Structural-metamorphic correlations between three Variscan segments in Southern Europe: Maures Massif (France), Corsica

Structural-Metamorphic Correlations Between Three Variscan Segments In Southern Europe: Maures Massif (France), Corsica(France)-Sardinia(Italy), And Northern Appennines (Italy)

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Abstract: Correlations of the geological elements between different segments of the Variscan Belt in southern Europe (Maures Massif, Corsica-Sardinia Block, Northern Apennines) allow to define a common structural-metamorphic evolution from Early Carboniferous syn-collisional event to the Late Carboniferous-Early Permian, extensional shearing events. In particular, the composite extensional tectonism in the Maures Massif (e.g. the Grimaud Fault) and Sardinia (e.g. the Posada-Asinara Line) consists of two shearing events: a ductile event in the amphibolite facies and and a following ductile (greenschist facies)/brittle and brittle event. During the latter event, syn-tectonic magmatism took place. The correlation of the pre-Alpine successions of the Northern Apennines with ones of the Central and NE Sardinia suggests a possible continuation of the Posada Valley Zone and the Posada-Asinara Line within the Tuscan segment of the Variscan belt. Also on the basis of paleogeographic data, we suggest that, during the Carboniferous-Permian times, the Maures Massif, Corsica-Sardinia block and the Tuscan part of Adria (Northern Apennines) were likely adjacent in the southern part of the Variscan Belt.

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Introduction

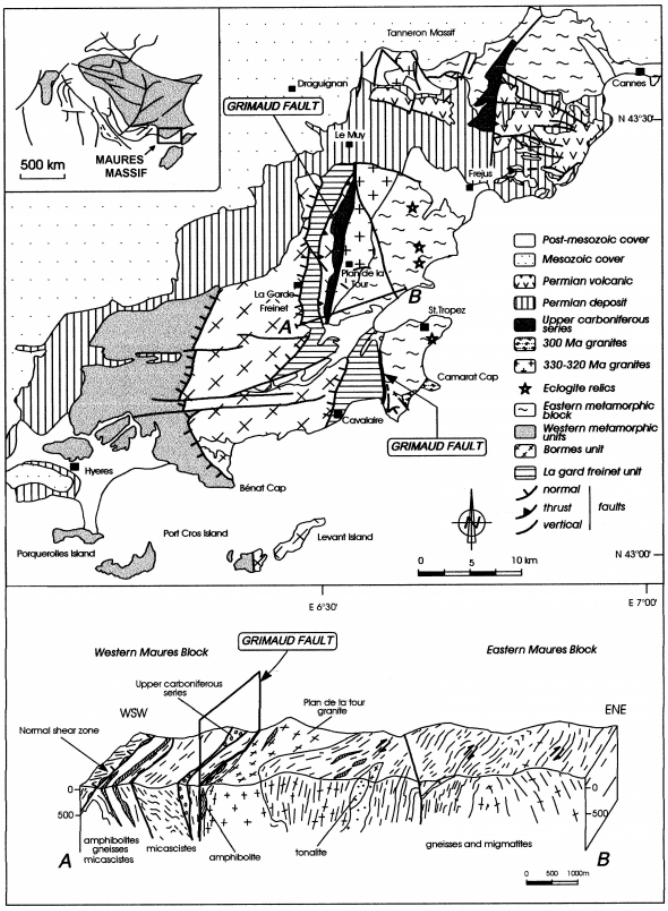
The Maures Massif, the Corsica-Sardinia block and the Paleozoic basement of the Northern Apennines are different segments of the southern part of the Variscan Orogenic Belt (Elter et al., 2004; Vai & Martini, 2001 and references therein). Late Paleozoic megashears (Artaud & Matte, 1977; Rau & Tongiorgi, 1981; Ziegler, 1984; Neugebauer, 1989; Vai, 1991 and references therein) and the Tertiary separation and counterclockwise rotation of the Corsica-Sardinia Block from the European Plate and of the peninsular Italy from the former block (Montigny et al., 1981; Rehault et al., 1984; Vigliotti & Langenheim, 1995; Carmignani et al., 1995; Sartori, 2001 and references therein), and the Late Oligocene-Miocene Northern Apennines tectogenesis (which produced polyphase regional metamorphism and tectonic slicing in the Tuscan Paleozoic successions: Carmignani & Kligfield, 1990; Elter & Pandeli, 1990, 1993; Conti et al., 1991; Pandeli et al., 1994) complicate the correlations between the considered segments. This paper aims to summarize the structural-petrographic data about the Variscan successions of the Maures Massif, Corsica-Sardinia block and Northern Apennines and to define their relationships within the southern part of the Variscan Belt.

Tectono-Metamorphic Evolution Of The Three Variscan Segments

The Maures Massif

The Maures Massif (Figure 1) comprises two main tectono-metamorphic blocks, the Western Block (WB) and the Eastern Block (EB), which are in tectonic contact along the Grimaud Fault (Pin & Peucat, 1986, Pin, 1990, Onezime et al., 1999, Morillon et al., 2000).

Figure 1. Geological sketch map of the Maures Massif

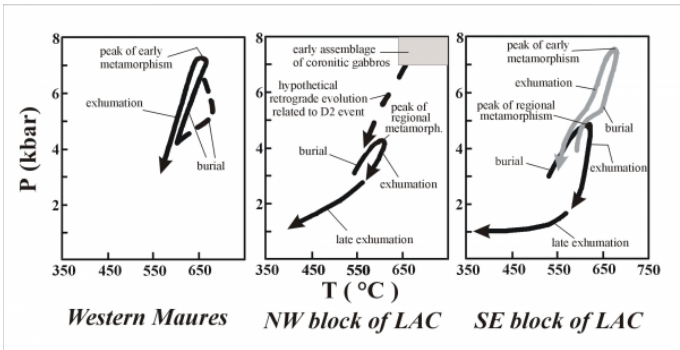


Geological sketch map of the Maures Massif and cross section (after Elter et al., 2004; modified from Morillon et al., 2000). The inset map shows the position of the Maures Massif in the Variscan Belt of France and respect to the Corsica-Sardinia block.

The Western Block consists of three metamorphic units: 1) the Upper Western Unit (UWU) composed of phyllites; 2) the Middle Bormes Unit (MBU) characterized by the Bormes orthogneiss dated 344 15 Ma, (Mossavau, 1998), paragneiss, micaschists, and minor amphibolites; 3) the Lower La Garde-Freinet Unit, made up of orthogneiss, leptynites, meta-gabbros, meta-serpentinites and garnet-spinel meta-peridotites, and sillimanite-bearing micaschists and migmatites. The geochemical trend of the ultramafites (Bellot et al., 1998) show a provenance from Lower Oceanic Crust.

