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THE VARISCAN BASEMENT OF NORTHERN SARDINIA (ITALY): FIELD GUIDE TO THE EXCURSION IN THE BARONIE REGION

Abstract - After a short and updated geologic overview of the Variscan belt in Sardinia a field trip in the Baronie area (in the northeastern portion of the island) is described. We choose six stops that can be easily reached and visited in one day. They are among the best outcrops where the tectono-metamorphic history of this sector of the Variscan belt was unravelled.

Key words - Variscan basement, Sardinia, tectonics, metamorphism, geological field trip.

Riassunto - *Il Basamento Varisico della Sardegna settentrionale (Italia): guida all'escursione della regione delle Baronie*. Dopo un breve e aggiornato inquadramento del lembo di catena Varisica affiorante in Sardegna viene descritto un itinerario geologico nella regione delle Baronie in Sardegna settentrionale. Sono state scelte sei località facilmente accessibili dove, nell'arco di una giornata, è possibile osservare alcuni dei più classici affioramenti di rocce Paleozoiche coinvolte nell'orogenesi Varisica che hanno permesso di decifrare la complessa storia tettonica e metamorfica di questo settore di catena orogenica.

Parole chiave - Basamento Varisico, Sardegna, tettonica, metamorfismo, escursione geologica.

Introduction

The Variscan basement in Sardinia is an almost complete section across the South Variscan belt showing the transition from the low- up to the medium-high-grade basement (Fig. 1). The basement shows beautiful expositions of folded, sheared and metamorphosed Paleozoic rocks poorly affected by Alpine tectonics.

The aim of the field trip is to show the effects of progressive deformation and metamorphism along one of the most classical geological transect in the Variscan belt in Northern Sardinia located in the Baronie area (Fig. 2). From south to north we can clearly observe the effects of the D1 compressional deformation with south verging recumbent folds and shear zones affected by a D2 deformation, with strain increasing northward and tectonic transport parallel to the belt. The Paleozoic rocks underwent progressive Barrovian-type metamorphism increasing northward. The classical place where it is well-observable is the Baronie transect. In the Asinara Island and Anglona we can observe the superposition of the high-grade metamorphic complex over the medium-grade rocks. The effects of HT-LP metamorphism, affecting the Barrovian one, are evident at the microscopic-scale and at the outcrop scale also by the growth of cm- to dm-size andalusite porphyroblasts. The relations among late orogenic plutons, dykes and metamorphytes are clearly exposed in the proposed transect. During this field trip the classical results of the tectonic and metamorphic studies in the Variscan belt of Sardinia will be shown (Carmignani *et al.*, 1994; Ricci *et al.*, 2004 and references therein) together with the new results reached after intense researches performed in the last few years by the researchers from Pisa University (funded by Italian Ministery of Research and University of Pisa) in collaboration with researchers from Cagliari, Sassari and Siena Universities.

It is worth to note the new structural and geological mapping at 1:10.000 scale of the Asinara island, Anglona and Baronie with the systematic observation of structural elements, the late D1 shear zones related to beginning of exhumation, the relationship between D2 transpressional deformation and the exhumation of the basement, the datation by Ar-Ar of the D1 and D2 deformation events, the recognition, for the first time, of sinistral shear zones along the Posada-Asinara Line and the change in the classical zonation of Barrovian metamorphism in the Baronie due to the finding of staurolite + biotite appearance several kilometres southward with respect to the position of the classical isograd (Carosi *et al.*, in prep.).

However, some important aspects in the tectonic evolution of the Sardinian Variscan belt are still matter of debate such as: the existence of an oceanic suture, the pre-Variscan evolution and the presence of a pre-Variscan basement and, finally, the position of the Corsica-Sardinia microplate during the upper Paleozoic and its correlations with the other fragments of the Southern Variscan belt.

Regional geological setting

The present position of Sardinia and Corsica islands is due to a 30° anticlockwise rotation of the Corsica-Sardinia block away from Europe caused by opening of the Western Mediterranean Ligurian-Provençal basin. The age of the rifting phase is dated to Oligocene (from 30 to 24 Ma) followed by a short Early Miocene oceanic accretion (ages ranging from 23 to 15 Ma, Ferrandini *et al.*, 2000 and references therein). Then the structural pre-drift directions, namely Variscan, have to be restored of ~30° with respect to the stable Europe.

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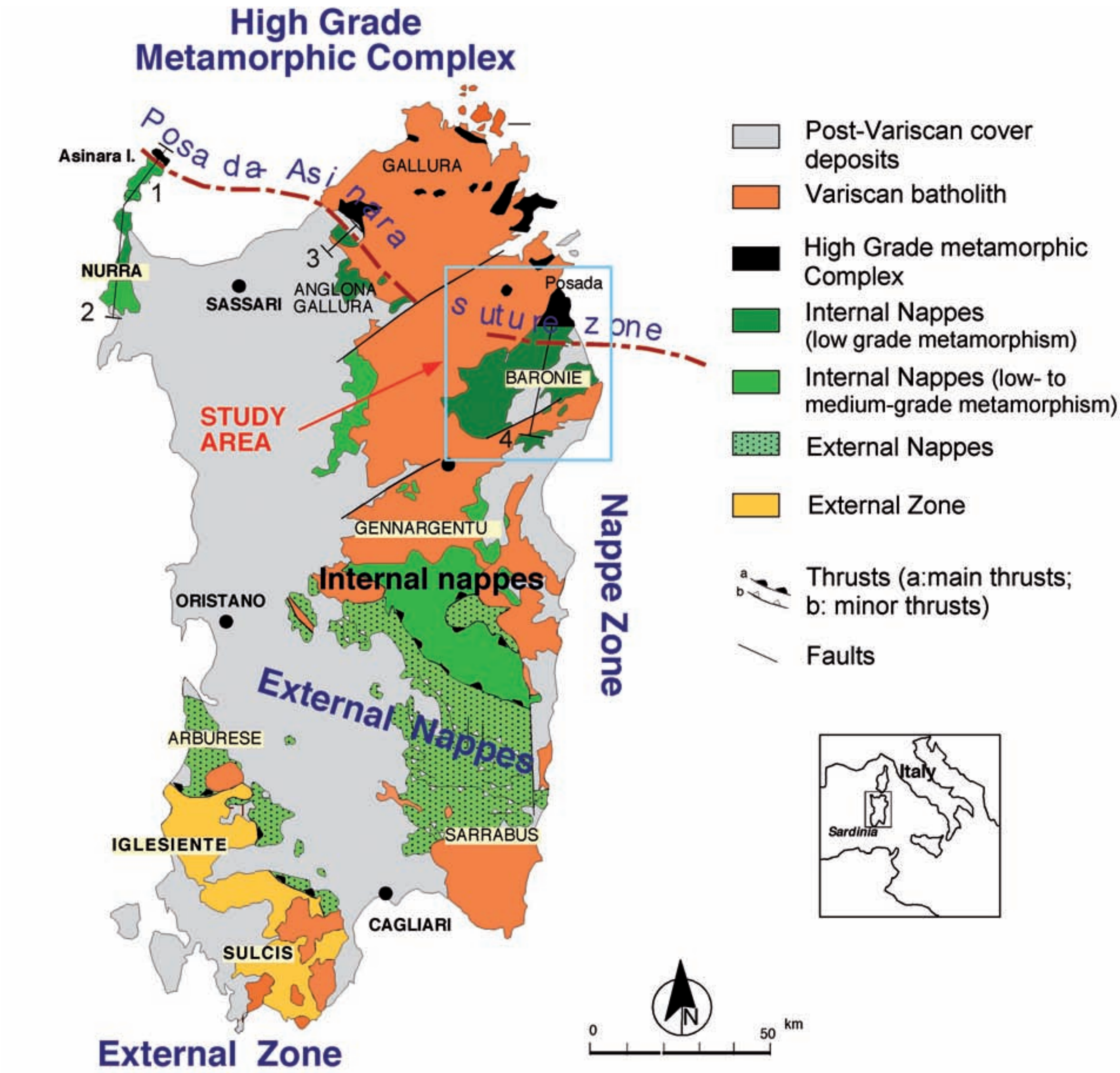

Fig. 1 - Tectonic sketch-map of the Variscan belt in Sardinia and location of the study areas (from Carosi *et al.*, 2005). Trace of geological cross section: 1. Asinara Island; 2. Nurra peninsula; 3. SW Gallura region; 4. Baronie region.

The largest part of Sardinia and Western Corsica islands is made up of a Permo-Carboniferous batholith emplaced between 340 and 280 Ma into a Variscan basement which crops out more extensively in Sardinia than in Corsica.

In northern Sardinia and in central and southern Corsica the pre-Permian basement has been affected by Variscan tectono-metamorphic imprint. This basement consists mainly of high-grade metamorphic rocks and was termed the «inner zone» by Carmignani *et al.* (1979) (Fig. 1), and according to these authors it could represent the witness of a continental collision. The different structural Variscan zones were defined in Sardinia where Variscan metamorphic formations widely crop out and were more extensively surveyed.

