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PLATINUM GROUP ELEMENT MINERALIZATION IN “BALLROOMS” OF THE  
J-M REEF OF THE STILLWATER COMPLEX, MONTANA

by

Matthew P. Harper

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geology

Brigham Young University

March 2004



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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Matthew P. Harper

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Matthew P. Harper in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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## ABSTRACT

### PLATINUM GROUP ELEMENT MINERALIZATION IN “BALLROOMS” OF THE J-M REEF OF THE STILLWATER COMPLEX, MONTANA

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Master of Science

The J-M Reef of the Stillwater Complex, Montana (a large layered mafic intrusion), is one of the highest grade platinum group element (PGE) deposits known in the world, producing primarily palladium and platinum in a 3.4:1 ratio. “Ballrooms” of the Stillwater Complex are anomalously wide areas within or stratigraphically below the J-M Reef that host platinum group element mineralization. Ballrooms have two typical morphologies (type 1 and type 2); the first is an abrupt thickening of the mineralization that extends below the Reef Package and the second is a gentle widening of the Reef Package and associated reef mineralization to a width of over 6 m. Ballrooms are highly variable in size. Minimum dimensions for ballroom designation are a thickness (perpendicular to strike) of 6 meters and a length of 5 meters (parallel to strike).

Mineralization contacts are irregular but sharp and are characterized by a dramatic decrease in sulfide content (from one to two percent in ballrooms to only trace amounts, <ppm, in the footwall rock) in a very short distance (approximately 1 m). Remobilized sulfides replace exsolution lamellae in orthopyroxene and fill fractures in and between silicate mineral grains and are commonly found in samples with large magmatic sulfide blebs.

Whole rock major and trace element compositions of rocks from ballrooms exhibit a strong geochemical control by cumulus phases. There are no significant major or trace element differences in the rocks from the two ballroom types. Moreover, cumulate mineralogy in ballrooms shows no variation from cumulate mineralogy in the J-M Reef. Magnesium, Fe, and Cr exhibit a strong correlation with one another and the other major elements but do not correlate with Cu, Ni, and S. This indicates that Cu, Ni, and S were controlled by processes other than those controlling the distribution of the major elements in cumulus phases.

Cl-rich hydrous phases in the ballrooms (apatite and phlogopite) are evidence for the presence of Cl-rich fluids that interacted with melt in the mineralized zone, inferred to coincide with the growth of cumulus silicate phases. Pegmatitic textures also evidence the presence of fluid. The concentrated fluids played the major role in the formation of these anomalously rich ore morphologies.

This fluid likely originated when intercumulate melt became fluid saturated during crystallization of the cumulate pile at the base of the magma chamber and migrated upward as Boudreau (1999) suggests. This fluid appears to have been

concentrated in some areas to form locally enriched areas of PGE mineralization (ballrooms). Areas of extensive fluid-melt interaction could produce type 2 ballrooms, while type 1 ballrooms were formed where there was little or no melt present when the upwelling fluid became sulfide saturated.

The fluid generation and migration may have been caused by an eruption of flood lava from the crystallizing magma chamber. It is possible that even a small eruption from the chamber could generate a large enough pressure decrease to induce fluid saturation in the melt remaining in the cumulate pile. This process may have repeated each time lava erupted from the evolving chamber and created multiple sulfide horizons in the Stillwater Complex.

Evidence of sulfide remobilization and low temperature secondary alteration is abundant in ballrooms. The secondary alteration phases include sericite, zoisite/clinozoisite, serpentine, magnetite, pyrite, talc, and chlorite. A regional metamorphic event at 1.7 Ga that changed the Pb isotopic composition of the sulfides is likely the cause of the alteration. This low temperature hydrothermal event locally remobilized sulfides, chalcophile elements, and PGEs in the J-M Reef and ballrooms and may have variably depleted or enriched parts of the mineralization. This remobilization of sulfides, chalcophile elements, and PGEs has had a significant influence on the local distribution (centimeters to a few meters) of PGE bearing sulfides.

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The BYU geology department generously provided access to their laboratories and research instruments to complete my analyses.

My advisor Eric Christiansen spent countless hours helping me collect and interpret my data, acted as a sounding board to bounce ideas off of, and was patient with me through months of unending questions. I would also thank my committee Jeff Keith and Mike Dorais for their advice and help throughout the process.