The Eastern Block is mainly made up of of migmatites derived from orthogneisses and paragneisses containing amphibolitic eclogite lenses (Le Cartelle eclogite: Bodinier et al., 1986, Crevola et al., 1991). The migmatization process dates to 325 ± 8 Ma and 333 ± 3 Ma (Morillon et al., 2000). Four generations of syn-kinematic to post-kinematic plutons intruded EB since 334 ± 10 Ma to 297 ± 5 Ma (Amezou, 1988, Mossavau, 1998) fig. The metamorphic, magmatic and tectonic evolution of EB suggests a continuous orogenic history (Vauchez & Bufalo, 1988) in an area of rapid crustal thickening determined by large-scale thrusting within continental crust. In particular, the following metamorphic-magmatic evolution can be pointed out for EB (see P-T paths in Figure 2):

Figure 2. Summary of P-T-t-d paths



Summary of P-T-t-d paths (redrawn from Bellot et al., 2003); Western Maures = Western Block (WB); LAC = Leptyno-Amphibolitic Complex = Eastern Block (EB).

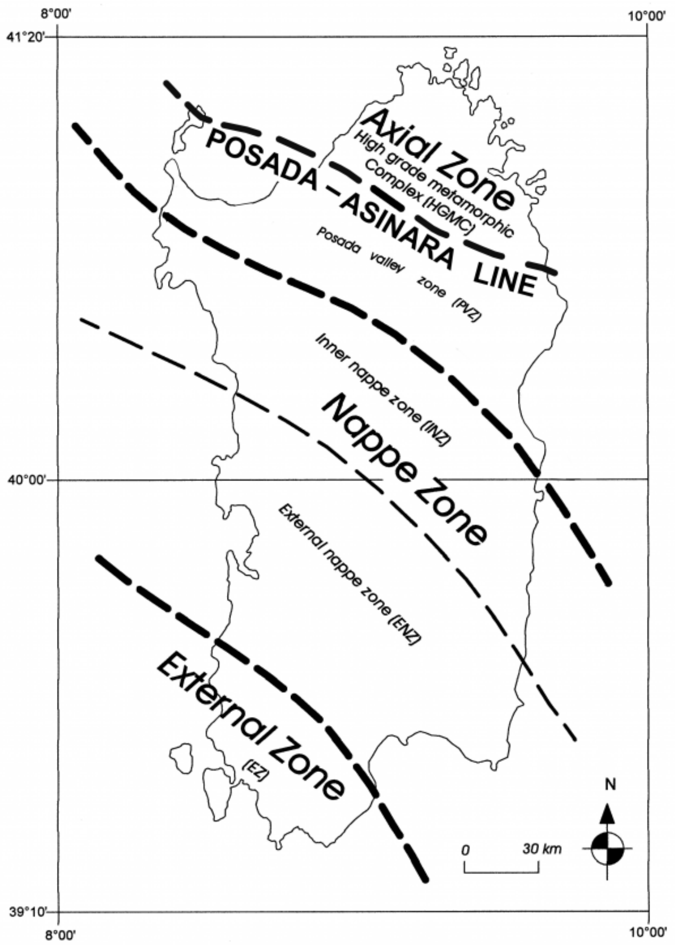
a. an early HP metamorphism which is linked to relict eclogites and to white kyanite+talc-bearing micaschists (Buscail & Leyreloup, 1998). Moreover, Bellot et al. (2003) recognized coarse-grained amphibolites characterized by P= 7-8 kbar and T= 750°-700° C;
b. a HT/LP metamorphism involving anatectic melting and syn-kinematic non-coaxial deformation (Vauchez & Bufalo, 1988), dated at 345 ± 15 Ma - 339 ± 16 Ma (U/Pb age on zircon: Moussavou et al., 1998);
c. the intrusion of the first generation of anatectic granitoids at 334 ± 10 Ma (Amezou, 1988; Moussavou, 1998);
d. a MT/LP to LT/LP metamorphism (e.g. the fine-grained amphibolites from P 4-6 kbar, T 550° - 650° C to P 2 - 4 kbar, T 350°-500° C of Bellot et al., 2003), syn-tectonic with sinistral strike-slip shear zone (Grimaud Fault) in which the early anatectic granitoids were mylonitized (Vauchez & Bufalo, 1988);
e. a moderate cataclastic reactivation of the Grimaud Fault with a dextral sense of shear; syn-tectonic to the emplacements of the Plan-de-la Tour and Rouet granites (Onezime et al., 1999) whose emplacement is dated 334 ± 5 Ma (Moussavou et al., 1998).
f. the intrusion of the anatectic granites at 320-325 Ma (Vauchez & Bufalo, 1988; Moussavou et al., 1998);
g. the beginning of exhumation (320-330 Ma: Morillon et al., 2000) with diachronous cooling ages on both sides of the Grimaud Fault (320 Ma for WB and 305 to 300 Ma for EB) ;

The late exhumation in the Maures Massif was probably associated with two orthogonal stages of extension (Faure, 1995) and/or with a transfer fault zone (Burg et al., 1994).

The Sardinian Massif

The Variscan Sardinia (Figure 3) consists of four Northwest to Southeast - trending tectono-metamorphic zones : the External Zone (Foreland area), the Nappe Zone, the Posada Valley Zone ("Inner Nappes" of Carmignani et al., 1992; "Low to Middle Grade Metamorphic Complex of the Axial Zone" of Oggiano & Di Pisa, 1992) and the High Grade Metamorphic Complex (HGMC, "High Grade Metamorphic Complex of the Axial Zone" of Oggiano & Di Pisa, 1992; Axial Zone of Elter et al., 2004 and Corsi & Elter, 2005). An evident northeastward increase of the metamorphic grade is recognizable going from the sub-greenschist/greenschist facies of the External Zone /Nappe Zone, to the high grade amphibolite facies and migmatites within the Axial Zone (Franceschelli et al., 1982) including scattered retrogressed granulite and eclogite lenses. The isograds of Barrovian regional metamorphism are parallel to the Northwest-Southeast strike of the tectono-metamorphic zones. The stratigraphic and tectono-metamorphic features of each zone are shown below (the readers are referred to cited authors and Carmignani et al., 2001 for details):

Figure 3. Regional distribution of the Variscan tectono-metamorphic zones



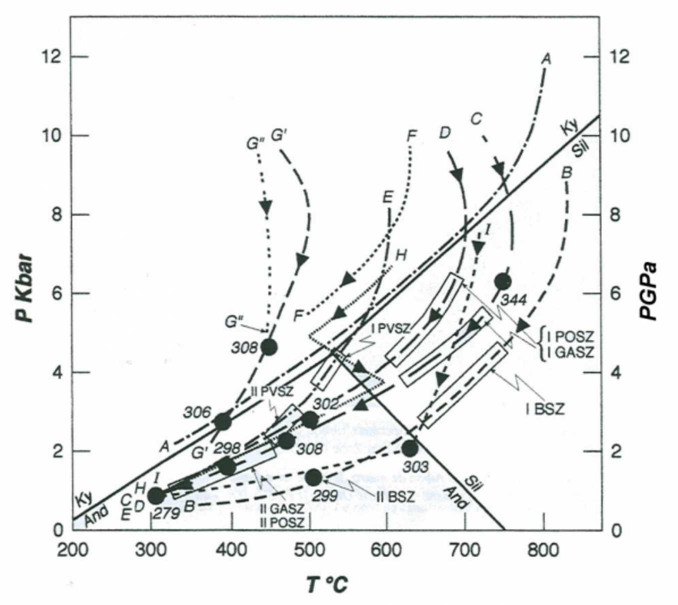
Regional distribution of the Variscan tectono-metamorphic zones in Sardinia (modified from Elter et al., 2004).

