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High-grade Metamorphics from NE Sardinia, Italy
High-grade metamorphics from NE Sardinia, Italy
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**Regional geology**

Four tectono-metamorphic zones with decreasing grade from NE to SW were distinguished in the Sardinian Variscides (Fig.1): 1) “Inner zone” or “Axial zone” (northern Sardinia), consisting of medium- to high-grade metamorphic rocks and migmatites of Precambrian (?) to Lower Palaeozoic age; 2) Internal Nappe zone (central-northern Sardinia), made up of low- to medium-grade crystalline units; 3) External Nappe zone (central-southern Sardinia), including low-grade metamorphic rocks; 4) External zone (southern Sardinia), characterised by very low- to low-grade metamorphic rocks (Carmignani *et al.*, 2001 and references). Elter *et al.* (2004) set a new zone “The Posada Valley Zone” between the Internal Nappe Zone and the Axial Zone.

In “Inner” or “Axial zone” two metamorphic complexes have been identified:

1) The High Grade Metamorphic Complex (HGMC) or Migmatite Complex in Fig. 1, consisting of gneisses and migmatites with a metamorphic grade reaching the sillimanite + K-feldspar isograd. Bodies and lenses of mainly Ordovician granitic-granodioritic orthogneisses, mafic and ultramafic metamorphic rocks with eclogite to granulite relics and calc-silicate nodules are frequently embedded within the HGMC. The migmatite of the HGMC, near Golfo Aranci, mainly shows the composition of immature graywacke siliciclastic sediments originated from weathering and erosion of felsic Ordovician magmatic rocks (Giacomini *et al.*, 2006). These migmatites give U-Pb zircon ages scattered between 3 Ga and about 320 Ma with a first main cluster between 480 and 450 Ma and a second one from about 650 to 550 Ma. Variscan ages are rare and mostly limited to thin rims overgrowth on older grains.

2) The low- to medium-grade metamorphic complex L-MGMC (mainly amphibolite-facies metamorphic complex in Fig. 1), largely outcropping adjacent to the southern side of the Posada-Asinara Line, in central-southern Asinara, northern Nurra, Anglona and the northern Baronie regions. According to Cappelli *et al.* (1992) and Carmignani *et al.* (2001 and references) the Posada-Asinara line is a “South Hercynian Suture Zone” between the Armorica and Gondwana plate margin.

From Ordovician to Early Carboniferous several magmatic events took place in Sardinia. According to Memmi *et al.* (1983), Di Pisa *et al.* (1992) and Franceschelli *et al.* (2003) basaltic to rhyolitic calc-alkaline volcanic rocks were emplaced during the Early to Middle Ordovician in the sequences of the Nappe and Inner zones. Ordovician acidic plutonic (478-456 Ma) and basic volcanic rocks, at present orthogneisses or amphibolites, outcrop in northern Sardinia. Afterwards, during the time interval between Caradoc-Ashgill and Silurian, alkaline within-plate
basalts were emplaced as subvolcanic bodies, sills and dykes, in central and south-western Sardinia, Gerrei, Iglesiente-Sulcis and Sarcidano. Finally, from Devonian (?) to Carboniferous within-plate alkali- basalts were emplaced as proved by the geochemistry of metavolcanic rocks, metagabbros and metadolerites embedded in the Paleozoic sequences of the External and Internal Nappe zones.

**Variscan deformation**

The metamorphic basement was involved in the polyphased history of the Variscan orogeny. Up to five deformation phases were distinguished. The D₁ phase produced SW vergent overturned folds and, in southern Sardinia, slaty cleavage that shows, as one moves northwards, a gradual transition into S₁ strain-slip axial plane foliation. In the high-grade rocks, S₁ schistosity is rarely recognisable in the intrafoliar folds (Elter et al., 1986).

![Fig. 1. Tectonic sketch map of the Variscan Belt in Sardinia (modified from Carmignani et al., 2001).](image)
The D₂ phase in NE Sardinia has been interpreted by Carosi and Palmeri (2002) as a transpressional deformation event generating the S₂ schistosity that transposed the S₁ one. The D₃ phase, moderately overprinting the S₂ schistosity, generated upright concentric open folds showing spaced cleavages in the limbs and crenulation cleavages in the hinges (Franceschelli et al., 1982a; Elter et al., 1986). In the Posada shear zone, the D₄ phase is evidenced by C-type shear band crenulation cleavages, the product of a non coaxial-shearing concentrated in cataelastic mylonitic rocks (Elter 1987). In the same shear zone, a final D₅ phase gave rise to a large flexure parallel to the orogenic trend, as revealed by the uplift of the axial zone with respect to the schistose envelope (Helbing et al., 2006).

According to Carmignani et al. (1992, 1994) and Carosi and Palmeri (2002) during the first collisional phase D₁, the HGMC on the NE side of the Posada-Asinara line overthrusts the L-MGMC on the SW side of the same tectonic line. This overthrusting produced early inversion of metamorphic zones in underthrust units. According to Carosi and Palmeri (2002), transpressional tectonics lasted during the entire D₂ and D₃ phases up to the uppermost Carboniferous, and caused not only a slowing of the exhumation rate but also both reversal and west-to-northwestward displacement of the L-MGMC, bringing internal crystalline Nappes onto the migmatites of the HGMC. This means that Nappe transport changed from orthogonal to the belt in D₁ to a parallel trend in D₂. According to Elter et al. (1999) the basement of NE Sardinia is a high-grade gneiss dome bounded by a series of retrogressive shear zones (Golfo Aranci shear zone to north and Posada shear zone to south) and mantled by medium-grade schists and gneisses. This structure is recently confirmed by Helbing et al. (2006).

In the evolution of the Sardinian Variscan basement, a key role was played by a composite network of shear zones (Elter et al., 1986, 1990, 1999, 2004; Elter and Ghezzo, 1995) displaying complex evolution from early HT/LP stages to late MT-LT/LP conditions associated with changes in the sense of movement. Two shearing events were distinguished: an Early Shear Event and a Late Shear Event. The Early Shear Event is characterized by two non coaxial deformation phases recognisable on the S₂ schistosity: an earlier top-to-the-NW phase and a later top-to-the-NE/SE phase. The top-to-the-NW phase is scattered and is recognisable in the kyanite and amphibole migmatites. The Late Shear Event affected the HGMC in kilometric to metric scale sub-vertical to vertical strike slip shear zones. On the basis of strike and sense of shear, two types of coeval strike slip shear zones can be recognised in the HGMC: a dextral NW – SE trending shear zone and a sinistral NE – SW trending one.
A detailed structural investigation on the northern Sardinia basement, made by Elter and coworkers in the last twenty years, is shown in Fig. 2. \( S_2 \) shows two different trends: a northern sector (north of Olbia, stations 1-15) with a NW-SE strike trend and a southern sector (Tamarispa-Porto Ottiolu sector, stations 17-33) with a NE-SW trend. At the Sanalvò area (station 16) between the northern and southern sectors, \( S_2 \) strikes E-W. \( S_2 \) plunges to the SW at stations 1, 2, 4, 5, 15, 29 and to the NE at stations 3, 6, 8, 16; towards the SE at all stations in the sector Tamarispa-Punta dell’Asino, Porto Ottiolu (stations 17 to 32), while \( S_2 \) is vertical at stations 10, 11, 12, 13, north of Olbia. Only at Monte Candela (station 7), \( S_2 \) strikes NS and plunges to the E.

