. They are the northernmost, E-W trending branch of this Alpine belt, linked to the Eastern Alps in the west and to the Eastern Carpathians in the east. The present-day structure of the Western Carpathians was derived from the Late Jurassic to Tertiary (Alpine) orogenic processes connected with the evolution of the Tethys Ocean, in a long mobile belt sandwiched between the stable North European Plate and continental fragments of the African origin. Albeit the Western Carpathians belong to Neo-Europa, their pre-Mesozoic basement rocks represent distinctive analogues of the basement ones known in the Meso- and Paleo-Europa (Stille, 1924). A typical feature of the Carpathians mobile belt is the presence of huge reworked slices of the pre-Alpine crystalline basements within the Mesozoic and Cenozoic sedimentary successions that have been deformed into large-scale nappe structures. The polyorogenetic history of pre-Mesozoic basement is characterised by juxtaposition of various terranes and/or blocks that in most cases originated at the Gondwana margin due to multistage tectonic evolution with large-scale nappe and strike-slip tectonics, what resulted in the European Variscan collisional orogeny. The pre-Alpine crystalline basement crops out mainly in the central Western Carpathians (CWC), heart of the Western Carpathians, consisting of three principal crustal-scale superunits from north to south - the Tatricum, Veporicum and Gemericum. The igneous rocks of various origins form an important constituent of these basement fragments. The Variscan HT/MP metamorphism with concomitant widespread granitic magmatism heavily overprinted pre-Variscan basement precursors and partly masked polyorogenic history of the CWC.

There were identified following pre-Variscan igneous rocks within the CWC basement:

a) Cambrian to Ordovician - layered (leptynite) amphibolite complex (LAC) consisting of layered amphibolites enclosing lenses of retrogressed eclogites and metaultramafics;

b) Cambrian to Ordovician - granitic to tonalitic orthogneisses (OG) with lenses of granulites newly rediscovered after 100 years, often associated to the LAC;

c) Devonian - volcano (ophiolite)-sedimentary suite (DVS) locally with evolution of the iron-bearing Lahn-Dill-type volcano-sedimentary complexes.

The Variscan dioritic to leucogranitic rocks (Upper Devonian to Permian in age) vastly penetrated these pre-Variscan magmatic/metamorphic suites.

LAC suite dated by SHRIMP at 505 to 480 Ma (Putiš *et al.*, 2009), P-T estimates indicate for standard banded amphibolites with garnet and clinopyroxene-bearing eclogite relics, high grade (1.0~1.4 GPa and 700~800°C) conditions, whereas omphacite + garnet + quartz + phengite bearing relics show HP conditions up to 2.5 GPa and 700°C (Janák *et al.*, 1996, 2007). These amphibolitic rocks having geochemical characteristics SiO_2 = 46~57 wt. %, with a lower ratio of Rb/Sr = 0.1~0.3, and $^{87}Sr/^{86}Sr(i)$ = 0.704~0.706, $\varepsilon Nd_{(i)}$ = 3.33~6.32, lower values of $\delta^{18}O_{(VSMOW)}$ = 5.8~7.3‰ and $\delta^{34}S_{(CDT)}$ = -0.26~1.86‰, as well as Pb isotopes $^{206}Pb/^{204}Pb$ = 18.16~18.62 and $^{207}Pb/^{204}Pb$ = 15.54~15.66 were originated from mantle dominated source.

OG suite dated by single grains CLC TIMS and SHRIMP at 515 to 460 Ma (Gaab *et al.*, 2006; Putiš *et al.*, 2009), metamorphic conditions were similarly masked by the Variscan migmatization reaching up to ca. P = 0.8~1.0 GPa and T = 700~800°C. Geochemical characteristics: SiO_2 = 70-77 wt. %, K_2O/Na_2O = 0.54~1.38; Rb/Sr = 0.8~2.3; slightly enriched contents of Ga, Y, Th, U, and Co, whereas Sr and Zr have depleted. Generally, have peraluminous character (ASI = 1.0~1.4). REE's have low values and show slightly U-shaped pattern with a pronounced negative Eu-anomaly. Initial $^{87}Sr/^{86}Sr(i)$ values range between 0.712 and 0.725

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and $\varepsilon Nd_{(i)}$ between -2.6 and -5.0 are suggesting rather for their crustal source alike their whole rocks Pb/Pb isotopic characteristics ($^{206}Pb/^{204}Pb$ = 19.58~20.65, $^{207}Pb/^{204}Pb$ = 15.67~15.76 and $^{208}Pb/^{204}Pb$ = 38.95~40.10) in fact feed-back from the lower crustal metaigneous source can be seen.

DVS suite dated by SHRIMP at 390-370 Ma (Putiš *et al.*, 2009), have distinctive lower P/T conditions ca. 300~350 MPa and 500~550°C. Geochemical characteristic is compatible to the relic of the upper part of the oceanic crust, composed of deep-water sediments, basalts, gabbros and gabbroic differentiates. Most basalts have chemical compositions very close to that of typical normal middle ocean ridge basalts with $\varepsilon Nd_{(i)}$ = ca. +9 (Ivan *et al.*, 2007).

The Variscan granitic rocks were related to distinct sources and/or geotectonic position from subduction-related I-type, through syn-collisional S-type to late- and post-orogenic A- and Ss-type granites. A complex study integrating petrological, geochemical and/or isotope data have been performed during last decades, resulting in distinguishing of following rock suites: a) mafic suite gabbros & diorites rocks (M-s) intrusive age 370 Ma; b) biotite granodiorite to hornblende-biotite tonalite I-suite (I-s) with intrusive age 365-355 Ma; c) two micas granodiorites to granites S-suite (S-s) intrusive age 360-350 Ma; d) biotite granodiorite to granite A-suite (A-s) intrusive age 270-260 Ma; and e) suite of specialized ore-bearing, biotite granodiorite to biotite-muscovite granite (S_s-s) intrusive age 265-250 Ma. The Sr isotopes with $^{87}Sr/^{86}Sr_{(i)}$ values 0.702-0.706 (M-s), 0.704-0.709 (I-s), 0.706-0.714 (S-s), 0.705-0.709 (A-s), and 0.707-0.725 for Ss-suite suggest for significant crustal recycling and mantle related influence for mafic varieties of the CWC granites. Similarly Nd isotopic characteristics with $\varepsilon Nd_{(i)}$ values 0.9 to 5.8 (M-s), -2.8 to +2.2 (I-s), -7.0 to -1.3 (S-s), -3.1 to 1.9 (A-s), -4.4 to -0.2 (Ss-s) indicate recycling of vertically zoned lower and/or middle crust with significant contribution from basic metaigneous rocks. The stable isotopes with $\delta^{18}O_{SMOW}$ (in ‰) for M-s = 6.6-8.4; I-s = 7.6-9.9; S-s = 9.0-11.3; A-s = 7.8-8.0; and S_s-s = 9.9-11.5 together with $\delta^{34}S_{CDT}$ (in ‰) for I-s = -2.9 to 2.6; S-s = -1.0 to 5.7; A-s = -2.0 to -0.7; and S_s-s = 4.5 suggest for mixed sources in metasedimentary and basic metaigneous rocks. The Li isotopic values $\delta^{7}Li_{SVEC}$ (in ‰) M-s suite = -0.5~-3.7; I-suite = -1.2~0.5; S-suite = -3.2~7.0; A-suite = 4.7~6.6; S_S-suite = -0.42~1.22 look to have a meta-igneous/metapelitic parentage with addition of metasomatised mantle for M-s and A-s (Magna *et al.*, 2010). The zircon Hf isotope study of the CWC granitic and related rocks brings following $\varepsilon Hf_{(t)}$ values: M-s gabbro = -2.98~2.83; I-suite tonalites = -0.3~7.48; S-suite granites = -7.79~2.51; A-suite granites = 0.19~9.96; S_S-suite granites = -5.35~-0.75 indicating substantial crustal recycling and/or significant participation of mantle material as potential source for M-s, I-s, and A-s rocks types. Noteworthy, that mantle contribution to their genesis has rather character of re-melted mantle derived mafic lower crust than fresh input of juvenile mantle melt to the Devonian (± Permian) subduction zone what suggest the Hf model ages of zircons from these rocks. The Hf DM crustal residence model ages vary for the Western Carpathians M-s varying in 0.9~1.1 Ga, I-s tonalite 0.9~2.9 Ga, S-s granites 0.9~1.75 Ga, A-s granites 0.7~1.5 Ga; and SS-suite 1.17~1.43 Ga. However, these Hf model ages are slightly older then WR two stages $Nd_{(DM)}$ model ages with following values: M-s = 0.62~0.9 Ga, I-s = 0.86~1.39 Ga, S-s = 1.15~1.6 Ga, A-s granites 0.85~1.03 Ga; and SS-suite 1.01~1.40 Ga. Generally, two-stage Depleted Mantle Nd model ages (T^{Nd}_{DM}) of 0.6~1.75 Ga (mostly >1 Ga) resemble upper intercept ages from U-Pb zircon single grain dating by TIMS, SIMS and SHRIMP (Poller & Todt, 2000; Poller *et al.*, 2005; Putiš *et al.*, 2009; Kohút *et al.*, 2009, 2010), indeed some restite zircons grains are in core as old as 1.9~2.6 Ga. Ongoing discussions and correlations suggest for similarity to the Variscan evolution of the Bohemian Massif, the Massif Central and the Iberian Peninsula in microcontinents derived from the northern margin of the Gondwana supercontinent.

Generally, there were recognised following principal stages of the orogenic development within the pre-Alpine basement of the CWC: an Early Paleozoic cycle of Gondwana rifting - pan-African stage, followed by subduction and amalgamation of oceanic lithosphere and/or convergence of microcontinents during Eo-Variscan period; proper collisional tectonics marked by lithospheric thickening with the formation of crustal scale nappe structures and large transcurrent faults - Meso-Variscan stage; lithosphere delamination (slab breakoff) resulting in rapid post-collisional uplift and/or extensional tectonics - Neo-Variscan stage.

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Heterogeneity and complex development of Variscan lower continental crust inferred from whole-rock geochemistry and SHRIMP zircon dating of the Náměšť Granulite Massif (Bohemian Massif, Czech Republic)

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The crust mantle interaction is a key to understanding deep-seated thermomechanical processes in large orogens, and behavior of subcontinental mantle during continental collision in particular. Felsic kyanite garnet ternary feldspar granulites bearing volumetrically minor, but petrogenetically important, "orogenic peridotite" fragments (garnet or spinel peridotite, pyroxenite and associated eclogite), represent a rock assemblage typical of the high-grade orogenic root in the European Variscan Belt (Gföhl Unit in the Moldanubian Zone of the Bohemian Massif). A recent interpretation is based on lithological structure, geochemistry and geochronology of this rock sequence (Schulmann *et al.*, 2009; Lexa *et al.*, 2011). According to this model, the granulites represent originally deepest part of the double thickened crust, while the metabasic layer corresponds to the original lower crust of the Moldanubian Continent located bellow middle crustal, mostly metasedimentary units of Late Proterozoic to Early Paleozoic age. The granulite-peridotite complexes are thus interpreted as a lower crustal allochton with Saxothuringian affinity emplaced underneath autochthonous Moldanubian crust (Janoušek *et al.*, 2004; Janoušek and Holub 2007; Lexa *et al.*, 2011) by mechanism called tectonic relamination (Hacker *et al.*, 2011).

In our study, we focus on the geochemical and geochronological investigations of all three main lithologies of the Náměšť Granulite Massif (NGM) in the E part of the Gföhl Unit: (i) felsic Ky-Grt granulite, (ii) Spl and Grt peridotite and (iii) Grt amphibolite enveloping the NGM. The remarkably uniform whole-rock geochemical signature of the felsic granulite displays the same compositional characteristics as other granulite massifs throughout the Moldanubian Zone (Janoušek *et al.*, 2004). The NGM metabasite envelope corresponds to E-MORB or Within Plate Tholeiite resembling Late Cambrian-Early Ordovician occurrences at the eastern margin of the Bohemian Massif. The Mohelno peridotite is interpreted as a harzburgite of asthenospheric origin, only later refertilized.

For *in situ* (SHRIMP) U-Pb dating. granulite zircons from metamorpho-structural fabrics S1, S2 and S3 were selected along with rare grains from amphibolite envelope of the NGM sharing S3 fabric with the granulites (Kusbach *et al.*, 2012). Cathodoluminescence images reveal the presence of dark zircon cores and light and thin metamorphic rims in a few grains. No oscillatory zoning was observed but some grains show sector zoning. Zircon from the felsic granulite yielded two distinct maxima in ages, at ~353 and ~339 Ma, interpreted as timing the HP metamorphic peak and partial melting during the early stages of uplift, respectively. The Early Devonian protolith ages (~400 Ma) differ from ~450 Ma protoliths for other granulite bodies from the Moldanubian Zone and Saxon Granulite Massif (Kempe *et al.*, 2000; Kröner *et al.*, 2000; Friedl *et al.*, 2004).

The current work shows that the three studied lithologies could not have originated in a single geodynamic environment. The felsic granulites represent a subducted Early Devonian continental crust, while the tholeiitic metabasites were probably generated during Cambro-Ordovician rifting. Based on these characteristics and contrasting P-T data we adopt a model of lower crustal relamination of low-density continental crust below autochthonous dense mafic root of the Moldanubian Continent. The difference in Zrn ages attributed to the HP metamorphic climax between the Náměšť granulite (~353 Ma) and other granulite massifs (~340 Ma; *e.g.*, Wendt *et al.*, 1994; Kröner *et al.*, 2000; Friedl *et al.*, 2011) is interpreted in terms of diachronous emplacement and different time scale of thermal maturation of western and eastern portions of the relaminated crust. Our work also shows that the mantle was refertilized before its incorporation into the crust, a feature typical of asthenospheric mantle below slow spreading rifts. Therefore, it is very likely that the Late Devonian history

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recorded in the mantle fragment (whose cooling was constrained by the Sm-Nd age of ~370 Ma: Medaris *et al.*, 2006) reflects heterogeneous nature of the local subcontinental mantle lithosphere related to the Devonian rifting (most likely in back-arc of the Saxothuringian subduction), i.e. unrelated to the surrounding felsic granulites. The place of juxtaposition of the mantle fragment to the granulite is impossible to determine, but the likely Late Devonian age coincides well with the onset of the magmatic-arc related plutonic activity in the Teplá-Barrandian Unit (Štěnovice and Čistá plutons, as well as orthogneisses in the roof pendants of the Central Bohemian Plutonic Complex; Košler *et al.*, 1993; Žák *et al.*, 2011). In conclusion, the Mohelno peridotite represents an autochthonous heterogeneous lithospheric mantle fragment that was sampled by felsic (granulite) crust during relamination process. This mechanism can explain significant variations and P-T conditions of mantle material enclosed nowadays in individual granulite massifs of the Bohemian Massif.

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Variscan orogeny in Bohemian Massif and French Massif Central: Differences and similarities

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Starting with Suess (1926), the Variscan belt was interpreted as the result of Devonian to Carboniferous Himalayan-Tibetan type continent-continent collision. In the published models, the orogenic evolutions of Bohemian Massif, Black Forest/Vosges and French Massif Central were considered similar. However, recent investigations lead us to revisit this uniformitarian framework. The main goal of this contribution is to discuss the main differences and similarities between the individual segments of the European Variscan belt.

Bohemian Massif (BM): Geophysical modeling provided a four-layer model composed of 10 km thick light crust above Moho overlain by 5 to 10 km thick dense crust followed by a layer of medium-density rocks (Guy *et al.*, 2011). Low-density rocks, several kilometers thick, form the uppermost layer, again. The bottom low-velocity, light crust is modeled as felsic HP granulites known from the surface. The high-density layer corresponds to eclogitized mafic rocks. The intermediate density layer can be approximated by metasedimentary middle and upper crust of the Moldanubian and Teplá–Barrandian domains.

We established (Schulmann *et al.*, 2009) that all criteria defining an Andean type convergence are well preserved in the Bohemian Massif. It is thus considered as a supra-subduction orogen of double crustal thickness and its architecture as a result of a 60 m. y. lasting SE-ward subduction of the Saxothuringian Ocean evolving to continental underthrusting. From West to the East, the subduction system consists of 1) suture zone (serpentinite-, blueschist- and “C-type” eclogite-bearing mélange derived from the Saxothuringian passive margin and Ordovician oceanic crust, 2) fore-arc upper crust (Teplá–Barrandian domain) of the upper plate, 3) Late Devonian-Early Carboniferous magmatic arc, 4) deep crustal root (the Moldanubian domain, with HP felsic granulites, “A and B-type” eclogites and garnet peridotites) and migmatites/anatectic granites, and 5) Neo-Proterozoic Brunia continental backstop.

The litho-tectonic zonation of the Moldanubian domain has been historically established in Lower Austria, being, from top to bottom: high-pressure felsic granulites containing large bodies of garnet/spinel peridotites and mantle-derived eclogites (orogenic lower crust), mafic lower crust containing relics of “B-type” eclogites and orogenic middle crust (orthogneisses and metasediments) (Fuchs, 1977). This structure led to the development of nappe tectonics concept, with the hot deep crustal material representing thrusted allochtonous klippen resting upon medium-pressure gneissic units (Suess, 1926: Tollmann, 1980; Matte *et al.*, 1990). We, however, interpret the felsic HP granulites as an allochthonous orogenic lower crust underthrust bellow a pre-existing eclogitized mafic horizon (“B-type” eclogites) stacked beneath the upper plate during oceanic subduction (Štípská *et al.*, 2008; Janoušek *et al.*, 2004; Lexa *et al.*, 2011). The early Carboniferous underthrusting (relamination) of Saxothuringian felsic and radioactive crust was able - after c. 10-15 m. y. of thermal incubation - to generate significant heat supply leading to drastic rheological weakening of both deep felsic and mafic orogenic crust triggering activation of Rayleigh-Taylor instability and development of gravity overturns. Vertical material transfers and subsurface lateral spreading of the HP felsic granulites and related “A-type” eclogites are the consequences of gravity overturns and we call this new tectonic process laterally-forced overturn (LFO, Schulmann *et al.*, 2012).

The Black Forest/Vosges domain displays a similar crustal architecture and orogenic evolution with respect to the Bohemian Massif.

French Massif Central (FMC): Available data from ECORS profiles as well as the information obtained from enclaves sampled by Quaternary volcanoes indicate that the crust above the Moho is formed by a layered mafic horizon. Up to now, there is no evidence for the presence of a continuous lowermost light felsic crustal layer.

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Compared to the BM, the FMC does not reveal well-preserved vestiges of Andean type convergence and the precise location of oceanic suture zones is still a matter of debate. The global architecture of the FMC is best described in its eastern part, with from North to South (Ledru *et al.*, 1989; Faure *et al.*, 2009): 1) Visean (335-320) volcanics, pyroclastic deposits, terrigenous sediments and granodiorites. These unmetamorphosed rocks unconformably overlie or intrude 2) Mid- to late-Devonian calc-alkaline plutonic, volcanic and volcano-clastic rocks (Morvan magmatic arc, Pin *et al.*, 1982) and back-arc Brevenne-Beaujolais ophiolite dated at 366 ± 5 Ma (Pin and Paquette, 1998). The position of this calc-alkaline series argues for a South-dipping subduction (closure of the Saxothuringian oceanic domain: Faure *et al.*, 1997, 2009). To the south, the two series are separated by a ~345 Ma dextral wrench fault from the 3) Upper Gneissic Unit (UGU) characterized from top to bottom by (Lardeaux *et al.*, 2001): 385 ± 5 Ma old ortho- and para-derived migmatites to granulites and a lowermost subduction complex including 415 ± 5 Ma old “B-type” eclogites and garnet peridotites. In the UGU, a NE-SW stretching lineation and shear criteria are coherent with top-to-the SW displacement (Burg and Matte, 1978; Matte, 1989; Ledru *et al.*, 1989; Faure *et al.*, 2009) related to the North-dipping underthrusting of the 4) Lower Gneissic Unit (LGU) composed of amphibolite-facies metasediments, metarhyolites and numerous metagranites. The LGU suffered an intense Stephanian (310-295 Ma) tectono-thermal reworking leading to the emplacement of the Velay granitic/migmatitic dome (Ledru *et al.*, 2001) bounded to the north by the Pilat detachment ductile fault (Malavieille *et al.*, 1990). To the south, the LGU rests upon the 5) Para-autochthonous Unit, composed of a thick metapelites/metagraywacke series (Cevennes micaschists) with minor quartzites and volcanics. Both the Para-autochthonous Unit and the LGU are interpreted as remnants of the thinned northern Gondwanan continental margin (Matte, 1989). To the South, the Para-autochthonous Unit overthrusted 6) the so-called Southern Paleozoic Fold and Thrust Belt.

Summing up, we discuss the following main similarities and differences between the Bohemian Massif and the French Massif Central:

• Crustal-scale geometry and orogenic architecture: in the BM the lower crust is composed of 10 km thick felsic layer situated beneath a mafic one. The BM is a supra-subduction orogen of double crustal thickness mainly derived from the Upper plate, except for exhumed felsic orogenic lower crust, which comes from the Lower plate. In contrast, the current lower crust of the FMC consists of a layered mafic crust (gabbros, mafic granulites and minor felsic granulites) located beneath a stack of mainly felsic units. The FMC architecture is derived from both Upper and Lower plates.

• Subduction processes: in the BM these were marked by 60 m.y. lasting continuous SE-dipping subduction leading to the formation of blueschist-facies rocks with A, B and C-types of eclogites and significant arc magmatism. In contrast, the FMC reveals B-type eclogites and discontinuous arc magmatism related to a polyphase subduction, initially North-dipping (early closure of the MC Ocean) followed by Devonian to Carboniferous South-dipping subduction.

• Continental underthrusting: underthrusting of felsic radiogenic Saxothuringian crust in the BM lead to the development of laterally-forced gravity overturns and exhumation of orogenic lower crust while in the FMC the mechanism consisted in northward underthrusting of Gondwanan crust associated with crustal-scale folding of stacked units.

• Late Variscan tectono-thermal reworking: associated in the BM with production of Late Carboniferous (330-300 Ma) post-tectonic to syn-collisional anatectic granites while in the FMC the thermal reworking was significantly more important. It was accompanied by syn- and post-thickening extension leading in the LGU to the emplacement of Late Carboniferous to Early Permian granite/migmatitic domes contemporaneous with sedimentary basin development at upper crustal levels. The latter was clearly associated with extensional tectonics.

SIMS U-Pb zircon dating of migmatites and high Mg-K intrusions from the Variscan orogenic complex of Corsica: from crustal anatexis to mantle melting

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Continental collision initiates with the subduction of the continental passive margin, and proceeds to the break-off of oceanic lithosphere from continental lithosphere causing high grade metamorphism and syn- to post-collisional magmatism (Davies and von Blanckenburg, 1995). Precise determination of the timing and duration of metamorphism and syn- to post-collisional magmatism are fundamental to understand the evolution of collisional orogeny. The Variscan orogenic complex of Corsica preserves complete records of granulite- to amphibolite-facies metamorphism, crustal anatexis and a full spectrum of syn- to post-collisional magmatic rocks.

High-precision SIMS U-Pb zircon age determinations are conducted in this study on the amphibolite-facies migmatites and the high Mg-K suite (HMK) magmatic rocks from Corsica. Four migmatite samples were collected from Fautea, Vignola and Belgodère. Zircons separated from anatexites and/or diatexites of these migmatites yield consistent crystallization ages of ca. 345 Ma. Three HMK monzonites and one monzogabbro enclave from Calvi pluton of NW Corsica yield indistinguishable U-Pb zircon ages of ca. 330 Ma.

Our high-precision SIMS zircon U-Pb dating results indicate that the regional migmatization associated with amphibolite-facies metamporphism occurred synchronously at ca. 345 Ma, which is coeval with the formation of locally exposed Al-rich granitoids (Paquette *et al.*, 2003). It is noteworthy that our new ages for the HMK rocks are ca. 10 Ma younger than those (ca. 340 Ma) of previously reported. There is a ca. 15 m.y. time interval between anatexis of the thickened crust and partial melting of the metasomatized mantle to form the HMK mafic rocks.

Taking into account of the age for the high pressure and high temperature granulites from SE Corsica (Giacomini *et al.*, 2008), we interpret the three major discrete tectonothermal events between 360 Ma and 330 Ma as attributed to a slab break-off during the continental collision (Davies and von Blanckenburg, 1995). A tearing of the subducting oceanic lithosphere initiates with the asthenosphere rising to fill the void and cause high pressure and temperature metamorphism of the overlying continent at ca. 360 Ma. The lithosphere breaking proceeds and finally triggers the break-off of the subducting slab, resulting in exhumation and anatexis of the subducted crust to form migmatites and Al-rich granitoids at ca. 345 Ma. The rising of hot asthenosphere due to slab break-off heats up the metasomatised continental lithosphere to ca. 1000°C, leading to HMK magmatism at ca. 330 Ma.

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The Cadomian orogen and its incorporation in the Variscan belt - A perspective from the Saxo-Thuringian Zone (Bohemian Massif)

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In the Bohemian massif, volcano-sedimentary complexes of the Cadomian basement were formed in an active margin setting along the northern Gondwana margin, while Cambro-Ordovician to Middle Devonian sedimentary rocks became deposited in a passive shelf setting on the southern margin of the Rheic Ocean. Origin of Late Devonian and Early Carboniferous rock complexes was strongly influenced by the tectono-magmatic processes during Variscan continent-continent collision of the supercontinents of Gondwana and Laurussia resulting in the formation of Pangaea. Transitional stages between Cadomian and Variscan Orogenies are sub-divided into following stages: (1) Early Cambrian to Early Ordovician rifting, (2) a rift-drift transition during Early and Middle Ordovician time leading to the opening of the Rheic Ocean followed by (3) passive margin deposits in the time span of Late Ordovician to Middle Devonian, and (4) closure of the Rheic Ocean during Late Devonian to Early Carboniferous plate tectonic processes. The latter one is characterized by the co-existence of marine shelf sedimentation, subduction-related magmatism, subduction and exhumation. There is no sharp break between the geological history linked to the Cadomian orogen and that of the Cambro-Ordovician, which finally led to the opening of the Rheic Ocean. Instead, the latter is viewed as a logical continuation of the geological history of the dying marginal orogen. A Cordilleran model is proposed for the final stages of the Avalonian-Cadomian orogen analogous to the Cenozoic history of ridge-continent collision in the area of Baja California in the Eastern Pacific. Such a model would explain both the geodynamic change from subduction-related processes to the opening of a new ocean and the excision of a long slice of continental crust like that which formed the micro-continent of Avalonia. All stages of the model are supported by a robust data set of U-Pb LA-ICP-MS ages of detrital and magmatic zircon grains.

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Blueschists from the Malpica-Tui Unit (NW Iberian Massif)

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The northwest section of the Iberian Massif provides information that helps to understand the evolution of the European Variscan Belt. A key aspect of this section is the presence of exotic terranes forming a huge and complex allochthonous sheet emplaced upon the sequences deposited on the passive margin of north Gondwana during the Late Devonian. They include a high-pressure and low- to medium-temperature belt that can be discontinuously traced throughout the Variscan orogen, and is located below several rock units with ophiolitic associations.

This high-pressure belt is interpreted as a coherent piece of continental crust formed by different rock units known in the NW Iberian Massif as the Basal Units. Their petrologic and structural study has constrained the P-T paths and the kinematics of the subduction concluding that Basal Units formed part of a subducting slab buried beneath Laurussia at the onset of the Variscan collision. The original polarity of the subducting slab was reconstructed on the basis of the paleo-pressures suggested by metamorphic parageneses, indicating that the subduction had an important westward component in present coordinates.

The Malpica-Tui Unit is the westernmost exposure of the Basal Units of the Allochthonous Complexes of the NW Iberian Massif. According to their metamorphism and tectonostratigraphy, the Basal Units can be separated in two sheets. In the Malpica-Tui Unit: (1) a Lower Sheet of continental affinity, where felsic orthogneisses and turbiditic metasediments predominate and (2) an Upper Sheet that represents a volcano-sedimentary sequence viewed as a more distal part of the same continental margin, extremely attenuated, and transitional to an oceanic domain.

The Upper Sheet of the Malpica-Tui Unit is entirely preserved in a small synformal structure (the Pazos Synform) and is formed by a basal layer of finely foliated amphibolites and greenschists with N-MORB chemistry (Cambre Amphibolites), and an overlying sequence of pelitic schists (Ceán Schists) with minor intercalations of bituminous schists, cherts and carbonates. The mafic rocks are strongly retrogressed blueschists that locally preserve lawsonite pseudomorphs. A several meters thick layer of mylonites and ultramylonites marks the contact between the Upper and the Lower Sheets.

Peak metamorphic conditions in the Lower Sheet are in the intermediate temperature eclogite facies, with a progressive transition to the blueschist facies in the eastern sections of the same units in the remaining allochthonous complexes. The Upper Sheet can be considered as a highly condensed metamorphic sequence with a basal part in the blueschist facies and an upper part without high-pressure relicts. The significant subtractive metamorphic jump between both sheets suggests that the mylonites that mark the contact are related to an extensional deformation.

The high-P pelitic schists (Ceán schists) crop out in the northern coastal section of the Malpica-Tui Unit and contain an initial chloritoid-glaucophane paragenesis, which is one of the classic high-pressure indicators for metapelites that has been reported in several high-P terranes around the world. The geological significance of the presence of glaucophane has been considered by several authors to explain Siluro-Devonian subduction and collision processes in the majority of the geotectonic models proposed for the Variscan orogen. The presence of rocks with comparable mineral associations is common in many of the European Variscan outcrops. Hence, the Basal Units of the NW Iberian Massif can be correlated with similar terranes with high-P and low- to intermediate-temperature metamorphism from Portugal to the northern areas of Eastern Europe, such as the Kaczawa Complex in the Polish Sudetes of the Bohemian Massif. In addition, similarities between certain geological units of the Armorican Massif (Brittany) and the Malpica-Tui Unit allows the correlation of the latter with the Île de Groix and Champtoceaux Complex particularly, since the age of the high-P metamorphism is the same in both terranes. This age has been tightly constrained to around 365-370 Ma in NW Iberia by $^{40}Ar/^{39}Ar$ geochronology on white micas from different lithologies, including eclogites, and by U-Pb zircon ages.

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PTd evolution of greenschist facies metapelites from the Variscan middle crust of the Peloritani Mountains (North Eastern Sicily)

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Introduction

Thermodynamic modeling of medium grade porphyroblastic metapelites assisted by statistical data handling of X-ray maps provided new and more reliable PT constraints for a remnant of the southern European Variscan chain, now incorporated in the southernmost termination (*i.e.* Peloritani Mountains) of the Calabria-Peloritani Orogen (CPO) as the result of Apennine nappe-pile stacking during the latest stages of the Alpine tectono-metamorphic evolution (Fig. 1a). In the Peloritani Mountains the effects of the Alpine evolution have obliterated only locally the Variscan structural features and metamorphic assemblages, allowing the pre-Alpine tectono-metamorphic history of this polyorogenic segment to be investigated (Fig. 1b). Nevertheless, a few PT paths have been up to now elaborated for the upper-middle crustal rocks of this sector of the Variscan chain. New integrated micro-structural and petrological techniques have been here implemented with the aim of reconstructing the tectono-metamorphic evolution of a segment of upper-middle Variscan crust which is currently represented, in the Peloritani Mountains, by the Mandanici Unit (*e.g.*, Ferla and Meli, 2007; and references therein) (Fig. 1c). In this view, medium grade metapelites, outcropping in three different areas (Savoca, Montagna di Vernà, Briga) and representative of the highest metamorphic grade levels of the Mandanici Unit, have been studied (Fig. 1c). Selected samples show porphyroblastic texture, that permits to better infer deformation-blastesis relationships, and growth zoning in PT-sensitive porphyroblasts (*e.g.* garnet), useful to determine reliable thermobaric variations.

Petrographic and microstructural features

Savoca metapelites are characterized by fine-grained lepidoblastic white mica + chlorite + biotite layers, alternating with minor granoblastic quartz + plagioclase levels and by poikilitic garnet, ilmenite, chloritoid and staurolite porphyroblasts. Apatite, zircon, monazite, tourmaline, hematite constitute the accessory phases. The main foliation in these rocks is an isoclinal folding schistosity (S1), crenulated by a second metamorphic-deformative event that produces a poorly developed S2. A first generation of garnet porphyroblasts is late-D2. A static phase (post-D2) causes the blastesis of randomly oriented staurolite, chloritoid, biotite, white mica, ilmenite and a second generation of garnet. Retrocession of garnet, biotite, chloritoid in chlorite, white mica and quartz is also observed (Fig. 1d).

Montagna di Vernà metapelites exhibit a dominant fine-grained white mica + chlorite lepidoblastic texture, with minor quartz + plagioclase granoblastic layers and widespread ilmenite and poikilitic garnet porphyroblasts. Apatite, monazite and zircon are present as accessory phases. An isoclinal folding schistosity has been pervasively obliterated by a crenulation schistosity (S2) that constitutes the main foliation superimposed, in turn, by a third schistosity (S3) likely produced during an extensional-shearing event (D3). Garnet porphyroblast cores crystallized during D2, according to the similarity between folding patterns of crenulated cores and quartz and ilmenite inclusion trails. Idioblastic inclusion-free rims, instead, are presumably late- to post-D2 (Fig. 1d).

Briga metapelites have a medium-grained dominantly lepidoblastic texture, with ilmenite and poikilitic garnet porphyroblasts up to 7 mm-sized. Isoclinal folding schistosity (S1) is only present as relic of fold hinges, while crenulation schistosity (S2) has been largely obliterated by a mylonitic fabric (S3), that represents the main foliation and comprises C'-type shear bands, mantled porphyroclasts, mica fish and foliation fish. Mineralogical assemblage is constituted by white mica, chlorite, quartz, plagioclase, garnet, ilmenite with zircon, monazite, tourmaline, hematite and titanite as accessory phases (Fig. 1d).

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Minerochemical elaboration and PT constraints

Fe-Mn-Mg-Ca X-ray maps and compositional transects in almandine garnet porphyro-blasts, -clasts of Savoca, Montagna di Vernà and Briga metapelites permitted to highlight a common growth zoning pattern, consisting in almandine content increment and spessartine content decrease from core to rim. In particular, chemical variations are quite gradual in Montagna di Vernà and Briga garnets, likely as a result of a continuous growth during the prograde evolution. Differently, a clear compositional dissimilarity exists between the Mn-poor rims and the Mn-rich cores of Savoca garnet porphyroblasts, suggesting a two-stages growth, the first one probably related to the late-D2 stage and the second one related to the static event.

Thermodynamic modeling, combined with microstructural analyses and minerochemistry data assisted by image processing elaboration of X-ray maps (Fig. 1d), has been performed to reconstruct PTd trajectories for the studied metapelites of each area (Fig. 1e). P-T pseudosections, calculated by means of Perple_X software package (Connolly and Petrini, 2002) in the TiMnNCKFMASH system, have been used to estimate peak conditions, considering Ti, in view of the widespread ilmenite porphyroblasts occurrence as well as Mn, because of the relatively high spessartine component in garnet and pyrophanite component in ilmenite. XRF bulk-rock compositions of metapelites were used as equilibrium volume compositions. Garnet isopleths intersections point to T = 515 °C and P = 0.90 GPa for the baric peak and T = -540 °C and P = 0.80 GPa for the dynamic metamorphic peak (Fig. 1e). The former can be related to the development of isoclinal folding schistosity, the latter can be associated to the development of crenulation schistosity. PT conditions of the static event, recorded only in Savoca metapelite, were tentatively estimated through paragenetic considerations at T ≈550 °C and P ≥ 0.50 GPa (Fig. 1E). Retrograde evolution was depicted after calculating a new effective bulk-rock composition, considering chemical fractionation associated to sequestration of specific chemical elements in garnet cores. P-T pseudosection was calculated in the NCKFASH system. The intersections between anorthite and phengite isopleths indicate temperature ranging between 420-460 °C and pressure of 0.30-0.60 GPa (Fig. 1e). This retrograde phase can be related to the development of Montagna di Vernà mylonitic foliation.

Conclusion

Geodynamic modeling of a metamorphic chain must rely on detailed PTd path reconstructions for the various units which constitute the nappe edifice. For this reason, we determined PTd paths for the medium grade metapelites of the Mandanici Unit. Integration of the results from the elaborated PTd paths suggest that this unit was involved in a Barrovian-type clockwise path characterized by baric peak conditions at temperature of ≈500 °C for pressure of ≈0.90 GPa followed by dynamic metamorphic peak associated with thermal relaxation at temperature of 540 °C for pressure of 0.80 GPa (Fig. 1f). Subsequent retrograde PTd constraints suggest the developing of a shearing stage (T≈420-460 °C and P≈0.30-0.60 GPa) followed by a late- to post-tectonic thermal increase (T≈550 °C and P≈0.50 GPa) (Fig. 1f). This results can be considered as a base for more realistic palinspastic reconstructions within the complex geological frame of the late-Paleozoic southern European margin, as well as for precise and detailed models of the metamorphic evolution of the Variscan continental crust.

