METAMORPHIC EVOLUTION OF ECLOGITIC AND GRANULITIC ROCKS OF THE AXIAL ZONE OF THE SARDINIAN VARISCAN CHAIN, NE SARDINIA

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INTRODUCTION

The High Grade Metamorphic Complex (HGMC, or Migmatite Complex) of the Axial Zone of the Variscan Sardinian chain is characterized by the widespread occurrence of metabasite bodies and lenses within the migmatites and gneisses (Carmignani *et al.*, 2001 and references therein). These metabasite bodies, decametric to hectometric in size, show polyphase metamorphic evolution and preserve evidences of high temperature (granulite facies) or high pressure (eclogite facies) metamorphism (Cruciani *et al.*, 2011, 2012; Franceschelli *et al.*, 2002, 2007; Scodina *et al.*, 2019).

This study is focused on the retrogressed eclogites and granulites from NE Sardinia cropping out a few kilometres North of Olbia. A geological survey was carried out and a schematic geological map of the studied area, comprising Iles, Montigiu (Mt.) Nieddu, Nodu Pianu and Sos Aranzos localities, was drawn. Several samples from the various lithologies were collected and then analyzed; the petrographic features, mineral chemistry and geochemical data were used for the determination of P-T conditions by thermodynamic modelling and conventional geothermobarometry.

The P-T paths reconstructed for the studied metabasites are discussed in the geodynamic scenario of the Variscan Sardinian chain. A new geodynamic model for the evolution of the studied rocks is also proposed.

GEOLOGICAL SETTING AND FIELD GEOLOGY

The Migmatite Complex of the Axial Zone (or Inner Zone, Fig. 1a) consists mostly of paragneiss and HP migmatite with polyphase deformation (Cruciani *et al.*, 2008, 2014; Fancello *et al.*, 2018; Massonne *et al.*, 2013) and sillimanite + K-feldspar metamorphic grade (Franceschelli *et al.*, 2005). Orthogneisses, calc-silicate nodules and metabasite with eclogite and granulite facies relics also occur (Cruciani *et al.*, 2011, 2012; Franceschelli *et al.*, 2007). In the HGMC a polyphase ductile deformation was recognized and described by several authors (Carosi *et al.*, 2005; Cruciani *et al.*, 2015; Elter *et al.*, 2010). The early syn-collisional deformation phase (D1; Carmignani *et al.*, 1994) is only documented by the transposition of centimetre-thick leucosomes in the HGMC. The D2 deformation phase is related to the development of NE-verging folds and dextral shear zones (*e.g.*, Posada-Asinara line, Carosi *et al.*, 2012 and references therein). The D3 phase consists of upright metric to decametric open folds associated with an S3 axial-plane crenulation cleavage. The D4 phase is displayed by metric to decametric folds with sub-horizontal axial planes (Cruciani *et al.*, 2015). The intrusive rocks of the Sardinia-Corsica batholith are widely distributed in the Inner Zone of Variscan Sardinia (Casini *et al.*, 2015 and references therein) and also in other areas of the metamorphic basement.

The studied rocks are located a few kilometres NE of Olbia (around Mt. Nieddu locality; Fig. 1b) where two large lensoid metabasite bodies crop out. The retrogressed eclogites at Iles locality occur as a massive to weakly foliated lens shaped body (about 600 m long and parallel to the S2 regional foliation), characterized by garnet (up to 1-2 cm in size) and kyanite porphyroblasts surrounded by whitish symplectitic microstructures and coronas (Fig. 2a). The amphibolite lens at Mt. Nieddu consists of two distinct lithologies: amphibolites and banded amphibolites and ultrabasic amphibolites. The amphibolites/banded amphibolites, characterized by an alternation of whitish plagioclase- and dark-green amphibole-rich layers (Fig. 2b), locally show centimetric-thick layers with several garnet porphyroblasts up to 1 cm in size.

