Outline of the Variscan basement of Sardinia

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Abstract - In Sardinia a quasi-complete section of the southern branch of the Variscan orogenic belt crops out, characterized by non-metamorphosed to high-grade rocks, whose age ranges from Early Cambrian to Early Carboniferous, and that are involved in a complex polyphase deformation. The main result of the Variscan orogeny in Sardinia is a tectono-metamorphic partition with, from north to south: an Inner Zone, with medium to high grade metamorphism, thrusted over a Nappe Zone, with green schist metamorphism that overthrusted a Foreland Zone not affected by regional metamorphism. The pre-Variscan succession is well exposed in the Foreland and Nappe zones where four main synthemes can be recognized: i) a Lower Cambrian to Lower Ordovician terrigenous and carbonatic succession deposited in the Gondwana passive margin, sealed by an angular unconformity related to the Sardic Phase, ii) a Middle-Upper Ordovician magmatic complex, both intrusive and effusive, probably related to an Andean-type plate convergence, iii) a terrigenous to carbonatic succession from Late Ordovician to Early Carboniferous, again related to a passive margin evolution; iv) finally a flyschoid Culm-like succession accredited to Early Carboniferous.

Key words - Variscan orogenic belt, tectonics, stratigraphy, Sardinia.

Introduction

In Sardinia a segment of the southern branch of the European Variscan orogen crops out, involving metamorphic rocks aging from Early Cambrian to Early Carboniferous, and a late orogenic magmatic complex emplaced during Late Carboniferous and Permian (Fig. 1).

Restoring the eastward drifting and counter-clockwise rotation of the Sardinia-Corsica block occurred in early Miocene time (Arthaud & Matte, 1966, 1977; Alvarez, 1972; Westphal et al., 1976; Matte, 2001; Gattacceca et al. 2007), both stratigraphical and tectonic features of the Sardinian metamorphic basement find their prolongation in the Variscan domains of the South European margin, although some problems arise about the pre-Variscan paleogeography (Edel et al., 1981; Robardet, 2003). According to most of the authors, the European Variscides, before being dismembered and/or incorporated in the Alpine orogens, belonged to an arched orogenic belt that run from the Iberian Peninsula to the French Massif Central (Ibero-Armorican Arc) (Matte, 1986; Vai & Cocozza, 1986) (Fig. 2). The Sardinian metamorphic basement is thus a part of the South European Variscides that resulted (Matte, 2001) from the diachronic collision between Laurentia-Baltica to the NW and Gondwana to the SE. Between these two continents the occurrence of small, intermediate continental plates, as Avalonia and the so called Armorica-Terrane-Assemblage (Franke, 2000) or Hun Superterrane (von Raumer et al., 2003) contributed in generating a complex orogenic belt. In fact they are generally assumed to have been detached from Gondwana during the Ordovician and docked to Laurentia and Baltica before the Carboniferous collision between Gondwana and Laurussia; hence within the orogenic belt different oceanic sutures separate the different terranes.

