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P–T evolution of eclogite-facies metabasite from NE Sardinia, Italy: Insights into the prograde evolution of Variscan eclogites

Gabriele Cruciani [a], Marcello Franceschelli [a,*], Chiara Groppo [b]

[a] Dipartimento di Scienze della Terra, Via Trentino 51, Università degli Studi di Cagliari, I-09127, Cagliari, Italy
[b] Dipartimento di Scienze Mineralogiche e Petrologiche, Università degli Studi di Torino, via Valperga Caluso 35, 10125 Torino, Italy

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ABSTRACT

A petrological study of the Punta Orvili metabasite in NE Sardinia has been carried out, integrating quantitative pseudosection modelling with reaction balancing, with the aim of reconstructing the metamorphic evolution and P–T path.

The Punta Orvili metabasite preserves microstructural evidence of: (i) a pre-symplectite polyphase and prograde stage (M1) indicated by the occurrence of amphibole inclusions in garnet, by Na-rich diopside and by compositional zoning in garnet, clinopyroxene and amphibole; (ii) a symplectite stage (M2) represented by the occurrence of Cpx_2+Pl_1 symplectite; (iii) a corona stage (M3) documented by the formation of micrometre-thick $Pl_2 \pm Am_3 \pm Ilm$ coronas around garnet; and (iv) a late stage (M4), documented by the growth of epidote and albite and by the replacement of biotite and clinopyroxene by chlorite. The M1 pre-symplectite stage has been modelled by P–T pseudosections calculated in the NCKFMASTH model system at $a(H_2O)=1$ (for $a(H_2O)=0.5$ temperature values are ~50 °C lower). Mg and Ca zoning in garnet and Na zoning in clinopyroxene testify to a progressive increase in temperature and pressure during garnet and clinopyroxene growth from 610<T<630 °C, 1.7<P<1.8 GPa up to 620<T<650 °C, 1.9<P<2.1 GPa, allowing to reconstruct a prograde segment of the P–T path. Peak pressure conditions were reached in the amphibole–eclogite-facies field. Destabilization of clinopyroxene led to the formation of Cpx_2+Pl_1 symplectite (M2 stage) at P–T conditions of 760<T<800 °C, 0.9<P<1.0 GPa.

The corona stage (M3) was modelled in the NCFMASTH model system using the bulk composition of the effectively reacting microdomain, calculated from mineral compositions and stoichiometric coefficients of the corona-forming reaction. T = 610–670 °C and P~0.7 GPa have been determined for this stage. Presumed P–T conditions of the latest re-equilibration stage (M4 stage) are around 300–400 °C and 0.2–0.3 GPa.

The prograde evolution of the Punta Orvili metabasite took place under a geothermal gradient of ~10 °C/km, compatible with a relatively hot subduction of a small, young marginal basin. Subsequent increase of the geothermal gradient up to 20–30 °C/km suggests that subduction was followed by the Variscan continental collision.

The P–T path of the Punta Orvili metabasite has significant analogies with that of the retrogressed eclogite of Golfo Aranci, NE Sardinia, and with other eclogites from the Migmatite Complex of NE Sardinia.

1. Introduction

Over the last two decades the reconstruction of the prograde P–T path in eclogites has been receiving a great deal of attention, as it provides an insight into thermal and metamorphic evolution of palaeosubduction zones. The detailed investigation of the prograde evolution of eclogites was initially based on: the identification of prograde assemblages preserved as inclusions in garnet and/or omphacite (e.g. Möller, 1998, 1999; Pognante et al., 1980), and thermobarometry applied to mineral inclusions (e.g. Carson et al., 1999; Clarke et al., 1997; Elvevold and Gilotti, 2000; Page et al., 2003; Štípská and Powell, 2005) and/or zoned minerals (e.g. Endo et al., 2009; Marmo et al., 2002; O'Brien, 1997; O'Brien and Vràna, 1995; Štípská and Powell, 2005). More recently, improvements in thermodynamic databases and solid solution models (e.g. Green et al., 2007; White et al., 2007) and the development of methods that account for the possible fractionation of bulk composition due to the growth of garnet porphyroblasts (e.g. Evans, 2004; Gaidies et al., 2006; Groppo and Rolfo, 2008; Marmo et al., 2002; Stüwe, 1997; Zuluaga et al., 2005), have increased the popularity of thermodynamic modelling (i.e. pseudosections) for reconstructing the prograde P–T trajectories of eclogites (e.g. Groppo et al., 2007, 2009; Powell and Holland, 2008; Štípská and Powell, 2005; Štípská et al., 2006; Wei et al., 2003, 2009).