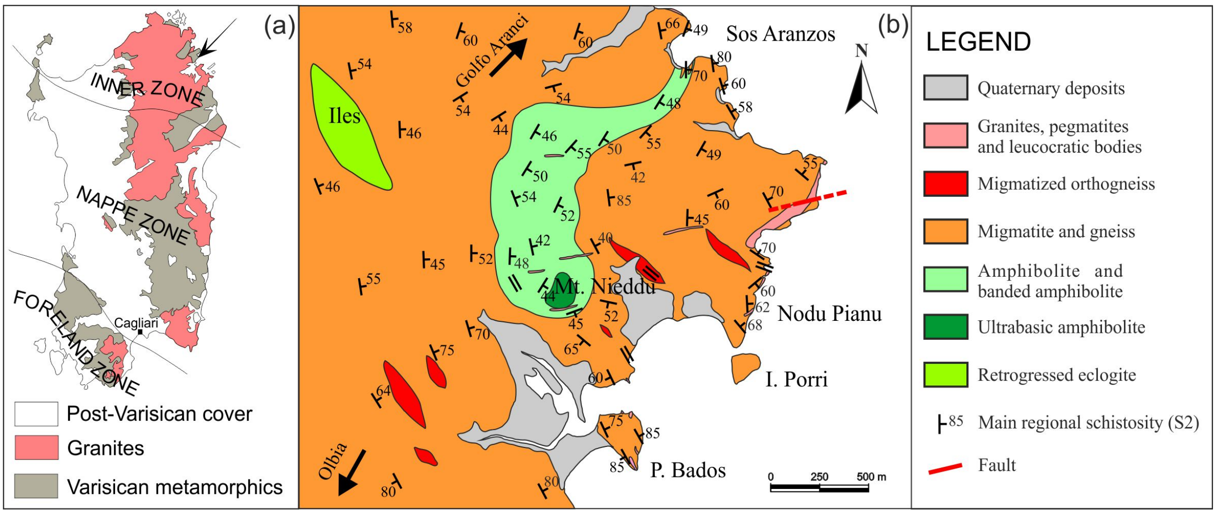

Fig. 1 - a) Simplified tectonic sketch map of the Sardinian Variscan chain. b) Geological sketch map of the Mt. Nieddu area (modified from Scodina *et al.*, 2019).

The ultrabasic amphibolites are a heterogeneous group of rocks which are featured by coronitic microstructures around igneous relics of olivine and plagioclase (Fig. 2c). They occur as a small lens (about 100 m in length and 40-50 m in width) of dark and massive rocks within the banded amphibolites. The metabasites are surrounded by coarse-grained migmatites with stromatic fabric, which derived from an original psammitic to pelitic sequence.

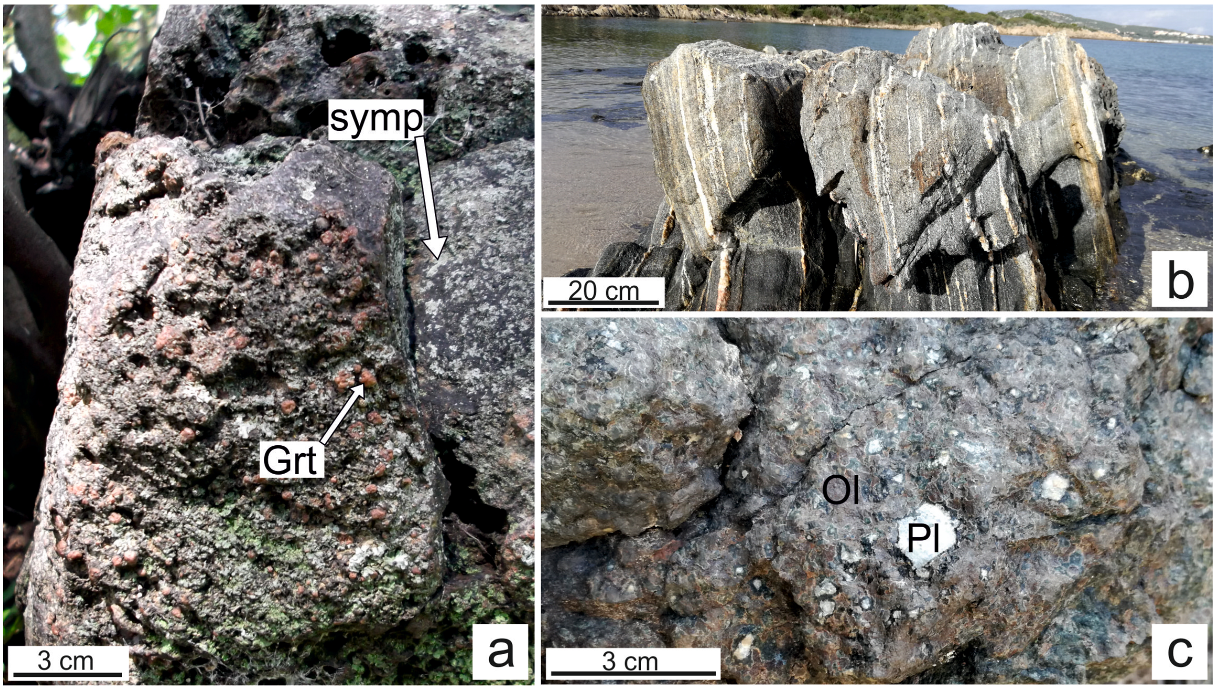

Fig. 2 - Field photograph of the metabasites in Mt. Nieddu area. a) Retrogressed eclogites with garnet porphyroblasts, Iles locality. b) Alternation of plagioclase- and amphibole-rich layers in the banded amphibolites of Mt. Nieddu. c) Ultrabasic amphibolites: the coronitic microstructures around olivine and plagioclase are visible to the naked eye. Abbreviations: Grt: garnet; Ol: olivine; Pl: plagioclase; symp: symplectite.

