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Influences of the Tonga Subduction Zone on seafloor massive sulfide deposits along the Eastern Lau Spreading Center and Valu Fa Ridge

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Abstract

This study investigates the morphology, mineralogy, and geochemistry of seafloor massive sulfide (SMS) deposits from six back-arc hydrothermal vent fields along the Eastern Lau Spreading Center (ELSC) and Valu Fa Ridge (VFR) in the context of endmember vent fluid chemistry and proximity to the Tonga Subduction Zone. To complement deposit geochemistry, vent fluid analyses of Cu, Zn, Ba, Pb and $H_{2,(aq)}$ were completed to supplement existing data and enable thermodynamic calculations of mineral saturation states at *in situ* conditions. Results document southward increases in the abundance of mantle-incompatible elements in hydrothermal fluids (Ba and Pb) and SMS deposits (Ba, Pb, As, and Sb), which is also expressed in the abundance of barite ($BaSO_4$) and galena (PbS) in SMS deposits. These increases correspond to a decrease in distance between the ELSC/VFR and the Tonga Subduction Zone that correlates with a change in crustal lithology from back-arc basin basalt in the north to mixed andesite, rhyolite, and dacite in the south. Barite influences deposit morphology, contributing to the formation of horizontal flanges and squat terraces. Results are also consistent with a regional-scale lowering of hydrothermal reaction zone temperatures from north to south (except at the southernmost Mariner vent field) that leads to lower-temperature, higher-pH vent fluids relative to mid-ocean ridges of similar spreading rates (Mottl et al., 2011). These fluids are Cu- and Zn-poor and the deposits formed from these fluids are Cu-poor but Zn-rich. In contrast, at the Mariner vent field, higher-temperature and lower pH vent fluids are hypothesized to result from higher reaction zone temperatures and the localized addition of acidic magmatic volatiles (Mottl et al., 2011). The Mariner fluids are Cu- and Zn-rich and vent from SMS deposits that are rich in Cu but poor in Zn with moderate amounts of Pb. Thermodynamic calculations indicate that the contrasting metal contents of vent fluids and SMS deposits can be accounted for by vent fluid pH. Wurtzite/sphalerite ((Zn, Fe)S) and galena (PbS) are saturated at higher temperatures in higher-pH, Zn-, Cu-, and Pb-poor ELSC/VFR vent fluids, but are undersaturated at similar temperatures in low-pH, Zn-, Cu-, and Pb-rich vent fluids from the Mariner vent field.

Indicators of pH in the ELSC and VFR SMS deposits include the presence of co-precipitated wurtzite and chalcopyrite along conduit linings in deposits formed from higher pH fluids, and different correlations between concentrations of Zn and Ag in bulk geochemical analyses. Significant positive bulk geochemical Zn:Ag correlations occur for deposits at vent fields where hydrothermal fluids have a minimum pH (at 25 °C) < 3.3, while correlations of Zn:Ag are weak or negative for deposits at vent fields where the minimum vent fluid pH (at 25 °C) > 3.6. Data show that the compositions of the mineral

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linings of open conduit chimneys (minerals present, mol% FeS in (Zn,Fe)S) that precipitate directly from hydrothermal fluids closely reflect the temperature and sulfur fugacity of sampled hydrothermal fluids. These mineral lining compositions thus can be used as indicators of hydrothermal fluid temperature and composition (pH, metal content, sulfur fugacity).

Keywords: Hydrothermal vent; Black smoker; Mineral deposit; Sulfur fugacity; pH

1. INTRODUCTION

Seafloor massive sulfide (SMS) deposits form as acidic, metal- and sulfide-rich hydrothermal fluids discharge into cold, alkaline, sulfate- and oxygen-rich seawater. Such hydrothermal fluids are a product of rock-dominated hydrothermal reactions that occur along mid-ocean- and back-arc spreading centers when seawater that has percolated into the earth's lithosphere is heated by hot rock or magma sourced from the earth's mantle. The composition of these hydrothermal fluids is controlled by the nature of the chemical reactants (e.g. crustal host rocks and evolved seawater ± magmatic volatile fluids), the relative proportions of these reactants, and reaction zone conditions (e.g., temperature, pressure, extent of equilibration) (Von Damm, 1995). Similarly, the mineral contents, elemental compositions, and mineral textures of seafloor massive deposits reflect both the composition of venting hydrothermal fluids and the specifics of interactions between hydrothermal fluids, surrounding seawater, geologic structures, and existing mineral deposits.

