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Texturally and compositionally non-equilibrated granulitized eclogite from Punta de Li Tulchi, Sardinian Variscan chain: a microstructural and thermodynamic study

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Metamorphic evolution of non-equilibrated granulitized eclogite from Punta di li Tulchi (Variscan Sardinia) determined through texturally controlled thermodynamic modelling

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ABSTRACT
The metamorphic evolution of a granulitized eclogite from Punta de li Tulchi NE Sardinia, Italy, reconstructed utilizing a combined microstructural (symplectitic, coronitic and kelyphytic features) and thermodynamic approach, involved a complex metamorphic history with equilibrium attained only at a domainal scale. Microstructural analysis and mineral zoning allow recognition of reactants and products involved in successive balanced mineral reactions. The $P-T$ conditions at which each microstructure was formed are further constrained by calculating isochemical phase diagrams (pseudosections) for the composition of effectively reacting domains. A pre-symplectite stage developed during prograde metamorphism under conditions ranging from 660-680°C, 1.6-1.8 GPa to 660-700°C at 1.7-2.1 GPa. Pseudosections calculated for subsequent clinopyroxene + plagioclase and orthopyroxene + plagioclase symplectitic coronae using the composition of effectively reacting microdomains suggest temperature in excess of 800°C and pressures of 1.0-1.3 GPa. Modelling the development of later plagioclase + amphibole coronae around garnet during decompression yields conditions of 730-830°C and 0.8-1.1 GPa. $\text{H}_2\text{O}$ (wt%) isomodes indicate that the granulitized eclogites were $\text{H}_2\text{O}$-undersaturated at peak-$P$ conditions and during most of the subsequent heating and decompression. This allowed the preservation of prograde garnet zoning in spite of the strong granulite-facies overprint. The $P$-$T$ evolution of Punta de li Tulchi granulitized eclogite is very similar in shape to that registered by other NE Sardinia retrogressed eclogites thus suggesting a common tectonic scenario for their evolution.

Key words: granulitized eclogite, corona textures, $P-T$ pseudosection, Variscan Sardinia

INTRODUCTION
The European Variscan belt is well known for the widespread occurrence of rocks that experienced extreme metamorphic conditions, from the high/ultra-high pressure (HP/UHP) eclogite-facies conditions to high/ultra-high temperature (HT/UHT) granulite-facies conditions (e.g. Nasdala & Massonne, 2000, Massonne 2001; Lardeaux et al., 2001; Rötzler & Romer, 2001). The unusual high peak $P$-$T$ conditions registered by these rocks suggest a tectonic scenario dominated by relatively high $dT/dP$ gradients (e.g. O’Brien, 2008), in contrast with the low $dT/dP$ gradients typical of mature subduction zones. Knowledge of the metamorphic evolution of these rocks is therefore highly relevant to orogenic processes. Several studies have estimated peak $P$-$T$ conditions of eclogites and/or granulites in the European Variscan orogen (see O’Brien & Rötzler, 2003 for a review). However, petrological modelling of the complete $P$-$T$($t$) paths has only progressed in recent times. The majority of $P$-$T$($t$) paths for the European Variscan eclogites and/or granulites are based on $P$-$T$ results of conventional thermobarometry, $P$-$T$ grids and/or multi-equilibrium thermobarometry (PTGibbs and TWQ methods) (e.g. Bohemian Massif: O’Brien et al., 1997, Willner et al., 1997, Rötzler & Romer, 2001, Nakamura et al., 2004; Massif Central: Lardeaux et al., 2001, Berger et al., 2010; Argentera Massif: Ferrando et al., 2008; SE Corsica: Giacomini et al., 2008; NE Sardinia: Franceschelli et al., 1998, Cortesogno et al., 2004, Giacomini et al., 2005a). More recently, the pseudosection approach has been successfully applied to the study of the metamorphic evolution of Variscan granulites (e.g. Štípská et al., 2006; Tajčmanová et al., 2006; Racek et al., 2006; Cruciani et al., 2011).

Independent of the method used, reconstructing the $P$-$T$($t$) evolution of the European Variscan HP/HT rocks is particularly challenging because most are granulites derived from former eclogites. Consequently, original HP minerals usually show the effects of a HT overprint and are only locally preserved. For example, omphacite is commonly transformed into plagioclase +
clinopyroxene symplectites, and mineral compositions commonly re-equilibrated under high-temperature conditions. Symplectic, coronitic and kelyphytic reaction textures are very common in these rocks and witness lack of textural equilibrium. Compositional equilibrium is at best attained at microdomainal scale. For example, plagioclase compositions may vary significantly between different reaction domains.

The success of the pseudosection method closely relies on the preliminary and detailed interpretation of the reaction textures (O’Brien & Ziemann, 2008; Powell & Holland, 2008) to identify the effectively reacting equilibration volume. This paper applies this approach to a granulitized eclogite from the Punta de li Tulchi outcrop in Variscan Sardinia. Franceschelli et al. (1998) already recognized the multi-stage P-T evolution of these rocks based on conventional thermobarometry and petrogenetic grids. However, the here presented new microstructural interpretation of reaction textures and corresponding pseudosections allows a considerable refinement of the metamorphic evolution (including the prograde segment) by solving the problem of domainal textural and compositional equilibrium.

GEOLOGICAL SETTING
The Sardinian Variscan chain consists of the following tectono-metamorphic zones with metamorphic grade increasing from SW to NE (Fig. 1): (i) the External Zone, (ii) the Nappe Zone, further subdivided into the External and Internal Nappe Zones, and (iii) the Internal or Axial Zone (Carmignani et al., 2001 and references therein). The Axial Zone is subdivided into a Migmatite Complex known as the High-Grade Metamorphic Complex (HGMC) and a southern Low to Medium-Grade Metamorphic Complex (L-MGMC) separated by the Posada-Asinara tectonic line (Fig. 1a,b). Metamorphic grade of metapelites and metapsammites in NE Sardinia rapidly increases towards the NE through a Barrovian sequence consisting of a biotite, garnet, staurolite + biotite, kyanite+biotite, sillimanite, and sillimanite + K-feldspar zone. The garnet zone is subdivided into garnet + albite and garnet + albite-oligoclase zones (Franceschelli et al., 2005).

In northern Sardinia five Variscan deformations have been recognized (Franceschelli et al., 2005; Helbing et al., 2006). The earliest of these (D1) is witnessed by rare intrafoliar folds and relic S1 cleavage (Elter et al., 1986). D2 generated the most pervasive folds with E-W trending axes and an associated S2 schistosity dipping S to SW. This phase has been interpreted in terms of transpressional tectonics by Carosi & Palmeri (2002). The D3 phase produced open folds associated with a spaced crenulation cleavage but attaining the character of a pervasive schistosity (S3) north of Olbia. In the fault rocks of the Posada Valley shear zone (Elter et al., 2010), a D4 phase is recognized from shear bands and associated crenulation cleavages indicating a component of top to the NW followed by a top to the NE/SE shearing. In the same shear zone, D5 produced a large flexure parallel to the orogenic trend, witnessed by the uplift of the Axial Zone with respect to the schistose envelope (Helbing et al., 2006).