Fig. 2. Average strike of regional \( S_2 \) schistosity on the metamorphic basement of NE Sardinia.
The L₁ (K-feldspar + quartz) mineralogical lineation plunges to the SE in stations 3, 6, 8, 10, 12-16, 27, 28, 30. L₁ plunges both towards the NW, SW and NE in stations 2, 11, 17, 18, 19, 32, 33. Associated with the L₁ is a top-to-the-NW shear sense (stations 1-16, 19, 27, 30). Kinematic indicators are directed towards the N at the station 17 while in stations 32 and 33 they are directed towards the NE. Worthy of note is that S₂ changes in strike, but the L₁ generally plunges towards the NW in both sectors.

The L₂ (sillimanite + muscovite + quartz) lineation was measured in stations 1, 3, 11-13, 17, 19, 21, 23, 25-27, 29-31. L₂ plunges generally to the SE except in stations 3, 22, 25, 30 where the dip is different, both towards the NE and SW. Related to L₂ is a top-to-the-SE shear sense.

The L₃ (biotite and/or muscovite) lineation was recognised in stations 2, 4-7, 9-15, 17, 19, 24, 25, 30, 32, 33. L₃ generally plunges to the SE except in stations 7, 19, 24 and in 32, 33 where it plunges to the NE and to the SW, respectively. Related to L₃ is a top-to-the-SE shear sense.

Fig. 3. Metamorphic zonation in the Variscan basement of northern Sardinia (modified from Franceschelli et al., 1982a). The Al₂SiO₅ is sillimanite and/or andalusite in north-central and NW Sardinia.
**Variscan metamorphic zonation, events and geochronological data**

A very impressive feature of the metamorphic zoning in NE Sardinia (Fig. 3) is the fast increase in metamorphic grade in a restricted 40 km wide area, from the biotite to the sillimanite + K-feldspar zone. The metamorphic zoning in NE Sardinia has been studied by observing the regional distribution of AKFM minerals (Franceschelli *et al.*, 1982a). Six zones were distinguished from south to north: 1) biotite; 2) garnet; 3) staurolite + biotite; 4) kyanite + biotite; 5) sillimanite; 6) sillimanite + K-feldspar i.e migmatite zone (Fig. 3). The garnet zone is further subdivided into lower and upper garnet zones (i.e. garnet + albite and garnet + albite-oligoclase zones of Franceschelli *et al.*, 1982b).

According to Franceschelli *et al.* (2005a), the existence of pre-Variscan deformation and metamorphism in northern Sardinia (see Helbing and Tiepolo, 2005) has not been proven to date with exhaustive and convincing argumentation.

The P-T paths of Variscan metamorphic rocks of northern Sardinia are shown in Fig. 4 (redrawn from Franceschelli *et al.*, 2005a). Recent radiometric data suggest the following sequence of Variscan events in Sardinia. An early phase of HP metamorphism characterised the beginning of the Variscan orogenic cycle in Sardinia. Evidence of this event is given only by some metabasites with eclogitic relics embedded within the HGMC or L-MGMC. The age of the protoliths is Middle Ordovician, as suggested by three U-Pb zircon ages of 453±14 Ma, 457±2 Ma and 460±5 Ma, respectively yielded by metabasites with eclogite relics (Palmeri *et al.*, 2004; Cortesogno *et al.*, 2004; Giacomini *et al.*, 2005a). An age of 400±10 Ma was hypothesised for the eclogite formation in NE Sardinia by Palmeri *et al.* (2004), on the basis of U-Pb SHRIMP zircon data. A similar age of 403±4 Ma, interpreted as dating the high-grade event, was found by Cortesogno *et al.* (2004) for eclogites included in the HGMC. Giacomini *et al.* (2005b) propose a Middle Ordovician protolith age for eclogites embedded within the the Sardinian HGMC, an Early Visean age for eclogite facies metamorphism and a Late Visean age for amphibolite facies metamorphism, i.e. respectively ages of 460-450 Ma, ~345 Ma and ~320 Ma. Did the migmatite experience the HP event revealed by the enclosed eclogite lenses? Apart from kyanite relics observed in plagioclase suggesting HP values, no UHP minerals such as coesite or diamond, has thus far been found in migmatite. Di Vincenzo *et al.* (2004), show that the early thickening stage of the D1 event did not start before ~360 Ma and likely took place at 345-340 Ma, in agreement with the Tournaissian age (355-345 Ma) of deformed metamorphic rocks from SE Sardinia, and with an 40Ar-39Ar age of 345±4 Ma on actinolite from a metagabbro (Del Moro *et al.*, 1991). Moreover, the time interval between 360 to 345 Ma is consistent with the minimum theoretical
time lapse of 20 Ma indispensable for the transformation of a passive to active collisional margin and for the starting of exhumation (Thompson et al., 1997). In particular, Di Vincenzo et al. (2004) found apparent $^{40}$Ar-$^{39}$Ar ages of 340-315 Ma for muscovites in the garnet zone, with the oldest ages (340-335 Ma) for syn-D$_1$ white mica, and age clustering at 320-315 Ma for most syn-D$_2$ white mica.

Fig. 4. Sketch showing the pressure and temperature evolution in the northern Sardinia basement. P-T paths are redrawn from: a, b (Nurra) Franceschelli et al. (1990); c, d (Asinara Island) Carosi et al. (2004); e, l, m (Western Gallura, Anglona) Ricci (1992); f (granulitic rocks from Montiggiu Nieddu) Franceschelli et al. (2002); g (E: retrogressed eclogites and M: migmatite near Golfo Aranci) Giacomini et al. (2005a); h (eclogitic rocks from P.ta de li Tulchi) Franceschelli et al. (1998); i (metapelitic rocks from garnet to sillimanite+ K-feldspar zones, NE Sardinia) Franceschelli et al. (1989), Ricci et al. (2004). U.Grt = upper garnet zone; L.Grt = lower garnet zone. Al$_2$SiO$_5$ triple point after Holdaway (1971). Mineral abbreviations according to Kretz (1983).

