Per. Mineral. (2004), *73*, 73-83
SPECIAL ISSUE 2: A showcase of the Italian research in metamorphic petrology

http://go.to/permin

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY,
ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment, Archaeometry* and *Cultural Heritage*

Unravelling the tectono-metamorphic evolution of medium-pressure rocks from collision to exhumation of the Variscan basement of NE Sardinia (Italy): a review

Carlo Alberto Ricci[1,5], Rodolfo Carosi[2], Gianfranco Di Vincenzo[3],
Marcello Franceschelli[4]* and Rosaria Palmeri[5]

[1] Dipartimento di Scienze della Terra, Università di Siena, Via del Laterino 8, 53100 Siena, Italy
[2] Dipartimento di Scienze della Terra, Università di Pisa, Via S.Maria 53, 56126 Pisa, Italy
[3] Istituto di Geoscienze e Georisorse, CNR Pisa, Via Moruzzi 1, 56124 Pisa, Italy
[4] Dipartimento di Scienze della Terra Università di Cagliari, Via Trentino 51, 09126 Cagliari, Italy
[5] Museo Nazionale dell'Antartide, Via del Laterino 8, 53100 Siena, Italy

Abstract. — The basement of NE Sardinia consists of magmatic-sedimentary sequences affected by a polyphase deformation (D_1, D_2, D_3 and D_4)) and an increase in the metamorphic grade northwards, toward the inner zone of belt. D_1 is mainly detected in the low-grade zone, while D_2 is widespread in the basement but partitioned into domains with prevailing folding in the southernmost areas and shearing in the north-central part. D_2 structures were later overprinted by two main systems of open to tight folds. On the basis of the mineral assemblages of pelitic and quartz-feldspathic rocks, six metamorphic zones have been distinguished. From south to north they are: biotite, garnet, staurolite + biotite, kyanite + biotite, sillimanite + muscovite and sillimanite + K-feldspar. The P-T path of different metamorphic zones is a typical clockwise one due to thermal relaxation after a homogeneous thickening stage. The metamorphic peak is pre- to-syn S_2 in the garnet and staurolite zones, whereas in the sillimanite zones it is essentially syn-S_2. In biotite and garnet zones, both the D_1 and D_2 stages of tectono-metamorphic evolution can be documented. In the garnet zone, petrological evidence indicates that from the S_1 to the S_2 mineralogical assemblage there was an increase in temperature (up to 30°C), along with a decrease in pressure (0.2-0.6 GPa). From the staurolite + biotite zone to the sillimanite + K-feldspar-zone, the D_1 phase is not clearly documented, and samples recorded only the retrogressive path after the thermal climax. The field gradient is nearly concave towards the temperature axis. This is a consequence of the diachronous development of the main parageneses and fabrics in the six metamorphic zones during the exhumation stage. An age of about 340 Ma, found on syn-S_1 celadonite-rich white mica, is interpreted as the time of maximum thickening stage in the garnet zone; ages of 315-320 Ma for syn-S_2 muscovites are attributed to the end of chemical re-equilibration of white mica during the D_2 stage. The emplacement of granitoids in the axial zone has had no influence on the early exhumation of the lower crust, but the different exhumation rate may be related to the transpressional tectonic regime which affected NE Sardinia during Variscan orogeny.

Riassunto. — Il basamento della Sardegna nordorientale è costituito da una sequenza magmatica-sedimentaria interessata da una deformazione polifasica (D_1, D_2, D_3 e D_4) e da un incremento del grado metamorfico verso la zona assiale della catena. La deformazione D_1 è documentata principalmente nelle zone di basso grado metamorfico, mentre la D_2 è diffusa in tutto il basamento ma ripartita in domini a prevalente piegamento nelle aree meridionali e a prevalente shear nella parte centro-settentrionale. Le strutture

---

* Corresponding author, E-mail: e-mail: francmar@unica.it

D_2 sono state successivamente interessate da due sistemi di pieghe. Sulla base delle associazioni mineralogiche delle rocce pelitiche e quarzofeldspatiche, sono state distinte sei zone metamorfiche. Procedendo da sud verso nord esse sono: biotite, granato, staurolite +biotite, cianite + biotite, sillimanite + muscovite e sillimanite + K-feldspato. La zona a granato è stata ulteriormente suddivisa in una zona a granato + albite ed in una zona a granato + oligoclasio. Il percorso P-T delle rocce delle varie zone metamorfiche è un tipico percorso orario; il picco del metamorfismo è pre-sin-S_2 nella zona a granato e nella zona a staurolite + biotite, mentre è essenzialmente sin- S_2 nella zona a sillimanite. Nella zona a biotite possono essere facilmente documentati sia lo stadio D_1 che quello D_2 dell'evoluzione metamorfica. Nella zona a granato, evidenze petrologiche, indicano che tra lo sviluppo della S_1 a quello della S_2 si è verificato un incremento della temperatura fino a 30°C ed una diminuzione della pressione di 0,2-0,6 GPa. La fase D_1, dalla zona a staurolite + biotite a quella a sillimanite + K-feldspato non è chiaramente documentabile perchè le rocce hanno conservato solo il percorso P-T retrogrado dopo il picco del metamorfismo. L'età di circa 340 Ma, fornita dalle miche bianche celadonitiche sin-S_1 della zona a granato, è stata interpretata come l'età del massimo ispessimento crostale della zona a granato. L'età di 315-320 Ma determinate nelle muscoviti sin-S_2 è stata interpretata come l'età in cui è terminato il riequilibrio chimico della mica bianca durante la fase D_2. La messa in posto dei granitoidi nella zona assiale non ha influenzato il corso dei primi stadi dell'esumazione della crosta.