The presence of actively venting massive sulfide deposits on the seafloor provides an opportunity to directly sample hydrothermal fluids as well as mineral deposits that either precipitated directly from venting hydrothermal fluids (e.g., the mineral linings of black smoker chimneys) or from mixtures of hydrothermal fluids and seawater. Such samples provide insight into SMS deposit formation. Previous sampling along back-arc spreading centers has revealed a diversity of hydrothermal fluid chemistry and SMS deposit types that can be related to variations in seafloor lithology and the influences of subduction-zone geologic processes (e.g., Hannington et al., 2005 and references therein; Ishibashi et al., 2006; Takai et al., 2008; Reeves et al., 2011; Mottl et al., 2011; SRK Consulting, 2012). Moreover, SMS deposit formation processes are thought to be closely analogous to those of volcanic-associated massive sulfide deposits, an important class of base-metal ore deposit (Hannington et al., 1995; 2005). In this context, the study of active SMS deposits along back-arc spreading centers is especially important as more than 80% of volcanic-associated massive sulfide deposits are thought to have formed in similar geologic settings (Barrie and Hannington, 1999; Franklin et al., 2005; Hannington et al., 2005).

The Eastern Lau Spreading Center (ELSC) and Valu Fa Ridge (VFR) in the Lau back-arc Basin of the southwestern Pacific Ocean (Fig. 1) are ideal settings in which to study the effects of subduction-zone geologic processes on actively forming SMS deposits. From north to south, a near-linear decrease in distance between the ELSC/VFR and the adjacent Tofua Volcanic Arc is accompanied by systematic variations in spreading center morphology, spreading rate, and seafloor lithology (Taylor and Martinez, 2003; Martinez et al., 2006; Ferrini et al., 2008; Bézos et al., 2009; Escrig et al., 2009; Sleeper and Martinez, 2014). In turn, these variations have been linked to differences in hydrothermal fluid chemistry (Fouquet et al., 1993a; Ishibashi et al., 2006; Takai et al., 2008; Mottl et al., 2011), SMS deposits (Fouquet et al., 1993a; Tivey et al., 2005; Ferrini et al., 2008; Takai et al., 2008), and biological communities (Podowski et al., 2009; Beinart et al., 2012; Flores et al., 2012). Analyses by Mottl et al. (2011) of ELSC and VFR hydrothermal fluids document systematic regional-scale trends in vent fluid chemistry related to a southward decrease from 20°S to 22°S in the temperature of hydrothermal reaction zones and a transition to more felsic lithology with a subducted sediment component closer to the subduction zone. The distinct chemistry of vent fluids from the Mariner vent field at 22°10′S, which includes low fluid pH and high dissolved gas contents, is an exception and consistent with a higher reaction zone temperature and the addition of acidic magmatic volatiles (Mottl et al., 2011).

This report provides a systematic overview of the morphology, mineralogy, and geochemistry of SMS deposits from six active hydrothermal vent fields along the ELSC and VFR. From north to south, these vent fields are: Kilo Moana, TowCam, Tahi Moana-1, ABE, Tu'i Malila, and Mariner (Fig. 1). This report also presents data on the concentrations of dissolved metals (Cu, Zn, Pb, Ba) and H_2 in hydrothermal fluids collected from these vent fields (Table 1) that supplement previously published data from Mottl et al. (2011), allowing comparison of vent fluid chemistry with corresponding SMS deposits. Vent fluids and open conduit chimney linings collected as paired samples are investigated by modelling fluid speciation and mineral saturation at *in situ* conditions. Overall, comparisons of ELSC/VFR SMS deposit composition and morphology with hydrothermal vent fluid compositions, placed in the regional geologic context of the Tonga Subduction Zone, provide greater insight into SMS deposit formation processes.

2. GEOLOGIC SETTING

The ELSC and VFR are active back-arc spreading centers located at the southern end of the Lau Basin west of the islands of Tonga (Fig. 1A). From a regional perspective, the Lau Basin is the northern section of a 2000 km-long southward-propagating extensional tectonic region, within which the ELSC and VFR span a transition from arc rifting in the south to ocean spreading in the north (Fig. 1A; Parson and Wright, 1996). To the south, this extensional