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Talc–carbonate alteration of ultramafic rocks within the Leka Ophiolite Complex, Central Norway

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ABSTRACT

Petrographic and geochemical analyses of partly and completely serpentinized and carbonated peridotites within the ultramafic section of the Leka Ophiolite Complex have been used to elucidate the evolution of alterations and identify possible fluid sources. The alterations show no evidence for any major deformation and are located along low-angle structures that were formed in a late stage of the structural evolution of the ophiolite complex. Modeling of mineral equilibria in the SiO_2–MgO–FeO–Fe_2O_3–CaO–$H_2O \pm CO_2$ system has been utilized to constrain the conditions during serpentinization and carbonation.

The partly altered peridotites consist of the mineral assemblage olivine–clinopyroxene–serpentine–magnetite–brucite and formed at temperatures <410 °C by infiltration of aqueous fluids. Completely serpentinized rocks with the mineral assemblage serpentine–magnesite–magnetite–dolomite formed at temperatures <500 °C and low X_{CO2} ($\leq$0.05) by the breakdown of the minerals in the partly altered peridotites. Talc–carbonate rocks formed by the breakdown of the serpentine in the previously formed serpentinite rock at temperatures <550 °C and elevated X_{CO2}, which resulted in the stabilization of the assemblage talc–magnesite–magnetite–dolomite. Carbon isotope values determined for dolomite from crosscutting carbonate lenses within the talc–carbonate rock yield $\delta^{13}C$ values of ~−5 indicative of a mantle source for the carbon required for the carbonation. Oxygen isotope values $\delta^{18}_{SMOW}O$ of ~10.8–11.3‰ together with initial $^{87}Sr/^{86}Sr_{i\,=\,400Ma}$ values of 0.7029 and 0.7063, suggest dehydration of rocks with mantle affinity as a source for the fluids. Based on analytical results and field observations we propose that the formation of the talc- and carbonate-bearing alteration zones is caused by the focused infiltration of fluids that originated at the bottom of already partly serpentinized ophiolite complex during extension-driven burial at the late stage of the Caledonian orogeny.

1. Introduction

Serpentinization and carbonation of ultramafic rocks involve the replacement of anhydrous primary minerals such as olivine and pyroxene by water-bearing (e.g. serpentine, talc, brucite, etc.) and carbonate minerals during infiltration of H_2O–CO_2 fluids (O'Hanley, 1996). The process of serpentinization and carbonation of ultramafic rocks has been studied extensively in ophiolite complexes and ultramafic lenses at high temperatures (>200 °C) (Böhlke, 1989; Evans, 1977; Evans and Trommsdorff, 1974; Frost, 1985; Griffis, 1972; Hansen et al., 2005; Schandl and Naldrett, 1992), low temperatures (<50 °C) (Barnes et al., 1973; Kelemen and Matter, 2008; Mirnejad et al., 2008), and through experiments and modeling (Hövelmann et al., 2011; Klein and Garrido, 2011; Klein and McCollom, 2013; Paukert et al., 2012).

A large number of isotope studies on serpentinized and carbonated peridotites demonstrate that isotopic constraints provide a useful tool in interpreting the source of the fluids responsible for the alteration (Auclair et al., 1993; Beinlich et al., 2012; O'Hanley, 1996; Schandl and Naldrett, 1992; Schwarzenbach et al., 2013). The carbon source is commonly the most difficult to constrain, and has typically been assigned to dehydration reactions of carbonate-bearing sediments, seawater or magmatic degassing (O'Hanley, 1996). Oxygen isotope values determined from carbonated peridotites span a wide range of $\delta^{18}O \approx 4.5$ to 33‰ (Auclair et al., 1993; Böhlke, 1989; Kelemen et al., 2011; Mirnejad et al., 2008). Strontium concentrations and $^{87}Sr/^{86}Sr$ ratios in the mantle rocks can be readily changed during alteration and can be used to trace the source of the fluids (O'Hanley, 1996; Wickham et al., 1994).