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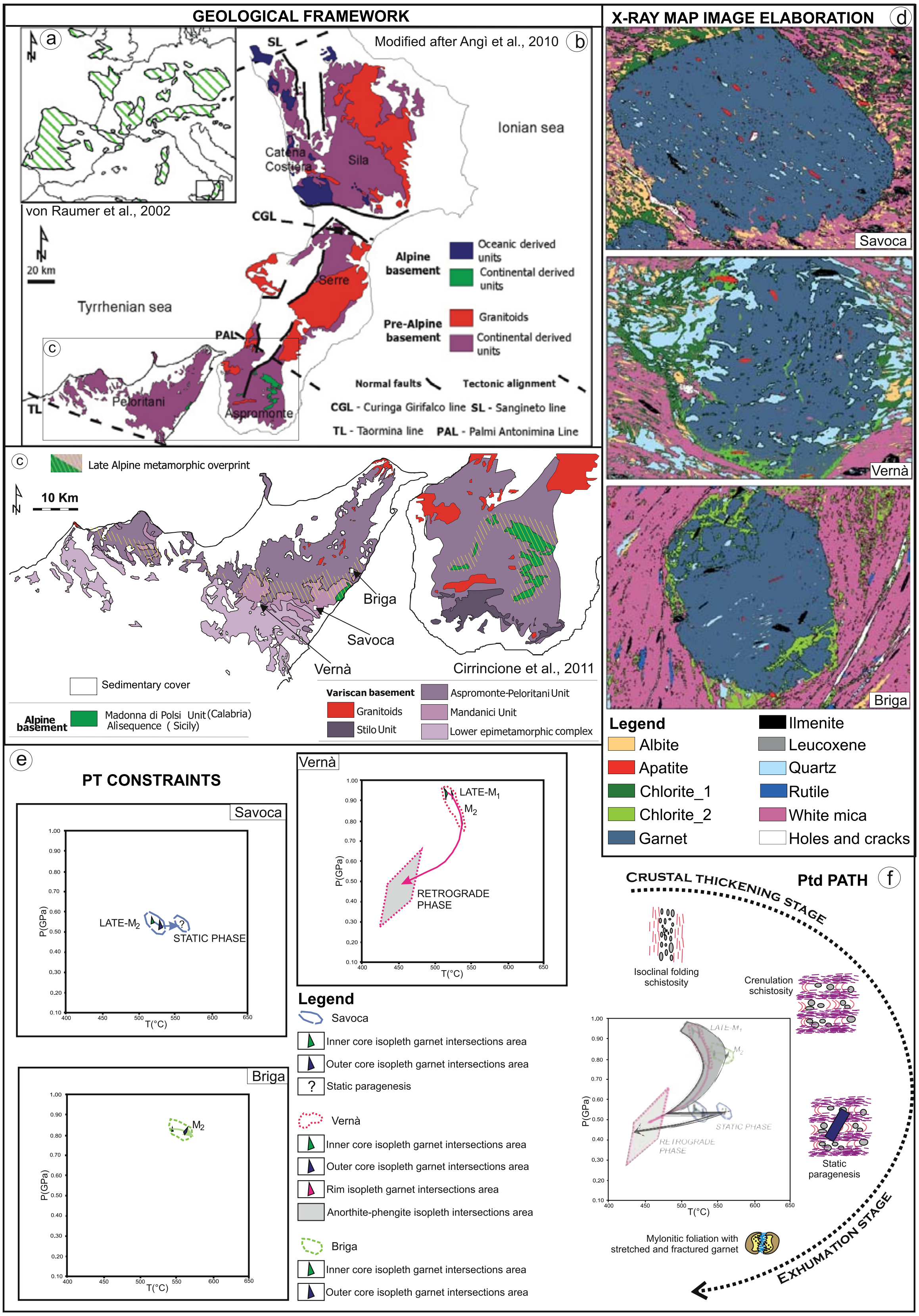
GEOLOGICAL FRAMEWORK
X-RAY MAP IMAGE ELABORATION
a
von Raumer et al., 2002
Modified after Angì et al., 2010
b
Ionian sea
Tyrrhenian sea
Sila
Catena Costiera
Serre
Peloritani
Aspromonte
SL
CGL
PAL
TL
20 km
Alpine basement
Oceanic derived units
Continental derived units
Pre-Alpine basement
Granitoids
Continental derived units
Normal faults
Tectonic alignment
CGL - Curinga Girifalco line
SL - Sangineto line
TL - Taormina line
PAL - Palmi Antonimina Line
c
Late Alpine metamorphic overprint
10 Km
Briga
Savoca
Vernà
Cirrincione et al., 2011
Sedimentary cover
Alpine basement
Madonna di Polsi Unit (Calabria)
Alisequence (Sicily)
Variscan basement
Granitoids
Stilo Unit
Aspromonte-Peloritani Unit
Mandanici Unit
Lower epimetamorphic complex
d
Savoca
Vernà
Briga
Legend
Albite
Apatite
Chlorite_1
Chlorite_2
Garnet
Ilmenite
Leucoxene
Quartz
Rutile
White mica
Holes and cracks
e
PT CONSTRAINTS
Savoca
LATE-M2
STATIC PHASE
Briga
M2
Vernà
LATE-M1
M2
RETROGRADE PHASE
P(GPa)
T(°C)
Legend
Savoca
Inner core isopleth garnet intersections area
Outer core isopleth garnet intersections area
Static paragenesis
Vernà
Inner core isopleth garnet intersections area
Outer core isopleth garnet intersections area
Rim isopleth garnet intersections area
Anorthite-phengite isopleth intersections area
Briga
Inner core isopleth garnet intersections area
Outer core isopleth garnet intersections area
f
Ptd PATH
CRUSTAL THICKENING STAGE
Isoclinal folding schistosity
Crenulation schistosity
Static paragenesis
Mylonitic foliation with stretched and fractured garnet
EXHUMATION STAGE

Linking modern and ancient large hot orogens through numerical modelling

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Modern orogens are studied exclusively using geophysical methods which allow to assess the existence of principal crustal layers, heat flow and the general rock density distribution within crust, thereby providing bulk orogenic architecture in a single time snapshot. In contrast, fossil orogens provide direct observations of orogenic architecture in a deep erosion section through orogenic crust. In these orogens, combined petrological, structural and geochronological studies provide constraints on material and heat transfers through time. Recent studies have shown striking similarities between the Paleozoic formation of the Bohemian Massif and the recent evolution of the Andean and Tibetan orogenic systems which makes the correlation of modern and ancient large hot orogens possible (Schulmann *et al.*, 2009).

Here we present a numerical model of thermomechanical processes which closely reproduces the sequence of tectonic and thermal events during crustal thickening, exhumation of lower crust and continental indentation reconstructed from geological record along the retroside of the Variscan orogen in the Bohemian Massif. This area is marked by several thousand square kilometres of a flat-lying orogenic lower crust underlain by a basement promontory along a 300 km long collisional front (Schulmann *et al.*, 2008). This is supported by gravity surveys which show that the limit of the basement promontory extends up to 100 kilometres towards the internal part of the orogenic root from the todays exposure of the orogenic front (Guy *et al.*, 2011). Combined structural and petrological studies revealed that the orogenic lower crust (high-pressure granulites and mafic eclogites) was vertically extruded from depths of about 60 kilometres along the steep margin (ramp) of the basement promontory. The observed transition from sub-vertical to sub-horizontal fabrics occurs in different depths from 35 to 15 kilometres and is marked by different P-T-t paths of exhumed lower crustal blocks. The vertically extruded rocks are reworked by flat fabrics reflecting the flow of hot material into some horizontal channel developed between the upper boundary (flat) of the basement promontory and the overlying orogenic lid.

We compare the numerical model with geophysical signature of the modern orogenic systems involving Bouguer gravity anomalies, surface heat flow and presence of partially molten horizontal zones imaged by seismic and magnetotelluric surveys. Based on this comparison a multistage evolution of large hot orogen is predicted marked by massive vertical material and heat transfers followed by horizontal flow of exhumed hot material along subsurface crustal channel.

The modelling is performed using the open source finite element software for multiphysical problems Elmer (http://www.csc.fi/english/pages/elmer) which was extended for this purpose by user-written procedures for compositional convection, visco-plastic deformation of crustal materials, surface processes (erosion and sedimentation) and isostatic compensation.

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Significance of orogenic collapse in pre-structuring the continental lithosphere and subsequent rifting: role of inheritance, granulites, and magmatic underplating

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One of the major achievements of the plate tectonic theory is the description of repeated opening and closing of ocean basins, also referred to as the "Wilson Cycle". Although the Wilson Cycle, proposed by J. Tuzo Wilson in 1965, represents the most basic concept of plate tectonics, it is yet unclear what controls the localization and formation of plate boundaries, and what is their spatial and temporal evolution during continental breakup and seafloor spreading. In particular the importance of inheritance within the continental crust and underlying mantle, which can be thermal, structural or compositional, is yet little understood. This is mainly due to the fact that for a long time rift systems and orogens were studied independently one from each other, despite the fact that it was common knowledge that these processes follow and consequently overprint each other. In my presentation I will discuss using the example of the Tethys–Atlantic and Variscan-Alpine systems in Western Europe the link between orogenic and rifting processes. Indeed, the Carboniferous to present evolution of Western Europe represents one of the best-documented Wilson cycles. Mapping of the Mesozoic rift systems in Western Europe suggests that these rift systems were strongly controlled by late Variscan extensional events related to the emplacement of mafic magmas and the formation of granulites at deep crustal levels during Permian time. However, it is yet unclear how this event controlled in detail the complex spatial and lateral evolution of the subsequent rift systems and their rift architecture. Understanding this complex interaction between inherited and active rift processes is a prerequisite to understand the complex paleogeographic evolution of the Alpine and Variscan system in Western Europe. Based on the example of the Alpine Tethys and Atlantic rift systems in Western Europe, I will discuss the importance of lithospheric inheritance resulting from the Variscan orogeny and how it may have influenced the evolution of the following rift systems.

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The late Variscan HT/LP metamorphic event in the Iberian branch of the Variscides: Relationships with crustal thickening, nappe emplacement, orocline development, and crustal evolution

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Late Variscan metamorphism in the Iberian Massif is characterized by high-T and low-P associations overprinting a Barrovian zonation developed during -and partly following-crustal thickening related to the Variscan collision. The high-grade rocks, commonly reaching sillimanite-K feldspar-muscovite out parageneses and locally even granulitic (biotite out) conditions, crop out at the core of gneiss domes where partial melting, migmatite development and syn-kinematic granitoids are abundant. Gneiss domes are often bounded on top by ductile detachments that, like the domes, formed during an extensional phase of deformation reflecting thermal relaxation and the subsequent collapse of the thickened continental crust.

Gneiss domes occur at three domains of the Iberian Massif, the West Asturian-Leonese (WALZ), Central Iberian (CIZ) and Ossa-Morena (OMZ) zones. In the CIZ and WALZ, the migmatitic areas are disposed along a broad thermal lineament where syn-kinematic Variscan granitoids are also particularly abundant. This lineament coincides with the internal zone of an arc delineated by early Variscan structures of the CIZ, with a curvature opposite to that of the Ibero-Armorican arc (Figure).

The existence of an orocline in central Spain marked by the trends of Variscan folds was first mentioned by Staub (1926, 1927), who named it the Castilian bend. The arc was discussed by Lotze (1929), whose influential contribution on the division of the Variscides of the Iberian Meseta (Lotze, 1945) consigned it to oblivion. Ignored for decades, Aerden (2004) noticed the arc in the patterns delineated by the Variscan folds in the Central Iberian Zone, the reason why Martínez Catalán (2011) proposed the name of Central Iberian arc. Aerden also pointed out that magnetic anomalies in Spain (Ardizone *et al.*, 1989) delineate the arc in the central part of the country. The map of magnetic anomalies of the whole Iberian Peninsula depicts an inner zone with tightly folded, relatively strong anomalies, and an outer zone of faint and more openly curved magnetic lineaments.

At the core of the Central Iberian arc, in NW Iberia, a huge nappe stack forms the Galicia-Trás-os-Montes Zone (GTMZ), where five allochthonous complexes and the underlying parautochthon include units derived from the northern Gondwana platform and continental edge, ophiolites marking the suture of the Rheic Ocean, and pieces of a Cambro-Ordovician ensialic island arc (Martínez Catalán *et al.*, 2009). Coherently with its position, the lowermost thrust sheet of the GTMZ, known as the parautochthon, is in places affected by extensive migmatization related to the thermal lineament at the axis of the Central Iberian arc. The GTMZ does not presently extend to the central part of the Iberian Massif, but migmatization affects the lower parts of the autochthonous metasedimentary sequences, ranging from Neoproterozoic to early Paleozoic in age. However, high-temperature rocks are not the only lithologies cropping out along the lineament, and migmatites and syn- to postkinematic granitoids alternate with greenschists to amphibolite facies rocks along it.

In this contribution, we discuss the high-T and low-P late-Variscan evolution and the distribution of gneiss domes in the GTMZ, CIZ, and WALZ. For the domes of Lugo and Sanabria, a series of thermal models developed by Alcock *et al.* (2009) show that their development is consistent with thermal relaxation following crustal thickening, including thickening caused by thrusting of the NW Iberian allochthon. The models also explain the main recognized pulses of granite production. Recent thermobaric estimations on the metamorphic evolution of the Iberian Central System (Rubio Pascual *et al.*, 2012) have shown that during the Barrovian event, the rocks reached pressures largely in excess to those than can be reasonable for the thickened sedimentary pile above. An additional overburden of 10-15 km may have been supplied by the GTMZ allochthon reaching the area, and/or associated syn-orogenic flyschoid deposits (“Culm”), none of which is currently preserved there.

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Given the structural position of the NW Iberian allochthon (GTMZ), the distribution of the gneiss domes in the CIZ and WALZ, and the pressures reached by the previous event of intermediate-P in the two latter zones, we explore the relationships of the high-T/low-P event with crustal thickening, nappe emplacement, and orocline development.

Furthermore, we compare the domains with and without gneiss domes in the CIZ and WALZ with seismic reflection profiles ESCIN and ALCUDIA, in NW and Central Iberia respectively (Ayarza *et al.*, 1998; Martínez Poyatos *et al.*, 2012). Where migmatization is absent, the profiles are characterized by a 5-6 s (TWTT) wide high reflectivity zone in the lower continental crust. Conversely, in areas of extensive migmatization, only a narrow 1-2 s wide band occur at the crust bottom, below a transparent basement 5-7 s wide. The Mohorovicic discontinuity is commonly well seen in both cases, normally at 10 s, but under the WALZ, it reaches 12 s and the reflectivity in the lower crust is concentrated in two bands at 7-9 and 11-12 s respectively. The latter suggests duplication, probably by underthrusting of the lower crust of the Cantabrian Zone (CZ), a foreland thrust belt characterized by thin-skinned tectonics and more than 50% shortening.

Lower crustal reflectivity results from heterogeneous composition with high impedance contrasts plus ductile deformation of Variscan and perhaps older events: horizontal extension and vertical flattening would occur during collapse of the thickened crust following thermal relaxation, and in the WALZ, it may result in part from underthrusting of the lower crust of the CZ acting as an indentor. The lack of a wide reflective band in the lower crust of areas with abundant migmatites and granitoids seem to indicate intense remobilization of the crust during the latest orogenic stages. Melts cutting across the previous banding may have distorted it, and would produce an intricate and disorganized pattern of reflections which would hide the remaining low-dipping layering in most of the lower crust.

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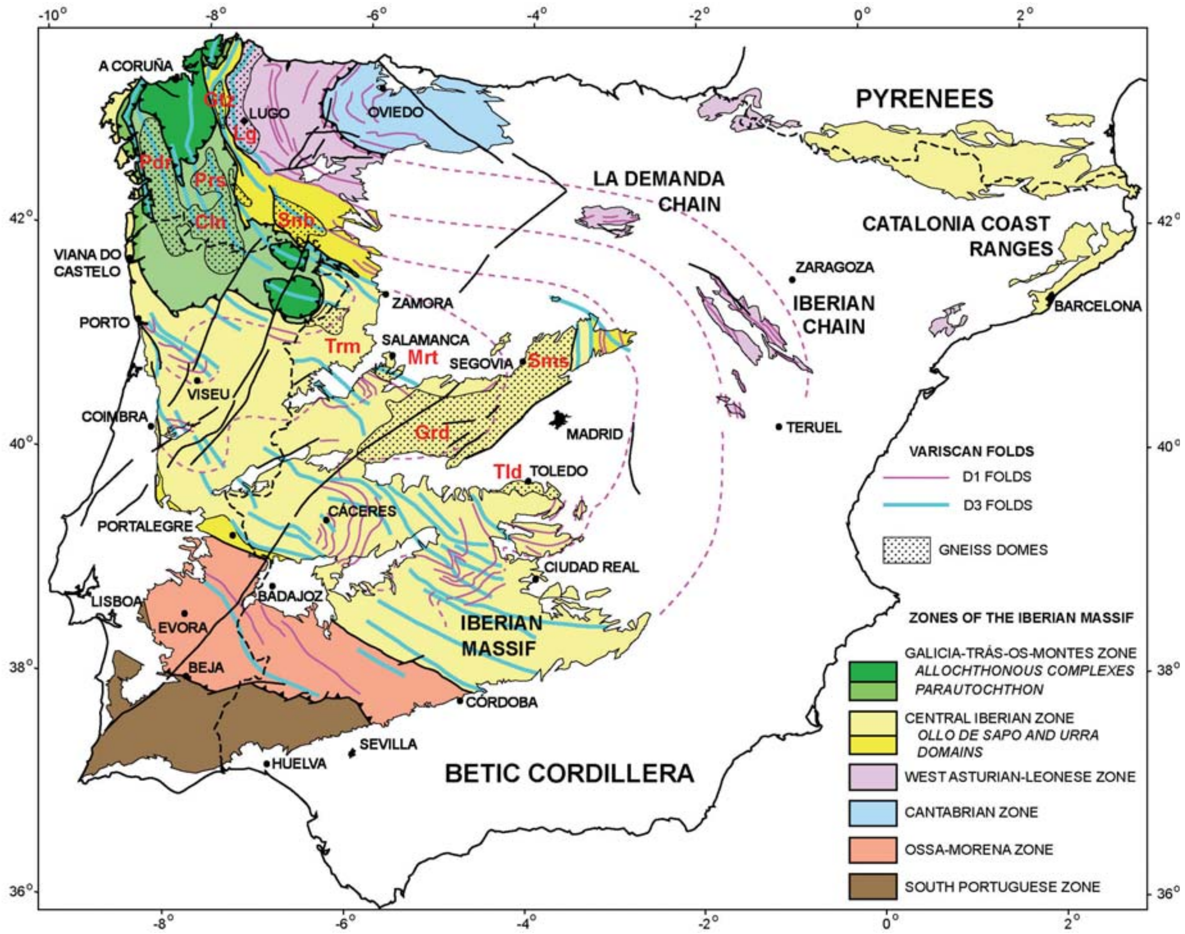

Map of the Variscan basement in the Iberian Peninsula showing the zones of the Iberian Massif and the axial traces of the main Variscan folds. The Central Iberian arc is outlined by traces of D1 folds and by dashed lines when inferred. Also indicated is the position of gneiss domes occupying a central position in the Central Iberian arc. Domes: Cln- Celanova; Grd- Gredos; Gtz-Guitiriz; Lg- Lugo; Mrt- Martinamor; Pdr- Padrón; Prs- Peares; Snb- Sanabria; Sms- Somosierra; Tld- Toledo; Trm- Tormes.

Geometry and correlation of the nappe stack in the Ibero-Armorican arc across the Bay of Biscay: a joint French-Spanish project
Part 2: the models

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The main stages of the tectonic evolution of the Ibero-Armorican segment of the Variscan belt are as follows:

Model based on W France

1. A long history of arc development and collapse (due to subduction roll-back?), largely hidden by the subsequent tectonic events, but recorded in the Upper Allochthon by (i) an early metamorphic cycle, with a first generation of eclogites (**410-405 Ma**) followed by partial melting (**390 Ma**), (ii) evidence for marine transgression over an emerged land during the late Pragian - early Emsian (**410-400 Ma**), and (iii) erosion of a continental, dominantly volcanic source during the early Eifelian (*i.e.* **400-395 Ma**).

2. North-vergent subduction of an oceanic domain under the Upper Allochthon, the latter being intruded by gabbro-dioritic bodies of undisputable calc-alkaline chemistry, dated at about **380-360 Ma** ("ligne tonalitique limousine"), and possibly associated to the development of a back-arc basin (poorly-dated but surely Devonian mafic volcanics from the Chantonnay syncline, extensive felsic volcanism with massive sulfide bodies developed during the Famennian from the Morvan to the Vosges).

3. North-vergent subduction of the Lower Allochthon, with the deepest slices recording a second eclogite-facies event in the Variscan belt (*e.g.* Cellier) at about **370-360 Ma** (Late Devonian, Famennian).

4. Thrusting of the Upper Allochthon over the Middle and Lower Allochthon, resulting in the development of an inverted metamorphism, with synkinematic biotite-staurolite-kyanite parageneses indicating P-T conditions of about 8 kbar, 600°C just below the main thrust contact, dated at about **350-340 Ma** (Early Carboniferous).

5. Reworking of the suture zone resulted in the deposition of thick (2-3 km) detrital sequences in fault-bounded, deep lakes located in transtensional basins (Ancenis basin, of probable late Visean age *i.e.*, 340-330 Ma) on top of the nappe pile.

6. Initiation and development of the Ibero-Armorican arc (**320-300 Ma**), with development of the South-Armorican Shear Zone, and contemporaneous detachment faults in the South-Armorican domain.

Model based on NW Iberia

1. Continental arc development during Late Cambrian, followed by back-arc spreading and subsequent subduction and exhumation recorded by (i) calc-alkaline magmatism at **500 Ma** (Upper and Lower Allochthons), closely followed by intermediate pressure metamorphism reaching granulite facies (uppermost allochthon), (ii) generation of oceanic lithosphere starting at **500 Ma** (Vila de Cruces), and deposition of back-arc sequences (upper sequence of the Lower Allochthon), (iii) felsic, partially alkaline magmatism related to continental rifting at **490-470 Ma** (lower sequence of the Lower Allochthon), and (iv) early high-pressure metamorphic event generating eclogites followed by decompressive partial melting at **410-390 Ma** (lower group of the Upper Allochthon).

2. North-vergent subduction of an oceanic domain under the Upper Allochthon, as suggested by generation of suprasubduction zone ophiolites at **400-395 Ma** (Careón, Morais-Talhinhas), followed by their imbrication by underthrusting at **390-380 Ma**.

3. North-vergent subduction of the outermost margin of Gondwana as recorded by eclogite and blueschist facies metamorphism in the Lower Allochthon during the second high-pressure event recorded in the allochthonous complexes, at about **370-360 Ma**.

4. Thrusting of the Lower Allochthon over the Parautochthon followed by out-of-sequence thrusting of the Upper and Middle Allochthon over the Lower Allochthon,

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and of the Parautochthon over the Autochthon. Thick syn-orogenic flysch deposits ("Culm") were laid down in depocenters in front of the active thrusts, becoming imbricated as they progressed. "Culm" deposition spans 380-330 Ma whereas active thrusts involving the Allochthon and Parautochthon took place at 345-335 Ma.

5. Thrusting propagated toward more external parts of the belt, while the hinterland underwent gravitational collapse and attenuation giving rise to migmatitic domes and extensional detachments.

6. Strike-slip faulting and late upright folding developed contemporaneously with the tightening of the Central Iberian arc (**315-305 Ma**), which was closely followed by that of the Ibero-Armorican arc (**305-295 Ma**).

Concluding remarks

Steps 1 to 6 in both branches of the Ibero-Armorican arc have clear similarities and some differences which, far from being incompatible, may complete the evolutionary picture of the whole ensemble, but the location of the Variscan suture poses a fundamental problem to establish the plate evolution.

In a "one-ocean model", the Rheic Ocean separates Gondwana and its northern palaeomargin (i.e. the future Lower Allochthon) from Avalonia - Laurentia - Baltica.

A "two-oceans model" assumes that two oceanic sutures are present in the Variscan belt, one to the north of the Armorican Massif (the Rheic Ocean), and the other to the south. It follows, that (i) the root zone of the allochthonous complexes of the Ibero-Armorican arc would be located along the Nort-sur-Erdre Fault, and (ii) the oceanic domain now found in the Middle Allochthon would be a "Galician-Massif Central ocean", not the Rheic Ocean.

In the "one-ocean model", if the suture were located at the Nort-sur-Erdre Fault, the Central Armorican Domain would represent the upper plate and the Central Iberian Zone the lower plate, implying that both zones were separated by the Rheic Ocean from the Late Cambrian to the Late Devonian. However, there is a close stratigraphic similarity between the Central Armorican Domain and the Central Iberian Zone. The fact that the Iberian Autochthon and Central Armorica seem to lie on different sides of the suture can also be explained by the Nort-sur-Erdre Fault being just the main among the South Armorican dextral shear zones. It may have cut across the suture, displacing it and repeating the Allochthon/Parautochthon/Autochthon ensemble. The suture would then be rootless in both domains, with the present terrane distribution being a consequence of wrench tectonics.

The "two-oceans model" poses one problem, because of the close biogeographicand stratigraphic links between the Central and Northern Armorican Domains on one side and the Central Iberia on the other side. It is unconceivable that these were separated by an oceanic domain (*i.e.* they were part of the same continental microplate, which can be called Ibero-Armorica). Following this model, we are obliged to propose a "cryptic" suture separating the Central Iberian Zone in two domains.

Hidden treasures: a data compilation on granites from the Eastern French Massif Central

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Granites of the Massif Central have been intensively studied in the 1960-80s by French (and other) universities; trough BRGM 1/50 000 scale geological mapping; and as part of Au and U exploration programs in Limousin, Margeride or Bois Noirs. Most of the data however is dispersed and hidden in old theses, internal reports or data bases and geological map explanations. We searched for all this information, and compiled all the data we could find, restricting ourselves to the Eastern part of the Massif Central (East of the Sillon Houiller fault); and built a postgreSQL/postGIS database that can be searched and queried either from the data table, or geographically (using postGIS, or using a GIS software as a front-end).

Our database includes a total of > 3600 analyses ; 2000 of which are from granitic plutons (the rest being coeval lavas, metamorphic/migmatitic basement, as well as vaugnerites (214) and various enclaves (250), from microgranular mafic enclaves to xenoliths). Nearly 3200 samples (including 1780 granites) are spatially localized, from sample maps or published coordinates, typically with a ca. 1 km accuracy. A majority of the samples come from outcrop sampling; however we also have the results of 8 drill holes (around U prospect in the Montagne Bourbonnaise and Mont-Lozère), representing 400 analyses.

Most of the data is derived from old sources. Therefore, the majority of the samples were reliably analysed only for a limited range of elements. We have major elements data for most of the samples; some trace elements (typically Rb or Ba by XRF, or even wet chemistry in some cases) for 580 granites, and modern determinations (including REE and modern INAA or ICP analyses) for only 240 of them. On the other hand, modal proportions are available for 400 samples including 250 granites, 80 vaugnerites and 60 enclaves of all sorts.

Collectively, the database allows to discuss the differences between different granite types; the vaugnerite-enclave-granite relationships; the compositional diversity of granites at all scales, from a few meters (drill hole data), to the scale of one single pluton, to regional scale distribution. In some case (the Margeride granite), a clear geographic control on the granite's composition is observed. Through the understanding of granites genesis, the relationship between granites and enclaves and the ages of magmatic events, this database provides an access to the composition and the evolution of the lower crust in the Eastern Part of the French Massif Central.

Figure 1 illustrates some of the information that can be extracted from our database. Cartographic representation (panel a) reveal the un-even distribution of samples; it could also be used to discuss regional trends and patterns (distribution of rock types or ages, systematic chemical variations, etc).

More conventional geochemical diagrams (panels b and c) can be used to explore the composition of granites. For instance, the difference between the granite types identified on the 1/1 000 000 geological map of France (BRGM, 1996 & 2003) is clearly seen in geochemistry; furthermore, the specificity of the Margeride pluton (uniquely aluminous and magnesian, with peraluminosity anti-correlated with mafics content) becomes obvious, as it does not compare with the other, notionally comparable peraluminous porphyroid plutons. The Velay anatectic complex also appears to differ from the "ordinary" peraluminous granites, witnessing its different nature (nearly in-situ core of a migmatitic dome, rather than upper crustal intrusive; also see Villaros & Moyen, this meeting).

The relations between granites, minor mafic types (vaugnerites *s.l.*) and enclaves is depicted in panel c, for the Velay region. Unsurprisingly, the mafic enclaves plot in between the mafic intrusives and the host plutons, evidencing the hybridization of mafic magmas in the plutons. The mafic types cover a large geochemical range from norites, to monzonites, to syenodiorites; this diversity cannot be attributed to interactions with the host, but must reflect a primary diversity, pointing to complex processes occurring in the sub-orogenic mantle during the Carboniferous.

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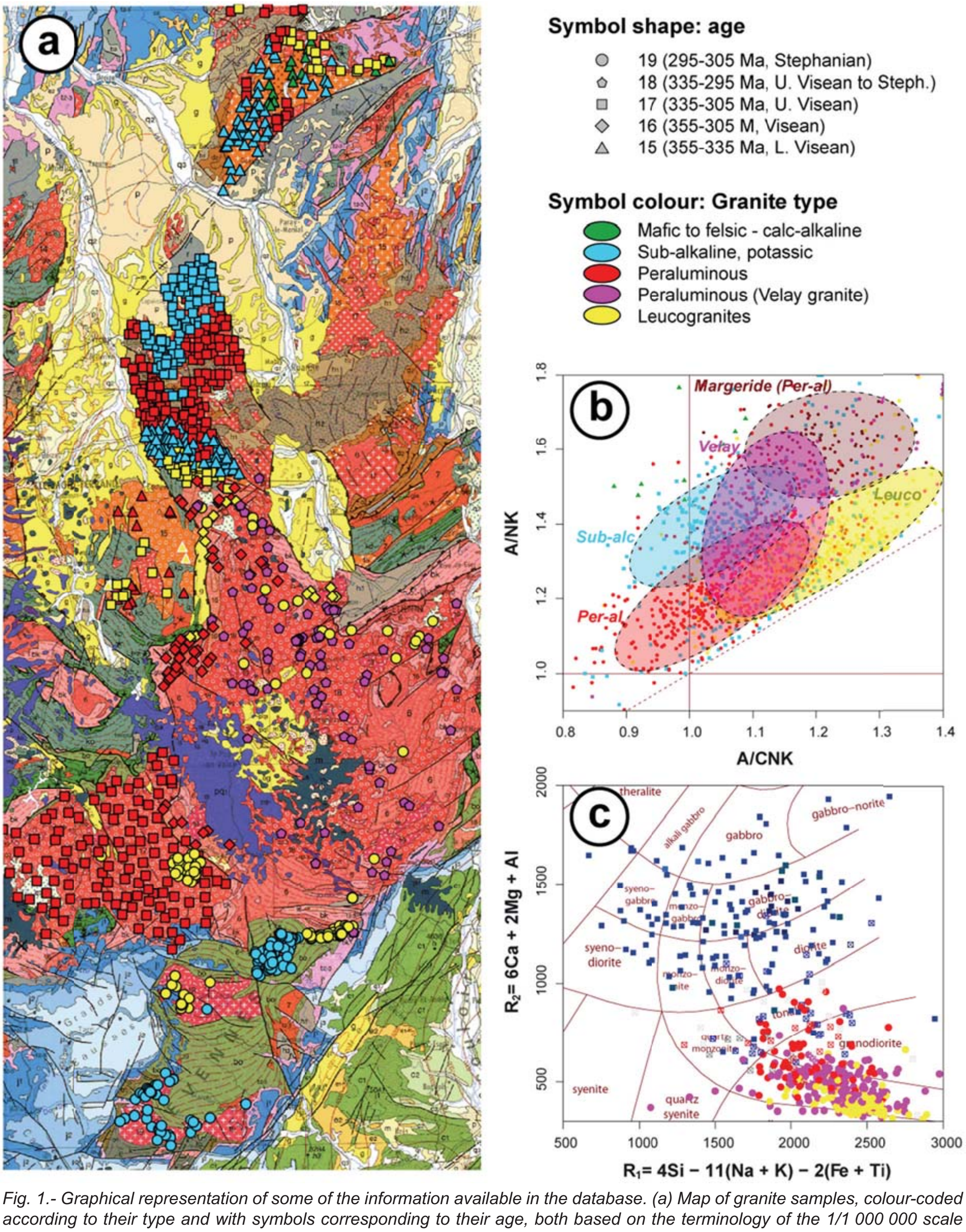

Fig. 1.- Graphical representation of some of the information available in the database. (a) Map of granite samples, colour-coded according to their type and with symbols corresponding to their age, both based on the terminology of the 1/1 000 000 scale geological map of France (background). (b) Shand (A/NK vs. A/CNK) diagram for 1800 granite samples in the database. The difference between granitic types is obvious. (c) De la Roche (R1-R2) diagram for 700 samples from the Velay complex and related plutons, including enclaves (empty symbols, light blue) and mafic types (vaugnerites etc; dark blue squares).

Late Variscan lithospheric scale oroclinal buckling in Iberia. Insights from analogue modeling

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Introduction

The existence of an orocline implies an originally linear orogenic belt that has been bent in a subsequent deformation event. Although the existence of oroclines is well-known, there are not many ways to understand their kinematic evolution and how they develop. There is even discussion on whether they develop as thin skinned structures or they have a lithospheric scale.

The Western European Variscan Belt is characterized by a highly arcuate geometry known as Ibero-Armorican Arc. The evolution of the arc has been constrained paleomagnetically as an orocline that was generated from an almost initially linear belt in its core, the Cantabrian Zone, located northern Iberia (Weil *et al.*, 2002,). Oroclinal buckling took place in the uppermost Carboniferous, between ca. 310 and 300 Ma (Pastor-Galán *et al.*, 2011), and, among other interpretations, it is considered to have been ultimately caused by the self-subduction of the Pangean global plate (Gutiérrez-Alonso *et al.*, 2008). Given the large scale of this plate-scale structure, it is bound to have had a profound effect on the whole lithosphere and consequently the effects of the involvement of the lithosphere should be recognized in structures and geological features of different nature and at different scales developed coevally with the orocline. Among the effects of the orocline development, continental-scale strike slip shear zones have been interpreted to accommodate the rotation in the outer parts of the Ibero-Armorican Arc. In addition to the shearing, coeval or subsequent voluminous magmatism, even present in the foreland fold-and-thrust belt, has also been interpreted as being related to the mass transfer processes taking place during the oroclinal buckling of the mantle lithosphere which likely caused a lithospheric delamination and replacement (Gutiérrez-Alonso *et al.*, 2004).

Because there is a good control on the crustal processes that accommodated the lithospheric buckling, and there are also intrusive rocks that were originated due to the involvement of the lithospheric mantle, we can try to model the response of the whole lithosphere that results from the buckling of the Variscan orogen. Nowadays, analogue modeling is the only reliable way to understand the lithospheric behavior in 3D due to the computer power limitations for mathematical accurate 3D modeling.

Methods

In order to perform the modeling of the buckling process and it is subsequent lithospheric detatchment we have performed a two stage experiment in which, using consistent materials and thermal boundary conditions, we have first simulated the oroclinal buckling process in a thermo-mechanical press. In this experiment we have modelled the resulting geometry after buckling an initially linear lithospheric segment. The second simulation was performed adding gravity to the previously obtained geometry, by means of a thermo-centrifuge machine, to test the possibility of lithospheric detatchment where the mantle lithosphere had been previously thickened.

The initial experiment is based on shortening of a 30 cm long elongated model composed of four layers: (i) the sub-lithospheric mantle, made with *Beck's orange plasticine*, (ii) the listospheric mantle, consisting of different kinds of plasticine whose physical properties are described in Pastor-Galán *et al.* (in press). The shortening in the thermo-mechanical apparatus led to a horseshoe shaped buckle fold with a vertical axis. This experiment has been performed repeatedly, at varying strain rates, using models with different thickness of the mantle lithosphere. All the experiments were performed at a constant temperature profile to hold the viscosity contrast between lithospheric and sublithospheric mantle. The deformed models were imaged using computer tomography (CT) in order to visualize the lithospheric response to the oroclinal buckling.

Once obtained the results of this former experiment we extended the experimentation with a second step, consist-

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ing in centrifuge experiments to study the effect of gravity on the mantle lithospheric thickening obtained in the core of the modeled oroclinal buckling. Because of the physical limitations of the experiment, we have carried this second step reproducing the obtained geometry in the original models with the same materials but re-scaled to the proportions of the centrifuge (8 cm long and 10 cm wide). The applied centrifuge is a Rotosilenta 630 RS. Models were preheated between 50º to 60°C and centrifuged at 300 G from 1 to 30 minutes.

		Lower-crust	**Lithospheric-mantle**	**Asthenosphere**
ρ (kg/m^3)	Experiment	1250	1400	1250
	Nature	3100	3360	3100
	Scaling factor	0,4	0.41	0.4
η_{eff} (Pa·s)	Experiment	12900	57300	590
	Nature	1,13x10^{21}	5x10^{21}	5.15x10^{19}
	Scaling factor	1.146x10^{-17}	1.146x10^{-17}	1.146x10^{-17}
n	Experiment	7,8*	4.37	3.41
	Nature	From 4 to 8	From 2 to 5	From 2 to 5

Table 1.- Scaling parameters used in the modeling experiments.

Results and Discussion

The first experiments show that during orocline buckling, regardless of the thickness of the different layers used or the strain rate, the mantle lithosphere is thickened in the core of the orocline and is thinned in the outer arc (fig. 1). Differences in the shape acquired by the thickened mantle lithosphere are observed in relation with the initial lithospheric thickness considered. While the initially broader mantle lithosphere thickens by generating a cone shaped mullion or a very tight conical shaped fold, the initially thinner mantle lithosphere thickens by conically shaped and recumbent folds or is duplicated by thrusting in a similar way to subduction zones. On the other hand, the thinning in the outer arc is always obtained by radial tension fractures. Moreover, in some experiments strain was accommodated by dextral shear zones.

Lithospheric thickening has been studied as causing lithospheric detatchment in different scenarios (*e.g.* Schott B., Schmeling, 1998). The centrifuge experiments reveal that detatchment of the lithospheric thickening (root) with the analogue materials selected is possible and easy to get when the model is heated up to 60ºC. Nevertheless, at T < 55º there is no evidence for detachment even if centrifuging over any properly scaled scenario (more than 20 minutes at 300 G).

The new experimental results are in agreement with the models proposed by Gutiérrez-Alonso et al. (2004) about the expected lithospheric thickening under orocline buckling conditions and provide new possible geometries for this thickened lithosphere that back up the digital models proposed by Schott B., and Schmeling (1998). Furthermore, the detatchment of the selected materials to model the lithosphere behavior is possible under certain properly scaled analogue conditions and can explain the abundance of post-orogenic magmatic rocks in the core of the Ibero-Armorican Arc.