THE SARDINIAN VARISCAN BELT

The Variscan basement in Sardinia shows a prominent NW-SE trend (Carmignani *et al.*, 1979, 1994 and references therein) characterized by nappes, tectono-meta-

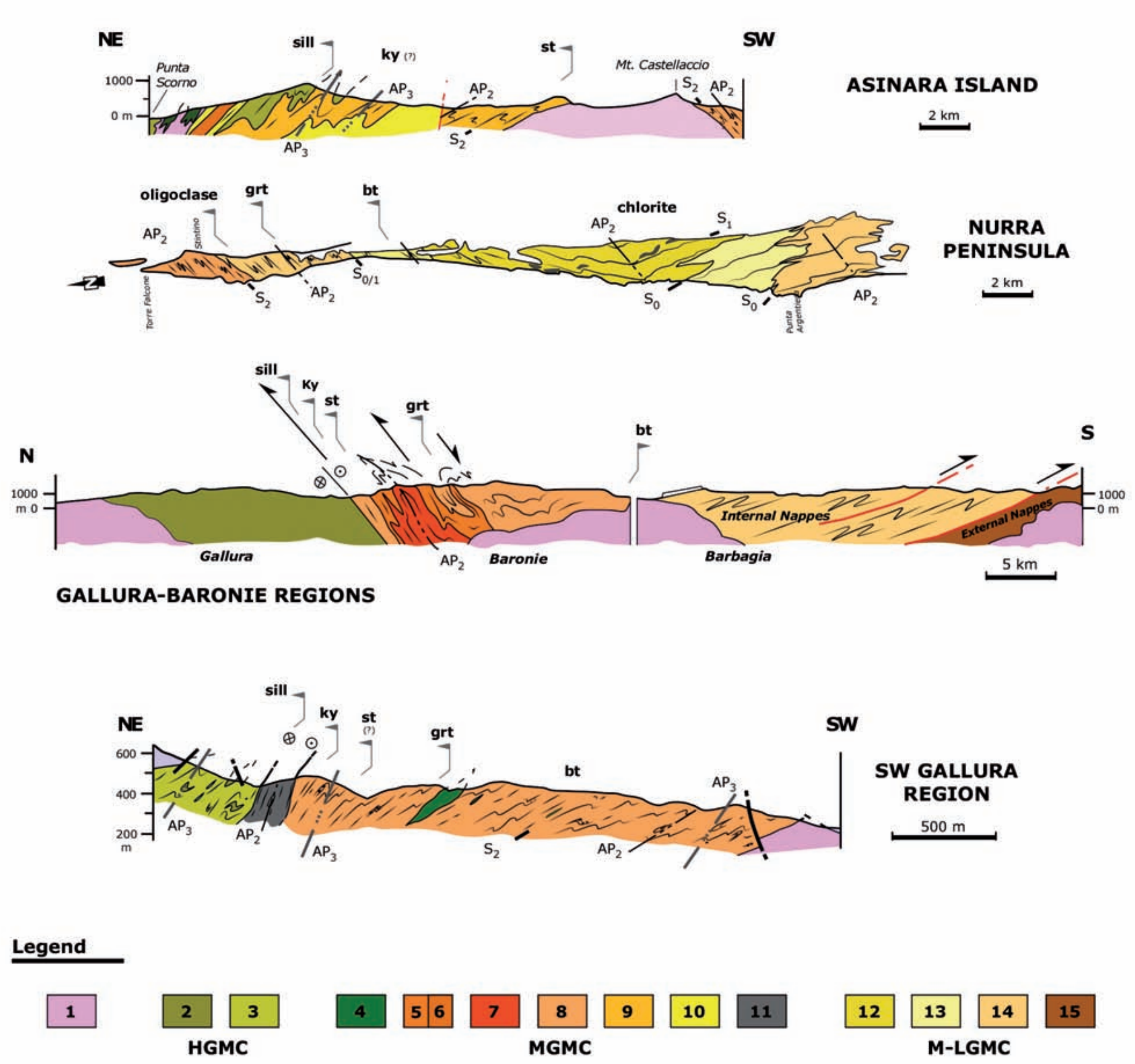

Fig. 2 - Geological cross sections (1-4) throughout the Variscan basement of northern Sardinia in the three study areas (see Geological map of Northern Sardinia, Carosi *et al.*, 2005).
1 - Variscan granitoids. HGMC (High-Grade Metamorphic Complex): 2 - Migmatites. 3 - High-grade mylonites. MGMC (Medium-Grade Metamorphic Complex): 4 - Eclogites relics. 5 and 6 - Orthogneisses. 7 - Augen gneisses. 8 - Metasedimentary complex in amphibolites facies. 9 - Metasedimentary complex with HT-LP metamorphic overprinting. 10 - Mylonitic micaschists in amphibolites facies. 11 - Phyllonite belt. L-MGMC (Low- to Medium Grade Metamorphic Complex): 12, 13 and 14 - Internal Nappe. 15- External Nappe.
(Modified after Carmignani *et al.*, 1979; Oggiano & Di Pisa, 1992; Carosi & Oggiano, 2002; Carosi & Palmeri, 2002; Carosi *et al.*, 2004).

morphic zoning and shortening similar to those developed in continent-continent collision type orogen.
It is composed of Carboniferous magmatic rocks and Cambrian-Lower Carboniferous igneous-sedimentary sequence with metamorphic grade increasing from South to North.

The collisional structural frame results in three different structural zones (Carmignani *et al.*, 1979, 1982, 1994) (Fig. 1):

1. A foreland «thrusts-and-folds» belt consisting of a metasedimentary sequence ranging in age from upper (?) Vendian to lower Carboniferous, which

crops in SW part of the island, with a very low grade to greenschist facies metamorphic imprint.
2. A SW verging nappe building (central Sardinia) which equilibrated mainly under greenschist facies conditions, consisting of a Palaeozoic sedimentary sequence bearing a thick continental arc-related volcanic suite of Ordovician age.
3. An inner zone («axial zone») (northern Sardinia and southern Corsica) characterised by medium- to high-grade metamorphic rocks with migmatites and by abundant late-Variscan intrusions.

According to Carmignani *et al.* (1994) the inner zone consists of two different metamorphic complexes:

1. A polymetamorphic high-grade complex made up of anatexites and metatexites hosting minor amphibolite bodies which equilibrated in HT-LP conditions which corresponds to the northernmost part of the island and extends to Corsica. In spite of this late re-equilibration, in places granulite relic assemblages of high-intermediate P and unknown age are still detectable (Miller *et al.*, 1976; Ghezzo *et al.*, 1979; Franceschelli *et al.*, 1982; Di Pisa *et al.*, 1993).
2. A medium grade, chiefly metapelitic complex, consisting of micaschists and paragneisses bearing kyanite ± staurolite ± garnet (Franceschelli *et al.*, 1982) and including quartzites and N-MORB metabasalts boudins (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 (Oggiano & Di Pisa, 1992; Carmignani & Oggiano, 1997) and it coincides with a wide transpressive shear belt (Carosi & Palmeri, 2002) and it is affected by late Variscan shear zones (Elter *et al.*, 1990).

Thrusting of complex A onto complex B has been inferred in places where the contact is not complicated by late Variscan retrograde dextral strike-slip shear (Oggiano & Di Pisa, 1992).

Within the collisional frame the high-grade migmatitic complex has been regarded as a crustal nappe comparable to the inner crystalline nappe of the French Massif Central and the high strained complex B has been regarded by Cappelli *et al.* (1992) as the Sardinia segment of the south Variscan suture zone which re-equilibrated under intermediate pressure amphibolitic conditions. As a matter of fact some of the metabasalts embedded within the high-strain kyanite bearing micaschists and in the high-grade complex retain clear relics of eclogitic assemblages (Miller *et al.*, 1976; Cappelli *et al.*, 1992; Oggiano & Di Pisa, 1992; Cortesogno *et al.*, 2004; Giacomini *et al.*, 2005).

However, the presence of a suture in northern Sardinia separating the low- to medium-grade metamorphic rocks of Gondwanian origin from the high-grade metamorphic rocks belonging to the Armorica microplate, as proposed by Cappelli *et al.* (1992) has been recently questioned by several authors mainly on the basis of the presence of ophiolites and presence of similar Ordovician orthogneisses and similar evolution both south and north of the Posada-Asinara Line (Helbing & Tiepolo, 2005; Giacomini *et al.*, 2005, 2006; Franceschelli *et al.*, 2005).

Moreover, Sardinia has been recently attributed by several authors to the «Hun Superterrane» (HS) (Stampfli *et al.*, 2000, 2002; von Raumer, 1998; von Raumer *et al.*, 2002, 2003; Franceschelli *et al.*, 2005; Giacomini *et al.*, 2006), a ribbon-like continent detached from the northern margin of Gondwana during Silurian-Devonian times. In this picture the main subduction of oceanic crust happened (below the Gondwana continent) at the northern margin of the HS (e.g. NW Iberia) during Late Ordovician to Devonian producing eclogites at nearly 440-360 Ma, whereas the southern margin (to which Corsica-Sardinia belonged) underwent extensional tectonics leading to the opening of the Paleo-Tethys. Only at the Devonian/Carboniferous boundary the southern passive margin of the HS became active with the subduction of the Paleo-Tethys crust northward below the southern margin of HS (Stampfli *et al.*, 2002; Giacomini *et al.*, 2006). During this stage continental crust in Sardinia underwent the main phase of southward migrating deformation and prograde Barrovian-type metamorphism.