a. The Paleozoic successions of the External Zone (Foreland area), cropping out in the southwestern corner of Sardinia, are weakly deformed and metamorphosed (anchizone to lowermost greenschist facies) and include neritic Early Cambrian to Early Ordovician carbonates and siliciclastics which are unconformably overlain (Sardinian Unconformity) by continental/coastal to epicontinental marine sediments of Middle Ordovician to early Carboniferous age;

b. The Nappe Zone successions crops out in the central part of Sardinia and consists of Late Cambrian-Early Ordovician basinal marine siliciclastics which unconformably (Sardinian Unconformity or Sarrabus Unconformity) rest below Middle Ordovician mostly acidic volcanites, Late Ordovician neritic and Silurian-Devonian marine epicontinental sediments and Early Carboniferous "Culm"-like syn-orogenic siliciclastics. The Nappe Zone can be divided into two subzones based on their structural - metamorphic evolution: an External Nappe Zone (ENZ) and an Internal Nappe Zone (INZ). The ENZ was affected by lower greenschist facies metamorphism, whereas the INZ is characterized by an increase in metamorphic grade up to the passage high-grade greenschist facies/amphibolitic facies, notwithstanding that, according to Carosi et al. (1992) and Carmignani et al. (2001), the staurolite zone of the amphibolitic facies was attained in the deepest Mt. Grighini Unit. In particular two tectono-metamorphic complexes can be recognized in the INZ: the Lula Complex (albite-biotite zone: Elter et al., 1986) and the S.Lucia Complex (oligoclase + biotite zone: Elter et al., 1986) The INZ is in tectonic contact with the Axial Zone across the Posada Valley shear zone (Elter et al., 1990, 1999, 2004).

c. the Posada Valley Zone is characterized by MT/MP condensed isograds and by a metamorphic evolution syn-kinematic with non-coaxial deformation (Elter et al., 1999, 2004 and references therein). The Posada Valley Zone is here considered a transitional metamorphic complex from the Nappe Zone to HGMC. The northern border of the Posada Valley Zone is represented by a segment of the most important regional tectonic line, the so-called Posada - Asinara Line (Figure 3). This about 3 km-thick, dextral strike-slip shear zone developed in greenschist facies conditions which overprinted the condensed isograds metamorphism. An earlier amphibolite facies, extensional, non-coaxial deformation event (Corsi & Elter, 2005) can be identified in some scattered pods of leptyno-amphibolitic rocks with eclogitic relics (Torpè amphibolites: Memmi et al., 1983; Cappelli et al., 1992; "eclogite B" in Cortesogno et al., 2004) hosted in the ultramylonite. The thermometric calibrations provide T in the range 610° - 700° C for P about 1.3-1.5 Gpa for the eclogitic event (Cortesogno et al., 2004).

Figure 4. P-T- t paths for some metamorphic zones



P-T- t paths for some metamorphic zones of the Variscan basement in Sardinia: A-A: P-T-t path of the granulites from NE sardinia; B-B, C-C, I-I: P-T-t path of the sil+kfs zone in the Barrabisa, Golfo Aranci and Porto Ottiolo, and Anglona areas respectivelly; D-D: P-T-t path of the sil+ms zone in the Porto Ottiolo area; E-E/F-F: P-T-t path of the ky+st+bt zone in the Posada Valley area; G'-G' and G"-G": P-T-t path of the gt+bt zone (INZ); H-H: P-T-t path of the bt zone in the Grighini area (ENZ) (after Elter et al., 1999).

In particular, the Posada Valley Zone can be divided into two Units, an Upper Unit (UU) and Lower Unit (LU, Elter et al., 2004). Two complexes are identified in the UU: the Siniscola - Monte Longu Complex (metasediments in the albite+oligoclase+biotite zone) and the Lodè-Mamone Complex (Ordovician orthogneisses). The four complexes distinguished in the LU are (from top to bottom): 1) the Punta Gortomedda Complex (metasediments in the staurolite + biotite zone), 2) the Bruncu Nieddu Complex (metasediments in the kyanite + biotite zone), 3) the Upper Punta Figliacoro Complex (an assemblage of metasediments in the kyanite + biotite zone and N-T MORB eclogitic leptyno-amphibolites in a mylonitic context: Torpè amphibolites in Memmi et al., 1983; Cappelli et al., 1992) and 4) the Lower Punta Figliacoro Complex (sillimanite-bearing micaschists).

d. The Axial Zone is the High Grade Metamorphic Complex (HGMC, Elter et al., 2004) which comprises the sillimanite+muscovite and the sillimanite+K-feldspar metamorphic zones (Elter et al., 1986). The HGMC consists mainly of migmatites deriving from paragneiss and orthogneiss that contain lenses of amphibolites with relics of eclogitic (Punta de Li Turchi eclogites of 957 Ma: Miller et al., 1976; Ricci & Sabatini, 1978; "eclogite A" of Cortesogno et al., 2004) and/or granulitic (Montiggiu Nieddo amphibolites and P.ta Scorno amphibolites: Ghezzo et al., 1979, 1982; Castorina et al., 1996) metamorphism. Cortesogno et al. (2004) defined for the Punta de Li Turchi eclogites geothermobarometric parameters of T= 690° - 760° C for minimun pressure about 1.3 Gpa.

Post- orogenic fluvial and lacustrine siliciclastic successions, Westphalian/Stephanian-Autunian (including anthracite bodies: e.g. San Giorgio basin in Iglesiente) and Late Permian-Middle Triassic in age, with local intercalations of calc-alkaline volcanites are also present in several part of the island (Carmignani et al., 2001 and references therein).

The Paleozoic metamorphic-magmatic evolution of Sardinia is characterized by (Figure 4):

a. A syn-collisional crustal shortening event, characterized by a first prograde migmatization event with T 700°-650° C and P 9-10 kbar (Cruciani et al., 2002; Corsi & Elter, 2005), that develops in a time span of 380-350 Ma in the HGMC (Carosi & Palmeri, 2002);
b. Late Carboniferous - Early Permian extensional tectonics that affected the whole belt and was due to gravitational collapse of the previously thickened crust (Elter et al., 2004, Corsi & Elter, 2005). The geometric and kinematic features of extensional tectonism include a complex network of composite shear zones syn-tectonic to a second migmatization event (Corsi & Elter, 2005) which took place in a time span from 350 - 300 Ma with T600°-450° C and P 4-6 kbar (Ferrara et al., 1978; Ricci, 1992).

The complicate shear zone network was generated by two shear events (Elter et al., 1999): an Early Shear Event and a Late Shear Event. The early shear zones are not yet radiometrically dated, but they are cut by the later ones (Elter et al., 1999, 2004) which develop during a time span between 320 - 300 Ma (Muzio, 2003).

