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## Petrography and Geochemistry of Post-Magmatic Hydrothermal Alteration and Mineralization in the J-M Reef, Stillwater Complex, Montana

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### Introduction

The mineralogy and textural associations of magmatic silicates, alteration minerals, base metal sulfides (BMS) and platinum group minerals (PGM) were determined for seven underground core samples (2000 DDH's 68, 71, 85, and 148) from the East Boulder Mine. The samples were selected to characterize extensive alteration and variations in alteration intensity observed in the J-M Reef and footwall. The samples were also used to investigate secondary BMS in the reef and to determine if PGM are associated with the secondary BMS. Thin sections were examined by transmitted and reflected light microscopy, and with a scanning electron microscope using an energy dispersive spectrometer for X-rays (SEM-EDS). The results reveal that both the primary magmatic and secondary hydrothermal BMS have associated PGM. The alteration assemblage is dominantly chlorite, talc, tremolite, calcite, clinozoisite and magnetite. Hydrothermal alteration and mineralization are associated with thin dilational fractures that provided channel ways for hydrothermal fluids. The assay data for the four core holes indicate that there is an inverse relationship between degree of hydrothermal alteration and ore grade that could explain some of the variability in the grade and thickness of the J-M Reef.

### Alteration and Mineralization

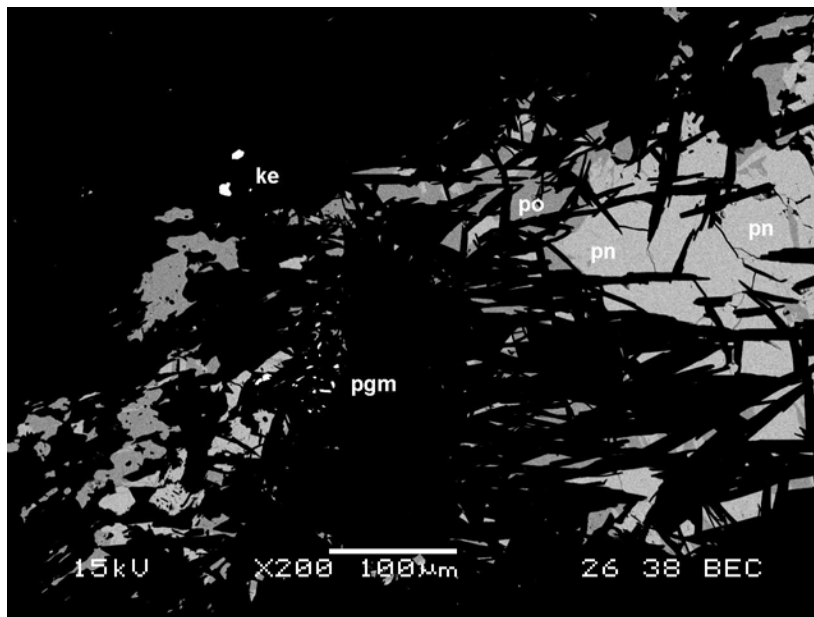
The BMS identified include pyrrhotite, pentlandite, chalcopyrite and pyrite. PGM were found in four of the six polished thin sections, in approximately 35 grains. Seven different minerals were identified, with moncheite (PtTe<sub>2</sub>) and Pd tellurides being the most common; sperrylite (PtAs<sub>2</sub>), isoferroplatinum (Pt<sub>3</sub>Fe) and native platinum were also found. The grain sizes range from a 130 µm moncheite grain down to Pd tellurides and moncheite grains that range from 1 to 5 µm.

Alteration intensity, as estimated from thin sections, decreases from 90% in footwall sample 68-1 to 10% in sample 148-1. Samples 71-1, 71-2, 71-3, 71-4, and 85-1 display decreasing alteration intensity in the order listed between end members (68-1 and 148-1). The BMS and PGM were found to have two