Giacomini et al. (2005a), considering the petrological features of a 344±7 Ma-old leucosome from a NE Sardinia migmatite (Ferrara et al., 1978), proposed an age of ~345 Ma for the muscovite dehydration melting event that affected the Golfo Aranci gneisses. Recently, an Eo-Variscan (Devonian?) age has been proposed by Corsi and Elter (2006) for partial melting in the
HGMC of NE Sardinia. A pervasive fluid infiltration into metabasite lenses from the surrounding migmatites transformed anhydrous granulite facies assemblages into hydrated upper amphibolite facies assemblages at 352±3 Ma (zircon resetting age by Giacomini et al., 2005a). The 344 and 352 Ma ages indicate that partial melting and metasomatic processes started soon after the end of the D1 phase, with attainment of peak temperatures very close to the D1-D2 boundary.

Similarly, Elter et al. (1999) proposed that age values around 350 Ma, 345±4 (Del Moro et al., 1991) and 344±7 Ma (Ferrara et al., 1978) in the axial zone divided the end of collisional tectonics, with peak pressure attainment (D1 phase), from the beginning of the extensional tectonics, exhumation and uplift (D2 phase). Ricci et al. (2004) similarly wrote that “the 345 Ma age could therefore be close to the collisional stage or represents the beginning of the exhumation”.

The outcrops in Anglona region and Asinara Island, show that Barrovian metamorphic mineral assemblages were overprinted by late Variscan (Rb-Sr age of 303±6 Ma on muscovite, Del Moro et al., 1991) HT/LP parageneses linked to gravitative collapse, exhumation of the chain and shallow emplacement of intrusive granitoids (high-K calc-alkaline type, 310-290 Ma, Di Vincenzo et al., 2004). 40Ar-39Ar and Rb-Sr ages from 305 to 298 Ma were obtained by Laurenzi et al. (1991) on muscovites from the synkinematic leucogranites of the Monte Grighini shear zone, deformed by shear movements. A reasonable age of ~ 300 Ma could be attributed to the Sardinian Late Shear Zone.
Descriptions of the stops in the excursion of High-grade metamorphics from NE Sardinia.

First day:
Itinerary: Fluminimaggiore (Hotel Antas), Punta dell’Asino, Porto Ottiolu-Punta de li Tulchi, Tamarispa, Posada Valley, Posada (Hotel Donatella)

We move from Hotel Antas in Fluminimaggiore towards the road 131 “Carlo Felice”. The Carlo Felice runs along the Campidano graben which is mainly covered by Pliocene sediments and, northwards from Oristano, by Pliocene-Pleistocene volcanic rocks. Near to Abbasanta we take the road 131bis towards Nuoro. Nuoro is the most important city of Barbagia laying on the granitic rocks of the Sardinia batholith. The 131bis runs along the so-called “Faglia di Nuoro” which is a Tertiary strike-slip fault. After Nuoro, crossing the low-grade metamorphic rocks of the Variscan basement and the Mesozoic limestones of Monte Albo, we reach the Siniscola city and, after a few kilometers, the Valley of the Posada river, near to the omonymous village. On the top we see the “Castello della Fava” which is the old Posada village. From the nearby village of Budoni, we leave the road 131 and move towards Tanaunella and then Punta dell’Asino beach.

Fig. 5. Index map of field trip on the high-grade metamorphic rocks from NE Sardinia.
STOP 1.1 - Fibrolite nodules in the paragneisses of Punta dell’Asino

The rocks outcropping at Punta dell’Asino are paragneisses containing fibrolite nodules, orthogneiss and minor migmatite. The structure is dominated by the D₂ folds and related S₂ schistosity. The wavelength of D₂ folds is between 1-50 cm and the axes strike N 120-130° and dip southwards. S₂ schistosity is oriented N 5-30° plunging 20-40° towards ESE. Shear folds associated to quartz-rich σ-porphyroclasts with a synkinematic top-to-the-SE sense of shear can be observed. On the S₂ plane a mineralogical lineation defined by quartz rods and fibrolite nodules oriented N 130-140° plunging 20-40° towards SE is recognisable. The paragneisses consist of variable proportions of biotite, plagioclase, quartz, minor garnet, apatite and zircon. On the basis of SiO₂/Al₂O₃ vs. K₂O/Na₂O ratios the protoliths of the paragneisses were mainly greywackes. Near to the contact with the orthogneiss, the paragneiss is very rich in quartz veins about 0.5-5 cm thick and 10-80 cm long which are more and more frequent as the fibrolite nodules increase. The length and width of the fibrolite nodules range from 0.2 to 5 cm and from 0.1 to 1 cm, respectively. The nodules are wrapped around by S₂ schistosity and often by a thin biotite rim. They consist of fibrolite (30-70%), quartz, biotite, minor plagioclase, garnet, small prismatic sillimanite, sporadic kyanite, apatite, tourmaline, and Fe-oxides. According to Franceschelli et al. (1991) the fibrolite nodules are the result of the folding and transposition of lens-shaped fibrolitic segregations formed by a base-leaching process during the amphibolite facies Variscan metamorphism.

We take the Road 125 (known as “Orientale Sarda”) towards Porto Ottiolu. Porto Ottiolu is a beautiful village with a characteristic piazzetta facing the turistic port. Along the coast from Porto Ottiolu to Punta de li Tulchi we walk for about one kilometer on igneous and sedimentary-derived migmatite, micaschist, paragneiss with fibrolite nodules, and metabasite with eclogite facies relics. The metamorphic rocks are crosscutted by granitic, pegmatitic and mafic dykes. Lunch at Porto Ottiolu.
STOP 1.2 - Contact between the migmatised orthogneiss and its sedimentary cover

In this stop (Fig. 6) we can observe an Ordovician migmatised orthogneiss, in contact with its sedimentary cover, now consisting of paragneiss and layered migmatite.

Fig. 6. Geological sketch map of Porto Ottiolo-Punta de li Tulchi area. Location of the stops and cross-section are also shown.

The contact between the orthogneiss and the surrounding paragneiss and migmatite is parallel to the regional $S_2$ schistosity. The $S_2$ locally transposes an early foliation ($S_1$?), rarely recognisable in the intrafoliar folds of the paragneiss (Fig. 7).