In places this collisional frame is complicated by the occurrence of a neovariscan (300 Ma) HT-LP re-equilibration affecting both the metamorphic complexes (Del Moro *et al.*, 1991; Oggiano & Di Pisa, 1992). This late HT-LP metamorphic evolution has been related by Oggiano & Di Pisa (1992) to the post-collisional gravitative collapse of the chain, chiefly on the base of its age and of some meso and micro-structural evidences but, alternatively, it could be related to late Variscan intrusions.

The geochronological data in Nurra and in western Gallura the available Ar-Ar data on amphibole and muscovite yielded ages close to 350 Ma (Del Moro *et al.*, 1991). In north-eastern Sardinia an upper limit to the collision-related metamorphism could be represented by the age of 344 ± 7 Ma (Rb-Sr age of isotopic exchange blocking among different compositional domains on a banded gneiss; Ferrara *et al.*, 1978). More recent data yielded ~330 Ma (U-Pb dating on zircons; Palmeri *et al.*, 2004), 350-320 Ma (U-Pb datings on zircons; Giacomini *et al.*, 2006) and at 330-340 Ma (Ar-Ar on white micas; Di Vincenzo *et al.*, 2004) for the collision related metamorphism. It is worth noting that U-Pb dating on zircons (Palmeri *et al.*, 2004; Cortesogno *et al.*, 2004; Giacomini *et al.*, 2005) suggests a HP event bracketed between ~450 and ~350 Ma in the retrogressed eclogites of northern Sardinia.

The D2 transpressional deformation is constrained at 310-320 Ma (Ar-Ar on white micas on S2 foliation; Di Vincenzo *et al.*, 2004). The upper limit of the age of the deformation is constrained by the crosscutting Carboniferous granitoids at ~290-311 Ma (Rb-Sr whole rock isochron; Del Moro *et al.*, 1975).

The structural and metamorphic evolution of the inner zone is well exposed along the three transects provided in the field trip (Figs. 1 and 2).

The D1 collisional event is well-recorded in the study transects producing SW facing folds, top to the S and SW shear zones and the main fabric in the low-grade metamorphic rocks in southern part of the section (Carmignani *et al.*, 1979; Simpson, 1989; Franceschelli *et al.*, 1990; Carosi & Oggiano, 2002; Montomoli, 2003). Recent structural investigations highlighted the occurrence of a regional D2 transpressional deformation related both to NNE-SSW direction of compression and to a NW-SE shear displacement (Carosi & Oggiano, 2002; Carosi & Palmeri, 2002; Carosi *et al.*, 2004, 2005). The deformation is continuous and heterogeneous, showing a northward strain increase, indicated by progressively tighter folds, occurrence of F2 sheath folds and vorticity analysis. D2 transpression is characterized by the presence of a crustal-scale shear deformation overprinting previous D1 structures, related to nappe stacking and top-to-the S and SW «thrusting». The L2 prominent stretching lineation points to an orogen-parallel extension and to a change in the tectonic transport from D1 to D2 (Fig. 3). Orogen-parallel extension could be attributed to the position of Sardinia close to the NE part of the Cantabrian indenter during the progressive evolution of the Ibero-Armorican arc (Carosi *et al.*, 1999; Conti *et al.*, 2001; Carosi & Oggiano, 2002; Carosi & Palmeri, 2002) or to a general progressive curvature of the belt, as well as to the presence of an irregular collided margin. It has been suggested that D1 phase developed during initial frontal collision whereas D2 deformation characterized the progressive effect of horizontal displacement during the increasing curvature of the belt. The Nurra-Asinara transect is a clear example of heterogeneous transpressional deformation partitioned in the space (Carosi *et al.*, 2004; Iacopini, 2005). We have detected a switch in the attitude of L2 stretching lineation, going northward, from nearly sub-horizontal and parallel to A2 fold axes to down-dip in the northern part of the Asinara Island according to theoretical models of transpression proposed by Tikoff & Teyssier (1994).

It is worth to note that in the classical view of the Barrovian metamorphism in northern Sardinia the appearing of sillimanite has been put in a prograde metamorphic sequence after kyanite (Franceschelli *et al.*, 1982, 1986, 1989 and Ricci *et al.*, 2004 with references therein). It is certainly true for temperature but not for pressure that shows decreasing values of at least 0.3-0.4 GPa passing from the kyanite to the sillimanite + muscovite zone (see Carosi & Palmeri, 2002 and Ricci *et al.*, 2004). Moreover, in this area, as well as in SW Gallura and Asinara Island (Carosi *et al.*, 2004a,b, 2005), the sillimanite starts to grow along the S2 foliation whereas porphyroblastic staurolite and kyanite grew before S2 foliation. We therefore suggest that the prograde Barrovian metamorphism reached the kyanite zone and from broadly during D2 medium pressure metamorphic rocks and migmatites were decompressed (isothermal decompression in the migmatites according to Carosi *et al.*, 2004a and Giacomini *et al.*, 2005) and subsequently reached the sillimanite stability field.

So instead of a classical entire Barrovian sequence we consider the basement of northern Sardinia affected by a more complex metamorphic evolution characterized by an earlier prograde metamorphism of broadly Barrovian type acquired during the underthrusting of continental crust reaching the higher pressures in the kyanite stability field followed by a nearly isothermal decompression from D1 to D2 reaching the sillimanite stability field, followed in some places (e.g. SW Gallura and Asinara island) by a further HT-LP metamorphic event.

Geological itinerary in northeastern Sardinia

We move to the north-eastern coast of Sardinia and we cross the Variscan structure from north to south starting from the High-Grade Metamorphic Complex to reach the Medium-Grade Metamorphic Complex NE of Mt. Albo.

The six stops proposed in this itinerary (Figs. 4, 5, 6a,b) have been modified after the field guide books of Carmignani *et al.* (1982) (Società Geologica Italiana), 1986 (IGCP project n.5), 1993 (Gruppo Informale di Geologia Struttuarle), 1994 (16th General Meeting of the International Mineralogical Association) and review by Franceschelli *et al.* (2005). The number of the stops has been chosen in order to give an essential view of the tectonometamorphic history of the Variscan basement in the time span of one day. In the most stops the GPS coordinates (WSG84 reference) are given in order to facilitate the finding of the outcrops.

We reach Olbia and we continue to the South along the SS125 road «Orientale Sarda». The first stop is on the left in correspondence of the turistic village of Porto Ottiolu.

Stop 1. Porto Ottiolu - Punta de li Tulchi

From Porto Ottiolu we follow a footpath for few hundred of metres going to Punta de Li Tulchi where we can observe migmatites of sillimanite + k-feldspar zone, calc-silicate nodules and boudins of retrogressed eclogites.

The migmatites are constituted by migmatized orthogneisses, biotite-rich gneisses, stromatic migmatites. At Punta Ottiolu stromatic migmatites, dictyonitic and nebulitic migmatites and discordant decimetric leucosomes crop out. Dyctionitic leucosomes, fine grained and with granitic composition, are abundant within the shear bands of the orthogneiss.

Centimetric-size shear bands, related to emplacement of leucosomes, affect the migmatites. They have been interpreted by Elter *et al.* (1999) as a regional system of shear zones affecting the migmatites during collision, connected to a network of extensional shear zones giving rise to an extensional gneiss dome in the HGMC of NE Sardinia.

According to Carmignani *et al.* (1994b) we can observe a considerable evolution of the leucosomes at the point that the stripped or banded structures disappear and the rock loses the regular layering. In the migmatites we can found grey-green calc-silicate nodules and pods (5-30 cm). They have spheroidal to ellipsoidal shapes, are fine grained and lack in any foliation.

According to Franceschelli *et al.* (1998) two main types of metabasites with eclogite relics can be distinguished: garnet-pyroxene-rich and amphibole-plagioclase-rich layers (Fig. 7).

The meaning and the age of the eclogites is still controversial and debated since the paper by Cappelli *et*