KEY WORDS: *Pelitic and psammitic schist, barrovian metamorphism, P-T path, Variscan orogeny, NE Sardinia*

INTRODUCTION

The Sardinia basement represents a nearly complete section of a segment of the southern European Variscan belt, which experienced polyphase tectono-metamorphic evolution and Barrovian type metamorphism (Franceschelli *et al.*, 1982a, Elter *et al.*, 1986). In Sardinia, the crystalline basement covers an area of about 12,000 sq km and is equally subdivided into plutonic and metamorphic rocks. This basement has been the object of intense petrological investigation since the seventies and is now considered one of the best example of Variscan orogeny in Europe. This paper reviews the tectono- metamorphic features in pelitic and psammitic schists of NE Sardinia and on the basis of available data, discusses the continuous tectono-metamorphic evolution from low to high grade.

OUTLINE OF THE SARDINIAN VARISCAN BELT

The Sardinian basement is a NW-SE trending segment of the Southern Variscan belt (Matte, 1986; Carmignani *et al.*, 1994 and references therein) characterized by nappes, tectono-metamorphic zoning and shortening similar to those that developed in continent-continent collision type orogen. It is composed of Carboniferous magmatic rocks and Cambro-Lower Carboniferous igneous-sedimentary sequences, with metamorphic grade increasing from South to North. Three major tectonic and metamorphic zones have been distinguished by Carmignani *et al.* (1994 and references therein): i) a foreland «thrusts and folds» belt (SW Sardinia), consisting of a metasedimentary sequence ranging in age from (?) Upper Vendian- Lower Cambrian to Lower Carboniferous, with a very low greenschist facies metamorphic imprint; ii) a SW-verging nappe zone (central Sardinia), consisting of a Paleozoic metasedimentary sequence, including a volcanic suite of Ordovician age, affected by greenschist facies metamorphism; iii) an inner zone («axial zone») (northeastern Sardinia and southern Corsica) characterized by medium- to high-grade metamorphic rocks with migmatites and by abundant late-Variscan intrusions.

In northern Sardinia, Carmignani *et al.* (1994) proposed subdividing the axial zone into two different complexes: the first complex made up of metapelites, metasandstones and quartzites, metamorphosed under intermediate pressure greenschist to amphibolite facies conditions; the second one characterized by high grade metamorphic rocks, consisting principally of amphibolite facies migmatites containing large amounts of orthogneisses ranging in age from 440 to 490 Ma (Ferrara *et al.*, 1978; Cruciani *et al.*, 2003; Helbing, 2003), and scattered mafic bodies retaining granulitic and/or eclogitic relic assemblages (Miller *et al.*, 1976; Ghezzo *et al.*, 1979; Franceschelli *et al.*, 1998). According to Cappelli *et al.* (1992) these two complexes were juxtaposed throughout a «suture zone»: the Posada-Asinara line. A different view was expressed by Carosi and Palmeri (2002), who interpreted this line as a wide Variscan transpressional shear belt. The existence of a «suture zone» in northeastern Sardinia has recently been questioned by Helbing (2003) on geological and geochronological bases. The Variscan tectono-metamorphic events were accompanied and followed by the emplacement of abundant intrusive rocks. These igneous rocks emplaced in a time span of about 60 Ma (Di Vincenzo *et al.*, 1994; Carmignani and Rossi, 1999) and consist of: 1) an earlier syn-tectonic Mg-K calc-alkaline association identified only in northwestern Corsica and emplaced at ~330-345 Ma during peak amphibolite-facies metamorphism; 2) a late to post tectonic high-K calc-alkaline association which postdates the D_2 structures in metamorphic rocks and crops out in both Corsica and Sardinia (Rossi and Cocherie, 1991). In Sardinia, the high-K calc-alkaline association also includes strongly peraluminous granitoids whose emplacement occurred at the same time of that of the high-K calc-alkaline *s.s.* granitoids (Di Vincenzo *et al.*, 1994 and references therein). The emplacement of the late- to post-tectonic high-K calc-alkaline granitoids occurred from 310 to 280 Ma. The youngest ages (280-290 Ma) refer to the post-tectonic leucogranites

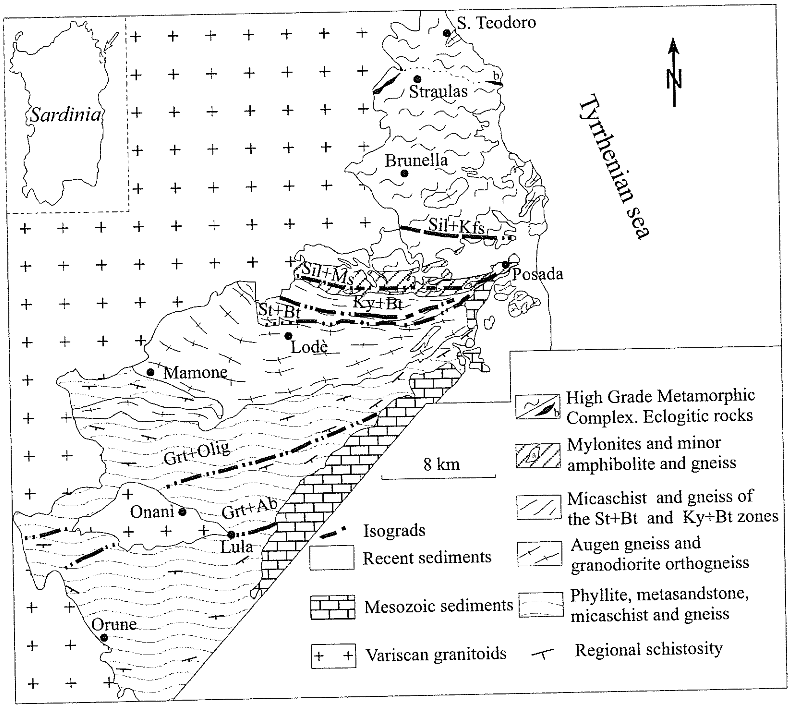

Fig. 1 – a) Geological sketch map and metamorphic zoning in NE Sardinian basement (modified from Franceschelli *et al.*, 1982a; Elter *et al.*, 1986; Carmignani *et al.*, 2001; Helbing 2003).