Outcrops of metabasites preserving eclogite facies relics only occur in the Axial Zone surrounded by migmatites and gneisses of the HGMC or within mylonitic schists and gneisses of the L-MGMC (Fig. 1a). Metabasites with eclogite-facies relics are known since the pioneering work of Miller et al. (1976). More recent work has mainly concentrated on eclogitic rocks of the Migmaitite Complex (Franceschelli et al., 1998., 2007; Cortesogno et al., 2004; Giacomini et al., 2005a) and of the L-MGMC (Cortesogno et al., 2004). Cortesogno et al. (2004) recognized different types of eclogites with different tectono-thermal evolution in the Migmaitite Complex versus the L-MGMC. Franceschelli et al. (1998) and Giacomini et al. (2005a) recognized the polyphase metamorphic evolution of retrogressed eclogites from Punta de li Tulchi (Fig. 1c) and Golfo Aranci respectively. They distinguished five metamorphic stages corresponding to a pre-eclogite-, eclogite-, granulite-, amphibolite- and greenschist-facies conditions.
SHRIMP U-Pb dating of zircons of the Punta de li Tulchi retrogressed eclogites (Palmeri et al., 2004) yielded weighted means of 453 ± 14 Ma, 400 ± 10 Ma and 327 ± 7 Ma interpreted to represent the protolith age, the high-pressure eclogitic event (or Pb loss during the Variscan event), and amphibolite-facies retrogression, respectively. A similar protolith age (460 ± 5 Ma) was obtained by Giacomini et al. (2005a) from magmatic zircon preserved in the Golfo Aranci eclogites. These ages also agree with an age of 457 ± 2 Ma obtained by Cortesogno et al. (2004) for a first zircon population recovered from an eclogite body in the Migmatite Complex. A second zircon population yielded an age of 403 ± 4 Ma and was interpreted as the age of zircon crystallization during the high-grade event, probably the eclogite event. Zircon ages for eclogites of the Migmatite Complex cluster around the Early Visean (326-345 Ma), interpreted as the age of the HP event, and between the Late Visean and Stephanian (304-299 Ma), attributed to post-HP amphibolitic re-equilibration (Giacomini et al., 2005b). Based on correlations between the Maures Massif, Corsica-Sardinia Block, and Northern Apennine segments of the Variscan Belt, Elter & Pandeli (2005) propose a common structural-metamorphic evolution from the Early Carboniferous syn-collisional event to the Late Carboniferous-Early Permian, extensional shearing.

FIELD GEOLOGY
The Punta de li Tulchi retrogressed eclogite crops out as an E-W oriented, 100 m long × 20-30 m thick lens embedded within the nebulitic migmatites of Porto Ottiolu locality (Fig. 1c). The lens is parallel to the E-W-oriented pervasive regional schistosity of the hosting migmatites which also contain some decimeter-sized eclogite nodules near to the main eclogite body. Towards the south, the contact between the main eclogite body and the surrounding migmatite is marked by a meter-sized granitic body. The Punta de li Tulchi outcrop consists of a regular alternation of brownish garnet-pyroxene-rich and greenish amphibole-plagioclase-rich layers (Fig. 2a), striking E-W and dipping 50°N. The contact between these layers is sharp or transitional. Garnet-pyroxene-rich layers in turn exhibit an internal layering defined by alternating dark, garnet-rich, and white, clinopyroxene + plagioclase symplectite-rich, layers that are generally parallel to the S2 in the surrounding migmatites. Locally, however, individual lobes of the symplectic lamellae are oblique to S2 (Fig. 2b,c), possibly indicating mimetic growth along a pre-existing S1 schistosity. According to Franceschelli et al. (2007) an amphibole-rich front with vanishing boundaries clearly cuts the S2 in the garnet-pyroxene layers. The amphibole + plagioclase-rich layers show an E-W oriented S2 foliation followed by a N80-SE30°-oriented S3 foliation, defined by the alignment of elongated millimeter-sized white pods (Fig. 2d). Locally, the S3 foliation is crosscut by late shear zones (Fig. 2d), containing a mylonitic foliation with aligned coarse-grained biotite flakes.

The host migmatite is an orthogneiss containing a weak S2 foliation oriented N 100° SW 45°. The age of the igneous protolith is unknown but a similar orthogneiss from Golfo Aranci and near Tananella yielded zircon ages of 469 ± 3.7 Ma (Giacomini et al., 2006) and 458 ± 7 Ma (Helbing & Tiepolo, 2005), respectively. The orthogneiss consists of zoned microcline, Na-rich plagioclase, quartz, biotite, ± garnet, and late crosscutting muscovite. Towards Punta de li Tulchi, the biotite content of the migmatised orthogneiss decreases and the rocks acquire a nebulitic appearance. Leucosomes align parallel to the main S2 foliation and also along the later shear zones. The migmatised orthogneiss is crosscutted by subvertical granitic dykes striking N 130° and ranging in thickness from a few meters to a several decameters.

PETROGRAPHY AND MICROSTRUCTURAL FEATURES
The studied granulitized eclogites contain variable amounts of garnet, omphacite, Ca-clinopyroxene, orthopyroxene, amphibole, plagioclase, biotite and quartz, with accessory epidote, rutile, ilmenite and apatite, monazite, zircon and very rare titanite, Fe-oxide and Fe-sulphides (Figs
The modal abundances of these minerals vary significantly for garnet-pyroxene versus amphibole-plagioclase rich layers described separately below.

**Garnet + pyroxene layers**

The garnet + pyroxene layers mainly consist of garnet, clinopyroxene, plagioclase and amphibole. Garnet forms anhedral, strongly fractured, poikiloblasts up to 5 mm in size (Fig. 3a) containing multiple omphacite inclusions (Cpx\textsubscript{1}, mineral abbreviations according to Fettes & Desmons, 2007) up to 300-400 μm in length (Fig. 3b). Garnet also includes euhedral amphibole grains (Am\textsubscript{1}) up to ∼50-70 μm in size and quartz (Fig. 3c), as well as rounded grains of apatite. In both garnet and omphacite, several tiny rutile grains (Fig. 3b,c) and inclusions of zoned epidote grains (up to a few tens of microns in size) were found. Omphacite inclusions in garnet have a very thin and sharp, light colored rim of diopsidic clinopyroxene. Omphacite is rare in the matrix, but locally occurs as large crystals containing small quartz and Fe-sulphides inclusions. Omphacite in garnet is commonly partially replaced, mostly at the rim, by Cpx+Na-Pl symplectite.

The most striking feature of the retrogressed eclogites is the very fine grained intergrowths between clinopyroxene (Cpx\textsubscript{2}) and plagioclase (Pl\textsubscript{1}) lamellae (Cpx\textsubscript{2}+Pl\textsubscript{1} symplectite, Fig. 3d-f), as also commonly observed in other metabasite lenses with eclogite-facies relicts from NE Sardinia (Franceschelli et al., 2007). The Cpx\textsubscript{2}+Pl\textsubscript{1} symplectite is widespread in the matrix and replaces former omphacite, only locally preserved as very rare relics. Although pyroxene in the symplectite is mostly clinopyroxene, in a few samples symplectic orthopyroxene (Fig. 3e) is also present. Where both ortho- and clinopyroxene occur in the symplectite, they usually occur separately in two distinct symplectite types (i.e. Cpx\textsubscript{2}+Pl\textsubscript{1} and Opx+Pl\textsubscript{1}). However, where the two symplectites are in contact (Fig. 3e) and despite the sharp boundary between them, the orientation of the plagioclase lamellae does not vary significantly and some lamellae are continuous across this boundary (Fig. 3e). Orthopyroxene is generally found in two different microstructural positions: (i) as anhedral crystals associated with the Cpx\textsubscript{2}+Pl\textsubscript{1} symplectite around garnet porphyroblasts, but not having themselves a symplectitic appearance (Fig. 3d,f) and, (ii) as a more or less continuous corona surrounding corroded quartz grains in the matrix (Fig. 4b). In both the cases, orthopyroxene is commonly partially replaced by cummingtonite (Am\textsubscript{2}) at the outermost rim (Figs 3f & 4b).

