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Petrologic and stable isotopic studies of a fossil hydrothermal system in ultramafic environment (Chenaillet ophicalcites, Western Alps, France): Processes of carbonate cementation

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ABSTRACT

The Late Jurassic Chenaillet ophiolitic complex (Western Alps) represents parts of an oceanic core-complex of the Liguria-Piemonte domain. A model for the origin and evolution of the Chenaillet ophicalcites based on textural and isotopic characterization is presented. The Chenaillet ophicalcites correspond to brecciated serpentinized peridotites that record seafloor shallow serpentinization at a minimum temperatures of 150 °C followed by authigenic carbonation. Carbonation starts with a network of micrometric to millimetric pre- or syn-clast formation calcite veins accompanied by a pervasive carbonation of residual olivine and serpentine inside the serpentinite mesh core. A matrix of small calcite (<50 μm, 12 μm in average) cemented clasts after their individualization. Texture of the breccia, grain size distribution within the matrix, and chrysotile clusters support rapid cementation from a strongly oversaturated fluid due most likely to hydrothermal fluid cooling and decompression. Later fluids infiltrated by multiple crack formation and some dolomite locally formed along serpentinite-calcite interfaces. Carbonates have $\delta^{13}C$ (VPDB) values that range between $-5‰$ and $+0.4‰$. The lower values were obtained for calcite within the serpentinite clasts. The $\delta^{18}O$ (VSMOW) values have a range between $+11‰$ and $+16‰$ in carbonated clasts. The $\delta^{18}O$ values in the matrix are fairly homogeneous with an average at $+12‰$ and the late calcite veins have values between $+12.5$ and $+15.5‰$. These values suggest a relatively high temperature of formation for all the carbonates. Carbonates within clast are mainly characterized by a formation temperature in the range of 110 °C to 180 °C assuming a $\delta^{18}O$ value of seawater of 0‰, the matrix forms at a temperature of ca. 165 °C. Late veins are characterized by a formation temperature ranging between 120and 155 °C. We propose a model where serpentinization is followed by discrete carbonation then brecciation and cementation as a consequence of continuous hydrothermal fluid circulation in the serpentinite basement. This is comparable to observations made in the stockwork of present-day long-lived oceanic hydrothermal systems.

1. Introduction

The non-uniform flow of basaltic melt (Tucholke and Lin, 1994) leads to amagmatic segments of the mid-oceanic ridges. This favors the exhumation of ultramafic rocks on the oceanic seafloor along detachment faults at (ultra)-slow spreading ridges (<55 mm/yr; Mével, 2003; Schroeder et al., 2002). It results in the formation of corrugated megamullions structures, the so-called Oceanic Core Complexes (OCCs, Ildefonse et al., 2007; MacLeod et al., 2009). In this setting, seawater circulation along large transform faults enhances peridotite alteration (Blackman et al., 2002; Cannat et al., 2006; Evans, 2004; McCaig et al., 2010). Here, the minerals olivine and pyroxene in peridotite are far from thermodynamic equilibrium and water-rock interaction produces serpentine that represent a major mineralogical component of the oceanic lithosphere. While the serpentinization reactions are common whatever the dynamic setting of the oceanic lithosphere, petrological and geochemical studies have shown that this reaction is favored along detachment faults: first at high temperatures (300–500 °C), often in relation with gabbroic intrusions (Alt et al., 2012; McCaig et al., 2010), but then develops pervasively close to the ocean floor (~200 °C) due to hot marine water circulation activated by heat generated through the exothermic serpentinization reaction itself (Allen and Seyfried, 2004; Früh-Green et al., 2003; Kelley et al., 2001). While serpentinization takes place over a wide range of temperature, the maximum reaction rate for serpentinization reaction is observed around

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250–300 °C (Martin and Fyfe, 1970). The maximum depth for serpentinization can be several kilometers at slow spreading ridges (Cannat et al., 2010). The interaction of seawater with ultramafic rocks results in the development of characteristic mesh textures and veins composed of chrysotile and lizardite (the most abundant varieties of serpentine in hydrothermal environments or low-grade metamorphism; Evans, 2004; Wicks and Whittaker, 1977). Moreover, peridotite hydration is accompanied by incorporation of a large amount of mobile trace elements (e.g. Bonatti et al., 1984; Decitre et al., 2002; Kodolányi et al., 2011; Vils et al., 2008) and the production of H_2, which are released into the hydrothermal fluids (Charlou et al., 2002; Evans et al., 2013; Frost, 1985).