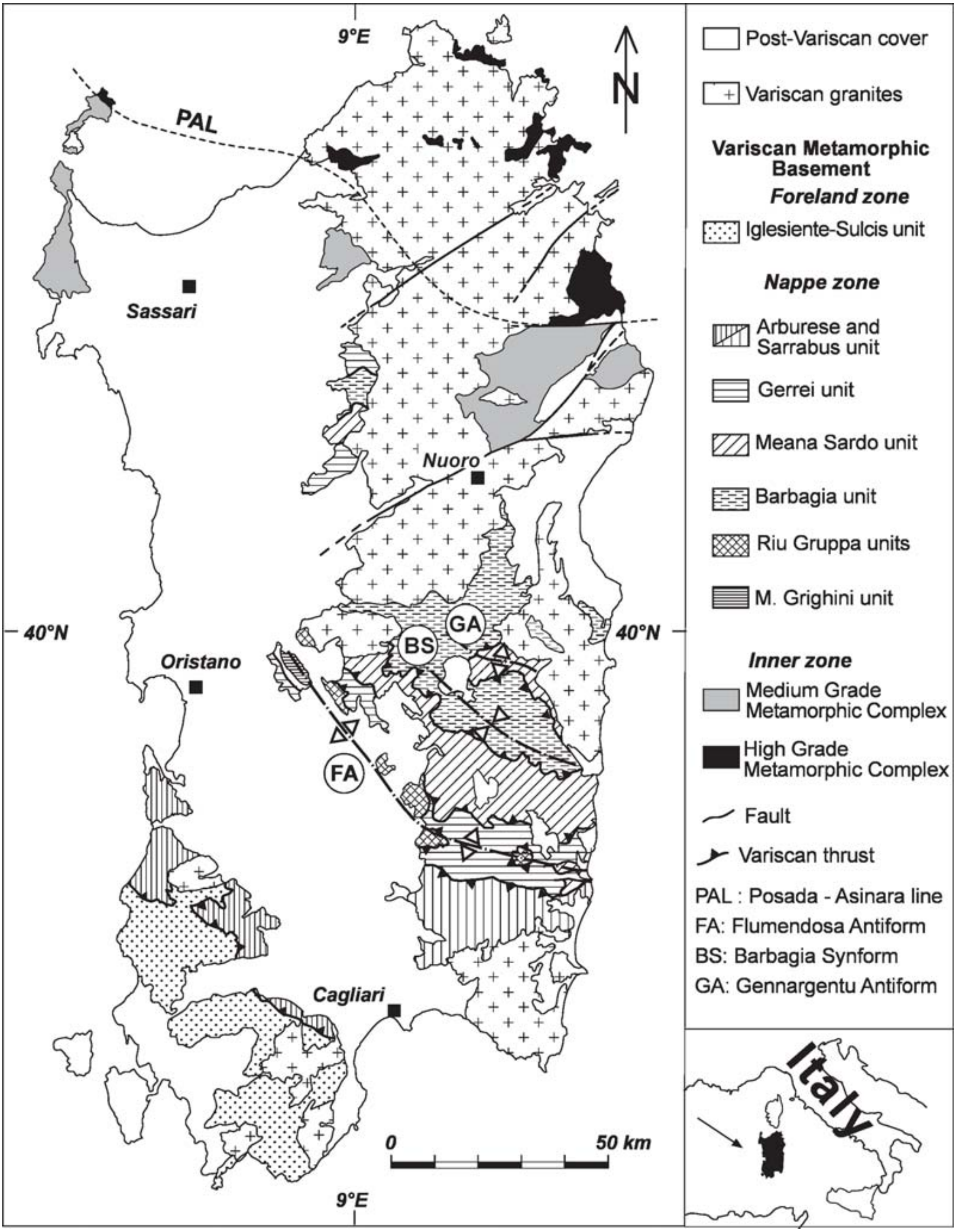


Fig. 1 - Geological sketch map of the Sardinian Variscides.