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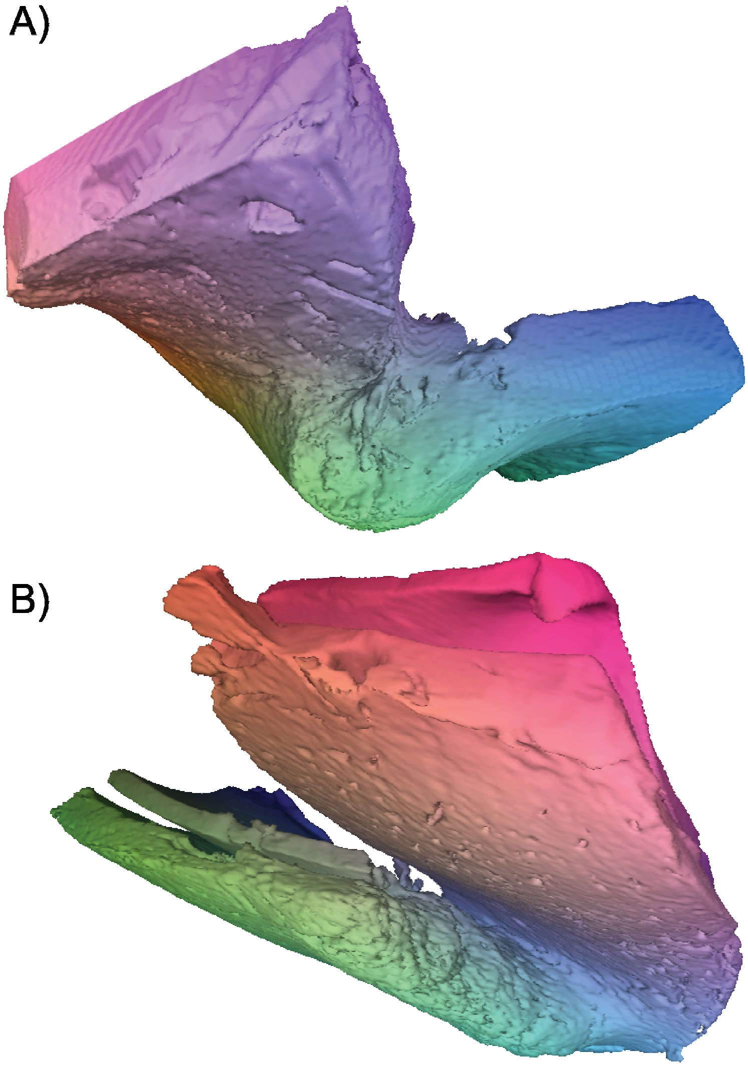

Fig. 1.- A) CT image of an originally 2 cm thick mantle lithosphere analogue after orocline buckling. The image depicts that the lithosphere has thickened as a conical tightened fold in the core of the orocline. B) CT image of an originally 1 cm thick mantle lithosphere analogue after the buckling. This model has thickened duplicating the mantle lithosphere as a conical recumbent folding in in the outer part and in a thrust way y the inner root.

New data about the Pre-Variscan Evolution of Peri-Gondwana Terranes, a Contribution from Southern Sardinia

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Several models have been proposed about the pre-Variscan reconstruction of peri-Gondwana terranes, nevertheless, more gaps still remain because the palaeogeography reconstruction is extremely complex (Stampfly & Borel 2002; von Raumer *et al.*, 2002; Alvarez & Shimabukuro, 2009).

Sardinia is one of these peri-Gondwana terranes linked to the Paleozoic margin of Northern Gondwana, that during Carboniferous was incorporated in the European Variscan Belt and where some tectono-metamorphic zones can be distinguished including a parautochthonous Foreland Zone (FZ) in the southwest and a allochthonous Nappe Zone (NZ) in the central Sardinia. We investigated its Paleozoic basement using detrital zircon U-Pb with the aim to detect the terrigenous provenance of the metasedimentary successions belonging both to the NZ and to the FZ. In the NZ sample we performed U-Pb coupled with Lu-Hf for determining the crustal evolution of its source.

Some authors (among them: Loi & Dabard, 1997) supposed that the NZ tectonic units (*e.g.* Sarrabus-Arburese Unit) and the authochtonous (*e.g.* Iglesiente Area) derived from two depositional and geographically separated areas, suggesting an intermediate position between North Gondwana and Baltica for the Nappe Units. Recently Avigad *et al.* (2011) supposed that the Cambrian sediments of the Sardinia FZ may have been fed from different sources suggesting a location along the north Gondwana margin likely easternmost from classic reconstructions.

Three samples have been collected:

- a quartz-arenite sample from the FZ representing a pre-Sardic phase succession, belonging to the Cabitza Fm. (CORI sample), attributed to the Cambrian-Ordovician boundary on stratigraphic coprrelation;
- two quartz-arenite samples from the external NZ, from the Bithia Unit (AF0828 sample) and from the Sarrabus Unit (SST 5100 sample), respectively representing a pre-Sardic phase sample and a post-Sardic phase sample.

The U-Pb and Lu-Hf analyses by LAM-ICP-MS were carried out using the Finnigan Neptune coupled to a Nd-YAG laser ablation system (New Wave Research, USA) at the Geochronology Laboratory of the Universidade de Brasília.

U-Pb analyses were performed on seventy grains from the post-Sardic phase (SST 5100 sample), on seventytwo grains from AFO828 sample and eighty seven grains from CORI sample (Fig. 1).

The studied samples show different age populations. Sample SST510 shows a main peak (450 Ma) probably linked to the last volcanic products of the magmatic arc developed on continental crust during Katian, well documented also in other fragment of the European Variscan belt; this sample also presents no Archean and scarce Paleoproterozic zircons that are indeed well represented by the pre-Sardic phase samples. The samples belonging to the pre-Sardic phase (CORI and AF0828) show a strong relationship with a Pan-African magmatic event (750 and 550 Ma). All samples received input by the Grenvillian sources, presented by Tonian and Stenian population, suggesting a possible Amazonian source for the Paleozoic sediments for the Sardinia like yet proposed for to the N-Iberia (Pereira *et al.*, 2012). Considering the lacking of Middle and Upper Mesoproterozoic input (1250-1600 Ma) in all samples analysed is plausible to consider this like a period of igneous quiescence. Only in the FZ is recorded a 1.2 Ga zircon input, not recognized in the NZ. These differences in the source area between the sedimentary rocks of the FZ and the NZ fit with some evidences recognized in their lithostratigraphic successions: i) in the FZ there are not the volcanic rocks related to the Katian magmatic arc that crop out in the NZ and that are recorded in the detrital zircons from sample SST510; ii) in the Upper Ordovician succession of the NZ the typical Gondwana fauna is coupled with a Baltica-related fauna, whereas this last one

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totally lack in the Upper Ordovician succession of the FZ (Loi & Dabard, 1997). These data suggest that during the Upper Ordovician, the NZ and FZ, although both belonging to the North Gondwana, received sedimentary input from different source areas.

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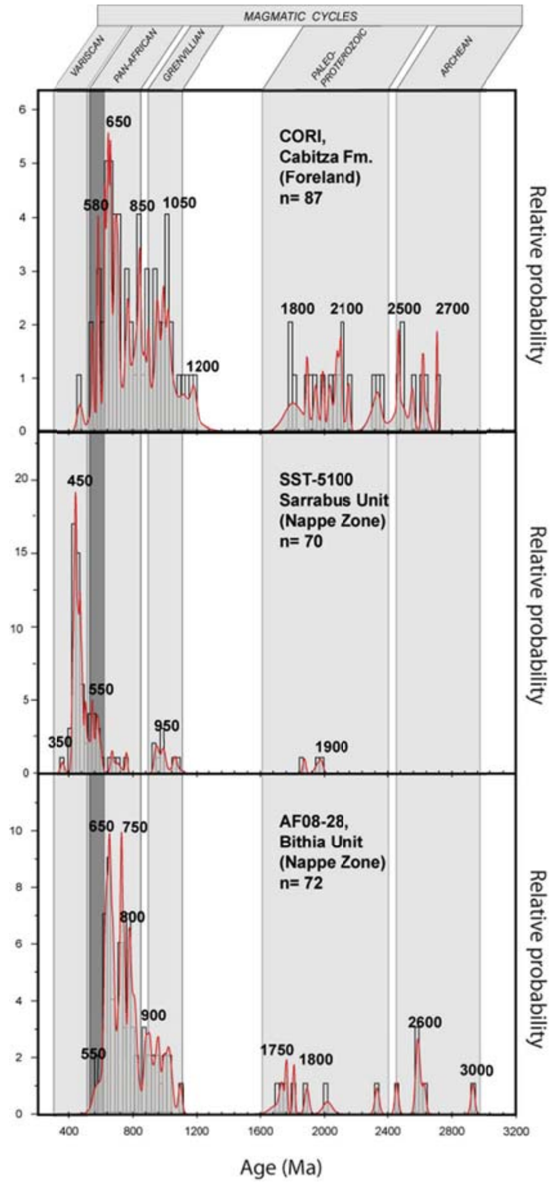

Fig. 1.- U-Pb results shown in frequency histogram for the Palaeozoic Sardinian samples, for the younger ages (< 900 Ma) have been used the $^{238}U/^{206}Pb$ ratios and for the older have been used the $^{207}Pb/^{206}Pb$.

Polyphase structural and metamorphic evolution of Variscan superstructure, Teplá-Barrandian unit, Bohemian Massif

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Teplá-Barrandian Unit (TBU) represents the largest relict of orogenic superstructure within Variscan Bohemian Massif characterised by common occurrence of well-preserved pre-variscan and early-variscan fabrics. It is mostly composed of medium to low-grade Neoproterozoic metasediments unconformably overlain by Paleozoic unmetamorphosed sequences and therefore it offers excellent opportunity to study not only superposition of individual structures but also their P-T evolution using thermodynamic modelling.

We present here the preliminary data collected along the Střela river profile, which exposes a continuous crustal section across the western margin of the TBU. We identified three distinct deformation stages and related fabrics, each characterised by systematic spatial variations of P-T conditions and structural styles.

The eastern part of the studied area is dominated by subhorizontal metamorphic foliation (S_1) originated via complete transposition of original bedding and showing normal metamorphic zonation from very-low grade in upper part to at least garnet zone in structurally lower part. From the east to the west, the S_1 foliation is progressively reworked by north-south trending steep S_2 slaty cleavage formed by large-scale upright folding and transposition. The metamorphic conditions increase together with degree of reworking from chlorite zone in the east to kyanite zone in the west. The structural style as well as prograde character of metamorphic evolution shows that major thickenning of TBU occurred during D_2 deformation.

In contrast, the western part of the studied area is characterised by dominance of S_2 fabrics, which are progressively transposed by tight to isoclinal folds F_3 accompanied with SE dipping axial plane cleavage S_3 towards contact with Mariánske-Lázně complex (MLC). The S_3 cleavage is associated with significant vertical shortening and retrogression of S_2 metamorphic assemblages in sillimanite stability field. We interpret the S_3 fabrics as a result of activity of a large-scale detachment zone responsible for unroofing of the MLC.

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Structure and metamorphism of the Axial Zone of the Pyrenees in the south-western sector of the Lys-Caillaouas massif (Huesca, Spain)

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Introduction

In the Axial Zone of the Central Pyrenees, Paleozoic rocks deformed and metamorphosed during the Variscan Orogeny, subsequently affected by an Alpine thrust, crop out. Pre-Upper Ordovician series have pre-Variscan structures too. This work was carried out in Lys-Caillaouas Massif, constituted by metasedimentary rocks from Cambro-Ordovician to Devonian which have been deformed during the Variscan Orogeny and affected by the high temperature metamorphism originated by the Variscan granitoid emplacement. Previously, this zone was studied by Clin (1964), who constructed a map of the western sector of the massif, where the principal stratigraphic units were mapped. Geologists from Leiden elaborated maps of the Axial Zone, and the south-western sector of Lys-Caillaouas Massif was studied by Wennekers, whose contributions were collected later by Zwart (1979). More recently, De Bresser *et al.* (1986) provided new information about structure and metamorphism, and Kriegsman *et al.* (1989) made a detailed microstructural study, later extended by Aerden (1994). Ultimately, Hilario (2004) characterized the relationship between the Variscan deformation and the Lys-Caillaouas granite.

The objective of this work is to study the structures of the south-western ending of the Lys-Caillaouas Massif, trying to establish a temporal sequence. This will make possible to understand the genetic meaning of the structures, and its relationship with the metamorphism. To achieve this purpose, a geological map and a cross-section were constructed (fig. 1) and we made a study of the microstructures in this area.

Stratigraphy

In the geological map of figure 1, pre-Silurian rocks were described by Hartevelt (1970) in eastern Pyrenees. The units from older to younger are:

- *Jujols Series*: Alternating quartzite and slates or schistes from Cambrian to Middle Ordovician age.

- *Rabassa Formation*: Quartzitic conglomerates, discontinuous, unconformably over the Jujols Series. This unconformity was interpreted as the result of an extensional event (García-Sansegundo *et al.*, 2004).

- *Cava Formation*: Sandstones with sericitic matrix, which change to quartzite and sandstones. Frecuently, they have decimetric calcareous intercalations towards the top.

- *Estana Formation*: Constituted by grey siliceous limestone and shales, discontinuous, with thickness less than 10 meters.

- *Ansobell Formation*: Composed by grey shales, with centimetric or milimetric-scale fine grain sandstone intercalations.

The thickness of Upper Ordovician sequence is about 550 meters. At the top of this sequence 200 meters of Silurian ampelitic shales and slates crop out. On top, alternating Devonian limestones and shales of the Rueda formation appear, described by Mey (1967).

Structure and metamorphism

Observing the geological map and the cross-section in the figure 1, and attending to the microscopic study and the criteria of superposition of structures, the following deformation phases have been recognized:

- *Pre-Variscan structures*: This phase consists of a cleavage (Se) which has been observed in thin section, only present in the pre-Upper Ordovician rocks of the Jujols Series. No associated folds have been found in the study area.

- *Variscan structures D1*, are the principal structures and are well development in the North of Eriste-Vallarties Fault (EVF) (fig. 1), corresponding to inclined, North-verging folds with E-W to NW-SE axial trend and kilometric-scale. The main foliation (S1) is associated with these folds, consisting in a cleavage or schistosity, subparallel to axial

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planes, generated in low grade metamorphic conditions. When metamorphism is medium grade, S1 is a schistosity. Moreover, in this conditions clorite, biotite, garnet, staurolite and andalucite porphidoblasts grow up on S1 foliation. Many porphidoblasts have strain-shadows and a slight rotation in pebbles of Rabassa conglomerate and some porphidoblasts was observed, suggesting a post-D1 weak shear deformation. This is confirmed in some places where foliation S1 is folded by this shear deformation.

- *Variscan structures D2* have been only observed in the South of FEV, consisting in a subvertical creanulation cleavage (S2) associated with upright, tight and E-W trending folds. In the southern area of the Lys-Caillaouas Massif, they are the main structures, affecting Devonian layers and part of Silurian shales.

The FEV has E-W direction, from vertical to steep dip to the north and separates two domains. In the northern one, the main structures are D1 folds and S1 cleavage, where the Silurian slates exhibit a well developed cleavage S1 undeformed by subsequent structures. In the southern domain of the study area, D2 structures dominate: S1 is intensely folded by D2 structures.

In the North portion of the map of the Figure 1, there is another NW-SE trending fault, vertical, that displaces a kilometric-scale D1 fold, raising the northern part. This fault is cut by other NE-SW trending, transversal faults.

Alpine structures have not been found, however, some described faults, could have had an Alpine reactivation.

Conclusions

Between two principal Variscan deformation phases described in this work, a rise of temperature and a growth of porphyroblasts were produced, caused by medium grade metamorphism. This episode is associated with a weak shear deformation, and it could be related to the Lys-Caillaouas granite intrusion.

On the other hand, in the south-western sector of Lys-Caillaouas Massif, two structural domains have been recognized: In the northern one, structures D1 are the principal and, in the South, the main structures are D2. Both domains are separated by the FEV, responsible for this spatial distribution of Variscan structures. This fault corresponds to a D2 thrust, whose hanging wall is situated in Lys-Caillaouas Massif with the basal décollement within or below Jujols series. The gently dipping to the North fold axial plane, developed in the hanging wall, is observed in the cross-section of figure 1, and is interpreted as the frontal ramp associated with this thrust. In the southern part of the FEV, the basal décollement probably is situated nearly the Silurian shales, and is responsible for the D2 folds development in the southern portion of the study area.

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Geodynamic evolution of Southern Europe from late Palaeozoic to Early Mesozoic

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The Late Carboniferous to Late Triassic period marks in Southern Europe the transition between the last phase of Variscan orogenesis and the opening of the Liguria-Piedmont ocean. The Variscan chain was formed, at least in part, by the collision between the supercontinents of Gondwana (to the south) and Laurasia (to the north) that followed the northward subduction of the Palaeotethys ocean. The SE border of this SW-NE collisional belt was located along the Morocco- Algerian- Tunisian margin of Gondwana, while in former Italy run probably around the North Adriatic Sea, where an Upper Ordovician granodiorite body was drilled by AGIP Oil Company along the exploratory well "Assunta 1", close to the Venice Lagoon. Such intrusive rock (448 ±18 Ma) is capped by a Triassic sedimentary cover and is substantially undeformed and not affected by post-emplacement metamorphic overprints. Therefore this area could represent the southern foreland of the Variscan orogen, which involved Southern France, Sardinia, Corsica, Tuscany and North Italy.

After the Variscan orogenesis, during Late Carboniferous and Early Permian, the Southern European segment of the chain was affected by a discontinuous continental sedimentation, filling fault-bounded and strongly subsiding intra-continental basins. A widespread volcanism took place, with ignimbrites, tuffs and lava flows of calc-alkaline acidic and intermediate composition. In Northern Italy a maximum thickness of more than 2000 m was reached by the "Bozen Volcanite Complex". Several intrusive bodies of the same age also occurred. These events are consistent with a transcurrent tectonic regime, that locally induced crustal stretching, and upwelling of the asthenosphere. Many basins can be interpreted as strike-slip or pull-apart basins that developed along major faults as the Cevennes Fault (in southern France), the western Corsica lines, the Campidano, Posada-Asinara (in Sardinia), the Canavese, Cossago-Mergozzo-Brissago, Engadina, Val Camonica and Giudicarie lines (in the Alps). These widespread dextral strike-slip deformations along an ENE palaeo-trend, subparallel to the Variscan orogen, can be explained by the progressive Late Carboniferous-Early Permian transformation of the Gondwana-Eurasia collisional margin into a diffuse dextral transform margin, due to the onset of the subduction of the Palaeotethys active oceanic ridge under the Laurasia continental plate and the progressive rotation of the plate convergence from NW-SE to WNW-ESE.

During the Middle Permian, when the Illawarra Reversal geomagnetic event took place (~265 Ma), a significant geodynamic change affected Southern Europe. Volcanism ended, the sedimentary successions were interested everywhere by a marked stratigraphic gap and a new tectono-sedimentary cycle began. It is characterized by a large-scale molassic sedimentation, more or less continuous, without major unconformities, with clastic deposits (conglomerates or sandstones), rich in quartz, deriving from the dismantling of the residual Variscan relief. In particular, the central Variscan belt was subjected to huge erosional and peneplanation events in a relatively stable continental environment and, during Permo-Triassic, to a westward marine ingression. The major regional angular unconformity of the Middle Permian probably reflects a pulse of deformation, which induced faulting, gentle folding, uplift and erosion or non-deposition. This event can be related to the so-called "Mid-Permian Episode" sometimes coeval with a (trans)compressional activity.

The most significant geological event of the Mid-Late Permian was the progressive separation of the Cimmerian continent from the northeastern border of Gondwana, which was followed by the opening of Neotethys. This important rifting process was probably caused by the end of the subduction of Palaeotethys spreading axis beneath the eastern Variscan orogen and the rotation of the Gondwana- Laurasia convergence direction towards WNW-ESE. In the central Alps the pre-

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monitory signs of a rifting regime are clearly recognizable only since the Mid-Triassic, when the development of the Jurassic Liguria-Piedmont ocean was preceded by a new complex magmatic cycle, which is mainly characterized by rhyolitic tuffs, large volumes of acidic to shoshonitic subvolcanics, abundant extrusives and high-K calc-alkaline to shoshonitic subaerial volcaniclastic rocks. The occurrence in Late Carnian of transitional basaltic dykes (217 ± 3 Ma) and continental tholeitic lavas preludes to the onset of the rifting together with the deposition of a new major rifted extensional carbonate sequence represented by the Carnian-Norian “Dolomia Principale” and its basal breccias.

The granulites of the Campo Unit (Central Alps): witnesses of Permian orogenic collapse and Jurassic hyper-extension

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The final stages of Variscan orogeny within the Alpine realm are classically characterized by the emplacement of large felsic and mafic complexes at all crustal levels during lithospheric extension in the Permian. At deeper levels, these mostly mafic intrusions can be linked to the formation of granulites. This as yet little understood tectono-magmatic event modified the compositional and thermal structure of the Variscan lithosphere and may have controlled the strain and magmatic evolution during the opening of the Alpine Tethys. To better understand these processes, we initiated a multidisciplinary research project coupling structural geology, igneous and metamorphic petrology and geochronology in the former hyper-extended Adriatic rifted margin outcropping in the Austroalpine Campo Unit (SE-Switzerland and N-Italy).

The Campo Unit is composed of metamorphic rocks (kyanite-garnet-staurolite bearing micaschists and amphibolites) of unknown (probably Variscan) age, that record amphibolite-facies conditions. A gabbroic plutonic complex (the Sondalo gabbro) was emplaced during late-Carboniferous and early-Permian times between ca. 300 and 270 Ma. This intrusion produced a metamorphic contact aureole leading to partial melting of the surrounding rocks. Thin-section observations show destabilization of muscovite, appearance of sillimanite, spinel, cordierite, crystallization of a large amount of garnet and finally to the disappearance of biotite and potassic feldspar. As a consequence, granulitic rocks composed of garnet, sillimanite, cordierite and spinel are formed in an intra-plutonic position. The late evolution of the area is marked by static crystallization of andalusite. Preliminary qualitative P-T estimates indicate a barrovian prograde path, perturbed during the retrogression by the intrusion of the mafic body at around 5-6 kbar, cause transient heating of the surrounding metasediments to ≈ 900°C. The lack of orthopyroxene, characteristic for low-pressure granulites is interpreted as proving the low exhumation rate of the area during the Permian temperature peak.

These lithologies are cross-cut by the rift related Eita shear zone, which finally exhumed the Campo unit during the Jurassic rifting in the first kilometers of the crust. This exhumation is documented by $^{40}Ar/^{39}Ar$ ages on muscovite and biotite, which are ranging between 180 and 200 Ma.

Studying the Permian intrusions, their relations to the host rocks and their exhumation processes enables to establish (1) a snapshot of the crustal architecture in Permian time and (2) characterize the tectonic, thermal and magmatic evolution from the Permian orogenic collapse to subsequent Jurassic rifting. In order to get better constrains on the P-T-t conditions from the formation to the exhumation of the granulites, we will use thermodynamic modeling and $^{40}Ar/^{39}Ar$ dating.

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Thermal and Mechanical interactions in the Variscan crust: insights from South Bohemian metapelites

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The core of the Bohemian Massif is build-up of middle and lower crustal rocks of the Moldanubian unit and the orogenic upper crustal Tepla-Barrandian Unit, composed by low grade metasediments and volcanics. In the Bohemian massif the petrological studies were so far focused on high grade rocks (granulites, migmatites, eclogites) and only rarely on rocks equilibrated at mid-crustal conditions (Skrzypek *et al.*, 2011). The studied area allows examining the three different units located in between the orogenic lower crust outcrop of the Blanský les granulite massif to the north and large Moldanubian batholith to the south. The unit package consists of the varied unit composed of paragneisses with intercalations of amphibolites and marbles, over the monotonous unit composed of paragneisses hosting eclogitic bodies. Further south, these units overlies the Kaplice micaschists intruded by Moldanubian batholiths with clearly lower grade conditions compared the two other northerly units.

Field work observations allowed us to define three distinct deformation events, shared by all three units. Locally preserved N-dipping vertical foliation S1 is refolded by ubiquitous isoclinal F2 folds. The latter event generates a NW shallow dipping fabric (S2), which is dominant in the area. Finally, a late D3 event is responsible for development of heterogeneous F3 crenulation folds.

Varied and monotonous biotite-sillimanite paragneiss are locally anatectic as shown by the presence of K-feldspar, large amount of sillimanite and the rare occurrences of highly corroded muscovites in the S1 foliation. Optically zoned plagioclase feldspars are showing K-feldspar, sillimanite and kyanite inclusions. Garnets ($Alm_{0.60}$, $Prp_{0.19}$, $Sps_{0.19}$, $Grs_{0.02}$) reveal a flat profile. The late evolution of rock is characterized by the static growth of cordierite. Pseudosection based P-T estimates gives an isothermal decompression from peak conditions of 10-12kbar/800°C to 5kbar/700°C.

Muscovite-biotite micaschists of the Kaplice unit are characterized by a low content of kyanite, andalusite and sillimanite, rare skeletal staurolites and small garnets aligned in the S1 foliation. Kyanite and sillimanite are syntectonically growing in the S1 structure and are refolded by the D2 phase. Retrograde path is characterized by static growth of cordierite and andalusite. Chemically zoned almandine garnets (Alm0.76-0.66, $Prp_{0.07-0.04}$, $Sps_{0.16-0.09}$, $Grs_{0.15-0.05}$) allow us to reconstruct the prograde part of the P-T path from 5kbar/525°C to 6kbar/650°C, followed by a isothermal decompression to 4kbar/650°C. Only the end of the P-T path is shared with the monotonous and the varied unit.

Cooling ages of ca. 341-339 Ma for the $^{40}Ar/^{39}Ar$ on hornblende chronometer and 337 Ma for the $^{40}Ar/^{39}Ar$ on biotite showed a simultaneous cooling of the Blanský les granulite massif and the varied unit. However, in the south of the studied area, the $^{40}Ar/^{39}Ar$ chronometer is reset between 313 and 288 Ma.

Granulitic orogenic lower crust is exhumed along vertical extrusion channel (Franěk *et al.*, 2011) from 18kbar/800°C to mid crustal depths. The structurally coherent mid-crustal rocks of the monotonous unit reveal similar decompression path from 10-12 kbar/800°C to mid crustal levels ~5kbar/700°C. In contrast, the rocks of Kaplice unit show similar fabric pattern marked by first burial from 5kbar/525°C to 6kbar/650°C and subsequent exhumation to 4kbar/650°C. Afterwards, both formations followed coupled P-T paths which are associated with development of S2 foliation. The latter deformation event is therefore interpreted as a result of the lateral subsurface flow as proposed in other parts of the Bohemian massif (Skrzypek *et al.*, 2011). The difference of P-T evolution between the

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Kaplice micaschists and adjacent mid-crustal rocks is interpreted in terms of local burial of orogenic superstructure into mid-crustal depth simultaneously with the exhumation of deeply buried crust. The study of the Kaplice Unit is therefore a unique opportunity to study the deepest part of orogenic suprastructure in the field. The discrepancy of cooling ages between the rapidly cooled granulites, adjacent paragneisses and Kaplice micaschists is interpreted in terms of re-heating of the south-eastern part of the orogenic system by the Moldanubian batholiths.

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Inverted metamorphic field gradient towards a Variscan suture zone (Champtoceaux Complex, Armorican Massif, France)

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A common feature of orogenic belts associated with continental collision is the presence of crustal-scale thrusts that superpose high-grade metamorphic units over lower-grade units. The result is an inverted metamorphic zoning. Structural elements associated with these thrusts are commonly overprinted by later tectonic events, and inverted metamorphism is commonly the only trace of continental collision in old orogens. Despite numerous field-based studies and numerical models, the development of inverted metamorphic zoning, its preservation and exhumation remain controversial, although it is a key-point in understanding of orogenic processes.

We describe, date and constrain the *P-T* conditions of a syntectonic inverted metamorphic sequence associated with continental collision and crustal-scale thrusting in one of the key regions of the late Palaeozoic Variscan belt of Western Europe - the Champtoceaux Complex (Armorican Massif, France), interpreted as a trace of the Variscan suture zone between Laurussia and Gondwana. The Complex consists of several stacked units, some of them eclogite-bearing, that are sandwiched between two main pieces of continental crust - the Parautochthon and the Upper Allochthon. Moderately to steeply dipping foliation parallels the main lithological boundaries. From the bottom to the top of the metamorphic rock pile, the following sequence testifies to the syntectonic temperature increase: chlorite-biotite-bearing metagreywackes (Parautochthon); orthogneisses with eclogite lenses; micaschists with chloritoid-chlorite-garnet; orthogneisses; micaschists with staurolite-biotite-garnet with chloritoid inclusions (Lower Allochthon); and migmatites with boudins of eclogite and kyanite-biotite-garnet-bearing metapelitic lenses (Upper Allochthon). Mylonitic amphibolites with lenses of serpentinised peridotite mark the boundary between the Lower Allochthon and the overlying Upper Allochthon, suggesting the presence of a major thrust. We infer that the latter is responsible for the development of the inverted metamorphic zoning.

Multiequilibrium thermobarometry and pseudosections calculated with THERMOCALC indicate that equilibration temperatures of the syntectonic peak metamorphic assemblages increase upwards in the rock pile from <500°C in the Parautochthon to >650°C in the Upper Allochthon. These rocks represent therefore an inverted metamorphic sequence. The temperature increase of more than 150°C occurs over less than 4 km (normal to the foliation). This yields a metamorphic field gradient of more than 38°C.km-1. However, all units equilibrated at similar pressures between 7 and 10 kbar.

In the Upper Allochthon, chronological results on muscovite suggest initial cooling from c. 343 Ma (muscovite Rb-Sr) to c. 337 Ma (muscovite ^{40}Ar-^{39}Ar). A subsequent very rapid temperature decrease is suggested by the synchronous closure of the muscovite and biotite K-Ar and biotite Rb-Sr isotopic systems (c. 337-335 Ma). This cooling is also recorded in the Upper Micaschists of the Lower Allochthon and in the Parautochthon with muscovite ^{40}Ar-^{39}Ar ages of c. 336-334 Ma and 332 Ma, respectively. Ages of c. 343 Ma inferred from disturbed muscovite spectra from the Parautochthon are possibly linked to a previous higher pressure metamorphic event in this unit.

The interpretation of the inverted metamorphic field gradient relies on two different observations. First, textural relations evidence that peak metamorphic assemblages in all units are syntectonic, associated with the development of the main foliation. Rocks in the footwall of the major contact, display syntectonic heating and pressure increase. No significant pressure gradient, expected in the case of inversion due to post-metamorphic ductile or brittle deformation, is associated with the observed peak temperature gradient. Second, no major (semi)brittle shear-zones are observed at the boundary between the units (despite good outcrop conditions). For example, the serpentinites, a rheologically very weak lithology, do not present faults or microfaults, suggesting that no deformation took place after the development of the olivine-bearing foliation at temperatures higher than 600°C.

Therefore, the observed metamorphic inversion is not merely the result of post-metamorphic deformation of the

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isograds or overthrusting of units that previously displayed a "normal" sequence of metamorphic zones. Rather, it can be suggested that the development of the inverted metamorphism in the Champtoceaux Complex resulted from a thermal perturbation induced by the emplacement of the hot, possibly migmatitic Upper Allochthon nappe overriding a cooler footwall and was contemporaneous with major crustal thrusting and associated pervasive ductile deformation. The preservation of this inverted field gradient was possible because of fast cooling, tentatively associated with the syn-compressional denudation of the tectonic pile, expressed by the detachment at the top of the nappe pile. The efficiency of cooling is best shown by the near-coincidence of Rb-Sr and ^{40}Ar-^{39}Ar ages, obtained on both sides of the major thrust.

Finally, we highlight similarities with other regions of the West-European Variscan belt (Iberian massif, French Massif Central) and suggest that inverted metamorphic zoning is systematically associated with the contact between the Lower and Upper Allochthons.

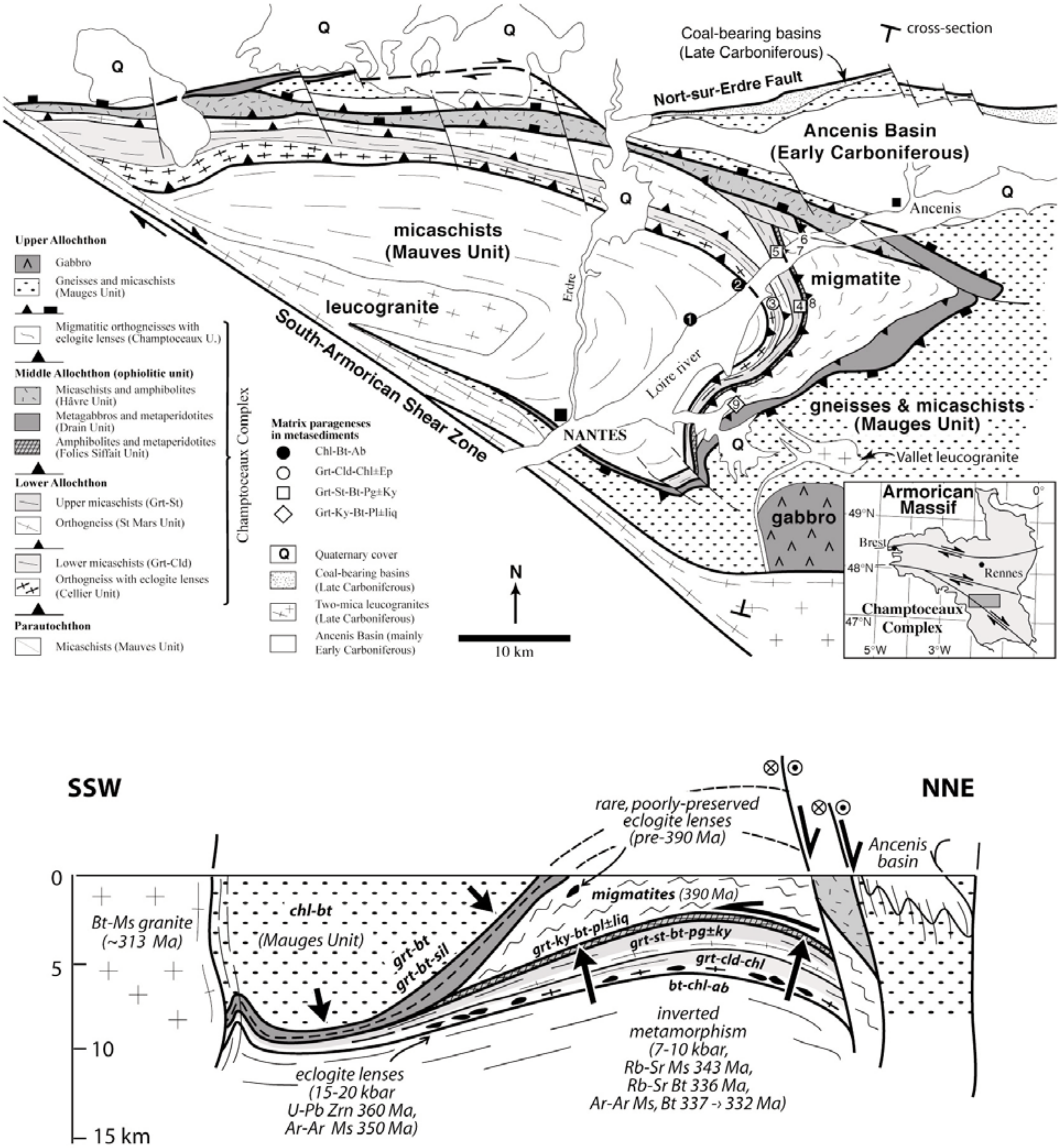

Figure: Sketch geological map of the Champtoceaux complex and its location within the Variscan Armorican Massif, Western France (inset). Shear zones at the bottom of the Hâvre and Mauges units are thrusts reactivated as normal faults. Numbers refer to the location of the studied samples. Interpretative cross-section including the metamorphic history of the Champtoceaux area. Synkinematic assemblages associated with the main, nappe-forming, deformation, and post-dating the eclogite-facies event in the Champtoceaux Complex are indicated. Thick black arrows indicate increasing metamorphic grade. It thus appears that (i) an inverted metamorphic field gradient is found in the Champtoceaux Complex (with temperature increasing from the micaschists of the Parautochthon to the contact with the Upper Allochthon migmatites), and (ii) a normal field gradient is found at the base of the Mauges Unit.

Investigations of the role of a mylonitic zone as contributor of the final mush emplacement and the solid-state deformation of a granitoid pluton: implications for Late Variscan kinematics in the Southern Carpathians (Romania)

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Middle-Late Carboniferous magmatism is widespread in the West and Central European Variscides where it has been mainly ascribed to post-collisional processes. Although relatively unknown, a Late Variscan well represented plutonism is also present in the pre-Alpine basements of the Southern Carpathians and the Balkans [1, 2], in agreement with the implication of this area in the Variscan orogeny.

In Western Europe, this post-collisional magmatism has been variously related to crustal thinning induced by extensional tectonics [3] or, more recently, to a synconvergent transpressive setting (*e.g.*, [4]) also evidenced in other parts of the Variscides (Pyrenees - [5]; Alps-Mediterranean - [6]). In fact, the relationships between plutonic rocks and transcurrent tectonics have been recognized for a long time, and the study of syntectonic granitoid plutons turns out to be interesting to investigate the tectonic regime prevailing during their emplacement and cooling.

