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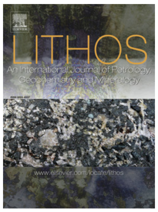

Ultramafic clasts from the South Chamorro serpentine mud volcano reveal a polyphase serpentinization history of the Mariana forearc mantle

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ABSTRACT

Serpentine seamounts located on the outer half of the pervasively fractured Mariana forearc provide an excellent window into the forearc devolatilization processes, which can strongly influence the cycling of volatiles and trace elements in subduction zones. Serpentinized ultramafic clasts recovered from an active mud volcano in the Mariana forearc reveal microstructures, mineral assemblages and compositions that are indicative of a complex polyphase alteration history. Petrologic phase relations and oxygen isotopes suggest that ultramafic clasts were serpentinized at temperatures below 200 °C. Several successive serpentinization events represented by different vein generations with distinct trace element contents can be recognized. Measured in situ Rb/Cs ratios are fairly uniform ranging between 1 and 10, which is consistent with Cs mobilization from sediments at lower temperatures and lends further credence to the low-temperature conditions proposed in models of the thermal structure in forearc settings. Late veins show lower fluid mobile element (FME) concentrations than early veins, suggesting a decreasing influence of fluid discharge from the subducting slab on the composition of the serpentinizing fluids. The continuous microfabric and mineral chemical evolution observed in the ultramafic clasts may have implications as to the origin and nature of the serpentinizing fluids. We hypothesize that opal and smectite dehydration produce quartz-saturated fluids with high FME contents and Rb/Cs between 1 and 4 that cause the early pervasive serpentinization. The partially serpentinized material may then be eroded from the basal plane of the suprasubduction mantle wedge. Serpentinization continued but the interacting fluids did not carry a pronounced sedimentary signature, either because FMEs were no longer released from the slab, or due to an en route loss of FMEs. Late chrysotile veins that document the increased access of fluids in a now fluid-dominated regime are characterized by reduced trace element contents with a slightly increased Rb/Cs ratio near 10. This lack of sediment-dominated geochemical signatures consistently displayed in all late serpentinization stages may indicate that the sediment-derived fluids have been completely reset (i.e. the FME excesses were removed) by continued water–rock reaction within the subduction channel. The final stage of buoyant rise of matrix and clasts in the conduits is characterized by brucite-dominated alteration of the clasts from the clast rim inward (independent of the intra-clast fabric relations), which corresponds to re-equilibration with alkaline, low-silica activity fluids in the rising mud.

1. Introduction

Subduction zones are sites of intense mass transfer between the subducting plate and the Earth's mantle. The incoming slab of oceanic lithosphere (sediments, as well as variably (altered and) hydrated mafic and ultramafic rocks) releases a generally high but variable fluid flux (Bebout, 2007). As a consequence of rheological contrasts between the juxtaposed rock-types, shearing and metasomatism evolve a complex mélange zone atop the slab (i.e., the subduction channel) where rocks and fluids are extensively modified (Cloos and Shreve, 1988a,b). The inventory of slab lithologies and the thermal structure determine where fluids leave the slab and where they enter the subduction channel (Deschamps et al., 2013; Reynard, 2013; Schmidt and Poli, 1998; Spandler and Pirard, 2013). In particular, the flux of fluids is affected by the local setting, e.g., the geotherm of the subduction zone, the slab dipping angle and the presence, or absence, of an accretionary sedimentary wedge, and the nature of the slab itself (e.g. slow versus fast spread oceanic lithosphere). During subduction, the downgoing

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slab progressively releases fluid (Hyndman and Peacock, 2003): at shallow depths by porosity compaction and dehydration reactions of sediments, at intermediate depths by dehydration of sediments and altered oceanic crust, and, at greater depths, by continued dehydration of oceanic crust and deserpentinization of the subducting lithospheric mantle (Rüpke et al., 2002, 2004; Schmidt and Poli, 1998). The geochemical signature of the fluids' source lithologies is recorded by fluids and rocks affected by subduction zone processes: forearc springs, metasomatized melange material, serpentinized mantle wedge peridotites, and arc volcanism inherit the distinctive trace element contents of the reacting fluids (Fryer et al., 1999; Hattori and Guillot, 2003, 2007; Hulme et al., 2010; Mottl et al., 2003, 2004; Pabst et al., 2012; Parkinson and Pearce, 1998; Savov et al., 2005a).

Mud volcanoes are a characteristic feature of the forearc of the Mariana subduction zone system (Fryer et al., 1985, 1999, 2000). Located along the outer half of the deeply fractured Mariana forearc, diapiric mud volcanism has formed large edifices from extrusion of blueschist and serpentine mud, up to 50 km in diameter and up to 2 km high (Fryer et al., 1990, 1999; Oakley et al., 2007). Systematic studies of pore waters and vent fluid compositions suggest that the fluids fueling the serpentine mud volcanoes are released from breakdown of hydrous phases in the subducting slab. Most noticeably, these fluids have lower chloride, Mg, Ca, Sr, Li, and Si concentrations, and higher pH, alkalinity, K, Na, Rb, Cs and Ba contents than seawater, indicating slab dehydration and water–rock interactions in the conduits feeding the mud volcanoes (Benton et al., 2001; Hulme et al., 2010; Mottl, 1992; Mottl et al., 2003, 2004; Wheat et al., 2008). The mud volcanoes' sample rock material and fluids from the slab–mantle interface at the base of the conduits (estimations of slab depths below South Chamorro and Conical seamount vary between 20 and 27 km; see e.g. Mottl et al., 2003, and the following section). In principle, the erupted material can either originate from a shallower depth and has been dragged down to the base of the conduits, or contain fluids and melange material from deeper parts of the slab–mantle interface below the base of the feeding conduits, that migrated upward in the subduction channel (e.g., Bebout, 2007). However, geothermobarometry studies of metabasite schists from South Chamorro seamount (Fryer et al., 2006; 250–300 °C at ~0.4–0.5 GPa, corresponding to a depth of ~12–15 km) and Conical seamount (Maekawa et al., 1993; ~175–250 °C and 0.5–0.65 GPa, ~15–19.5 km) indicate that the clasts originate from depths slightly above the base of the feeding conduits. The erupted clast and mud materials hence record changes in the composition of the slab-sourced fluids, progressively released and accumulated in shallow and intermediate depths during subduction.