THE METAMORPHIC BASEMENT OF NORTHEASTERN SARDINIA

The structural and metamorphic evolution of the NE Sardinian basement is characterized by a polyphase deformation history in which heterogeneous deformation and metamorphic grade increases northwards, towards the inner portion of the belt. Four main stages of ductile deformation D_1, D_2, D_3 and D_4 have been recognized. The D_1 deformation stage is characterized by overturned folds, facing SW and syn- to late-D_1 ductile to brittle shear zones, with a top-to the SW sense of shear (Carmignani *et al.,* 1994). D_2 is related to a transpressional deformation event (Carosi and Palmeri, 2002) that overprinted the D_1 structures on regional scale. D_2 is partitioned into domains with prevailing folding in the southernmost areas and shearing in the north-central part. D_2 structures have later been overprinted by two main systems of open to tight folds (F_3 and F_4) (Carosi and Palmeri, 2002).

The metamorphic grade over a distance of about 40 km increases from the biotite to the sillimanite + K-feldspar zone. Metamorphic zoning of pelitic sequences from NE Sardinia (Fig. 1), based on the regional distribution of AFM minerals, has been described by Franceschelli *et al.* (1982a) and Elter *et al.* (1986) and consists of six metamorphic zones which from south to north are: 1) biotite, 2) garnet, 3) staurolite + biotite, 4) kyanite + biotite, 5) sillimanite + muscovite, 6) sillimanite + K-feldspar. The garnet zone has been further subdivided into garnet + albite zone and garnet + olioclase zone. Although an abrupt change is evident from the lithological and tectonic point of view corresponding to Posada line of Carmignani *et al.* (1994), a gradual transition from medium (staurolite and kyanite zones) to high-grade zones (sillimanite + muscovite and K-feldspar zones) is indeed apparent from the metamorphic standpoint.

The biotite zone. This zone is the lowest grade metamorphic zone recognized in NE Sardinia. A few kilometres south of the village of Lula (Fig. 1), rocks still preserve evidence of sedimentary bedding S_0, which is overprinted by two metamorphic foliations (Fig. 2a): the S_1 and S_2 foliations, well detectable both on a meso- and microscopic scale. S_0 sedimentary foliation is marked by the alternation of pelitic, psammitic and quartzite layers isoclinally folded by F_1 folds. S_1 foliation is a pervasive and continuous foliation and is defined by white mica, biotite, chlorite flakes and/or by elongated quartz and feldspars. Albite porphyroblasts show helicitic inclusions of mica, quartz and carbonaceous matter. Other observed minerals include carbonate, K-feldspar and epidote. S_1 white mica is a Na-poor, celadonite-rich muscovite. Plagioclase is the most abundant mineral, consisting mainly of homogeneous albite (1-4% An). Chlorite is a Mg-Fe chlorite, and the X_{Mg} (Mg/Mg+Fe) of biotite ranges from 0.40 to 0.50.

F_2 folds are open to closed, showing a similar geometry whose axes trend nearly NW-SE, with highly scattered plunges. S_2 axial plane foliation is an evolved, discrete crenulation cleavage and mainly includes white mica and chlorite. S_2 schistosity is overprinted by S_3 crenulation cleavage due to later F_3 and F_4 folds that are rarely accompanied by new blastesis.

Garnet + albite and garnet + oligoclase zones. The main features of garnet zones are the increase in the grain size of mineral constituents and the appearance of oligoclase. S_1 foliation is still well recognizable in the hinges of F_2 folds and in thin sections is preserved in mica-rich microlithons or as helicitic inclusions in albite and garnet porphyroblasts (Fig. 2b). S_1 minerals include celadonite-rich white mica, chlorite, biotite, and quartz, and are usually included within porphyroblasts (up to 2 mm in size) of albite (Fig. 2c). Inclusion trails show different types of arrangements: rectilinear, gently or strongly folded. These microstructures could be interpreted as the gradual deformation of S_1 foliation during the D_2 stage. The D_2 strain increases northwards and, in this zone, S_2 becomes the main pervasive foliation. The S_2 foliation strikes WNW-ESE and dips strongly towards SSW, it is an advanced discrete S_2 crenulation cleavage dominated by white mica and minor chlorite and biotite. S_2 minerals include white mica, garnet, oligoclase, biotite and opaque minerals and it envelops albite porphyroblasts. Garnet from the matrix is anhedral, deeply fractured and partially replaced by biotite or chlorite, while garnet preserved by albite is euhedral and rarely fractured.

Garnet in the garnet + albite zone shows, from core to rim, evident, bell- shaped, Mn zoning accompanied by an increase in Ca content and in X_{Mg} ratio. Garnet in the garnet + oligoclase zone is characterized by chemical zoning quite similar to the garnet in the previous zone. Ca content gradually increases from the core to an outer core zone, where maximum value is reached, and then abruptly decreases towards the rim (Franceschelli *et al.*,1982b). Garnet grew in response to a prograde reaction involving chlorite as a reactant, together with other Ca-bearing minerals that could have led to the formation of the Ca-rich garnet core. Possible reactions are (Franceschelli *et al.*, 1982b; Connolly *et al.*, 1994):

(I) chlorite + muscovite + quartz =
= garnet + biotite + H_2O
(II) carbonate + epidote = garnet + CO_2 + H_2O