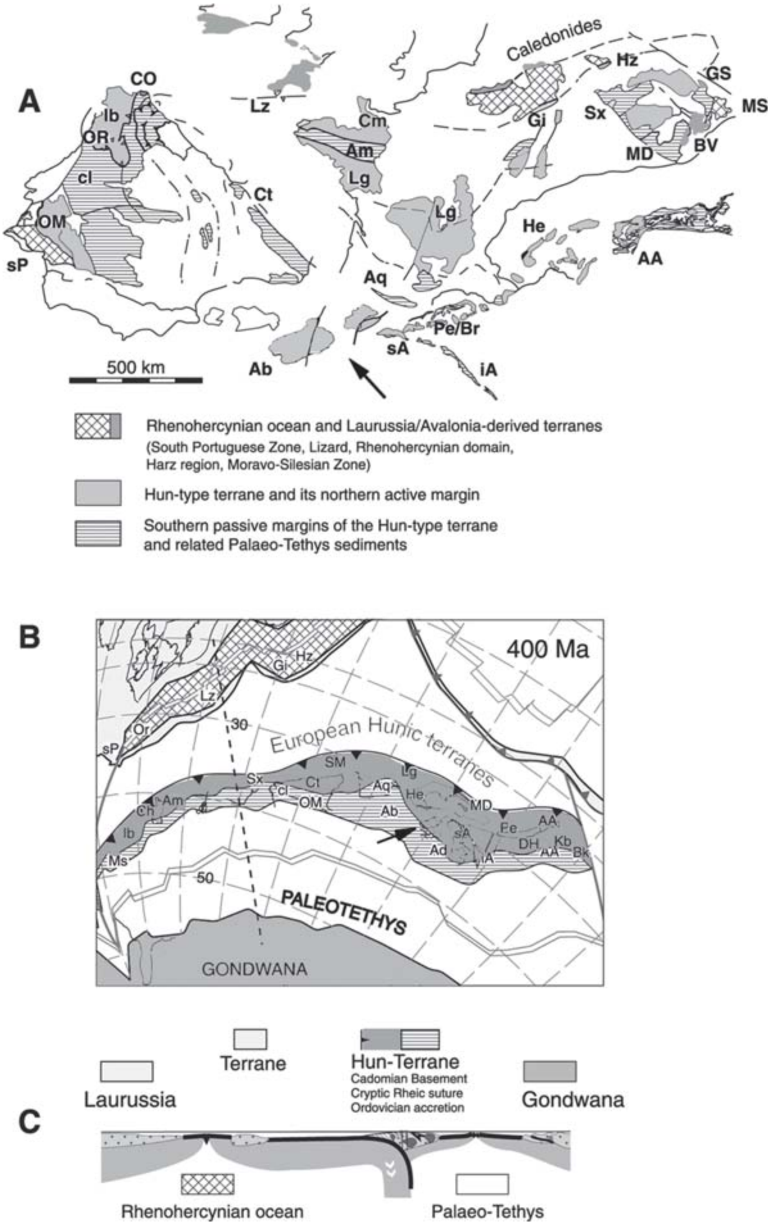


Fig. 2 - Schematic tectonic sketch map of the European Variscides. A) Reconstruction at Permian times (modified from Stampfli et al., 2001); B) Tectonic sketch reconstruction at Silurian times (modified from Stampfli & Borel 2002); C) Tentative schematic section at Silurian times. Abbreviations: AA, Austro-Alpine; Ab, Alboran plate; Ad, Adrias.str.; Am, Armorica; Aq, Aquitaine/French Pyrenees; Bk, Bolkardag; BV, Brunovistulian; Ch, Channel Islands; cI, central Iberia; Cm, Cadomia s.str.; CO, Cabo Ortegal; Ct, Cantabria–Asturia; Spanish Pyrenees; DH, Dinarides–Hellenides; GS, Gory Sowie; Gi, Giessen-nappe; He, Helvetic; Hz, Harz Mountains; iA, Intra-Alpine terrane; Ib, Iberia, NW-allochthon; Kb, Karaburun; Lg, Ligerian; Lz, Lizard; MD, Moldanubian; Ms, Meseta, Morocco; MS, Moravo-Silesian; OM, Ossa Morena; Or, Ordenes ophiolites; Pe, Penninic; Pe/Br Penninic/Brianconnais; sA, South Alpine; SM, Serbo-Mazedonian; sP, South Portugese; Sx, Saxothuringian. The black arrow indicates the position of Sardinia and Corsica.

As for the Sardinian segment of this chain, a simplified scheme can be described in terms of a collisional (D1) deformation, with Barrow type metamorphism increasing northwards during the Early Carboniferous, and in terms of an extensional deformation (D2), which affected the shortened orogenic wedge, leading to HT/LP metamorphism and emplacement of the Sardinia-Corsica Batholith during Late Carboniferous-Early Permian.

The main feature of the continental collision is a tectono-metamorphic zoning that, according to Carmignani et al. (1987), consists of (Fig., 3):

· A Foreland Zone in the SW (Iglesiente-Sulcis region), characterized by strong diagenesis to very-low-grade metamorphism;
· A tectonic Nappe Zone, within green schist facies metamorphic grade, in southeastern and central Sardinia overthrusted on the foreland;
· An Inner Zone, highly deformed with medium to high-grade metamorphism.

Three main tectonic phases with different tectonic transport direction (Carmignani et al., 1994) characterize the collisional deformation both in the Nappe Zone and in the Foreland Zone (Conti et al., 2001; Funedda, 2008):

i) the main syn-metamorphic phase is characterized by kilometric isoclinal folds and large thrusts with a "top-to-the-south" tectonic transport (D1 Phase of Carmignani & Pertusati, 1977; Gerrei and Meana Phase of Conti et al., 2001);
ii) non-cylindrical folds and wrench-thrusts characterize the second collisional phase. These regional structures commonly show a "top-to-the-west" tectonic transport (D2 Phase of Carosi & Oggiano, 2002; Sarrabus Phase of Conti et al., 2001). The structures owing to this phase are remarkably exposed close to the foreland, at Nurra in northwestern Sardinia, close to the PAL (Posada-Asinara line) and also in the Goceano region (Oggiano, 1994);
iii) finally, a third deformation phase gave rise to km-scale open upright folds with NNW-SSE oriented axis (Flumendosa Phase of Conti et al., 2001; D3 Phase of Oggiano & Di Pisa, 1988).