PETROGRAPHIC FEATURES AND METAMORPHIC EVOLUTION

The retrogressed eclogites from Iles are featured by garnet porphyroblasts surrounded by symplectitic (clinopyroxene + plagioclase) and coronitic (amphibole + plagioclase) microstructures (Fig. 3a).

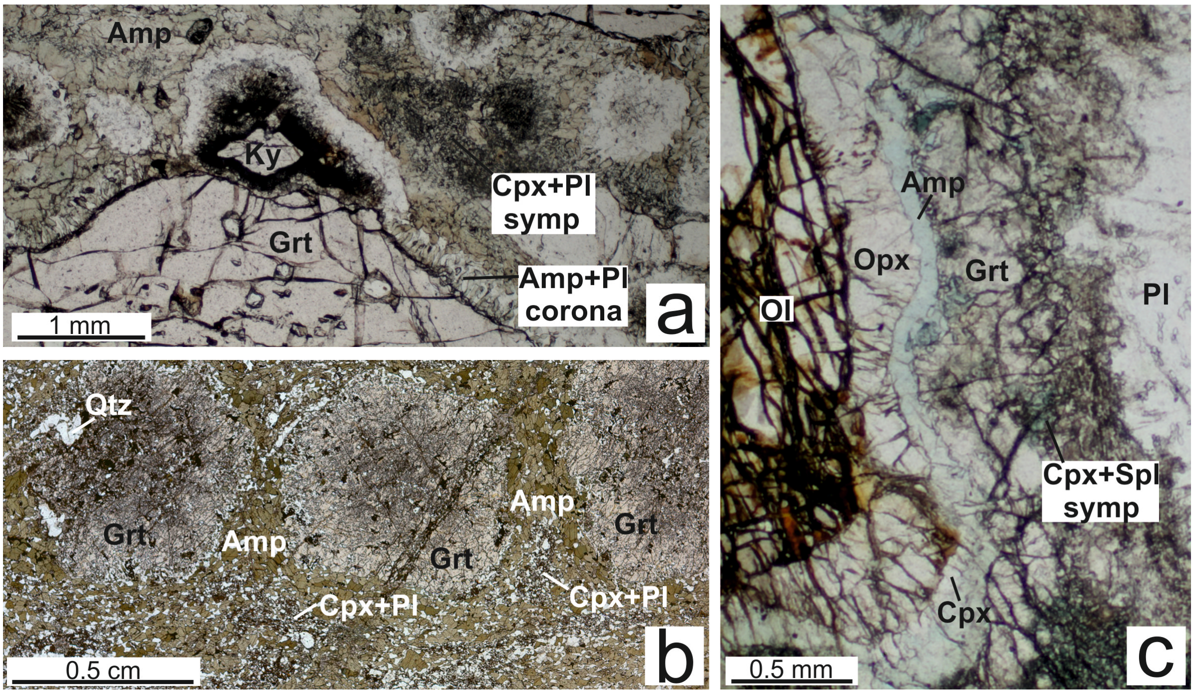

Fig. 3 - Microphotographs (plane polarized light) showing the most relevant microstructures of metabasites in the area of Mt. Nieddu. a) Overview of the main minerals in the Iles retrogressed eclogite. b) MN14A thin section sample of the garnet-bearing layers in the banded amphibolites of Mt. Nieddu. c) Coronitic microstructures around igneous olivine and plagioclase in the layer B of ultrabasic amphibolites. Abbreviations: Ky: kyanite; Amp: amphibole; Cpx: clinopyroxene; Opx: orthopyroxene; Spl: spinel; Qtz: quartz; other mineral abbreviations as in Fig. 2.

Kyanite porphyroblasts are surrounded by coronas of anorthite + spinel/sapphirine lamellae. Kyanite crystals are uncommon among the Sardinian eclogites (Cruciani *et al*., 2019). The eclogite-facies characteristic mineral, omphacite, can be found only as inclusion in garnet. The dark-coloured matrix is mainly made up of green amphibole. Based on these textural features around garnet and kyanite, four stages of metamorphic evolution have been distinguished: pre-symplectite, symplectite, corona and post-corona.