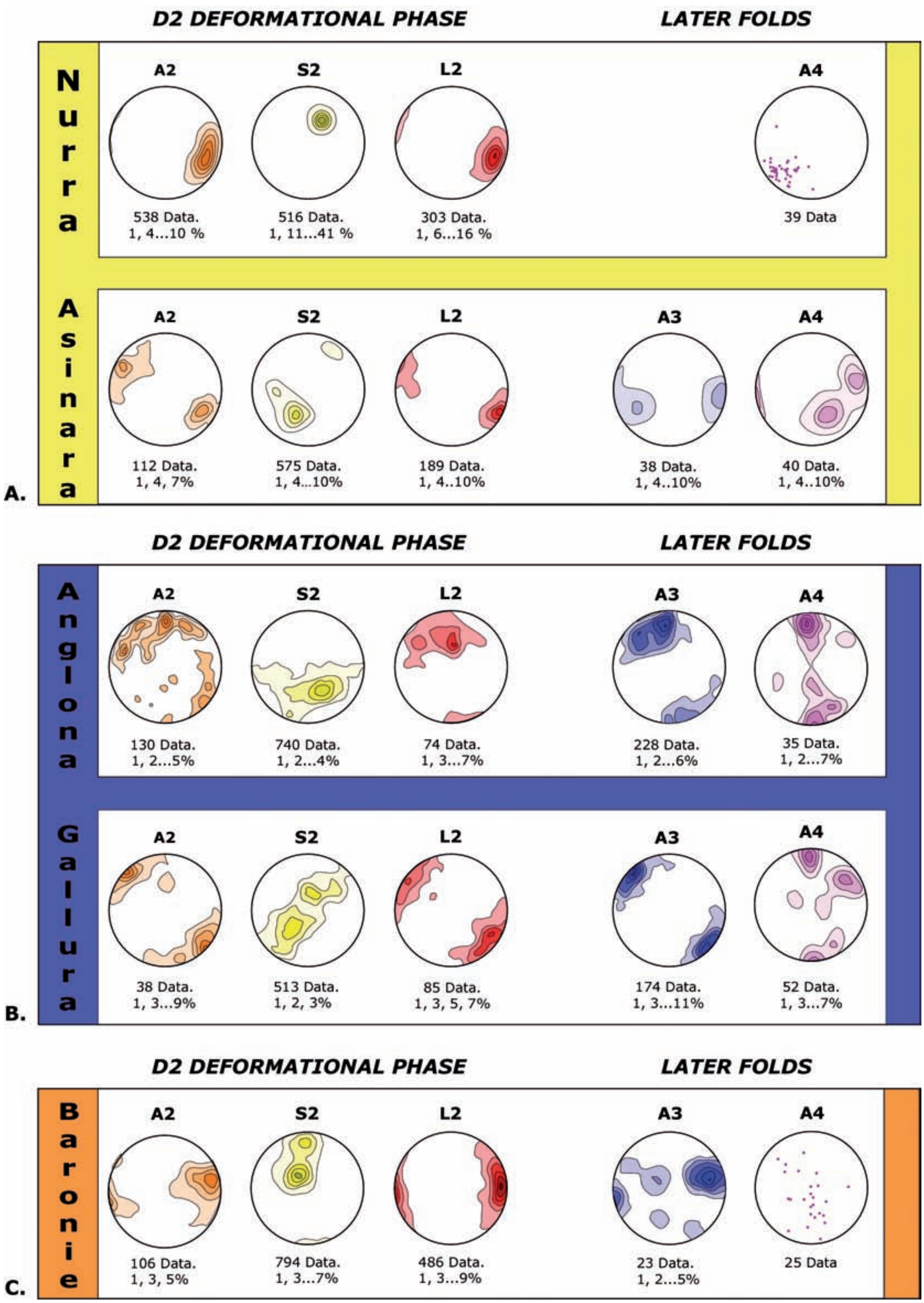

Fig. 3 - Stereographic projections (Schmidt equal area projection, lower hemisphere) of the main structural elements in the study areas (from Carosi *et al.*, 2005).
A: Nurra-Asinara zone; B: Anglona-SW Gallura zones; C: Baronie zone. A2: axes of F2 folds; S2: second phase schistosity; L2: stretching lineation. A3 and A4 are referred to later fold axes.

Fig. 4 - Topographic map and stops in the Baronie area (modified from Michelin.com).

al. (1992) interpreting them as an evidence of a paleo-suture and giving to the protolithes an age of 957 ± 93 Ma. Recent U-Pb zircon data point to protolith ages at around 460 Ma (Cortesogno *et al.*, 2004; Palmeri *et al.*, 2004; Giacomini *et al.*, 2005).

We come back to the SS125 road «Orientale Sarda» and we continue southward to the crossroad to the village of Tanaunella. We move few hundred meters northward to Porto Ainu and we walk a little bit to reach Punta dell'Asino.

***Stop 2*. Punta Batteria - Punta dell'Asino. Migmatites and associated rocks of sillimanite+k-feldspar zone (coord. N40° 41' 34.7"; E009° 44' 12.5")**

A typical sequence of the migmatitic complex of the sillimanite + k-feldspar zone is exposed along the coast between Punta Battera and Punta dell'Asino. Moving to the north we encounter different lithologic types such as:

– biotite-sillimanite mesocratic gneisses (Fig. 8);
– stromatic migmatites with rare Ca-silicate lenses;
– stromatic migmatites with abundant leucosomes and mesocratic gneisses and Ca-silicate lenses and nodules;
– granodioritic orthogneisses.

The main foliation is the regional S2 foliation striking about E-W and dipping towards the south. Mesoscopic evidences of pre-S2 foliation are scanty; late folds with variable geometries are abundant (Fig. 9).

Biotite-sillimanite mesocratic gneisses in the outcrop of Punta dell'Asino show, on the foliation, abundant iso-oriented rods constituted by quartz and fibrolitic sillimanite.

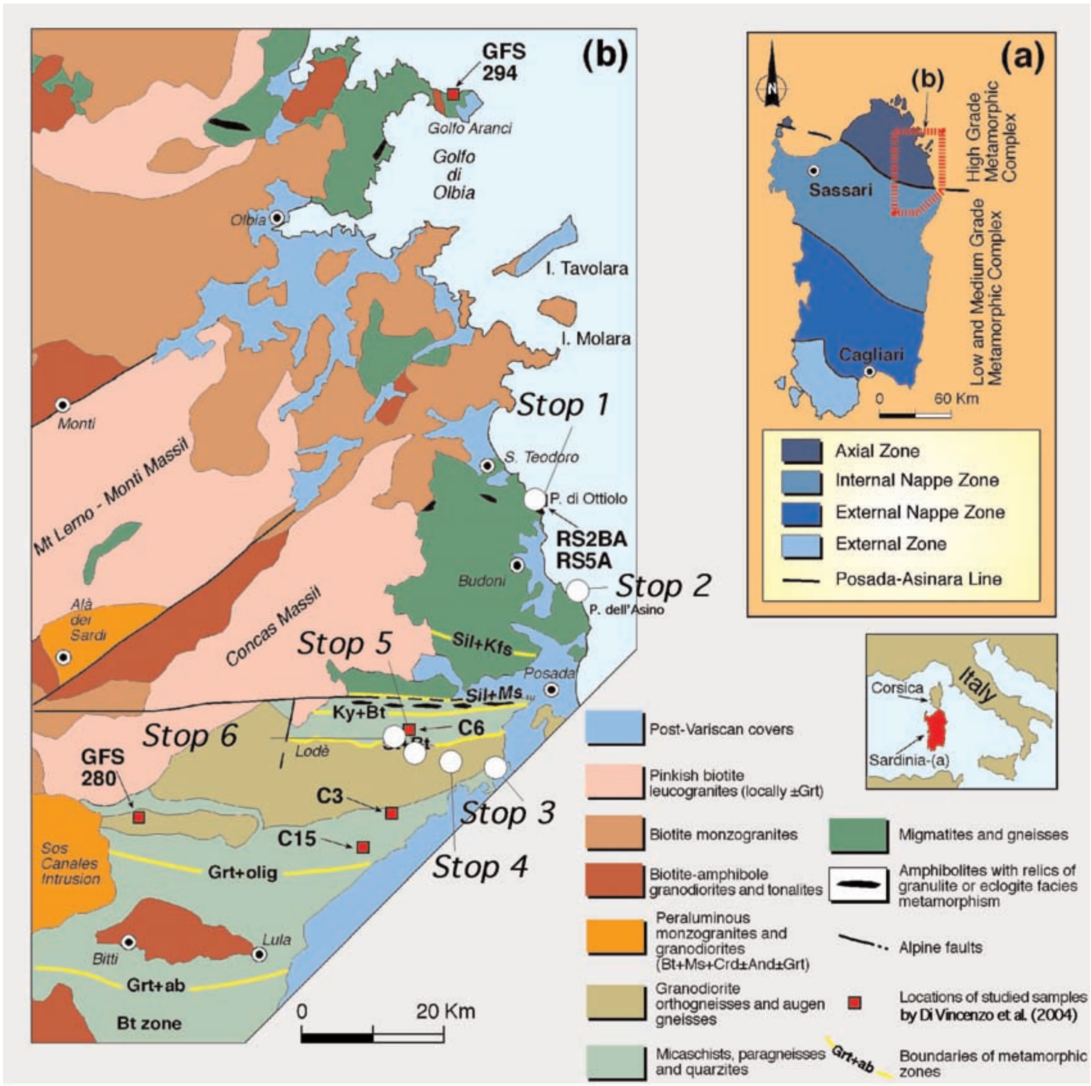

Fig. 5 - Geological sketch map and stops of the itinerary in the Baronie area (modified after Di Vincenzo *et al.*, 2004).

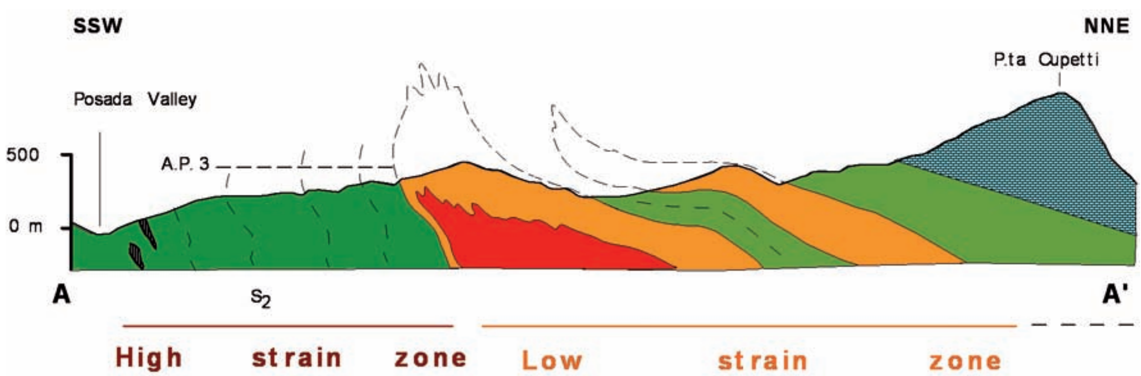

Fig. 6a - N-S geological cross section in the Posada Valley. See the geological map (Fig. 6b) for explanations of the colours (modified after Carosi & Palmeri, 2002).