After collisional deformations and crustal thickening, negative tectonic inversion occurred involving extension at middle-upper crustal layers, plutonism, HT-LP metamorphism, exhumation of deep tectonic units and Late Carboniferous-Permian basins. Though the origin is controversial, most authors have considered this combination of processes to be related to the post-orogenic collapse (Dessau et al., 1982; Oggiano & Di Pisa, 1988; Conti et al., 1999; Oggiano & Casini, 2008).

Age of deformation

The age of deformation is related to the Variscan orogeny as supported by both stratigraphical and radiometric data:

a) in the Foreland and External Nappe zones the youngest formations affected by thrusting and folding and related regional metamorphism are Early Carboniferous in age (Maxia, 1983; Barca & Olivieri, 1991; Barca et al., 1992, 2003; Corradini et al., 2003;), whereas the oldest rocks not involved in both Variscan deformation and regional metamorphism are those infilling the Late Carboniferous - Early Permian basins (Cocozza, 1967; Del Rio, 1973; Fondi, 1979; Pittau et al., 2008).

b) In the Inner Nappe Zone (Nurra) Ar/Ar ages on syn-D1 amphibole yielded 340 Ma, and Rb/Sr blocking ages on white micas from D1-related fabrics in the medium-grade metamorphic complex (kyanite zone) yielded ages in the range of 350 Ma (Del Moro et al., 1991). Similar Ar/Ar ages were obtained on white micas from the same metamorphic complex (Ferrara et al., 1978; Di Vincenzo, 2004;).

c) The age of the late orogenic extensional deformation can be inferred by the blocking age of white micas in the areas affected by HT/LP (Asinara and Anglona) metamorphic evolution, where low angle normal shear and low angle normal fault led to core complexes-type structures. The mica age of this tectono-metamorphic event ranges between 320 and 300 Ma, showing a good fitting with the Ar/Ar age on amphibole from the same areas (Di Pisa & Oggiano, unpubl.). Those data overlaps that of the calk-alkaline plutonic association of the Sardinia-Corsica Batholith which emplaced between 311 and 274 Ma, mostly related to the post-collisional extensional events (Del Moro, et al. 1972, 1975; Cocherie, 1978; Ghezzo & Orsini, 1982; Oggiano, et al. 2005). The HT/LP metamorphic event also fits the U/Pb age of 321±0.8 Ma yielded by an anatectic, peraluminous, synkinematic granite, which emplaced within dextral shear zone (Oggiano et al., 2007).

Tectono-stratigraphic setting

Foreland Zone

A well constrained meta-sedimentary succession crops out in the Foreland Zone, ranging from the Lower Cambrian to the Lower Carboniferous (Carmignani et al., 2001b, and references therein), affected by an anchizonal regional metamorphism (Fig. 4). This

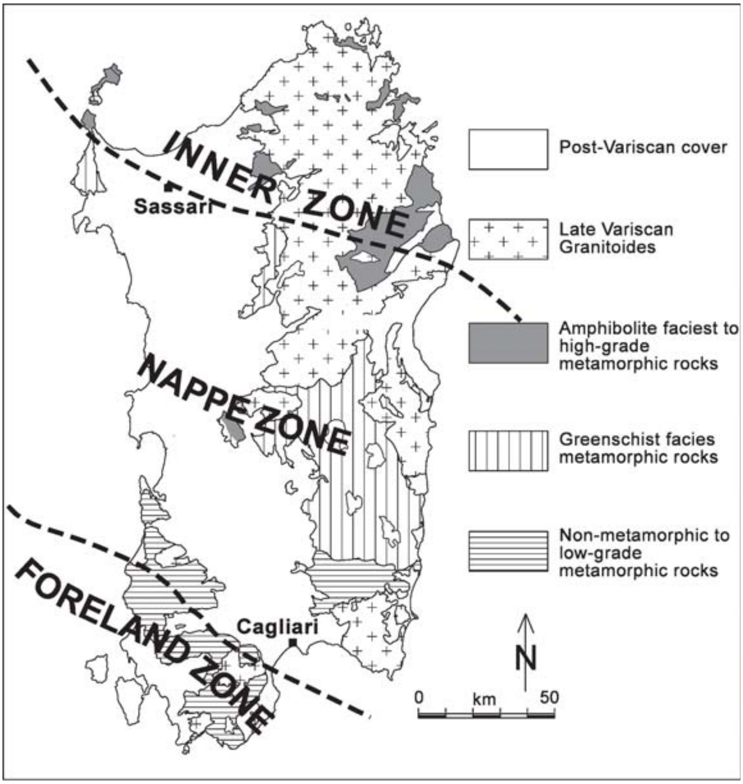


Fig. 3 - Tectonic and metamorphic partition of the Sardinian Variscides.