The recent underwater observations of the seafloor attest to the diversity of hydrothermal systems in response to the heterogeneity in the oceanic lithosphere i.e. spreading rates, cracking intensity, fluid infiltration depth, and volcanic activity (Andreani et al., 2007; Boschi et al., 2006; McCaig et al., 2010; McCaig and Harris, 2012; Petersen et al., 2009). They reveal that (ultra)mafic rocks might be locally associated with carbonate deposits (Denny et al., 2016; Früh-Green et al., 2003). The presence of carbonated peridotite within serpentinite basement (Bach et al., 2011; Eickmann et al., 2009a, 2009b) or the development of a carbonate chimney (Früh-Green et al., 2003) in hydrothermal systems (e.g. Lost City or Logatchev hydrothermal field,) raised many questions on the link between serpentinization and carbonation reactions, and emphasized the complexity of hydrothermal systems at slow spreading ridges (Kelley et al., 2001; Schrenk et al., 2004). The hydrothermal cell development is intimately linked to dynamics of the oceanic lithosphere and magmatic activity and can either involve sediments, ultramafic rocks or tholeiitic intrusions (Bach et al., 2011; McCaig and Harris, 2012; Mottl, 1983). Carbonates in hydrothermal systems can be formed from different fluids, at ambient seawater temperatures to hydrothermal conditions. The complex fluid behavior in hydrothermal systems can lead to carbonate formation in peridotites either during heating of seawater, cooling of hydrothermal fluid or as a consequence of mixing of the hydrothermal fluid with seawater (Eickmann et al., 2009a, 2009b; Klein et al., 2015) as a response of the evolution of the hydrothermal loops in long lived hydrothermal systems (Bach et al., 2011; Schwarzenbach et al., 2013).

Such rocks were found in several locations within the Liguria-Piemonte relicts (Lemoine, 1980). Different interpretations for the origin of ophicalcites in the Ligura-Piemonte and in other ophiolites have been proposed: (1) the result of mechanical mixing of hydrothermal carbonates and reworked ultramafic rocks as a consequence of tecto-sedimentary activity during obduction and exhumation (Bernoulli and Weissert, 1985; Bortolotti and Passerini, 1970; Früh-Green et al., 1990; Gianelli and Principi, 1977; Lemoine, 1980), (2) carbonation of oceanic basement due to infiltration of seawater or fluids derived from pelagic sediments (Bernoulli, 1974; Clerc et al., 2014; Deményet al., 2007; Früh-Green et al., 1990; Schwarzenbach et al., 2013; Treves and Harper, 1994; Tucholke et al., 2013), (3) metasomatic reactions related to endogenic alkaline fluids circulation (Trommsdorff et al., 1980) or (4) the result of gas infiltrations related to underlying mantle activity (Bonatti et al., 1974; Haggerty, 1991). Nevertheless, the source of $CO_2$and CaO remains debated and they might have different origins, including marine carbonate dissolution, metamorphic or mantel origin, or a combination thereof.

Ophicalcites with various petrological and textural characteristics are found in the upper part of serpentinites in the Chenaillet ophiolite and were interpreted to result from a succession of carbonation events (Lemoine et al., 1987). A detailed petrologic, textural, and geochemical (including C- and O-isotopic measurements) study of ophicalcite breccias of the Chenaillet (W. Alps, France-Italy border) is presented here. The aim is to delineate the sequence of carbonation and determine the processes leading to the formation of the ophicalcites.