Garnet porphyroblasts embedded within the Cpx\textsubscript{2}+Pl\textsubscript{1} symplectite are in turn surrounded by well-developed composite corona microstructures (kelyphites, Figs 3a,b,d,e & 4a). The kelyphite consists of a continuous, thin plagioclase layer (Pl\textsubscript{2}) associated with blebs of coronitic amphibole (Am\textsubscript{3}) and anhedral ilmenite (Fig. 4a). The thickness of the Pl\textsubscript{2}+Am\textsubscript{3} corona ranges between ~70 and 300 μm. Anhedral orthopyroxene and ilmenite crystals discontinuously occur at the outer margin of the Pl\textsubscript{2}+Am\textsubscript{3} corona, in contact with the Cpx\textsubscript{2}+Pl\textsubscript{1} symplectite. Both orthopyroxene and ilmenite are locally corroded by coronitic amphibole. Amphibole also occurs as brownish to pale-green, frequently zoned crystals (Am\textsubscript{4}) in the rock matrix (Fig. 4c) and as minor late actinolitic amphibole (Am\textsubscript{5}) growing at the expense of pyroxene or Am\textsubscript{4} in the rock matrix.

Biotite occurs (i) as very rare small inclusions in garnet, (ii) as small flakes aligned along S\textsubscript{2} and S\textsubscript{4} in the matrix or corroding garnet and amphibole crystals, and (iii) in the most re-equilibrated samples also as coarse-grained up to 0.5 mm sized crystals in several decimeter-thick shear zones.

**Amphibole + plagioclase layers**

The amphibole + plagioclase layers (Fig. 2a) are made up of “elongated white pods” (Franceschelli et al., 1998, Fig. 2d) mainly deriving from the intimate intergrowth of plagioclase with greenish and brownish amphibole (Fig. 4d) replacing garnet, relics of which are sometimes found in the cores of white pod. Other minerals identified in these layers are ilmenite, quartz, titanite, as well as rare biotite and chlorite. Amphibole is by far the most abundant mineral occupying up to 50-60 vol% and defining the S\textsubscript{2} foliation, whereas S\textsubscript{3} is defined by the shape elongation of the white pods.
MINERAL CHEMISTRY

The chemical composition of minerals from two garnet-pyroxene layer samples (E9, E10) and one amphibole-plagioclase layer sample (E19) was determined with a fully automated Cameca SX 50 electron microprobe at the IGAG-CNR Roma. Operating conditions were 15 kV accelerating voltage, a beam current of 15 nA and a 5–10 µm variable spot size. Natural and synthetic wollastonite, olivine, corundum, magnetite, rutile, orthoclase, jadeite, pure Mn, pure Cr, fluorophlogopite, and baryte were used as standards. Microstructural study, BSE imaging, and additional EDS analyses were performed with a FEI Quanta 200 SEM equipped with an EDAX-EDS detector at Cagliari University. Selected microprobe analyses of garnet, clinopyroxene, plagioclase, amphibole, and ilmenite of sample E9 are reported in Table 1, whereas those of samples E10 and E19 are reported in Tables S1, S2. Mineral compositions, including additional analyses not reported in Tables 1, S1, S2, are plotted in Figs 5, 6b, 7. Structural formulae have been calculated on the basis of 12, 6, and 8 oxygens for garnet, clinopyroxene, and plagioclase respectively. Fe$^{3+}$ content has been calculated from charge balance for pyroxene and according to Droop (1987) for garnet. Amphibole structural formula has been calculated using the Amph-IMA Program with 23 oxygen and a normalization scheme according to Mogessie et al. (2004).

Garnet

Garnet is almandine- (Alm = 53-65 mol%)pyrope- (Prp = 15-25 mol%) and grossularite-rich (Grs = 15-26 mol%), with minor spessartine content (Sps ≤ 3 mol%). Compositional traverses and qualitative X-ray maps through some selected garnet crystals (Figs 5 & 6) reveal two different domains, a core and a rim, recognizable on the basis of their spessartine content, which is low and homogeneous in the core (Sps ≤ 1.3 mol%) and significantly higher in the rim (Sps ≥ 1.3 mol%). The thickness of the rim domain is generally < 100 µm (average of 65-75 µm), independent of garnet diameter (Fig. 6a). As a consequence, larger garnet porphyroblasts (> 1 mm in diameter) generally preserve a large core domain, whereas small garnet porphyroblasts (< 500 µm in diameter) eventually do not preserve any core domain. Garnet cores show a systematic decrease of grossularite counterbalanced by a slightly increase in pyrope from an inner core to an outer core (inner core: Grs$^{2.2-2.6}$, Prp$^{1.7-2.0}$; outer core: Grs$^{1.8-2.3}$, Prp$^{2.0-2.3}$). Garnet rims have a significantly higher spessartine and almandine contents (Sps$^{1.3-3.0}$, Alm$^{55-65}$) and lower pyrope and grossularite (Prp$^{15-25}$, Grs$^{15-23}$) with respect to garnet core.

Pyroxene

Clinopyroxene inclusions in garnet (Cpx$^1$) is omphacite (Fig. 7a) with $X_{Na}$ between 0.34 and 0.38, $X_{Mg}$ between 0.69 and 0.79 and a low Fe$^{3+}$ content (up to 0.10 a.p.f.u.) [$X_{Na} = Na/(Na+Ca); X_{Mg} = Mg/(Mg+Fe)$]. Compositional traverse through Cpx$^1$ included in garnet reveals a very thin rim characterized by a sharp decrease of Na (to $X_{Na} \sim 0.10-0.14$). Omphacite in the matrix shows a lower $X_{Na}$ content ($X_{Na}=0.25-0.30$) than omphacite included in garnet, and a similar $X_{Mg}$. Clinopyroxene from the symplectite (Cpx$^2$) is diopside to augite (Fig. 7b) with Ca = 0.90-0.91 a.p.f.u., $X_{Mg}$ between 0.70-0.80 and very low $X_{Na}$ and Fe$^{3+}$ content ($X_{Na} = 0.03-0.06; Fe^{3+} = 0.00-0.08$ a.p.f.u.). Orthopyroxene belongs to the enstatite-ferrosilite join (Fig. 7c). $X_{Mg}$ ratio in orthopyroxene ranges from 0.51 to 0.54, the Al content is ~0.02 a.p.f.u. and Fe$^{3+}$ content is between 0.03 and 0.13 a.p.f.u. No compositional difference has been observed between orthopyroxene in the rare symplectitic microstructures and orthopyroxene from the matrix.