The amphibolites/banded amphibolites are characterized by a coarse-grained granoblastic texture with a slight crystal anisotropy. The most abundant phase (≥50 vol%) is green amphibole due to the strong metamorphic re-equilibration in the amphibolite facies partially overprinting igneous phases and previous metamorphic mineral parageneses. Plagioclase is idioblastic and can reach modal amounts of 50-70 vol% in white bands and 20-30 vol% in dark-green bands. Quartz, epidote and chlorite occur in variable modal amounts (from 1 to 15 vol%). The centimetric-thick layers within these rocks are featured by several garnet porphyroblasts up to 1 cm in size, in a matrix made up of amphibole and plagioclase, quartz and flakes of a fine-grained symplectite of clinopyroxene + plagioclase (Fig. 3b). These garnet-bearing layers represent the first stage (stage 1) of the metamorphic evolution of these rocks, whereas the mineral assemblage of the host rock (stage 2) represents the subsequent retrograde re-equilibration. Finally, a third stage represented by the local growth of late phases in both garnet-bearing layers and host amphibolites has also been identified.

The ultrabasic amphibolites are massive and dark-coloured inhomogeneous rocks. On the basis of the distribution of minerals and their microstructures three main compositional layers have been distinguished (layers A, B, and C: Cruciani *et al*., 2002; Franceschelli *et al*., 2002). Layer A is featured by the occurrence of igneous olivine grains, locally rimmed by a discontinuous thin layer of orthopyroxene. Amphibole and chlorite are also abundant. Layer C is made up of abundant amphibole and garnet (the latter being up to 60-70 vol%). Layer B shows the most striking feature of these rocks: the occurrence of multilayer corona textures around olivine and plagioclase relics. The coronitic microstructures consist of single or composite thin corona of orthopyroxene and clinopyroxene around olivine as well as spinel + clinopyroxene symplectite and garnet coronas around plagioclase. All these minerals were partially replaced by amphibole (Fig. 3c). On the basis of petrological and microtextural features of coronitic textures, four stages of mineral formation have been distinguished (Scodina *et al*., 2020): *i*) an igneous stage, *ii*) a first stage of metamorphic re-equilibration, documented by the coronitic and symplectitic minerals, *iii*) a second metamorphic re-equilibration stage, represented by the massive overgrowth of amphibole in the coronitic assemblages, and *iv*) a third metamorphic stage documented by the local growth of late phases.

GEOTHERMOBAROMETRY AND P-T PATH

The early metamorphic evolution of the retrogressed eclogites (pre-symplectite stage) was reconstructed on the basis of garnet compositional zoning and P-T pseudosection calculations (using the software Perple_X; Connolly, 1990). The P-T path of these rocks reveals a first prograde segment until baric peak P-T conditions of T = 620-690°C and P = 2.0-2.3 GPa were reached in eclogite facies. Subsequently, the rocks underwent a slight temperature increase accompanied by a pressure decrease until they reached their thermal peak at HP conditions in the granulite/eclogite facies (T = 650-700°C and P = 1.4-2.1 GPa). The resulting clockwise P-T path (Fig. 4a) is similar to that observed for other Sardinian eclogites described in the literature and also for the HP migmatites occurring at Mt. Nieddu area (Fig. 4b; Cruciani *et al*. 2008, 2014; Massonne *et al*., 2013).

The microstructural investigations and thermodynamic modelling on the banded amphibolites and on their garnet rich layers allow to define their following P-T evolution; these rocks firstly recorded an isothermal pressure increase up to the metamorphic peak (stage 1: T = 690-740°C, P = 1.3-1.4 GPa), before the retrograde equilibration in amphibolite facies (stage 2: T = 560-620°C, P = 0.7-0.8 GPa). The resulting P-T path is anticlockwise (Fig. 4c).

The geothermobarometric results obtained from the ultrabasic amphibolites indicate P-T conditions of P = 0.2-0.5 GPa and T = 780-850°C for the igneous crystallization and of P = 1.3-1.7 GPa and T = 680-730°C for garnet growth (first stage), which correspond to the metamorphic peak. A later second stage, which led to the corona destabilization, occurred at amphibolite-facies P-T conditions. These results reveal an anticlockwise P-T path (Fig. 4d), in agreement with the one reconstructed for the adjacent banded amphibolites (Scodina *et al*., 2020).

DISCUSSION AND GEODYNAMIC SCENARIO

The petrographic data and the geothermobarometric results evidenced that, in the area of Mt. Nieddu, metamorphic rocks with different metamorphic evolution (clockwise and anticlockwise) occur. These rocks experienced a complex history in the geodynamic context of the evolution of the Variscan basement, when the collision between the peri-Gondwanian terranes (previously accreted to Laurussia) and Gondwana took place. This different metamorphic evolution for adjacent rocks can be explained with a model in the light of the geodynamic scenario recently proposed by Massonne *et al*. (2018) for southern Corsica and northern Sardinia. This model, reconstructed after the P-T-t evolution of garnet-bearing micaschists from the area of Porto Vecchio (SE Corsica), is suitable to explain the P-T path of the metabasites studied here. The difference of the peak pressure conditions between the micaschists from southern Corsica and the here studied metabasites is the result of a greater depth reached by our rocks, a different position of them between the colliding plates and likely also to their different protolith nature (basic-ultrabasic *versus* sedimentary).