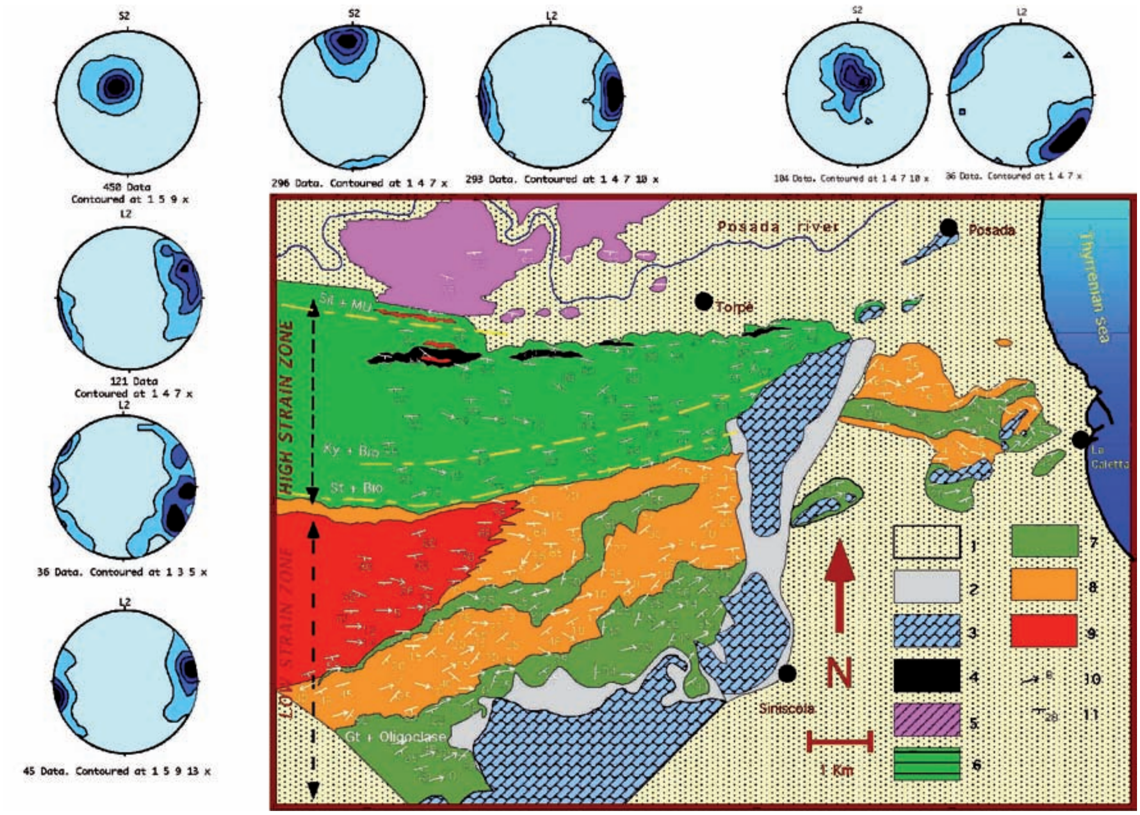

Fig. 6b - Geological and structural map of the Baronie area south of Posada Valley (modified after Carosi & Palmeri, 2002).
1: Continental beach deposits (Pliocene-Quaternary); 2: Slope debris (Quaternary); 3: Carbonate platform sediments, continental and evaporites (Triassic-Jurassic-Cretaceous); 4: Amphibolites with relics of granulite facies parageneses; 5: Migmatitic complex of Sill + Mu and Sill + K-feldspar zones (344 ± 7 Ma); 6: Micaschists and porphyroblstic paragneisses of St + Bt and Ky + Bt zones; 7: Phyllites and metasandstones of Bt zone; micaschists and paragneisses of Grt + Ab and Grt + (Albite + Oligoclase) zones; 8: Granitic augen gneisses (441 ± 33 Ma); 9: Granodioritc orthogneisses (458 ± 31 Ma); 10: trend and plunge of L2 stretching lineation; 11: strike and dip of mylonitic foliation (S2).

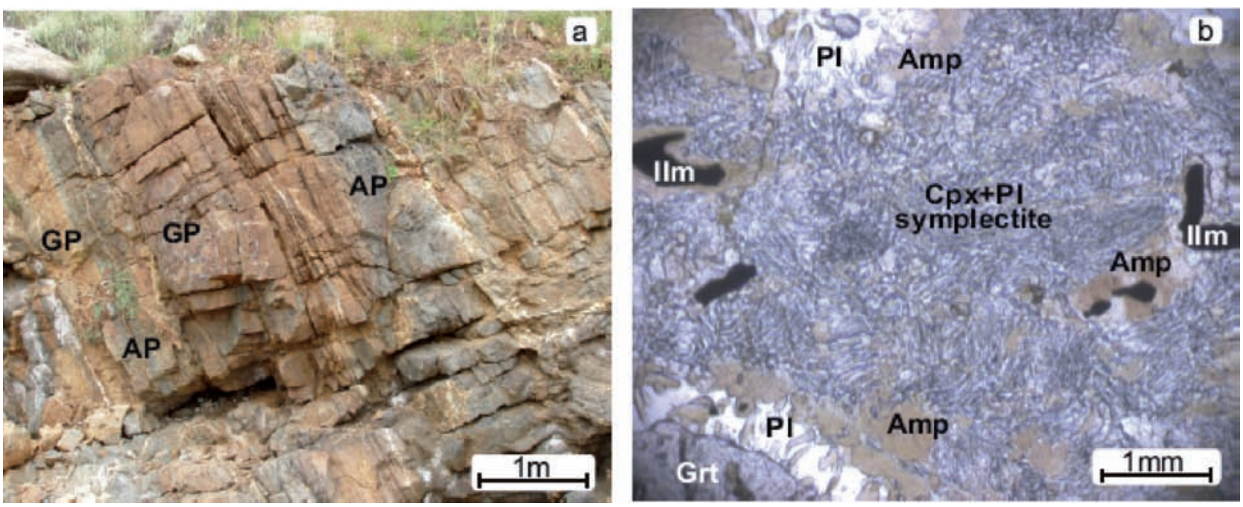

Fig. 7 - Metabasites with eclogite (Stop 1).
A: Alternation of garnet-pyroxene (GP) layers and amphibole-plagioclase (AP) layers in the eclogite outcrop at Punta de li Tulchi (NE Sardinia); B: Photomicrographs showing metamorphic evolution of eclogite from Punta de li Tulchi; diopsidic clinopyroxene and Na-plagioclase symplectite resulting from destabilisation of omphacites; in the upper and lower left corners, note the kelyphytic structure around garnet. One polar (from Franceschelli *et al.*, *Journal of Virtual Explorer* 2005).

Fig. 8 - Sillimanite and muscovite bearing nodules in mesocratic gneiss (Stop 2).

Fig. 9 - Late folds in quartzitic layers in sillimanite bearing migmatites (Stop 2).

According to Franceschelli *et al.* (1991) they are the result of the decomposition of biotite induced by the activity of hydrogen ions through the model reation:
$Bt+H^+ = Sil+SiO_2+(K^+, Mg^{2+}, Fe^{2+})+H_2O$.
Leucosomes are rare in this outcrop whereas they are abundant near Mt. Rasu: here the rock bodies can reach up to 1m in thickness. The leucosomes are sometimes garnetiferous with aplogranite composition and parageneses which include Qtz+Pl+Kfs+Grt±Bt±Sil±Ms. Associated mesocratic gneisses are lacking in k-feldspar and contain, together with Qtz+Pl+Bt+Ms+Grt+Sil, some relics of kyanite.
Near Mt. Ruju, mesocratic gneisses are partially lacking in leucosomes, and contain abundant Ca-silicates nodules. These nodules have spheroidal to ellipsoidal shapes, are fine grained, and lack in any foliation. They show concentric zoning: the light green to pink core consists of Qtz+Pl+Cpx+Grt; the green to dark green rim is characterized by the increase of the amount of horneblende and sphene, instead of Cpx+Grt.
The granodioritic orthogneiss crops out near Mt. Nuraghe. It shows augen to banded structures and is relatively homogeneous, containing only some E-W trending mafic inclusions.
Based both on petrographic and chemical data, the orthogneiss is quite similar to the granodioritic orthogneiss of Lodè and plot on the same Rb-Sr whole rock isochron of 458 ± 31 Ma (Ferrara *et al.*, 1978). New U-Pb analyses on zircons confirm this age (458 ± 7 Ma; Helbing & Tiepolo, 2005).
We come back to the road SS125 «Orientale Sarda» and we continue southward to Siniscola and then to Lodè villages.

