

## Mineralogical and Geochemical Aspects of the Rainbow Hydrothermal Field on Mid-Atlantic Ridge at 36°14'N and 33°53'W

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The Rainbow hydrothermal field was discovered by the submersible Nautila during the FLORES cruise in 1997 at 36°14'N and 33°53'W on the Mid-Atlantic Ridge. Since then, much attention has been paid to this hydrothermal field, because it is characteristically hosted in serpentinized ultramafic rocks through which hydrothermal activity has been taken place. In 1998, the Rainbow hydrothermal field and its surrounding area were mapped and sampled during the RV Yokosuka and DSV Shinkai 6500 diving program as a part of MODE'98 MEGATRIN cruise. From mineralogical and geochemical viewpoints, we have investigated various massive sulfide samples collected from the hydrothermal field, including active chimney, inactive chimneys, collapsed inactive chimney and sulfide blocks.

Anhydrite, observed exclusively in an active chimney, is precipitated initially by mixing of high temperature hydrothermal fluids with ambient cold seawater. Corrected filling temperatures and salinities of fluid inclusions trapped in anhydrite fall in the range of 267 to 364°C with a mean of 317°C and 4.0 to 6.7 eq.wt.%NaCl, respectively. Once the anhydrite chimney wall grows to an appropriate thickness and hydrothermal fluids are protected from further mixing with seawater, then Cu-Fe-S minerals begin to precipitate within the inside of the chimney. The intermediate and central zones of the active chimney are composed mainly of isocubanite and chalcopyrite, respectively, suggesting an increase of Cu/Fe ratios in the fluids with increasing temperatures with time. Bornite occurs as fine-scale veins or aggregates along the margin of isocubanite and chalcopyrite, suggesting that after precipitation of these sulfides the residual fluids have changed toward lower  $f_{O_2}$  with decreasing temperatures. Minor amounts of euhedral pyrite (or marcasite) and anhedral sphalerite (4.91 to 6.56 mole%FeS) occur in anhydrite-rich portion. Mineralogical zonation in the active chimney reflects a change in thermal and chemical conditions within the chimney.

A clear mineralogical zonation is also observed in the inactive chimneys. Pyrrhotite occurs mainly in the central zone, whereas isocubanite and anhedral sphalerite (14.21 to 34.11 mole%FeS) are localized in the intermediate zone with the outer zone composed mainly of dendritic and colloform sphalerite (1.38 to 11.48 mole%FeS), outward-growing dendritic pyrite and secondary Fe-hydroxide. The absence of anhydrite in the inactive chimneys is explained by dissolution below 180°C in the outer zone or by non-precipitation in the central and intermediate zones, respectively. As indicated by the occurrence of pyrrhotite and its compositions, as well as fluid inclusion data, the inactive chimneys are likely to have been formed under lower temperature and lower  $f_{O_2}$  conditions than the active chimney.

Sulfide blocks and collapsed inactive chimney are dominated by isocubanite with small amounts of chalcopyrite, pyrrhotite and sphalerite, suggesting that a few meters tall inactive chimneys and sulfide mounds may largely be composed of isocubanite.

Particularly, Co-Ni-S minerals, including linnaeite, millerite and cobalt pentlandite in close association with chalcopyrite and bornite, were observed for the first time in an active seafloor hydrothermal system. Textural relations indicate that cobalt pentlandite and chalcopyrite were earliest-formed minerals, followed by bornite and then by linnaeite and millerite.

Sulfide minerals in the Rainbow massive sulfides are characterized by high contents of Co: isocubanite (1.74 wt%); chalcopyrite (0.50 wt%); pyrrhotite (2.03 wt%); pyrite (1.75 wt%); and sphalerite (0.58 wt%), all being the highest values yet reported. Isocubanite usually contains chalcopyrite with various exsolution textures. Based on bulk chemical compositions of isocubanite with exsolved chalcopyrite and/or pyrrhotite and phase relations for the Cu-Fe-S system, it is suggested that the intermediate solid solution (iss) field may extend toward more Fe-rich side than the experimentally determined field. Mineral assemblages observed in the Rainbow massive sulfides are similar to those in other hydrothermal fields hosted in basaltic rocks, suggesting that physical conditions of formation were similar each other. However, isocubanite is predominant in the Rainbow massive sulfides, whereas chalcopyrite or pyrite is the major ore mineral with a trace or minor isocubanite in those from other hydrothermal fields. No silicate mineral is observed in the Rainbow massive sulfides, possibly due to low SiO<sub>2</sub> contents in the fluids, whereas silicate phases, including amorphous silica, are common in other massive sulfides. The most important mineralogical and geochemical differences between both hydrothermal types are the occurrence of the Co-Ni-S minerals and high contents of Co in sulfide minerals, which can be brought about by hydrothermal circulation through ultramafic host rocks. In the Rainbow hydrothermal field, seawater sinks down into serpentized peridotites through faults and fissures and is then changed into high temperature fluids by heat originated from exothermal serpentization reactions. Throughout the processes, ore-forming elements, such as Fe, Cu, Zn, Mn, Ni and Co, are leached out from the ultramafic rocks. Such fluids discharge onto the seafloor and then mix with ambient cold seawater, with the resultant formation of the Rainbow seafloor massive sulfide deposits. The aforementioned hydrothermal circulation associated with serpentization is supported by various chemical data previously obtained for the Rainbow fluids, including anomalously high contents of H<sub>2</sub>, CH<sub>4</sub> and total Fe and low SiO<sub>2</sub> content. Moreover, ore-forming materials dissolved are in part precipitated before the fluids vent the seafloor, probably forming a stringer zone beneath the sulfide mound. Even in basaltic rocks-hosted environments, however, if hydrothermal circulation is intense, significant amounts of Co can be incorporated into Cu-Fe-Zn-S minerals without forming Co-Ni-S minerals in seafloor massive sulfide deposits. The presence or absence of the Co-Ni-S minerals in a

seafloor hydrothermal deposit is closely linked to whether the hydrothermal field is hosted by ultramafic rocks.

It is expected that Co contents of sulfide minerals can provide more constraint on the geologic environment of on land Besshi-type deposits.

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