Upon the entry of garnet into the assemblages, the composition of the plagioclase is close to that of pure albite (1-4% An). In the upper garnet + oligoclase zone, the plagioclase displays a large albitic core (1-4% An) and a thin oligoclase rim (Fig. 2d) approaching peristerite composition (18-22% An). Small grains of plagioclase (16-18% An) also occur along the S_2 foliation. Biotite (X_{Mg} = 0.40 - 0.50) and chlorite (X_{Mg} = 0.30-0.50) are widespread in the garnet zone and occurs as flakes parallel to the S_2 foliation or surrounding plagioclase and garnet porphyroblasts. Celadonite-rich white mica (Si^{4+} up to 3.4 apfu on 11 oxygens) is only a syn D_1 relic within albite or a coarse-grained deformed flake along S_2 (Di Vincenzo *et al.*, 2004) and muscovite (Si^{4+} =3.0 apfu on 11 oxygens) is the main mica along S_2 foliation. Fe-rich chloritoid and staurolite are sometimes present in Al-rich metapelite. In situ ^{40}Ar-^{39}Ar laser analyses on micaschists (Di Vincenzo *et al.*, 2004) yield ages up to ~340 Ma for syn-S_1 phengite and of ~320 Ma for syn-S_2 muscovite. A later crenulation cleavage is attributed to D_3 and D_4 folding.

Temperature conditions for the thermal peak of the garnet zone (Franceschelli *et al.*, 1989; Carosi and Palmeri, 2002; Di Vincenzo *et al.*, 2004) have been estimated up to 453°C for the upper garnet + oligoclase zone and from 520 to 560°C for the deeper garnet + oligoclase zone. Pressures for the latter zone at metamorphic peak conditions has been estimated in the range between of 0.7 to 0.9 GPa (Di Vincenzo *et al.*, 2004).

The staurolite + biotite zone – The appearance in the field of the staurolite + biotite association coincides with the contact between pelitic and granitic augen gneiss units (Franceschelli *et al.*, 1982a). From this metamorphic zone up to the sillimanite + K-feldspar zone, the D_1 fabric is completely transposed by D_2, and only the S_2 foliation, which strikes W-E and WNW-ESE and dips moderately to strongly towards the S and the SW, can be identified. It bears an oblique stretching lineation (L_2) marked by the alignment of chlorite, muscovite, quartz and biotite and by stretched and fractured porphyroblasts of staurolite and garnet. Rocks in 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 (Fig. 2e). Garnet is anhedral and rounded and encloses quartz, biotite, and chlorite and displays bell-shaped zoning from core to rim for Mn. Towards the rim, Mg and Fe gradually increase and Ca decreases. Staurolite occurs as elongated prisms, enclosing abundant phyllosilicates, quartz and graphite. Staurolite is chemically homogeneous and Fe-rich. Mg content is up to 0.50 apfu, and the X_{Mg} ratio ~ 0.17. X_{Mg} of biotite is ~ 0.50. Muscovite is celadonite-poor (Mg+Fe up to 0.42). The reaction in the KFMASH system (Spear and Cheney, 1989)