In the Variscan terranes a prograde metamorphic evolution has been reported for eclogites from many locations, including for example the Bohemian Massif (e.g. O'Brien, 1997; Štípská and Powell, 2005; Štípská et al., 2006), South Carpathians, Romania (e.g. Medaris et al., 2003), Savona crystalline massif of Italy (e.g. Messiga et al., 1991), Gföhl Unit of the Moldanubian Zone (e.g. Faryad et al., 2010).

* Corresponding author.
E-mail address: francmar@unica.it (M. Franceschelli).

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Although eclogites are not common in the Variscan chain of Sardinia (only four major sites — the most widely studied are Punta de li Tulchi and Golfo Aranci outcrops, see Franceschelli et al., 2007 for a review), a prograde metamorphic history has also been suggested for some of these eclogite occurrences. Following the study by Miller et al. (1976), Franceschelli et al. (1998, 2007) suggested that a pre-eclogite stage is preserved in the Punta de li Tulchi eclogite based on the findings of tschermakite and zoisite relics entrapped in garnet porphyroblasts. A prograde stage has also been suggested by Giacomini et al. (2005a) for the Golfo Aranci eclogites. These authors attributed edenite–andesine inclusions preserved in kyanite porphyroblasts to a prograde, pre-eclogitic metamorphism that occurred under amphibolite-facies P–T conditions. In the metabasite from Punta Orvili the zoning patterns of clinopyroxene and garnet porphyroblasts (i.e. Na increasing towards the clinopyroxene rim; Ca decreasing and Fe and Mg increasing toward the garnet rim) preliminarily suggested that these rocks recorded a prograde portion of their metamorphic history in the eclogite facies (Franceschelli et al., 2007). Currently available data on the P–T evolution of Sardinian eclogites have been obtained chiefly from conventional thermobarometry (Cortesogno et al., 2004; Franceschelli et al., 1998, 2007) and/or Thermocalc Average PT methods (Giacomini et al., 2005a) applied on peak and prograde assemblages, whereas the pseudosection approach has never been applied so far.

The focus of this paper is on the poorly studied Punta Orvili metabasite, which differs from the other well studied Sardinian eclogites for a number of reasons: (i) geochemical data suggest that the igneous protolith of the Punta Orvili metabasite has an alkaline affinity (Cruciani et al., 2010), whereas all the other Sardinian eclogites are MORB-type tholeiites (Cappelli et al., 1992); (ii) the Punta Orvili metabasite is among the few Sardinian eclogites that do not contain orthopyroxene, whereas the more widely studied Punta de li Tulchi and Golfo Aranci eclogites are orthopyroxene-bearing rocks (Franceschelli et al., 2007); and (iii) the Punta Orvili metabasite belongs to the Low to Medium Grade Metamorphic Complex of Carmignani et al. (1992) or Hercynian Metamorphic Complex with Dominant Amphibolite Assemblages of Carmignani et al., (2001) whereas the other well studied Sardinian eclogites belong to the Migmatite Complex.

A detailed petrological study of the Punta Orvili metabasite has been performed by integrating quantitative pseudosection modelling and reaction balancing, with the aim to: (i) reconstruct, using the most recent petrologic approaches, the metamorphic evolution and P–T path of a still poorly investigated Sardinian eclogite; (ii) compare the P–T evolution of the Punta Orvili metabasite with the other eclogites from northern Sardinia; and (iii) discuss the obtained P–T history of Punta Orvili metabasite in the context of the Variscan chain of Sardinia.

2. Geological setting

2.1. The Variscan chain of Sardinia

The Variscan chain of Sardinia is a branch of the southern European Variscides. From South to North, it has been classically divided into an External Zone (SW Sardinia), a Nappe Zone (central Sardinia) and an Axial or Internal Zone (northern Sardinia). The latter is further divided into the Migmatite Complex and the Low to Medium Grade Metamorphic Complex, respectively North and South of the Posada–Asinara Tectonic Line (Carmignani et al., 1992, 2001) (Fig. 1). In southern and central Sardinia the degree of Variscan metamorphism changes progressively from very low to low grade, whereas in northern Sardinia (Axial Zone) it varies from low to high grade, reaching the sillimanite + K-feldspar grade north-eastwards.