Our study presents a petro-structural study of the syntectonic Carboniferous Cherbelezu pluton (Almăj Mountains, SW Romania) that belongs to the Upper Danubian Alpine Nappe and crops out along a pre-existing major verticalized formation, the Corbu Mylonitic Zone (CMZ). The study investigates the role of the CMZ on the deformation recorded during the mush emplacement and cooling. It can give information not only on the general relationships between faulting and mush emplacement but also on the concomitant Late Variscan regional kinematics occurring in this poorly studied area. We performed a detailed microstructural study of this granitoid, and used anisotropy of magnetic susceptibility (AMS) as well as shape preferred orientations (SPO) inferred from image analysis (IA). The surrounding rocks preserve evidence that the CMZ, which developed first as a collage lineament for a Devonian ophiolite, has been reactivated as a sinistral strike-slip fault before the pluton emplacement. Microstructural investigations of the granitic facies indicate that the pluton has undergone superimposed deformations during its cooling, from submagmatic to LT conditions. Foliation and lineation patterns obtained by AMS and SPO - both methods giving similar results - reflect either magmatic/submagmatic or solid-state flows. Magmatic flow, preserved in the western and southern parts of the pluton, is characterized by concentric foliation pattern with both divergent and parallel lineations, the latter pointing to an early transcurrent regime. Subsequently, a solid-state deformation, recorded during the pluton cooling and restricted to its eastern and northern parts, argues for the concomitant CMZ activity under a sinistral transpressive regime. This is supported by the P' and T parameter distributions, especially for SPO results, this technique showing clear advantages for the interpretation of the fabric scalar parameters.

The Cherbelezu pluton belongs to a Carboniferous plutonism that is widespread in the Southern Carpathian - Balkan zone. Considering the distribution of all the Carboniferous granitoids present in this region before the clockwise Alpine rotation characteristic of this area, these plutons appear aligned along a WNW-ESE axis that closely corresponds to the initial orientation of the CMZ. Although their position relatively to the CMZ is variable, the similar ages of these plutons (327-310 Ma) could indicate a coeval magmatic event occurring after the stacking of the various gneissic units, the ophiolitic massifs and the metasedimentary sequences. Their alignment and distribution on both sides of the CMZ could reflect a common linear melting source, the localisation of the melt inside the CMZ and its subsequent extrusion in the adjacent units. Our structural study on the Cherbelezu pluton indicates sinistral kinematics prevailing during its emplacement. The elongated shapes of the other granitic bodies, except for the younger Petrohan granitoid (304 Ma), could also suggest syntectonic emplacements likely controlled by wrench tectonics.

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Recording of the easternmost Variscan ophiolitic complex: accretion and obduction of the Balkan-Carpathian oceanic crust (BCO - Romania, Serbia, Bulgaria) evidenced by Sm-Nd and Ar-Ar geochronology

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The Alpine Upper Danubian Nappe crops out in a tectonic window in the segment connecting the South Carpathians (South Banat, Romania) and the NE of the Balkans (Deli Jovan and West Stara Planina, Serbia and Bulgaria). Effects of the Alpine orogeny in this area are limited to low-grade Cretaceous metamorphism and Oligocene dextral strike-slip faults in relation with the clockwise rotation of the South Carpathians orogenic segment [**1**].

The pre-Alpine basement of this Upper Danubian Nappe displays an important tectonic marker in the form of the Balkan-Carpathian Ophiolite (BCO). This ophiolite (~ 500 km²) has been dismembered in four ophiolitic massifs by the Oligocene dextral strike-slip fault system of Cerna-Timok: Tisovita Iuti (TI-Romania), Deli Jovan and Zaglavak (DJ and Z-Serbia) and Tcherni Vrah (TV-Bulgaria). Together, these massifs display all the components of a classical ophiolitic assemblage from north to south [**2, 3, 4**]. The entire crustal unit is relatively thick (3 km) and forms a normal pile dipping to the southwest.

However, the age of accretion of this oceanic crust is controversial; it is either considered as 1) Late Proterozoic-Early Cambrian, on the basis of doubtful stratigraphic relations with paleontological evidences (Archaeocyathids and Acritarchs [**3, 4**]) and on U-Pb zircon isotope dilution (U-Pb age of 563 ± 3 Ma) obtained on a metagabbro from the Tcherni Vrah ophiolitic massif [**5**], or 2) Early Devonian, considering the ages obtained on gabbros from the Deli Jovan massif by [**6**] (406 ± 24 Ma by Sm-Nd mineral isochron, 399 ± 5 Ma by U-Pb zircon isotope dilution, 405 ± 3 Ma by U-Pb SHRIMP zircon).

It is generally accepted that the BCO corresponds structurally to the tectonic contact between two high-grade Proterozoic units [**7, 8**]. However, on the basis of the age assumption, the BCO has been variously considered as part of a Panafrican [**4, 9**], Caledonian [**8, 10**] or Variscan suture [**3, 6, 7**].

Our study gives new geochronological constraints for the accretion of the BCO and new petrostructural and geochronological data on a specific and localized metasomatic event, interpreted as linked to the obduction processes.

Sm-Nd dating has been realized on fresh gabbroic rocks from the TI and DJ massifs. The samples analyzed consist of 4 olivine gabbros from TI to realize isochrons on separated minerals (clinopyroxene, plagioclase and whole rock) and 4 supplementary samples displaying various pyroxene contents to cover a large $^{147}Sm/^{144}Nd$ ratio (clinopyroxenite from TI, olivine gabbro, troctolite and pyroxene troctolite from DJ). Several samples have been duplicated to check the reproducibility of the measurements. The olivine gabbros appear as several meters large magmatic 'bubbles' intrusive in layered gabbros that display a SL magmatic fabric. No deflection of the gabbroic layer has been observed at the contact between the two rocks, ensuring that the layered gabbros, even if already oriented, were still at the mush stage when intrusion occurs. Consequently, the two rocks can be considered as nearly concomitant in terms of cooling.

The isochron obtained on the 8 whole rocks (**Fig 1A**) gives an age of 409 ± 38 Ma (MSWD = 3.8) whereas those on separated minerals show younger ages (**Fig. 1B**) of 386 ± 25 Ma (MSWD = 1.8), 390 ± 52 Ma (MSWD = 2.7), 382 ± 46 Ma (MSWD = 4.7) and 380 ± 34 Ma (MSWD = 2.1). The first age could be interpreted as the magmatic accretion, in agreement with the ages obtained by [**6**]. So, the Proterozoic age that is currently used in the literature to characterize the BCO [**4, 5**] should be rejected. The age of 563 Ma, obtained on zircon by [**5**], should be widely questioned because the method used is isotope dilution. Also,

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the Dalgi Dial olisostrome, which contains Acritarchs, has been recently ascribed to the Devonian [**7**].

Despite the fact that the younger ages overlap the errors obtained for the whole rocks isochron, they probably indicate a re-opening of the isotopic system at the scale of the minerals. This hypothesis would imply a reheating of the BC-oceanic crust after the accretion, possibly due to an intra-oceanic overthrust occurring during the early stages of the closure of this basin.

In parallel, we studied a deformation zone that is preferentially located in the northeastern part of the massifs. This zone displays a juxtaposition of deformed and undeformed upper oceanic crust lithologies (mainly amphibolitic gabbroic rocks), which are locally affected by an uncommon listvenitic metasomatism. We have characterized this metasomatism in the Tisovita Iuti complex where it is best developed. It consists of a metasomatic assemblage composed of zoisite + calcite + Cr-chlorite + Cr-muscovite developed on amphibolitized gabbros under strongly hydrated and carbonated conditions at temperatures around 280°C [**11**]. Petrostructural data obtained on these amphibolitic and listvenitic gabbros indicate that the mylonitic deformation is preferentially located in the metasomatic lithologies, which may be associated to an oblique thrusting event with a dextral component with a top to the west (before Alpine rotation coordinates).

To constrain this event, $^{40}Ar/^{39}Ar$ dating has been performed on two Cr-muscovites from slightly and highly listvenitized gabbros issued from the mylonitic Eastern part of the TI massif. Results give plateau ages of 372.6 ± 1.3 Ma and 360.6 ± 1.2 Ma respectively (**Fig. 2**). We interpret these ages as the intense metasomatic processes affecting amphibolitic gabbros - at the origin of listvenitic rocks - in localized zones. As the mylonitic deformation observed in these rocks appears contemporaneous to their metasomatism, it is likely that an important intra-oceanic thrusting occurred at proximity of a continental margin during Late Devonian times, to explain such large and CO2 - rich chemical remobilisations.

Based on the 3 ages obtained on the ophiolitic rocks, we confirm that an oceanic domain was present during the Early Devonian times (~ 410-400 Ma) in this eastern part of the future Variscan Belt. The early closure of this oceanic domain could have been initiated rapidly after the accretion of the BC crust, at about 390-380 Ma. Moreover, this scenario is constrained by the ages of the listvenitic metasomatism (370-360 Ma), which probably reflects the final stage of an intra-oceanic obduction near or onto a continental margin. Consequently, the new ages obtained for both accretion and obduction processes for the BCO involve necessarily a relatively narrow oceanic basin or a ridge accretion located near a continental margin.

These results imply the occurrence of a Variscan oceanic suture in the Eastern part of the Variscan Belt, classically ending in the Sudetes Area (Poland). It is in agreement with [**12**], who proposes the existence of a Devonian open sea environment (Paphlagonian Ocean) in this area, interpreted as an equivalent of the Rheno-Hercynian Sea by [**13**].

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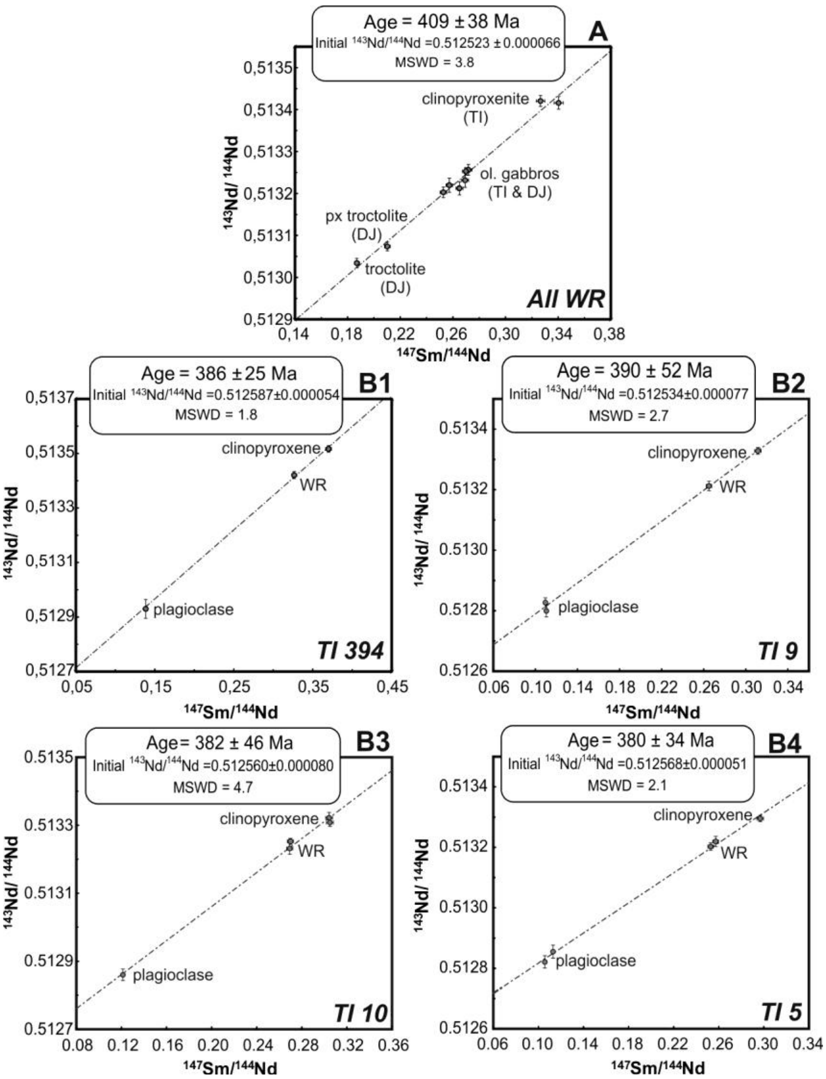
Age = 409 ± 38 Ma
Initial 143Nd/144Nd =0.512523 ± 0.000066
MSWD = 3.8
A
clinopyroxenite (TI)
ol. gabbros (TI & DJ)
px troctolite (DJ)
troctolite (DJ)
All WR
143Nd/ 144Nd
147Sm/144Nd
Age = 386 ± 25 Ma
Initial 143Nd/144Nd =0.512587±0.000054
MSWD = 1.8
B1
clinopyroxene
WR
plagioclase
TI 394
Age = 390 ± 52 Ma
Initial 143Nd/144Nd =0.512534±0.000077
MSWD = 2.7
B2
clinopyroxene
WR
plagioclase
TI 9
Age= 382 ± 46 Ma
Initial 143Nd/144Nd =0.512560±0.000080
MSWD = 4.7
B3
clinopyroxene
WR
plagioclase
TI 10
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B4
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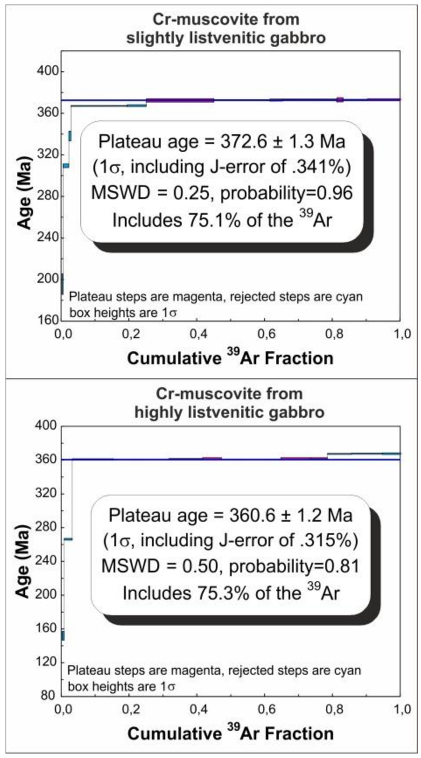
WR
plagioclase
TI 5


Cr-muscovite from slightly listvenitic gabbro
Plateau age = 372.6 ± 1.3 Ma
(1σ, including J-error of .341%)
MSWD = 0.25, probability=0.96
Includes 75.1% of the 39Ar
Plateau steps are magenta, rejected steps are cyan
box heights are 1σ
Age (Ma)
Cumulative 39Ar Fraction
Cr-muscovite from highly listvenitic gabbro
Plateau age = 360.6 ± 1.2 Ma
(1σ, including J-error of .315%)
MSWD = 0.50, probability=0.81
Includes 75.3% of the 39Ar
Plateau steps are magenta, rejected steps are cyan
box heights are 1σ
Age (Ma)
Cumulative 39Ar Fraction

Thermal budget of the European Variscides

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The origin and significance of the extensive HT-LP province established in the Variscan belt during the Carboniferous-Permian transition, c.a. 300 Ma, has been debated for decades. Four main sources would have contributed to the late Variscan thermal budget: i) increase of Mantle heat flow (Q0), ii) advection of melts iii) selective enrichment of $^{238,235}U$, ^{232}Th and ^{40}K in the middle and upper crust, and iv) viscous shear heating (HS).

All these sources have been tentatively used to explain the late Variscan HT event. Mantle is inferred to be the main contributor in the French Massif Central and Central Iberia (*e.g.* Faure *et al.*, 2010; Martínez-Catalán *et al.*, 2009). In both areas, a mechanism of slab break-off and thermal erosion of the sub-continental lithospheric mantle is invoked to explain the strong attenuation of geotherms. Recently, Lexa *et al.* (2011) challenged this view demonstrating that temperatures in excess of 900°C could have been reached in the lower crust of the Bohemian Massif mainly because of progressive enrichment of heat-producing elements. Upward migration of hot silicate melts has been occasionally invoked to explain the hot gradients in the Pyrenean region and in the Corsica-Sardinia block. Shear heating was generally considered insignificant and never computed in previous works. However, a quantitative solution to the HT metamorphism in the Variscan chain is still lacking.

Here we focus on the thermal budget of the Variscan crust by comparing one-dimensional numerical models with a literature database on PT conditions recorded at ca. 350 Ma and ca. 300 Ma. A purely conductive geotherm has been calculated at 350 and 300 Ma from two model crusts, designed by matching the available geophysical, geologic and geochronologic constraints. The crustal heat production rate is inferred from the $^{238,235}U$, ^{232}Th and ^{40}K composition of the Corsica-Sardinia section. The values obtained (about 500 measures) are similar, within experimental errors, to those reported from analogous rocks in the Bohemian Massif, Iberia, Armorica and other Tepla-Barrandian type sections. Given the reconstructed heat production rate of the model crust, Q_0 and H_S have been calculated by inverse modelling, adjusting their size within the range of geologically reasonable values to best fit the PT constraints. Results of numerical modelling show that most P-Tt-data at c.a. 350 Ma, age of Barrowian-type metamorphism in Sardinia (Giacomini *et al.*, 2008), can be well reproduced by a purely conductive geotherm assuming realistically low Q_0 values. The ca. 300 Ma P-T-t data set instead cannot be reproduced by any reasonable conductive geotherm. Best-fitting the set of thermobarometric constraints on the middle crust would requires, in fact, a Q_0 of 35-45 mW m^{-2}. These Q_0 values fall within the range of values proposed for extensional regions such as the Basin and Range and the Rhine Graben (Jaupart and Mareschal, 2007), but force the geotherm to violate dramatically the thermal boundary defined by the dry peridotite solidus. We suggest that HT-LP conditions in the upper part of the Variscan crust cannot be explained without upward migration of hot, lower-crustal or mantle-derived melts that induced near-isothermal conditions in the lower crust and steep geotherm at shallower levels.

The geodynamic significance of the Variscan HT-event can be inferred from the calculated heat potential of the Mantle in Carboniferous times. In fact, the reference Q_0 in stable continental shields ranges between 12-18 mW m^{-2} (Jaupart and Mareschal, 2007) although the upper bound may be extended to 24 mW m^{-2} (Russell *et al.*, 2001). Values as high as 40-60 mW m^{-2} are instead typical of extending regions such as the Basin and Range province (Ketcham, 1996) . These high Q_0 values require delamination of the sub-continental Mantle or, for upper bound values up to 75-90 mW m^{-2} observed above hot spots like Hawaii (Harris *et al.*, 2000) positioning the astenosphere directly at the base of the crust. In active compressional margins, the geotherm is not in equilibrium because of coupled crustal thickening and erosion (Jaupart and Mareschal, 2007). Disequilibrium of the thermal structure could be even more amplified by

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intervening slab break-off or lithospheric stretching, although Mantle is expected to recover near steady-state conditions in less than 10 Ma (Davies and von Blanckenburg, 1995). Our models calculated at ca. 350 Ma requires Q_0 between 4 and 14 mWm^{-2} to reproduce the data set compiled from P-T-t paths of the Moldanubian zone. These low Q_0 values are indistinguishable from the present-day Mantle heat flow in the Alps or the Himalayan range (Vosteen *et al.*, 2003), therefore we argue that a purely conductive geotherm may explain the eo-Variscan Barrowian metamorphism. Interpretation of the thermal structure calculated at 300 Ma is less obvious. The high temperatures recorded across different crustal sections have been frequently explained in terms of delamination of the Mantle lithosphere, slab breakoff or both. The timing of HT-LP metamorphism however does not match the likely age of the slab breakoff in the Variscan belt, bracketed between c.a. 360-370 Ma (the oldest age of HP assemblages) and c.a. 340-335 Ma (age of sin-collisional Mg-K plutons, Paquette *et al.*, 2003). Our results confirm this hypothesis as the predicted Moho heat flow around 300 Ma should be than 24 mWm^{-2} to avoid unrealistically high temperatures never recorded in the lower crust (Orejana *et al.*, 2011). This value is surprisingly close to the mean value of stable geotherms, while delamination of the lithospheric mantle requires at least 30-50 mWm^{-2} (Polyak *et al.*, 1996). Still higher values are expected if ongoing breakoff places the hot astenospheric mantle directly at the base of the crust (Davies and Von Blanckenburg, 1995). Based on these arguments, we propose that HT metamorphism in the Variscan belt is related to focused melting in the lower crust and advection of melts to shallower crustal levels.

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New structural insights, GIS analysis and thermobarometrical study in the Montagne Noire axial zone (French Massif Central): Implication for the late Variscan intracontinental tectonics

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TRAP Pierre, CARRY Nicolas, MARQUER Didier, GONCALVES Philippe

The Montagne Noire (MN) of the southern Variscan French Massif Central consists in (1) a dome-shaped core with migmatites, gneisses and micaschists of Proterozoic to Ordovician age mantled by (2) an upper crustal sequence made of low-grade to un-metamorphosed sedimentary rocks of Paleozoic age. Great exposure from the un-metamorphosed upper crust toward the migmatitic lower crust makes the MN a great natural laboratory for studying the mechanisms responsible for the crustal flow at different levels within the orogenic crust of the large and hot Variscan orogen. However, the tectonic setting of the MN is still highly disputed, and numerous models have been proposed to account for the structuration of the metamorphic axial zone. A first order disagreement is exemplified in recent studies proposing that the flow of lower crustal rocks and structuration of the axial zone formed either in (1) an extensional setting with upper crustal stretching and upward lower crustal flow (Van den Driessche and Brun, 1992, Rey *et al.*, 2011) or (2) in a compressionnal setting (Demange, 1998, Malavieille, 2010, Franke *et al.*, 2011).

In order to bring new insight about the very controversial MN gneissic dome, we here present a georeferenced dataset bringing together most of the published structural, petrological and geochronological data on the entire gneissic dome. More than 6000 data have been referenced at that time. The obtained corresponding geographic information system (GIS) representation reveals that only the easternmost part of the axial zone was studied in detail whereas the other parts of the dome suffer a lack of data. In particular, further structural work in the western part of the dome and precise thermobarometrical constraints are still needed. Consequently, a field based structural analysis within the western part of the dome (Nore massif) and a thermobarometrical study of ten kinzigitic rocks sampled along a N-S trending cross section in the middle part of the dome were conducted.

The field analysis together with the multi-scale vision given by the geodataset allows us to discuss the geometry and strain partitioning within the gneissic core. Three foliations named S1, S2 and S3 are identified: An early flat lying S1 foliation, located in lower structural levels, is folded in upright ENE-WSW folds. This foliation is simultaneously transposed by a subvertical S2 foliation that defines an E-W trending high-strain corridor with a dextral kinematic component in the middle part of the dome. Along dome terminations, S1 and S2 are transposed by a S3 foliation limited to the upper part of the dome. Lineation trajectories do not show any radial attitude. Several lineations are defined: (1) A crenulation lineation L1 formed after NW-SE directed horizontal shortening of S1, (2) an E-W directed and weakly plunging L2 stretching lineation occurs on the subvertical S2, (3) a NE-SW directed $L3_i$ intersection lineation between S1 and S3 accompanied by a synchronous NE-SW directed $L3_s$ stretching lineation mainly observed at the very top of the dome. L3 plunges toward the NE and the SW in the eastern and western edge of the dome, respectively. Kinematic criteria along L3 show an opposite sense of shearing with top-to the NE and top-to the SW in the NE and SW dome terminations, respectively.

Petrological forward modeling using pseudosection approach (Perple_X software, Connoly *et al.*, 2002) revealed similar metamorphic evolution for the ten metasedimentary rocks samples along the N-S trending profile. The migmatitic rocks, with a quartz + feldspar + biotite + sillimanite + garnet + cordierite assemblage registered a clockwise evolution with a peak pressure around 8 ± 1 kbar and 750 ± 50°C, a near isothermal decompression down 4 ± 1 kbar and 680 ± 50°C before final retrogression to surface conditions.

The structural and thermobarometrical results are not in accordance with a N-S trending extension but argue in favor of a transpressionnal setting in the lower crust and synchronous E-W directed collapse of the upper crust. A

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preliminary tectonic model with the following evolution is proposed: Crustal thickening is responsible for S1 subhorizontal development in the lower crust. This is followed by crustal scale folding of S1 and vertical shearing (S2) in a global transpressive regime. The folding initiates uplift of lower crust in core of NE-SW trending domes. In the same time, thinning in the upper crust though gravitational collapse (S3) contributes to the final exhumation of lower crustal material. The model suggests a strong decoupling of deformation between the upper and the lower crust.

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Constraints on polyphase P-T evolution of mantle rocks from Dunkelsteiner Wald granulite massif

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The orogenic lower crust exposed in the Bohemian massif is characterised by common occurrences of felsic granulites accompanied by mafic or ultramafic rocks of mantle origin, such as peridotites, pyroxenites or eclogites. We present a detailed petrological study of garnet bearing pyroxenite/eclogite from the Dunkelsteiner Wald granulite massif (Lower Austria) to constrain complex PT evolution of mantle derived lithologies. The primary mineral assemblage equilibrated in medium pressure and very high ambient temperature is overprinted during significant increase of pressure followed by decompression. All this occurred in advection dominated environment accompanied with minor temperature changes. This scenario is supported by following observations and successions of mineral assemblages: the first population of garnets with low Grs and high Prp content characterised by presence of numerous Si rich polyphase inclusions (probably representing former melt) reflects primary conditions in very HT but relatively lower P. The Grs content of these garnets doesn't exceed 20% and shows minor increase followed by decrease towards the rims. The subsequent high pressure stage is represented by the second generation of garnet with high Grs content (up to 30% in the cores) that are free of polyphase inclusions and coexists with clinopyroxene (present in matrix and as inclusions) with high jadeite content (18% in the cores). Both phases show compositional zoning - Grs content in garnet decreases to 15% towards rim, jadeite in clinopyroxene decreases to 12% together with increase in CaTs content reaching values of 10%. Moreover, small garnet grains with composition corresponding to the rim composition of second garnets (high XMg ratio and low Grs content) nucleated on both generations of garnet. This compositional zoning is in agreement with substantial and almost isothermal decompression. The final retrogression and cooling is documented by further decrease in Grs content and XMg ratio in outermost rims of all the present garnets, whereas the margins of clinopyroxene show decrease in both jadeite (10%) and CaTs (7%). Locally, the plagioclase, pargasitic amphibole and orthopyroxene assemblage is formed along grain boundaries and fractures.

The unusual and spectacular feature of studied mafic rocks is limited occurrence of intermediate rocks with symplectitic textures along contacts with the felsic granulites. This rocks contain relics of mineral assemblage observed in the pyroxenites - high-Ca garnets with high Na and Al clinopyroxenes present either as large grains in matrix or inclusions in garnets. However, the dominant assemblage is represented by low-Ca garnet and diopsidic clinopyroxene with subordinate orthopyroxene, all of them forming symplectitic intergrowths with plagioclase. This lithology seems to represent a result of significant mass transfer between former garnet clinopyroxenite/eclogite and surrounding felsic granulites. If this hypothesis is valid, than all the complex PT evolution recorded by mantle derived rocks had to occurred before the association with the felsic granulites manifested by formation of reaction textures. The estimates of PT conditions of symplectites formation indicate considerably lower pressure conditions compared to those estimated for the garnet clinopyroxenite/eclogite.

It should be noted that together with the fact that the felsic granulites themselves have suffered a polyphase deformation history that could lead to mechanical mixing and obliteration of the original relationships with other lithologies, we should be aware of possible misinterpretations of PT evolutions of the mafic and intermediate granulites as they can bear.

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Pre-Mesozoic Alpine basement - tradition and new insight

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Pre-Mesozoic Alpine basement has been known since the early 19th century; this long experience allowing comparison with equivalent basements in- and outside of the Alps. The Alpine orogenic events reworked the Variscan basement and its Mesozoic cover, resulting in a polyphased metamorphic overprint, where the intensity starts in lower greenschist facies conditions in the external western parts of the Alpine belt, but reached the highest amphibolite facies grade in the southern inner part of the Alps. A large field experience on classical Variscan basement areas has been necessary to properly identify their equivalents in the Alpine domain, in particular where all lithologies have been recrystallized in greenschist facies conditions and are uniformly green colored! Meticulous and patient fieldwork by many working groups in all kinds of weather conditions resulted in a synthesizing overview [von Raumer and Neubauer, 1993]. A growing number of precise age data and the chemical analyses of former magmatic rocks helped identifying these basement areas as part of the Gondwana margin [von Raumer 1998]. New ideas on plate tectonic reconstructions [*e.g.* Stampfli and Borel, 2002; Stampfli *et al.*, 2011] helped to better understand the more global pattern and to see the Alpine basements in a new light - not as a “problem” - but as normal constituents of the adjacent Variscan basement areas, an idea hitherto applied only with hesitation! The following lines present an abbreviated version of the many parallels existing between non-Alpine and Alpine basement areas [comp. von Raumer *et al.*, 2011].

A Neoproterozoic-Early-Paleozoic active margin setting, now generally accepted for the Gondwana margin, had been presented first for the Penninic and Austroalpine basements [Frisch and Neubauer 1989], and specified by Schaltegger [1997] and Schulz [2008], and detrital zircons from metasediments and magmatic rocks testify for distinct Gondwanan sources not younger than early Paleozoic [Schaltegger and Gebauer, 1999]. The metasediments of the various polymetamorphic basement areas present astonishing similarities, and their sedimentary sources should not be searched only in the west- and central African shield, but also in eastern Gondwana domains and in the Indian and Chinese blocks. Length of transporting rivers and periods of sediment recycling may account for a large variety of sources.

From the Cambrian onwards, striking parallels can be observed within Alpine basement assemblages, where the main lithostratigraphical sequence is characterized by metapelite-metagraywacke series, interlayered with finely layered tourmalinite beds and/or acidic and metabasic volcanics or intrusive rocks. A striking feature are the widely distributed “Erlan-felses”, which are calcsilicate lenses, representing in most cases the relics of fold hinges of doubly folded carbonate horizons of probably lower to middle Cambrian age. During the Variscan metamorphic overprint, they became hosts of scheelite-skarns. They are not only widely distributed in non-Alpine Variscan domains along the former Gondwana margin, but also in the Moroccan Anti-atlas and even in the Appalachian domain. Three major events were identified in the subsidence patterns of metasediments along the Gondwana margin [von Raumer *et al.*, 2008], confirming an accelerated rifting since the Ordovician, and a general active margin setting along the entire Gondwana margin [Stampfli *et al.*, 2011].

From the Cambrian onwards, the future Alpine domains and their contemporaneous neighbors at the Gondwana margin were dominated by several magmatic pulses, representing one of the major global magmatic events and characterized in the best way [Stampfli *et al.*, 2011] by a long-lasting crustal extension and arc development, identifying the evolution of a cordillera along the Gondwana margin. In contrast to the more western areas like the Iberian blocks, where the Rheic Ocean opened around 470 Ma, its more eastern parts, comprising the Alpine basement areas and Tethyan blocks, was situated close to a transform margin along the S-Chinese segment of

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Gondwana. A more complicated evolution was accompanied there by several magmatic pulses, which is not only seen in the Alpine domains but also in the Carpathian and Serbo-Macedonian domains. But it is probable, that the earlier, Ollo-de-Sapo type magmatic series, so well known from the Western Gondwana margin, had their parallels in the Alpine domains too, before the juxtaposition with South-China-derived basements that introduced a new active margin setting between 470-450 Ma. A pre-Ordovician (older basement) evolution should be distinguished from the middle Ordovician to Silurian evolution, more restricted to the eastern Gondwana margin, characterizing the complex plate-tectonic evolution of the included basement areas like the Alps and adjacent basement areas.

As comprehensive reconstructions were still lacking, the well-known Variscan configuration of Central Europe *[e.g.* Matte, 2001; Franke *et al.*, 2000] had no arguments for including the Alpine domains in a logical way, although "it is a matter of fact, that the Alpine basement displays a nearly continuous outcrop of the Variscan orogen" [Schaltegger, 1997a, p. 261]. Distinct pulses of granitoid evolution [Bussy et al. 2000; Finger and Steyrer, 1990; Schaltegger and Corfu, 1995] have their time equivalents in the non-Alpine Variscan domains, and the Visean vaugnerite distribution as a time marker represents the Variscan continental collision across very distinct Alpine and non-Alpine Moldanubian-type basement areas. This global collisional scenario has been subsequently replaced, since the Late Carboniferous, by the ongoing shortening and strike slip under rising geothermal conditions [Capuzzo *et al.*, 2003; Schaltegger 1997b], before all these puzzle elements underwent the complex Alpine reorganization.

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Durbachites-Vaugnerites - a time-marker across the European Variscan basement

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Vaugnerites/durbachites (or melasyenites) and high-K granitic rocks follow in de la Roche's [1980] R1-R2-diagram a sub-alkaline trend including the fields of quartz-monzonites, monzogranites and leuco-monzogranites, representing varieties of K-Mg rich magmatic rocks. Characterized by a decreasing K-value in Sabatier's [1980] Mg-k diagram, their mineral assemblage combines generally K-feldspar, quartz, plagioclase, Mg-rich biotite, actinolitic hornblende, ± clinopyroxene ± orthopyroxene with titanite, apatite and pyrite, and their geochemical composition is well characterised [Janoušek & Holub, 2007; Scarrow *et al.*, 2009].

Durbachites-Vaugnerites and their derivatives are observed in a large domain of the European Variscan basement, the external domain of the Alps comprised, and linear distribution trends of such rocks have been already related to present-day prevailing tectonic structures [*e.g.* Rossi *et al.*, 1990]. But their mere geographical distribution cannot satisfy any genetic large-scale model, needing a correlation in their contemporaneous Variscan framework. Consequently, von Raumer [1998], based on Stampfli [1996], emphasised a linear trend in a Visean reconstruction, where the durbachite-bearing basement areas of the Tauern Window and the Alpine External Massifs were correlated with those of Corsica, the French Central Massif, Black Forest, Vosges, and the Bohemian Massif for the Visean time segment, confining the southern limit of durbachite-vaugnerite occurrences to the southern limits of the External Alpine massifs. As comparable rock-assemblages became known in NW Spain and specific local plate-tectonic scenarios have been discussed, it is proposed, that all these basement areas could be correlated in their large-scale plate-tectonic setting to the Variscan continental collision. It is consequently interesting to interpret the general plate-tectonic situation of this specific group of magmatic rocks in the light of recent plate-tectonic reconstructions [Stampfli *et al.*, 2011], allowing to reconstitute the Visean trace of the former subducting lower plate across very different late-Variscan tectonic units in Europe.

Very distinct rock-types and generations of intrusions are hidden behind the general terms of durbachite- vaugnerite, emplaced between about 345 to 330 Ma, and this variation, undoubtedly, is the mirror of the multiple crustal processes influencing on their final aspect during the Variscan collision: i) the subduction of oceanic crust under Gondwana and Laurussia and the Devonian opening of Paleotethys; ii) the Visean continental collision between Avalonia-Laurussia and Gondwana-derived continental pieces, and iii) the Late Carboniferous final collision and continuation of subduction of Paleotethys in the Tethyan area.

The main features, after the late Devonian continental subduction, are shortly characterised by the formation of: i) Visean granulites, their derived fluids and direct contamination with the lithosspheric mantle characterise the HP- evolution; followed subsequently by ii) granulite emplacement and HT-MP overprint; and iii) emplacement of granulites accompanied by the intrusion of ultrapotassic melts derived from the lithospheric mantle.

Considering the evolution of subduction zones in the rather narrow space spanning between the Rhenohercynian and Palaeotethyan oceans during the Carboniferous time period [Stampfli *et al.*, 2002] may explain the subsequent thermal evolution underneath the Variscan orogen, where, in the sense of Chemenda *et al.* [1996], a multiple magmatic evolution was triggered by the steps of subduction, extension behind a subduction zone, and, subsequently, by slab break-off and delamination.

Henk *et al.* [2000] discussed a linear trend of magmatic evolution parallel to the Variscan orogen, where molten lithosphaeric mantle underwent the thermal evolution during slab break-off and delamination [comp. Gerya and Stöckhert, 2006]. The late Variscan increasing juxtaposition of terrane-assemblages and subsequent collision lead to

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the general narrowing of the orogen, where the geographic distribution of the durbachite-vaugnerite localities appears in the Visean time segment as clusters near distinct tectonic lineaments [Stampfli *et al.*, 2011], thus showing the global situation of juxtaposing geodynamic units along distinct tectonic limits, accommodating the stretching tectonic units in a regime of continental collision. If interpreted in the 330 Ma-reconstruction, the grouping of localities suggests even the distribution of a hot thermal field (hot spot like) where, in the corresponding N-S section, coincide subduction, collision, break-off, delamination and underplating in a rather narrow corridor. Alcock *et al.* [2009] applied the model of pressure-temperature-time paths in a thickening and subsequently eroding crust for the crustal evolution of the autochthonous domains in northwestern Iberia, where the older granodiorites and tonalites, containing the vaugneritic melts, could have formed simply through anatexis of lower crust within 25-30 Ma after onset of the crustal thickening. They intruded structures, which are related to the emplacement of the allochthonous Malpica-Tuy HP-unit around 350 Ma.

The global model of subduction and thickening crust holds also for the Moldanubian basement areas [Finger *et al.*, 2007; Schulmann *et al.*, 2009], where the double line of durbachitic magmatic bodies is related to the general crustal thickening and imbrication around the Visean. Differences may appear due to the intensity of heat transport and formation of granulitic melts, producing either large plutonic bodies of Durbachites or, as in many localities of the Variscan basement areas, leading to the more reduced size of mingled molten blobs of vaugnerites in a granodioritic-monzodioritic host.

As consequence of collision, an opening slab-window and delamination will raise the heat-influx from the lower crust, leading to granulitic P-T conditions and to melting of lithospheric mantle accompanied by metasomatic processes, conditions which triggered, supposedly since the Visean, the formation of the K-Mg-melts. It is evident, that the Visean scenario of collision suffered, consequently, the strong transformations induced by regional strike-slip and crustal thickening, leading to the destruction of the former collisional scenario, becoming gradually replaced, since the Late Carboniferous, by a global shear zone under raising thermal conditions and formation of granitoid melts, intersecting the puzzle-stones of the former Visean collision zone.