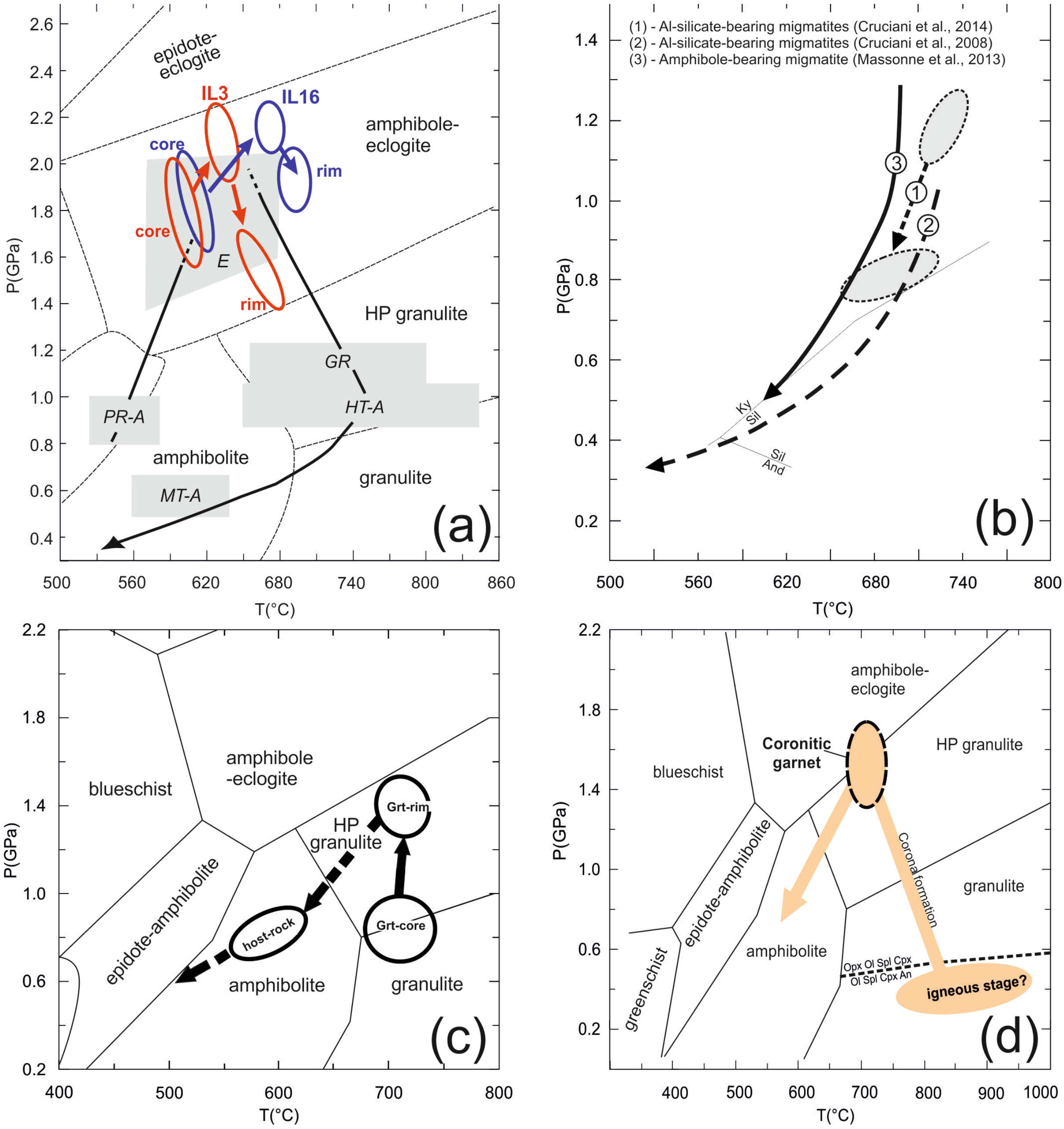

Fig. 4 - Different P-T evolution (clockwise *vs*. anticlockwise) for the metamorphic rocks in the area of Mt. Nieddu. a) P-T path of the retrogressed eclogite reconstructed by Cruciani *et al*. (2019) (red and blue ellipses for IL3 and IL16 samples, respectively), compared to the complete P-T path of the same rocks reported by Giacomini *et al*. (2005) (grey areas). b) P-T path of the migmatites surrounding the metabasites in the Mt. Nieddu area. P-T paths 1, 2, 3 refer to migmatite and amphibole-bearing migmatite, respectively (Cruciani *et al*., 2008, 2014; Massonne *et al*., 2013). c) Reconstructed P-T path of the banded amphibolites by Scodina *et al*. (2019). d) P-T path of the ultrabasic amphibolites reconstructed after the coronitic textures of layer B (Scodina *et al*., 2020). Facies fields after Liou *et al*. (1998).