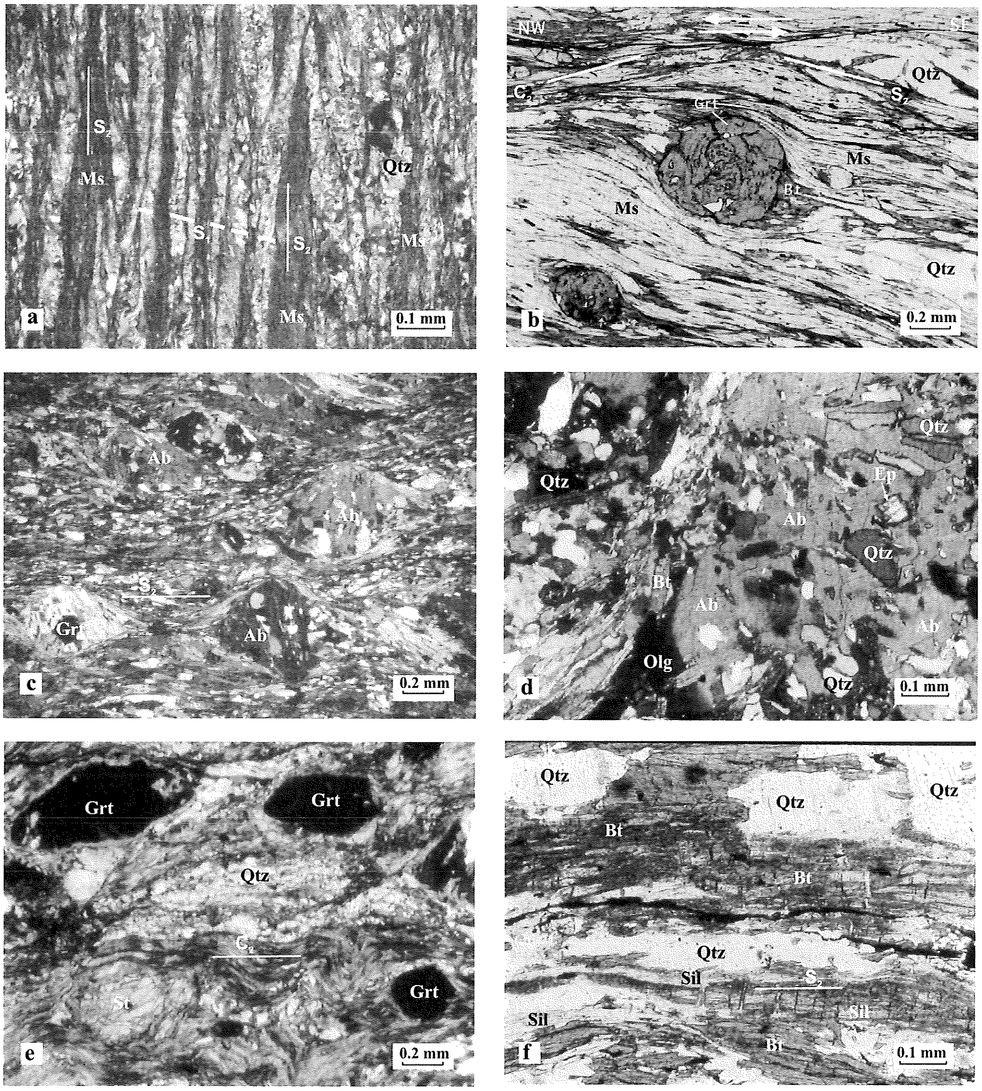

Fig. 2 – Photomicrographs showing typical texture from rocks in the NE Sardinia basement: A) Biotite schist from biotite zone showing S_1 and S_2 schistosities at high angle. Crossed polars. B) D_2 Shear bands and D_2 rotated garnets in garnet-bearing micaschists. Top-to-the NW sense of shear. One polar. C) Albite porphyroblasts enveloped by S_2 schistosity. The albite contains inclusions of garnet, quartz and phyllosilicates. Quartz-feldspatic schist from garnet zone. Crossed polars. D) Typical plagioclase zoning in the garnet + oligoclase zone showing an albitic core and a thin oligoclase rim. The albite core contains inclusions of quartz, epidote and phyllosilicates. Crossed polars. E) Stretched staurolite and garnet porphyroblasts along the mylonitic foliation. Samples from Monte Tundu, staurolite +biotite zone. Crossed polars. F) Fibrolite growing on and around biotite oriented along the S_2 schistosity in a gneiss from the High Grade Metamorphic Complex. One polar. Mineral abbreviation as in Kretz (1983). Olig = oligoclase; S_1 = S_1 schistosity; S_2 = S_2 schistosity; C_2 = mylonitic foliation.

(III) garnet + chlorite + muscovite =
staurolite + biotite + quartz + H_2O

can be considered responsible for the genesis of the staurolite + biotite assemblage.

Temperatures and pressures in the range of 570-625°C and 0.7-1.0 GPa have been reported by Franceschelli *et al.* (1989) and Di Vincenzo *et al.* (2004) for the thermal peak conditions.

In situ ^{40}Ar-^{39}Ar ages on muscovite along S_2 foliation range between 315 and 320 Ma and overlap with those obtained for syn-D_2 white micas of the garnet zone (Di Vincenzo *et al.*, 2004). Younger ages (~300-310Ma) were detected in white mica grown on staurolite or, intergrown with biotite on garnet.

The kyanite+biotite zone – This zone is marked by the first appearance of kyanite+ biotite association, about 0.5 km northwards of the staurolite + biotite isograd. Rocks consist of porphyroblasts of staurolite, kyanite, and plagioclase enveloped in a mylonitic matrix of quartz, muscovite, biotite, chlorite and ilmenite. Garnet often occurs as euhedral clear or cloudy inclusions in staurolite, or plagioclase and rarely in kyanite porphyroblasts. Clear garnet contains calc-silicate micro-inclusions of idiomorphic anorthite, epidote and margarite (Connolly *et al.*, 1994). Garnet that occurs in the matrix or as cloudy inclusion have a similar composition. The average core and rim compositions of these garnets are Alm_{76}, Py_{11}, Sps_7, Grs_6, and Alm_{75}, Py_{10}, Sps_9, Grs_6, respectively. The clear garnet inclusions within staurolite are more calcic and zoned with an average core and rim composition of Alm_{62}, Grs_{18}, Py_7, Sps_3 and Alm_{67}, Grs_{17}, Py_{10}, Sps_6 (Connolly *et al.*, 1994). Plagioclase included in garnet is extremely calcic (67-99% An) while that enclosed in cloudy garnet has a compositional range from 22 to 59% An. The X_{Mg} of biotite ranges from 0.4 to 0.5. Muscovite is Na- and celadonite poor.

The incoming of kyanite + biotite is attributed to the KFMASH discontinuous reaction (Spear and Cheney, 1989):

(IV) staurolite + chlorite + muscovite =
kyanite + biotite + quartz +H_2O

Temperatures up to 595°C and pressures up to 0.67 GPa have been reported by Franceschelli *et al.* (1989) for the metamorphic peak conditions.

The sillimanite + muscovite zone – Rocks from this zone, near the kyanite+ biotite area, commonly show a mylonitic texture (Elter *et al.*, 1999 and references therein). Northwards, rocks show a gneissic fabric due to a compositional layering made up of quartzo-feldspathic and mafic minerals aligned along the main S_2 foliation. Mineral dimensions are approximately 0.1-0.3 mm, except for sillimanite needles, which are commonly associated with biotite crystals and/or included in quartz, plagioclase and muscovite. Garnet is fine-grained, unzoned, and almandine-rich, with spessartine content up to 15% and grossularite between 3 and 7%. The X_{Mg} of matrix biotite ranges from 0.35 to 0.43. Plagioclase shows fairly uniform oligoclase composition. Relics of staurolite and kyanite may be sporadically found. The formation of sillimanite with newly formed garnet can be attributed to the discontinuous KFMASH reaction (Spear and Cheney, 1989)

(V) staurolite + muscovite + quartz =
= garnet + biotite + Al_2SiO_5 + H_2O.

Franceschelli *et al.* (1989), estimated a temperature of 605°C and pressure of ~ 0.4 GPa for rocks in this zone, representing a stage in the retrograde path for these rocks.