Fig. 7. Intrafoliar fold in the paragneiss of Porto Ottiolo with $S_2$ axial plane schistosity which transposes an early $S_1$ foliation.
The migmatised orthogneiss is a slightly schistose rock with a $S_2$ foliation oriented N 100° SW 45°. On the XY plane of $S_2$ schistosity, a down-dip polyminalogical lineation of K-feldspar + quartz rods oriented N 20° SW 45° can be observed. The orthogneiss consist of zoned K-feldspar (microcline), biotite, quartz, plagioclase (An$_{20-33}$), ± garnet, and coarse-grained retrograde muscovite. Two types of granitic leucosomes (Qtz + Kfs + Pl + Bt ± Grt + Ms) can be observed: folded centimetric thick leucosomes and leucosomes developed along shear zones.

The paragneisses are dark-colored rocks consisting of an alternation of medium- to fine-grained layers. On the basis of SiO$_2$/Al$_2$O$_3$ vs. K$_2$O/Na$_2$O ratios the protoliths of the paragneisses were greywackes to arkoses. The layered migmatites consist of K-feldspar, biotite, quartz, plagioclase (An$_{5-31}$), sillimanite, rare kyanite relics, garnet and abundant retrograde muscovite. In the paragneisses and layered migmatite, a NS-S 48° muscovite down-dip lineation and isoclinal folds with axial plane schistosity are recognisable. The regional schistosity is transposed by shear bands oriented EW- S 25° with kinematic indicators (S-C planes) relating to a top-to-the-N shear component. The retrograde muscovite grows over sillimanite spots oriented N 50° NE 10°, clearly visible at the outcrop scale. The paragneiss and layered migmatite are also characterised by the occurrence of late folds with sub-horizontal axes oriented N 70°. The P-T path of the migmatite of Porto Ottiolu area has been discussed by Cruciani et al. (2001). The P-T path of some migmatites south from Porto Ottiolu is reported in Fig. 4i.

Post-Variscan mafic, granitic and pegmatitic dykes mainly oriented N 120-140°, crosscut the metamorphic basement.

STOP 1.3 - Migmatitic orthogneiss, nebulitic migmatite and granitic dykes

Several leucosomes in the migmatised orthogneiss are deformed by folds with sub-vertical axes. At the contact between the leucosomes and the migmatised orthogneiss, a biotite-rich selvedge is commonly present. Two different types of leucosomes can be identified: early-formed leucosomes (with strongly variable composition) characterised by biotite trails concordant with the foliation of the migmatised orthogneiss, and leucosomes along shear zone. The early formed leucosomes locally show a variable abundance of K-feldspar (Cruciani et al., 2001). Granitic dykes oriented N 130° subvertical, ranging in thickness from a few meters to a few decimetres, cross-cut both the migmatised orthogneiss and the paragneiss.

An elliptical-shaped (1 m × 15 cm) zoned calc-silicate nodule (Grt + Qtz + Amp + Ep + Cpx) with the longer axis parallel to the regional schistosity occurs in the paragneiss, near to the granite dykes. Near to the contact with the paragneiss a dark-coloured, fine-grained thin rim can
be observed. About 100 m north from the calc-silicate nodule, lenses of micaschists and paragneiss with centimetric fibrolite-rich nodules also occur.

Towards Punta de li Tulchi, the biotite content in the migmatised orthogneiss decrease and the rocks acquire a nebulitic appearance. Near to the eclogite, high-temperature metamorphic shear bands oriented N 70° with S-C structures indicating a left shear component can be observed in the migmatised orthogneiss. The shear bands are intruded by discordant leucosomes (Fig. 8) emplaced along dextral shear zones oriented N 170° vertical. The leucosome intrusion corresponds to a Rieddle fracture system with the master fault oriented N 170° and the R2 oriented N 115°. Tension gashes with synkinematic intrusion of leucosome are also present in the migmatised orthogneiss (Corsi and Elter, 2006).

Fig. 8. Migmatised orthogneiss showing a shear band intruded by a granitic leucosome. A D₂ and a late-D₂ (black thick line) shear deformation is also present (modified from Corsi and Elter, 2006).

STOP 1.4 - Metabasites with eclogite-facies relics of Punta de li Tulchi

At Punta de li Tulchi, eclogites form a 100 m long, 20-30 m thick lens with a N80°-60° orientation, enclosed within migmatites. Near the main body, two decimetre-sized eclogite nodules are also embedded within the migmatites. The northern contact between eclogites and nebulitic migmatites is marked by a 20-30 cm thick dark amphibole-rich layer and quartz-rich veins. Moving south, orthogneiss in contact with eclogites, locally shows strong evidence of brecciation.

The eclogites consist of alternating garnet-pyroxene-rich (GP) and amphibole-plagioclase-rich (AP) layers parallel to the main schistosity that may refer to a granulitic stage.
The layers, sharply to poorly defined, show preferred 50° N dipping, EW direction. Locally, at the microscope scale, individual lobes of the symplectitic lamellae are roughly aligned along a preferred orientation forming a high angle with S2 defined by garnet elongation. This feature could indicate a mimetic growth of lobes along an older S1 schistosity. Moreover, the amphibolitisation of the original granulitic rock is clearly recognisable in some parts of the outcrop where an amphibolitic front with faded contours cuts the S2 or replaces granulitic layers.

The GP layers are mainly made up of medium/coarse-grained zoned poikiloblastic garnet up to 5 mm in size (Alm50-62 Prp19-27 Grs16-26 Sps1-3) with inclusions of omphacitic pyroxene, euhedral amphibole (from actinolite to tschermakite), quartz, rutile, and epidote. The matrix consists of fine-grained symplectites of plagioclase (An19-36), small lath-shaped clinopyroxene (diopside-augite) after omphacite, orthopyroxene, various types of amphibole and minor Fe-oxides. Amphibole in the matrix commonly shows a pale-green core surrounded by a brown thin rim and ranges in composition from tschermakite to Mg-hornblende. The colourless amphibole replacing orthopyroxene is a cummingtonite with X\text{Mg} \sim 0.7. X\text{Mg} in some zoned garnet crystals smoothly increases from core (0.25) to an intermediate zone (0.36) and then decrease in the rim (0.24). The grossularite content generally decreases gradually from core to intermediate zone and rim (0.748; 0.668; 0.584 a.p.f.u., respectively). Garnet margins in contact with clinopyroxene-plagioclase symplectites are surrounded by radial kelyphytic corona consisting of pale-green prismatic blebs of brown to green amphibole (from tschermakite to Mg-hornblende) and plagioclase (An51-96). The late pale green amphibole replacing garnet is an actinolite with X\text{Mg} = 0.6-0.7.