In the model here proposed (Fig. 5), according to Massonne *et al*. (2018), the tectono-metamorphic evolution of the studied amphibolites (banded and ultrabasic) began in the Upper Devonian during subduction of oceanic crust under the peri-Gondwanan terrane which was previously accreted to Laurussia. These rocks were located probably in the hot, lowermost part of the upper plate, adjacent to the subducting slab, at depths around 35 km (0.8-0.9 GPa; Fig. 4c), whereas the retrogressed eclogites from Iles were part of the relatively cold subducting crust and reached greater depths (2.0-2.2 GPa, Cruciani *et al.*, 2019) (Fig. 5a).

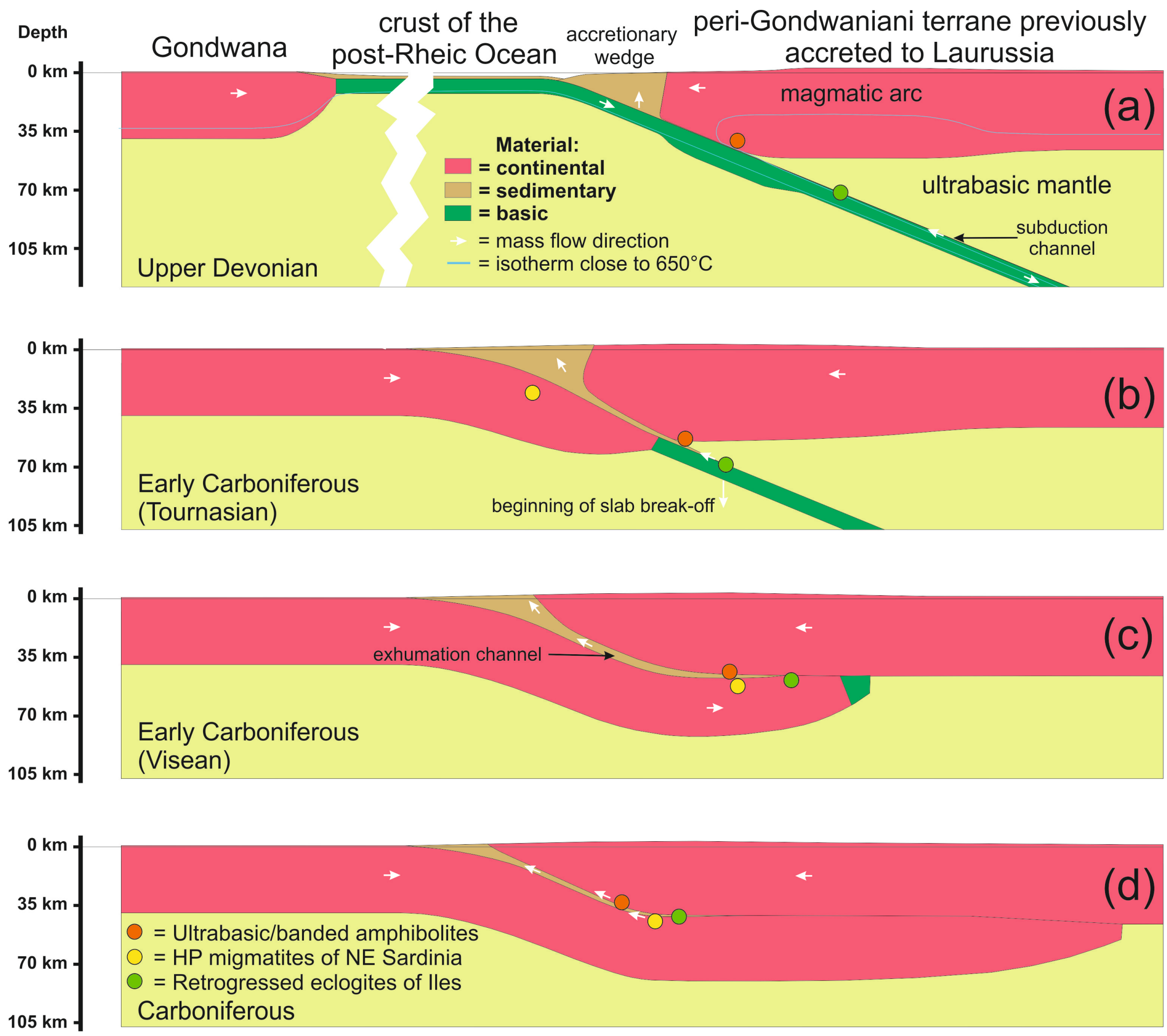

Fig. 5 - Geodynamic evolution sketch of the metamorphic rocks from the Mt. Nieddu area during the Variscan orogeny (modified after Massonne *et al.*, 2018 and Scodina *et al.*, 2019). a) Subduction of oceanic crust under the Laurussia plate and the peri-Gondwanan terranes; b) Continental collision and slab break-off event; c) Crustal thickening and beginning of the uplift in the exhumation channel shown by a white arrow; d) Exhumation of amphibolites (red dots), HP migmatites (yellow dots), and eclogites from Iles (green dots, Cruciani *et al.*, 2019) in the exhumation channel.