The early shear zones shows pervasive HT/LP metamorphism, coeval with non-coaxial deformation and variably trending foliation planes, is consistent with Northwest-Southeast mineral stretching lineations and a "top-to-the South-Southeast" shearing. This event may be in relation to extensional doming (Elter et al., 1999, 2004, Corsi & Elter, 2005). By contrast, the late shear zones are characterized by dominantly dextral strike-slip movement (Elter et al., 1990, 1999, 2004, Corsi & Elter, 2005). Some of them are associated with syn-kinematic granodiorites and tonalities whose emplacement ages range from 320 Ma to 300 Ma (Bralia et al., 1982/83; Poli et al., 1989; Muzio, 2003). The metamorphic conditions of the LSE show different patterns (Elter et al., 1999). In fact, those associated with synkinematic intrusions are characterized by HT texture, while the LSE shear zones characterized by retrograde metamorphism show metamorphic conditions in the greenschist facies (e.g., the Posada Valley Shear Zone) or in the low-grade amphibolitic conditions (e.g. the Ottiolu Shear Zone).

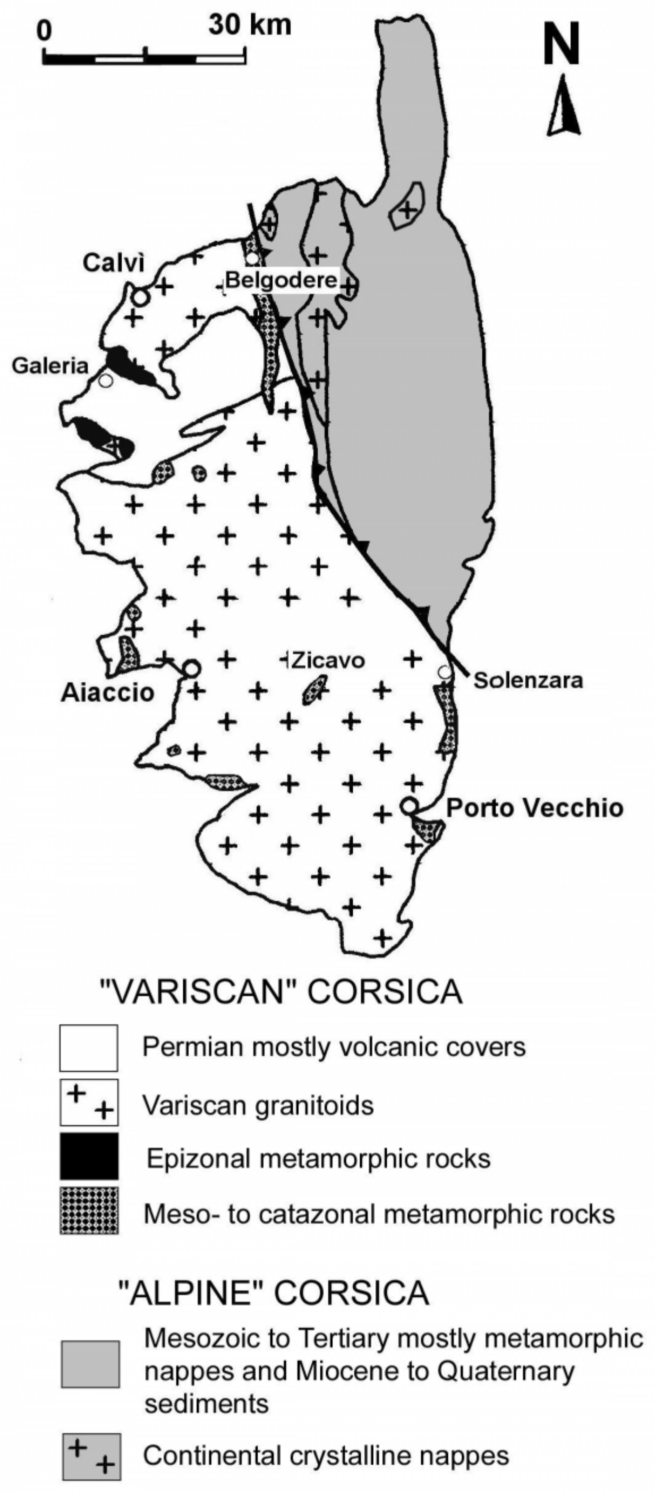
Extensional tectonics gave rise to the fast exhumation of amphibolite facies rocks, with the thermal perturbation due to tectonic unroofing causing HT/LP metamorphism and anatexis (Elter et al., 1999) which produced late-tectonic granitoids (307-299 Ma granodiorites, tonalites and monzogranites, Del Moro et al., 1975; Bralia et al., 1982/83; Poli et al., 1989) with rare gabbroic masses (307 Ma, Bralia et al., 1982/83; Poli et al., 1989). The fast uplift also quenched the stability of the amphibolitic facies paragenesis in the upper levels where deformation developed through brittle processes. During this event, large scale late- to post-tectonic intrusive magmatism (298-289 Ma leucogranites, Del Moro et al., 1975; Bralia et al., 1982/83; Poli et al., 1989) took place.

The post-tectonic granitoids are not foliated, and their Northeast-Southwest direction of emplacement is orthogonal to the axis of the Variscan belt. In contrast, the earlier magmatic bodies are generally foliated and sub-parallel to the belt axis.

The Variscan Corsica

The Variscan Belt in Corsica (Figure 5) (Carmignani & Rossi, 2001; Durand Delga et al., 2001) is mainly represented by a wide composite granitoid batholith and volcanics which mostly hide the original relationships within the units of this Variscan segment. The magmatic evolution of the Variscan Corsica consists of the polyphase emplacement of three magmatic associations occurred during Late Carboniferous-Permian-?Early Triassic times (Durand-Delga et al., 2001; Del Moro et al., 1975; Cocherie et al, 1984, 1992, 1994; Bonin et al., 1998 and references therein). At the boundary Late Carboniferous-Early Permian, especially the north-western part of the Variscan Corsica was extensively covered by calc-alkaline volcanites of andesite-dacite and dacite-rhyolite compositions (Vellutini, 1977). According to Paquette et al. (2003) four emplacement stages of the magmatic bodies can be distinguished: a) Post-collisional peraluminous granites at about 346 Ma; b) Syn-orogenic (Palagi et al, 1985; Menot & Orsini, 1990), high Mg-K calc-alkaline granitoids at about 338 Ma; c) late orogenic Calc-alkaline granitoids and volcanics at about 305 Ma during the extension and shearing of the Corsica Variscan segment; d) Layered mafic-ultramafic complexes, and metaluminous and (per-) alkaline granitoids at about 280-285 Ma. The same authors also suggest that d) magmatic event was linked to the pre-Alpine continental rifting.

Figure 5. Geological sketch map of Corsica.



Geological sketch map of Corsica.

Late Carboniferous, anthracite bearing siliciclastics are present at Osani, Mausoleo-Asco and Punta di L'Acciolu.

Pre-Late Carboniferous Variscan successions are locally recognizable as host rocks of the granitoid composite batholith in some places of Variscan Corsica (e.g. Belgodere-Castifao-Corscia, Aiaccio, Osani, Porto Vecchio, Solenzara, Zicavo and Galeria).

