



# Garnet clinopyroxenite layers from the mantle sequences of the Northern Apennine ophiolites (Italy): Evidence for recycling of crustal material

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## ARTICLE INFO

### Article history:

Received 28 March 2012

Received in revised form

18 July 2012

Accepted 20 July 2012

Editor: T.M. Harrison

Available online 31 August 2012

### Keywords:

garnet pyroxenite

ophiolite

subcontinental mantle

crustal recycling

Nd–Hf isotopes

Northern Apennines

## ABSTRACT

This study aims to define the origin of garnet clinopyroxenite layers from the mantle sequences of the External Ligurian ophiolites. These mantle sequences retain a subcontinental origin and were exposed at a Jurassic ocean–continent transition. The garnet clinopyroxenites are mafic rocks with Mg# values of 66–71. Their chondrite-normalised REE patterns are characterised by severe LREE depletion ( $Ce_N/Sm_N=0.1\text{--}0.2$ ) and nearly flat (Type-A pyroxenites) to moderately enriched HREE (Type-B pyroxenites). In addition, Type-A pyroxenites display a small positive Eu anomaly. The whole-rock REE variations are paralleled by the garnet REE compositions. We attribute the major and trace element characteristics of the garnet clinopyroxenites to recycling of gabbroic protoliths that underwent partial melting under eclogite facies conditions. The garnet clinopyroxenites may represent variably evolved garnet + clinopyroxene cumulates formed by eclogite-derived melts. In an alternative hypothesis, Type-A and -B pyroxenites are residual rocks after eclogite melting and cumulates derived from the eclogite melts, respectively. The high pressure fractionation event that gave rise to the garnet clinopyroxenites is considered of Triassic age on the basis of Sm–Nd and Lu–Hf isotope correlations. The Nd–Hf isotopic compositions of the garnet clinopyroxenites in the Triassic ( $\epsilon_{Nd} = +4.7$  to  $+7.6$ ,  $\epsilon_{Hf} = +4.4$  to  $+12.8$ ) lie below the mantle array, in agreement with recycled ancient MOR-type material. The oxygen isotopic composition of garnet and clinopyroxene from the garnet clinopyroxenites ( $\delta^{18}O = +4.9\text{‰}$  to  $+5.2\text{‰}$ ) may be reconciled with subduction-related recycling of the lowermost oceanic crust, or delamination and foundering of underplated gabbros from the continental lithosphere. The potential involvement of the garnet clinopyroxenites in the melting processes that gave rise to the MOR-type oceanic crust in the Jurassic would account for the moderate Nd isotope variability and the garnet geochemical signature of the ophiolitic basalts.

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## 1. Introduction

The occurrence of garnet pyroxenites in the upper mantle has received large attention for their implications on the fate and recycling of subducted or delaminated crust and for their possible contribution to the basalt petrogenesis (e.g. Sobolev et al., 2007; Gerbode and Dasgupta, 2010; Stroncik and Devey, 2011). For instance, pyroxenite layers in orogenic massifs are considered as useful proxy for describing mixed peridotite–pyroxenite sources invoked for the origin of plume-related basalts (Pearson and Nowell, 2004). In addition, the involvement of garnet–pyroxenites in the melting process that give rise to mid-ocean ridge basalts was proposed to explain their geochemical garnet signature and

Nd–Hf isotope heterogeneity (e.g. Hirschmann and Stolper, 1996; Salters and Dick, 2002; Standish et al., 2008).

The petrogenesis of pyroxenites found in the subcontinental mantle is controversial (see Bodinier and Godard, 2003; Downes, 2007). A major distinction may be formulated between origin by solid-state recycling into mantle of crustal material, possibly followed by partial melting during emplacement (Allegre and Turcotte, 1986; Kornprobst et al., 1990; Blichert-Toft et al., 1999; Yu et al., 2010), and crystal-melt accumulation into mantle conduits from melts of a peridotite source (Bodinier et al., 1987; Downes, 2007) or of subducted oceanic crust (Pearson et al., 1993; Van Acken et al., 2009). Melt–rock reactions and related peridotite replacement was also recognised as a viable mechanism for the origin of some mantle pyroxenites, as indicated by experimental investigations (Yaxley and Green, 1998; Lambart et al., 2012) and geochemical studies of orogenic peridotite massifs (Garrido and Bodinier, 1999; Blichert-Toft et al., 1999;

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Le Roux et al., 2007) and xenoliths (Aulbach et al., 2007; Dantas et al., 2009).

In this work, we present a petrological and geochemical study of garnet clinopyroxenites enclosed in the mantle sequences from the External Ligurian Jurassic ophiolites (northern Apennine, Italy). These mantle sequences were emplaced in an extensional setting along a fossil ocean–continent transition, where embryonic oceanic crust was associated with rocks of continental origin (Marroni et al., 1998; Tribuzio et al., 2004; Montanini et al., 2008). We wish to determine whether the garnet pyroxenite layers formed by the injection of melts derived from a peridotite source, or they represent recycling products of crustal rocks. For this purpose, major and trace elements were determined in minerals and bulk pyroxenite samples. In addition, Nd–Hf isotope ratios were measured on whole-rocks and pyroxene separates to fingerprint the mantle reservoirs from which the pyroxenite parental melts/protoliths formed. Furthermore, oxygen isotope compositions of minerals were obtained to highlight the possible involvement of components from the continental crust, oceanic sediments or seawater-derived hydrothermal fluids.