Amphibole

All amphibole textural varieties, except cummingtonite, are calcic according to Leake et al. (1997). Amphibole inclusions in garnet (Am$^1$) are pargasite, aluminopargasite to magnesiohornblende with
Si = 5.87-6.00 a.p.f.u., Al = 2.60-3.49 a.p.f.u., Fe$^{3+}$ = 0.1-0.5, and X$_{Mg}$ = 0.59-0.61 (Fig. 7d,e). Amphibole replacing orthopyroxene (Am$_2$) is cummingtonite with X$_{Mg}$$\sim$0.7. Coronitic amphibole (Am$_3$) associated to coronitic plagioclase (Pl$_2$) is magnesiohornblende to pargasite with Si between 6.42 and 6.65 a.p.f.u., Fe$^{3+}$ between 0.35-0.42 and X$_{Mg}$$\sim$0.63. Brownish to greenish amphibole in the rock matrix (Am$_4$), distinguished from Am$_3$ on microstructural basis, is zoned with a composition ranging between Mg-hornblende, pargasite to edenite and X$_{Mg}$ ratio variable between 0.55 and 0.65. Amphibole (Am$_5$) replacing clinopyroxene is actinolite to ferroactinolite with X$_{Mg}$ ranging between 0.45 and 0.55.

Plagioclase
Plagioclase associated to clinopyroxene in the symplectite (Pl$_1$) has oligoclase composition, ranging between Ab = 74-81 mol%. Plagioclase (Pl$_1$) associated to orthopyroxene shows a wider range of compositions (Ab $\sim$73-91 mol%). Plagioclase from the kelyphites (Pl$_2$) shows an increase of Na content from the inner to the outer side of the corona (Ab=61-72 mol% to Ab=77-87 mol%, respectively). Plagioclase from the white pods is labradorite to andesine characterized by albite content in the range 42-61 mol%.

METAMORPHIC EVOLUTION CONSTRAINED BY MICROSTRUCTURES
The detailed interpretation of the microstructural features previously discussed for the garnet-pyroxene layers allows reconstruction of the metamorphic evolution of the studied samples in terms of their reaction history, i.e. in terms of reactants vs. products involved in the main prograde vs. retrograde reactions (Fig. 8).

Pre-symplectite stage
The earlier portion of the metamorphic history (pre-symplectite stage) (Fig. 8a) is recorded by mineral inclusion and compositional zoning of garnet porphyroblasts. Abundant omphacite (Cpx$_1$), rutile, quartz, epidote and amphibole (Am$_1$) inclusions in poikiloblastic garnet as well as the high jadeite content of omphacite (X$_{Na}$ ratio up to 0.38) suggest that these minerals (Grt + Cpx$_1$ + Qtz + Rt) represent the stable assemblage corresponding to pre-symplectite eclogite-facies conditions. Euhedral amphibole (Am$_1$) and epidote only occur as inclusions in garnet and are therefore interpreted as prograde minerals. This eclogitic assemblage is also consistent with the occurrence of rare omphacite relics in the matrix, pervasively replaced by the Cpx$_2$+Pl$_1$ symplectites. Although diffusion-controlled retrograde re-equilibration of garnet rims probably occurred (< 100 µm wide) as suggested by high Mn content (Sps ≥ 1.3 mol%), most of the garnet zoning is likely to represent the prograde path, at least in the larger porphyroblasts as discussed further in more detail. Garnet zoning shows a progressive increase in pyrope and a decrease in grossularite components from the inner core to the outer core (Figs 5 & 6), which is consistent with growth during increasing pressure and temperature and documented previously for other Variscan granulitized eclogites (e.g. O’Brien, 1997). How and why the prograde garnet zoning survived the pervasive high temperature overprint is discussed in the following sections.

Cpx$_2$+ Pl$_1$ and Opx+ Pl$_1$ ± Ilm symplectite/corona stage
This stage corresponds to the growth of two different symplectic microstructures, namely the Cpx$_2$+Pl$_1$ and the Opx+Pl$_1$ symplectites (Fig. 8b). The Cpx$_2$+Pl$_1$ symplectites are more abundant, pervasively replacing omphacite in the matrix and locally also omphacite crystals included in garnet where these communicate with the matrix through fractures. Reaction modelling by the least square method (CSpace version 1.01, Djinn Works, Torres-Roldan et al., 2000) applied to the composition of Cpx$_1$ (omphacite), symplectic plagioclase (Pl$_1$) and clinopyroxene (Cpx$_2$) from sample E9.
(Table 1) yielded the following balanced reaction accounting for the formation of Cpx$_2$+Pl$_1$ symplectites, in agreement with Zhao et al. (2001) and Groppo et al. (2007a,b):

1. \[0.81 \text{Cpx}_1 + 0.05 \text{Qtz} \rightarrow 0.55 \text{Cpx}_2 + 0.21 \text{Pl}_1\]

The Opx+Pl$_1$ symplectites are very rare and, being mostly surrounded by amphibole (Am$_3$), their relationships with both Cpx$_2$+Pl$_1$ symplectites and garnet are not unequivocal, although they always occur close to garnet porphyroblasts. Apart from the Opx+Pl$_1$ symplectites, orthopyroxene is commonly also found as (i) anhedral crystals (partially replaced by Am$_3$) at the outer margin of Pl$_2$+Am$_3$ coronae of garnet, and in contact with the former Cpx$_1$ (now replaced by Cpx$_2$+Pl$_1$ symplectites), and (ii) as more or less continuous Opx coronae isolating corroded quartz crystals from the former Cpx$_1$ (now replaced by Cpx$_2$+Pl$_1$ symplectites). Altogether, this evidence suggest that: firstly, both garnet and the omphacitic clinopyroxene Cpx$_1$ were likely involved in the orthopyroxene growth, whose occurrence at the outer margin of the Pl$_2$+Am$_3$ corona is probably a remnant of a former Opx+Pl$_1$ corona later replaced by the Pl$_2$+Am$_3$ assemblage (cf. Zhao et al., 2001); secondly, quartz and the Cpx$_1$ were likely involved in the orthopyroxene coronitic growth around quartz in the matrix. In both the cases, the orthopyroxene growth is roughly contemporaneous to the Cpx$_2$+Pl$_1$ symplectites development.

Considering the composition of omphacitic clinopyroxene (Cpx$_1$), garnet outer core (i.e. before the retrograde re-equilibrated rim), orthopyroxene and symplectitic plagioclase (Pl$_1$) from the same sample, the following balanced reactions can explain: (i) the development of Opx+Pl$_1$ coronae around garnet now almost completely replaced by the Pl$_2$+Am$_3$ assemblage plus the rare Opx+Pl$_1$ symplectites (reaction 2), and (ii) the occurrence of coronitic orthopyroxene around quartz relics in the matrix (reaction 3).