The AP layers consist of elongated white pods of plagioclase-amphibole oriented along a N 80°-SE 30° S3 foliation. Relics of clinopyroxene + plagioclase symplectites, orthopyroxene, and colourless amphibole occur in the matrix. The modal proportion of amphibole reaches 50-60%. The S1 schistosity is completely obliterated and the main rock foliation is defined by the orientation of the matrix amphibole crystals. Most of the white pods are strongly aligned with a later S3 foliation, which, in turn, is crosscutted by a later shear band.

The P-T path of metabasites of Punta de li Tulchi is shown in Fig. 4h. The complex evolution of the eclogitic rocks may be summarised as follows:

Pre-eclogite stage: The occurrence of euhedral tschermakite and zoisite in the garnet core might be interpreted as a pre-eclogite amphibolite-epidote stage.

Stage I - The eclogite stage (T=550°-700°C; minimum pressure: 1.3GPa) documented by the occurrence of omphacite relics, garnet porphyroblasts, quartz, zoisite, rutile and barroisite (?).
Stage II - The granulite stage (700°-850°C; 1.0-1.2GPa) is documented by the destabilisation of omphacite and by the growth of clinopyroxene-plagioclase symplectite, sometimes with orthopyroxene and amphibole.

Stage III - The amphibolitisation (T=550°-640°C; P=0.3-0.7GPa) of the granulite assemblage led to the formation of amphibole-plagioclase kelyphite between garnet porphyroblasts and pyroxene-plagioclase symplectites and to the growth of amphibole on orthopyroxene. Tschermakite to Mg-hornblende, plagioclase, cummingtonite, ilmenite, titanite and biotite are coexisting phases.

Stage IV - The later greenschist stage (T=300°-400°C; P=0.2-0.3GPa) is characterised by actinolite, chlorite, epidote s.s., titanite, sericite.

Major element composition of some selected GP and AP layers of the eclogite from Punta de li Tulchi is shown in Table 1. According to the SiO$_2$ –Zr/TiO$_2$ diagram (Winchester and Floyd, 1977) the rocks plot in the field of sub-alkaline basalts. Except for Rb, the GP and AP layers show quite similar trace element contents. Both GP and AP layers exhibit a slightly convex light-REE pattern, mostly a slight negative Eu anomaly, and a flat heavy-REE pattern (Fig. 9a). In the Ti-Zr-Y discrimination diagram of Pearce and Cann (1973) they plot in the field of Mid-Ocean Ridge Basalts (Fig. 9b).

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<th>Layer</th>
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<td>1.84</td>
<td>0.45</td>
<td>0.51</td>
<td>1.95</td>
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Table 1. Major element composition for some selected samples of garnet-pyroxene (GP) and amphibole-plagioclase (AP) layers of the eclogite from Punta de li Tulchi (from Franceschelli et al. 1998).
We return to the main road and after a few km we take a secondary road to Tamarispa. The road crosses the so-called San Lorenzo orthogneiss.

STOP 1.5 - Calc-silicate marbles of Tamarispa

In this stop we can see extremely coarse-grained garnet crystals in calc-silicate marbles (carbonate-silicate rocks, IUGS) hosted in the HGMC (Elter and Palmeri, 1992). The outcrop consists of two NE-SW trending, 3-5m thick, 10-20m long elliptical calc-silicate lenses. The foliation and the mineralogical-extensional lineations of the calc-silicate marbles are the same as that of the surrounding migmatites.

Calc-silicate marbles are characterised by poikiloblastic garnet (Grs\textsubscript{83-96}) up to 15 cm in diameter and by a weak schistose matrix made up of wollastonite, calcite (up to 20 %), small garnet, diopside (X\textsubscript{Mg} = 0.60-0.71), ± quartz, ± plagioclase, epidote, and titanite. Poikiloblastic garnet contains small salitic clinopyroxene, wollastonite and calcite inclusions forming a millipede-like structure.

Temperature from 650 to 850°C and \(X_{\text{CO}_2}\) between 0.006 to 0.013 have been estimated by Elter and Palmeri (1992).
Calc-silicate marbles are crosscut by two types of veins. Type I veins, up to 8-10 cm thick and 4-5 m long, originating from the surrounding migmatite, are made up of quartz, calcite, epidote, K-feldspar, Fe-rich-clinopyroxene, apatite, titanite, albite, and muscovite; type II veins, a few millimetres in thickness, often originating from type I, are mainly made up of calcite, pectolite \([\text{Ca}_2\text{NaH(SiO}_3\text{)}_3]\), and quartz.

The formation of pectolite occurred after metamorphic peak conditions and may be related to the circulation of Na-K-rich metasomatic fluids originating from the surrounding migmatites.

*After the stop 1.5 we return to Posada at the Hotel Donatella. During the travel, after Brunella, we can observe the landscape of the Posada Valley. In a panoramic place we will have a brief talk about the geological significance of the Posada-Asinara line and Posada shear-zone.*
Second day:
Itinerary: Posada, Olbia, Monte Plebi, Montiggiu Nieddu, Punta Sirenella, Olbia airport.

Our second day field trip starts at Posada, where we take the main road to Olbia. After Olbia, from the main road we head towards Monte Plebi, which appears as a high relief of about 350 meters.

Fig. 10 (a) Geological sketch map of Olbia-Golfo Aranci area (modified from Giacomini et al., 2006). Geological sketch maps of: (b) Monte Plebi, (c) Punta Sirenella-Punta Bados, (d) Montiggiu Nieddu.
STOP 2.1- Layered amphibolite sequence of Monte Plebi

The amphibolites at Monte Plebi (Fig. 10a,b), enclosed in migmatites, form a lenticular body up to 250 m long and about 60-70 m wide, and show moderate foliation parallel to the S\textsubscript{2} regional schistosity. From bottom to top, four different (A, B, C, D) layers (Fig. 10b) were distinguished by Franceschelli et al. (2005b).

Layer A is 20-30 m long and 10 m thick. It consists of alternating white and dark bands whose thickness, generally ranging from a few millimetres to a few centimetres, may reach a maximum of 90-100 cm for white bands and 20 cm for dark ones.

Layer B consists of two different lenticular bodies: the first one (B\textsubscript{1}) is completely enclosed in layer A; the second one (B\textsubscript{2}) occurs at the boundary between layer A and the overlying layer C. These lenses, with a maximum thickness of 5 m, are made up of dark, massive ultramafic rocks, locally with millimetric garnets.

Layer C, 20-30 m long and 6 m thick, lies between layers B\textsubscript{2} and D and shows alternation of prevailing dark bands and minor white ones. Millimetric garnet crystals occur in the dark bands. Layer D is 60 m long and 15 m thick. It lies at the top of the amphibolite sequence and consists of white bands prevailing over dark ones.