2. Geological setting, previous work, and sample localities

The legacy of the Jurassic opening of the Tethys is exposed as mafic-ultramafic units in the Western Alps, including the Chenaillet complex (Fig. 1a) (Bertrand et al., 1982; Caby, 1995; Li et al., 2013). The lithological succession (i.e. basalts, gabbros, and exhumed peridotites) is comparable to those found in the Liguria-Piemonte ophiolites of the Apennine (Barrett and Spooner, 1977; Lagabrielle and Cannat, 1990). The similarity of the lithological sequence observed in the Chenaillet complex with the one recorded at slow spreading Mid Ocean Ridges (MORs) established the Chenaillet unit as an analogue of present day OCCs (Chalot-Prat and Bourlier, 2005; Festa et al., 2015; Lagabrielle et al., 2015; Lagabrielle and Lemoine, 1997; Manatschal et al., 2011). Recent studies on the mantle composition throughout the Alpine Tethys units suggests that the Chenaillet ophiolite belongs to the most oceanward portion of the hyper-extended margin rather than to a true ocean (Picazo et al., 2016; Rampone et al., 1996).

Many of the ophiolitic units from the Alpine belt are affected by high-pressure metamorphism (10–15 Kbar) related to the subduction of the Tethys domain (Dal Piaz and Ernst, 1978; Tricart and Schwartz, 2006). However, the Chenaillet massif records only oceanic prehnite–pumpellyite to amphibolite facies conditions (Mevel et al., 1978), related to sea-floor exhumation. The apatite and zircon fission track analyses performed on plagio-granite reveal that the massif was cooled before 65 Ma (Schwartz et al., 2007) and has escaped the high pressure Alpine metamorphic overprint (Bertrand et al., 1987; Lagabrielle et al., 2015; Lewis and Smewing, 1980; Manatschal et al., 2011). The Chenaillet unit was obducted onto the proximal European margin during the Cretaceous convergence between Europe and Adria (e.g. Lagabrielle, 1987) and has been affected by anchi-facies metamorphism (Goffé et al., 2004). The zircon and apatite fission track ages of 118and 65 Ma respectively in the Chenaillet unit suggests that the two chronometers have escaped complete resetting(Agard et al., 2002). The unit consists of a thin thrust sheet (<1km) overlying the HP-LT units (*Schistes lustrés*) of the western Alps.

The Chenaillet massif consists of a continuous magmatic series with serpentinized peridotite, small bodies of gabbro with olivine (pseudomorphosed into chlorite), plagioclase (albitized) and accessory clinopyroxene (Chalot-Prat and Bourlier, 2005) crosscut by tholeiitic feeder dykes. The basalts have an *E*-MORB composition and overlie the exhumed mantle in an up to 400 m thick series (Bertrand et al., 1987). The lower part of the unit is mostly brecciated.

The cooling of the oceanic lithosphere is related to its exhumation during Jurassic hyper-extension. Oceanic metamorphism and tectonism results in flaser gabbros, metasomatism, and high-temperature, low pressure amphibolite paragenesis (Mevel et al., 1978). Magmatic rocks now sit on ultramafic basement (Lagabrielle and Lemoine, 1997) composed of massive serpentinites, derived mainly from a lherzolitic protolith (Bertrand et al., 1982; Caby, 1995; Chalot-Prat and Bourlier, 2005; Lafay et al., 2013). Dunitic and pyroxenitic domains are present locally, as well as mylonites formed at high-temperature (Manatschal et al., 2011). Serpentinites are mainly characterized by mesh and bastite textures, classical textures for serpentinization after olivine and pyroxene respectively.

The ophicalcites studied in this contribution consist of an almost continuous, up to 10 m thick layer of breccia (Fig. 1b and c), overlain by massive serpentinites. The contact between serpentinite and breccia is sometimes sharp and lenses of serpentinite interleaved with ophicalcite (Fig. 1c). The total outcrop surface of this unit does not exceed a few hundred square meters. Samples were collected from different zones (c) and (e) in Fig. 1a). The breccia is composed of slightly rounded, veined serpentinite clasts of variable size (up to a few tens of centimeters) embedded in a cement of grey carbonates (Fig. 1e and f). The matrix contains serpentine, locally forming micro-breccia, causing