2. \[0.13 \text{Grt} + 0.78 \text{Cpx}_1 = 0.39 \text{Pl}_1 + 0.47 \text{Opx}\]

3. \[0.17 \text{Grt} + 0.06 \text{Cpx}_1 + 0.88 \text{Qtz} + = 0.31 \text{Pl}_1 + 0.30 \text{Opx}\]

At the outer margin of the Pl$_2$+Am$_3$ coronae of garnet, large anhedral ilmenite grains are present, surrounded and locally partially replaced by the Pl$_2$+Am$_3$ assemblage. Ilmenite occurs in a microstructural position similar to that of orthopyroxene, i.e. in between garnet and the former Cpx$_1$ (now replaced by Cpx$_2$+Pl$_1$ symplectites). Ilmenite and orthopyroxene, however, were never observed occurring together at the outer margin of the coronitic microstructures. This suggests that the ilmenite development could be related to a reaction involving garnet, the former omphacite and a Ti-rich phase (rutile), but not orthopyroxene. Considering the composition of garnet outer core (i.e. before the retrograde re-equilibrated rim), omphacitic clinopyroxene (Cpx$_1$), ilmenite, symplectitic plagioclase (Pl$_1$) and clinopyroxene (Cpx$_2$), the following balanced reaction can explain the presence of ilmenite in the coronitic structures:

4a. \[0.04 \text{Grt} + 0.79 \text{Cpx}_1 + 0.11 \text{Rt} = 0.24 \text{Pl}_1 + 0.54 \text{Cpx}_2 + 0.11 \text{Ilm}\]

Both reactions (3) and (4) involve garnet and omphacitic clinopyroxene (Cpx$_1$) as reactants, and only differ from reaction (2) regarding the presence of quartz or rutile as additional reactant phases. Consequently, all these reactions probably occurred at the same P-T conditions as a function of variable compositions of micro-domains. In addition, combining reaction (4a) with reaction (1), the following balanced equilibrium may be obtained:

4b. \[0.05 \text{Grt} + 0.77 \text{Cpx}_1 + 0.07 \text{Qtz} + 0.12 \text{Rt} = 0.26 \text{Pl}_1 + 0.54 \text{Cpx}_2 + 0.12 \text{Ilm}\]

This more complete reaction explains the growth of both Cpx$_2$+Pl$_1$ symplectites and the Ilm+Pl$_1$ coronae between garnet and omphacite.

**Pl$_2$+Am$_3$ corona stage**

This stage is documented by the development of amphibole (Am$_3$) + plagioclase (Pl$_2$) assemblage at the expense of the former Opx$_1$+Pl$_1$+Ilm corona around garnet (Fig. 8c). Pl$_2$+Am$_3$ coronae commonly replace garnet, whereas coronitic amphibole usually replaces symplectitic Cpx$_2$ and
coronitic Opx and Ilm grains. These textures indicate that the Pl$_2$+Am$_3$ coronae postdate the Opx+Pl$_1$+Ilm coronae as already concluded by Zhao et al. (2001) for similar granulitized eclogites.

The growth of amphibole implies that H$_2$O was available in the system. However, the exclusive occurrence of Am$_3$ in coronitic microstructures suggests that H$_2$O was limited to these domains rather than pervading the whole rock. By combining the composition of garnet, original coronitic plagioclase (Pl$_1$), actual coronitic plagioclase (Pl$_2$) and amphibole (Am$_3$), the following balanced reaction may account for the development of the Pl$_2$+ Am$_3$ corona assemblage in intermediate positions between garnet and the original Opx+Pl$_1$ corona:

$0.04 \text{Grt} + 0.70 \text{Pl}_1 + 0.01 \text{H}_2\text{O} = 0.72 \text{Pl}_2 + 0.01 \text{Am}_3$.

Since Am$_4$ has a chemical composition similar to that of Am$_3$ and has been distinguished only on microstructural basis, the growth of Am$_4$ in the matrix should be ascribed to the same metamorphic stage.

**Late stage metamorphic evolution**

The later stage of metamorphic evolution is documented by the local growth of actinolite, chlorite, very minor epidote and titanite in the rock matrix. Syn-D$_4$ biotite growth along shear bands is also tentatively attributed to this stage for which Franceschelli et al. (1998) estimated $P-T$ conditions of $\sim$300-400 °C and $< 0.2-0.3$ GPa.

**METAMORPHIC EVOLUTION CONSTRAINED USING THE $P-T$ PSEUDOSECTION APPROACH**

The $P-T$ pseudosections have been calculated in the NCKFMASHTH system using Perple_X (Connolly, 1990; 2009). Details of the calculation are given in the Appendix section. A detailed description of the topology of each pseudosection is considered beyond the scope of this article, therefore the variance of each field as well as the complete set of compositional isopleths and isomodes are provided as supplementary material.

**Modelling the pre-symplectite stage**

Microstructural features described above suggest that the pre-symplectite equilibrium assemblage (Grt + Cpx$_1$ + Qtz + Rt ± Am$_1$) pervasively grew throughout sample E9, and therefore that the earlier portion of the $P-T$ evolution can be modelled based on the bulk composition measured by XRF (Table 2). The corresponding $P-T$ pseudosection is shown in Fig. 9.

Based on the observed vs. modelled mineral compositions, the following $P-T$ conditions are obtained:

i) An early prograde stage is constrained by the composition of Cpx$_1$ (preserved as inclusions in garnet: $X_{Na}=0.34$) and garnet inner core (Grs$=22-26$ mol%; Prp$=17-20$ mol%) at 660-680°C and 1.6-1.8 GPa. The equilibrium assemblage modelled at these $P-T$ conditions (i.e. Cpx + Grt + Qtz + Am + Qtz + Rt + Bt, with biotite $< 1.5$ vol%) is consistent with most of the petrographic observations.

ii) A later prograde stage is constrained by the composition of outer cores of garnets (Grs$= 18-23$ mol%; Prp$=20-23$ mol%), as well as by Cpx$_1$ composition (omphacite inclusions are also preserved in the outer garnet core: $X_{Na}=0.34$) at 660-700°C and 1.7-2.1 GPa. These $P-T$ conditions lie inside the same four-variant Cpx + Grt + Qtz + Am + Qtz + Rt + Bt field of the earlier prograde stage, but closer to the upper boundary of the amphibole stability field.

The overall $P-T$ evolution modelled by the $P-T$ pseudosection of Fig. 9 is therefore characterized by a prograde increase in both $P$ and $T$ from about 600°C, 1.0 GPa to 690°C, 1.9 GPa. However, since the garnet rim shows evidence of a diffusion-controlled retrograde re-equilibration (i.e. the original rim composition is no more available), peak $P-T$ conditions could have been
slightly higher than that here modeled, more likely in the amphibole-absent five-variant Cpx + Grt + Qtz + Rt + Bt field.