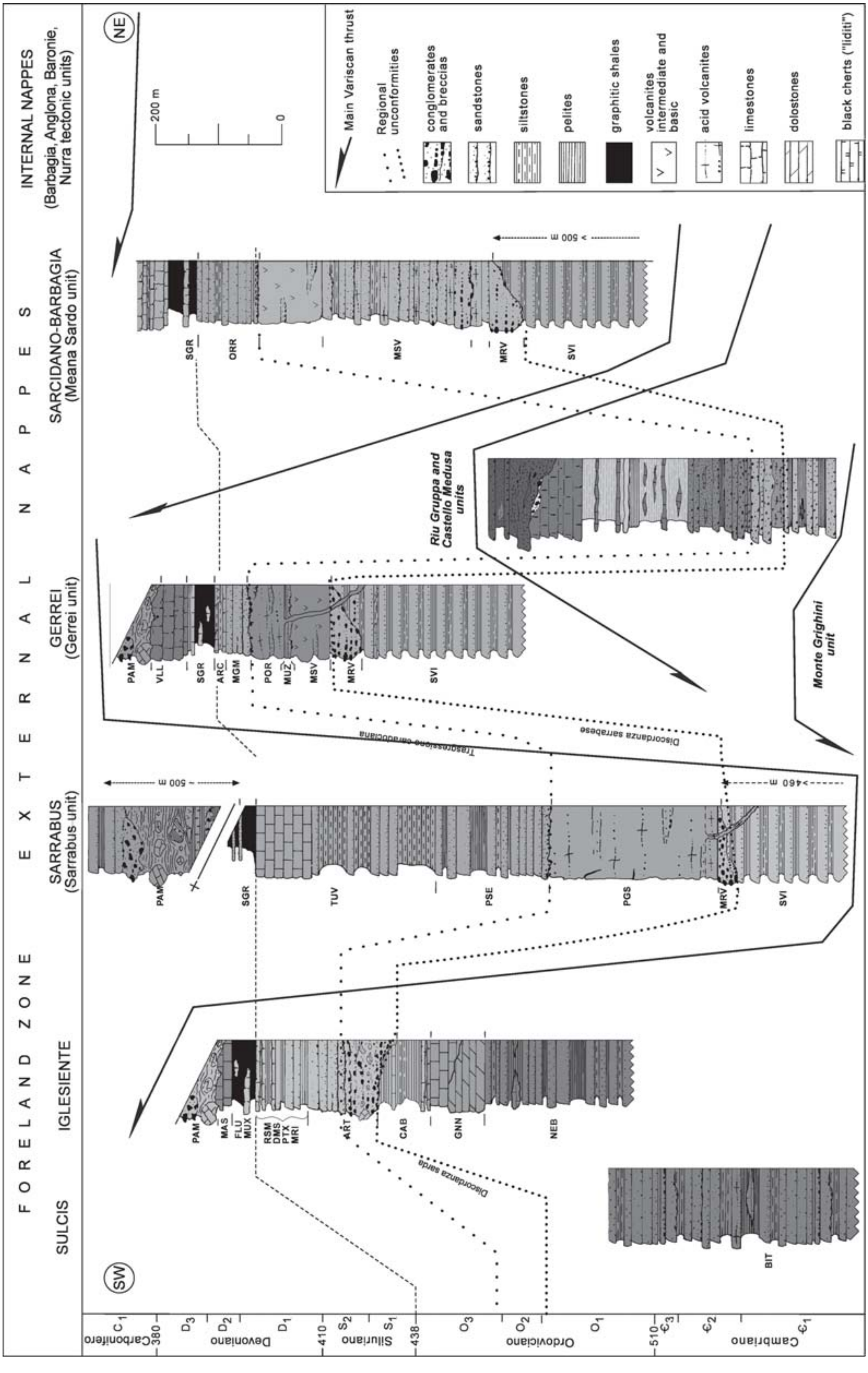
succession comprises two sequences separated by an important angular unconformity (Sardic Unconformity).