The sillimanite + K-feldspar zone – Migmatites are the most widespread rocks in this metamorphic zone. Mesosomes are medium-grained, with a fabric defined by the alignment of biotite parallel to S_2 schistosity. They consist of quartz, plagioclase, biotite, garnet, fibrolite, muscovite and K-feldspar. Sillimanite needles are commonly associated with biotite crystals (Fig. 2f). Kyanite occurs sporadically as relic mineral. Retrograde white mica overgrew on fibrolite on both mesosome and leucosome. Leucosomes are coarse-grained, poorly-foliated rocks, tonalitic to granitic and rarely trondjemitic in composition. Plagioclase is a poorly zoned oligoclase with a slight decrease in albite content from core to rim. Garnet (approx. 0.6 mm in diameter) is almandine-rich (59-67%), with high pyrope (up to 11%) and spessartine (10-30%), but low grossularite (<4%) content. The X_{Mg} of biotite ranges from 0.30 to 0.50. The muscovite dehydration-melting reaction (Petö, 1976; Patiño-Douce and Harris, 1998):

(VI) muscovite + plagioclase + quartz =
= K-feldspar + Al_2SiO_5 + melt

accounts for the above observations.

Temperatures up to 750 °C and pressures at 0.6-0.8 GPa have been reported for the formation of migmatites (Palmeri, 1992; Cruciani *et al.*, 2001). Temperature from 560 to 640 °C and pressure around 0.4 GPa have been obtained with the garnet-biotite geothermometer (Franceschelli *et al.* (1989). According to Franceschelli *et al.* (1989), the garnet biotite-geothermometer in the rocks of the sillimanite + K-feldspar zone, does not record peak metamorphic conditions but only equilibration along the P-T path.

In situ argon ages on muscovites, from both migmatitic orthogneiss and metasedimentary stromatic migmatite from Punta de li Tulchi, yielded a closely comparable and restricted

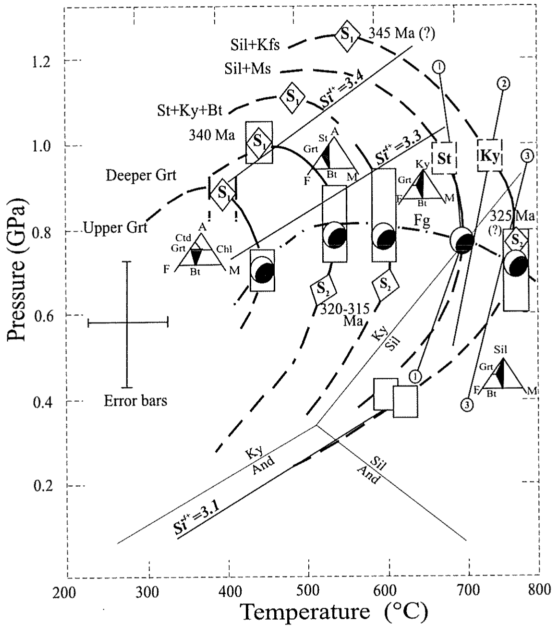

Fig. 3 – P-T path for metamorphic zones of NE Sardinia Variscan basement redrawn after Franceschelli *et al.* (1989).The boxes represent P-T estimations. S_1: first foliation, located along a linear gradient from the origin to T = 450 °C and P = 0.1 GPa. S_2: second foliation, based on P-T estimates. Squares are relic minerals; black and white circles are the metamorphic peak. Ages on S_1 are from Di Vincenzo *et al.* (2004) and Ferrara *et al.* (1978). Ages on S_2 are from Di Vincenzo *et al.* (2004), and Palmeri *et al.* (1997). Fg field gradient; Reaction curves: aluminum silicate triple point according to Holdaway (1971); (1): Breakdown of Staurolite (Spear and Cheney, 1989); (2): Ms + Pl + Qtz = Kfs +Sil + Bt+ melt (Petö, 1976); (3): Ms + Pl + Qtz = Kfs + Sil + melt (Patiño-Douce and Harris, 1998). Isopleths of Si^{4+} for white mica Si contents (atoms per formula unit) are from Massonne and Schreyer (1987). Mineral abbreviations from Kretz (1983); Olig = oligoclase.

age-variation from ~300 Ma to ~320 Ma (Di Vincenzo *et al.,* 2004).

DISCUSSION

Temperature and pressure estimates along with petrographical and geochronological constraints allow the reconstruction of the P-T paths for the various metamorphic zones in northeastern Sardinia (Fig. 3). As already reported by Franceschelli *et al.* (1989) the P-T path is a typical clockwise one considered due to thermal relaxation after a homogeneous thickening stage (England and Thompson, 1984). However, recent structural and geochronological data (Carosi and Palmeri, 2002; Di Vincenzo *et al.,* 2004) induce new considerations on P-T paths and the tectono-metamorphic evolution of northeastern Sardinia. Albite and oligoclase + garnet zones are the only ones in which both the D_1 and D_2 stages of tectono-metamorphic evolution can be documented. From the staurolite + biotite zone to the sillimanite + K-feldspar-zone, samples documented only the retrogressive path after the thermal climax (Franceschelli *et al.,* 1989; Ricci, 1992). In fact, in most cases, aside from a few mineralogical relics such as kyanite, preserved as inclusion in the plagioclase of migmatites, intense D_2 deformation and the temperature reached during the metamorphic peak obscured the record of the earlier D_1 stage. In low- to medium-grade zones, petrological evidence indicates that, moving from the mineralogical assemblage along S_1 (formed during the D_1 stage) to the assemblage along the S_2 foliation (formed during the D_2 stage), there was an increase in temperature (up to 30°C), while pressure was to some extent decreasing (0.2-0.6 GPa).

