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Mineralogical and chemical mass changes in mafic and ultramafic rocks from the Logatchev hydrothermal field (MAR 15°N)

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ABSTRACT

Mineralogical and geochemical investigation of altered host rock samples from the Logatchev hydrothermal field reveal a large variety of alteration styles at this site. Serpentinization is most intense in former harzburgites and dunites varying between 90–95%, whereas gabbros are mostly rather fresh. A combination of serpentinization, interaction with hot hydrothermal fluids, melt/rock interaction, and low-temperature seafloor weathering lead to significant gains and losses of major and trace elements. Serpentinization within the Logatchev hydrothermal field proceeds mainly isochemical for the major elements, except for a loss of TiO_2 and CaO. However, the concentration of the trace elements Cu, Nb, Ba, La, Sm, Eu, Th or U increases significantly in the serpentinites. Gabbroic intrusions act as a sink for MgO during alteration due to the formation of chlorite and serpentine after clinopyroxene. Interaction between gabbros and hydrothermal fluids leads to significant redistribution of SiO_2, TiO_2, CaO, and Na_2O as well as numerous trace elements. The different styles of alteration and their associated element changes reveal that samples from the entire Logatchev field have been influenced by hydrothermal fluids to some degree. Therefore, the hydrothermal fluid-dominated alteration of the ultramafic oceanic crust is a sink for many trace elements which were provided by mafic intrusions and mobilized by hydrothermal fluids and melt-rock interaction, whereas the gabbros accumulate high amounts of Mg from the seawater. Summarized the alteration processes at Logatchev are a combination of serpentinization, melt/rock interaction of serpentinites and mafic intrusions, and low-temperature seafloor weathering.

1. Introduction

Abyssal peridotites representing sections of the upper mantle can be exposed at the seafloor by faulting associated with extension and crustal thinning on slow and ultraslow spreading ridges. The exposed peridotites are usually intimately associated with gabbroic intrusions (Cannat, 1996; Escartin et al., 1997; Escartin and Cannat, 1999). Although the total length of ridge axis along which peridotites are exposed is unknown, Dick et al. (2003) estimated that about one third of the 55,000 km global ridge system comprises ultraslow ridges (spreading rate <20 mm/a) and that these will largely be floored by peridotites. Direct estimates for the MARK area (Mid-Atlantic Ridge (MAR), 23°N, spreading rate 23 mm/a) suggest 23% of the seafloor there comprises mantle rock (Cannat et al., 1995). These upper mantle lithologies will therefore be an integral part of hydrothermal interaction processes at divergent plate boundaries.

Once emplaced, the peridotites will be subject to a variety of processes which modify their composition, including melt/rock interaction associated with the intrusion of gabbro, hydrothermal circulation and seafloor weathering, all of which will substantially modify the primary rock compositions in characteristic ways. Deciphering the relative importance of these processes would allow us to estimate their individual influence on the final composition of the ultramafic oceanic crust.

The hydrothermal systems associated with peridotitic ridge areas have been shown to have unique chemistry, emitting particularly CH_4 and H_2-rich plumes into the hydrosphere (Bougault et al., 1993; Charlou et al., 1998). Examples of active sulfide-forming hydrothermal sites situated on ultramafic mantle rocks at the MAR include the Rainbow field (German et al., 1996; Douville et al., 2002), Logatchev field (Mozgova et al., 1999; Cherkashev et al., 2000), Ashadze field (Beltenev et al., 2003) and the newly-discovered Nibelungen field (Melchert et al., 2008).

Infiltration of circulating seawater into peridotite initiates substantial geochemical and mineralogical changes due to reactions transforming olivine and pyroxene into serpentine minerals and other phyllosilicates. The energy budget, fluid compositions and composition of hydrothermal precipitates at these systems are inferred to be closely related to serpentinization/alteration processes in the peridotites and gabbros. Additionally, many recent studies have described

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the effects of different alteration styles for diverse geological settings: Melt/rock interaction mobilize elements with high field strength (HFSE) and light rare-earth elements (LREE) in about equal proportions (Niu, 2004; Paulick et al., 2006). Alteration under high fluid/rock ratios at low, as well as high temperatures influence significantly the budgets of major and trace elements, as well as the formation of secondary minerals in different manners (Hart et al., 1974; Macdougall et al., 1979; Verma, 1992; Jochum and Verma, 1996; Talbi et al., 1999; Lackschewitz et al., 2000a; Bach et al., 2003).

The Logatchev hydrothermal field at the Mid-Atlantic Ridge (14°45′N) is one of the most prominent active ultramafic-hosted hydrothermal sites. Studies of serpentinites and gabbroic rocks from this area have shown that serpentinization, hydrothermal activity, as well as the interaction of ultramafic host-rocks with mafic intrusions are all major processes affecting crustal and fluid compositions (Bach et al., 2004; Paulick et al., 2006). In the following, we will show evidence for significant and characteristic changes in the bulk rock and mineral composition associated with various stages of alteration. The overall goal of this study is to characterize, based on alteration mineralogy and geochemistry , the sub-seafloor alteration processes in an active ultramafic-hosted, high-temperature hydrothermal system and to provide new insights into the interaction between hydrothermal fluids, melts and the various amounts of peridotite and gabbroic rocks in the sub-seafloor. Key questions include: What kinds of processes influence the physico-chemical composition of the hydrothermal fluids? What is the chemical exchange, e.g. the elemental gains and losses, during serpentinization/alteration in an ultramafic-hosted hydrothermal system?

Answers to these questions will, in turn, provide important constraints on the budget of exchange processes between the lithosphere and the hydrosphere in slow- and ultraslow-spreading environments.