The first sequence starts with the Lower Cambrian Nebida Group (Cocozza, 1979; Pillola, 1991, 1995), made up by sandstones and pelites with carbonatic archeocyata-bearing mounds (Matoppa Fm.), oolitic limestones followed by sandstones and quarzites in alternation with limestones and dolostone (Punta Manna Fm.). In the Iglesiente region the apparent thickness reaches about 250 m. The Gonnesa Group (Lower Cambrian) follows the Punta Manna Fm. It consists of well stratified dolostone at the base (Santa Barbara Fm., previously knows as Dolomia rigata Mb.) and by grey massive, sometime dolomitic, limestone, (San Giovanni Fm., previously knows as Calcare Ceroide Mb.), with rare fossil content. Its total thickness is about 200 m (Rasetti, 1972; Cocozza, 1979; Bechstadt et al., 1994). The sequence is terminated by the Iglesias Group, the base of which is the nodular limestone of the Campo Pisano Fm. (previously known as Calcare nodulare), about 50 m thick, bearing trilobites, brachiopoda, echinodermata of Middle Cambrian. This formation grades into shale and siltsones of the Cabitza Fm., about 150 m thick, ranging in age from Middle Cambrian to Early Ordovician (Pillola et al., 2008). This sedimentary succession is truncated by the Sardic Unconformity: an angular unconformity which was related to an eo-Caledonian tectonic phase (Stille, 1935, 1939; Cocozza & Valera, 1966). Above the unconformity metaconglomerates, megabreccias (“Puddinga Ordoviciana” Auct.) and phyllites of the Monte Argentu Fm. rest (Laske et al., 1994, and references therein); their thickness ranges from few decameters to 200 m. Upwards the siliciclastic sediments of Late Ordovician age (Leone et al., 1991; Loi et al., 1992) crop out (from the base to the top: Monte Orri, Portixeddu, Domusnovas and Rio San Marco formations) followed by black shales and limestones of Silurian-Early Devonian age (Gnoli et al., 1990) (Genna Muxerru, Fluminimaggiore and Mason Porcus formations).

Unlike the Nappe Zone, in the Foreland Zone no volcanic succession has been recognized during the Middle Ordovician emergence phase. Volcanics occur, but as reworked pebbles in the basal member of the Rio San Marco Fm. On the top of Middle Devonian a syn-orogenic Lower Carboniferous rests (Barca et al., 1998), interpreted as Culm-like flysch.

The succession of the Foreland Zone of southwestern Sardinia exhibits no significant Variscan metamorphic imprint: both the pre-Sardic and post-Sardic sequences are non-metamorphic or anchimetamorphic at Iglesiente (Franceschelli et al., 1992). Whether metamorphism and significant deformation were associated with the Sardic phase is still matter of debate; some authors reject the concept of a Sardic “folding” phase (Minucci, 1935; Graulich, 1953; Del Bono, 1965; Brouwer, 1987) and attribute the structuring of the External Zone exclusively to the Variscan tectonism (Lüneburg & Lebit, 1998; Lüneburg et al., 1999).

Fig. 4 - Litho-stratigraphical synthetic columns of the tectonic units in the external nappes and Foreland zone. Abbreviations: ARC: “Argilloscisti di Rio Canoni”; ART: M. Argentu Formation (Puddinga Auct.); BIT: Bithia Formation; CAB: Cabitza Formation; MRV: “Metaconglomerato di Muravera”; DOM: Domusnovas Formation; FLU: Fluminimaggiore Formation; GNN: Gonnesa Formation; MGM: “Metarcose di Genna Mesa”; MUX: Genna Muxerru Formation; MUZ: “metarenarie e quarziti di Su Muzzioni”; NEB: Nebida Formation; ORR: Orroeledu Formation; MAS: Mason Porcus Formation; MRI: Monte Orri Formation; PAM: Pala Manna Formation; MSV: Monte Santa Vittoria Formation; PGS: “Porfidi grigi del Sarrabus”; POR: “Porfiroidi”; PSE: Punta Serpeddì Formation; PTX: Portixeddu Formation; RSM: Rio san Marco Formation; SGR: “Scisti a Graptoliti” + “Ockerkalk”; SVI: “Arenarie di San Vito”; TUV: Tuviois Formation; VLL: “Calcari di Villasalto”.


