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Deciphering the tectonic-geodynamic context of the gem-quality "*noble serpentine*" deposit formation combining microstructural, chemical and micro-Raman analyses in Palaeozoic olivine-bearing marbles and serpentine-hosting rocks (Pizzo Tremogge, Margna unit – Austroalpine, Val Malenco – Central Alps, Italy)

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ABSTRACT

The gem-quality "*noble serpentine*" of Pizzo Tremogge (Val Malenco, Italy) is included in Palaeozoic olivine-bearing marbles, occurring in the Margna unit, Central Austroalpine domain. A detailed inspection of serpentine samples reveals the presence of the three serpentine species (lizardite, chrysotile and antigorite) occurring in different microstructural domains.

Serpentine samples were investigated to obtain microstructural information preserved in the serpentine species by optical microscopy, X-ray powder diffraction, Electron Microprobe Spectrometry and Micro-Raman spectroscopy, the last of which is considered a reliable method for the identification of the different serpentine species.

Two types of "*noble serpentine*" have been identified: the yellow-green type characterized by fine-grained aggregates in marbles and the green type localized in fibrous veins in association with calcite and quartz.

The identification of the different serpentine types allowed us to recognize three stages of mineral crystallization characterized by: i) the formation of olivine-bearing marbles (Stage 1), ii) the growth of lizardite after olivine or within lizardite-rich veins (Stage 2) and iii) the replacement of lizardite by antigorite in marbles and by antigorite + clinohumite in veins (Stage 3).

These stages clarify the complex geodynamic-tectonic evolution of the Margna-Malenco system. The Paleozoic olivine-bearing marbles (Margna protoliths, Stage 1) are subjected to extensional tectonics that brings the Margna protoliths close to the Malenco in a thinned-extended-type passive margin (Stage 2). Finally, an inversion of tectonics leads to the subduction and collision of the Margna-Malenco system during alpine convergence (Stage 3). All this suggests that gem-quality "*noble serpentine*" deposits may be related to different geological contexts.

1. Introduction

Deposits of the gem-quality "*noble serpentine*", have been described worldwide associated with serpentinite or serpentinite-marble. Serpentinite rocks are observed in various tectonic settings and are common in various metamorphic and geodynamic contexts: from blueschist to eclogite facies conditions during subduction and exhumation, as well as in hydrothermal conditions during lithospheric extension due to the oceanic hydration and to alteration of olivine and magnesium-rich silicates from seawater (Evans, 2004; Evans et al., 2013; Mével, 2003). Recent works have also proposed a subduction-collision geodynamic context for the formation of "*noble serpentine*"-rich serpentinite deposits in the Urals (Posukhova et al., 2012, 2013).

Serpentinites are chiefly composed of the serpentine-mineral group, which includes hydrous magnesium phyllosilicates with an ideal chemical formula $Mg_3Si_2O_5(OH)_4$. From a crystallographic point of view,

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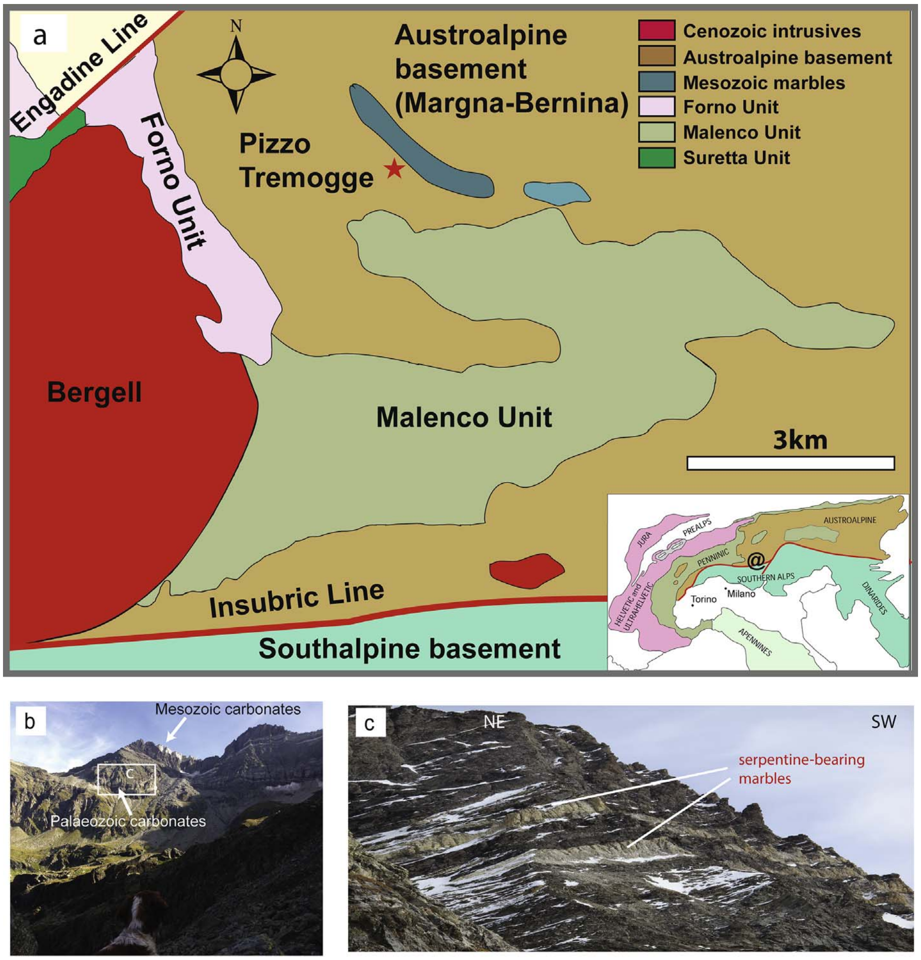