**Modelling the symplectite and corona stages**

The metamorphic stages following the eclogite-facies peak-\(P\) conditions are characterized by the widespread development of symplectites, coronae and kelyphites. These microstructures are the results of metamorphic reactions occurring at the scale of small domains, not represented by whole-rock composition. In order to model \(P-T\) conditions, the method of Groppo et al. (2007a, b) was applied (see also Cruciani et al., 2008, 2011) for calculating the composition of the effectively reacting microdomains that were involved in the formation of symplectites and coronae based on mineral compositions in sample E9 (Table 1) and the stoichiometric coefficients of the previously deduced balanced reactions (2) to (5). Different \(P-T\) pseudosections (compositions in Table 2) representative of the developed microstructures were then calculated as detailed below.

i) **Opx+Pl\(_1\) symplectite/corona** – These microstructures were modelled using the effective bulk composition obtained from reaction (2). The calculated \(P-T\) pseudosection, reported in Fig. 10a, shows that the equilibrium (2) is a continuous reaction that occurred across a relatively large \(P-T\) interval, at > 800°C. Moving along a decompression path from about 1.7 GPa to 1.0 GPa, garnet and clinopyroxene are consumed (\(\Delta\text{Grt} = -13\) vol%; \(\Delta\text{Cpx} = -9\) vol%), whereas plagioclase and orthopyroxene are produced (\(\Delta\text{Pl} = +14\) vol%; \(\Delta\text{Opx} = +10\) vol%), consistent with the predictions of reaction (2). The \(P-T\) conditions at which the Opx+Pl\(_1\) symplectites and coronae grew are further constrained by the Pl\(_1\) (\(X_{Na} = 0.74-0.78\)) and orthopyroxene (\(X_{Mg} = 0.51-0.54\)) compositions at > 800°C, and 1.0-1.3 GPa (Fig. 10a).

ii) **Cpx\(_2\)+Pl\(_1\) symplectite and Ilm+Pl\(_1\) coronae** – The effective bulk composition used to model these microstructures was obtained from the balanced reaction (4a), whose reactants are the same as in reaction (2) except for rutile. The appearance of ilmenite at the expenses of rutile (in the presence of garnet and clinopyroxene) occurs in a relatively narrow \(P\)-interval at > 800°C. Passing from the rutile-bearing (and ilmenite-absent) fields at 1.5 GPa to the ilmenite-bearing (and rutile-absent) field at 0.8 GPa, garnet, clinopyroxene and rutile are consumed (\(\Delta\text{Grt} = -10\) vol%; \(\Delta\text{Cpx} = -12\) vol%; \(\Delta\text{Rt} = -4\) vol%) and plagioclase and ilmenite are produced (\(\Delta\text{Pl} = +17\) vol%, \(\Delta\text{Ilm} = +6\) vol%), in agreement with the predictions of reaction (4a). Plagioclase composition (\(X_{Na} = 0.74-0.78\)) further constrains the \(P-T\) conditions at > 800°C and 0.9-1.2 GPa (Fig. 10b).

iii) **Pl\(_2\)+Am\(_3\) corona** – The growth of the Pl\(_2\)+Am\(_3\) assemblage has been modelled using the effective bulk composition obtained from the balanced reaction (5). In the calculated pseudosection (Fig. 10c) this continuous reaction occurs on a large \(P\)-interval at > 650°C. The calculated plagioclase (\(X_{Na} = 0.62-0.68\)) and amphibole (\(Si = 6.4-6.6\) a.p.f.u.; \(X_{Mg} = 0.61-0.63\)) compositional isopleths provide further \(P-T\) constraints on the formation of Pl\(_2\)+Am\(_3\) corona, modelled at 730-830°C, and 0.8-1.1 GPa (Fig. 10c). Moving along a decompression path in this \(P-T\) range, garnet is consumed (\(\Delta\text{Grt} = -2\) vol%), whereas plagioclase and amphibole (\(\Delta\text{Am} = +3\) vol%; \(\Delta\text{Pl} = +1\) vol%) are produced, in agreement with microstructural evidence. The progression of reaction (5) led to the formation of white pods (Fig. 4d) that widespread occur in the Am-Pl layers (Fig. 2d).

**DISCUSSION**

**Attainment of equilibrium on a dominal scale and preservation of the prograde history**

Microstructural evidence and the results of thermodynamic modelling both show that sample E9 experienced a complex polyphase metamorphic history characterized by a prograde HP eclogite-facies event followed by a HT granulite-facies stage. A temperature increase of about 150°C occurred during decompression from ~ 2.0 GPa to ~ 1.0 GPa.

Reconstruction of the pre-granulitic history was possible thanks to the preservation not only of the prograde HP microstructures, but also of the garnet prograde compositions, in spite of the
widely HT overprint. In particular, garnet compositional maps show that, apart from a ~100 µm wide Mn-rich rim likely due to retrograde, diffusion controlled, re-equilibration and resorption, garnet cores preserve a well documented zoning coherent with its prograde growth at increasing pressure and temperature (i.e. Grs decreases and Prp increases from the inner to the outer core). Although the standard types of diffusion models predict that the prograde garnet zoning should be mostly reset during heating at > 700°C (e.g. Caddick et al., 2010), O’Brien (1997) first documented the possibility of garnet preserving its prograde compositional profile in granulitized eclogites from the Bohemian Massif. Since then, several other studies have reported examples of preserved prograde garnet zoning at high temperatures (e.g. O’Brien et al., 1997; Zhao et al., 2001; Štípská & Powell, 2005; Medaris et al., 2006; Groppo et al., 2007a, 2012; Cruciani et al., 2011). The samples studied by O’Brien (1997) are characterized by abundant symplectitic and coronitic microstructures similar as described here for sample E9 and also implying attainment of equilibrium only at the scale of microdomains. This led O’Brien (1997) to suggest that grain boundary diffusion and material transport have a major influence on the development of diffusion zoning and that slow grain boundary diffusion could invalidate the standard types of diffusion models.

In the specific case of sample E9, calculated H2O (wt%) isomodes (Fig. 11a) show that the amount of water available in the system progressively decreases from ~1.4 wt% at ~600°C to < 0.1 wt% at the eclogite-facies peak-P conditions (i.e. the system was H2O-saturated during its prograde evolution; Guiraud et al., 2001). Approximately at peak-P conditions, the P-T trajectory becomes tangential to the H2O isomodes, thus implying that the mineral assemblage was H2O under-saturated during the subsequent evolution, i.e. metamorphic reactions could not proceed until H2O-saturated conditions were again reached or, alternatively, H2O was introduced from outside. Sample E9 remained H2O-saturated during heating and decompression up to ca. 800°C at 1.5 GPa, when the P-T path becomes tangential to an H2O content contour (Fig. 11a) (see Guiraud et al., 2001 for the interpretation of H2O-saturated vs. H2O-undersaturated conditions). Along the subsequent heating and decompression path, the system became again slightly H2O-saturated (i.e. the P-T path intersects the H2O isomode contours towards decreasing values, despite the overall H2O content being extremely low), thus allowing the development of coronitic and symplectitic microstructures within very local domains. Fig. 11a shows that during cooling and further decompression, sample E9 was again H2O-undersaturated (i.e. the P-T path intersects the H2O isomode contours toward increasing values of H2O content), thus implying that metamorphic reactions could have operated along this portion of the P-T path only if H2O was introduced from outside. Consequently, the growth of amphibole in the Pl2+Am3 assemblage at the expense of the former Opx+Pl1 coronae and in the rock matrix (Am4) required an external fluid. Depending on the amount of introduced H2O and hence, on the longer or shorter persistence of H2O-saturated conditions, the Pl2+Am3 corona and the Am4 in the matrix could have developed at different scales, ranging from the thin (70-300 µm) Pl2+Am3 coronae around garnet of the garnet-pyroxene layers, to the widespread plagioclase + amphibole assemblage observed in the “white pods” of the amphibole-plagioclase layers. These layers thus represent different hydration degrees of the eclogitic assemblage by migrating fluids in agreement with the observation of Franceschelli et al. (2007) of a late-stage “amphibolitization front” crosscutting the regional foliation.