FORELAND ZONE
EXTERNAL NAPPES
INTERNAL NAPPES
(Barbagia, Anglona, Baronie, Nurra tectonic units)
SULCIS
IGLESIENTE
SARRABUS
(Sarrabus unit)
GERREI
(Gerrei unit)
SARCIDANO-BARBAGIA
(Meana Sardo unit)
Riu Gruppa and Castello Medusa units
Monte Grighini unit
SW
NE
200 m
0
Main Variscan thrust
Regional unconformities
conglomerates and breccias
sandstones
siltstones
pelites
graphitic shales
volcanites intermediate and basic
acid volcanites
limestones
dolostones
black cherts ("liditi")
Carbonifero
Devoniano
Siluriano
Ordoviciano
Cambriano
Discordanza sarda
Discordanza sarrabese
Trasgressione caradociana
~ 500 m
> 500 m
>460 m
PAM
MAS
FLU
MUX
RSM
DMS
PTX
MRI
ART
CAB
GNN
NEB
BIT
SGR
TUV
PSE
PGS
MRV
SVI
VLL
ARC
MGM
POR
MUZ
MSV
ORR

The similarity of the Palaeozoic of the External Zone of Sardinia (Iglesiente) with the Montagne Noire succession (Arthaud, 1970) makes it possible to attribute these formations to the Gondwana margin, that acted as foreland during Early Carboniferous collision.

Nappe Zone

The Nappe Zone is divided in two parts: the external nappes, close to the foreland, characterized by a well defined litho-stratigraphic succession, and the inner nappes, closer to the Inner Zone, where clastic monotonous metasediments prevail, with interlayered rare metabasites.

Although the External Nappe Zone extent ranges from the northwestern side (Nurra) through the central part (Goceano) to the southeastern side of the island (Sarrabus-Gerrei), only the latter is generally described, due to its better exposition and low metamorphic grade that allows biostratigraphical investigations.

The best exposed section of the nappe stack outcrops in the southeastern part of the island, where the deepest tectonic unit is the Castello Medusa-Riu Gruppa unit overridden by the Gerrei unit.

Northward the Meana Sardo unit in turn overrides the Gerrei unit. The Barbagia unit, of still poorly constrained age, occupies the top of the stack. Southward the Sarrabus unit lies above both the Gerrei and Meana Sardo units, hence it is also the shallowest tectonic unit in the Nappe Zone. Other units of the nappe stack crop in central-northern Sardinia, where the Ozieri unit is overridden by the Fiorentini unit (Oggiano, 1994), and in the Nurra region of nortwestern Sardinia (Li Trumbetti and Canaglia units; Oggiano & Mameli, 2006) (Fig. 4).

The lithostratigraphical succession that characterizes the different tectonic units is similar among the external nappes, but differences arise in that of the inner nappes.
The succession of the external nappe shows the following stratigraphical features:
1) A siliciclastic succession at the base (Arenarie di San Vito Fm., also reported as Arenarie di Solanas Fm.) (Calvino, 1959) dated from Middle Cambrian to Early Ordovician (Naud & Pittau Demelia, 1987; Di Milia & Tongiorgi, 1993). The top of the San Vito sandstone is unknown due to an erosive truncation (Sarrabese Unconformity; Calvino, 1959) that corresponds to the Sardic Unconformity.
2) On the unconformity surface a thin nonmarine metaconglomerate (Metaconglomerati di Muravera; Carmignani et al., 2001a) and huge amounts of volcanic rocks rest: Monte Santa Vittoria Fm. (Carmignani et al., 2001a), Porfiroidi Fm., Porfidi grigi del Sarrabus Fm. (Calvino, 1956). They form a calc-alkaline suite, made up of andesitic to dacitic and rhyolitic rocks, about Middle Ordovician in age (Buzzi et al., 2007). The varied Ordovician volcanogenic formations are the most complete and best preserved within the South European Variscides. Their origin is related to an Ordovician arc that developed on the north-Gondwana margin as a consequence of the subduction of oceanic crust under continental crust (Andean type convergence) (Di Pisa et al., 1992, Stampfli & Borel, 2002). The age of the volcanic activity is well constrained by both stratigraphy and palaeontology; it post-dates the Sarrabese (i.e. Sardic) Unconformity and pre-dates the Katian transgression.
3) Shoreface to shelf sandstone and mudstone (Loi et al., 1992), deposited during the Katian and Hirnantian throughout the palaeogeographic domain of the Nappe Zone, as testified by the terrigeneous formations of the Upper Ordovician (Orroeledu Fm., Rio Canoni Shales, Punta Serpeddì Fm. and Tuviois Fm.) (Bosellini & Ogniben, 1968; Naud, 1979; Barca & Maxia, 1982; Loi, 1993; Loi & Dabard, 1997). These sediments contain interbedded metabasites and basic to intermediate meta-epiclastites. Locally, a submarine emplacement is indicated by pillow basalt embedded within fossiliferous Late Ordovician