Three main lithotypes can be distinguished: ultramafic layers, mafic layers (dark bands) and silicic layers (white bands).

Ultramafic layers - They consist of rocks made up of: i) green amphibole (up to 95-98%) and opaque minerals; ii) green amphibole (75-85%), garnet (15-20%) and opaque minerals (3-5%), and iii) green amphibole (95-98%), biotite (2-3%) and opaque minerals (1%). Rare small quartz and plagioclase crystals are also present.

Mafic layers - The dark bands show different proportions of major components: i) fine-grained green amphibole (65-75%), plagioclase (15-20%), quartz (10-15%), biotite (0-2%), opaque minerals (2-3%), rare garnet; ii) coarse-grained green amphibole (70-80%), plagioclase (20-30%) and rare opaque minerals.

Silicic layers - The white bands are coarse-grained rocks made up of plagioclase (60-75%), green amphibole (15-30%) and quartz (10-15%). Small amounts (1-2%) of opaque minerals and rare chlorite are also present.

Chemical composition of some selected samples of ultramafic, mafic and silicic layers from Monte Plebi are reported in Table 2.
Table 2. Major element composition of some selected ultramafic (UML), mafic (ML) and silicic (SL) layers from Monte Plebi (from Franceschelli et al., 2005b).

Field, geochemical and isotopic data suggest that ultramafic, mafic and silicic layers represent repeated sequences of cumulates, basic and acidic rocks similar to macrorhythmic units of mafic silicic layered intrusions.

Fig. 11. (a) Chondrite-normalised REE pattern and (b) $^{143}$Nd/$^{144}$Nd vs. $^{147}$Sm/$^{144}$Nd diagram for Monte Plebi layered amphibolite (from Franceschelli et al., 2005b). Dark and light grey fields, respectively, include the basic-ultrabasic and felsic rocks of leptyno-amphibolite complexes from Innocent et al. (2003).
All Monte Plebi rocks have extremely low Nb, Ta, Zr, Hf content and high LILE/HFSE ratios, a feature inherited from the original mantle sources. The mafic and ultramafic layers show slight and strong LREE enrichment respectively (Fig. 11a). Mafic and ultramafic samples (Fig. 11b) yielded $\varepsilon_{\text{Nd}}(460) = +0.79/ +3.06$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.702934 - 0.703426$, and four silicic samples $\varepsilon_{\text{Nd}}(460) = -0.53/-1.13$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.703239 - 0.703653$. Significant differences in Nd isotope ratios between mafic and silicic rocks prove that both groups evolved separately in deeper magma chambers, from different mantle sources, with negligible interaction with crustal material, and were later repeatedly injected within a shallower magma chamber.

We return to Olbia, where we take the main road to Golfo Aranci. On the eastern coast the road runs along the Tyrrhenian Sea and through recent quaternary deposits. On the road we can observe reliefs of a marked morphology, made up of late Hercynian granitoids, and lower reliefs, mainly made up of migmatites. On the right we can see the Tavolara Island and Capo Figari facing the small Figarolo Island. The two islands are made up of Jurassic carbonaceous sediments, clearly discordant with the underlying Palaeozoic metamorphic basement. From the main road we turn right and head towards Montiggiu Nieddu, which appears as two little reliefs: the higher is 91 meters above the sea level.

STOP 2.2 - Ultramafic and plagioclase-banded amphibolites of Montiggiu Nieddu

Two main lithotypes outcrop at Montiggiu Nieddu: the ultramafic amphibolites and the plagioclase-banded amphibolites (Fig.10 a,d). On the top of the hill, we can observe the field aspect of the ultramafic amphibolites. The regional $S_2$ schistosity is the axial plane foliation of decametre folds (Fig. 10d). The contact between the ultramafic amphibolites and the plagioclase-banded amphibolites appears to be igneous and strikes N 40° and dips SE 45°. It is cut by the secondary foliation, striking N 40° and dipping SE 30°. On the XY plane, a monomineralogical down dip lineation N 160° SE 30° made up of amphibole occurs, while on the XZ plane, some kinematic indicators related to a top-to-the-SE component of shear (Fig. 12) are recognisable ($\sigma$-porphyroclast made up of amphibole surrounded by plagioclase coronas and quartz + feldspar ribbons folded by isoclinal folds).

The ultramafic amphibolites, massive to weakly schistose rocks with garnet and amphibole visible to the naked eye, consist of relics of igneous phases (plagioclase: An$_{89-98}$; olivine: Fo$_{68-71}$; orthopyroxene: En$_{74-76}$; clinopyroxene: Di$_{80-88}$) and metamorphic minerals (mainly orthopyroxene; diopsidic clinopyroxene; plagioclase: An$_{8-1-74}$; garnet: Alm$_{49-62}$ Prp$_{18-27}$ Grs$_{16-25}$ Sps$_{1-3}$; Mg-rich chlorite; clino and orthoamphibole) in variable proportions.
Based on the distribution of the relics of igneous minerals, three main compositional layers (A, B, C) have been identified in the ultramafic amphibolites.

Layer A is made up of coarse-grained olivine, chlorite, amphibole, spinel, minor pyroxene, garnet, and rare plagioclase.

Layer B is made up of coarse-grained plagioclase, olivine, pyroxene, spinel, garnet, and amphibole. In Layer B, which is a layer with an approximate thickness of 4 m, the widespread occurrence of plagioclase crystals surrounded by coronitic garnet and strongly altered crystals of olivine can be observed by the naked eye.

Layer C consists mainly of porphyroblastic garnet, pyroxene, large amphibole grains (up to 5 cm), and minor plagioclase.

The ultramafic amphibolites enclose nodules up to 20 cm in diameter, mainly made up of coarse-grained garnet, often surrounded by a dark amphibole rim. The nodules are made up of garnet, amphibole, spinel, and large amounts of epidote. Garnet-rich veins, striking N 40° and dipping NW 25°, surrounded by a dark amphibole rim and amphibole and/or epidote-rich veins are also present.

On the top of the hill, we can also observe the alternating dark-green and white bands of the banded amphibolites. The dark-green and white bands are made up of plagioclase ($\text{Ab}_{13-88}$), amphibole ($\text{Mg}$-hornblende), garnet ($\text{Alm}_{45-50} \text{ Prp}_{26-37} \text{ Grs}_{10-18} \text{ Sps}_{1-2.5}$), clinopyroxene (diopside, $X_{\text{Mg}} \approx 0.80$), orthopyroxene, and biotite ($X_{\text{Mg}} \approx 0.50$). In the white bands, amphibole crystals up to 5 cm in size are visible. Amphibole and garnet show $\sigma$-porphyroclast structures on the XZ plane related to a top-to-the-SE component of shear correlated with the same tectonic framework of the surrounding migmatites.
The P-T path of Montiggiu Nieddu metabasites is shown in Fig. 4f. The post-igneous metamorphic evolution of Montiggiu Nieddu metabasites may be divided into three stages:

Corona Stage- Primary igneous olivine and anorthite reacted under granulite conditions (T=700-750°C, P ∼ 0.8-1.0 GPa), to produce coronas consisting of orthopyroxene, clinopyroxene, green spinel and garnet. Brown amphibole replaced igneous ortho and clinopyroxene.