2. Regional setting

The Logatchev hydrothermal Field was first discovered in 1993 by Russian scientists (Batuyev et al., 1994; Cherkashev et al., 2000) and is part of an ultramafic-hosted hydrothermal system comprising three fields (Logatchev 1–3) situated around 14°45′N, 44°59′W (Fouquet et al., 2007).

The Logatchev-1 hydrothermal field (LHF-1) is located on a plateau directly below a 350 m high cliff at water depths of 3060 m to 2900 m. It extends at least 800 m in a NW–SE and 400 m in a SW–NE direction (Fig. 1A).

Two main areas of high-temperature (high-T) hydrothermal activity make up the central part of the field: (i) an area of four “smoking craters” and one chimney structure (Candelabra, Anna-Louise, Irina I, Site "A" and Site “B”) and (ii) the large mound of Irina II with black smoker chimneys at its top as well as the Quest smoking crater (Fig. 1B). Site “F” (Kuhn et al., submitted for publication) is a low-temperature diffuse venting site recently discovered in the same area. Schmidt et al. (2007) have reported physico chemical properties of the hydrothermal fluids that are characterized by temperatures of up to 350 °C and very high concentrations of dissolved methane and hydrogen (up to 3.5 mM and 19 mM, respectively) which they attributed to the influence of serpentinization processes.

Extensive bathymetric and video mapping has revealed three factors which appear to control the location of the Logatchev hydrothermal field: (1) cross-cutting faults, (2) young basaltic volcanism, and (3) slump structures (Kuhn et al., submitted for publication; Kuhn et al., 2004b). The talus comprising the slump structures was probably generated during major tectonic events related to uplift of the rift valley walls. Hydrothermal circulation has taken place throughout this talus material, altered the rock debris and formed a hydrothermal deposit on top of the debris flow.

Host rocks of the LHF-1 are both serpentinized peridotites and gabbronorites with the former dominating. Remarkable are samples of coarse-grained websterites, orthopyroxenites and Opx-rich, pegmatoidal norites, which were interpreted as magmatic cumulates from the crust/mantle transition zone (Kuhn et al., 2004b).

The harzburgites and dunites are extensively serpentinized (>90–95%) with only the harzburgites occasionally showing relicts of pyroxene or more rarely olivine (Fig. 2A). The gabbroic rocks are much fresher, generally being only moderately altered (10–20%) by chloritization and/or serpentinization.

3. Methods

During this study, we analyzed 31 seafloor samples from the active Logatchev hydrothermal field, all taken by TV-guided grab. The rock samples were gently disaggregated in an agate mortar before separating the fine fraction. After drying, the samples were divided into fine (<63 μm) and coarse fractions (>63 μm) by wet sieving. Grain size separation into silt (2–63 μm) and clay fraction (<2 μm) was performed according to Stokes' law by settling the particles in water filled cylinders (Atterberg, 1912; Moore and Reynolds, 1989).

The bulk rock and clay-fraction mineralogy was determined by X-ray diffractometry (XRD) at IFM-Geomar, Kiel and the Institute for Geosciences, University of Kiel, Germany, using a Philips X-ray diffractometer PW 1710 with automatic divergence slit and monochromatic CoKα or CuKα radiation. Bulk rock samples were powdered and pressed to tablets for measurements. Oriented clay samples were produced by vacuum filtration onto a 0.15-μm filter. Measurements on the clay samples were carried out on both air-dried and glycol-saturated samples. Processing of the raw data was performed using the freeware MacDiff (Petschick, 2001).

Major element concentrations of the 29 bulk rock samples (17 serpentinites, 12 gabbroic rocks) were determined by X-ray fluorescence spectrometry (XRF) at the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover where two X-ray spectrometers run in WDS-mode. The precision of the method is about 0.01 wt.%. More than 50 certified reference materials (CRM) are used for the calibration of the X-ray spectrometers. Data are automatically internally corrected for spectral overlaps as well as for matrix effects using the de Jongh method (alpha values).

The major element concentration of single minerals was determined by microprobe on three serpentinites and one moderately altered gabbro as representatives of the main lithologies present at Logatchev. The microprobe analyzes were carried out with a JXA8900 R electron probe microanalyzer at the Institute for Geosciences, University of Kiel.

The concentrations of trace elements were determined on 14 serpentinites and 3 gabbros by ICP-MS using a VG Plasma-Quad PQ1 at the Institute of Geosciences of the University of Kiel and a Finnigan MAT Element 2 double-focusing, single collector ICP-MS at the Department of Geosciences of the University of Bremen, Germany. All samples were dissolved by performing a pressurized HF–HCl–HNO_3-aqua regia attack (Garbe-Schönberg, 1993). The accuracy of the analyses was monitored using international rock standards AGV-1 (andesite), BHVO-1, BHVO-2 and BIR-1 (basalts), JR-1 (rhyolite) and UB-N (serpentinite) (Govindaraju, 1994; Wilson, 1997; Jochum et al., 2005). Our values are generally within <5% of the recommended values for most elements. The precision of duplicates as well as repeated analyses is better than 5% for most elements.

4. Results

4.1. Petrology and mineralogy

An overview of the mineral assemblages found in samples from the Logatchev hydrothermal field is given in Table 1.

X-ray diffraction studies show that lizardite is the dominant serpentine mineral, (Fig. 2A,B) often found together with magnetite. Lizardite is characterized by distinct reflections at 7.33 Å, 4.6 Å, and 3.6 Å, 2.50 Å, 2.15 Å, 1.79 Å (Fig. 3A). In contrast to lizardite, chrysotile exhibits