The metamorphic basement of north Sardinia underwent a polyphase Variscan deformation. Up to five (D_1 to D_5) deformation phases have been recognized (Franceschelli et al., 2005, Helbing et al., 2006 and references therein). The D_1 phase produced S_1 schistosity recognizable as rare intrafoliar folds (Elter et al., 1986) transposed and overprinted by the D_2 deformation. The D_2 phase generated the most evident structures in the Migmatite Complex, i.e. folds with E–W trending axes accompanied by S_2 axial plane schistosity. D_2 has been considered a transpressional deformation by Carosi and Palmeri (2002). The D_3 phase, gently superimposed on the previous D_2, produced open folds with spaced cleavages, in the South, and pervasive schistosity, locally, North of Olbia. The D_4 phase is mainly restricted to the cataclastic, mylonitic rocks cropping out in the Posada Valley shear zone, where C-type shear band crenulation cleavages were generated by non coaxial-shearing. In the same shear zone, the D_5 deformation gave rise to a large flexure parallel to the orogenic trend, as witnessed by the uplift of the Axial Zone with respect to the schistose envelope (Helbing et al., 2006). More details on metamorphism and deformation in the Axial Zone can be found in the extended review of Variscan orogeny in Sardinia by Franceschelli et al. (2005) and the recent paper of Elter et al. (2010).

2.2. Eclogite occurrences in northern Sardinia

Metabasites with eclogite-facies relics have been found in the high-grade gneisses of the Migmatite Complex and in the medium-grade gneisses of the Low to Medium Grade Metamorphic Complex. The two occurrences of eclogitic rocks were described as eclogite A and eclogite B respectively by Cortesogno et al. (2004).

In the Migmatite Complex the eclogitic rocks occur as boudins parallel to, and enveloped by, the E–W striking S_2 schistosity. Except for the hectometre-size bodies and lenses cropping out at Golfo Aranci, Punta Tittinosu and Punta de li Tulchi, most of the eclogites from the Migmatite Complex are metre-sized (Franceschelli et al., 2007). Most of the eclogites from the Migmatite Complex studied so far contain orthopyroxene.

The metabasites from the Low to Medium Grade Metamorphic Complex occur as decametre size lenses and boudins in gneiss and mylonitic gneiss of Asinara Island, Anglona, and along the Posada Valley shear Zone. However, only the metabasites from Anglona retain relics of eclogite-facies assemblages (Cortesogno et al., 2004). Orthopyroxene has not been observed up to now in the eclogites hosted in the medium-grade gneisses.

The protoliths of Sardinian eclogites are mostly MORB-type tholeiites (Cappelli et al., 1992), as evidenced by their slightly convex LREE patterns, slightly negative Eu anomaly and flat HREE patterns, except for the metabasite from Punta Orvili that exhibited an alkaline affinity (Cruciani et al., 2010).

Different stages have been recognized in the evolution of eclogites from Sardinia. In particular, Franceschelli et al. (1998) recognized five stages in the Punta de li Tulchi retrogressed eclogites, which are also discussed by Giacomini et al. (2005a) for the Golfo Aranci eclogites: (i) a pre-eclogitic stage under amphibolite-facies conditions; (ii) a peak-P eclogite stage documented by the occurrence of omphacite relics in garnet; (iii) a granulite stage characterized by the growth of Px + Pl (abbreviations according to Fettes and Desmons, 2007) symplectites after omphacite; (iv) an amphibolite stage with the development of amphibole + plagioclase coronas around garnet, and (v) a greenschist to sub-greenschist stage characterized by the growth of actinolite, chlorite, epidote, titanite, sericite, and rare prehnite.

Regarding the geochronological data on Sardinian eclogites, Palmeri et al. (2004) found U–Pb zircon ages in the Punta de li Tulchi eclogite giving three weighted means of 453 ± 14, 400 ± 10 and 327 ± 7 Ma. The first age was interpreted as the protolith age, the second was considered as the likely age of the HP eclogitic event or the result of Pb loss during the main Variscan event, while the third was attributed to the final retrogression to amphibolite-facies conditions. Magmatic zircons from the Golfo Aranci eclogites yielded a mean age of 460 ± 5 Ma, interpreted as the protolith age by Giacomini et al. (2005a). This value fits well with the protolith age of 453 ± 14 Ma