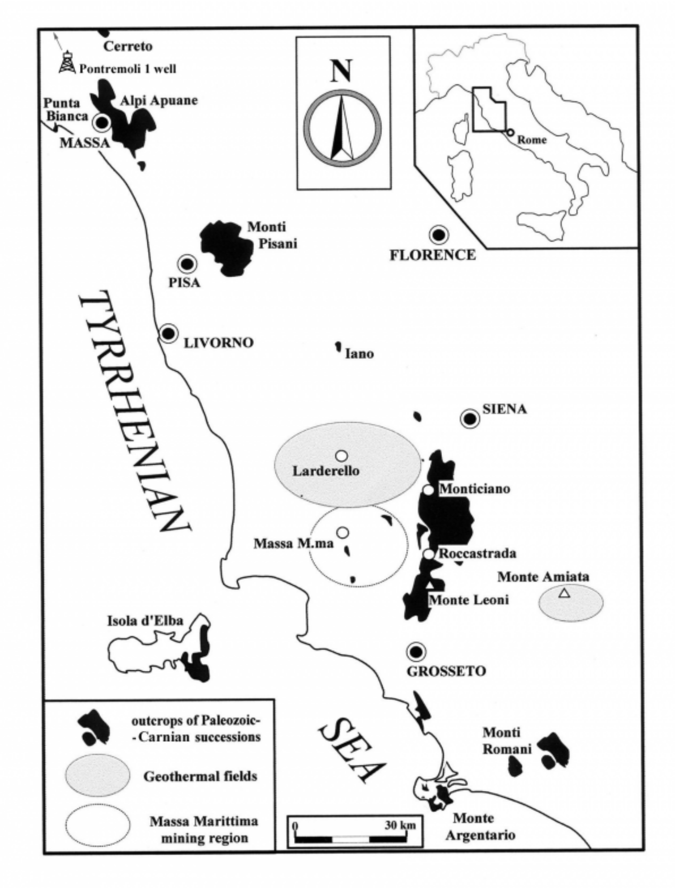
In particular, the pre-granitoids rocks can be attributed to two metamorphic domains (Durand-Delga et al., 2001 and references therein):

a. A meso-to-catazonal domain, which is the continuation of the HGMC of NE Sardinia and crops out at Porto Vecchio-Solenzara, Zicavo, west of Aiaccio, Belgodere-Castifao-Corscia and in the Valinco Gulf (Bellini, 1971; Palagi et al., 1985). It is characterized by polymetamorphic and polydeformed orthogneisses, paragneisses and migmatites (Rossi, 1998). A peculiar feature is the presence of: a) a "leptyno-amphibolitic complex", consisting of: amphibolites with a "continental" tholeiitic and T- MORB affinity with local cumulitic structures (Palagi et al., 1985a), and associated orthogneisses (e.g. the 338 Ma Belgodere orthogneiss: Paquette et al., 2003), possibly deriving from Ordovician granitoids (Rossi, 1998); b) a migmatitic complex, included in a Barrovian metamorphic sequence, with eclogitic relics providing evidence of early HP metamorphism (Belgodere eclogites: Palagi et al., 1985b)
b. An epizonal domain, which is characterized by sericite-chlorite micaschists and amphibolite bands and by the Paleozoic succession of Galeria consisting of pre-Cambrian metasiliciclastics with levels of metabasites which underlies a ?Cambro-Ordovician to Early Carboniferous sequence (similar to those of the Central Sardinia). This succession is characterized by a low metamorphic grade (Ricci e Sabatini, 1978).

The Pre-Alpine Basement Of The Northern Apennines

The Paleozoic and Triassic successions of the Northern Apennines (see locations in Figure 6) were strongly involved in the Alpine Orogeny in the Oligocene-Miocene times (27 to 12 Ma). In particular, these rocks suffered polyphase greenschist facies tectono-metamorphism and were dissected in several tectonic units (Carmignani & Kligfield, 1990; Elter & Pandeli, 1990, 1993, 1994, 1996; Bertini et al., 1991; Conti et al., 1991; Pandeli et al., 1994; Franceschelli et al., 2004; Pandeli et al., 2005). Moreover, the Paleozoic successions, as part of the overlying covers, underwent HT-LP metamorphism during the emplacement of the post-tectonic, Late Miocene-Quaternary granitoids in southern Tuscany (e.g. in the subsurface of the Larderello-Travale geothermal field: Batini et al., 1983; Elter & Pandeli, 1990; Franceschini, 1998; Carella et al., 2000; Gianelli & Ruggieri, 2002; Musumeci et al., 2002; Pandeli et al., 2005) and Tuscan Archipelago (e.g. in the eastern Elba Island: Barberi et al, 1969; Duranti et al., 1992; Bortolotti et al., 2001; Garfagnoli et al., 2005). The Alpine metamorphism and tectonics largely obliterated the fossiliferous content and textures of the pre-Carboniferous rocks and juxtaposed different portions of the Variscan crust (Elter & Pandeli, 1996; Pandeli et al., 2005). The restoration of the original stratigraphic successions was mostly made through lithostratigraphic and petrographical-geochemical correlations with the correspondent, well-dated stratigraphy of Central Sardinia (Bagnoli et al., 1979; Conti et al, 1991; Pandeli et al., 1994 and references therein).

Figure 6. Regional distribution of the outcrops



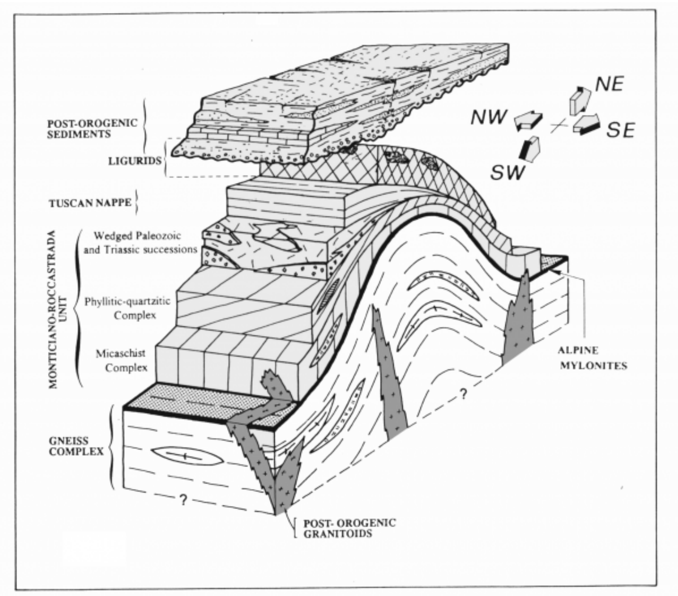
Regional distribution of the outcrops of the Paleozoic-Triassic metamorphic successions (in black) in the Northern Apennines.

In particular, the outcropping stratigraphic successions (e.g. Punta Bianca, Apuan Alps, Mts. Pisani, Monticiano-Roccastrada Ridge, eastern Elba Island, Mts. Romani) are made up of ?Late Cambrian-to Devonian units similar to those of the Central Sardinia. These rocks often preserve pre-Alpine, greenschist facies schistosity relics which Conti et al. (1991) and Pandeli et al. (1994) referred to the Sudetian Event of the Variscan Orogeny. At places, Middle Carboniferous foredeep siliciclastics and Late Carboniferous-Permian, continental to marine successions also occur (e.g. Mts. Pisani, Iano, Monticiano-Roccastrada Ridge; Mts. Leoni, Mt.Argentario, eastern Elba Island: Pandeli et al., 1994, 2004; Pandeli, 2002 and references therein).