Recent geochronological data on syn-S_1 celadonite-rich white mica of ~ 340 Ma, was attributed by Di Vincenzo *et al.* (2004) to the D_1 stage, and interpreted as the time of the maximum thickening stage in the garnet zone; the clustering of ages around 315-320 Ma found on syn-S_2 celadonite-poor white micas from the garnet and staurolite zones was instead attributed to the end of the chemical re-equilibration (including neo-crystallization) of white mica during the D_2 stage. This interpretation agrees with independent age constraints which suggest that the Variscan continental collision in the Internal Nappes cannot have commenced earlier than ~360 Ma and, taking into account that the emplacement of the widespread late-tectonic plutonism (310-280 Ma) postdate the D_2 transpressive structures, the D_2 deformational event should be older than ~310 Ma. By contrast, the temporal evolution in the High Grade Metamorphic Complex is less constrainable. Ferrara *et al.* (1978) reported a Rb-Sr whole-rock age of 344 ± 7 Ma obtained from a banded migmatite with trondhjemitic leucosomes. When assigning to this age a geological meaning, one should take into account that leucosomes show trondhjemitic compositions. This implies that either they are considered the product of metamorphic differentiation (Palmeri, 1992) or of water-fluxed melting (Patiño Douce and Harris, 1998), they should be assigned to an earlier process during the prograde metamorphism of a thickening orogenic belt. The ~345 Ma age could therefore be close to the collisional stage or represent the beginning of exhumation. This inference agrees with the U-Pb SHRIMP age on zircon of 327 ± 7 Ma for amphibolite rocks with eclogite relics (Palmeri *et al.*, 1997), which was attributed to a zircon growth phase related to the main, amphibolite-facies, Variscan event.

Fig. 3 (redrawn after Franceschelli *et al.*, 1989) synthesizes all available petrological, geochronological and structural data. From Fig. 3 it appears that the metamorphic peak is pre-to-syn S_2 in the garnet and staurolite zones, whereas in the sillimanite zones it is essentially syn-S_2. An age of ~ 345 and of ~ 325 Ma are tentatively attributed to the thickening stage and to the thermal peak (syn-S_2) in the highest grade zones, respectively.

The P-T paths of the different metamorphic zones (Fig. 3) allow us to infer a field gradient based on the time when the metamorphic peak was reached in the different metamorphic zones that is nearly concave towards the temperature axis, as already evidenced by Franceschelli *et al.* (1989). As suggested by Franceschelli *et al.* (1989) this is not the expression of changing gradients from low to high grade zones, but a consequence of the diachronous development of the main parageneses and fabrics in the different zones during the exhumation stage.

The age constraints on granitoids emplacement (310-280 Ma) and on the development of D_2 tectono-metamorphic stages (320-315 Ma) exclude any influence exerted by the emplacement of granitoids in the axial zone on the early exhumation of the lower crust. The transpressional tectonic regime affecting NE Sardinia during the Variscan orogen (Carosi and Palmeri, 2002) and in particular, the progressive change from frontal (during the early stages of contraction, D_1) to oblique convergence (during the D_2 stage) has an important role in the equilibration and exhumation of metamorphic rocks in the orogenic belts. If confirmed by further research, the higher exhumation rate of migmatites with respect to lower-grade rocks during the first stage of exhumation, as can be deduced from thermo-barometric and geochronological data, can be attributed to a decreasing strength of the lower crust and to the prevalent pure-shear component of the transpressional tectonic regime.

Moreover, the gradual change from frontal to oblique convergence implies (Thompson et *al.,* 1997) that during the late development of D_2, the exhumation rate slowed and became comparable to isostatic erosion.

REFERENCES

Cappelli B., Carmignani L., Castorina F., Di Pisa A., Oggiano G. and Petrini R. (1992) — *A Hercynian suture zone in Sardinia: geological and geochemical evidence.* Geodin. Acta, **5**, 101-118.

Carmignani L., Carosi R., Di Pisa A., Gattiglio M., Musumeci G., Oggiano G. and Pertusati P.C. (1994) — *The hercynian chain in Sardinia (Italy).* Geodin. Acta, **7**, 1, 31-47.

Carmignani L., Oggiano G., Barca S., Conti P., Salvatori I., Eltrudis A., Funedda A. and Pasci S. (2001) — *Geologia della Sardegna. Note illustrative della Carta Geologica della Sardegna a scala 1:200.000.* Mem. Descr. Carta Geol. It., **60**, 283 pp.

Carmignani L. and Rossi P. (1999) — *Carta geologica e strutturale della Sardegna e della Corsica (1:500 000).* Servizio Geol. It. - BRGM Service Géologique National.

Carosi R. and Palmeri R. (2002) — *Orogen - parallel tectonic transport in the Variscan belt of northeastern Sardinia (Italy): implication for the exhumation of medium-pressure metamorphic rocks.* Geol. Mag., **139**, 497-511.

Connolly J. A.D., Memmi I., Trommsdorff V., Franceschelli M. and Ricci C.A. (1994) — *Forward modeling of calc-silicate microinclusions and fluid evolution in a graphitic metapelite, northeast Sardinia.* Am. Mineral., **79**, 960-972.

Cruciani G., Franceschelli M., Caredda A.M. and Carcangiu G. (2001) — *Anatexis in the Hercynian basement of NE Sardinia, Italy: a case study of the migmatite of Porto Ottiolu.* Mineral. Petrol., **71**, 195-233.

Cruciani G., Franceschelli M. and Jungs S. (2003) — *Zircon morphology and Pb-Pb dating of amphibole bearing migmatite from the Variscan chain of NE Sardinia, Italy.* Abstract vol. of the FIST Geoitalia 2003, 4°, 209-210.

Di Vincenzo G., Carosi R. and Palmeri R. (2004) — *The relationship between tectono-metamorphic evolution and argon isotope records in white mica: constraints from in situ ^{40}Ar-^{39}Ar laser analysis of the Variscan basement of Sardinia (Italy).* J. Petrol., **45**, 1013-1043.

Di Vincenzo G., Elter F.M., Ghezzo C., Palmeri R. and Ricci C.A. (1994) — *Petrological evolution of the Palaeozoic basement of Sardinia.* Petrology, geology and ore deposits of the Palaeozoic basement of Sardinia. In: "*Guide–book to the field excursion (B3)*". Carmignani, L., Ghezzo, C., Marcello A., Pertusati P. C., Pretti S., Ricci C.A. and Salvadori I. (eds). 16th General Meeting of the IMA, 21-36.

