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

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ABSTRACT. — The basement of NE Sardinia consists of magmatic-sedimentary sequences affected by a polyphase deformation (D1, D2, D3 and D4) and an increase in the metamorphic grade northwards, toward the inner zone of belt. D1 is mainly detected in the low-grade zone, while D2 is widespread in the basement but partitioned into domains with prevailing folding in the southernmost areas and shearing in the north-central part. D2 structures were later overprinted by two main systems of open to tight folds. On the basis of the mineral assemblages of pelitic and quartzfeldspathic 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 S2 in the garnet and staurolite zones, whereas in the sillimanite zones it is essentially syn-S2. In biotite and garnet zones, both the D1 and D2 stages of tectono-metamorphic evolution can be documented. In the garnet zone, petrological evidence indicates that from the S1 to the S2 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 D1 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-S1 celadonite-rich white mica, is interpreted as the time of maximum thickening stage in the garnet zone; ages of 315-320 Ma for syn-S2 muscovites are attributed to the end of chemical re-equilibration of white mica during the D3 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 (D1, D2, D3 e D4) e da un incremento del grado metamorfico verso la zona assiale della catena. La deformazione D1 è documentata principalmente nelle zone di basso grado metamorfico, mentre la D2 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
D₂ 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-S₂ nella zona a granato e nella zona a staurolite + biotite, mentre è essenzialmente sin-S₂ nella zona a sillimanite. Nella zona a biotite possono essere facilmente documentati sia lo stadio D₁ che quello D₂ dell’evoluzione metamorfica. Nella zona a granato, evidenze petrologiche, indicano che tra lo sviluppo della S₁ a quello della S₂ si è verificato un incremento della temperatura fino a 30°C ed una diminuzione della pressione di 0,2-0,6 GPa. La fase D₁, dalla zona a staurolite + biotite a quella a sillimanite + K-feldspato non è chiaramente documentabile perché le rocce hanno conservato solo il percorso P-T retrogradato dopo il picco del metamorfismo. L’età di circa 340 Ma, fornita dalle miche bianche celadonitiche sin-S₁ nella zona a granato, è stata interpretata come l’età del massimo ispessimento crustale della zona a granato. L’età di 315-320 Ma determinate nelle muscovite sin-S₂ è stata interpretata come l’età in cui è terminato il riequilibrio chimico della nica bianca durante la fase D₂. La massa 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 Sardinia 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 gneissic 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 gneissich 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 gneissich to amphibolite facies conditions; the second one characterized by high grade metamorphic rocks, consisting
principally of amphibolite facies migmatites containing large amounts of orthogneiss 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., 1976; Franceschelli et al., 1998). According to Ceppelli 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 D2 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 D1, D2, D3 and D4 have been recognized. The D1 deformation stage is characterized by overturned folds, facing SW and syn- to late-D1 ductile to brittle shear zones, with a top-to the SW sense of shear (Carmignani et al., 1994). D2 is related to a transpressional deformation event (Carosi and Palmeri, 2002) that overprinted the D1 structures on regional scale. D2 is partitioned into domains with prevailing folding in the southernmost areas and shearing in the north-central part. D2 structures have later been overprinted by two main systems of open to tight folds (F2 and F4) (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 + oligoclase 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 S0, which is overprinted by two metamorphic foliations (Fig. 2a): the S1 and S2 foliations, well detectable both on a meso- and microscopic scale. S0 sedimentary foliation is marked by the alternation of pelitic, psammitic and quartzite layers isoclinally folded by F1 folds. S1 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. S1 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.

F3 folds are open to closed, showing a similar geometry whose axes trend nearly NW-SE, with highly scattered plunges. S2 axial plane foliation is an evolved, discrete crenulation cleavage and mainly includes white mica and chlorite. S2 schistosity is overprinted by S3 crenulation cleavage due to later F3 and F4 folds that are rarely accompanied by new blastsesis.