The P-T pseudosection approach applied on non-equilibrated samples: a challenging analysis
The concept of equilibration volume, i.e. the scale on which it is plausible to suggest that the minerals were in equilibrium with each other (e.g. Powell & Holland, 2008), plays a crucial role for thermobarometry involving pseudosections, because the chemical composition of the equilibration volume is the starting point for the calculations. Therefore, the application of the pseudosection approach to a clearly non-equilibrated sample, such as the studied granulitized eclogite E9, would seem not recommendable. On the other hand, it is the non-equilibrated nature of the sample that
allows the calculation of the equilibria relevant for the development of coronitic and symplectitic microstructures, because both the reactants and the products are still preserved. The challenge of this study has been to exploit the unique possibility offered by such microstructures for calculating balanced reactions between reactants and products at different stages of the metamorphic path, to constrain the composition of effectively reacting microdomains in which symplectites and coronae grew, and to construct corresponding pseudosections and determine $P-T$ conditions.

This study demonstrates that the bulk compositions calculated by combining mineral compositions of both reactants and products with the stoichiometric coefficients of the balanced reactions are representative of the effectively reacting symplectitic and coronitic micro-domains. The results of the pseudosection calculation may be considered reliable if the modelled isomodes and compositional isopleths are consistent with both the observed mineral assemblages/compositions and the inferred equilibria. Furthermore, if some of the domainal microstructures show mutual relationships suggesting their contemporaneous growth (such as the Opx+Pl and the Ilm+Pl coronae), the $P-T$ constraints obtained from the two different pseudosections should be the same. The latter provides an important additional test for the reliability of pseudosection results.

**Comparison with other Sardinian eclogites**

The $P-T$ path of the Punta de li Tulchi granulitized eclogite (Fig. 11a) is markedly similar to the paths deduced for retrogressed eclogites from the Migmatite Complex (Axial Zone) at Golfo Aranci (Giacomini *et al.*, 2005a) and for the Punta Orvili metabasite (Cruciani *et al.*, 2011) (Fig. 11b). The latter is assumed to belong to the Low to Medium Grade Metamorphic Complex (Nappe Zone), because it crops out very close to the Posada-Asinara shear zone (Fig. 1); the retrogressed eclogite there has a different bulk composition and lacks orthopyroxene (e.g. Franceschelli *et al.*, 1998; Cruciani *et al.*, 2011).

The first portion of the $P-T$ path for the three retrogressed eclogites consists of a prograde increase of both $P$ and $T$ to eclogite-facies peak conditions (1.9-2.1 GPa, 600-700°C). After the eclogite stage, they underwent significant re-equilibration under granulite-facies conditions (700-800°C, 1.0-1.2 GPa), followed by high-$T$ amphibolite-facies metamorphism (650-800°C; 0.7-1.0 GPa). Comparing the $P-T$ paths calculated at the same $a$H$_2$O for the eclogites from the three different localities (Fig. 11b), it appears that the Punta de li Tulchi eclogite records peak temperatures about 40-50°C higher than those of Golfo Aranci retrogressed eclogite and 90-100°C higher as those of Punta Orvili metabasite. However, changing $a$H$_2$O shifts the whole $P-T$ trajectories towards lower or higher temperatures (e.g. lowering $a$H$_2$O from 1.0 to 0.5 results in a shift of about 50°C toward lower $T$; compare Fig. 11a and Fig. 11b). It is therefore difficult to assess whether the different modelled peak-$T$ for the three localities reflect true differences in temperatures, and/or are due to different $a$H$_2$O. Independent of the absolute $P-T$ values registered by the Golfo Aranci, Punta Orvili and Punta de li Tulchi eclogites, however, it is worth noting that their $P-T$ evolutions are very similar in shape, thus suggesting a common tectonic scenario for their evolution.

The new data presented for the Punta de li Tulchi granulitized eclogite are substantially in agreement with the geodynamic scenario proposed by Cruciani *et al.* (2011) for the evolution of the NE Sardinia eclogites. According to these authors the prograde evolution of the eclogites took place under a geothermal gradient of $\sim$10°C km$^{-1}$, compatible with a relatively hot subduction of a small, young marginal basin rather than with the prolonged subduction of a wider more thermally mature oceanic plate. The subsequent increase of the geothermal gradient to 25-30°C km$^{-1}$ marks the beginning of the Variscan continental collision. The following exhumation of the granulitized eclogites to relatively shallow crustal levels, was accompanied by re-equilibration under granulite-
to HT amphibolite-facies conditions, most likely during a period of protracted continental collision.

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REFERENCES


APPENDIX

Pseudosection calculation.
The phases considered in the modeling are: amphibole, biotite, white mica, clinopyroxene, orthopyroxene, garnet, plagioclase, zoisite/clinozoisite, ilmenite, rutile, quartz, chlorite and titanite. Solid solution models are: Holland & Powell (1998) for garnet and white mica, Holland & Powell (1996) for orthopyroxene, Green et al. (2007) for clinopyroxene, Holland et al. (1998) for chlorite, Dale et al. (2005) for amphibole and Newton et al. (1981) for plagioclase. All iron is considered as bivalent because all the phases have negligible Fe$^{3+}$, and the very rare (<< 1 vol%) Fe$^{3+}$-bearing epidote inclusions within garnet core are interpreted as prograde relics.
Mn has not been considered in the calculation, because its content in garnet is very low and homogeneous and it mainly enters in the diffusion-controlled retrograde rim of garnet. All the pseudosections have been calculated at $aH_2O$=1.0. However, the effects, on the pseudosection topologies, of a lower $aH_2O$ have been also investigated. Lowering the $aH_2O$ results in a general shift of all the field boundaries and compositional isopleths toward lower temperatures. In particular, a shift of about 30-40°C is observed if the $aH_2O$ is set at 0.5.

FIGURE CAPTIONS
Fig. 1. (a): Geological sketch map of NE Sardinia coast. (b): Main structural elements of the Variscan chain of Sardinia from Carmignani et al. (2001). PAL: Posada-Asinara Line. (c): Sketch map of Punta de li Tulchi area.

Fig. 2. Field photographs of Punta de li Tulchi granulitized eclogite. (a): Alternation of decimeter-scale (GP) Grt-Px layers and (AP) Am-Pl layers; (b): Grt-Px layers showing millimetric S2 oriented clinopyroxene + plagioclase symplectites and garnet porphyroblasts. Grt-Px layers show a decrease in crystal size resembling mylonite (M). (c): Detail of the Grt-Px layer shown in Fig. 2b (rectangle). Reddish garnet crystals with a dark corona are surrounded by the clinopyroxene + plagioclase symplectite (white). (d): White pods (WP) in the Am-Pl layers elongated as the S3 schistosity. The S3 schistosity is cut by millimeter-scale shear bands.