The amphibolites were buried up to depths of 50-55 km (1.4 GPa; Fig. 4c) either by attachment (tectonic or subduction erosion) to the subducting oceanic crust or (less likely) by thickening of the upper plate during the Gondwana-Laurussia collision which occurred at the beginning of the Carboniferous.

After the continental collision, the oceanic crust linked to Gondwana was involved in a break-off event which is a common scenario invoked by many authors of recent studies of early Variscan rocks (Casini *et al.*, 2015; Giacomini *et al.*, 2008) (Fig. 5b). However, some slices of oceanic crust, turned to eclogite, were exhumed in the subduction channel and then attached to the downgoing continental plate and the exhumation channel just before the break-off event occurred. Subsequently, after a significant thrusting of Gondwana under Laurussia, around 345 Ma (Massonne *et al*., 2018), metamorphic rocks from both upper and lower plates were involved in a particle path (with an important strike-slip component according to Giacomini *et al*., 2008) in the exhumation channel (Fig. 5c). The studied amphibolites as well as rocks from the uppermost part of the lower plate (the HP migmatites from NE Sardinia) and eclogites derived from the oceanic crust (Cruciani *et al*., 2019) were involved in this event. All these rocks were brought together and tectonically mixed within the exhumation channel during lower and middle Carboniferous times, probably starting in the Visean (Fig. 5d).

CONCLUSIONS

The investigated area of the HGMC of NE Sardinia is characterized by the presence of metamorphic rocks featured by different P-T evolutions (clockwise *vs* anticlockwise), both related to a continental collision during the Variscan orogeny that involved continental slices from both upper and lower plates in an exhumation channel, as explained in the proposed geodynamic model.

The anticlockwise P-T path reconstructed for the banded amphibolites and the ultrabasic amphibolites is documented for the first time for the rocks of the metamorphic basement of Sardinia. This type of evolution is in contrast with the general evolution of the other metamorphic complexes of NE Sardinia (clockwise P-T path) and it represents a novelty for the comprehension of the migmatitic complex of Sardinia, that will deserve further studies.

REFERENCES

uCarmignani, L., Carosi, R., Di Pisa, A., Gattigu, M., Musumeci, G., Oggiano, G., Pertusati, P.C. (1994): The hercynian Chain in Sardinia (Italy). *Geodin. Acta*, **7**, 31-47.

Carmignani, L., Oggiano, G., Barca, S., Conti, P., Eltrudis, A., Funedda, A., Pasci, S., Salvadori, I. (2001): Geologia della Sardegna. Note illustrative della Carta Geologica della Sardegna in scala 1:200,000. *Memorie Descrittive Carta Geol. d'Italia.*, **60**, 283.

Carosi, R., Frassi, C., Iacopini, D., Montomoli, C. (2005): Post collisional transpressive tectonics in northern Sardinia (Italy). *J. Virtual Explorer*, **19**, paper 3.

Carosi, R., Montomoli, C., Tiepolo, M., Frassi, C. (2012): Geochronological constraints on post collisional shear belt in the Variscides of Sardinia, Italy. *Terra Nova*, **24 (1)**, 42-51.

Casini, L., Cuccuru, S., Puccini, A., Oggiano, G., Rossi, P. (2015): Evolution of the Corsica-Sardinia Batholith and late-orogenic shearing of the Variscides. *Tectonophysics,* **646**, 65-78.

Connolly, J.A.D. (1990): Multivariable phase diagrams: an algorithm based on generalized thermodynamics. *Am. J. Sci.*, **290**, 666-718.

Cruciani, G., Franceschelli, M., Marchi, M., Zucca, M. (2002): Geochemistry of metabasite from NE Sardinia, Italy: nature of protoliths, magmatic trend, and geotectonic setting. *Miner. Petrol.*, **74**, 25-47.

Cruciani, G., Franceschelli, M., Elter, F.M., Puxeddu, M., Utzeri, D. (2008): Petrogenesis of Al silicate- bearing trondhjemitic migmatites from NE Sardinia, Italy. *Lithos*, **102**, 554-574.