***Stop 3.* Road from Siniscola to Cantoniera di S. Anna and Lodè. Granitic augen gneiss (coord. N40° 35’ 00.7”; E008° 39’ 47.4”)**

We stop on the hairpin bends of the road few kilometres before reaching the upland, to observe granitic augen gneiss deformed by the D2 shearing phase and showing shear bands (Fig. 10). The granitic augen gneiss is mainly made up of layered bodies of augen gneisses alternated with thinner micaschist levels. The rocks have been originally considered the product of Variscan metamorphism over rhyolites and arkosic sandstone (Ferrara *et al.*, 1978) but they could represent an intrusive facies of Ordovician granitoids. The age has been constrained at 441 ± 33 Ma (Rb-Sr whole rock; Ferrara *et al.*, 1978).

***Stop 4.* Road from Siniscola - Cantoniera di S. Anna - Lodè (coord. N40° 04’ 20.0”; E009° 38’ 11.6”)**

At Cantoniera di S. Anna we turn on the left on the road to Lula village and on the north-eastern slope of Mt. Albo (made up of mesozoic limestones, dipping to the SE) we can observe the metamorphites of garnet + albite + oligoclase zone: micaschists, porphyroblastic paragneisses (Fig. 11) and granitic augen gneisses (Fig. 10). The contact between the basal levels of the porphyroblastic paragneisses and the granitic augen gneisses is visible. It is the southern limb of the Mamone-Siniscola D2 antiform (Fig. 3a,b): its nearly E-W trending axis, plunging to the est. The porphyroblastic paragneisses are characterized by the occurrence of millimetric plagioclase porphyroblasts with albite core and oligoclase rim (Franceschelli *et al.*, 1982) showing evidence of post-D1 and pre-D2 growth and including an internal foliation (S1). Internal S1 foliation is defined by inclusion trails of white mica, quartz, garnet and minor biotite (Figs. 12 and 13). Syn-D1 white mica are invariably celadonite-rich and paragonite-poor, whereas D2 micas usually show low-celadonite and high-paragonite composition. The external foliation envelops porphyroblasts and it is an advanced S2 crenulation cleavage dominated by white mica and minor chlorite and biotite. Garnet, oligoclase and opaque minerals are also found along S2. Microlithons relics of the S1 foliation and F1 fold hinges are preserved within S2.

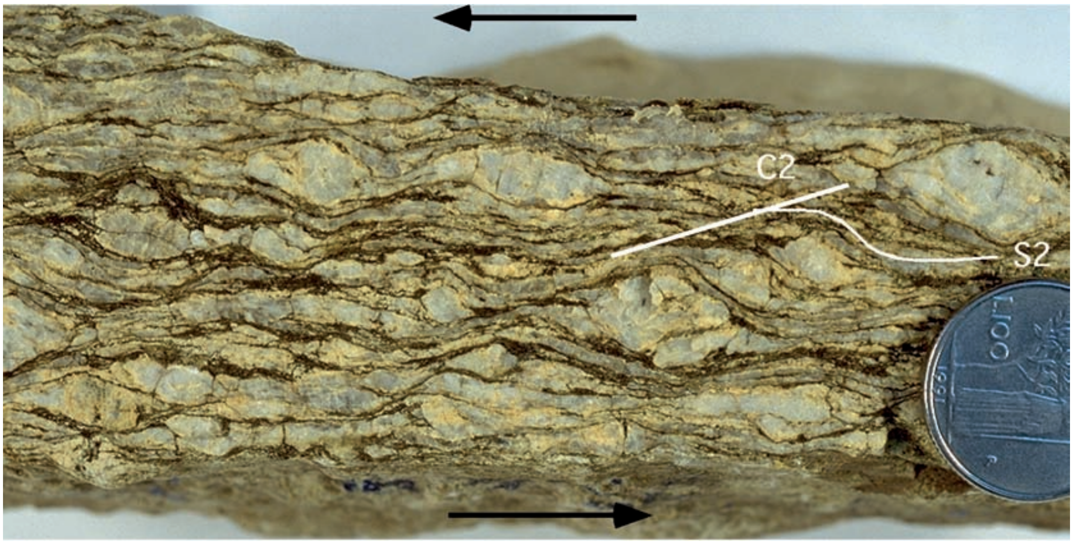

Fig. 10 - Shear bands in granitic augen gneiss. Top-to-the NW sense of shear (Stop 3).

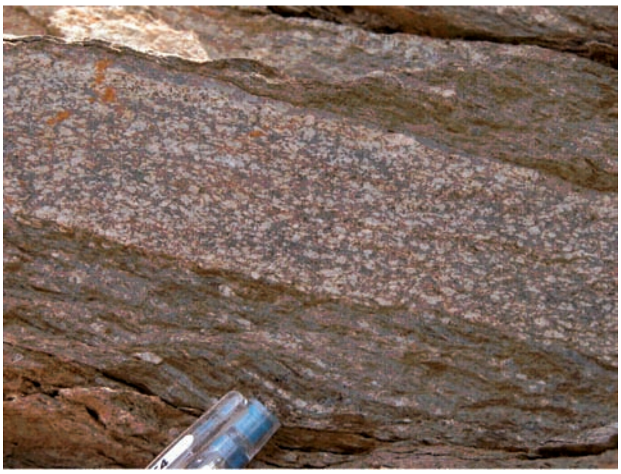

Fig. 11 - Porphyroblastic paragneiss and micaschists with top-to NW shear bands (Stop 4).

In situ Ar-Ar laser analyses of white micas yelded ages of ~340-315 Ma (Di Vincenzo *et al.*, 2004). It is worth noting that the oldest ages (335-340 Ma) were detected in syn-D1 white mica generation not texturally and chemically re-equilibrated at upper crustal levels. Syn-D2 white mica ages cluster at 315-320 Ma.

The estimated temperatures for the garnet-albite-oligoclase zone range from 453°C to 521°C moving from the upper to the deeper part of this zone. Pressure obtained form Grt-Bt-Ms were around 0.7-0.8 GPa (Franceschelli *et al.*, 1989). Carosi & Palmeri (2002) and Di Vincenzo *et al.* (2004) reported temperatures of 500-550°C and pressures of 0.8-1.1 GPa during D1 and 550-600°C and pressures 0.7-0.9 GPa for the D2 phase (Figs. 14 and 15).

***Stop 5.* Road from Siniscola to Lodè. Cantoniera Mt. Tundu. Granodioritic orthogneiss with C-S fabric (coord. N40° 35’ 40.4”; E009° 35’ 34.0”)**

Few kilometers after Cantoniera di S. Anna we stop on the right at Cantoniera di Mt. Tundu. Few dozen metres north of the Cantoniera house we can observe granodioritic orthogneiss with a prominent C-S fabric and C’ structures pointing to a top-to-the NW sense of shear («dextral»)(Figs. 16 and 17). The main foliation (S2) is nearly vertical and strikes nearly E-W and preserve a large number of melanocratic inclusions which are flattened along the S2 foliation.

In origin they were intrusive rocks of granodioritic composition with a radiometric age of 458 ± 31 Ma (RbSr whole rock; Ferrara *et al.*, 1978) and 456 ± 33 Ma (U-Pb on zircons; Helbing & Tiepolo, 2005) that underwent an amphibolite facies metamorphism of Variscan age (age of closure of mineral 290-310 Ma; Ferrara *et al.*, 1978).

***Stop 6.* Road from Siniscola to Lodè; Mt. Bruncu Nieddu. Staurolite and garnet bearing micaschists (coord. N40° 36’ 0.6”; E009° 34’ 56.6”)**

We stop few hundred meters north of the contact between orthogneisses and micaschists. At the entrance of a small forestal road, near the gate, we can observe cm-size staurolite and garnet porphyroclasts on the S2 foliation of the micaschists (Fig. 18). The porphyroclasts of garnet, staurolite and plagioclase, grown between D1 and D2 deformation events, so that they are flattened, rotated and sometimes reduced in grain size during the D2 event (Figs. 19, 20, 21, 22, 23 and 24). This is regarded as the first appearance of staurolite in northeastern Sardinia (Franceschelli *et al.*, 1982, 1986, 1989a; Carmignani *et al.*, 1982, 1994; Ricci *et al.*, 2004 with references) marking the staurolite-in isograd. However, recent investigations revealed that staurolite + biotite appears nearly 10 km south of the clas-

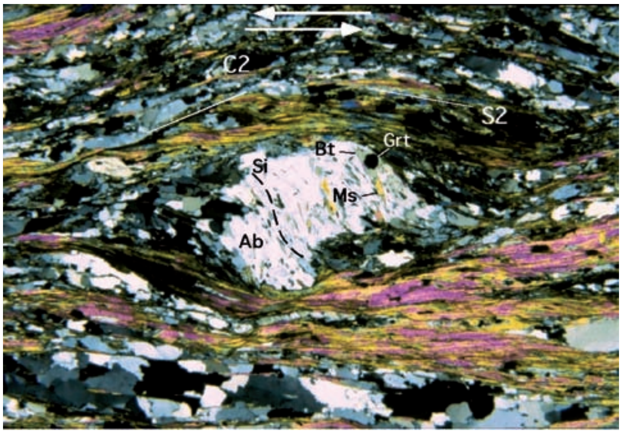

Fig. 12 - Albite porhyroblast (Ab) including a sigmoidal inclusion pattern (Si) marked by quartz, garnet (Grt), biotite (Bt), muscovite (Ms) and graphite (Stop 4). Si is nearly continuous with S2 foliation. S2-C2 fabric points to a top-to NW sense of shear (Micaschist of the garnet + (albite+oligoclase) zone, CPL, 52x) (Carosi & Palmeri, 2002).