Fig. 3. Photomicrographs and BSE images showing the relevant microstructures of the Punta de li Tulchi granulitized eclogites. (a) Overview of the granulitized eclogite (sample E9). Coronitic garnet set in a Cpx2+Pl1 symplectite matrix. Grt-Px layer. Plane Polarized Light (PPL). (b) Coronitic garnet with inclusions of omphacite (Cpx1), rutile and amphibole (Am1). Quartz is also included in Cpx1. Grt-Px layer. BSE image. (c) Detail of Am1, rutile and quartz inclusions in garnet. Grt-Px layer. BSE Image. (d) Detail of Cpx2+Pl1 symplectite matrix around garnet. Orthopyroxene occurs in the matrix and at the interface between the Pl2+Am3 corona and the Cpx2+Pl1 symplectite. Grt-Px layer. BSE image. (e) Rare Opx + Pl1 symplectite preserved in a Grt-Px layer sample. Cpx2+Pl1 and Opx+Pl1 symplectites are surrounded by matrix amphibole (Am4). BSE image. (f) Detail of orthopyroxene at the interface between Cpx2+Pl1 symplectite and Am1+Pl2 kelyphite. Orthopyroxene is partially replaced by cummingtonite. Grt-Px layer. BSE image.

Fig. 4. Photomicrographs and BSE images showing the relevant microstructures of the Punta de li Tulchi granulitized eclogites. (a) Corona around garnet made up of plagioclase (Pl2), amphibole (Am3) and anhedral ilmenite. Grt-Px layer. PPL. (b) Quartz grain surrounded by orthopyroxene and Cpx2 clinopyroxene. The contact between quartz and pyroxenes is marked by a cummingtonite layer. Grt-Px layer, BSE image. (c) Medium-grained matrix amphibole (Am4) showing a pale green core surrounded by a brownish discontinuous rim. Grt-Px layer. PPL. (d) Microstructural features of layers containing white pods of amphibole and plagioclase (Am-Pl layers). PPL.

Fig. 5. Compositional variations of garnet core and rim in mol%. (a) pyrope vs. spessartine. (b) grossularite vs. spessartine. (c) almandine vs. spessartine. Additional garnet analyses not reported in Tables 1,S1 are also shown.

Fig. 6. (a) Schematic sketch of garnet zoning and kelyphite microstructure (redraw of Fig. 3b). (b) Zoning profile of garnet from Fig. 3b. The trace of the profile is shown in Fig. 6a.

Fig. 7. (a), (b), (c) Clinopyroxene and orthopyroxene classification in the (Wo+En+Fs)-Jd-Ae and Wo-En-Fs diagrams (Morimoto, 1988). (d), (e) Ca-amphibole classification in the diagram after Leake et al. (1997). All textural types of amphiboles are reported. Additional pyroxene and amphibole analyses not reported in Tables 1, S1, S2 are also shown.

Fig. 8. Microstructure and reaction history of sample E9. (a) pre-symplectite eclogitic stage; (b) Cpx2+Pl1 and Opx+Pl1 symplectite/corona stage; (c) Am3+Pl2 corona stage. Fig. 8c is a redraw of part of the microstructure shown in Fig. 3d.

Fig. 9. (a) P–T pseudosection (NCKFMASTH system) calculated at aH2O = 1 for the bulk composition of Grt-Px layer sample E9 (compositions in Table 2). White, light-, medium-, and dark-grey fields are di-, tri-, quadri-, and penta-variant fields, respectively. Dotted ellipses represent
P-T conditions for pre-symplectite stages estimated using clinopyroxene (b) and garnet (c,d) compositional isopleths.

**Fig. 10.** P–T pseudosections in the NCKFMASTH system calculated at aH₂O = 1 for the bulk compositions of the effectively reacting microdomains (Table 2). White, light-, medium-, and dark-grey fields are di-, tri-, quadri-, and penta-variant fields, respectively. Dotted ellipses in (a), (b), (c) represent the inferred P-T conditions of formation of Opx+Pl₁ corona/symplectite, Ilm+Pl₁ corona, and Am₃+Pl₂ corona, respectively, estimated using plagioclase, orthopyroxene and amphibole compositional isopleths. Some relevant modal abundances (vol.%) of garnet, plagioclase, pyroxenes, amphibole, rutile and ilmenite are represented by white dashed line. Isomodes of garnet, plagioclase, pyroxenes, amphibole, and ilmenite are given in Figs S1, S2, S3 of the Supplementary material.

**Fig. 11.** (a) P-T path of the Punta de li Tulchi granulitized eclogites as inferred from P-T pseudosections reported in Figs 9, 10. The H₂O isomodes (wt%) calculated for the pseudosection of Fig. 9 show that sample E9 was H₂O-saturated during its prograde evolution (continuous P-T path), whereas it was H₂O-undersaturated at peak-P conditions and during most of the following heating and decompression (dashed P-T path). Slightly H₂O-saturated conditions (but with H₂O < 0.1 wt%) were reached again at peak-T conditions, whereas during the following cooling and decompression the system was H₂O-undersaturated, thus suggesting that the growth of the late amphibole + plagioclase assemblage required the introduction of H₂O from outside. (b) Comparison between the P-T path obtained from the Punta de li Tulchi granulitized eclogite (P-T path 1, recalculated at aH₂O = 0.5 for the sake of comparison) with those obtained for the other Sardinian eclogites (Giacomini *et al*., 2005a: retrogressed eclogites from Golfo Aranci, P-T path 2; Cruciani *et al*., 2011: Punta Orvili metabasite, P-T path 3).

**TABLE CAPTIONS**

**Table 1.** Selected microprobe analyses and structural formula of garnet, pyroxenes, plagioclase, amphibole and ilmenite for Grt-Px layer sample E9. Trivalent iron has been calculated according to Droop (1987) for garnet and by charge balance for pyroxenes. Amphibole structural formula has been calculated according to Mogessie *et al*. (2004). Asterisk indicates mineral composition used in CSpace calculation.

**Table 2.** Bulk compositions used for pseudosection calculations

**SUPPLEMENTARY MATERIAL**

**Table S1.** Selected microprobe analyses and structural formula of garnet, pyroxenes, plagioclase, amphibole and ilmenite for Grt-Px layer sample E10. Trivalent iron has been calculated according to Droop (1987) for garnet and by charge balance for pyroxenes. Amphibole structural formula has been calculated according to Mogessie *et al*. (2004).

**Table S2.** Selected microprobe analyses and structural formula of plagioclase, amphibole and ilmenite for Am-Pl layer sample E19. Amphibole structural formula has been calculated according to Mogessie *et al*. (2004).

**Fig. S1.** Isomodes of plagioclase (a), orthopyroxene (b), garnet (c), and clinopyroxene (d) for the P-T pseudosection of Fig. 10a.
Fig. S2. Isomodes of plagioclase (a), ilmenite (b), garnet (c), and clinopyroxene (d) for the $P-T$ pseudosection of Fig. 10b.

Fig. S3. Isomodes of plagioclase (a), amphibole (b), and garnet (c) for the $P-T$ pseudosection of Fig. 10c.
Figure 1
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Figure 2
144x122mm (300 x 300 DPI)
Figure 4
177x156mm (300 x 300 DPI)
Figure 6
175x84mm (300 x 300 DPI)
Figure 7
306x234mm (300 x 300 DPI)
209x526mm (300 x 300 DPI)
Figure 9
296x343mm (300 x 300 DPI)
Figure 10
89x304mm (300 x 300 DPI)
Figure 11
247x185mm (300 x 300 DPI)
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