This study describes the petrological and isotopic evolution of focused zones of completely serpentinized and carbonated peridotites located within the Leka Ophiolite Complex (LOC) in Nord-Trøndelag, Norway (Fig. 1) and complements a series of recent articles (Austrheim and Prestvik, 2008; Iyer et al., 2008; Økland et al., 2012; Plümper et al., 2012a,b) investigating alteration of the ultramafic rocks on Leka. The investigated rocks provide a fossil analogue to carbonation of ultramafic rocks in a hydrothermal system. Forward modeling of the observed mineral assemblages in the SiO_2–MgO–FeO–Fe_2O_3–CaO–H_2O–CO_2 system is used to constrain the temperature and composition of the infiltrating fluids. Field relationships combined with radiogenic and stable isotopic

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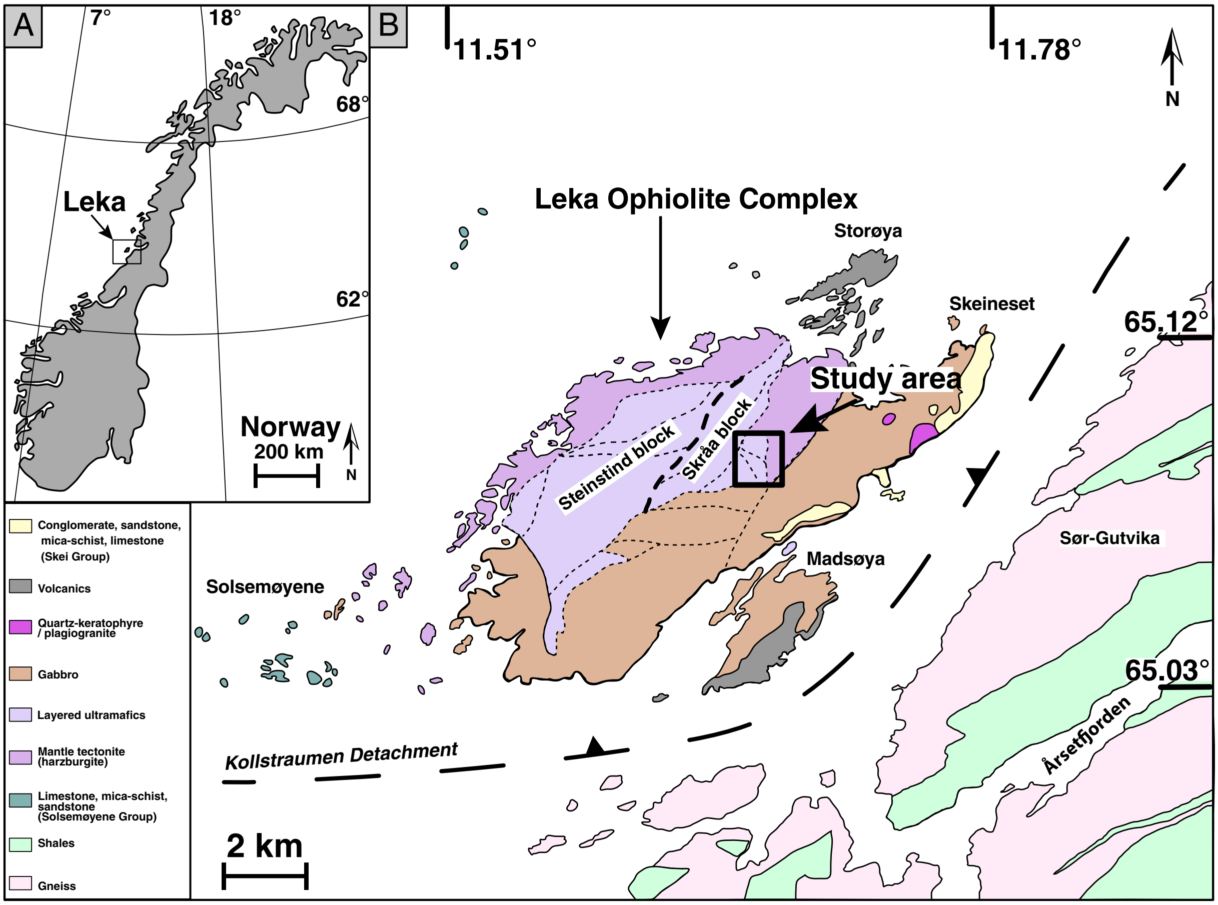