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. S1 foliation is still well recognizable in the hinges of F2 folds and in thin sections is preserved in mica-rich microlithons or as helicitic inclusions in albite and garnet porphyroblasts (Fig. 2b). S1 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 S1 foliation during the D2 stage. The D2 strain increases northwards and, in this zone, S2 becomes the main pervasive foliation. The S2 foliation strikes WNW-ESE and dips strongly
towards SSW, it is an advanced discrete S2 crenulation cleavage dominated by white mica and minor chlorite and biotite. S2 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 $X_{\text{Mg}}$ ratio. Garnet in the garnet + oligoclase zone is characterized by chemical 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$_2$O

(II) carbonate + epidote = garnet + CO$_2$ + H$_2$O

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 albite 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 ($X_{\text{Mg}} = 0.40 - 0.50$) and chlorite ($X_{\text{Mg}} = 0.30-0.50$) 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$^+$ 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$^+$ = 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 $X_{\text{Mg}}$ ratio ~ 0.17. $X_{\text{Mg}}$ 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 $D_3$ rotated garnets in gneiss. Biotite-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 albitic 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.
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 ⁴⁰K/Ar-³⁹Ar ages on muscovite along S₂ foliation range between 315 and 320 Ma and overlap with those obtained for syn-D₂ 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 Al₃Mg₅, Py₁₁₁, Sp₅₇, Gr₅₆, and Al₇₅₇, Py₁₅₉, Sp₃₉, Gr₉₆, respectively. The clear garnet inclusions within staurolite are more calcic and zoned with an average core and rim composition of Al₃₂₆, Gr₅₁₈, Py₇₇, Sp₅₃ and Al₇₅₇, Gr₅₁₇, Py₁₅₁₀, Sp₅₅ (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 Xₐ₈ 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):

\( \text{III} \quad \text{garnet + chlorite + muscovite} = \text{staurolite + biotite + quartz + H}_2\text{O} \)

\( \text{IV} \quad \text{staurolite + chlorite + muscovite} = \text{kyanite + biotite + quartz + H}_2\text{O} \)

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 quartzofeldspathic and mafic minerals aligned along the main S₂ 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 Xₐ₈ 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):

\( \text{V} \quad \text{staurolite + muscovite + quartz =} \)

\( \text{= garnet + biotite + Al}_2\text{SiO}_3 + \text{H}_2\text{O} \)

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 S₂ 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. 0.5 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):

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\text{(VI) muscovite} + \text{plagioclase} + \text{quartz} = \text{K-feldspar} + A_2SiO_5 + \text{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

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**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. S1: first foliation, located along a linear gradient from the origin to \( T = 450 \) °C and \( P = 0.1 \) GPa. S2: second foliation, based on P-T estimates. Squares are relic minerals; black and white circles are the metamorphic peak. Ages on S1 are from D. Vincenzo et al. (2004) and Ferrara et al. (1978). Ages on S2 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 + Si + melt (Petö, 1976); (3): Ms + Pl + Qtz = Kfs + Si + melt (Patiño-Douce and Harris, 1998). Isochores 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 D₁ and D₂ 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 migmatisites, intense D₂ deformation and the temperature reached during the metamorphic peak obscured the record of the earlier D₁ stage. In low- to medium-grade zones, petrological evidence indicates that, moving from the mineralogical assemblage along S₁ (formed during the D₁ stage) to the assemblage along the S₂ foliation (formed during the D₂ 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-S₁ celadonite-rich white micas of ~ 340 Ma, was attributed by Di Vincenzo et al. (2004) to the D₁ 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-S₂ 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 D₂ 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 pluton (310-280 Ma) postdate the D₂ transpressive structures, the D₃ deformational event should be older than ~310 Ma. By contrast, the temporal evolution in the High Grade Metamorphic Complex is less constraining. 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 (Patino 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 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-syn S₂ in the garnet and staurolite zones, whereas in the sillimanite zones it is essentially syn-S₂. An age of ~ 345 and of ~ 325 Ma are tentatively attributed to the thickening stage and to the thermal peak (syn-S₂) 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 Fraceschelli 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 D2 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, D1) to oblique convergence (during the D2 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 D2, the exhumation rate slowed and became comparable to isostatic erosion.

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