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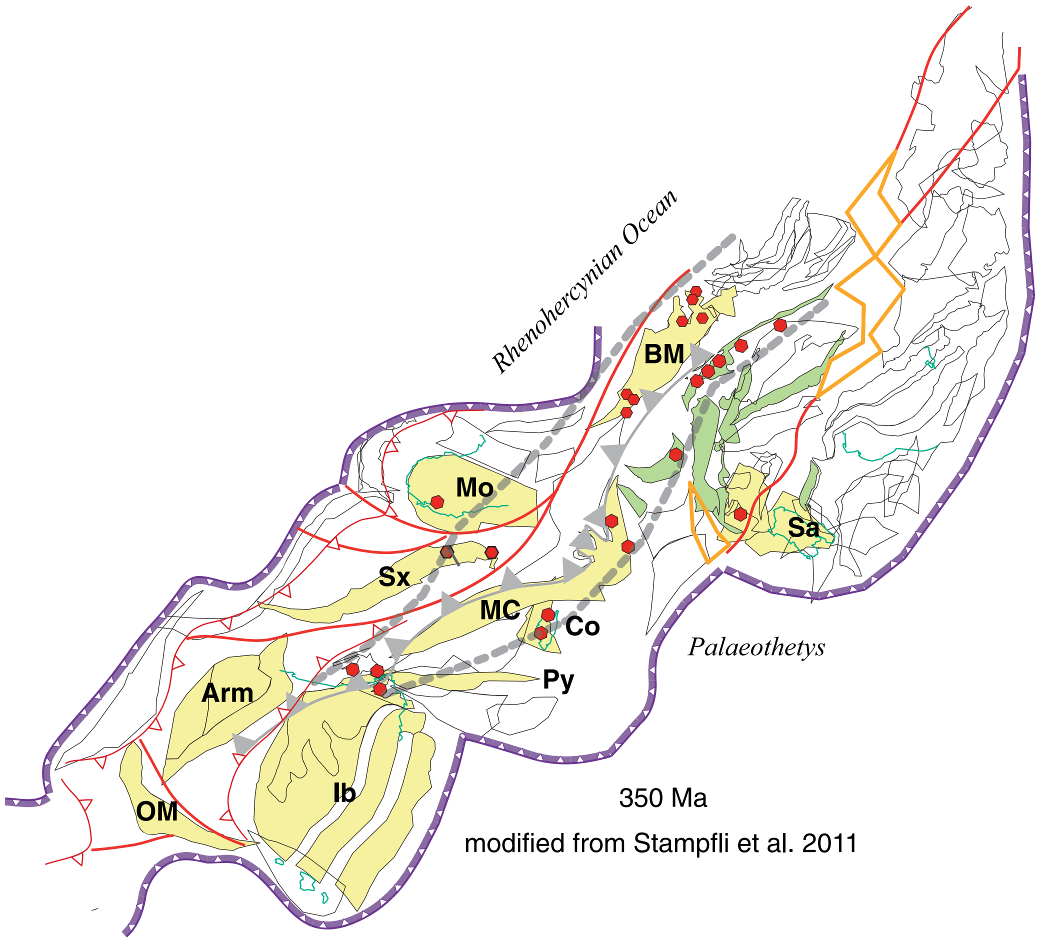

Fig. 1.- Reconstruction of the future Central European basements around 350 Ma (modified after Stampfli et *al., 2011), with their main geodynamic units (Hochard 2008) in their general tectonic collisional environment. Red dots: sites of durbachites; heavy dotted lines: limits of the lower subducting plate during Visean collision, including the Moldanubian type basement areas and the basements of the Alpine external domain. Basement areas like the Saxothuringian (Sx) and the Moldanubian domains (BM) will be in a more juxtaposed situation during the Late Carboniferous tectonic evolution, thus allowing for emplacement of the durbachitic magmas.*

Arm - Armorica; BM - Bohemian massif; Co - Corsica; Ib - Iberian basement units with allochthonous units; MC - Massif Central; Mo - Moesia; OM - Ossa Morena; Py - Pyrenees; Sa - Sardinia; Sx - Saxothuringia.

U-Pb-zircon precise dating of volcanic-plutonic formations in the Corsica Batholith: evidence of a thermal Upper-Stephanian to Lower Permian peak

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Plutonic rocks constitute the main outcropping part of the Corsica-Sardinia Batholith (CSB) emplaced from 308 to 275 Ma (early U1 Mg-K Visean magmatism is not accounted here). Field evidence of volcanic-plutonic relationships were established in the U2 magmatism of the CSB [Agriate desert, Golo canyon and Vizzavona pass as far as Northern Sardinia] but detailed chronological data were still lacking.

Large outcrops of U2 volcanic formations remain now restricted to the less eroded zone to the NW of Porto-Ponte Leccia line but volcanic and volcanic-sedimentary formations have been elsewhere widely eroded since Permian times (Fig. 1). They were probably covering the largest part of the whole batholith before Miocene, this is testified by the volcanic nature of pebbles that constitute a large part of the pre-Tortonian conglomeratic formations of Eastern Corsica. Precise U-Pb zircon dating (SHRIMP) was used to decipher the chronology and duration of different volcanic pulses and to better estimate time overlap between plutonics and volcanics emplacement in the Corsica-Sardinia batholith (CSB).

The results obtained very well fit with field data (Fig. 2) and indicate that the largest part of the volcanic formations (U2 and U3) mainly emplaced in c.a. 15 My from 293 to 278 Ma, in the same time as largest part of U2 monzogranodiorites and leucomonzogranites (295-280 Ma) and alkaline U3 complexes (c.a. 288 Ma) and the mafic ultramafic tholeiitic complexes (295-275 Ma) Fig. 3.

These results correlate with U-Pb zircon dating of HT-BP granulites from the Variscan deep crust - exhumed along the Tethys thinned margin in Corsica (Rossi *et al.*, 2006), Calabria (Micheletti *et al.*, 2008) and Ivrea zone (Vavra *et al.*, 1996), where the main age peak dated at about 285-280 Ma corresponds to the Variscan thermal maximum in the Southern Variscan Realm.

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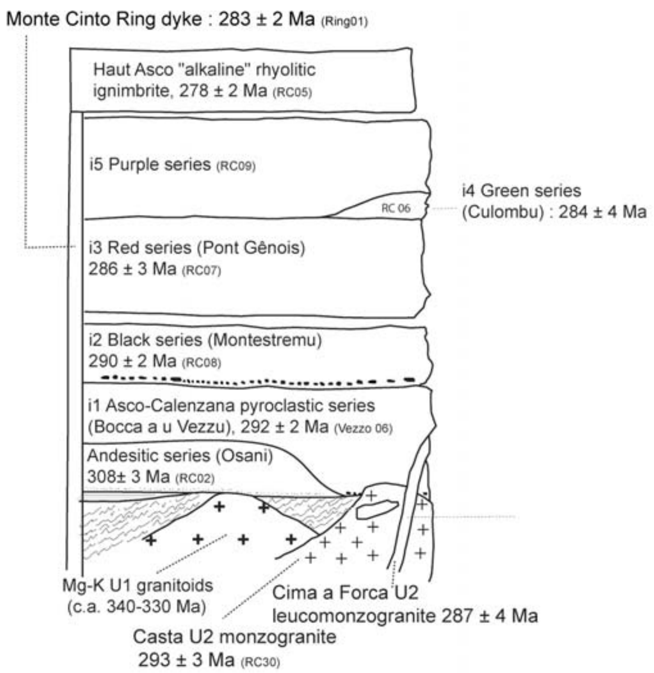

Fig. 2.- Synthetic log of the volcanic formations: field constrains and geochronological data.

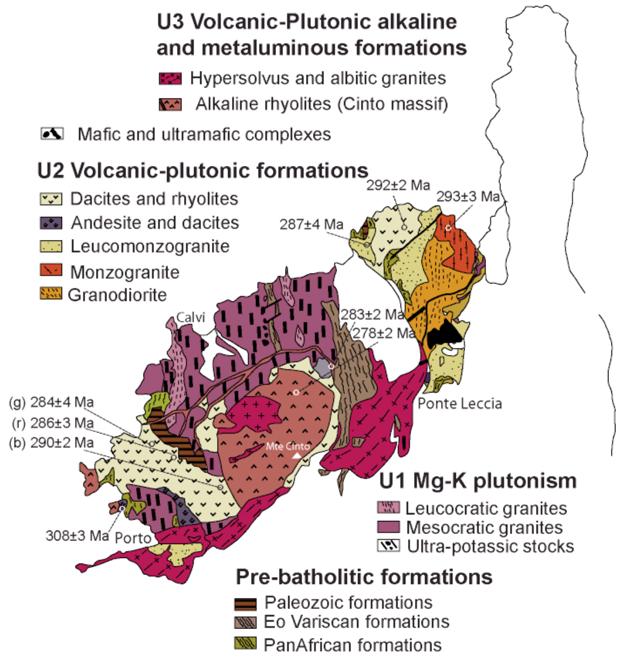

Fig. 1.- Sketch map of NW Corsica.

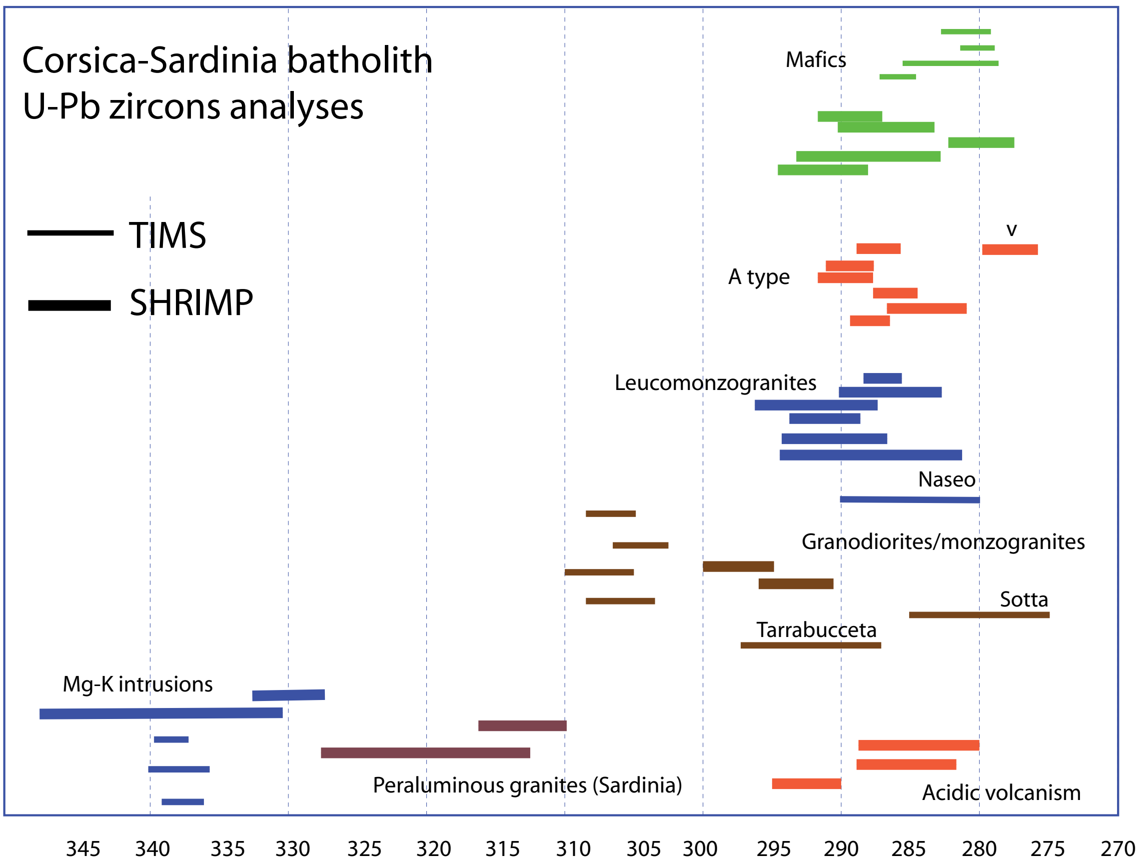

Fig. 3.- Summary of the U-Pb zircon dating on the Corsican part of the CSB.

From late Variscan to eo-Alpine: U-Pb on zircon record of the Lower Crust

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About 100 Ma without any important magmatic event bridge the gap between emplacement of Lower Permian volcanic plutonic formations and the emplacement of Jurassic ophiolites in the Liguro-Piedmont ocean.

U-Pb zircon dating on the Lower Crust (LC) of the future Tethyan margin have been investigated to unravel the tectonothermal modalities of the transition between Variscan and Alpine cycles.

In a granulite metamorphic environment new zircon growth can occur in the solid state. Once Zr incorporated into zircon, it is difficult to remobilize without dissolution; thus Zr available for new zircon growth must result from the breakdown of Zr-bearing minerals during prograde and/or retrograde events. In this light, peaks in the statistical curve of zircon ages in the LC and tectonothermal events recorded in the Upper-Crust ought to be correlated (Fig. 1).

Ion-microprobe/LA-ICPMS U-Pb zircon dating of metasedimentary granulites were performed on 4 LC spots: 1 on the African Margin, the Ivrea zone (Vavra *et al.*, 1999) and the 3 others on the Tethyan european margin: i) enclaves hosted by Miocene volcanoes at Bournac, Eastern French Massif Central; ii) basement of the Piedmont Alpine nappe of Santa Lucia in Corsica (Rossi *et al.*, 2006); and iii) in the Serre massif of Southern Calabria (Micheletti *et al.*, 2008).

The results on 2 of these four spots (Bournac, Serre) allow recognizing effects of the tectonothermal Ordovician activity, probably connected to the opening of the Armorican ocean, but this will not be discussed here. In every spot a roughly synchronous peak that corresponds to the Variscan metamorphic climax is at 295 Ma on the African margin and 285-280 Ma on the European side.

Considering that the 250-230 Ma peaks in the European crust and the 220 Ma peak at the African margin correlate respectively with the opening of the Ligurian branch of the Tethys and of the Lombardian rift of the Apulian-African margin, one can observe a shift of 15-20 Ma in the rifting of the margins. The rifting began earlier on the Western (*i.e.* European) realm.

No further pulse of zircon growth was recorded in the African margin after the rift opening (220 Ma peak), very probably because the shallower granulite on this side of the rift would have cooled faster than on the European side and/or because of a lack of magmatic input. At Santa Lucia, however, the more abundant zircon growth during the Mesozoic (200-160 Ma) could reflect the position of the granulitic metasediments within the Tethyan thinned margin prior to oceanization, where it would have been affected by retrograde metamorphism leading to a breaking down of Zr-bearing minerals and/or a higher thermal gradient.

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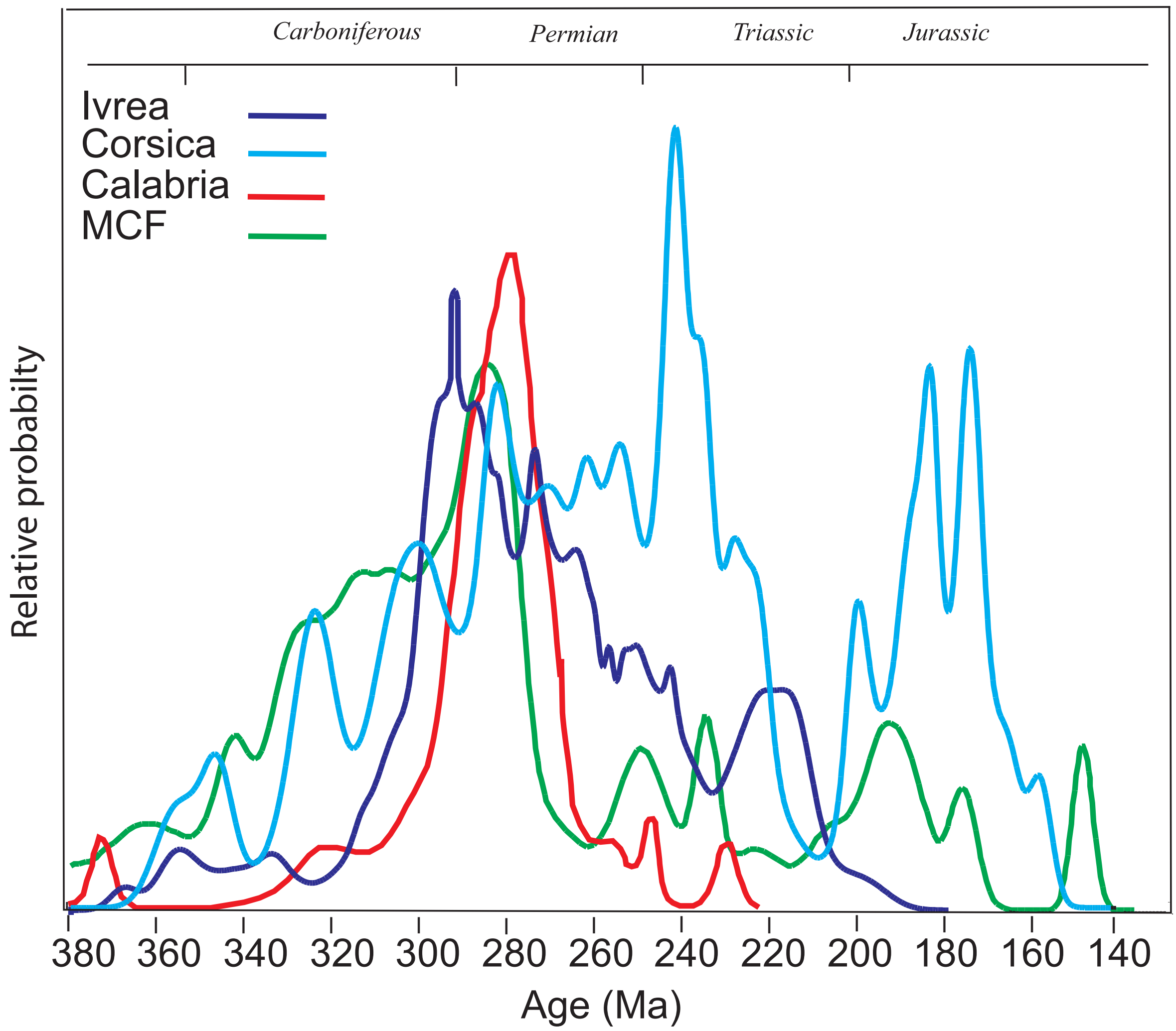

Fig. 1.- Relative probability plot of U-Pb zircon ages vs. age for granulitic metasediment from Lower crust: MCF (Bournac); Corsica (Santa Lucia); Calabria (Serre) and Ivrea.

Considering a new tectonic setting for the Devonian ophiolites of the Variscan suture: Isotope geochemistry and revised geochronology of the Purrido Ophiolite (Cabo Ortegal Complex, NW Iberian Massif)

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One of the ophiolitic units located in the allochthonous complexes of NW Iberia (Purrido Ophiolite) was interpreted as the remnants of Mesoproterozoic oceanic crust according to geochemical and geochronologicla data. New U-Pb zircon dating of an amphibolite sample confirms the existence of a dominant Mesoproterozoic zircon population with a refined age of 1155 ± 14 Ma (LA-ICP-MS). Nevertheless, the U-Pb zircon dating of two more amphibolite samples has provided new ages of 395 ± 3 Ma and 395 ± 2 Ma, respectively (SHRIMP), interpreted as the crystallization age. Hf isotope data in zircon show that most of the Devonian zircons crystallized from a juvenile depleted mantle source. The Mesoproterozoic zircons have relatively juvenile Hf isotopic composition reflecting some influence of an older component. Some few Devonian zircon crystals show evidence of mixing with an older component represented by the Mesoproterozoic zircons. The whole rock Sm-Nd isotope data indicate an important heterogeneity in the composition of the Purrido amphibolites, only compatible with the generation of their protoliths from two different sources.

Considering that the Purrido Ophiolite can be correlated with the most common Devonian ophiolites recorded along the Variscan suture in Europe, the evidence of some interaction of the mantle-derived magmatic source of these mafic units with a Mesoproterozoic basement to a extent remaining to be well known make difficult to interpret these ophiolites as regular oceanic domains. The new isotope data would be the clue to consider a new tectonic setting for these intriguing mafic assemblages.

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New characterization of basic rocks from Cap Pinet (Maures-Tanneron Massif, SE France): geodynamic implications for the Southwestern European Variscan belt

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The Maure-Tanneron Massif together with Corsica and Sardina represent the southern branch of the western European Variscan belt. The Maures Massif consists of three N-S striking lithotectonic units: the Western Maures, the Central Maures and the Eastern Maures. The Eastern unit is separated from the Central and Western units by the Grimaud N-S Strike-slip fault. Basic and ultrabasic bodies are present in all segments. They consist in small lenses or boudins widespread in the Eastern unit. In the other units, basic rocks are more voluminous and represent continuous lithological units of N-S orientation. The purpose of this study is to bring new structural, petrological and geochemical data lacking for basic rocks from the Eastern unit. Data for basic rocks from the other units being numerous, this will allow comparison between the different units and to discuss the significance of the Grimaud fault.

The studied basic bodies have been sampled in Cap Pinet (northern end of Pampelone Beach near St. Tropez). In this area the main lithologic units are migmatitic paragneisses associated to aluminous leucogranite dykes. Main foliation is sub-vertical with nearly N-S direction and bears a sub-horizontal stretching lineation. Unambiguous criteria allow defining a sinistral sense of shear with a top to the south displacement. Sheath folds parallel to stretching lineation and en echelon tension gashes perpendicular to stretching lineation which are filled with magmatic product argues for a transpressional regime synchronous of partial melting. Among these migmatites, two distinct basic bodies have been recognized: (i) a 20 m wide N-S elongated lens of amphibolites made of numerous small sub-lenses; (ii) 0.5-1 m diameters rounded rigid boudins of garnet-rich metabasites, with serpentinite at the edge.

Deformation in the amphibolite lens is similar to surrounding migmatites. Basal section of the sub-lenses reveals a better preserved core relative to the strong stretching deformation recorded at the rim. The core shows granulite facies mineral assemblage (garnet, diopside, hypersthene, biotite, brown amphibole, plagioclase, illmenite and quartz). The texture suggests retromorphoses from a previous eclogite (Kelyphite and symplectite), but no relictual omphacite has been found. The rim of the lenses show synkinematic reequilibration in amphibolite facies (pyroxene is replaced by green amphibole, minerals are all transposed in the lineation and relictual garnet is surrounded by plagioclase-amphibole pressure shadows).

The rigid boudins show foliation indicated by garnet-rich layers oblique to foliation of the surrounding migmatites. The boudins are garnet and diopside rich (granulite facies). Some calcite-rich veins transposed in the main foliation are observed. At the rim of the boudins, the granulite facies paragenesis is strongly reequilibrated in the amphibolite facies with diopside and garnet replaced by amphibole and plagioclase. Locally, greenschiste facies paragenesis (epidote, chlorite, K-feldspar and sericite) replaces amphibole. The serpentinite shows relic minerals of a spinel-peridotite. Olivine is replaced by serpentine, enstatite by tremolite and spinel by Fe-chromite.

Results from mineral analyses by EPMA allow thermobarometric calculation for all the metamorphic stages. Moreover pseudosections have been realized. Four metamorphic stages can be differentiated:

1) Eclogite facies stage: No direct observation of relic minerals, but expected from retromorphic textures in core of the main lens. No indicator in rigid boudins. Pseudosections suggest pressure peak between 1.3 and 1.7 GPa at 600-700°C.

2) Granulite facies stage: Observed in both type of basic bodies. Peak temperature bracketed between 700-750°C with isothermal decompression from 1.3 to 0.8 GPa.

3) Amphibolite facies stage: Observed in both type of basic bodies. Decompression from 0.8 to 0.45 GPa and cooling from 750 to 500°C.

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4) Greenschist facies stage: Observed in small rigid boudins. Cooling down to 300°C and decompression down to 0.3 GPa.

Geochemical analyses (major and trace elements) show that metabasites from the main lens have the same signature than metabasites from Central Maures (Briand *et al.*, 2002). They are interpreted as metatholeiites with N-MORB affinities. Metabasites from rigid boudins derived from the same protolith, but undergo two stages of hydrothermal alteration: (1) rodingitization prior the metamorphic imprint responsible for strong CaO-Al_2O_3 and Sr enrichments, as well as SiO_2 and Na2O depletions; (2) late metamorphic hydrothermalism responsible for LILE and LREE enrichments and crystallization of K-Feldspar and sericite.

Finally, Ar/Ar dating on muscovites from the aluminous leucogranite dykes yield plateau ages of 300 ± 2 Ma. This age dates cooling of the unit during tranpressive exhumation.

To summarize, our data shows that metabasite from the Eastern Maures is related to an oceanic seafloor subducted, then exhumed during collision. The timing of the different stages will be discussed on the basis of geochronological data available in the Maures massif. Moreover, metabasite from the Eastern unit bears many similarities with metabasite from the other units of the Maures massif: same protolith; same late P-T-deformation history (from amphibolite to greenschist stage associated with transpressive shearing, *e.g.* Bellot *et al.*, 2010). This argues that the Grimaud fault is an accident related to the late transpressive event.

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Relative contribution of crustal accretion and magmatic recycling in the Central Asian orogenic Belt - an analogue to the European Variscan belt

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In this contribution we discuss the major features of Carboniferous and Permian magmatism in relation to accretion of the Central Asian Orogenic Belt (CAOB) in South Mongolia. We propose a plausible geotectonic setting comprising crustal growth and crustal recycling in this huge accretionary orogen. The CAOB formed by accretion of continental blocks, accretionary wedges, magmatic arcs, back arcs, dismembered ophiolites, and post-accretion granitic rocks (Badarch *et al.*, 2002; Windley *et al.*, 2007). Three basically different models dealing with the CAOB tectonic evolution have been proposed: (1) the strike-slip duplication and oroclinal bending of a giant magmatic arc (Sengör *et al.*, 1993); (2) successive accretions of oceanic and continental terranes to the Siberian craton (Badarch *et al.*, 2002; Windley *et al.*, 2007), and (3) a two-stage evolution involving first the “Pacific” type accretion during the Devonian-Carboniferous followed by the “Tethysian” type oroclinal bending and collisional shortening during Permian to Jurassic (Lehmann *et al.*, 2010; Schulmann and Paterson, 2011). The latter model suggests that the first E-W directed shortening event is associated with the Japan-type arc magmatism developed in continental domains and imbrications of crust in oceanic domains. This period of E-W shortening is associated with an important net crustal growth. The second N-S directed convergence was responsible for re-folding of all previous structures by upright E-W trending folds, the development of major E-W striking cleavage fronts and the magmatic recycling of the previously formed crust (Kröner *et al.*, 2010).

We examine the mechanisms of Devonian to Carboniferous accretion related to development of major Japan type magmatic arcs on continental type crust of Early Paleozoic accretionary prisms in the area of Mongol and Chines Altai. This period is marked by emplacement of large volumes of tonalitic and granodiorite magmas associated within the regime of generalized E-W oriented shortening. The plutons are clearly syntectonic and reflect the major accretionary event that is marked in the field by huge N-S trending granitic and migmatitic domes. The Ordovician and Silurian oceanic crust of the Trans-Altai Zone is also affected by subduction related magmatism which produces metaluminous magnesian alkali-calcic granitoids at the time interval 330-300 Ma. These granitoids are apparently late to post-tectonic with respect to E-W shortening event. The most important magmatic event is related to Permian intrusions which are emplaced along two major belts forming limits between South Gobi continent, Trans Altai Zone in the south and Mongol Altai and Trans Altai Zones in the north. These A-type granitoids are mostly post-tectonic, without any fabric and are locally associated with important remelting of continental crust.

The geochronology and isotopic dating of critical fabrics and plutons from the studied region helped us to propose a tectonic model suggesting the migration of the E-W shortening from north to south during the main accretionary event. The timing, the mechanics and the style of deformation associated with the two major magmatic events differ between tectonic zones implying possible differences in the heat budget and mechanical anisotropy of the crust. The nature and the activity of fault boundary between principal tectonic zones are also discussed and a model of a reactivated palaeo-transform is proposed. Finally, the kinematics, heterogeneity and diachronous natures of the collisional and magmatic event are characterized and a model of an orthogonal shortening of oceanic and continental crust along with cycles of crustal growth and crustal recycling is proposed.

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Relating monazite chemical zoning to P-T path of the Northern Catena Costiera migmatites (Calabria, southern Italy): preliminary data

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The studied rocks belong to the deepest portions of the Variscan continental crust section which constitutes the highest structural element of the Northern Calabrian Arc. This lower crustal level consists mainly of Grt-Bt gneisses, Cpx-Opx granulites, migmatites, metaultramafic rocks intruded by Permo-Triassic gabbros. The Variscan and late-Variscan metamorphic evolution has been defined by several authors (Graessner & Schenk, 2001 in the Sila massif; Fornelli *et al.*, 2002 and Acquafredda *et al.*, 2006 in the Serre; Piluso & Morten, 2004 in the Catena Costiera); in particular, a migmatitic event has been evidenced at 295 Ma by Graessner *et al.* (2000). New petrographic, geochemical, petrological and geothermobarometric data carried on the migmatites outcropping in the northern Catena Costiera suggest that these rocks underwent two-stage partial melting (Scicchitano *et al.*, 2011; 2012). The first anatectic event started at the H2O-saturated solidus (P > 0.7 GPa; T ≈ 670-680°C) and proceeded firstly with a Ms dehydration-melting reaction (Ms ± Pl+Qtz = Sil + Kfs + L; P > 0.8 GPa, T ≈ 740-770°C) and then with a Bt dehydration-melting reaction (Bt + Sil = Grt + Kfs + L; P > 0.7 GPa, T ≈ 800°C). The metamorphic climax at P-T conditions of 0.8-0.9 GPa and 800°C was followed by an isothermal decompression during which the first melt started to crystallize by a melt-consuming reaction (Grt + Kfs + L = Bt+Sil). During this decompression stage a new anatectic event occurred by Bt dehydration-melting reaction (Bt + Sil + Qtz = Grt ± Crd + Kfs + L; P < 0.7 GPa, T ≈ 780-800°C). On cooling, the second melt started to crystallize firstly at the melt-consuming reaction (Grt ± Crd + Kfs + L = Bt + Sil + Qtz) and finally at the H2O-saturated solidus (L = Qtz + Kfs + Sil + Pl + H_2O; P < 0.4 GPa, T ≈ 660-670°C). The second anatectic event might be due to heating related to the Permo-Triassic gabbros emplacement, that have a minimum cooling temperature of about 800°C at 0.55 GPa (Liberi *et al.*, 2011); therefore, it may be related to a rifting geodynamic framework that marks the beginning of the Alpine cycle. Of course, only geochronological data could validate or not this hypothesis. For such reason, we characterized for the first time monazite grains observed in four migmatites samples (two restites, a nebulite and a leucosome) of the northern Catena Costiera by Scanning Electron Microscopy in order to investigate their microstructural relationships and their chemical zoning. This is the critical step to select the suitable domains for the subsequent electron microprobe and isotopic analyses.

In the restitic samples, monazite crystals are abundant and occur mostly as inclusions in Grt porphyroblasts, whereas only a few grains lie in the matrix. The majority are ≈ 20-60 µm in size with a few being ≈ 100-200 µm in size. They are generally rounded or angular fragments and occasionally they have subhedral shape; moreover, monazites often contain microfractures and do not preserve inclusions. A few monazite crystals are unzoned (Fig. 1a), whereas most of them shows patchy and near concentric zoning (Fig. 1b-d). The near concentric zoning is defined in some monazite crystals by a darker rim grown on a brighter corroded core (Fig. 1b) or conversely by a brighter rim grown on a darker corroded core (Fig. 1c). Chemical analyses obtained by EDS highlighted that bright BSE domains are enriched in Th (5.62 wt. % *vs* 3.87 wt. %) and Ca (0.81 wt. % *vs* 0.75 wt. %) compared to the dark BSE domains which are enriched in Y (2.54 wt. % *vs* 1.94 wt. %) and P (30.36 wt. % *vs* 28.95 wt. %); the REE content is very variable. Similarly, the monazite crystals showing a patchy zoning have the bright BSE domains enriched in Th (7.35 wt. % *vs* 4.34 wt. %) and Ca (1.32 wt. % *vs* 0.90 wt. %) and occasionally in U (1.75 wt. % *vs* 1.30 wt. %) compared to the dark BSE domains which are enriched in Y (3.94 wt. % *vs* 2.27 wt. %) and P (30.53 wt. % *vs* 28.96 wt. %); also in this case, the REE content is very variable. The unzoned monazite grains (Fig. 1a) have a chemical composition similar to that observed in the bright BSE domains of zoned crystals. Generally, Th and U are positively correlated with Ca and Si suggesting the cheralite and huttonite substitution mechanisms (Spear & Pyle, 2003).

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Monazite crystals in the nebulitic sample are less abundant than in the restitic ones. All grains lie along the foliation planes, defined by Bt and Sil, near corroded and retrogressed Grt porphyroblasts. They are ≈ 100-400 μm and ≈ 20-60 μm in size and exhibit subhedral shapes; the majority have microfractures and inclusions of Bt and Sil crystals and/or Zrn grains. All monazite crystals observed in this sample are unzoned and have an Y content (3.98-5.12 wt. %) similar to that observed in the dark BSE domains of restites monazites. Furthermore, they are always characterized by a corona structure with monazite at the core surrounded by apatite±thorite±allanite aggregate (Fig. 1e). In particular, the reaction corona is characterized by a first rim where apatite±thorite intergrowths occur together with very small monazite relicts. According to Finger *et al.* (1998), preservation of monazite in the corona structure suggests that apatite is directly replacing primary monazite; additionally, the subhedral shape of the apatite rim suggests that it may represent the former rim of the primary monazite (Finger *et al.*, 1998). Only in one case, allanite was recognized as an outer rim that partly surrounds the apatite±thorite zone (Fig. 1e). As retrogressed monazites lie in the matrix along grain boundaries of major minerals, we interpreted the corona structure as a result of a fluid-monazite interaction, according to Finger *et al.* (1998).

In the leucosomatic sample, monazite crystals occur in the matrix and are surrounded by Sil or by Qtz. The majority are ≈ 20-70 μm in size with a few being ≈ 100-150 μm in size. They exhibit mainly a subhedral shape, but subrounded monazites are also observed particularly within Qtz (Fig. 1f). Monazites located within Qtz are fracture-free or less fractured compared to crystals associated with Sil; moreover, only an apatite inclusion was identified in a monazite crystal surrounded by Qtz. Also in this sample, a few grains with an apatite ± thorite ± allanite corona structure were recognized in the matrix near corroded and retrogressed Grt porphyroblasts and Bt aggregates. Generally, monazite crystals are unzoned, whereas only a few grains show patchy and near concentric zoning. Chemical analyses performed on near concentric zoned crystal highlighted that bright BSE core is enriched in Y (4.13 wt. % *vs* 3.93 wt. %), P (31.05 wt. % *vs* 30.84 wt. %), Th (5.65 wt. % *vs* 5.29 wt. %), U (1.18 wt. % *vs* 0.74 wt. %) and Ca (0.91 wt. % *vs* 0.70 wt. %) compared to the dark BSE rim which is enriched in Si (1.14 wt. % *vs* 1.04 wt. %); instead, the monazite showing a patchy zoning is enriched in Si (13.51 wt. % *vs* 11.60 wt. %) and P (24.80 wt. % *vs* 22.55 wt. %) in its brighter BSE domains and in Y (12.29 wt. % *vs* 3.85 wt. %), Th (8.29 wt. % *vs* 3.85 wt. %), U (2.07 wt. % *vs* 0.39 wt. %) and Ca (4.59 wt. % *vs* 3.75 wt. %) in its darker BSE domains. Finally, the unzoned monazites have a chemical composition similar to the unzoned grains observed in the restites. No meaningful chemical differences were identified between crystals associated with Sil and those surrounded by Qtz. The monazite crystals observed in the restitic samples seem to have recorded three different stages. The Th-rich and Y-poor domains are typical of the garnet zone, whereas the Th-poor and Y-rich domains are characteristic of the Sil zone (Spear & PyleE, 2003) and occurred during garnet breakdown (Kelly *et al.*, 2006). Therefore, we identified (1) a first Th-rich monazite generation (MnzI), possibly contemporary with the first Bt dehydration-melting reaction, which might give information about the age of the first anatectic event; (2) a second Y-rich monazite generation (MnzII), perhaps contemporary with the first melt-consuming reaction, which might give information about the age of the first crystallization process; (3) a third Th-rich monazite generation (MnzIII), possibly contemporary with the second Bt dehydration-melting reaction, which might give information about the age of the second anatectic event. Similarly, monazite crystals observed in the nebulitic sample could give further information about the timing of the first crystallization process (MnzII); however, all grains are characterized by a corona structure suggesting a fluid-monazite interaction which could have reset the U-Pb system (Bosse *et al.*, 2009). If the fluids responsible of monazite alteration were those released after final melt crystallization at the H_2O-saturated solidus, these monazites might give information about the age of later crystallization (MnzIV). Lastly, the monazite crystals surrounded by Qtz in the leucosome sample might give further constraints about the age of migmatization process which affected the migmatites of the northern Catena Costiera.