Fig. 1. A) Map of Norway with the location of the study area. B) Simplified geological map showing the regional geology and the Leka Ophiolite Complex (LOC) belonging to the Upper or Uppermost Allochthon of the Scandinavian Caledonides.

data are used to constrain the succession of the alteration and to elucidate the possible fluid sources.

2. Geological setting

The Leka Ophiolite Complex (LOC) is situated on the island of Leka (~90 km^2) in Nord-Trøndelag, central Norway (Fig. 1) and belongs to the Upper or Uppermost Allochthon of the Scandinavian Caledonides (Furnes et al., 1988; Prestvik, 1972). U–Pb zircon dating of a trondhjemite from the upper plutonic zone of the LOC yielded a crystallization age of 497 ± 2 Ma, suggesting its origin in the late Cambrian (Dunning and Pedersen, 1988). Geochemistry of the volcanic rocks on Leka together with the inferred crystallization sequence from the mantle cumulates suggest that the complex formed in a supra-subduction zone environment (Furnes et al., 1988). The ophiolite is now situated in a pull-apart setting which formed in a late orogenic stage during the Devonian extension in the Scandinavian Caledonides (Titus et al., 2002). The adjacent rock complex mostly consists of lower amphibolite-grade basement gneisses of the Northern Vestranden region, and the contact with the LOC is not exposed (Furnes et al., 1988).

In the LOC all the principal components of a typical ophiolite can be observed. This includes a lower, strongly deformed harzburgite unit (representing the depleted upper mantle), ultramafic cumulates, layered metagabbros, metabasalt dykes and pillow lavas (Fig. 1; Furnes et al., 1988; Prestvik, 1980). During or after the Caledonian obduction, the mafic and ultramafic rocks were folded into two open synclines with several tight folds formed within the ultramafic units indicating moderate-scale ductile deformation (Dunning and Pedersen, 1988; Titus et al., 2002). Later brittle deformation has led to the formation of faults on different scales. Two distinct fault sets can be observed: NE–SW trending larger/longer faults and a NW–SE trending set with smaller/shorter faults (Titus et al., 2002).

The rocks show weak pervasive metamorphism during the Caledonian orogenesis at the greenschist facies, with some evidence of relic amphibolite facies minerals in the gabbroic rocks and in the mantle tectonite, but the precise pressure estimates are lacking (Bucher, 1991; Furnes et al., 1988; Prestvik, 1972, 1980). Regional studies suggest that the LOC is a part of the Helgeland Nappe Complex belonging to the Uppermost Allochthon, which is inferred to be the highest stratigraphic unit in the Scandinavian Caledonides (Bucher, 1991; McArthur et al., 2013; Titus et al., 2002). Bucher (1991) suggested that the antigorite overprint observed in the ultramafic rocks on Leka is a consequence of the Caledonian metamorphism, which produced a regional metamorphic pattern in the ultramafic rocks in the central Norwegian Caledonides. According to this interpretation, the metamorphic grade increases from Leka in the southeast, to the Svartisen nappe complex in the northwest with estimated pressures of ~5 kbar for the rocks along the Helgeland coast, and pressures of ~1 to 3 kbar for the LOC.

3. Alteration zones

A distinct set of sub-horizontal, NW–SE trending faults occurs within the partly altered ultramafic rocks along which there is a macroscopically visible replacement of the original mineralogy (Fig. 2). The alteration zones are represented by rocks in which the mineral assemblage of the partly altered peridotites (olivine, clinopyroxene, serpentine, brucite and spinel-group minerals) has been altered to serpentine, carbonate and talc. The vertical thickness of the alteration zones is commonly in