In the subsurface of the Larderello-Travale geothermal field (Figure 7), the ?Late Cambrian/Ordovician rocks lie onto two mica, garnet-bearing micaschists which includes OFB (=Ocean Floor Basalts) hornblende amphibolite levels (Micaschist Complex: Puxeddu et al., 1984; Elter &

Pandeli, 1990). The same rocks also crop out at Cerreto Pass (northeastward of the Apuan Alps: Di Sabatino et al., 1979; Molli et al., 2002) and in southeastern Elba Island (Garfagnoli et al., 2005), and were crossed by the Pontremoli 1 oil well northward of the Apuan Alps (Pandeli et al., 2005). The coarse-grained, medium-grade Barrowian foliation of the mostly OFB amphibolites in the Cerreto outcrops is dated about 330 Ma by Molli et al. (2002). An Early Permian HT event was also defined in the micaschists of the Larderello field (about 285Ma age of a muscovite associated with pre-Alpine andalusite: Del Moro et al., 1982).

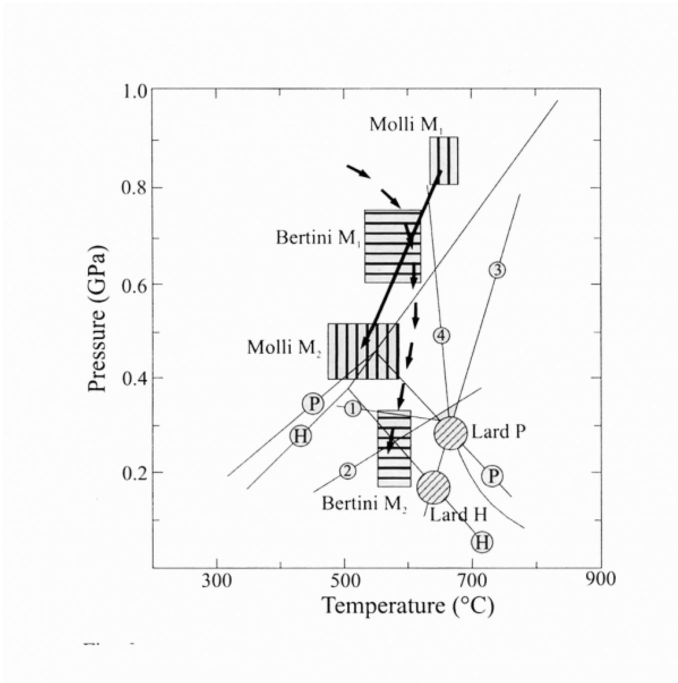
Figure 7. Geological sketch of the Larderello



Geological sketch of the Larderello geothermal field (after Elter & Pandeli, 1996).

Alpine quartz-mylonites separates the Micaschist Complex, pervasively affected by the Alpine tectono-metamorphism (and thus included in the Alpine Monticiano-Roccastrada Unit by Bertini et al., 1991), from the underlying Gneiss Complex, which preserves its Variscan framework (Elter & Pandeli, 1990; Pandeli et al., 1994, 2005). The Gneiss Complex consists of muscovite-biotite gneisses with interlayered orthogneisses, OFB amphibolites and minor calc-silicate rocks (Puxeddu et al., 1984; Pandeli et al., 1994). The pre-Alpine Barrovian minerals and textures in the Micaschists Complex are recognizable in the main foliation of the Gneiss Complex which suggest a similar Variscan metamorphic evolution (Elter & Pandeli, 1996; Franceschelli et al., 2004; Pandeli et al., 2005 and references therein)(Figure 8). In particular besides a higher peak P-T values for the gneisses (up to sillimanite-in), it passed through an earlier Barrovian-type intermediate P event (P 6-7 kb and T=550°-650° according to Bertini et al., 1994) to a subsequent lower P syn-tectonic event (P 2-3.5 kb and T=550°-600° according to Bertini et al., 1994). These P-T paths are comparable to ones of other well-known Variscan units of southwestern Europe and northern Africa (e.g. Central Massif, Maures Massif, NE-Sardinia, Calabrian-Peloritan arc, Bethic-Rifean belt: see Figure 6 in Elter & Pandeli, 1996 and Figs. 2 and 4 in this paper).

Figure 8. P-T paths of the Micaschist Complex

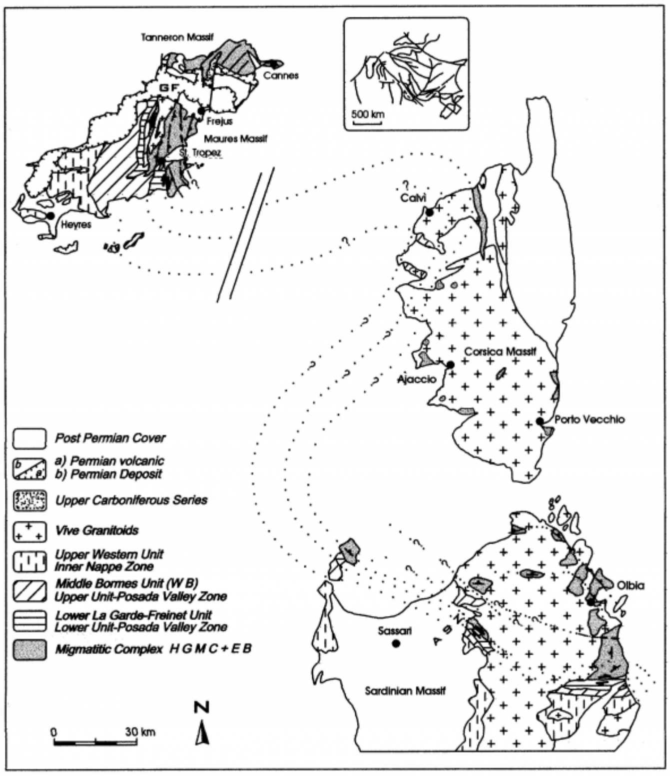


P-T paths of the Micaschist Complex and Gneiss Complex (after Franceschelli et al, 2004).

Discussion

Chabrier & Mascle (1975) first pointed out that the pre-Oligocene geological history of Provence and Sardinia is similar. In particular, the following correlations can be made with the units defined for the Maures Massif and for the Variscan Corsica and Sardinia (Figure 9):