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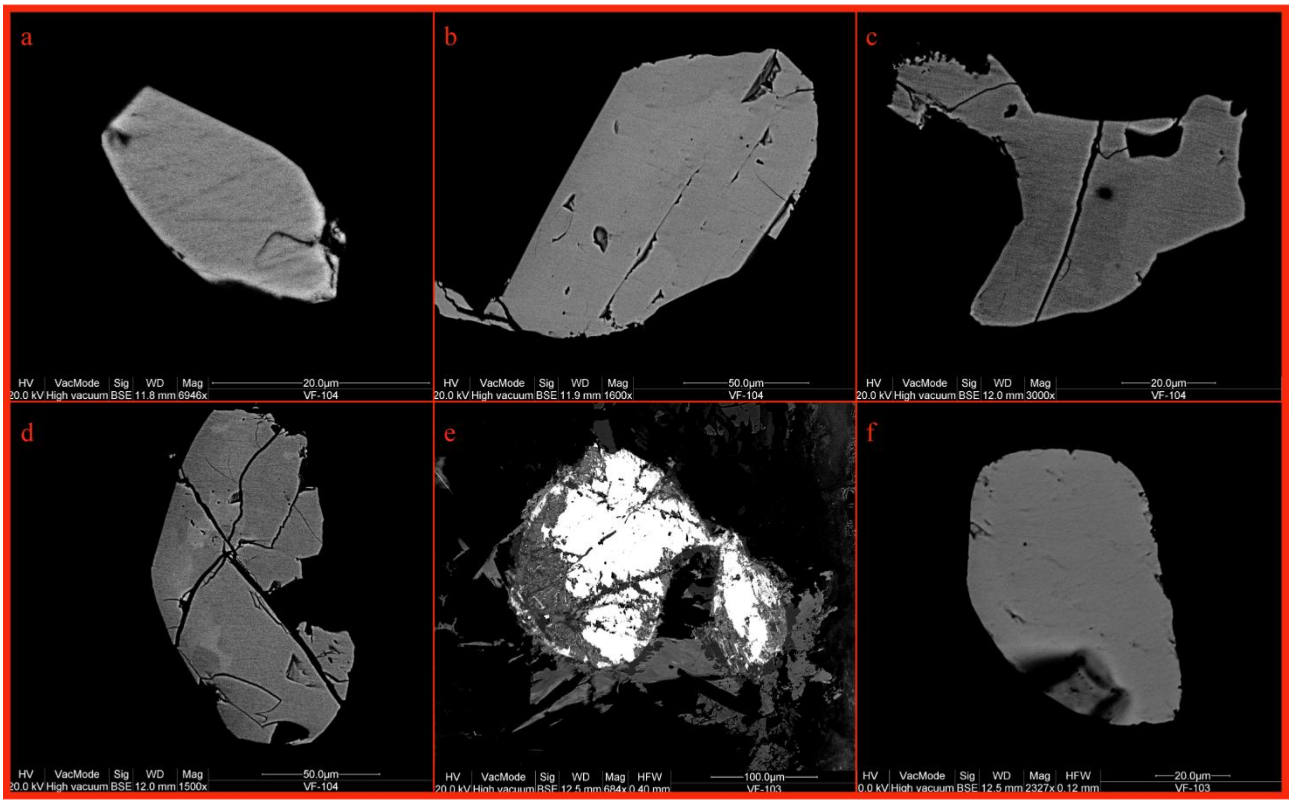

Fig. 1- (a) Unzoned monazite. (b, c) Monazites showing a near concentric zoning; in (b) a darker rim grown on a brighter core, whereas in (c) a brighter rim grown on a darker core. (d) Monazite showing a patchy zoning. (e) Apatite+thorite+allanite corona structure on monazite. (f) Sub-rounded monazite surrounded by Qtz.

Two-Stage Partial Melting in the Migmatites of the Northern Catena Costiera (Calabria, Southern Italy): Evidences from Petrographic, Petrological and Geothermobarometric Data

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The studied rocks belong to the deepest portions of the Variscan continental crust section which constitutes the highest structural element of the Northern Calabrian Arc. The rocks are constituted by Grt-Bt gneisses, Cpx-Opx granulites, migmatites, metaultramafic rocks and Permo-Triassic gabbros. The Variscan and late-Variscan metamorphic evolution has been defined by several authors (Graessner & Schenk, 2001 in the Sila massif; Fornelli *et al.*, 2002 and Acquafredda et alii, 2006 in the Serre; Piluso & Morten, 2004 in the Catena Costiera); in particular, a migmatitic event has been evidenced at 295 Ma by Graessner *et al.* (2000). New petrographic, geochemical, petrological and geothermobarometric data have been carried on the migmatites cropping out in the northern Catena Costiera, where the deepest levels of the crustal section are exposed together with mantle-derived rocks. The obtained data suggest that a second migmatitic event affected these rocks during a decompression event that testify for a lithospheric thinning. This fact, together with the emplacement of Permo-Triassic gabbros at the base of the crust, may be related to a rifting geodynamic framework that marks the beginning of the Alpine cycle.

The whole-rock chemistry highlighted the existence of granitic and tonalitic-trondhjemitic leucosomes. The high LREE-HREE fractionation observed in both types allowed us to interpret them as the product of the micas dehydration-melting reactions; however, the tonalitic-trondhjemitic compositions were interpreted as the result of the final crystallization at lower pressure H_2O-saturated solidus as suggested also by the observed Qtz + Kfs + Sil + Pl assemblage. The Nb negative anomaly observed in all leucosome samples suggests their crustal genesis. Furthermore, the whole-rock analyses obtained from eight migmatites and a Grt-Bt gneiss showed that the first ones are enriched in Al_2O_3 and depleted in Na_2O, CaO, MgO and TiO_2 compared to the second one: the enrichment in Al_2O_3 was attributed to the immobile geochemical behaviour of this element during the migmatization process, whereas the depletion in Na_2O, CaO, MgO and TiO_2 was attributed to the plagioclase and biotite involvement in melting reactions. The plagioclase involvement in melting reactions is highlighted also by the Eu and Sr negative anomalies observed in migmatites samples and absent in Grt-Bt gneiss. These features allowed us to interpret the Grt-Bt gneisses as the protoliths of the migmatites.

The geothermobarometric estimates were obtained from the interpretation of two P-T pseudosections constructed with the software THERMOCALC 3.33 (Powell & Holland, 1988) with an updated version of the internally consistent data set of Holland & Powell (1998; data set tcds55, file created 22 November 2003). Mineral-equilibria calculations were performed in the system NCKFMASH using the XRF composition of a nebulitic sample, for which the whole-rock chemistry suggested a little or no melt loss, and in the system FMASH using the XRF composition of a restitic sample with the aim of determining the P-T conditions in which partial melting and subsolidus reactions occurred, respectively. The new petrographic, microstructural and petrological data allowed us to suggest a clockwise P-T path for the migmatites of the northern Catena Costiera (Fig. 1). A relict crenulated foliation defined by Ms + Qtz and Qtz + Pl + Bt inclusions observed in Grt porphyroblasts were interpreted as prograde stage evidences and suggest that these rocks were in the g-mu-bi-H_2O stability field before partial melting occurred. Petrological data highlighted the existence of a first Grt generation (GrtI) characterized by flat zoning profiles for almandine, pyrope and spessartine in its interior, interpreted as a prograde relict that became completely homogenous at high temperatures. Moreover, petrological data showed the existence of a first Bt generation characterized by high Ti and Mg contents, interpreted as a restitic phase. The first anatectic event produced coarse-grained Qtz + Pl + Kfs leucosomes which describe a stromatic foliation and started at the H_2O-saturated solidus at P > 0.7 GPa and T ≈ 670-680°C. Once consumed all H_2O, partial melting of the g-mu-bi-liq assem-

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blage proceeded with a Ms dehydration-melting reaction, highlighted by the g-mu-bi-ksp-liq divariant field, at P > 0.8 GPa and T ≈ 740-770°C, according to the reaction (1) Ms ± Pl + Qtz = Sil + Kfs + L. Disappearance of the assemblage Ms + Qtz + Pl, corroded Ms dispersed in the matrix and a structural relict of Bt-Sil crenulated foliation are interpreted as a result of muscovite dehydration-melting (Kriegsman & Alvarez-Valero, 2010); evidences of sillimanite crystals cross-cutting Bt lamellae allowed to assume that Bt behaves as an inert phase during this reaction. Once consumed all Ms, partial melting of the g-ksp-bi-liq assemblage proceeded with a Bt dehydration-melting reaction that led to the g-ksp-liq stability field at P > 0.7 GPa and T ≈ 800°C, according to the reaction (2) Bt+Sil = Grt+Kfs+L. Corroded Bt lamellae dispersed in the matrix, Grt porphyroblasts with inclusions of Bt, Bt+Pl, Bt+Qtz or separated Bt and Fib are interpreted as a result of the biotite dehydration-melting, according to Vernon (2004) and Kriegsman & Alvarez-Valero (2010). Petrological data highlighted the existence of a second Grt generation (GrtII) defining the inner rim of the Grt porphyroblasts characterized by an enrichment in pyrope component and a depletion in almandine and spessartine components compared to GrtI which define the Grt porphyroblasts core; GrtII was interpreted as an incongruent phase. The metamorphic climax at P-T conditions of 0.8-0.9 GPa and 800°C was followed by an isothermal decompression during which the first melt crystallization led again to the Bt stability field (g-bi-ksp-liq), according to the melt-consuming reaction (2i) Grt + Kfs + L = Bt + Sil. The biotite and sillimanite crystals, observed in the lepido-nematoblastic layers describing a stromatic foliation together with leucosomes, are interpreted as a result of the melt-consuming reaction. The isothermal decompression is well-documented by the development of multiple coronas made of a Crd moat and of Crd + Spl ± Crn ± An symplectites at the Grt-Sil contact and Crd+Opx symplectites at the Grt-Ilm contact observed in restites (Piluso & Morten, 2004). The second anatectic event is highlighted by melt films that rim coarse-grained leucosomes crystals and by fine-grained Qtz + Pl ± Sil melt aggregates observed as patches within coarse-grained leucosomes. It started with a second Bt dehydration-melting reaction, highlighted by the g-bi-cd-ksp-liq divariant field, at P < 0.7 GPa and T ≈ 780-800°C, according to the reaction (3) Bt + Sil + Qtz = Grt ± Crd + Kfs + L. The cordierite crystals observed in the matrix and included in Grt porphyroblasts as well as small euhedral Grt without inclusions within the fine-grained melt aggregates are direct evidences of this reaction; the inclusions of Crd may possibly be interpreted as contemporary with Grt, according to Vernon (2004). Petrological data showed that the cores of small euhedral Grt without inclusions (GrtIII) have a similar composition to GrtII; therefore, GrtIII was also interpreted as an incongruent phase. On cooling, the second melt started to crystallize at reaction (3) producing randomly oriented Bt + Sil + Qtz, Bt + Qtz and Sil + Qtz intergrowths close to the corroded Grt and Crd porphyroblasts interpreted, according to KRIEGSMAN & Alvarez-Valero (2010), as a result of melt-consuming reaction (3i) Grt ± Crd + Kfs + L = Bt + Sil + Qtz. The high Mg content observed in the Bt intergrowths suggests high temperatures of formation for this phase. Large modal amounts of Bt observed in some samples and small modal amounts of Kfs allowed to sustain the assumption of the melt-consuming reactions (Kriegsman, 2001; Brown, 2002; Kriegsman & Alvarez-Valero, 2010). Final crystallization occurred at the H_2O-saturated solidus at P < 0.4 GPa and T ≈ 660-670°C, according to the reaction (4) L = Qtz + Kfs + Sil + Pl + H_2O, as suggested by Qtz + Kfs + Sil + Pl assemblage identified in some leucosomes samples. The outer rim of Grt porphyroblasts and of small Grt without inclusions (GrtIV) is characterized by a depletion in pyrope component and an enrichment in almandine and spessartine components compared to GrtII and GrtIII, respectively; therefore, GrtIV was interpreted as a chemical zoning acquired during a later re-equilibration. The second anatectic event was followed by a subsolidus stage characterized by the hydration under amphibolite facies conditions with the Bt and St development at the expense of Grt and Sil and, finally, by the hydration under greenschists facies conditions (Piluso & Morten, 2004).

The tectonometamorphic evolution of the migmatites outcropping in the northern Catena Costiera follows a clockwise P-T path similar to that suggested by Graessner & Schenk (2001) in the Sila Massif, Fornelli *et al.* (2002) and Acquafredda et alii (2006) in the Serre Massifs and Piluso & Morten (2004) in the Catena Costiera. Graessner & Schenk (2001) and Piluso & Morten (2004) refer the first anatectic event to a Variscan collisional stage, whereas Fornelli *et al.* (2002) and Acquafredda *et al.* (2006) sustain that melting begins during a collisional stage and proceeds during subsequent decompression event. According to Acquafredda *et al.* (2006), the prograde stage of the migmatites cropping out in the northern Catena Costiera likely occurred in the kyanite stability field but the subsequent thermal equilibration caused the disappearance of this phase. A second anatectic event characterized by an extensive biotite dehydration-melting was recognized for the first time in the migmatites of the Catena Costiera. This anatectic event might be due to heating related to the Permo-Triassic gabbros emplacement, that have a minimum cooling temperature of about 800°C at 0.55 GPa (Liberi *et al.*, 2011).

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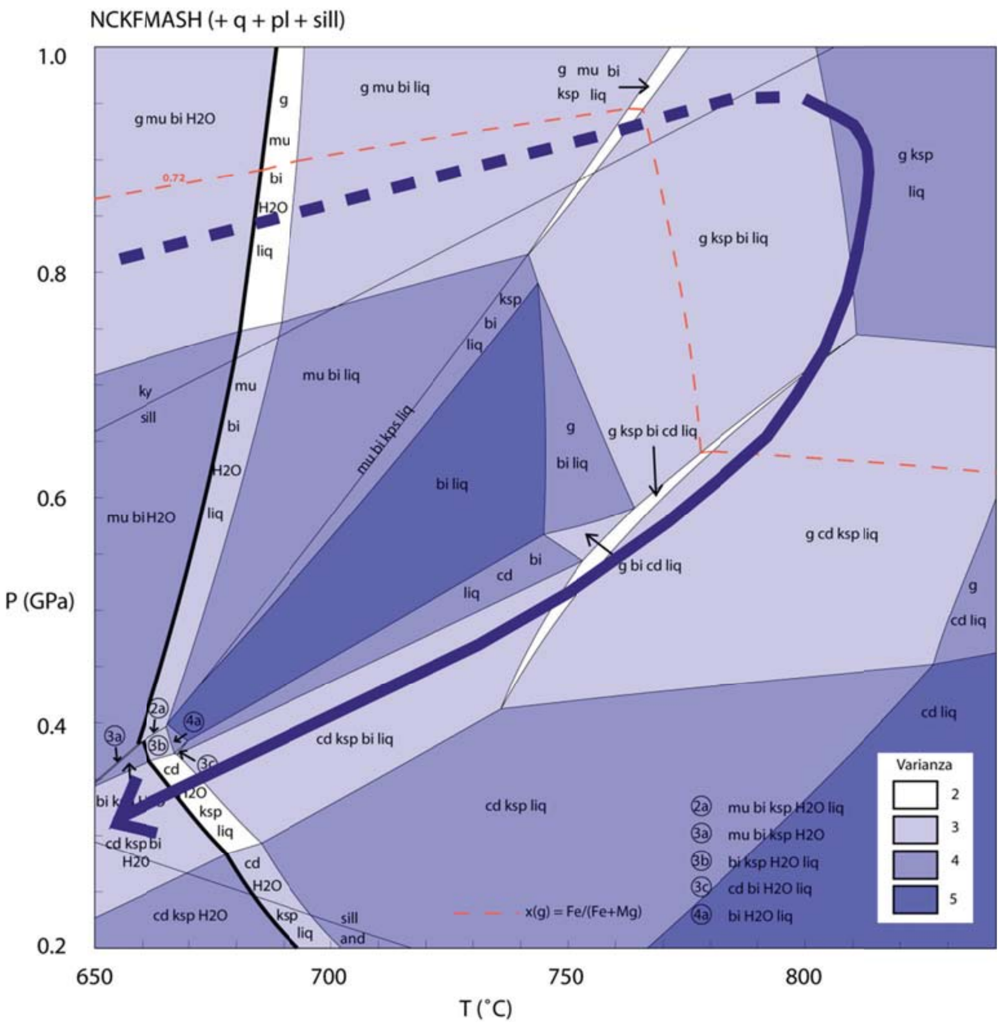

Fig. 1.- P-T pseudosection constructed using XRF composition of a nebulitic sample (N:C:K:F:M:A:S:H = 0.82:0.89:2.24:4.87:3.34:14.29:66.05:7.50, mol. %) showing a clockwise P-T path for migmatites of the northern Catena Costiera. Compositional isopleth for GrtIII is shown as dashed line.

Permian and Triassic basin development in relation to the emplacement and subsequent mineralisation of the Cornubian Batholith, SW England

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The continental red beds which crop out around the eastern part of the Cornubian Batholith (see fig. 1 below) include the Permian Exeter Group and the Triassic Aylesbeare and Sherwood Sandstone groups. The Exeter group can be subdivided into an older (latest Carboniferous to Early Permian) succession and a later (Mid- to Late Permian) succession separated by a distinct unconformity. The older part of the Exeter Group is interbedded with lamprophyric and basaltic lavas of the Exeter Volcanic Rocks, and geochronological work on these has demonstrated that the early red bed sedimentation was, in part synchronous with, and, in some cases pre-dates the emplacement of the granite plutons and associated minor intrusions. The later part of the Exeter group records the unroofing of the Dartmoor Pluton, and rapid erosion of a substantial supra-batholithic volcanic edifice, now essentially represented by clastic debris. Combining these data with fluid inclusion and geochronological studies on Sn-W-base metal mineralisation gives valuable insights to the tectonic evolution of the region, including rates of uplift and the extent of red bed sedimentation. Triassic mineralisation in N-S trending veins, on a regional scale, records an episode of E-W extension and a tectonic watershed in the Pangaean crust.

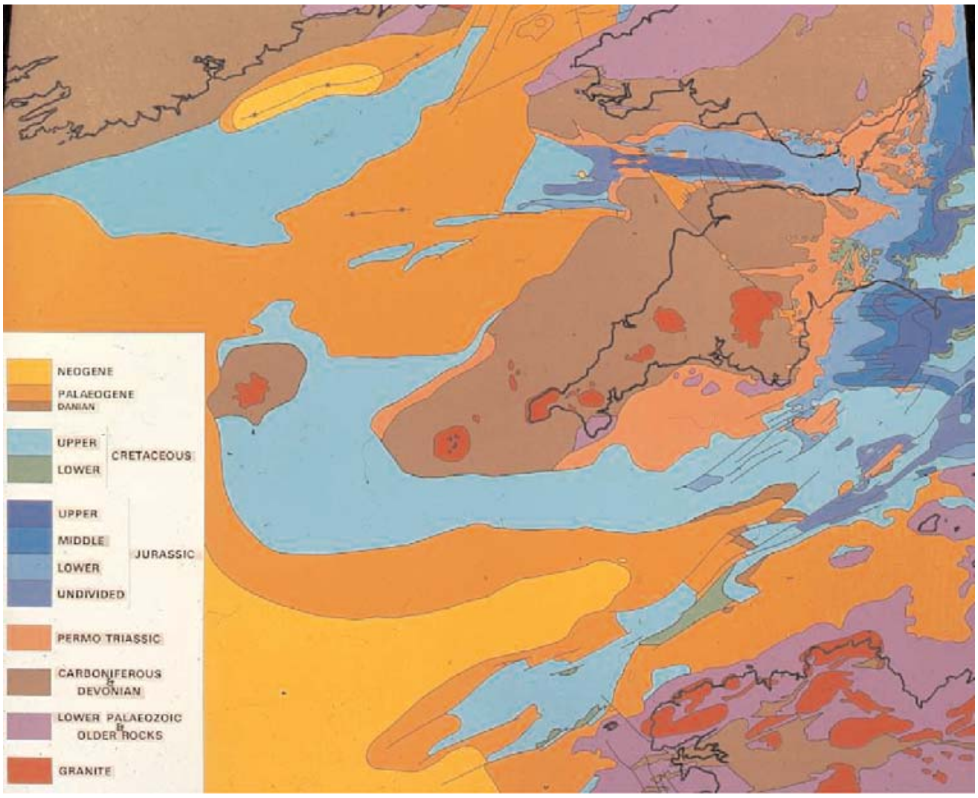

Fig. 1.- Geology of the Cornubian Peninsula and Western Approaches.

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Latest Carboniferous to Early Permian post-Variscan tectonics and magmatism in the Rhenohercynian Zone of SW England

SHAIL Robin

The Variscan tectonic evolution of SW England records the development of a Devonian-Early Carboniferous passive margin (Rhenohercynian Zone) that was subsequently strongly inverted during convergence and collision with an upper plate accretionary complex and magmatic arc (Saxothuringian Zone); Shail and Leveridge (2009). The Rheic/Rhenohercynian suture is imaged on seismic reflection profiles in the English Channel.

Variscan convergence across southern Britain ceased during the latest Carboniferous (c. 305-300 Ma); peak regional metamorphism in the lower plate is generally sub-greenschist facies (Warr *et al.*, 1991). In SW England, dextral wrench movements between the Bray Fault and St Mary's Wrench Zone, 450 km to the west, were accompanied by the extensional reactivation of the Rheic/Rhenohercynian suture and the frontal segment of the Bristol Channel-Bray Fault Zone, together with reactivation of other Variscan thrust and transfer faults (Shail and Leveridge, 2009). Secondary folds, cleavages and faults developed during the extensional reactivation of thrust faults indicate a dominant top-to-the-SSE shear sense and that the NNW-SSE extensional regime persisted until c. 275 Ma.

Exhumation of the lower plate was contemporaneous with Early Permian bimodal magmatism c. 295-270 Ma (Chen *et al.*, 1993), alluvial/fluvial 'red-bed' sedimentation (Edwards *et al.*, 1997) and the development of the Plymouth Bay Basin above the reactivated Rheic/Rhenohercynian suture (Harvey *et al.*, 1994). Mafic igneous rocks comprise lamprophyres and basalts that occupy both upper and lower plate positions relative to the suture. Felsic igneous rocks constitute the dominant expression of magmatism in the lower plate; they comprise the Cornubian and Haig Fras batholiths together with subordinate rhyolite/granite sheets and rare rhyolite lavas.

Generation and emplacement of the Cornubian Batholith occurred over a 20+ Ma period in the Early Permian (Chen *et al.*, 1993). Geochronological data indicate that most plutons at this level were formed by the accumulation of multiple magma batches over a period of 4-5 Ma (*e.g.* Chen *et al.*, 1993). Gravity anomaly interpretations have typically over-estimated its thickness; most plutons are probably 7-8 km thick, and the Dartmoor Granite 10 km thick. Biotite and tourmaline granites are cogenetic but the topaz granites may represent separate source/melting events. Rhyolite/microgranite ('elvan') dykes correspond to the range of pluton compositions and at least locally had an eruptive expression.

Whilst predominantly crustally-sourced there is a minor direct contribution from mantle-derived melts. The older (>290 Ma) plutons (Isles of Scilly, Carnmenellis and Bodmin Moor granites) can be distinguished from the younger (<286 Ma) plutons (Land's End, St Austell and Dartmoor granites) by their texture, sparse or absent micro-granitoid enclaves, more aluminous compositions, lower femic elements, steeper REE patterns, more negative ε_{Nd} and higher NH_4^+, the presence of probable magmatic muscovite and a biotite:muscovite ratio <1. The younger plutons reflect an increased, but still minor, contribution of mantle-derived melts and, possibly, higher degrees of crustal partial melting.

The older plutons exhibit localized solid-state fabrics that suggest coupling with regional host rock deformation during reactivation of thrust and transfer faults. Magmatic state fabrics in later plutons (AMS/feldspar) are often composite and reflect regional deformation of magmas that had already acquired emplacement-related fabrics from internally driven movements and interaction with host rock roof and sidewall (Kratinova *et al.*, 2010).

W-Sn-Cu-As vein mineralisation associated with the Cornubian Batholith primarily reflects the structurally-controlled release of magmatic-hydrothermal fluids from crystallising magmas and variable mixing with meteoric and, to a lesser extent metamorphic and basinal fluids. Mineralised

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fracture systems in most granite plutons developed during the Early Permian NNW-SSE extensional regime but the youngest granite-related mineralisation was controlled by more complex Mid-Permian strike-slip regimes.

Early Permian felsic magmatism is resticted to relatively narrow zones in the lower plate of the Rhenohercynian suture (Cornubian Batholith) and the footwall of the Bristol Channel Fault Zone (Haig Fras Batholith). This spatial association suggests that movements on these major structures exerted the primary control on the thermal evolution of the lithosphere and generation of high melt volumes. The extensional thinning and exhumation of the lower plates brought about partial melting of lithospheric mantle, initially sourcing lamprophyres and then basalts, although an asthenospheric source for the latter is also possible (Leat *et al.*, 1987). These mantle-derived melts entered a lower crust that was already very hot, from the combined effects of convergence-related thickening and subsequent extension, and hence further contributed to progressive large-scale melting. Localized strike-slip-related decompressive melting along NW-SE fault zones may have contributed to the development of topaz granites. The granites are located above their source zones.

Direct observations regarding internal pluton construction and marginal contact relations are restricted to the uppermost 1 km. The transport of magma from source regions is inferred to have been along ENE-WSW to E-W trending and NW-SE trending faults and ductile shear zones. Emplacement of the plutons at current exposure levels was accommodated by roof uplift that brought about localised folding and/or tilting of host rocks. Pre-existing faults and joints, some parallel to foliation, determined the geometry of contacts. Direct evidence for stoping is limited, but assimilated host rocks might account for up to 5% of the magma at upper levels (Stimac *et al.*, 1995).

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What is the Carboniferous granitoid in fact? New isotopic and geochronological data from the Central Western Carpathians

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The Western Carpathians as a part of the extensive the Alpine - Carpathian orogenic belt include more or less conserved the Variscan/Hercynian units. These were, as relic structures, incorporated into the Alpine comprehensive tectonic framework during Upper Jurassic to Tertiary discontinuous convergence.

Basement structure is heterogeneous and consists of two contrasting types of the Variscan complexes, exhibiting pre-Alpine thrust tectonics: (1) high-grade metamorphic rocks- orthogneisses, layered amphibolites, migmatites - of Proterozoic/ Early Paleozoic age, and (2) lower-grade metamorphites- gneisses to micaschists of Early Paleozoic age (Bezák, 1994 and Putiš *et al.*, 2003, 2008). The Variscan granitoids form a miscellaneous cluster of rocks with different age, origin and tectonic position.

The composite Vepor pluton occupies a central part of the Western Carpathians domain (Slovenské Rudohorie Mts.). It is overthrusted on metamorphites and often deformed. The pluton consists of specific local named granitoids suite of I/S and some A type, also. The most distinguished, largest and cited is I-type "Sihla" tonalite, although, the I-type form a relatively minority part of Variscan granitoids (*e.g.* Broska-Petrík, 1993; Petrík-Kohút-Broska, 2001).

The "Sihla" tonalite to granodiorite is situated on the N side of the Muráň fault, but according to Hraško *et al.* (2005) small co-magmatic more basic, tonalitic body, so called Málinec tonalite exists on the S side of the Muráň fault. There is quite unknown, mindless, relevant data is still missing.

The Rb-Sr age of mica was determined from the Málinec tonalite. The concentrations of Sr, Rb and $^{87}Sr/^{86}Sr$ in biotite were measured by TIMS using the isotope dilution technique and cation exchange chromatography. The initial ratio $^{87}Sr/^{86}Sr$ of 0,704655 was determined by analyses of apatites; the age was calculated from biotite, although age calculations of biotite highly enriched in radiogenic ^{87}Sr are not sensitive to the initial 87Sr/86Sr ratio. The biotite with $^{87}Sr/^{86}Sr$ = 0,768391 yielded a surprisingly young 116 ± 5 Ma.

This Lower Cretaceous age probably represents the age of the last thermal event when the tonalite was heated above the closure temperature of Rb-Sr system of biotite and clearly allocate important role to the thermal and tectonic reworking of basement into the Alpine structures.

On the other side, we try to recognize several events by U-Th-Pb CHIME monazite dating on fully molten gneissic to migmatitic relics or xenolites in Málinec I-type tonalite. Results show continuously min. Middle Carboniferous age - 321 ± 5 Ma without any signs of new, younger monazite growing.

The newest precise spot U-Pb SHRIMP / SIMS zircon data from the "Sihla" I-type granitoids indicates they were emplaced during Early Variscan/Early Carboniferous - 349,9 ± 4,4 Ma to 357 ± 2,5 Ma (Siman unpublished new data, Broska *et al.*, 2011), contemporaneously to the S-type granites. Unlike, former works based on conventional U-Pb zircon dating suggest a Late Carboniferous age - 303 ± 5 Ma (Bibikova *et al.*, 1990).

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The origin of high geothermal gradient: post-orogenic extension or large intrusion in the middle crust? A case study from the Agly Massif, French Pyrenees

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The thermal structure of the continental crust modeled by classical heat transfer equations, which involve heat production, conduction and advection terms, predicts a steady increase of temperature with depth. However, the shape of the observed geotherm in many high-metamorphic domains appears to be much more complicated, with huge geothermal gradient (> 100°C/km?) in the upper crust and a steep gradient in the mid and lower crust. Three geodynamic models are classically invoked to explain these high geothermal gradients: (1) post collisional extension, with high mantle flux due to asthenospheric mantle uplift, that leads to magma underplating and partial melting of the lower part of the thinned crust (Thompson and England, 1984), (2) crustal thickening associated with the melting of the crust and the intrusion of large volumes of granites in the intermediate crust (Lux *et al.*, 1986; De Yoreo *et al.*, 1989) or (3) Subduction associated with large magma supply. In these three cases, the settings are associated with long-lived plutonism and partial melting in the middle and lower crust. Thus, in order to model accurately the thermal structure of the crust, it is critical to include the effects of melt transfer and the buffering effect of partial melting reactions (Depine *et al.*, 2008).

In the French Variscan domain many examples of high grade massifs (St-Barthelemy, Montagne Noire, Agly, Velay, Aston...) are characterized by high geothermal gradient and LP-HT metamorphism developed between 320 and 300 Ma. The tectonic significance of this LP-HT event at the scale of the Variscan belt is still a matter of debate: Is it related to a lithospheric scale post-collisional extension event, to crustal compressional doming or is it the local expression of large magma emplacement in the middle crust.

The Agly massif, the easternmost North Pyrenean Massif, shows a continuous cross section from the unmetamorphosed upper crust to the high-grade middle crust. It provides a unique opportunity to observe and quantify the thermal structure of the late Variscan continental crust. This massif, that was exhumed during the tertiary tectonic, consists of a lower to middle Paleozoic cover overlying a gneissic core that was interpreted as crystalline basement (Fonteilles, 1967). The Ordovician micaschists are characterized by a continuous metamorphic evolution from greenschist to upper amphibolite facies conditions with an estimated geothermal gradient up to 150°C/km in some places in the massif, while the “basement” shows amphibolite to granulite facies conditions with quasi-isothermal evolution (Fonteilles, 1976; Delay, 1990). The "basement" was intruded at 315 Ma by the syn-tectonic Ansignan charnockite (Respaut and Lancelot, 1983), and the post-tectonic Saint-Arnac granite at 307 Ma (Olivier *et al.*, 2004). The age of the metamorphism is unknown but assumed to be coeval with the Charnockite emplacement.

Two Variscan deformations affect the Agly massif. A D1 deformation is responsible for the development of the main flat lying foliation. This D1 deformation event is coeval with the emplacement of the charnockite at 315 Ma and to some extent to the development of the abnormal geothermal gradient. S1 foliation contains a shallow dipping stretching lineation striking to the N20. The gneissic basement is affected by many localized gently dipping high strain zones with either a top-to-the-south or to-the-north normal sense of shear consistent with the N20 stretching direction (Bouhallier et al., 1991). During a D2 deformation, the S1 foliation is variably transposed into upright to plunging folds with an E-W axis. This deformation is responsible for the bulk structuration of the Agly anticline mainly exposed in the gneissic rocks and the Roque-courbe syncline that affect the Ordovician to Devonian cover. This D2 deformation is also responsible for the inverted metamorphic gradient observed in the northern part of the massif. We suggest that the D2 deformation occurred during a large scale transpressional regime (Olivier *et al.*, 2004), contemporaneously to the magmatic intrusion of the Saint-Arnac granite at 307 Ma. If the D1 paleogeometry is

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restored before the intrusion of the Saint-Arnac pluton and the D2 event, it appears that the thickness of the micaschist cover of the northern part of the massif (Rasiguère area) is significantly thinner than in the southern area (between Força-Real and Caladroy). Therefore, we suggest that a detachment with a bulk top-to-the-north kinematics was responsible for the juxtaposition of high grade rocks of the “basement” with the lower grade micaschists and the northern thinning of the Ordovician cover at around 315 Ma.

In order to reconstruct the paleogeotherm during the early D1 event (315 Ma) and discuss the origin of this thermal anomaly, a suite of rocks were sampled along a D1 cross-section that was restored from the late D1 extension and D2 transpressive event. Samples were taken from the upper part of the Ordovician cover to the deepest gneisses close the charnockite along an E-W profile. Samples from the cover are micaschists and are kinzigites in the gneissic basement. A petrological and thermobarometric estimation was performed using computed phase diagram sections and multi-equilibrium thermobarometry (Perple_X and avPT mode of Thermocalc) to reconstruct the P-T-t-D1 gradient of the Agly massif.

The Ordovician cover is characterized by a continuous LP metamorphic gradient from greenschist facies conditions to the fluid-saturated partial melting. The suite of simplified paragenesis observed is: chlorite-muscovite, biotite-muscovite, biotite-muscovite-cordierite, biotite-muscovite-andalousite, biotite-muscovite-sillimanite, biotite-sillimanite-K-feldspar and biotite-sillimanite-K-feldspar-melt. Average P-T estimation performed on these samples gives a geothermal gradient of 55°C/km with temperatures evolving from 500°C to 605°C for a pressure range fo 0.23-0.28 GPa. In the gneissic basement, kinzigite consist of garnet-cordierite-sillimanite-biotite. Computed phase diagram sections in the TiNaCaKFMASH system suggest a geothermal gradient of 8°C/km with a temperature of 725-765°C and a pressure range of 0.52-0.63 GPa. The charnockite was emplaced at about 0.62 GPa ± 0.05 GPa. The pressure gap of about 0.18 GPa (~ 6 km of terranes) between the partial melted micaschist and the uppermost kinzigite which is structuraly just a few hundreds of meter below the micaschist is interpret as the effect of the late D1 detachment.

Thermal modelling suggests that this abnormal D1 geothermal gradient cannot be produced only by heat transfer through conduction from the charnockite and associated mafic magmas. Using the approach of Depine *et al.*, (2008), which includes the effect of heat advection though melt transfer and the buffering effect of partial melting, we expect to reproduce the geotherm shape only if we impose melt migration through the entire gneissic basement section.

To conclude, the finite geothermal gradient observed in the Agly massif is the result of the superposition of several tectono-metamorphic events. (1) The D1 thermal event, at 315 Ma, induces the emplacement of a large volume of charnockitic and mafic magmas and the upward advection of heat, up to 0.35 GPa (~13 km). Heat advection occured by melt produced during high grade metamorphism and partial melting of Ordocician to Cambrian pelites and greywackes. The thermal buffering of dehydration melting produces near isothermal conditions in the middle crust (melt enhanced geotherm). The high geothermal gradient (55°C/km) observed in the upper crust, that is consistent with the low pressure andalousite-sillimanite transition, is a purely conductive geotherm between the surface and the uppermost part of the melt-enhanced geotherm (2) The late D1 event is characterized by a ~ North-South extensional event that induce the exhumation of the middle crust and its juxtaposition with shallower levels resulting locally in apparent gradients greater than 300°C/km (Rasiguère area). (3) The last event D2, which is contemporaneous with the emplacement of the Saint Arnac granite in a transcurrent setting, is responsible for the anticlinal structure (dome) of the Agly massif and the inversion of the metamorphic gradient in the northern part.

The Variscan Vosges Mountains (NE France): Saxothuringian or Moldanubian ?

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Since the early work of Kossmat, the Variscan Vosges Mountains have been subdivided into a northern Saxothuringian and a southern Moldanubian part. New structural, petrological and geochronological data for the whole Palaeozoic basement allow discussing this classical interpretation. The pre-collisional history of the Vosges basement corresponds to the Ordovician-Silurian deposition of the varied and monotonous sediments in different parts of a rifted basin. The subsequent Devonian-Carboniferous collision is characterised by four tectonometamorphic events. During the late Devonian, E-directed continental subduction of a passive margin sequence below a Neoproterozoic-Early Palaeozoic basement produced crustal thickening and later vertical extrusion of high-grade lithologies in the Central Vosges. At the same time, the opening of a narrow back-arc basin is evidenced in the Southern Vosges. The second deformation event is associated with the formation, at 340 Ma, of a major intra-orogenic boundary zone in the middle orogenic crust, most likely as a result of continuous underplating of felsic material at the base of the orogenic system. Deformation was coeval with the widespread intrusion of magnesio-potassic granitoids (Mg-K) at different crustal levels during a switch in stress orientation. In the early Lower Carboniferous, the originally E-W compressive stress field was replaced by N-S compression associated with thin-skinned tectonics in the upper orogenic crust. During this third tectonic event, a major decoupling occurred along the intra-orogenic boundary zone and left the deep part of the orogen devoid of any tectonic overprint. A later N-S extension event is reflected by the development of detachment systems which reactivated the intra-orogenic boundary zone during the late Lower Carboniferous. Extensional tectonics is explained in terms of gravitational collapse and thermal weakening of the middle crust due to high radiogenic heat production by the Mg-K granitoids. In the Northern Vosges, contemporaneous arc-type magmatism testifies for the S-directed subduction of the Rhenohercynian basin located to the North. It is therefore possible this process may have additionally controlled the orientation of the detachment systems which developed in the Central Vosges.

To sum up, the Early Palaeozoic sedimentary and magmatic record of the Vosges Mountains bears strong similarities to the Saxothuringian stratigraphy defined in Germany. However, some of these Early Palaeozoic rocks were subsequently involved in continental subduction and amalgamated with upper-plate rocks of Moldanubian affinity. In addition, the suture of this subduction is inferred to the North of the present-day Vosges basement, suggesting that the whole Vosges basement should be considered as the Moldanubian zone. Therefore, we propose that the Variscan Vosges Mountains rather correspond to a tectonic mixing of Saxothurigian and Moldanubian material.