Trace element bulk rock compositions of serpentinized ultramafic clasts and serpentine mud have been used to gain deeper insights into the composition of the serpentinized forearc mantle (Savov et al., 2007), and to deduce potential parent rocks of the serpentinizing fluids (e.g., Hulme et al., 2010; Pabst et al., 2012). At South Chamorro seamount, Ocean Drilling Program Leg 195 drilled Site 1200, where ultramafic clasts occur within a matrix of serpentine mud (D'Antonio and Kristensen, 2004; Fryer and Salisbury, 2006). These clasts record a complex serpentinization history and provide an excellent window into the prevailing fluid–rock interactions at, and above, the interface between the mantle wedge and the subducting lithosphere. Moreover, the microfabrics of the highly serpentinized harzburgite and dunite clasts exhibit evidence for multiple, successive serpentinization events in the forearc mantle (Salisbury et al., 2002).

Here, we present a detailed investigation of serpentinization microfabrics and in situ major and trace element contents of the individual, successive serpentine generations and the primary mantle minerals. As many of these clasts have preserved domains representing early-stage serpentinization, we can reconstruct much of the history of fluid–rock reaction in the Mariana forearc and identify potential sources of the serpentinizing fluids.

2. Setting and samples

2.1. South Chamorro seamount

South Chamorro seamount (Fig. 1A) is one out of two dozen active mud volcanoes of the Mariana forearc, located 85 km west the trench where the Mesozoic Pacific Plate is being subducted west–northwestward beneath the West Philippine Plate (Fryer et al., 1990; Fig. 1B). Estimates of the slab depth beneath Site 1200 range between 26 km (Fryer, 1996; Fryer et al., 1999; Hulme et al., 2010) and 20 km (Fryer and Salisbury, 2006; Oakley et al., 2007). The seamount is composed of unconsolidated flows of serpentine and blueschist mud with clasts of serpentinized mantle peridotite and minor blueschist fragments; the clasts represent lithologies from both the subducting plate and the suprasubduction-zone mantle (Fryer, 1996; Fryer and Fryer, 1987; Fryer et al., 2006; Salisbury et al., 2002).

The serpentine mud volcano was drilled in the year of 2000 at Site 1200 of the Ocean Drilling Program (ODP) during Leg 195. Site 1200 is located on a knoll at the summit of South Chamorro seamount in a water depth of 2930 m (Salisbury et al., 2002). Hole A was drilled to a depth of 147.2 meters below seafloor (mbsf) and recovered mainly serpentinized ultramafic clasts and minor amounts of the mud matrix. The mudflow matrix consists of c. 90% serpentine, as clay- to silt-sized lizardite, chrysotile and minor antigorite; accessory minerals of the mudflow matrix include brucite, talc, mixed-layer smectite/illite clays, chlorite, relict grains of primary silicates and Cr–spinel, amphibole and garnet; the sizes of clasts recovered from Site 1200 vary from a few mm to >1 m in diameter (Salisbury et al., 2002). In Hole 1200A, the peridotite clasts are predominantly harzburgites and minor dunites; serpentinization is extensive and ranges between ~40% and 100% with an average alteration of 95% for harzburgites and 75% for dunites (D'Antonio and Kristensen, 2004).

In this study, nine samples from the marginal parts of highly serpentinized clasts of harzburgite and dunite were selected for detailed petrographic and microanalytical geochemical investigations (Table 1). A second set of adjacent samples from the clasts' centers was chosen for thin section microscopy to identify the mineralogical and textural differences between clasts' rims and cores (Table 1).

3. Analytical methods

3.1. Electron microprobe

Major element analyses of mineral compositions were performed with a JEOL JXA-8900 electron microprobe at the University of Kiel (Germany). For most silicate minerals an accelerating voltage of 15 kV was used, with exception of garnet, spinel and iron oxides (20 kV). Measurement spot sizes were typically 1–5 μm in diameter. Standards were either natural minerals or synthetic materials. The CITZAF method of Armstrong (1995) was used for correction of the raw counts. Microscale element mappings and backscattered electron (BSE) images of rock microfabrics were used to complement microscopic observations.

3.2. Laser ablation ICP-MS

Analyses of major and trace element concentrations were carried out on thin sections by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) using a Thermo Element2 coupled to a NewWave UP193ss (wavelength 193 nm) at the Department of Geosciences of Bremen University. Helium (0.8 l/min) was used as carrier gas and argon (0.8–0.9 l/min) was added as make-up gas; plasma power was 1200 W. Samples and standards were ablated with an irradiance of ~1 GW/cm^2, and a pulse rate of 5 Hz. The laser beam diameter was typically between 25 and 100 μm. Prior to ablation the