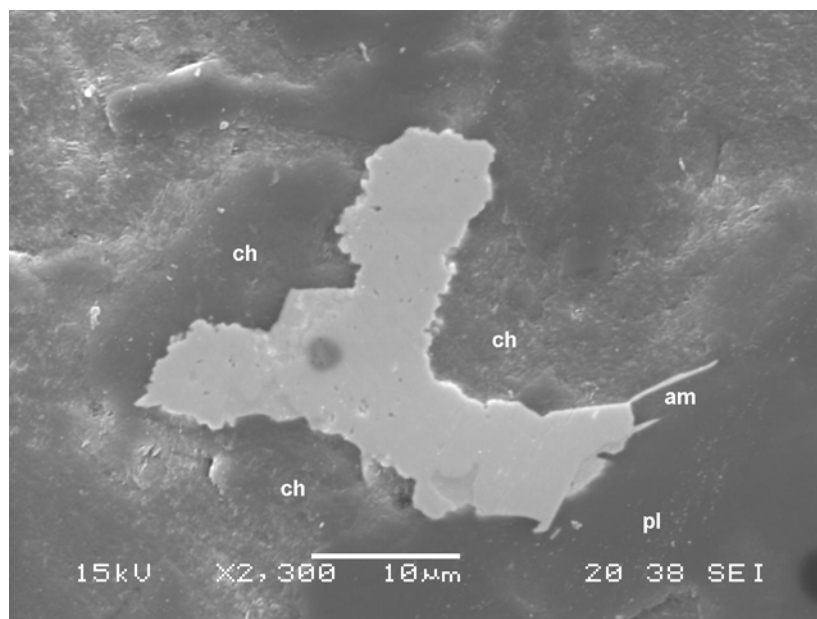
distinct textural associations related to the degree of hydrothermal alteration. The first association occurs in 148-1 and locally in 85-1, where BMS clots are interstitial to essentially unaltered plagioclase. These are probably primary magmatic sulfides. Some of these sulfide clots contain inclusions of native platinum and moncheite ranging from 80 to 130 µm at the BMS-gangue contact. These are the largest PGM grains identified.

The second textural association was observed in all of hole 71 samples and locally in 85-1. In these thin sections the BMS clots are strongly recrystallized and intergrown with hydrous alteration minerals (Fig. 1). These intergrowths occur with alteration minerals in veinlets and as fine grained sulfides intergrown with alteration minerals in replacements of primary silicates. The PGM found in these altered samples are typically fine grained (1-30 µm), located near recrystallized sulfide clots (Fig. 1), and intergrown with alteration minerals in veinlets and as replacements of primary silicates (Fig. 1, 2).

Eighteen (18) pentlandite grains were analyzed for Pd content and only one (sample 85-1; 3.77 wt% Pd) had Pd above the detection limit. Sixteen of the eighteen grains analyzed were from hole 71. The hydrothermal event that recrystallized the sulfide clots may have caused the Pd to exsolve from pentlandites and form the nearby Pd tellurides (Fig. 1), or be transported even further. Pyrite appears to have been an early magmatic sulfide. In the altered samples pyrite is partly to completely replaced by pyrrhotite, pentlandite and chalcopyrite. The replacement of pyrite by pyrrhotite and the presence of magnetite as a common alteration mineral implies that the hydrothermal fluids were under-saturated with sulfur. Chalcopyrite commonly occurs as a halo of fine (<50 µm) grains rimming BMS clots and in veinlets extending away from the BMS clots. This indicates that chalcopyrite was the BMS that was most commonly dissolved and reprecipitated during the hydrothermal event(s). The magmatic sulfide clots of sample 148-1 contain round calcite inclusions. This indicates that some of the calcite is of magmatic origin and that the late magmatic fluids were over-saturated in CO<sub>2</sub>.



**Figure 1.** Backscattered electron image of pentlandite (pn) with minor intergrown pyrrhotite (po) intergrown with lathy chlorite, talc and tremolite (black background), all replacements of olivine. Two small grains of keithconnite (ke;  $\text{Pd}_3\text{Te}$ ) are in the upper left center. Several very fine grains of moncheite ( $\text{PtTe}_2$ ) and telluropalladinite ( $\text{Pd}_9\text{Te}_4$ ; pgm) are in the lower left center. The large pentlandite clot intergrown with lathy chlorite does not contain detectable Pd. Sample 71-2.



**Figure 2.** Secondary electron image of sperrylite ( $\text{PtAs}_2$ ) grain intergrown with chlorite (ch; medium gray high relief surface), plagioclase (pl) and amphibole (am). The PGM is in a veinlet filled with chlorite and calcite. Sample 71-1.

**Table 1.** The geochemical results from the ore zone in four core holes, in relation to the degree of hydrothermal alteration observed in the thin sections.