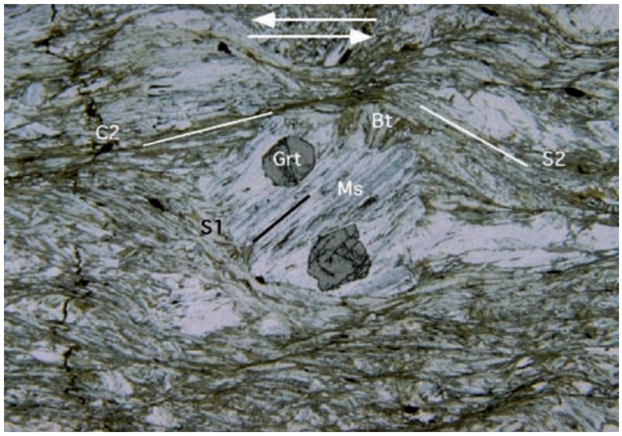

Fig. 13 - Albite porhyroblast including a straight inclusion pattern (S1 foliation), marked by garnet (Grt), biotite (Bt), muscovite (Ms) and graphite (Stop 4). S2-C2 fabric points to a top-to NW sense of shear (Micaschists of the Garnet + [Albite + Oligoclase] zone, PPL, 52 x).

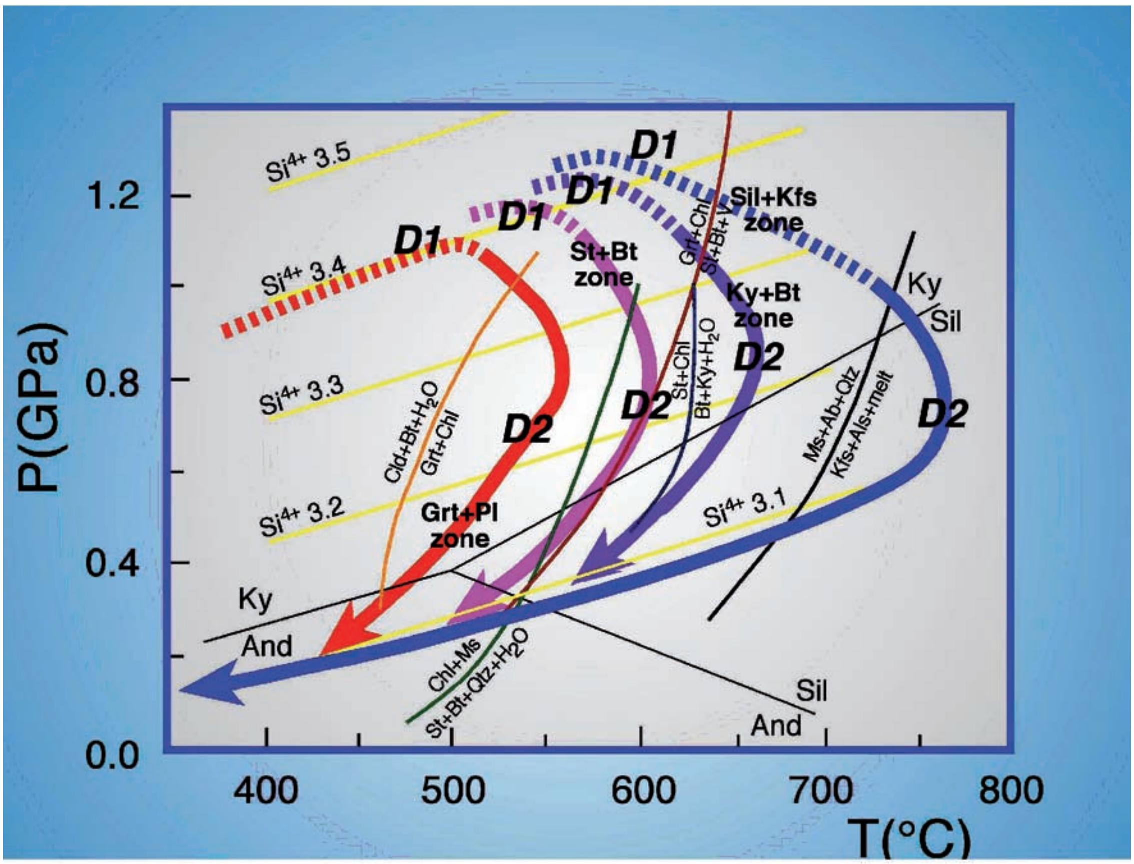

Fig. 14 - P-T-t paths for the different metamorphic zones of NE Sardinia (modified after Di Vincenzo *et al.*, 2004) (Stop 4).

TECTONIC SETTING	DEFORMATION	Qz Pl Grt Stau Ky Bt Ms Chl Ilm	Grt + Bt zone		Stau + Bt zone		Ky + Bt zone	
			T °C	P Kbar	T °C	P Kbar	T °C	P Kbar
CRUSTAL THICKENING	D1 S1 foliation		500-570	10-11	< 590	> 8	< 675	> 9
DEXTRAL TRANS-PRESSION	D2 S2 foliation + D3 F3 later folds ?		570	6-7	590-620	9-5	675	11-6
EXTENSIONAL COLLAPSE	D4 S4 foliation							

Fig. 15 - Synoptic table of the deformation phases and related estimations of pressures (kbar) and temperatures (°C) (Carosi & Palmeri, 2002) (Stop 4).

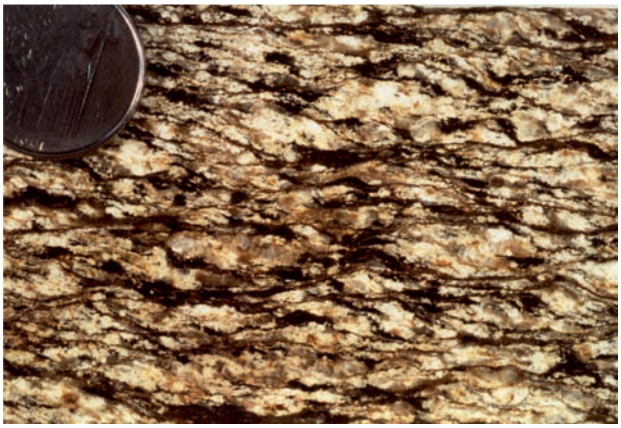

Fig. 16 - C-S fabric in the granodioritic orthogneiss (top-to-the NW sense of shear) (Stop 5).

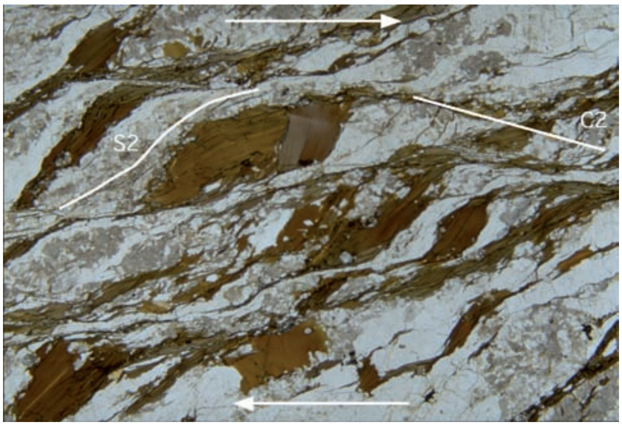

Fig. 17 - Photomicrograph of biotite fish in mylonitic granodioritic orthogneisses (top-to-the SE sense of shear. PPL; fov is nearly 3 mm) (Stop 5).

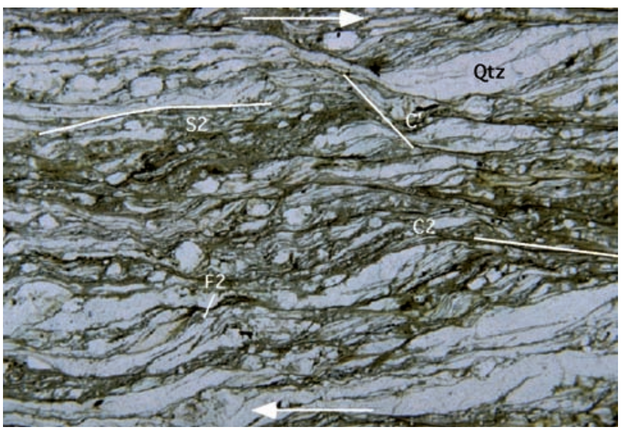

Fig. 18 - C-S fabric in mylonite from gneisses (PPL; fov is nealry 7 mm) (Stop 5).

Fig. 19 - Shear band cleavage in mylonites from gneisses in the high-strain zone in the Posada Valley (top-to-the NW sense of shear, PPL; fov is nearly 7.7 mm) (Stop 5).