Cruciani, G., Franceschelli, M., Groppo, C. (2011): P-T evolution of eclogite-facies metabasite from NE Sardinia, Italy: insights into the prograde evolution of Variscan eclogites. *Lithos*, **121**, 135-150.

Cruciani, G., Franceschelli, M., Groppo, C., Spano, M.E. (2012): Metamorphic evolution of non-equilibrated granulitized eclogite from Punta de li Tulchi (Variscan Sardinia) determined through texturally controlled thermodynamic modeling. *J. Metamorph. Geol.*, **30**, 667-685.

Cruciani, G., Fancello, D., Franceschelli, M., Scodina, M., Spano, M.E. (2014): Geothermobarometry of Al silicate-bearing migmatites from the Variscan chain of NE Sardinia, Italy: a P-T pseudosection approach. *Period. Mineral.*, **83(1)**, 19-40.

Cruciani, G., Montomoli, C., Carosi, R., Franceschelli, M., Puxeddu, M. (2015): Continental collision from two perspectives: A review of Variscan metamorphism and deformation in northern Sardinia. *Period. Mineral.*, **84**, 657-699.

Cruciani, G., Franceschelli, M., Scodina, M., Puxeddu, M. (2019): Garnet zoning in kyanite bearing eclogite from Golfo Aranci: new data on the early prograde P-T evolution in NE Sardinia, Italy. *Geol. J.*, **54 (1)**, 190-205.

Elter, F.M., Padovano, M., Kraus, R.K. (2010): The Variscan HT metamorphic rocks emplacement linked to the interaction between Gondwana and Laurussia plates: structural constraints in NE Sardinia (Italy). *Terra Nova*, **22**, 369-377.

Fancello, D., Cruciani, G., Franceschelli, M., Massonne, H.-J. (2018): Trondhjemitic leucosomes in paragneisses from NE Sardinia: geochemistry and P-T conditions of melting and crystallization. *Lithos*, **304-307**, 501-517.

Franceschelli, M., Carcangiu, G., Caredda, A.M., Cruciani, G., Memmi, I., Zucca, M. (2002): Transformation of cumulate mafic rocks to granulite and re-equilibration in amphibolite and greenschist facies in NE Sardinia, Italy. *Lithos*, **63**, 1-18.

Franceschelli, M., Puxeddu, M., Cruciani, G. (2005): Variscan metamorphism in Sardinia, Italy: review and discussion. *In*: "The southern Variscan belt". R. Carosi, R. Dias, D. Iacopini, G. Rosenbaum, eds. *J. Virtual Explorer*, **19**, Paper 2.

Franceschelli, M., Puxeddu, M., Cruciani, G., Utzeri, D. (2007): Metabasites with eclogite facies relics from Variscides in Sardinia, Italy: A review. *Int. J. Earth Sci.,* **96**, 795-815.

Giacomini, F., Bomparola, R.M., Ghezzo, C. (2005): Petrology and geochronology of metabasites with eclogite facies relics from NE Sardinia: constraints for the Palaeozoic evolution of Southern Europe. *Lithos*, **82**, 221-248.

Giacomini, F., Dallai, L., Carminati, E., Tiepolo, M., Ghezzo, C. (2008): Exhumation of a Variscan orogenic complex: insights from the composite granulitic-amphibolitic metamorphic basement of South-East Corsica (France). *J. Metamorph. Geol.*, **26**, 403-436.

Liou, J.G., Zhang, R.Y., Ernst, W.G., Rumble, D., Maruyama, S. (1998): High pressure minerals from deeply subducted metamorphic rocks. *In*: "Ultrahigh Pressure Mineralogy". R.J. Hemley, ed. *Rev. Mineral.*, **37**, 33-96.

Massonne, H.-J., Cruciani, G., Franceschelli, M. (2013): Geothermobarometry on anatectic melts – A high-pressure Variscan migmatite from Northeast Sardinia. *Int. Geol. Rev.*, **55**, 1490-1505.

Massonne, H.-J., Cruciani, G., Franceschelli, M., Musumeci, G. (2018): Anticlockwise pressure-temperature paths record Variscan upper-plate exhumation: example from micaschists of the Porto Vecchio region, Corsica. *J. Metamorph. Geol.*, **36**, 55-77.

Scodina, M., Cruciani, G., Franceschelli, M., Massonne, H.-J. (2019): Anticlockwise P-T evolution of amphibolites from NE Sardinia, Italy: geodynamic implications for the tectonic evolution of the Variscan Corsica-Sardinia block. *Lithos*, **324-325**, 763-775.

Scodina, M., Cruciani, G., Franceschelli, M., Massonne, H.-J. (2020): Multilayer corona textures in the high-pressure, metaultrabasic rocks of Mt. Nieddu, NE Sardinia (Italy): equilibrium versus disequilibrium. *Period. Mineral.*, **89(2)**, online April 2020.