Stage II- This amphibolite stage (T=580-640°C, P=0.4-0.6 GPa) is characterised by the formation of brown and green clinoamphiboles (between pyroxene and corona garnet), spinel, anthophyllite, talc, Mg-rich chlorite, corundum (?), plagioclase.

Stage III- Minerals (T ∼ 330-400°C, P<0.2-0.3 GPa), mostly replacing mafic minerals, consist of tremolite, chlorite, fayalite, epidote, albite, calcite, dolomite, serpentine.

Major elements of some selected samples of Layers A, B, C of the ultramafic amphibolites and dark (DB) and white bands (WB) of the banded amphibolites are reported in Table 3. On the basis of the CIPW norm, the rocks of Montiggiu Nieddu show a composition ranging from olivine mela-gabbros, quartz-gabbros, leuco-gabbros to trondhjemite (Ghezzo et al., 1979).

```
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<th>C</th>
<th>N</th>
<th>DB</th>
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Table 3. Major element composition for some selected samples of Layers A, B, C of the ultramafic amphibolites as well as dark (DB) and white bands (WB) of the banded amphibolites and garnet-rich nodule (N) from Montiggiu Nieddu (from Cruciani et al., 2002).

According to Ghezzo et al. (1979), the mafic-ultramafic amphibolites are genetically related by processes of cumulitic differentiation of an original continental rift type tholeiitic basaltic magma. This conclusion is supported by the fractionation trend in the CaO versus MgO diagram.
(Fig. 13a) redrawn from Cruciani et al. (2002). The Ti/Y-Nb/Y diagram suggests a tholeiitic affinity (Fig. 13b). The trace element pattern of the Montiggiu Nieddu metabasites is characterised by selective enrichment of incompatible elements, such as Sr, Rb, Ba, and Th, low abundance of K, Cr, Ni, and a relatively flat trend from Ta to Yb. REE abundance (Fig. 13c,d) ranges from 10 to 50 times the chondrite values. The chondrite-normalised REE pattern is slightly enriched in LREE compared to HREE.

We return to the Golfo Aranci-Olbia road and after about one kilometre, we turn left towards Punta Sirenella.

STOP 2.3- Migmatites of Punta Sirenella

At Punta Sirenella igneous- and sedimentary-derived migmatites outcrop. The following rock-types can be identified: migmatised orthogneisses, amphibole migmatites, and kyanite
migmatites with calc-silicate nodules. According to Cruciani et al. (2003) the amphibole
migmatites derive from an Ordovician igneous protolith (461±12 Ma). The field relationships
between the migmatised orthogneisses and the kyanite migmatites suggest that the latter could be
considered as the sedimentary sequence, in which the protolith of the migmatised orthogneisses
was intruded. On the basis of SiO₂/Al₂O₃ vs. K₂O/Na₂O ratios the sedimentary sequence was
made up of an alternance of greywackes and pelites (Fig. 14a). The kyanite migmatites with
decimetric to metric calc-silicate nodules occur in several areas of the HGMC of northern
Sardinia and can therefore be considered a guide level.

The migmatised orthogneisses show a N 155° NE 60° weak foliation and a K-feldspar +
biotite + quartz polynomineralogical lineation oriented N 110° SE 25°. The migmatised
orthogneisses contain a lense of about 50 m in length and 4-5 m in thickness of amphibole
migmatites. It is made up of quartz (30-45%), plagioclase (20-30%), K-feldspar, garnet (5%),
biotite and retrograde muscovite. Other minerals identified are apatite, zircon and galena. A
similar mineralogical composition can be observed in the neighbouring orthogneisses of Punta
Bados. The orthogneisses of P.Bados are characterised by the occurrence of coarse-grained
garnet crystals (up to 3-4 cm in size) with the following composition Alm₇₆ Prp₇₋₈ Grs₀₋₁ Sps₁₅₋₁₆.

The orthogneisses are peraluminous granitoids, ranging in composition between
monzogranitic to granodioritic terms. Their composition resembles that of the Ordovician
orthogneisses from Lodè-Mamone, S. Lorenzo, Golfo Aranci (Giacomini et al., 2006 and
reference). According to the Rb vs. Nb+Y content the orthogneisses show geochemical affinity
with volcanic arc granites.

REE pattern, 20 to 80 times the chondrite values, show a slight enrichment in LREE
compared to HREE and a marked negative Eu anomaly (Cruciani, 2003). In three orthogneiss
samples, the ¹⁴³Nd/¹⁴⁴Nd isotopic ratio ranges from 0.512295 to 0.512382. The εNd/460Ma, ranging
between -4.1 and -7.1, is lower than those reported by Giacomini et al. (2006) for the
orthogneisses of Golfo Aranci area. The (⁸⁷Sr/⁸⁶Sr)₄₆₀Ma ranges from 0.704866 to 0.713797.
These data demonstrated that the orthogneiss derived from a relatively young felsic-to-
intermediate crust (Giacomini et al., 2006).

The contact between the migmatised orthogneisses and the amphibole migmatites is parallel
to the metamorphic foliation. The amphibole migmatites show an N 145° NE 80° foliation,
which transposes early-formed leucosomes and rods of quartz + feldspars on the XY plane
oriented N 135° SE 25°. Sometimes in the mesosomes, 5-6 cm thick fine-grained strongly
foliated layers, with kinematic indicators (S-C planes, σ-porphyroclasts, and asymmetric
boudins), occur documenting a dextral sense of shear related to a strike-slip shear zone.
The leucosomes (from 2 to 4 cm in thickness) occur as pods and patches up to 30-50 cm long parallel to the main foliation. The most striking feature of the leucosomes is the occurrence of idioblastic amphibole grains up to 4-5 cm in size. A gradual transition in amphibole content has often been observed along the same leucosome or between different leucosomes. Some leucosomes are flanked by mafic selvedges up to a few mm in thickness, consisting of oriented biotite trails. In the amphibole migmatites, two different types of leucosomes can be observed. The first type is tonalitic in composition (Fig. 14b) made up of quartz, plagioclase, ± amphibole, ± garnet (<1-2%), and minor biotite (X_{Mg}~0.5). Accessory phases are apatite, zircon, and titanite. Trace amounts of K-feldspar are rarely preserved as wormy intergrowths in plagioclase. Albite content in plagioclase ranges from Ab_{42} to Ab_{56}. Amphibole is