Figure 9. Geological relationships between Sardinia-Corsica and Maures Massifs



Geological relationships between Sardinia-Corsica and Maures Massifs (modified from Elter et al., 1999)

a. The migmatitic complex of the Eastern Unit of the Maures Massif (Vauchez & Bufalo, 1998; Bellot et al., 2003) and of the HGMC of Sardinia (Elter et al., 1999, 2004) record a similar P-T path along a Barrovian clockwise trajectory (cfr. Figs. 2 and 4).
b. Like the HGMC of Sardinia (Punta de li Tulchi - Punta Tittinosu eclogites: Elter, 1987) and Corsica (Belgodere eclogites: Palagi et al., 1985), the migmatitic Complex in the EB of the Maures Massif contains lenses of amphibolitic eclogites (e.g. La Cartelle eclogite).
c. The migmatitic complex of the Maures Massif is characterized by a composite secondary foliation associated with heterogeneous ductile deformation related to non-coaxial deformation (Vauchez & Bufalo, 1998) with a "top to North" sense of shear. A similar structural evolution is described by Corsi & Elter (2005), for the HGMC of Sardinia: its composite migmatitic foliation is related to a polyphase non-coaxial deformation, an earlier with a "top to Northwest" sense of shear and an younger with a "top-to-South/ Southeast" shear component.
d. In both areas, migmatization processes are recognizable and they are substancially coeval with the non-coaxial deformation. However in Sardinia, Corsi & Elter (2005) point out the presence at least of two migmatization events as in the Variscan French Central Massif (Leloix et al., 1999, Faure et al., 2002). The migmatization is dated to 345-339 Ma in the Maures Massif (U/Pb data in Moussavou et al., 1998), while in Sardinia, an age of 344 Ma is pointed out for the second migmatization event (Ferrara et al., 1978).
e. In both areas the polyphase emplacement of the granitoid bodies occurred mostly in the same time interval: at 334 to 297 Ma ago in the Maures Massif and at 346 to 289 Ma ago in the Sardinia - Corsica block.

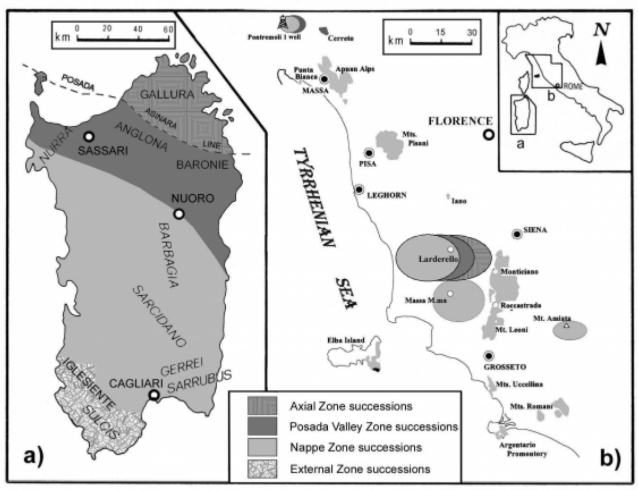
There are not only analogies between the migmatitic complexes, but also between other geological elements. The La Garde-Freinet Unit plays the same structural role of the Posada Valley Shear Zone: in fact, they both link the lower metamorphic units to the highest ones. In addition, there is a close correlation between the lithology and structural-metamorphic evolution of these two units: e.g. staurolite-biotite and kyanite-biotite micaschists are found in both units (Elter et al., 1986, Buscail & Leyreloup, 1998).

On the contrary meta-gabbros, meta-serpentinites and garnet-spinel meta-peridotites with an oceanic affinity (Bellot et al., 2003) found in the La Garde-Freinet Unit are not present in the Lower Unit of the Posada Valley Zone, but the N-T MORB Torpè orthoamphibolites (Cappelli et al., 1992) found in the Posada-Asinara Shear Zone suggest a possible correlation with the oceanic basic and ultrabasic rocks of the Mauri Massif.

The relationship between the La Garde-Freinet Unit and the Migmatitic Complex in the EB of the Maures Massif is characterized by the interposition of the Grimaud Fault, just like the Posada Valley Zone in Sardinia which separates the Internal Nappe Zone from the High Grade Metamorphic Complex. The Grimaud Fault shows a composite tectono-metamorphic evolution characterized by two events: sinistral strike-slip faulting followed by dextral strike slip faulting associated with the intrusion of the synkinematic Rouet-Plan de la Tour granite (Onezime et al., 1999). Also this fault separated two blocks (EB and WB) characterized by diachronous cooling (Morillon et al., 2000). Also the Posada Valley Shear Zone (Elter et al., 1990, 1999, 2004) is characterized by a composite tectono-metamorphic evolution, consisting in two events: the first in an extensional event under amphibolite facies conditions, followed by the second, dextral strike slip event under greenschist facies conditions. During the latter event, thermo-metamorphism, related to the emplacement of 320-300 Ma granodiorites, also occurred (Muzio, 2003). Therefore, the later greenschist facies evolution of the Grimaud Fault and of the Posada Valley Shear Zone is similar, in spite differences in the initial metamorphic evolution of these shear zones. Finally, lithological affinities can be pointed out between the ortho- and paragneisses, micaschists and amphibolites of the Middle Bormes Unit in the Maures Massif and those of the Upper Unit of the Posada Valley Zone (e.g. the orthogneisses of Lodè-Mamone Complex).

As it regards the correlation of the Variscan stratigraphic successions of the Northern Apennines with those of the Corsica-Sardinia block (Figure 10), the strong similarities in stratigraphy and in the pre-Alpine metamorphic grade between the greenschist Facies, ?Late Cambrian-Devonian Tuscan successions and the units of the External Nappe Zone, i.e.Gerrei, Sarrabus, Sarcidano, in Sardinia (Conti et al., 1991; Pandeli et al., 1994 and references therein) are evident. Also the rocks of the Micaschist Complex and of the Gneiss Complex have their equivalents in the Variscan units of Sardinia. In fact, rocks similar to Larderello micaschists, amphibolites and gneisses crop out in central and NE Sardinia. In particular, paragneiss and garnet- and staurolite-bearing micaschists characterized the deepest unit of the Nappe Zone (M.Grighini Unit) (Carosi et al., 1992), of the Low- to Medium- grade Complex of the Axial Zone (Franceschelli et al., 1982; Oggiano & Di Pisa, 1992) and of the Posada-Asinara Shear Zone (Elter et al., 1990; Carmignani et al., 1982, 2001). Further analogies can be found with the gneisses of the sillimanite+muscovite zone in the HGMC (Oggiano & Di Pisa, 1992). The syn-collisional Barrowian metamorphism evolution of the Low- to Medium- grade Complex of the Axial Zone (dated 336-350 Ma: Rb/Sr and Ar/Ar radiometric ages in Del Moro et al., 1991) shows evident analogies with respect to that of the Larderello gneisses and micaschists. For example, the plagioclase and garnet porphyroblasts, which include schistosity relics, is a typical feature not only of the Larderello rocks, but of those of the Garnet+albite+oligoclase and Staurolite+biotite Zones in the Sardinian Low- to Medium- grade Complex (Carmignani et al., 1982, 2001; Franceschelli et al., 1982; Oggiano & Di Pisa, 1988; Elter et al., 1989; Di Vincenzo et al., 2004) or LU in the Posada Valley Zone (Elter et al., 2004 and this paper). In addition, the garnet porphyroclasts show a prograde zoning (decrease of spessartine from core to rim: Franceschelli et al., 1982; Di Vincenzo et al., 2004) which is also present in the pre-Alpine garnets of the Larderello subsurface (Pandeli et al., 2005) and of the Cerreto Pass (Molli et al., 2002). The main foliation of the considered Sardinian rocks is overprinted by the thermometamorphic mineral assemblage connected to the Uppermost Carboniferous-Lower Permian, peraluminiferous magmatism (Granitoid Complex in Oggiano & Di Pisa, 1992; Ricci, 1992; Carmignani et al., 2001) of Northern Sardinia. This magmatic event is also likely testified, in the crystalline basement of Tuscany, by the crystallisation of andalusite+muscovite at 285 Ma in the Larderello micaschists.