Decreasing Alteration →				
Core Hole	68	71	85	148
Thickness (ft) and grade in oz/ton (Pt +Pd)	8.9' @ 0.20	6.3' @ 0.49	6.2' @ 0.67	6.7' @ 1.03
Pt g/mt aver. over ore thickness	1.31	3.69	5.73	7.21
Pd g/mt aver. over ore thickness	5.51	13.21	17.29	28.03
Cu g/mt aver. over or thickness	341.00	951.50	738.00	715.00
Pd/Pt, aver. over ore thickness	3.62	3.64	3.04	4.28
Cu/Pt, aver. over ore thickness	797.08	271.41	120.91	126.79
Cu/Pd, aver. over ore thickness	248.72	73.64	39.78	28.83

The hydrous alteration minerals lack any preferred orientation, indicating they are of hydrothermal rather than regional metamorphic origin. The intergrowth of chlorite and clinozoisite with secondary sulfides indicates a moderately low temperature alteration assemblage that probably formed between 230-320°C, based on studies of modern geothermal systems (Reyes, 1990). Recent experimental studies have demonstrated that Pt and Pd can be dissolved as bisulfide or chloride complexes at temperatures below 350°C (Gammons and Bloom, 1993; Pan and Wood, 1994; Gammons, 1996).

During core logging, fine white fractures less than 1 mm wide were commonly observed in the J-M Reef and locally in the footwall. The fractures are filled with chlorite and lesser amounts of carbonate, talc, BMS, and rarely PGM. The fractures are commonly oblique to stratigraphy, but have a range of orientations from sub-parallel to nearly normal to stratigraphy. They do not show a component of slip parallel to the fracture walls and are therefore considered dilational. They probably formed as late-magmatic cooling fractures or hydraulic fractures related to the hydrothermal event(s). Based on the dilational nature and hydrous assemblage in these fractures, they probably provided channel ways for hydrothermal fluids.

### Geochemistry

Comparison of the assay data and petrography for the four core holes reveals that there is an increase in ore grade with decreasing intensity of hydrothermal alteration (Table 1). Hole 148 has the least alteration and the highest grade (1.03 oz/ton (Pt+Pd) over 6.7 feet). In holes 85 and 71, the grades decrease to 0.67 oz/ton (Pt+Pd) over 6.2 feet and 0.49 oz/ton (Pt+Pd) over 6.3 feet, respectively. Core hole 68 has the lowest grade of 0.20 oz/ton (Pt+Pd) over 8.9 feet. The most altered sample was from hole 68 in the footwall of the reef. Although the reef in hole 68

was not examined in thin section, alteration, with fine fractures, and secondary sulfides is visible in hand specimen. The variation in grade of the four core holes could be related to a variation in primary mineralization rather than to intensity of alteration. However, considering the intensity of the recrystallization of the BMS in hole 71, it seems likely that such a hydrothermal event would have affected trace elements such as Pd and Pt. The present study indicates that the hydrothermal event was destructive and leached Pd and Pt. This is supported by the ratios of Pd/Pt, Cu/Pt and Cu/Pd in the four holes. The ratios were calculated for each sample interval and then averaged over the ore thickness. The Pd/Pt ratio decreases slightly in the altered core holes. Both the Cu/Pt and Cu/Pd ratios show a dramatic increase with increasing alteration intensity, indicating that Cu was added (or leached less) during depletion of Pd and Pt in the hydrothermal event. The increase in Cu ratios with increasing alteration is consistent with the petrographic evidence that chalcopyrite was the BMS that was most commonly dissolved and reprecipitated during the hydrothermal event(s).

### Discussion

Our results suggest that hydrothermal fluids locally recrystallized BMS clots and remobilized the sulfides and platinum group elements (PGE). The geochemical results from this study suggest that the hydrothermal fluids may have modified the J-M Reef by leaching Pd and Pt and adding (or leaching less) Cu. However, the distances across which the PGE were mobilized are uncertain; as are the overall effects on the grade of the deposit. The mass balance of PGE for a given volume of rock is also unknown. Our knowledge regarding the extent of the hydrothermal event, geometry of possible fluid conduits, nature of heat sources, and timing of events remains incomplete. Additional work along these lines should lead to a predictive model for use in

exploration and mining.

### **Acknowledgments**

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