metagreywacke in the external nappes (Lehmann, 1975; Di Pisa et al., 1992). Then, in the different units of the Nappe Zone, lies a Silurian succession typically represented by black graphitic shales and metasiltstones (Scisti a graptoliti; see Corradini & Ferretti, 2009, this volume), which have been well studied since the second half of XIX century because of their rich graptolite faunas (see Barca and Storch & Piras, 2009, this volume). The Silurian shale is everywhere overlain by a continuous Tentaculites-bearing marlstones (Scisti a Tentaculiti, Auct., see Corradini & Ferretti, 2009, this volume) and *Clymenia*-bearing shelf limestone that encompass the entire Devonian and base of the Carboniferous (Calcari di Villasalto, Carmignani et al., 2001a; Calcari a Clymenia, Olivieri, 1969; Corradini et al., 2003).

4) On the top of the Lower Carboniferous limestones, and sometimes directly on the Silurian black shales, a clastic succession rests, with an erosive unconformity (Pala Manna Fm., Barca et al., 2003). It consists mostly of sandstones and conglomerates, with olistoliths coming from the lowest formations, mainly marbles, completely involved in the Variscan structures, interpreted by the authors as a Culm-like deposits (Maxia, 1983; Barca, 1991; Barca & Olivieri, 1991).

Inner Zone

This part of the chain is characterized by medium to high grade metamorphic rocks consisting in:

a) a polymetamorphic high-grade complex made up of anatexites and metatexites hosting orthogneiss and minor metabasite with relic granulite associations, which generally re-equilibrated under LP/HT conditions. This latter complex crops in the northernmost part of the island and extends to Corsica (Ghezzo et al., 1979; Di Pisa et al., 1993). The early granulite event is preserved within layered mafic–ultramafic bodies, including metagabbroes, cropping out at Golfo Aranci (Ghezzo et al., 1979; Giacomini et al., 2006). An eclogite body with a granulitic overprint is exposed at Punta de li Tulchi (Miller et al., 1976; Franceschelli et al., 1998, 2005; Cortesogno et al., 2004) within a complex of orthogneiss and metapelite affected by widespread anatectic mobilization under amphibolite-facies conditions in the stability field of sillimanite and, locally, cordierite. U/Pb zircon ages of this eclogite, give 450 Ma for the protolith, whilst ages close to 400 Ma are interpreted as dating the crystallization of a second zircon population during eclogite metamorphism (Cortesogno et al., 2004). Leptynite-amphibolite complexes are also found on Asinara Island (Castorina et al., 1996) and near Olbia, the former exhibiting an alkaline and the latter (Franceschelli et al., 2005) a continental tholeiitic affinity.

b) a medium grade, chiefly metapelitic complex, consisting of micaschists and paragneisses bearing Ky+/- Stau +/- garnet and including quartzites and N-MORB metabasalts boudins retaining eclogitic assemblage (Cappelli et al., 1992).

The contact between these two complexes is well exposed along the Posada Valley (Elter, 1987) as well as in southern Gallura and Asinara island (Del Moro et al., 1991; Oggiano & Di Pisa, 1992; Carmignani & Oggiano, 1997), consisting of a mylonitic shear zone with evident dextral strike–slip component.

Within the collisional frame the high grade migmatitic complex has been considered made up of chiefly crustal slices comparable to the inner crystalline nappes of the French Massif Central and the high strained complex B has been regarded as the Sardinia segment of the South Variscan Suture Zone (Carmignani et al., 1994) which re-equilibrated under intermediate P amphibolitic conditions.

After the construction of the orogenic buildup a late post collisional tectonics linked to the gravitational an thermal collapse of the chain took place in concomitance with the emplacement of the Sardina Batholith.

The high grade complex is juxtaposed with the medium grade metamorphic complex by mean of thrust or wrench-thrust shear zone (Posada-Asinara Line) in proximity of which more or less retrogressed eclogite boudins scatter. For this reason the PAL was compared to the South Variscan Suture Zone by Cappelli et al. (1992).

Acknowledgements

Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaentological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

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