Figure 10. Geological relationships between the Variscan units of Sardinia and of the Northern Apennines



Geological relationships between the Variscan units of Sardinia and of the Northern Apennines.

A further analogy is given by the oceanic affinity of the orthoamphibolite levels within the Micaschist Complex and the Gneiss Complex (Puxeddu et al., 1984; Molli et al., 2002) that recalls the Variscan N-T MORB orthoamphibolite intercalations within the Posada-Asinara Shear Zone in Sardinia (cfr. Elter et al., 1990; Cappelli et al., 1992), whereas the other Paleozoic and Triassic metabasites of Tuscany are continental WP(=Within Plate) or calc-alkaline metavolcanites (Puxeddu et al., 1984; Conti et al., 1988; Pandeli et al., 1994; Pandeli, 2002 and references therein).

During the Carboniferous-Permian times, the paleogeographic reconstruction of the southern part of the Variscan Belt consider Provence, Corsica-Sardinia, Tuscan part of Adria and Iberia as discrete or composite terranes (e.g. Stampfli & Mosar, 1999; Stampfli et al., 2003; Von Raumer et al., 2003; Rau & Tongiorgi, 1981 and references therein; see also web site: www.sst.unil.ch) interposed between the stable Europe and Gondwana. According to some authors (e.g. Rau & Tongiorgi, 1981; Von Raumer et al., 2003), in the pre-Carboniferous times, these terranes were mostly far from each other, but they were adjacent during the Variscan Orogeny or, at least, not too far (e.g. Scotese et al., 1979; Rau & Tongiorgi, 1981; Gelmini, 1985; Vai & Cocozza, 1986; Neugerbauer 1989; Vai, 1991; Dercourt et al., 1993; Von Raumer et al., 2003; see also web site: www.scotese.com/earth.htm). Stampfli & Mosar (1999) and Stampfli et al. (2003) instead located the Calabria-Peloritani terrane between the Corsica-Sardinia and the Adria blocks. During the Late Paleozoic the Variscan architecture of the terranes was modified by strike-slip tectonics. In particular, in Provence and Corsica-Sardinia segments, the data point to a syn-extensional shearing during the Late Carboniferous-Early Permian (e.g. the Grimaud Fault and Posada-Asinara line respectively) which was probably connected to the well-known dextral strike-slip megashears. The latters, characterized by hundreds of kilometres throws, repeatedly crosscut the southern part of the Variscan Belt. In particular, during Late Carboniferous-Permian, the North Pyrenean Fault (e.g. Arthaud & Matte, 1975; 1977; Ziegler, 1984; Rau, 1990; Vai, 1991 and references therein) or the High Atlas Fault (e.g. Neugerbauer, 1989) approached Provence, Corsica-Sardinia and Adria.

The post-Permian tectonic events didn't substantially change the Permian relationships of these Variscan segments: the Jurassic opening and Late Cretaceous-Tertiary closing of the NeoTethys (Abbate et al., 1986; Bortolotti et al., 1990; Argnani, 2002 and references therein) as well as the syn- to post-collisional events of the Alpine Orogeny. The latter produced the Apenninic tectogenetic shortening and the development of the Ligurian-Balearic and Northern Tyrrhenian basins due to rotation of the Corsica-Sardinia block from Provence and the Italian Peninsula from the former respectively (Montigny et al., 1981; Rehault et al., 1984; Boccaletti et al., 1990; Vigliotti & Langenheim, 1995; Carmignani et al., 1995; Sartori, 2001; Vai & Martini, 2001; Argnani, 2002 and references therein).

Therefore, during the Late Carboniferous-Permian, Maures, Corsica-Sardinia and the Tuscan part of Adria can be located in the same sector of the Variscan Belt, as supported by the similar sedimentary (e.g. the strong analogies between the Paleozoic successions of the Northern Apennines and the Central Sardinia: Pandeli et al., 1994; Pandeli et al., 2005 and references therein), tectono-metamorphic and magmatic evolution and by the possible correlation of isopic tectono-metamorphic lineaments (Pandeli & Elter, 1996; Vai, 2001; Carmignani e al., 2001; Elter et al., 2004 and previous paragraphs).

So, we think that the Posada-Asinara Line and the Grimaud Fault don't represent different shear boundaries between terranes, but a single main shear zone (see also Carmignani et al., 2001 and Elter et al., 2004). Its possible prosecution in the Tuscan Variscan segment can be tentatively hypothesized by the presence of rocks similar to those of the Posada Valley Zone.

Conclusions

The correlation of the geological elements of the Maures Massif with those of the Sardinia-Corsica block, suggests a similar tectonic and metamorphic evolution of the Migmatitic Complex (Maures) and of the HGMC (Sardinia-Corsica). Moreover, the Grimaud Fault can be easily correlated with the Posada Valley Shear Zone (Figure 9). The union of the these tectonic lineaments in a single main shear zone outlines one of the most important tectonic element in the palinspastic reconstructions of the southern part of the Variscan belt. Both shear zones correspond to zones of early crustal weakness; their evolution under amphibolite facies conditions and their important strike-slip motion obliterated their original tectonic significance.

Geochemical data indicates an oceanic affinity for the amphibolite bodies in the PVSZ (Torpè amphibolites) which suggest that the Posada-Asinara and the Grimaud Fault shear zones could represent the reactivation of part of the Variscan suture zone. Therefore; the Migmatitic Complex of the Maures Massif (EB) and the HGCM in Sardinia would be part of the same plate ("Variscides Centrales") while the Upper Western Unit (UWU) of Maures Massif and the INZ in Sardinia would represent a different western plate (Variscides Externes) respect to the "Variscides Centrales", prior to Variscan orogeny. This hypothesis fits well in the structural evolution of the whole Variscan belt, particularly with the extensional features identified in some parts of the PVSZ and with the clockwise P-T-t path defined by these rocks. A major detachment fault (or thrust?) possibly developed in these early zones of weakness, and it was successively reactivated during the strike-slip movements which occurred 320-300 Ma ago all over the Southern Europe. The union of the HGMC in Sardinia-Corsica with the Migmatitic Complex of the Maures Massif may represent parts of the Hercynian Gneiss Dome (Elter et al., 1995) not involved in Alpine orogeny.

The pre-Triassic crystalline successions of the Northern Apennines can be correlated with correspondent units of Central (?Late Cambrian-Devonian Tuscan Successions = External Nappe Zone) and NE Sardinia (Micaschist Complex= Internal Nappe Zone and Posada Valley Zone pp.; Gneiss Complex= Posada Valley Zone pp. and/or sil+mu zone of HGMC) (Figure 10). In addition, all these successions suffered the same late- to post-tectonic thermometamorphism due to the Late Carboniferous-Early Permian granitoid intrusions. Therefore, in spite of the severe tectonic transpositions and slicing within the original Variscan crust occurred during the Alpine Orogeny in Tuscany, the data suggest a possible continuation of the Grimaud-Asinara-Posada Line within the Tuscan sector of the Variscan chain.

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