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The transition from Variscan collision to continental break-up in the Alps: advices from the comparison between natural data and numerical model predictions

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Alpine units are characterized by recurring tectonic and metamorphic rejuvenation, suggesting that continental rocks have been repeatedly forged in an active margin; fortunately the overprint related to Alpine convergence has not completely erased the markers of the earlier evolution in the pre-Alpine continental crust, dismembered during the Pangea break-up and re-accreted in the Alpine nappe belt. In the European Alps the exposure of Variscan structural and metamorphic imprints within the present-day Alpine structural domains indicates that before the Pangaea fragmentation, the continental lithosphere was thermally and mechanically perturbed by Variscan subduction and collision. When continental rifting does not develop on a stable continental lithosphere, geodynamic interpretation of igneous and metamorphic records, as well as structural and sedimentary imprints of rifting-related lithospheric extension, can be highly ambiguous since different mechanisms can be responsible for regional HT-LP metamorphism. While the metamorphic and igneous records of Variscan orogeny are widespread in the European continental crust, a diffuse igneous activity associated with HT metamorphism, accounting for a Permian-Triassic high thermal regime, is peculiar to the Alpine area. The overprint of HT Permian-Triassic evolution on the HP relics of the Variscan subduction and collision has been interpreted as induced either by late-orogenic collapse or by lithospheric extension and thinning leading to continental rifting (*e.g.* Lardeaux & Spalla 1991; Diella *et al.*, 1992; Ledru *et al.*, 2001). Even the interpretation of the geodynamic environment responsible for the development of intra-continental basins hosting the Permian volcanic products allows two possible alternatives: one envisaging a strike-slip dominated regime (Arthaud & Matte 1977; Cassinis & Perotti 1994), which is compatible with the evolution of a mature collisional setting (Molnar & Lyon-Caen 1988), the other a continental rifting tectonic setting (Siletto *et al.*, 1993; Selli 1998; Staehle *et al.*, 2001). In both cases the continental rifting promoting Mesozoic opening of the ocean within a lithosphere thermally softened and thinned by slab break-off processes is generally accomplished in the final stages of continental collision.

In order to reduce this ambiguity, we use two-dimensional finite element models to give new insights on the sequence of mechanisms operating during active ocean-continent convergence, followed by continental collision and pure gravitational evolution and on the regional geodynamic interpretation of the Paleozoic-Mesozoic evolution of the Alpine area. The modelling predictions of lithospheric thermal state and strain localization at different structural levels have been recently compared with a broad set of data on Variscan and Permian-Triassic metamorphism affecting the continental crust of the Helvetic to Southalpine domains, corroborated by the emplacement conditions of mafic intrusions, time interval of plutonic and volcanic activity and coeval onset of sedimentary environments (Spalla & Marotta, 2007; Marotta & Spalla, 2007; Marotta *et al.*, 2009). Such an integrated use of geological data and numerical modelling shows that active extension is required to achieve the thermal conditions allowing partial melting of the crust accompanying gabbroic intrusions and HT-LP metamorphism and leaves the restoration of the late-Variscan or Permo-Mesozoic original setting highly uncertain, even disregarding the Alpine tectonic reworking.

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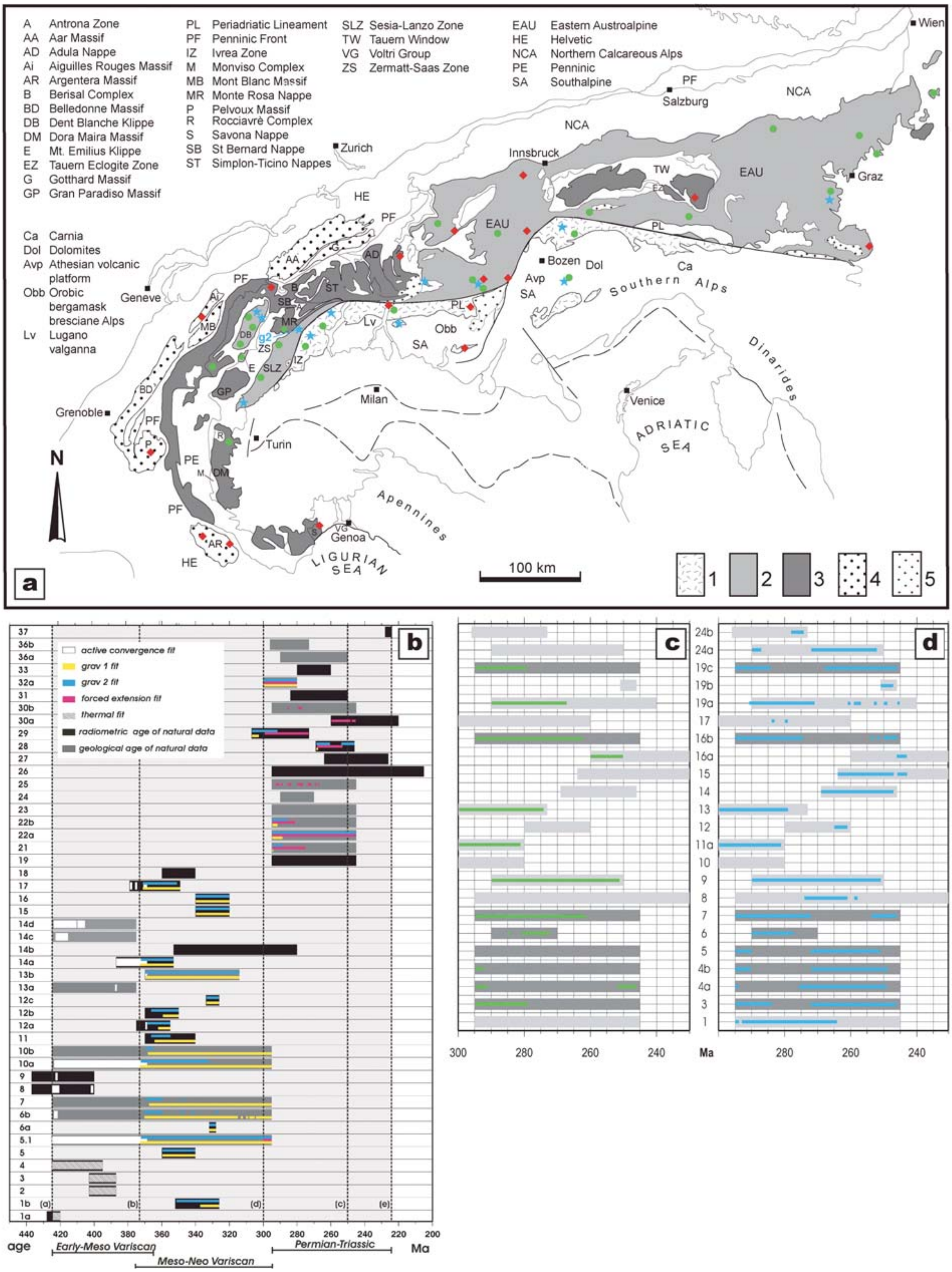

Fig. 1.- (a) Tectonic map of the Alps with the distribution of Variscan (red diamonds) and Permian-Triassic (green circles) metamorphic rocks and of the main Permian-Triassic gabbros (light blue stars), emplaced in the pre-Alpine continental crust. Legend: (1) Southalpine basement, (2) Austroalpine basement, (3) Penninic basement, (4) Helvetic basement, (5) Tertiary intrusive stocks. (b) Fit duration for natural data for all the modelled phases of the tectonic history. Light grey area represents the duration of numerical simulation. Vertical dashed lines indicate the crucial stages of the tectonic model: stage a, beginning of active convergence; stage b, end of active convergence and beginning of purely gravitational evolution; stage c, end of purely gravitational evolution; stages d and e indicate the starting and ending times for forced extension model, at a rate of 0.5 cm a-1. (c) and (d) Fit duration for natural data for forced extension models, at a rate of 1.0 and 2.0 cm a-1, respectively. Light grey and dark grey colours are used to differentiate the radiometric age estimates from the geologically determined ages of the natural data, respectively.

Variscan metamorphic evolution of the Monte Grighini Unit in central Sardinia

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The Monte Grighini Complex (fig. 1) crops out in the Nappe Zone of the Variscan chain in central Sardinia (Carmignani *et al.*, 2001). This complex, from bottom to top, consists of the Monte Grighini Unit, the Castello di Medusa Unit, and the Gerrei Unit. The Monte Grighini Unit is a sequence of metavolcanics, volcanoclastic arkoses and metasandstones, metapsammopelites, quarzites, and metapelites mostly middle-late Ordovician in age. The upper part of the sequence consists of phyllites and schists with intercalated centimeter- to decimeter-thick metasandstones. In the upper portion, thin layers of black graphitic schist and marble occur within the schists.

According to Musumeci (1992) the Monte Grighini Unit is characterized by a regional Variscan metamorphism being prograde from the biotite to the staurolite zones. The metamorphism is associated to two main regional deformational events which have led to axial planar schistosities (S_1 and S_2). The Monte Grighini Unit was intruded by granitoids, spanning in composition from tonalite to leucogranite, during the Carboniferous-Permian transition (303-298 Ma). The emplacement of the granitoids was synchronous with the activity of a wide dextral strike-slip fault known as the Monte Grighini shear zone.

In order to determine the P-T evolution of the Monte Grighini Unit, a systematic study of metapelitic rocks has been performed. In particular, the following rock samples were investigated in detail: (1) a strongly deformed micaschist (sample G53) coming from the northern part of the Monte Grighini Complex, where regional metamorphism reaches medium metamorphic grade and (2) a mildly deformed schist (sample BD6) from the central portion of the Monte Grighini Complex, where regional metamorphism is believed to be partly overprinted by contact metamorphism, due to granite emplacement. Sample G53 contains garnet + staurolite + biotite + potassic white mica + plagioclase + quartz. Accessory minerals are: chlorite + apatite + ilmenite + aluminosilicate + monazite + zircon + epidote + Fe-oxide. The partially corroded garnet in this rock can be as large as 5 mm. According to the inclusion mineralogy garnet is significantly zoned. Sample BD6 contains garnet + biotite + potassic white mica + chlorite + plagioclase + quartz. Accessory minerals are: apatite + ilmenite + aluminosilicate + monazite + Fe-oxide. The garnet in BD6 is nearly idiomorphic and up to 3 mm in size.

The mineral compositions have been analysed with an energy-dispersive system of a FEI QUANTA 200 scanning electron microscope. The zoned garnet of G53 has core compositions around $gros_{25}pyr_3alm_{64}spes_8$ and rim compositions around $gros_3pyr_7alm_{82}spes_8$. The garnet of BD6 is hardly zoned with an average composition around $gros_5pyr_9alm_{61}spes_{25}$. Rims are somewhat richer in pyrope component and poorer in spessartine component than the cores. Potassic white mica in G53 is heterogeneously composed. Highest Si contents per formula unit (pfu) are about 3.19 and seem to refer to the earliest generation. Lowest Si contents are around 3.09 pfu. In BD6, potassic white mica shows Si contents around 3.11 pfu.

The bulk-rock compositions of G53 and BD6, determined with a Panalytical MagiX PW2540 X-ray fluorescence spectrometer, were used for the calculation of pressure (P) - temperature (T) pseudosections employing the PERPLE_X software by Connolly (1990). These pseudosections were calculated in the system SiO_2-TiO_2-Al_2O_3-FeO-MnO-MgO-CaO-Na_2O-K_2O-H_2O-O_2 for the P-T range 1-11 kbar and 400-650°C with the data set of Holland & Powell (1998). The obtained pseudosections were contoured by various chemical parameters such as molar fractions of garnet and Si content of potassic white mica. We used the contoured diagrams to derive the P-T evolution from the above zonation of garnet and potassic white mica.

The early formation of garnet in sample G53 occurred at a pressure of 7.5 kbar and a temperature somewhat above 500°C. At this stage, the garnet core was in equilibrium with the potassic white mica with the highest Si

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content. Subsequently, the metamorphic temperatures increased and the pressures decreased based on the aforementioned zonation of garnet in G53. The P-T field of staurolite was reached probably at a peak temperature of 570°C and a pressure of 4 kbar. This thermal peak is compatible with the composition of the fairly homogeneous garnet in BD6.

The derived P-T path can be explained by a regional metamorphic event during the Variscan orogeny. The metasediments of the Monte Grighini Unit, were buried to depths of about 25 km and, successively, were slowly exhumed to experience moderate heating. At the moment, a similar metamorphic evolution do not seem to be recorded by other metamorphic sequences in the Variscan nappe zone of Sardinia. Indeed, the tectonic units that crop out in the vicinity of the Monte Grighini Complex usually show a lower grade of metamorphism, for instance, in the nearby external Nappe Zone of central Sardinia. Thus, the Monte Grighini Unit will be examined in more detail in the near future in order to obtain new data that allow us to better understand the Variscan metamorphic and tectonic processes in the Nappe Zone of Sardinia.

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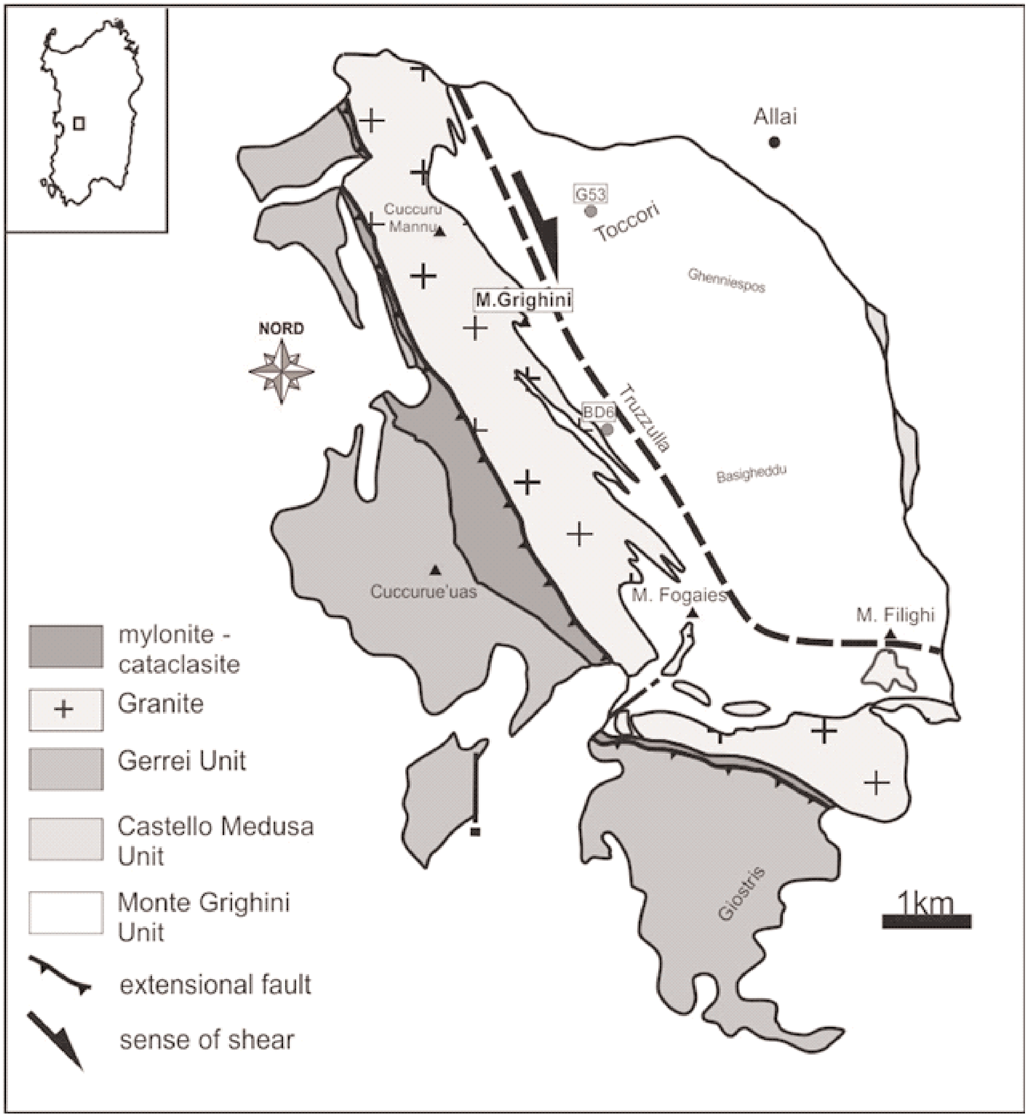

Fig. 1.- Simplified geology of the Monte Grighini Complex in Sardinia (see inlet map) according to Musumeci (1992). Locations of the samples for the detailed study are shown by sample numbers.

The Geodynamics of Pangea Formation

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Introduction

Pangea reached its final shape at the end of the Paleozoic, following a long history of terranes and continents accretion. The timing of these collisions is usually quite well known from sedimentary and metamorphic records, what is less clear is the kinematics of the terranes involved in these collisions.

In a new model developed at UNIL these last 10 years, a database including all possible constraints was used to produce a global plate tectonic model starting at 600 Ma (Hochard, 2008). Geodynamic units (GDU) were defined in the present day according to their geodynamic scenario in space and time, and then assembled as building stones to form terranes. Using the synthetic isochrones methodology (Stampfli & Borel, 2002), plates are reconstructed by adding/removing material, along plate limits. Plate velocities are major constraints in the kinematics of the involved terranes and continents.

This is an iterative process were geological data are always put forwards, but at a certain stage the model is also becoming a predictive tool, enabling to make choices according to plate tectonic principles. Having a global model in hand, it is also possible to derive the main forces acting at the plate boundaries at a given time, and this can be challenged through the analysis of geological data.

The full global model is reached around 520 Ma, enabling the exact measure of oceanic versus continental areas from that time onward. These variations produce the long-term eustatic variations, the eustatic curve derived from the model is very similar to the generally accepted long-term curve from the literature.

Cadomia and Gondwana

Between 600 and 500 Ma, the Cadomian arc system and the continents composing Gondwana were amalgamated. The last Pan-African magmatic events are thus synchronous to the Cadomian ones. The Cadomian arc system was partly derived from North China and Gondwana at first, the arc was link westward with Avalonia and the Amazon craton. Around 540 Ma, all these elements were in collision, forming a proto-Gondwana landmass. It is only after 500 Ma that Gondwana finally included continents such as Antarctica and Australia, and terranes such as the Himalayan domain and Pampia in south America.

This has quite some bearing on zircon distribution, pan-African zircons can also be Cadomian, and old basements are not found only in Africa, but also in China, Australia, etc… This is also the source of very widespread Gondwanan magnetic poles, mainly those older than 500 Ma. We constructed a new wander path for Gondwana, using the worldwide carbonate distribution for the pre Ordovician, then the Hirnantian pole as constrained by all the records of glaciation on Gondwana, and also the main geodynamic events that created kinematic changes, such as the opening of major oceans. But one of the main constraint comes from the velocities implied by such a wander path, we tried to average this to 8-10 cm/y, which is already quite fast for such a large continent.

One of the main challenges of these reconstructions was to find the homeland of small terranes. For the Paleozoic this is even more difficult as some of these terranes have been re-displaced after a former amalgamation. This is where a global plate tectonic model comes of use, as it has some predictive qualities, mainly the necessity to keep continuity and coherency along plate limits. This was done and redone for the last ten years for the blocks involved in the Variscan collision, and the placing of these blocks along the margin of Gondwana.

Northern Gondwana (Von Raumer *et al.*, 2002) was characterised by an active margin setting since the early Ordovician, and by the subsequent opening of the Rheic ocean, after a period of subsidence and rifting behind Avalonia-Hunia (*e.g.* Von Raumer and Stampfli, 2008).

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Consequently, the basement areas of these regions show a strong activity of crustal extension and rifting during the early Ordovician, accompanied by many intrusions. The detachment of Hunia from Gondwana gave birth to the eastern branch of the Rheic ocean, slightly younger (c. 460 Ma) than the western branch (Rheic s.str. c. 480 Ma). In the eastern part of the Gondwana margin, comprising among others the Alpine and Mediterranean domains, the Ordovician active margin started later than in the west and lasted until the Middle/Late Ordovician.

Thus, an overall geodynamic scenario can be constructed through the cessation of magmatic activity north of Gondwana and the diachronous onset of passive margin settings during the Ordovician. Geometries and velocities of tectonic plates at that time are also strongly constraining the origin of Avalonia and Hunia. Avalonia had to be accreted to Baltica-Laurentia and Hunia to North China during the Silurian (Wilhem, 2010).

Opening of Paleotethys

We are departing here from our previous model (Stampfli *et al.*, 2002) where Hunia was considered as the main ribbon like microcontinent leaving Gondwana during the opening of Paleotethys in the Silurian. The Silurian accretion of Hunia to North China implies that this accretion took place when the Paleotethys was not yet opened. Thus, Hunia represents a first train of terranes leaving Gondwana more or less at the same time than Avalonia (during the Ordovician). The second train of terranes leaving Gondwana in the Devonian has been called the Galatian superterrane (Stampfli *et al.*, 2011).

In the late Ordovician, both western and eastern segments of the Rheic made a single oceanic domain. North of Africa, the passive margin of Gondwana became again an active margin during the Devonian. This followed the collision of the passive margin with an intra-oceanic arc (Ligerian) and the partial obduction of the back-arc oceanic crust, followed by subduction reversal. This is well recorded by HP metamorphism corresponding to the eo-Variscan tectonic event (from c. 400 Ma to c. 370 Ma), and the emplacement of Devonian ophiolites along the Gondwana margin in Spain, France and Central Europe. In this suture are also found remnants of older oceans, either the Ordovician Rheic ocean (c. 460 Ma and younger) or older fragments (c. 500 Ma, *e.g.* Arenas *et al.*, 2007, 2009) related to the Qilian arc (part of Hunia left behind) and brought to the surface during the rifting, thus forming the toe of the Gondwanan Ordovician passive margin.

From the upper Ordovician to the Silurian, crustal extension is observed along the Gondwana margin through the sedimentary record, the subsidence patterns, the interruption of sedimentation and the intrusion of basic volcanics at different places (Von Raumer *et al.*, 2008). New monazite age-data (Schulz and von Raumer, 2011) confirm an early Silurian thermal event for the Aiguilles Rouges area. Located along the S-Chinese (Gondwana) margin this area is the witness of the transform type eastern Rheic margin. The emplacement of 450 Ma gabbros at different places and the many early Silurian acidic volcanics of the Noric Terrane, again, are the signature of an extending crust in the Alpine domain; the older ones (450-420 Ma) are related to the eastern Rheic opening, the youngest (410-380 Ma) to the opening Paleotethys (Von Raumer *et al.*, subm).

The Galatian Terrane Accretion To Eurasia

The Galatian superterrane was detached from Gondwana in segments, starting from the west, north of N-Africa with the detachment of the Armorica *s.l.* segment around 400 Ma, then the Ibero-Ligerian fragment after the eo-Variscan collisional event (c.390 Ma) and the Intra-alpine/Mediterranean segment just after (c. 380 Ma). A triple junction was established around the Arabian promontory, corresponding to the three branches of Paleotethys. The Iranian seaway separated the Iranian-Afghan domain from South China, the Sulu-Dabie seaway separated South China from the intra-Alpine/Mediterranean terranes, and the N-African seaway separated Gondwana from Armorica-Iberia.

These oceanic branches were back-arc basins that merged to give the Devonian Paleotethys. During their drifting, the Iberian-Intra-Alpine segment passed behind the Armorican one. This imbrication was even exaggerated when Armorica collided with the Hanseatic arc detached from Eurasia in the late Devonian. Then the most eastern and external part of the Galatian terrane (the Mediterranean blocks *s.l.*, comprising Italy, Greece, Turkey) by-passed the intra-Alpine blocks in a westward rotational movement following the overall kinematics of Gondwana. The Paleotethys mid-ocean ridge had been subducted by now, and a fair amount of coupling was possible between the rotating Gondwana plate and the active margin of Laurasia. Also, slab detachment in the Variscan collision zone allowed for a large amount of right lateral strike slip movement that even exaggerated the duplication of the former ribbon like Galatian superterrane.

Along Laurasia an arc extended from New-Foundland up to the Caspian area, the back-arc basin is represented by the Rhenohercynian oceanic domain in the west and the Paphlagonian pelagic domain in the east (*e.g.* Stampfli and Kozur, 2006). The Hanseatic arc is represented by terranes such as the S-Portuguese, Channel, East-Meseta and Mid-German Rise, and part of the Caucasus and Black-sea in the east. The Hanseatic terranes were imbricated with fragments of the Armorican or Meguma terranes around the Iberian landmass. We follow here the imbrication model of Martínez Catalán *et al.* (2007), where the amalgamated Armorican and Rhenohercynian terranes were indented by the Iberian promontory around 360-350 Ma. Finally in the Late Carboniferous, Gondwana collided with the terranes accreted around Laurasia, given birth to the final Variscan tectonic event.

Similar large ribbon like continental fragments left Laurentia to be accreted until the Triassic to South-America, Australia and Antarctica (the famous SAMFRAU geosyncline of Du Toit). Some large blocks/ribbons were re-detached from this collision zone in the late Carboniferous, to form the future Wrangelia, Stikinia terranes. The latter collided with terranes detached from the Pacific margin of Laurentia already in the Devonian, the detached terranes and the exotic ones will be re-accreted to North America from the Triassic to the Cretaceous, and thus never pertained to Pangea.

The other major blocks that participated to the build up of Pangea were Siberia and the Kazakhstan-Mongolia blocks, forming the pendant of the Variscan orogen in the east, the Altaids. A new model of this complex orogen was developed at Lausanne (Wilhem, 2010; Wilhem *et al.*, subm.), incorporating the latest data from Chinese and Russian colleagues, mainly regarding the ages of metamorphism and magmatism.

Multiple peri-Siberian accretion-collision events took place before the end of the Early Paleozoic. The Mongol-Okhotsk Ocean opened within this new accreted continent in the Early-Middle Paleozoic. The Kazakhstan Continent formed in the Early Silurian in Eastern Gondwana by the accretion-collision of several ribbon-microcontinents and island-arc-type terranes. Most Kazakhstan microcontinents originated in Gondwana from which they were detached in the Vendian to Middle Cambrian. Kazakhstania was finally created from the Arenigian to the Early Silurian. The completed Kazakhstania moved westward toward Siberia and Tarim-North China in the Middle-Late Paleozoic.

From the mid-Paleozoic, Siberia, Tarim-North China and Kazakhstania began to mutually interact. The new plate tectonic arrangements led to oroclinal bending and large-scale rotation of Kazakhstania during the Carboniferous, the main terminal sutures of the Altaids are Permo-Triassic. Following the completion of the Altaids, only the Mongol-Okhotsk remained opened until the Jurassic-Cretaceous. Siberia was not finally welded to Baltica before the end of the Triassic in the Arctic regions.

Conclusions

The global reconstruction model and database elaborated at the Lausanne university using plate tectonic and synthetic isochrone principles was of a great help in constraining geometries and plate velocities. These factors are fundamental when considering the wandering of a large plate such as Gondwana. But this would be useless without the repeated efforts of several generations of field geologists that gathered key information from the whole world, their work is strongly acknowledged here. The Lausanne model is now part of the Neftex Geodynamic Earth Model.

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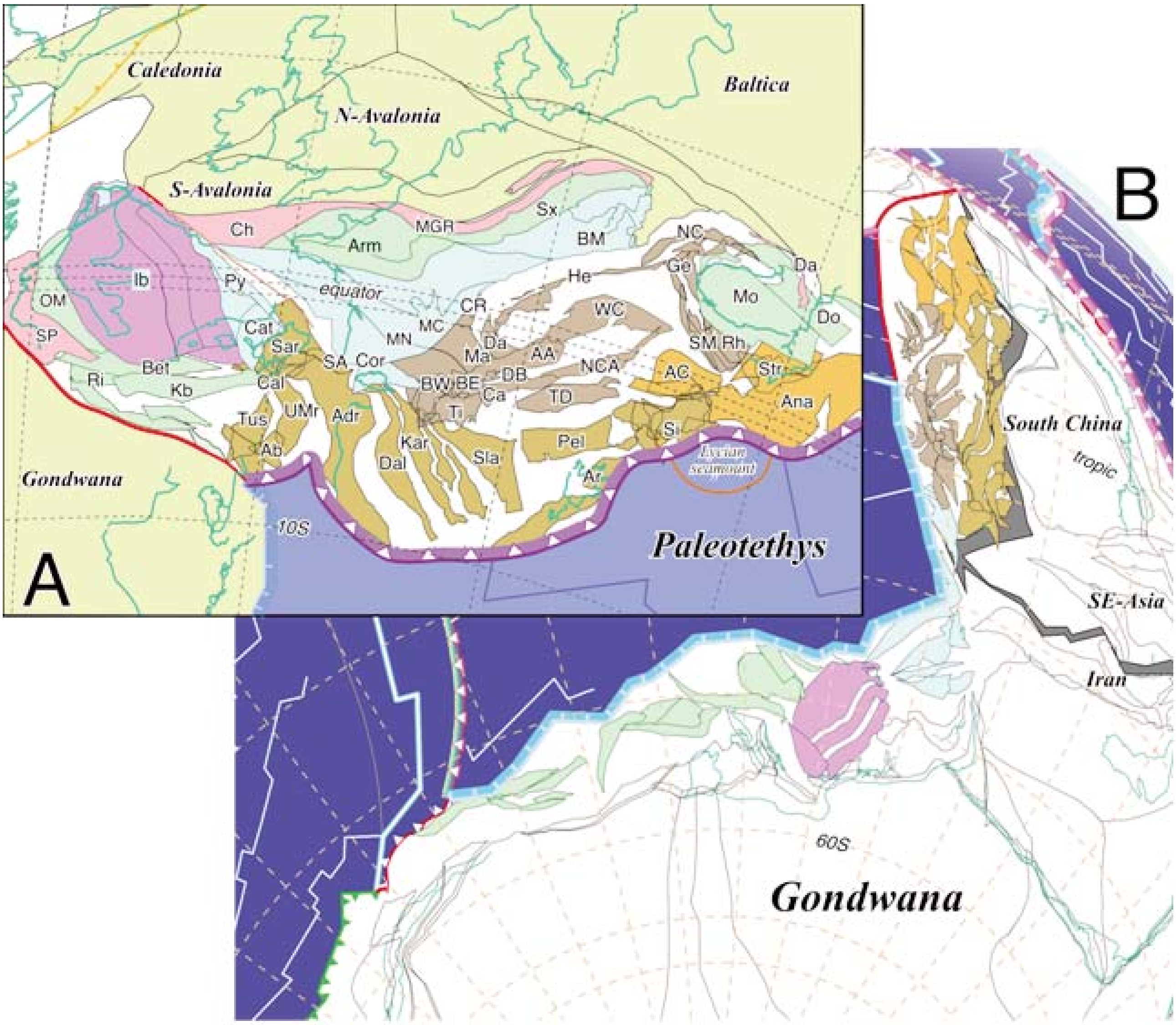

Fig. 1.- A) Distribution of the main Variscan terranes and their GDUs, in their post collisional situation at the end of the Carboniferous (modified from von Raumer et al. subm.) and B) in the Silurian before their detachment from Gondwana (modified from Stampfli et al.*, 2011), dark grey, rift zones.*

1) terrane derived from Laurasia :
- Hanseatic terrane : Ch, Channel; Da, Dacides; MGR, Mid German Rise; SP, South Portuguese;

2) terranes derived from Gondwana, former Galatian superterrane :
- Armorica terrane : Arm, Brittany-Normandy; Bet, Betic; Do, Dobrogea; Kb, Kabbilies; Mo, Moesia; OM, Ossa Morena; Ri, rif; Sx, Saxo-Thuringia.
- Ligerian terrane : BM, Barrandium-Moldanubia; Cat, Catalunya; Cor, Corsica; MC, Massif Central; MN, Montagne Noire; Py, Pyrenees.
- Intra-Alpine terrane : AA, Austroalpine; BE, Briançonnais East; BW, Briançonnais West; Ca, Carnic Alps; CR, Chamrousse; Da, Dauphinois; DB, Dent Blanche; Ge, Getic; He, Helvetic; Ma, Maures; NC, North Carpathians; NCA, Northern Calcareous Alps; Rh, Rhodope; SM, Serbo-Macedonia; Ti, Tisia; TD, Transdanubia; WC, West Carpathians.
- Mycenian terrane : Ab, Abruzzi; Adr - Adria; Ar, Arna; Cal, Calabria; Dal, Dalmatia; Kar, Karst; Pel, Pelagonia; SA, Southern Alps; Sar, Sardinia; Si, Sitia; Sla, Slavonia; Tus, Tuscania; UMr - Umbria-Marche.
- Galatian s.str. terrane: Ana, Anatolia; AC, Attica-Cyclades; Str, Stanja.

The Visean Mg-K magmatism as the result of the involvement of radiogenic heat production in the Variscan internal ("Moldanubian") zone. Evidence from the Vosges Mts (NE France)

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Late Variscan plutonic bodies are widespread in the Central and Southern Vosges Mts (NE France), part of the Moldanubian zone. They can be divided on the basis of age of emplacement into two major plutonic events, one early Visean Mg-K magmatism (345-335 Ma), the other slightly later peraluminous S-type magmatism (330-320 Ma).

The first Mg-K magmatism is also occurring in other Variscan Massifs (e.g. Bohemian Massif, Black Forest, External Crystalline Massif of the Alps and Corsica Batholith). This magmatic event is composed of two main Mg-K groups of intrusions:

i) The Central Vosges Mg-K (CVMg-K) group of intrusions (180km²) is composed of several bodies displaying three main rock types: a mafic end member made of an amphibole-biotite bearing syenite (so called *"durbachite"*) and two silicic end member made of porphyritic amphibole and biotite-bearing melasyenite to melagranite (so called Gagny (1968)'s "dark or black facies") and a porphyritic amphibole-biotite and biotite granite (so called Gagny (1968)'s "light facies or blue facies") that intruded the CVM at very different crustal levels. In their deepest part, CVMg-K plutons form intrusive sheets elongated parallel to NNE-SSW vertical fabrics of the hosting lower crustal felsic granulite and the so-called monotonous and varied gneissic units whereas some small stocks display intrusive contact in the very upper crustal Visean sediments of the Markstein Unit.

ii) The South Vosges Mg-K (SVMg-K) group of intrusions (260 km²) comprises three main rock types from plutonic main porphyritic type monzogranite (*Ballons granite*) and amphibole-biotite monzonite that represents mafic end member of its northern margin (Pagel, 1981), to high plutonic fine-grained type (*Corravillers granite*) to volcanic *"Molkenrain massif"* (Coulon, 1977; Coulon *et al.*, 1979; Schaltegger *et al.*, 1996). SVMg-K plutons were arranged according to E-W striking bodies intrusive only in the upper crustal Visean volcanosedimentary sequence of the Oderen Unit. The volcanic intrusion of the Molkenrain outcrops to the south and east of the *"Ballons granite"* and rocks composition ranges from high-K andesite to trachyte and rhyolite.

These Mg-K associations are characterized by K-feldspar megacrysts and augitic clinopyroxene, actinotic amphibole and biotite. Plagioclase shows composition ranging from labradorite (An60) for mafic rocks to albite (An5) for felsic rocks and zonation is very weak. XMg (0.60-0.65 for CVMg-K and 0.50-0.60 for SVMg-K) in biotite remains rather constant, according to increasing SiO_2 that is a characteristic feature of Mg-K magmatism. The REE content decreases according to increasing SiO_2 content and this trend characterises Mg-K associations where the REE content is controlled by mineral fractionation rather than differentiation of a melt. The high contents in Cr and Ni point to derivation from a mantle source. However, trace elements patterns show strong enrichment in light Rare Earth elements (LREE) $((Ce/Yb)_{NC}$ = 13-30 for CVMg-K and $Ce/Yb)_{NC}$ = 9-15 for SVMg-K), elevated concentrations of U, Th, large ion lithophile elements (LILE), depletion in Ti, Nb and Ta and weak Eu anomalies (Eu/Eu* = 0.6 for CVMg-K and Eu/Eu* = 0.7 for SVMg-K). Primitive mantle-normalized trace-elements patterns highlight a difference between the two associations: CVMg-K association is characterized by a pronounced negative Sr anomaly whereas SVMg-K association shows a pronounced negative P anomaly. This geochemical discrimination fits with Nd and $^{87}Sr/^{86}Sr$ values. Nd isotopic value with initial εNd ~ -7 for CVMg-K and εNd = +1.4- -5 for SVMg-K and Sr initial ratios $0.710<^{87}Sr/^{86}Sr<0.714$ for CVMg-K and $0.705<^{87}Sr/^{86}Sr<0.708$ for SVMg-K resemble continental crust. CV- and SV-MgK were generated in the same TP conditions from different protoliths respectively Neoproterozoic and Ordovician according to age of inherited zircon.

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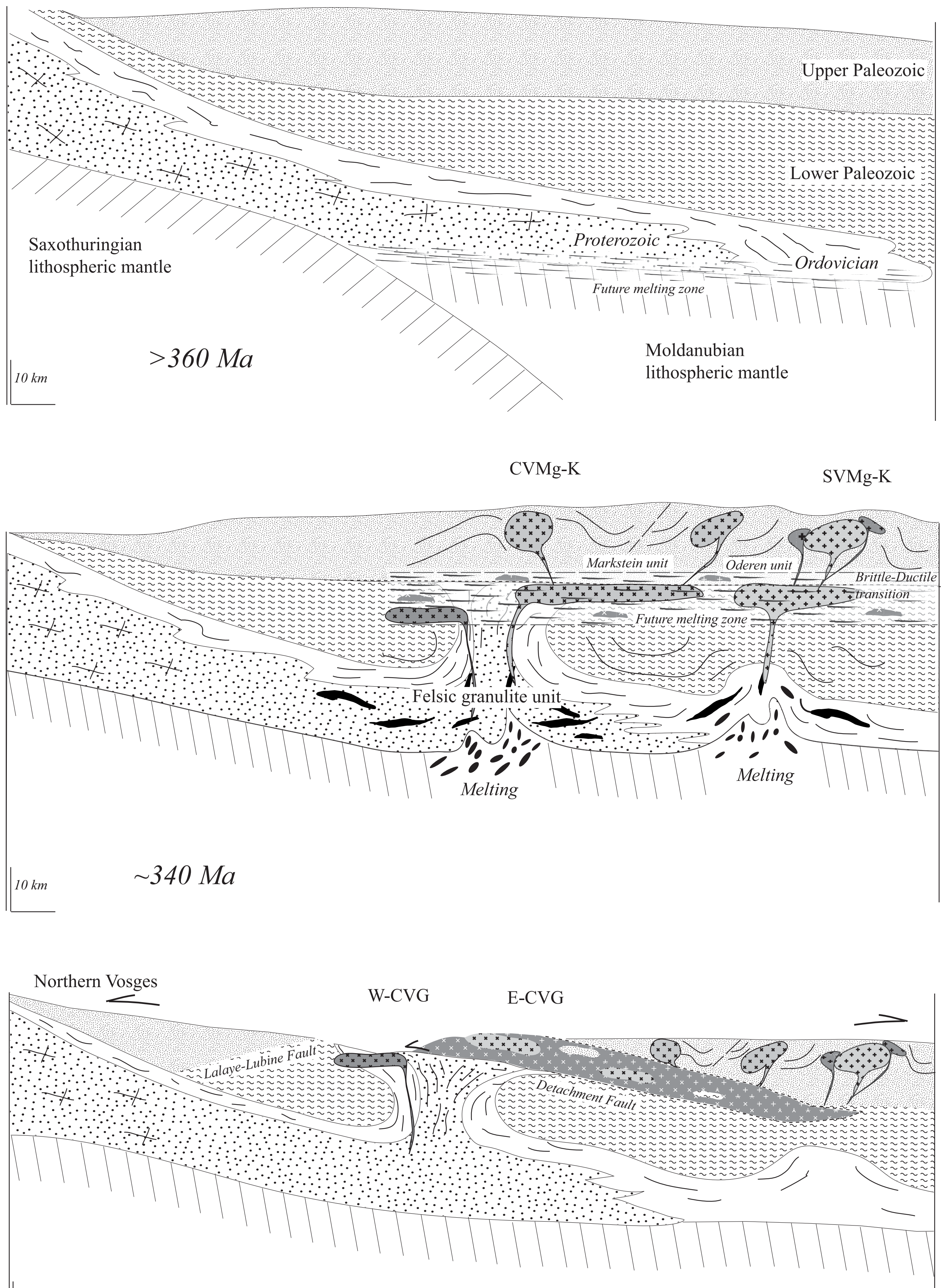
The genesis of Mg-K associations have been interpreted at the light of their close association with HT/HP metamorphism (Janousek and Holub, 2007) and be related with a slab break off where magmas were originated from mantle domains which were previously metasomatized/ contaminated by mature crustal material and melted by advected heat from the asthenosphere (Janousek and Holub, 2007).