Fig. 1. (a) Schematic Geological map of Val Malenco, Italy, at 1:125.000 scale, showing the Margna Unit and Australpine basement (light brown) with Mesozoic cover (dark blue), the Malenco Unit (light green), the Forno Unit (pink), the Southern Alps (light blue) and the Cenzoic intrusives of Bergell and Triangia (dark red). The Insubric and Engadine lines are also reported (modified after Adamo et al., 2009); (b) Palaeozoic and Mesozoic marbles cropping out at Pizzo Tremogge; (c) Palaeozoic serpentine-bearing marbles cropping out at Pizzo Tremogge pass. Panoramic view of the relations between marbles (white), amphibolites (dark brown) and paragneisses (not visible in figure). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

serpentines consist of superposed 1:1 alternating tetrahedral [SiO_4] and octahedral $Mg(O, OH)_6$ sheets and the different spatial arrangements of these layers result in three main structural varieties: the sheet form flat layers in lizardite, coiled cylinders in chrysotile and wavy structures in antigorite (Dodony et al., 2002; Laurora et al., 2011; Rinaudo et al., 2003; Wicks and O'Hanley, 1988).

The serpentines are schematically considered as pseudo-polymorphs even if important chemical differences exist, mainly due to the variable extent of the cationic substitutions in the structural sites (Viti and Mellini, 1997). The relative stability of each variety covers a wide range of metamorphic conditions: antigorite occurs under high-pressure and high-temperature conditions whereas lizardite and chrysotile are present in low-grade metamorphic rocks (Bromiley and Pawley, 2003; Hilairet et al., 2006; Padrón-Navarta et al., 2013; Ulmer and Trommsdorff, 1995, 1999; Wunder and Schreyer, 1997). Therefore, it is generally difficult to evaluate the P-T conditions under which serpentine minerals were subjected. Nevertheless, in the case of a well-constrained sampling area, the associated metamorphic rocks and related mineral parageneses allow an approximate knowledge of these conditions (Schwartz et al., 2013).

In this light, the correct identification of the serpentine varieties may be useful in providing fundamental data for evaluating the P-T conditions of metamorphic processes. Several analytical techniques have been used to identify serpentine minerals and to distinguish among them on the basis of their structural and chemical properties. Optical microscopy does not appear to be a valuable technique for their characterization because they have similar optical properties and are frequently fine grained and sub-microscopically intergrown. Transmission Electron Microscopy with EDS is the most reliable technique for serpentine identification but the sample preparation is difficult and time consuming and the interpretation of the electron diffraction pattern is not easy (Andreani et al., 2004, 2008). Wicks and O'Hanley (1988) reported that X-ray Diffraction was successfully used to distinguish among the three varieties. Rinaudo et al. (2003) proved that Micro-Raman Spectrometry is the most useful micro-characterization tool for resolving serpentine structural differences at the scale of the various grain generations. For instance, Groppo et al. (2006) investigated the serpentinite from the Lanzo Ultramafic Complex and demonstrated that micro-Raman allows a reliable identification of lizardite, antigorite and chrysotile, even when they are microscopically intergrown or form aggregates with other minerals. In Schwartz et al. (2013) Micro-Raman and Electron Microprobe Spectrometry (WDS) analyses combined with petrological observations of serpentine-bearing samples in the Western Alps gave useful insight into the estimation of the relative stability of each variety of serpentine and into the relationships of their distribution with the thermal evolution of the host-rock.

In the Central Alps a deposit of gem-quality serpentine, often referred to as "*noble serpentine*", occurs at Pizzo Tremogge, Val Malenco (Italy) and is included in Palaeozoic olivine-bearing marbles in the Margna unit (Central Austroalpine domain). Due to the compact microstructure and fine and green colour "*noble serpentine*" is used as gems and for ornamental carvings. Bedogné et al. (1993) and Benetti (1984) highlighted that the Pizzo Tremogge "*noble serpentine*" consisted of lizardite associated with white veins of calcite whereas Adamo et al. (2014, 2016) pointed out the simultaneous presence of lizardite, chrysotile and antigorite.

The geological and structural geodynamic context in which the