## 2. Geological and petrological framework

The opening of the Ligurian–Piedmontese basin in the Middle Jurassic was associated with uplift and denudation of subcontinental lithospheric mantle, which is currently exposed in the Alpine–Apennine belt. Some of these mantle bodies were affected by thermochemical erosion and refertilization processes related to asthenospheric upwelling during rifting and oceanization (e.g. Piccardo, 2008). Mantle sequences retaining their subcontinental origin are preserved in the Northern Apennines (External Ligurian units, Beccaluva et al., 1984) and in the Central Alps (Totalp, Müntener et al., 2004). Both External Ligurian and Totalp mantle sequences locally contain garnet pyroxenite layers whose petrogenesis is still partly unknown (Müntener and Hermann, 1996; Montanini et al., 2006). On the basis of highly siderophile elements and Os isotope compositions, Van Acken et al. (2008, 2009) proposed that some of the Totalp garnet pyroxenites formed by melts derived from subducted mafic crust.

The Jurassic ophiolites from the External Ligurian units of the northern Apennine occur in Upper Cretaceous sedimentary melanges, as large slide-blocks (up to km-scale) and in polygenic breccias. The mantle sequences consist of chemically fertile spinel–plagioclase lherzolites with disseminated Ti-rich amphibole and widespread spinel pyroxenite layers (Beccaluva et al., 1984). The mantle lherzolites locally retain extremely depleted Nd–Sr isotope compositions (Rampone et al., 1995), coupled with ancient Os model ages ( $\sim 1.6$  Ga, Snow et al., 2000), which argue for a long residence time in the subcontinental mantle. The garnet pyroxenite layers are rare and consist of thin ( $\leq 0.1$  m) websterites and up to m-scale thick garnet clinopyroxenites (Montanini et al., 2006). Some of the External Ligurian mantle bodies record interactions with asthenospheric melts under plagioclase facies to low pressure conditions, which are shown by plagioclase-enriched impregnated peridotites (Piccardo, 2008), intrusions of Middle Jurassic MOR-type gabbros (Tribuzio et al., 2004) and dyking of MOR-type basalts (Rampone et al., 1998; Montanini et al., 2008).

The garnet pyroxenites from the External Ligurian mantle bodies record an early stage of equilibration in the subcontinental lithosphere at  $T \sim 1100$  °C and  $P \sim 2.8$  GPa (Montanini et al., 2006). A garnet clinopyroxenite layer (sample AM322/1 of this study) yielded Sm–Nd and Lu–Hf internal mineral isochrons at  $186 \pm 2$  Ma and  $220 \pm 13$  Ma, respectively. These isochrons

were interpreted to record a retrograde history of cooling during the rifting-related exhumation. The high temperature decompression was followed by a polyphase brittle deformation evolution under decreasing temperature conditions, which was correlated with involvement of the mantle section in a detachment system leading to exposure at the seafloor (Montanini et al., 2006).

## 3. Selected samples and results

Eight garnet clinopyroxenites and two peridotite samples from the External Ligurian mantle bodies were selected for this work. Comprehensive information about field relationships, petrography, microtextures and major element mineral chemistry are reported in Montanini et al. (2006). Representative major element compositions of garnets and clinopyroxenes are included in the Supplementary material (Table A1), which also contains a delineation of the analytical techniques utilised in this study (Appendix A).

Three samples (AM322/1, AM322/2, AM322/3) were collected from adjacent portions of the centre of the 0.8 m thick garnet clinopyroxenite layer from Rio Strega (Fig. A1). These samples mostly consist of garnet and Al-rich clinopyroxene commonly displaying plagioclase exsolution lamellae. The garnet locally includes unexsolved Al-rich clinopyroxene with relatively high Na<sub>2</sub>O content (up to 2.5 wt%, Table A1); high temperature graphite and Fe–Ni sulphides occur as accessory (see also Montanini et al., 2010). These samples locally contain garnet-free granoblastic domains composed of orthopyroxene, Al-poor clinopyroxene, plagioclase and spinel.

The edge of the Rio Strega layer shows a foliation defined by an orthopyroxene + Al-poor clinopyroxene + plagioclase + Al-rich spinel assemblage, which is concordant with the orientation of the plagioclase facies foliation of the host mylonitic lherzolites. Two samples (AM407 and AM343) were collected from the edge of the layer, at a distance  $\sim 0.5$  m between each other. Sample AM407 retains garnet and Al-rich clinopyroxene porphyroclasts, whereas sample AM343 is garnet-free. The host Rio Strega peridotite (sample AM324) is characterised by porphyroclasts of orthopyroxene, clinopyroxene and spinel in a fine-grained matrix of olivine, pyroxene, plagioclase, spinel and Ti-rich amphibole.

Garnet clinopyroxenite AM371 was collected in the mantle body of Mt. Prinzerza (Fig. A1), from a  $\sim 0.2$  m thick pyroxenite layer with a foliation defined by an orthopyroxene + Al-poor clinopyroxene + plagioclase + Al-rich spinel assemblage. This sample includes spinel–pyroxene symplectites interpreted to have formed by garnet breakdown (Montanini et al., 2006). The host peridotite is an amphibole-bearing spinel–plagioclase mylonitic lherzolite (sample AM288b), structurally and compositionally similar to AM324 lherzolite from Rio Strega.

One garnet clinopyroxenite clast was collected from a polygenic breccia exposed along Rio Parola (Fig. A1). This sample has widespread relics of garnet and Al-rich clinopyroxene, and includes accessory graphite and Fe–Ni sulphides. Two portions of the same clast (samples E181/1, E181/2) were considered for this work. Both samples locally contain garnet-free granoblastic domains composed of orthopyroxene, Al-poor clinopyroxene, plagioclase and spinel.

Sulphide compositions in the garnet clinopyroxenites are consistent with early crystallisation as high temperature Fe–Ni–Cu monosulphides from an immiscible sulphide liquid. Graphite precipitation in the pyroxenite was related to interaction between this melt and a oxidised carbon-bearing medium (CO<sub>2</sub> or carbonate, Montanini et al., 2010).

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