The second peraluminous S-type magmatism represented by the Central Vosges Granite (so called *Fundamental granite*; Von Eller, 1961; Hameurt, 1967) was emplaced between 330 Ma (northern part; Schaltegger *et al.*, 1999; Kratinova *et al.*, 2007) to 320 Ma (southern part) and outcrops in the largest part of the Central Vosges Mts. This peraluminous "S-type" magmatism (860 km²) has to be divided according to field observations, ASM data, zircon inheritance, geochemical and isotopic data into two subgroups on each side of the Ste-Marie-aux-Mines - Bilstein Fault zone (Eastern-CVG and Western-CVG). CVG is characterized by small-sized crystals of K-feldspar, weakly zoned plagioclase (An25-An0). XMg (0.40-0.60) in biotite decreases with increasing of host rocks SiO_2 content. The rocks of CVG are about tens Ma younger than Mg-K but they are also characterized by a high content in LILE and show high REE fractionation ($(Ce/Yb)_{NC}$ = 4-30) but display a significant negative Eu anomaly (Eu/Eu* = 0.3-0.7). As for Mg-K associations, trace-elements patterns of E-CVG are characterized by a negative P anomaly whereas those of W-CVG show a negative Sr anomaly. Isotopic data of CVG bridge compositions between felsic SVMg-K and CVMg-K associations for Eastern part and intermediaire isotopic composition between mafic CVMg-K association and granulite and gneisses of Vosges Mts.

The new petrological, geochemical and isotopic data of Vosgian Mg-K rocks highlight the existence of two groups of Mg-K intrusions in the Variscan orogeny which might be related to the nature of the source of the magmas *e.g.* an enriched mantle-derived magma contaminated by in one hand mature and in other hand juvenile crustal material. Thus, a new geodynamic scenario which involves radiogenic heat production from subducted Saxothuringian continental crust under Moldanubian continental crust is proposed to explain petrological, geochemical and isotopic differences. The intrusion of Mg-K magma in middle crust could have shortly after involved partial melting of surrounding country rocks thanks to a huge radiogenic heat production and could have formed the CVG magma at 330 Ma.


Upper Paleozoic
Lower Paleozoic
Saxothuringian
lithospheric mantle
Proterozoic
Ordovician
Future melting zone
>360 Ma
Moldanubian
lithospheric mantle
10 km
CVMg-K
SVMg-K
Markstein unit
Oderen unit
Brittle-Ductile
transition
Future melting zone
Felsic granulite unit
Melting
Melting
10 km
~340 Ma
Northern Vosges
W-CVG
E-CVG
Lalaye-Lubine Fault
Detachment Fault
10 km
~320 Ma

Perunica microplate in Silurian period: implications from basalt geochemistry, palaeomagnetism and faunas (Prague Basin, Teplá-Barrandian Unit, Bohemian Massif)

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Introduction

Two palaeogeographic concepts exist for the Silurian development of the Teplá-Barrandian Unit (TBU, Bohemian Massif): (1) It may represent an isolated peri-Gondwanan microplate called Perunica [1], whose palaeolatitudes changed from ca. 40° S to 25° S over the time period from 440 Ma to 420 Ma [2] or (2) there was no such an independent terrane, the TBU was never widely separated from the adjacent Saxothuringian and Moldanubian units, and remained at palaeolatitudes 45° S till 420 Ma [3]. Current research integrates chemistry of synsedimentary basaltic volcanism and palaeomagnetic data from Silurian volcano-sedimentary complexes of the Prague Basin with relevant palaeobiogeographic models to solve this long-standing controversy.

Basalt geochemistry

After a gap in Late Ordovician-early Silurian (Katian-Rhuddanian), the basaltic volcanism of the Prague Basin revived in the late Aeronian (Llandovery) and, in particular, in Sheinwoodian (Wenlock). The volcanic activity carried on till late Silurian (Ludlow) and, scarcely, Early Devonian. The olivine basalt magma ascended along several deep-seated, ENE-WSW and WNW-ESE trending faults [4], which divided the basin into five major tectonic segments associated with their own volcanic centres.

Sheinwoodian-Gorstian effusive basalts (428-421 Ma) have alkaline character with steep REE patterns (LaN/YbN~3.8-13.5), high LILE abundances, no Eu anomalies, low Zr/Nb ratios (5.4-10.9) and positive Ti anomalies in NMORB-normalized spiderplots [5]. The whole-rock chemical signatures with fairly positive $\varepsilon^{Nd}{}_{425\ Ma}$ values (+6.9 to +5.2) point to a character transitional between EMORB and OIB. Furthermore, correlations of Nd isotopic data with independent geochemical parameters (*e.g.*, mg#, Zr/Nb, 1/Nd, Ni) not only demonstrate an important role for open-system processes such as crustal contamination, but also show relative independence of individual tectonic segments (e.g. volcanic centres). Intrusions into sedimentary strata of Hirnantian-Gorstian (late Ordovician-early Ludlow) age display geochemical signatures alike the effusive basalts. The only exception seems Ba and Sr, enriched in the intrusive basalts most likely due to hydrothermal fluid alteration.

High degree of REE fractionation and low HREE abundances in Silurian basalts suggest an origin by a low-degree partial melting of garnet peridotite mantle source. Their incompatible element ratios [6] and Nd isotopic signatures correspond to a within-plate (oceanic island or intra-continental rift) setting. Given the geochemical variation in basalts and the well documented existence of Neoproterozoic continental basement, the geotectonic setting for the Prague Basin in the Silurian times can be characterized by progressive attenuation and rifting of continental lithosphere connected with asthenospheric mantle upwelling.

Palaeomagnetism

Palaeomagnetic analyses performed on Silurian basalts, their contact aureoles and surrounding rocks involved: (1) progressive thermal demagnetization using the MAVACS (Magnetic Vacuum Control System) [7] equipment with step intervals of 60 to 40 °C, (2) demagnetization by Alternating Field (AF) technique using Superconducting Rock Magnetometer type 755 4 K with steps every 5 to 20 mT, (3) separation of the remanent magnetization (RM) components with the help of the multi-component analysis [8].

Two RM components were extracted from specimens. Component C1 is established by temperature range 160 and 440 ºC (480 ºC) and by AF field range of 10(20)-80(100) mT, probably reflecting the presence of magnetite or Ti-magnetite, with a component of magnetization (D = 138-217º, I = -27-46º). On the other hand, component C2

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belongs to temperature range 80-440 ºC (540 ºC) and/or AF field range 10–80(100) mT, probably reflecting magnetite or Ti-magnetite presence. Tilt-corrected mean direction of RM (D = 194-228º, I = 20-38º) corresponds to Permian or Triassic direction for the Bohemian Massif (with no significant rotation).

Hence, the following consequences must be taken into account while interpreting the dataset to establish palaeolatitudes: (1) fitting the Silurian directions [compared with the results from surrounding sedimentary strata (D = 205º, I = -28º)] resulted in palaeorotation of 160-175º [9, 10], and (2) the magnetization measured in Silurian volcanic rocks of the Prague Basin is likely to represent Permian to Triassic overprint.

Palaeolatitudes calculated from C1 component of the Prague Basin volcanic rocks fall in the interval of 16-28º S. Direction of component C2 suggests compatibility with palaeomagnetic results already known for the Permian period [11, 12].

Palaeobiogeography

Silurian faunas of European peri-Gondwanan terrains, and Avalonia and Baltica continents are well known, which enables independent testing of palaeogeographic reconstructions. Silurian communities inhabiting Prague Basin exhibit mixing of peri-Gondwanan (cooler water) and Baltic-Avalonian-Laurentian (tropical) faunas. Faunas of shallow water environment above the wave base are dominated with brachiopods, trilobites and, in particular, corals and stromatoporoids. Recurrent atrypid-dominated communities have their analogies in Baltica and Laurentia [13] although consisted mainly of endemic species. Similarly, the bivalve-dominated communities, which occupied high-energy environments on top of submarine volcanic highs in Wenlock and Ludlow, resemble Baltic faunas [14]. Corals and stromatoporoids, however, form only small patchy populations in contrast to reefs in Gotland or Avalonia.

Cephalopod limestone biofacies below the wave base, influenced by surface currents, contain bivalve-cephalopod faunas. Bivalve communities strongly resemble homological communities known from peri-Gondwanan basins, although Bohemian faunas are more diverse [15]. Pelagic and nektic cephalopods are also shared between peri-Gondwana and Prague Basin. Nevertheless, cephalopod limestones from Prague Basin contain diverse nautiloids with affinity to Baltica, Avalonia, and Laurentia. Even though many species are shared, numerous endemic nautiloids also originated in the Prague Basin. On the contrary, only rare nautiloids occurred in peri-Gondwanan basins, probably representing occasional visitors of Bohemian origin [16]. Off-shore faunas of the Prague Basin were characterized by largely cosmopolitan graptolites with some elements shared with either peri-Gondwana, Baltica or both. Nektic phyllocarid *Ceratiocaris papilio* in Ludfordian is otherwise known from Laurentia-Avalonia [17].

Taken together, the faunas of Prague Basin exhibit strong affinity to tropical faunas, in which respect they differ from typical peri-Gondwanan faunas. Prague Basin occurred in subtropical realm and was reached by south tropical current close to its southern termination. Faunas were formed by immigrants from tropical zone as anoxic conditions of early Silurian subsequently declined due activation of sea currents. Rather specific character of faunas and their stepwise expansion reflect combination of dispersion strategy, adaptability of immigrants and climatic and eustatic oscillation, *i.e.* opening/closure of migration pathways and sea current system changes.

Conclusions

In summary: (1) chemistry of basalts reflects within-plate setting with progressive attenuation and rifting of continental lithosphere (extensional regime), (2) palaeolatitudes obtained from palaeomagnetic measurements of Silurian volcano-sedimentary complexes of the Prague Basin fall within the interval of 16-28º S, and (3) faunas correspond well with the Prague Basin's position near 25° S, SW of Baltica and rather far detached from peri-Gondwanan basins. Thus, our results are consistent with the original concept of independent Perunica microplate [1], rather isolated from other Gondwana-derived terrains of the Variscan Europe.

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Modelling the genesis of the Velay granite (Eastern French Massif Central) - a thermodynamic approach

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The Velay Migmatitic Complex (Eastern French Massif Central) recorded successive partial melting events (Montel *et al.*, 1992), known as M3 (720°C and 5 kb) at 314 Ma and M4 (850°C and 4 kb) at 301 Ma (Montel *et al.*, 1992). The Velay dome is cored by a peraluminous (S-type) granite likely to be derived from a metasedimentary source. As most S-type granites, the Velay granite is characterized by important compositional variations for instance in Fe + Mg (maficity) or peraluminousity (A/CNK). The migmatites are considered to be part of the source of the granite. Thus the granite might have been formed during the melting stages recorded in M3 and M4.

Petrological modeling based on thermodynamic database (Holland and Powell, 2001), provides an interesting tool to study partial melting and melt composition. In the case of the Velay Complex we have been able to link the melting of a metapelite to metagreywacke source to the variation of composition observed in the granite. Additionally, the step-wise extraction of melt composition from source during calculation, allowed us to determine the compositional evolution of the solid residuum as well as mineral proportion and composition.

Results of modeling show that, despite incertitude related to the thermodynamic database and phase model definition, the composition of melt calculated matches the composition of the less ferromagnesian granites. It also shows that the composition variability of the granite can be directly linked to the change of melting reaction within the source. For instance, changes of maficity and XMg in the granite can be reproduced by adding up to 30 % of peritectic cordierite (produced in the source along with melt) to the corresponding melt (*i.e.* formed at the same P and T conditions). In the same way, Al, Na and K variations are directly linked to changes in melting reaction stoichiometry and the composition of melt obtained from calculations is very similar to the Al, Na and K composition of the granite.

Furthermore, the variations of residuum mineral composition indicate that at temperature above biotite stability the residuum have compositions extremely close to regional felsic granulitic xenoliths (described by Leyreloup, 1973). Altogether the amount of melt produced and extracted from the source does not exceed 20 %.Vol. This suggests that the volume of the residuum is 4 to 5 times larger the quantity of granite produced between M3 and M4. However, this last result is subject to uncertainties as the amount of melt produced is highly dependent to parameters used in the calculation such as H_2O, P-T conditions and melt behavior (extraction from the source or in-situ accumulation).

Finally, using petrological modeling based on thermodynamic database we have been able to reproduce the Velay granite compositional variation. These results imply that 1.) Granite composition images the composition of the source 2.) Compositional variability in the granite is the result of changes of melting reactions within the source.

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Age, distribution, nature, origin, and environmental impact of the Permo-Carboniferous European Northwestern-African magmatic province

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The so-called European Northwestern-African Magmatic Province (EUNWA, Fig. 1) (*e.g.*, Doblas *et al.*, 1998; see also Wilson *et al.*, 2004) was emplaced during Permo-Carboniferous- times, and has been linked to the gravitational collapse of the previously thickened and weakened Hercynian (Variscan) orogenic belt (the initial stages of the disruption of the Pangean supercontinent). The whole Variscan edifice collapsed through simple-pure shear low-angle extensional detachments during the late Variscan, giving rise to Basin and Range type extensional province in Europe, and northwestern Africa involving major low angle detachment faulting, unroofing of large metamorphic core complexes, and syn-extensional plutonic bodies, dyke and sill swarms and volcanic successions (*e.g.*, Doblas *et al.*, 1994). Coevally with an extensional scenario, Europe, and northwestern Africa were affected by a complex system of conjugate strike slips faults (NE-SW sinistral and NW-SE dextral) which partially disrupted the Variscan edifice, resulting in a new Permo-Carboniferous stress pattern with a N-S-oriented principal compressional axis (Arthaud and Matte, 1975; 1977). This episode was accompanied by sediment deposition and volcanism in transtensional and pull-apart basins (Youbi *et al.*, 1995; Doblas *et al.*, 1998), resulting from dextral transcurrent movements along an intracontinental zone located between Gondwana and Laurussia following an early proposal of Van Hilten (1964), later reinterpreted by Arthaud and Matte (1975; 1977). A whole range of chronometers have been applied to determine eruption ages from the EUNWA's magmatic rocks (*e.g.*, Timmerman *et al.*, 2009): Rb-Sr and K-Ar (whole-rock), $^{40}Ar/^{39}Ar$ (mineral separates) and U-Pb (zircon, titanite and perovskite). The duration of magmatic activity is currently estimated to span a period of ca. 100 million years, from the Early Carboniferous to the Upper Permian-Early Triassic (350-250 Ma), with several hiatuses in between (Upton *et al.*, 2004). Three main pulses can be distinguished at ca. 300 Ma, 290-275 Ma, and 250 Ma, and, in fact, each of these pulses can be considered a separate LIPs within the overall EUNWA event. These eruptive cycles are well represented in northwestern Africa (Morocco) and in southern Scandinavia and northern Germany. The huge volume of extruded and intruded magmatic products of the EUNWA magmatic province (example in the Oslo Graben, the estimated volume is at ca. 35,000 km^3 while in the North German Basin, the total volume of felsic volcanic rocks, mainly rhyolites and rhyodacites, was of the order of 48,000 km^3) has led to suggestions of a thermally anomalous mantle plume to explain this ca. 300 Ma pulse of magmatism (Ernst and Buchan, 1997; Torsvik *et al.*, 2008). In addition the 290-275 Ma and 250 Ma magmatic pulses would correlate with major LIPs in central and northern Asia, the 290-275 Ma Tarim and the 250 Ma Siberian LIPs (*e.g.*, Pirajno *et al.*, 2009). A significant detractor from a 300 Ma plume hypothesis is the helium isotope signature of lithospheric mantle xenoliths from the Scottish Permo-Carboniferous dykes, sills and vents (Kirstein *et al.*, 2004).

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The EUNWA magmatic province may have contributed to the great Gondwanan glaciation that occurred from the Late Devonian to the Late Permian (Veevers and Powell, 1987; Crowell, 1999; Isbell *et al.*, 2003). Glaciers achieved their maximum paleolatitudinal range between the middle Stephanian (ca. 305 Ma ago) and near the end of the Sakmarian (ca. 284 Ma ago) (Isbell *et al.*, 2003). This is the so-called icehouse-silicic large igneous province (SLIP) hypothesis (Cather *et al.*, 2009).

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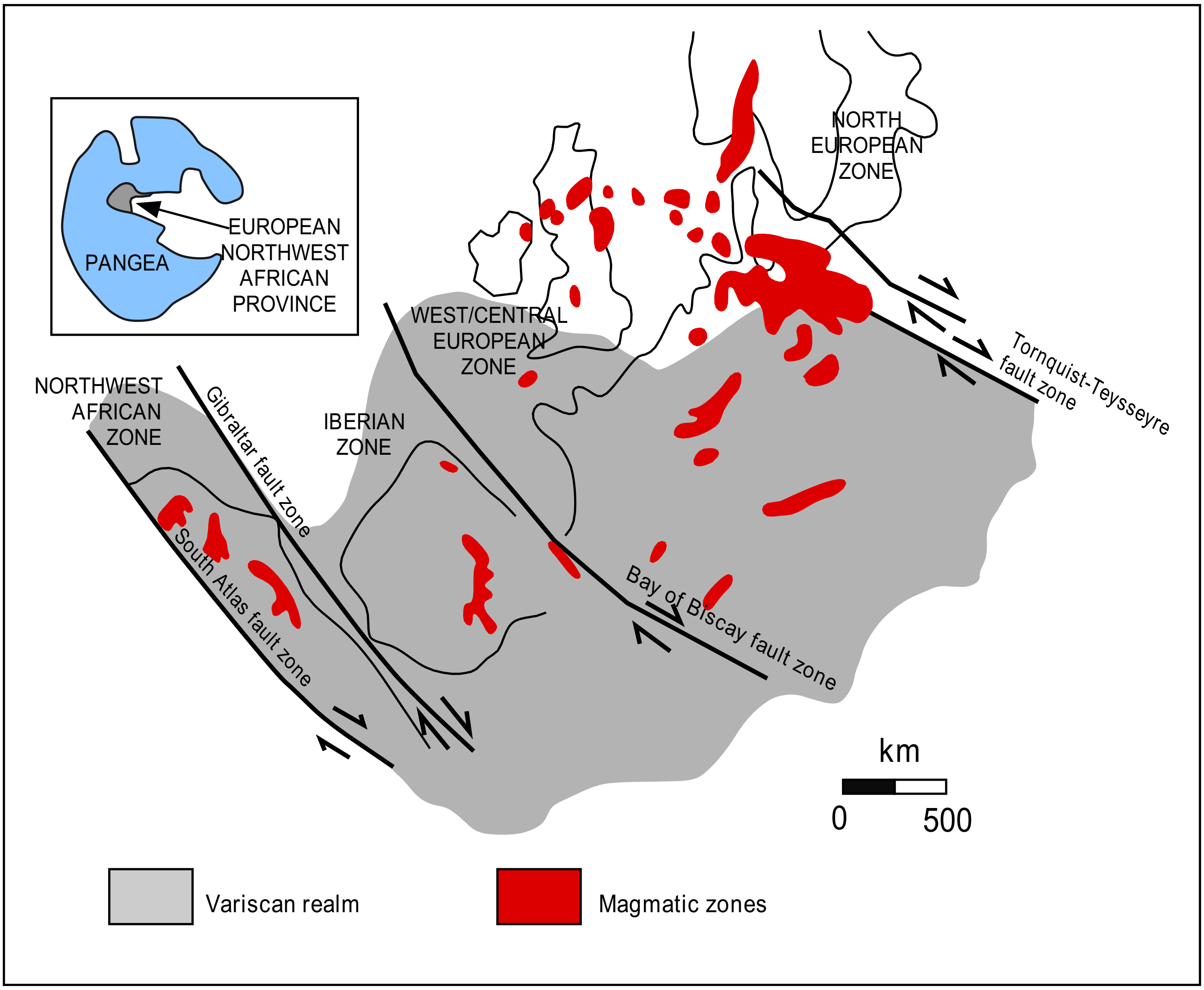

Fig. 1.- Schematic diagram depicting the Permo-Carboniferous-European northwestern-African magmatic province in the centre of the Pangean supercontinent (Doblas et al.*, 1998). Four lithospheric megablocks are defined, bounded by major dextral fracture zones (Bay of Biscay Fault Zone, Gibraltar Fault Zone, South Atlas Fault Zone and Tornquist-Teysseyre Fault Zone).*

Permian thinning of the Southalpine Variscan crust: insights by metamorphic pebbles and cobbles from post-orogenic conglomerates

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This contribution shows a method to constrain timing and modality of late orogenic collapse exploiting the geologic memory of pebbles and cobbles from their erosive clastic products.

In the crystalline basement of the Central Southern Alps (CSA; Fig. 1), mapped tectono-metamorphic units testify various stages of the Variscan convergence (*e.g.* Spalla & Gosso, 1999; Spalla *et al.*, 2005). The basement is non-conformably overlaid by Lower Permian continental sequences that filled Post-Variscan intramontane basins (Fig. 1), formed within a dextral transform zone (Bertoluzza & Perotti, 1997; Cassinis *et al.*, 2012). This transtensional tectonics announces the lithospheric thinning leading to Neothethys opening (*e.g.* Marotta *et al.*, 2009). Among these volcano-clastic sequences, syn-tectonic conglomerates (*e.g.* Berra & Felletti, 2011) represent alluvial fan deposits interbedded with lacustrine sediments (Cadel *et al.*, 1996; Gianotti *et al.*, 2001; Ori *et al.*, 1988).

Micro-structural, micro-chemical data, and superposed metamorphic assemblages have been derived in metamorphic pebbles and cobbles from the conglomerates. On this ground quantitative P-T paths of conglomerate basement sources were reconstructed and compared with those of the presently exposed tectono-metamorphic units (Fig. 1), shedding light on which type of tectonic unit from the Variscan basement was being eroded to feed intramontane basins in the Lower Permian.

This analysis has been performed on metamorphic pebbles and cobbles-rich conglomerates belonging to the Trompia and Orobic basins: namely the Dosso dei Galli Conglomerate (DGC) in the Trompia basin (Spalla *et al.*, 2009), conglomerates of Pizzo del Diavolo Formation (PDC) in the Eastern Orobic basin (Zanoni *et al.*, 2010), and Ponteranica Formation (PF) in the Western Orobic basin. Radiometric data on volcanics constrain the age of DGC at about between 283-280 Ma (Schaltegger & Brack, 2007), while a pyroclastic layer constraints the PDC age at about 278 Ma (Cadel, 1986). The Ponteranica Formation has been correlated to the Collio Formation of the Trompia basin (Nicosia *et al.*, 2000; Gianotti *et al.*, 2001). Pebbles and cobbles have been selected in order to avoid alteration and to have access to as much as possible rock types, superposed structures, and metamorphic assemblages.

Our results indicate that:

1) the P-T evolution of DGC pebbles and cobbles is coherent with the metamorphic evolution of the adjacent Tre Valli Bresciane Massif (Giobbi Origoni & Gregnanin, 1983). T_{max}-PT_{max} imprint reflects thermal gradients lower than the steady state geotherm and is compatible with the Variscan tectonic burial (Spalla *et al.*, 2009);

2) PDC pebbles and cobbles record two P-T paths compatible with that of the adjacent Val Vedello Basement and with that of NEOB (= North Eastern Orobic Basement)-B and NEOB-C tectono-metamorphic units (Spalla & Gosso, 1999). The T_{max}-PT_{max} imprint of both P-T paths is compatible with the Variscan collision, but recorded at different crustal level (Zanoni *et al.*, 2010);

3) PF pebbles and cobbles record two P-T paths both characterised by T_{max}-PT_{max} reflecting the Variscan collision at similar crustal condition. One path is similar to that of the adjacent Monte Muggio Zone (Spalla & Gosso, 1999). The other one records a HT-LP metamorphic re-equilibration postdating the Tmax-PTmax imprint and testifying a thermal regime ascribable to the exhumation of this Variscan basement during the Val Biandino pluton emplacement.

Pebbles and cobbles of intrusive rocks from Val Biandino pluton, whose youngest products are dated at 277 Ma (*e.g.* Thöni *et al.*, 1992), and of tourmaline-bearing breccias rejuvenate the PF age, as interpreted in the literature. In the central portion of the Orobic anticline tourmalinites have been dated between 249 and 240 Ma (Cadel *et al.*, 1987).

The conglomerate basement sources generally correspond to the basement units presently adjacent to the

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clastic sequences (Fig. 1) with the exception of PDC, where one of the two metamorphic sources could be one of the shallow tectonic units presently surfacing about 30 km away. An alternative explanation is the occurrence of a source, now completely eroded, which was exposed at the Permian times together with the tectono-metamorphic units occurring at present in the Val Vedello area.

Pebbles escaping the imprint related to the thermal relaxation induced by Variscan collision belong to the older DGC that occurs in the eastern part of CSA. The more mature orogenic thermal imprints are recorded in pebbles of the younger PF conglomerates outcropping in the western part of CSA. This indicates a westward rejuvenation of the exhumed basement units and suggests the migration of the extension triggering the deposition of these conglomerates; the same direction of the Permian crustal thinning propagation, anticipating the Triassic oceanisation, can be envisaged. This agrees with the opening direction propagation reconstructed for the Neotethys (*e.g.* Stampfli & Borel, 2002; Muttoni *et al.*, 2003) and with stratigraphical correlations between the present Oman and Spain regions, showing a westward marine ingression during Permian times (*e.g.* Cassinis & Neri, 1999; Angiolini *et al.*, 2003; Crasquin-Soleau *et al.*, 2004; Bourquin *et al.*, 2010).

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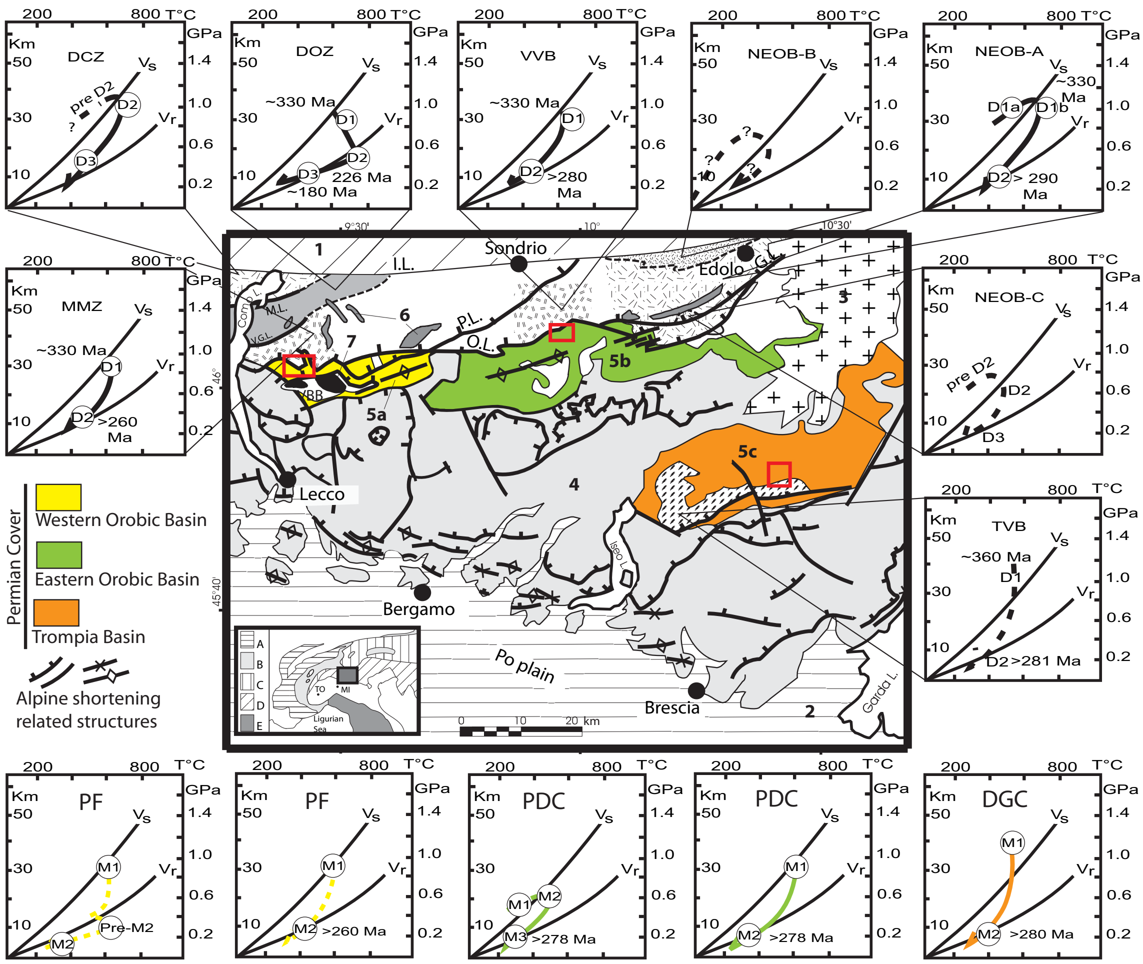

Fig. 1.- Crystalline basement of the Southern alpes.

Strain analysis, microstructure and rheological modeling of orthogneisses from two different thermal levels (Saxothuringian domain in Bohemian Massif)

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The rheological behavior of the felsic crust is frequently approximated by flow laws for quartz (*e.g.* Kronenberg and Tullis, 1984) or melt bearing quartz aggregates (Gleason and Tullis, 1995; Beaumont, 2001; Culshaw *et al.*, 2006) although it consists of polyphase mixtures of mineral aggregates, namely quartz, plagioclase and K-feldspar. Flow laws of polyphase rocks depend on flow laws of the constituent phases, their volume fractions and microstructures and were modeled for two-phase mixtures (*e.g.* Tullis *et al.*, 1991; Ji and Zhao, 1993; Ji and Xia, 2002). In our study, we combine the strain analysis of orthogneiss samples with microstructural and textural analysis to explain, how different deformation conditions influence the mutual mechanical behavior of quartz and feldspar. To analyze the degree of deformation partitioning between these minerals, we compare their viscosity ratios calculated from XZ sections of the deformation ellipsoid with a simple rheological self-consistent model. This model, developed by Treagus (2001), is based on Eshelby's (1957) analysis of deforming isotropic, two-dimensional and two phase mixture of Newtonian elliptical inclusions in Newtonian matrix.

We studied orthogneiss samples in Czech Republic from two different crustal units that were derived from the Tepla-Barrandian/Moldanubian microplate and thrust on the Saxothuringian domain during Variscan collision. Metamorphic conditions in the first unit, "Lower crystalline nappe" (LCN), were estimated at ca 600ºC and 1400 MPa (Konopásek and Schulmann, 2005). In contrast, the second unit - "Upper crystalline nappe" - reveals conditions 700 ± 20°C and 900 ± 100 MPa (Závada *et al.*, 2007). In LCN, orthogneisses are typical with K-feldspars that form rectangular shaped augens with domino-type disintegration along the perthite zones. These porphyroclasts are surrounded by a matrix of plagioclase and quartz ribbons. Strength of the LCN orthogneiss is strongly reduced by partial replacement of K-feldspar and complete replacement of plagioclase by fine-grained (10 µm) aggregate of albite-oligoclase grains (with interstitial quartz and mica grains). The latter is attributed to host-controlled nucleation of new grains that promotes grain-boundary sliding (GBS) of plagioclase during progressive deformation. In UCN orthogneiss, both feldspars show extremely elongated monomineralic bands enclosing only weakly elongated quartz lenses. The inversion of the viscosity contrast between K-feldspar and quartz from the „cooler" LCN unit to "hotter" UCN unit is explained by the melt-enhanced grain boundary sliding (GBS) for feldspars in contrast to quartz that deformed by dislocation creep for UCN.

For the rheological analysis of the LCN orthogneisses in light of the self-consistent model, quartz and plagioclase are regarded together as a matrix or interconnected weak layer - IWL (Handy, 1994) and K-feldspar as the inclusion forming competent phase. This simplification is justified by similar strain intensities of plagioclase and quartz in this unit. For the UCN orthogneiss, both feldspars forming the IWL are combined and their average strain intensity is compared with apparently competent quartz. This comparison of naturally strained rocks with a simplifed theoretical model describing mutual deformation of ideal Newtonian viscous fluids revealed interesting results. While viscosity ratio of LCN orthogneisses are systematically higher than predicted by the model, for the UCN orthogneisses, relative elongation of feldspars in contrast to quartz are approximated quite well. The mismatch between model and reality for the LCN unit is explained by only partial recrystallization of K-feldspars and elastic response of the cores of augens embedded within viscously deforming matrix of plagioclase and quartz. The almost perfect agreement between model and strained UCN orthogneisses likely reflects that the matrix - feldspars indeed deformed as a Newtonian viscous medium, as is predicted for GBS accomodated diffusion creep (Ranalli, 1995). These results highlight the strongly constrasting response of felsic crust during the collision at different crustal levels, typical with anastomozing shear zones and sigmoidal augens for the deeper levels of the superstructure and weak, ductile and

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mobile felsic rocks of the infrastructure that extrude along the suture zones of the colliding crustal blocks (Schulmann *et al.*, 2008; Jamieson *et al.*, 2011).

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Carboniferous to Permian migmatite formation in the Austroalpine continental basement (Valpelline unit) and its implication for the onset of the Alpine convergence

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The Valpelline unit is a km-sized slice of continental crust constituting part of the Austroalpine Dent Blanche nappe (NW Italy). The pre-Alpine evolution of this unit holds important clues for the Palaeozoic crustal structure at the northern margin of the Adria continent, for the history of rifting in the Alpine region, and thus for the thermo-mechanical regime that preceded the onset of the Alpine convergence (Gardien *et al.*, 1994; Manzotti, 2011; Manzotti *et al.*, accepted).

Reconstructed pre-Alpine P-T-d-t paths (Manzotti and Zucali, accepted) demonstrate that the Valpelline unit experienced an early re-equilibration under intermediate pressures amphibolite facies conditions and a following migmatite stage. This latter deeply influenced the rheology of deforming rocks during Carboniferous and Permian times, mainly due to viscosity and fabric gradients generated by the heterogeneous distribution of melt and restitic volumes. During migmatisation the most penetrative fabrics affecting all of the Valpelline lithotypes developed (Fig. 1).U-Pb dating of accessory phases indicates a Carboniferous to Permian age for the migmatite formation, which is followed by a granulite-amphibolite to greenschists facies transition from Permian to Triassic accounting for an exhumation associated with cooling.

The amount of melt is qualitatively estimated from meso- and microscopic observations and constrained evaluating assemblages compatibilities by thermodynamic modelling. The results, together with the geometry of leucosome nets, show that km-scale mechanical heterogeneities may have been produced during the Permian migmatite formation, which will cause crustal-scale density and fabric discontinuities able to localize the deformation during Alpine convergence.

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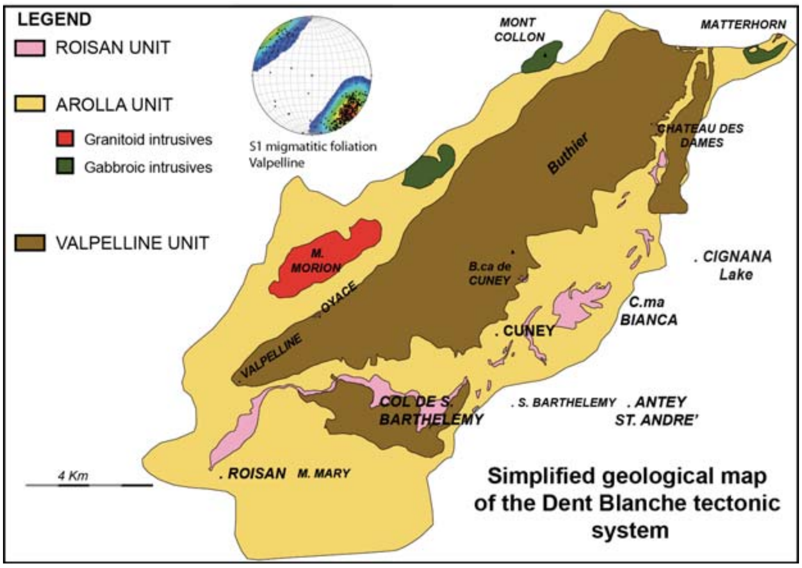

Fig. 1.- Geological map of the Dent Blanche system with stereographic projection of the poles to plane of the dominant migmatitic foliation S1.

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