a K-rich-pargasite (X_{Mg} ≅ 0.51) showing several small and rounded inclusions of plagioclase, quartz, garnet, and biotite. Sometimes retrograde biotite growth on amphibole as well as worm-like microstructures at the amphibole-biotite interface have been observed. Garnet (Alm_{51-53} Prp_{7} Grs_{32-34} Sps_{7}) occurs as small grains (~0.6 mm in diameter), usually enclosed in amphibole. The second type of leucosome, granodioritic to granitic in composition (Fig. 14b), is more rare, mainly fine-grained and characterised by the occurrence of K-feldspar (up to 30%). The mesosomes of the amphibole migmatite are made up of the same minerals in different modal proportions (Qtz: 35-45%, Pl: 35-45%, Bt: 10-20%, Amp: <5%, Grt <2%). X_{Mg} ratio of biotite is ≅ 0.49. Amphibole in the mesosome mainly occurs near to the contact with amphibole-rich leucosomes. P T-conditions recorded by the amphibole migmatites are T ~ 750°C, P ~1.0GPa. According to Cruciani (2003) the amphibole leucosomes were formed by partial melting of a biotite + plagioclase + quartz assemblage, with the contribution of a fluid phase.

In the kyanite migmatites the poles of S_{2} schistosity show a maximum between N 45° and N 58° dipping from 2° to 5° towards NW-SE. On the XY plane of S_{2} schistosity, three different poly-mineralogical lineations have been recognized: the oldest consists of rods and/or pencils of plagioclase + quartz; the second is a fibrolite + quartz mineralogical lineation striking N 158° and plunging towards SE of about 20°- 30°. This lineation makes an angle of about 0-20° with the previous mineralogical lineation; the third lineation consists of muscovite sometimes overprinting the fibrolite + quartz lineation. On the XZ plane of the S_{2} schistosity, many kinematic indicators (S-C planes, shear folds, crenulation cleavage, shear band boudins, σ and δ porphyroblasts etc.) are recognizable with different sense of shear. The D_{2} phase is followed by late deformation often associated (P. Bados) to axial plane schistosity. The leucosomes of the kyanite migmatites are mainly trondhjemitic in composition (Fig. 14b) and consist of plagioclase.
(An$_{19-25}$), quartz, biotite (X$_{Mg}$$\sim$0.5), garnet (Alm$_{64-67}$ Prc$_{11-16}$ Grs$_{3-5}$ Sp$_{8-20}$), sillimanite, kyanite, and trace amount of K-feldspar. More rarely, granitic leucosomes with abundant K-feldspar have also been found (Fig. 14b). The main textural features of the kyanite migmatites are the following: i) kyanite is partially replaced and rimmed by fine to medium grained muscovite; ii) fibrolite occurs as isolated needles growing on and mantling biotite flakes; iii) in trondhjemitic leucosomes, K-feldspar occurs as small rare crystals restricted to inclusions within coarse-grained biotite; iv) coarse-grained muscovite crosscutting the fabric includes fibrolite needles.

The trondhjemitic leucosomes were generated by H$_2$O-fluxed melting while the granitic leucosomes seem to have been formed by muscovite dehydration melting (Cruciani et al., 2005). The P-T path of some migmatites from Golfo Aranci area is shown in Fig. 4g. According to Cruciani (2003) partial melting started in the kyanite field (T$\sim$700°C and GPa$\sim$1; maximum PT conditions recorded) and continued (?) in the sillimanite field. After leucosome formation, migmatites underwent metamorphic re-equilibration (T$\sim$600-650°C, GPa=0.3-0.5) with the formation of fibrolite and fibrolite-rich nodules or veins. The last stage of metamorphic re-equilibration is documented by the pervasive growth of coarse-grained muscovite mostly crosscutting the S$_2$ schistosity.

Pegmatite dykes and veins with aplite patches oriented N 80° vertical crosscut the amphibole-rich migmatites. The pegmatites are made up of K-feldspar + biotite + muscovite ± tourmaline; at their boundaries they sometimes show quartz-rich domino structures associated with anhietic dextral shear fractures in a brittle regime related with the main N 80° sinistral strike slip shear zone.

Fig. 14. (a) Composition of paragneiss and mesosomes of migmatite from NE Sardinia in the classification diagram after Wimmenauer (1984); (b) normative Ab-An-Or content of the leucosome of migmatite from NE Sardinia Ab-An-Or classification for silicic rocks after Barker (1979).
STOP 2.4 - Calc-silicate nodules of Punta Sirenella

The calc-silicate nodules have an elliptical shape with the longer axis parallel to the regional schistosity. Their long dimension ranges from several centimetres up to 1-2 metres. Generally the nodules show an evident folding and compositional zoning. Based on their colour and grain size many nodules consist of a inner medium-grained and light-coloured zone and a fine-grained, dark-coloured rim. One or more intermediate concentric layers (up to 7-8) can generally be distinguished between the core and the rim. The inner medium-grained zone is mainly made up of quartz (up to 70%), garnet (5%) (Alm$_{45}$ Prp$_{7}$ Grs$_{39}$ Sps$_{8}$), clinopyroxene (up to 70%; XMg$\sim$0.60), plagioclase (An$_{80-95}$), and rare amphibole (Mg-hornblende). The fine-grained, dark-coloured rim (about 1-5 cm in thickness), consists of large amounts of epidote (up to 45%), amphibole ($\sim$15%), quartz ($\sim$ 20%), garnet ($\sim$ 10%) and opaque minerals ($\sim$10%). From the core to the rim the amount of amphibole increases, while garnet and clinopyroxene decrease. The intermediate layer is fine to medium-grained and ranges in thickness from 2 to 5 mm. It consists of a strongly variable amount of epidote (35-60%), opaque minerals, plagioclase (5-30%), garnet (5-10%), and clinopyroxene. This layer is commonly cut by several epidote-rich veins. A variable chemical composition, mainly in SiO$_2$, CaO, Al$_2$O$_3$ and MgO, can be observed between the various layers of the nodule.

The field-trip ends and the participants are accompanied to the airport and seaport of Olbia. Arrival at Olbia airport at 5:00 pm.

REFERENCES


Società Italiana di Mineralogia e Petrologia

85° CONGRESSO
Fluminimaggiore, 27-30 settembre 2006

Post-Session Field trip Guide
29-30 September 2006