Elter F.M., Faure M., Ghezzo C. and Corsi B. (1999) — *Late Hercynian shear zones in northeastern Sardinia (Italy).* Géol. Fr., **2**, 3-16.

Elter F.M., Franceschelli M., Ghezzo C., Memmi I. and Ricci C.A. (1986) — *The geology of Northern Sardinia.* In: «*Guide- book to the* *excursion of the Paleozoic Basement of Sardinia IGCP n°5»*. Carmignami L, Cocozza T, Ghezzo C, Pertusati P, and Ricci CA (eds). Newsletter Spec. Issue 87-97.

England P.C. and Thompson A.B. (1984) — *Pressure-temperature-time path of regional metamorphism. I. Heat transfer during the evolution of regions of thickened continental crust.* J. Petrol., **25**, 894-928.

Ferrara G., Ricci C.A. and Rita F. (1978) — *Isotopic ages and tectono-metamorphic history of the metamorphic basement of north-eastern Sardinia.* Contrib. Mineral. Petrol., **68**, 99-106.

Franceschelli M., Eltrudis E., Memmi I., Palmeri R. and Carcangiu G. (1998) — *Multi-stage metamorphic re-equilibration in eclogitic rocks from the Hercynian basement of NE Sardinia (Italy).* Mineral. Petrol. **62**, 167-193.

Franceschelli M., Memmi I., Pannuti F. and Ricci C.A. (1989) — *Diachronous metamorphic equilibria in the Hercynian basement of northern Sardinia, Italy.* In: «*Evolution of metamorphic belts*». Daly J.S., Cliff R.A. and Yardley B.W.D. (eds). Geol. Soc. Lond. Spec. Publ., **43**, 371-375.

Franceschelli M., Memmi I. and Ricci C.A. (1982a) — *Zoneografia metamorfica della Sardegna settentrionale.* In: «*Guida alla Geologia del Paleozoico sardo. Guide Geologiche Regionali*» Carmignami L., Cocozza T., Ghezzo C., Pertusati P. and Ricci C.A. (Eds.), Soc. Geol. It., 137-149.

Franceschelli M., Memmi I. and Ricci C.A. (1982b) — *Ca distribution between almandine-rich garnet and plagioclase in pelitic and psammitic schists from the metamorphic basement of north-eastern Sardinia.* Contrib. Mineral. Petrol., **80**, 285-295.

Ghezzo C., Memmi I. and Ricci C.A. (1979) — *Un evento granulitico nel basamento metamorfico della Sardegna nord-orientale.* Mem. Soc. Geol. It., **20**, 23-38.

Helbing H. (2003) — *No suture in the Sardinian Variscides: A structural, petrological, and geochronological analysis.* Tübinger Geowissenschaftliche Arbeitenm, Reihe **68**, 190 p.

Holdaway M.J. (1971) — *Stability of andalusite and the aluminium silicate phase diagram.* Am. J. Sci., **271**, 97-131.

Kretz R. (1983) — *Symbols for rock forming minerals.* Am. Mineral., **68**, 277-279.

Massonne H.J. and Schreyer W. (1987) — *Phengite geobarometry based on limiting assemblage with K-feldspar, phlogopite and quartz.* Contrib. Mineral. Petrol., **96**, 212-214.

Matte P. (1986) — *Tectonics and plate tectonics model for the Variscan belt of Europe.* Tectonophysics, **126**, 329-74.

Miller C., Sassi F.P. and Armari G. (1976) — *On the occurrence of altered eclogitic rocks in north-eastern Sardinia and their implication.* N. Jb. Geol. Paläont. Mh., **11**, 683-689.

Palmeri R. (1992) — *Petrography and geochemistry of some migmatites from northeastern Sardinia (Italy).* In: «*Contribution to the Geology of Italy with special regard to the Paleozoic basements. A volume dedicated to Tommaso Cocozza*». Carmignani L. and Sassi F.P. (eds). IGCP Project No. 276 Newsletter, **5**, 183-186.

Palmeri R., Fanning M., Franceschelli M., Memmi I. and Ricci C.A. (1997) — *New petrological and geochronological data on the eclogite of P.ta de Li Tulchi, NE Sardinia (Italy).* 5th Int. Eclogite Conference. Terra Nova, **9** Abstr. supl.1, 24.

Patiño Douce A.E. and Harris N. (1998) — *Experimental constraints on Himalayan anatexis.* J. Petrol., **39**, 689-710.

Petö P. (1976) — *An experimental investigation of melting relations involving muscovite and paragonite in the silica saturated-portion of the system* $K_2O\text{-}Na_2O\text{-}Al_2O_3\text{-}SiO_2\text{-}H_2O$ *to 15 Kbar total pressure.* Prog. in Exper Petrol. NERC London. 3rd report, 441-45.

Ricci C.A. (1992) — *From crustal thickening to exhumation: petrological, structural and geochronological records.* In: «*Contribution to the Geology of Italy with special regard to the Paleozoic basements. A volume dedicate to Tommaso Cocozza*» Carmignani L. and Sassi F.P. (eds). IGCP Project no. 276, Newsletter, **5**, 187-197.

Rossi P. and Cocherie A. (1991) — *Genesis of a Variscan batholith: field, petrological and mineralogical evidence from the Corsica-Sardinia batholith.* Tectonophysics, **195**, 319-346.

Spear F.S. and Cheney J.T. (1989) — *A petrogenetic grid for pelitic schists in the system* $SiO_2\text{-}Al_2O_3\text{-}FeO\text{-}MgO\text{-}K_2O\text{-}H_2O$. Contrib. Mineral. Petrol., **101**, 149-64.

Thompson A.B., Schulmann K. and Jezek J. (1997) — *Thermal evolution and exhumation in obliquely convergent (transpressive) orogens.* Tectonophysics, **280**, 171-184.