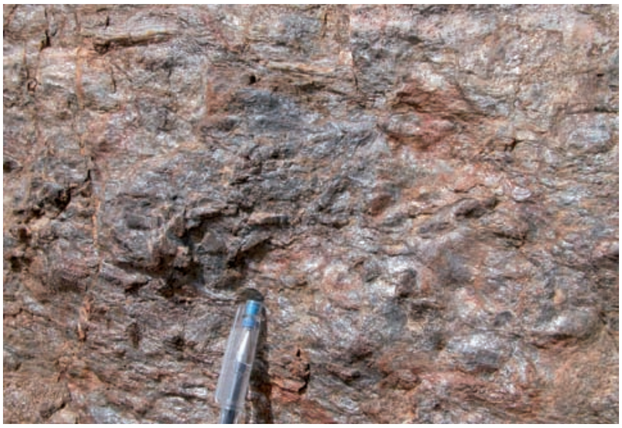

Fig. 20 - Cm-size staurolite porphyroclasts developed on the S2 foliation in micaschists at Stop 5.

Fig. 21 - Thin section from micaschist of the St+Bt zone (Staurolite is the brown-yellowish mineral) with shear bands developed during D2 shearing (top-to-the NW sense of shear, PPL; fov 30 mm) (Stop 6).

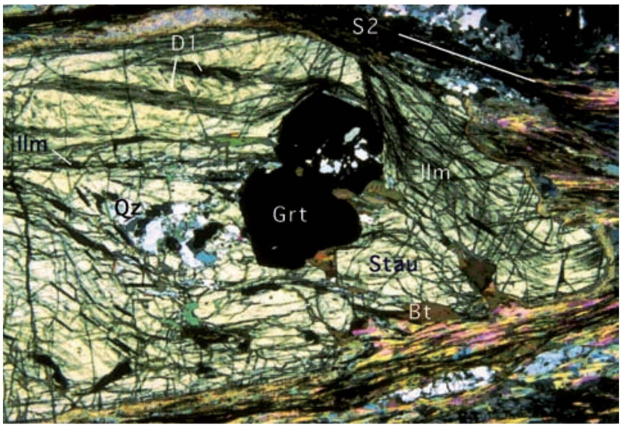

Fig. 22 - Photomicrograh showing stretched staurolite (Stau) porphyroblast, grown post-D1 and pre-D2, including D1 related minerals (Grt, Ilm, Bt, Qtz) (PPL; fov is nearly 1.8 mm) (Stop 6).

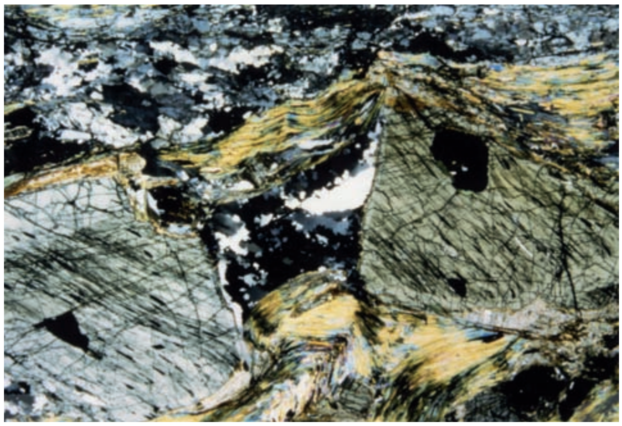

Fig. 23 - Photomicrograh showing stretched staurolite porphyroblast during D2 shearing (CPL; fov is nearly 2 mm) (Stop 6).

sical isograd pointing to a more complex interplay between Barrovian metamorphism and defornation in northeastern Sardinia.

Staurolite porphyroclasts are often fractured and stretched along the S2 foliation with quartz, biotite, chlorite and white mica growing in the separated fragments.

The D1 fabric is transposed by D2 and only the S2 foliation that strikes W-E and WNW-ESE and moderately to strongly dips toward the S and the SW can be identified. It bears an oblique sub-horizontal stretching lineation (L2) marked by the alignment of chlorite, muscovite, quartz and biotite and by the stretched and fractured porphyroclasts of K-feldspar, kyanite, staurolite (Fig. 24) and garnet. The rocks of the staurolite + biotite zone consist of staurolite, garnet and plagioclase porphyroblasts (up to 0.5 cm in size) often in a mylonitic matrix made up of phyllosilicates and quartz. Garnet is anhedral and rounded with quartz, biotite, and chlorite inclusions. Garnet shows a bell-shaped zoning from core to rim for Mn (Carosi & Palmeri, 2002). Towards the rim Mg and Fe gradually increase and Ca decreases. Staurolite occurs as elongated prisms with several phyllosilicates, quartz and graphite inclusions. Staurolite is chemically homogeneous and Fe-rich. Mg-content is up to 0.30 a.p.f.u. and X_{Mg} ratio ~0.17. X_{Mg} of biotite is 0.35. Muscovite is celadonite-poor (Mg+Fe up to 0.42).

Temperatures and pressures in the range of 570-625°C and 0.7-1.0 GPa respectively have been reported by Franceschelli *et al.* (1989) and Di Vincenzo *et al.* (2004) for the thermal peak. In situ argon ages on muscovite along S2 foliation are mainly within 310-320 Ma (Di Vincenzo *et al.*, 2004).

Moving northward for nearly 0.5 km along the forestal road we reach kyanite + biotite isograd.

The kyanite + biotite isograd is marked by the first appearance of kyanite crystals. The rocks consist of

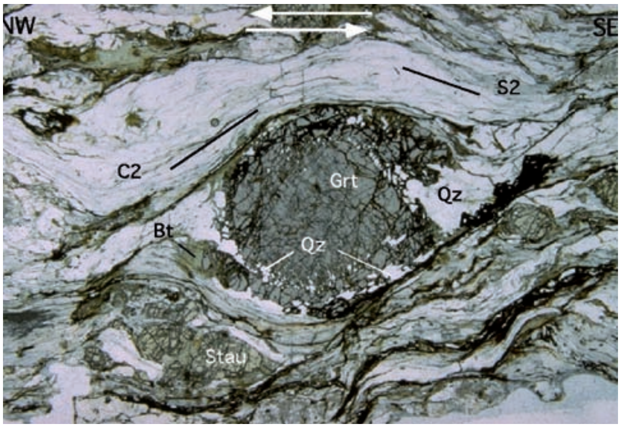

Fig. 24 - Syn-D2 rotated garnet (Grt) and relic staurolite (Stau): top-to-the NW sense of shear (micaschist from the St+Bt zone, PPL; fov is 4.5 mm) (Stop 6).

porphyroblasts of staurolite, kyanite, and plagioclase enveloped in a mylonitic matrix of muscovite, biotite, chlorite and ilmenite. Garnet often occurs as euhedral clear or cloudy inclusion in staurolite, plagioclase and rarely in kyanite porphyroblasts. The clear garnet contains calc-silicate micro-inclusions of idiomorphic anorthite, epidote and margarite. Garnet from the matrix or as a cloudy inclusion have a similar composition, with a slight increase in spessartine content from core to rim, and a concomitant decrease in the other garnet components. Plagioclase included in garnet is extremely calcic (An = 99-67) while the one enclosed in cloudy garnet has a compositional range of An = 22-59. X_{Mg} of biotite ranges from 0.8 to 1.2 and TiO_2 is up to 2.3%. Muscovite is Na- and celadonite poor (Ricci *et al.*, 2004).

Temperature up to 595°C and pressures up to 0.67 GPa have been reported by Franceschelli *et al.* (1989) and pressures > 0.9 GPa by Carosi & Palmeri (2002) for the metamorphic peak.

The micaschists are intruded by an undeformed Permo-Triassic dyke of camptonite (K-Ar age: 228 ± 3 Ma form Baldelli *et al.*, 1987) with mineralogical and textural feature of a lamprophyre. It is porphyritic with biotite and amphibole euhedral phenocristals.

At the bottom of the Rio Posada valley (Fig. 25) there is the sillimanite-muscovite isograd roughly coinciding with the first appearance of migmatitic rocks, characterized by quartz-plagioclase-muscovite bearing leucosomes. Franceschelli *et al.* (1989) estimated a temperature of 605°C and pressure of 0.4 GPa for this zone.

Going into the migmatites we enter in sillimanite + muscovite and in sillimanite + k-feldspar zone. The oldest structure observed in migmatites is a gneissose layering, pre-dating the most pervasive (S2) foliation.

Fig. 25 - Overview from south to north of the Posada Valley from Stop 5. In the far field there are mylonites from staurolite and kyanite bearing micaschists and paragneisses and going down to the Posada Valley we encounter granites and migmatites which made up the mountains in the far field.

Mesosomes are medium-grained, with a fabric defined by the alignment of biotite parallel to S_2 schistosity. Mesosomes consist of quartz, plagioclase, biotite, garnet, fibrolite, minor kyanite, muscovite and K-feldspar. Kyanite occurs sporadically as relic minerals. Retrograde white mica occurs in both the mesosome and the leucosome on sillimanite and K-feldspar. Leucosomes are coarse-grained, poorly-foliated rocks, tonalitic to granitic and rarely trondjemitic in composition.

Temperatures up to 750°C under which anatexis processes developed and pressures at 0.6-0.8 GPa have been reported for migmatites (Palmeri, 1992; Cruciani *et al.*, 2001). According to Giacomini *et al.* (2005) migmatization started in the kyanite stability field at about 750-800°C and pressures above 1.0 GPa.

Argon ages on muscovites from both migmatitic orthogneiss and metasedimentary stromatic migmatite from Punta de li Tulchi yielded a strongly comparable and restrict age-variation from ~300 Ma to ~320 Ma (Di Vincenzo *et al.*, 2004).

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