

COMPOSITION OF APATITE AND BIOTITE FROM THE STILLWATER COMPLEX,  
MONTANA: EVIDENCE FOR HYDROTHERMAL TRANSPORT OF PGE AND REE IN Cl-BEARING  
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Models for the origin of zones of platinum-group element (PGE) mineralization and associated REE enrichment in layered intrusions (1) range from strictly magmatic types (2,3) to those suggesting that hydrothermal fluids were important (4,5,6). Compositional data on biotite and apatite from the Stillwater Complex support the notion that Cl-bearing hydrothermal fluids, evolved during crystallization of the cumulus sequence, transported significant amounts of PGE and REE.

Biotite is a minor accessory mineral throughout the complex, and is most common as an interstitial spacefiller in the olivine-bearing rocks of the Ultramafic and Banded series. Apatite is a rare accessory mineral, and is usually associated with quartz-bearing portions of the thick anorthosite members (7). Within OB I (the lowermost olivine-bearing zone of the Banded series and host of the Main PGE zone), apatite and biotite are preferentially concentrated in coarse-grained to pegmatitic rocks with >60% olivine. Within OB I, biotite is also found as inclusions in chromite and apatite.

Apatite: Probe analyses of apatite from An II and the main PGE zone of OB I are shown in an OH-F-Cl ternary diagram in figure 1. Also plotted are published compositions of apatite from other layered intrusions. It is apparent that, while intercumulus apatites from An II have similar halogen contents to those from other layered intrusions, the apatite associated with the Main PGE-sulfide zone is unusually enriched in Cl (4.85 wt. % Cl). The ore zone apatite also contain high REE (0.58 wt. %  $Ce_2O_3$  and 0.28 wt. %  $La_2O_3$ ) compared with published apatite analyses from other layered intrusions.

Biotite: A plot of Cl vs.  $X_{Mg}$  in biotite from the Stillwater Complex and a variety of other igneous rocks is shown in figure 2. Fluorine varies from < 0.1 to 0.4 wt. %. The highest Cl content (0.54 wt % Cl) is from biotite associated with interstitial quartz in unaltered orthopyroxenite from the Ultramafic series, suggesting that much of the scatter is due to exchange with fluids which have altered all other samples to some degree (most commonly, serpentinization of olivine). A similar low temperature exchange of biotite with meteoric water has been observed in the Skaergaard Intrusion (8). However, regardless of the cause of the scatter, the Cl contents of Stillwater biotites are markedly higher than those of other layered intrusions, and are higher than that of a typical porphyry copper deposit.

It has been found experimentally that vapor/melt partition coefficients for a metal are proportional to the concentration of Cl in the vapor phase raised to a power equal to the valence state of the metal (e.g. 9). Thus, for a divalent metal, doubling the chlorine concentration of a fluid would lead to a four-fold increase in the metal concentration in the fluid. It follows that the PGE content of the sulfide and the Cl content of associated apatite should be related if both precipitated in the presence of a PGE-bearing fluid. This does indeed appear to be the case, as shown in figure 3, where the PGE concentrations of sulfide to the 1/2 power is plotted against wt % Cl in apatite for both the Picket Pin sulfide zone of An II and the Main PGE zone of OB I. The enrichment in Pt and Pd relative to the other PGE (i.e. Ir) is consistent with the higher solubility of Pt and Pd in Cl-complexing systems (10).

Finally, it has been noted that plagioclase immediately adjacent to olivine-rich rocks of OB I contain approximately 10 times the REE content of

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plagioclase some distance away (1). This observation supports a model of hydrothermal transport of REE as well as the associated PGE's, and is consistent with the calculations of Candela (11), who has shown that an exsolving Cl-rich vapor can extract significant amounts of REE from a crystallizing magma.

**Acknowledgements:** This work was supported by NASA grant NAG 9-84.

**References:** (1) Lambert and Simmons (1983) *Mining Engin.* 33:1291-1298. (2) Irvine et al. (1983) *Econ. Geol.* 78:1287-1334. (3) Campbell et al. (1983) *J. Petrol.* 24:133-165. (4) Boudreau and McCallum, in prep. (5) Kinlock (1982) *Econ. Geol.* 77:1328-1347. (6) Elliot et al. (1982) *Econ. Geol.* 77:1493-1510. (7) Salpas et al. (1983) *Proc. Lunar Planet. Sci. Conf.* 14th, *J. Geophys. Res.* 88:B27-B39. (8) Nash (1976) *Am J. Sci.* 276:546-557. (9) Holland (1972) *Econ. Geol.* 67:281-301. (10) Westland (1981) *Can. Inst. Mining. Metal. Spec. Volume* 23:5-18. (11) Candela (1984) *Geol. Soc. Am Abst.* with Program 16(6):462. (12) Barnes (1983) Unpub. Ph.D. thesis, Univ. of Toronto.

**Figure captions:** (1) F-OH-Cl plot for apatite from the Stillwater Complex and other sources as shown. OH calculated from stoichiometry, and may include substitutions or site vacancies. In this study, the analyses enclosed within a solid line are from a single probe mount. (2) Wt. % Cl vs.  $X_{Mg}$  in biotite from the Stillwater complex and other igneous rocks. (3) (PGE and Au content in sulfide fraction)<sup>1/2</sup> vs. Cl concentration in apatite from two mineralized zones in the Stillwater Complex. Sulfide composition for Main PGE zone is from (12).