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## INTRODUCTION

The Stillwater Complex is a late Archean layered mafic intrusion that hosts platinum group element (PGE) mineralization (Figure 1). Sulfide horizons occur throughout the stratigraphic sequence of the complex. The most PGE-rich of these horizons is the J-M Reef. It is one of the highest grade PGE sulfide-hosted deposits known, producing primarily palladium and platinum in a 3.4:1 ratio with rhodium, gold, silver, copper, cobalt, and nickel also recovered. The high grade of mineralization in the Stillwater Complex can partially be attributed to “ballrooms” which commonly host the highest grade PGE ore in the Stillwater Mine.

The term “ballroom” has been used loosely as a mining term at the Stillwater Mine to refer to the abrupt thickening of economic PGE mineralization to include rocks below and within the J-M Reef. Ballrooms were first discovered by the extensive underground mapping and diamond drilling program of Stillwater Mining Company. Ballrooms contribute significant amounts of PGE ore in the Stillwater Mine. However, the origin and nature of the ballrooms has been enigmatic.

Discovering and exploiting these high grade pockets can make the difference between an economic and subeconomic ore deposit. The East Boulder Mine on the J-M Reef (Figure 1 and 2) and the Picket Pin horizon (Figure 1 and 2) both lack ballrooms. The East Boulder mine (0.2-0.5 ounces per ton) is consistently lower grade than the Stillwater Mine portion of the reef (0.3 to multiple ounces per ton) and the Picket Pin horizon (consistently 0.1 opt) has an even lower grade than East Boulder.

The Stillwater Mining Company has studied the frequency and distribution of

ballrooms extensively in the workings of the Stillwater Mine. However, prior to this study, no chemical, mineralogic, or petrologic studies of ballrooms have ever been done. Zientek et al., (1990) studied the As, Bi, Hg, S, Sb, Sn, and Te geochemistry of the J-M Reef, McCallum et al. (1999) studied the Pb isotopes of sulfides and plagioclase in the J-M Reef, Boudreau et al. (1986) and Boudreau et al. (1997) studied the halogen geochemistry of the reef and Cl isotopes in apatite and phlogopite respectively. Many of these investigations may have included ballroom samples. No investigation has yet focused specifically on ballrooms and their distinguishing characteristics, and how they related to the reef mineralization.

The purpose of this study is to provide whole rock major and trace element analyses, mineral compositions, trace mineral identification, and structural and petrologic descriptions of ballrooms. This information is used to help develop a model for the formation of the ballrooms, origin of the sulfides, the cause of fluid-saturation, and the extent of fluid melt interaction in the mineralization process and post-magmatic alteration.

## GEOLOGIC SETTING

The Stillwater Complex is part of the Beartooth uplift that exposed Archean terrain during the Laramide orogeny (Figure 1). Approximately 6 km of uplift along five major high-angle reverse faults have brought the exposed section of the Stillwater Complex to its current location Jones et al. (1960). The complex is exposed for 45 km along strike and has a maximum exposed thickness of 6500 m. The base of the complex is exposed in the Beartooth Mountains where it is in contact with metasedimentary rocks.

A more complete review of the geology is given by several others (e.g., Czmannske and Zientek, 1985).

### *Age*

Premo et al. (1990) calculated a U-Pb age of  $2704 \pm 1$  Ma for the Stillwater Complex that agrees well with the Sm-Nd age of  $2701 \pm 8$  (DePaolo and Wasserburg, 1979) and ages of  $2711 \pm 1$  Ma,  $2712 \pm 3$  Ma, and  $2703 \pm 10$  Ma,  $2704 \pm 25$  Ma for the mafic sills and dikes associated with the complex. These mafic sills and dikes are presumed to represent the parent magma of the complex (Helz, 1985; Premo et al., 1990).

### *Stratigraphy*

The stratigraphy of the complex was recorded in detail by McCallum et al. (1980) and Todd et al. (1982). Both stratigraphic subdivisions are still used as the frame work for research in the complex (Figure 2). Stillwater Mining Company uses the subdivisions of Todd et al. (1982) while many independent researchers use those of McCallum et al. (1980). The Stillwater Complex is divided into five major series (Figure 2) the Basal Series, Ultramafic Series, and the Lower, Middle, and Upper Banded Series. These five series are further divided into sixteen zones based on cumulate mineralogy. The Basal Series has disseminated sulfides with pods of massive to matrix sulfides (Page et al. 1985). The Ultramafic Series hosts ten chromite horizons, some with associated minor sulfide. The Lower, Middle, and Upper Banded Series host ten sulfide horizons spread throughout the upper two thirds of the complex.

The major sulfide horizon is the PGE-mineralized J-M Reef (roughly 2700 m from the base). It is located in the Lower banded series within Olivine-bearing zone 5 of

the Troctolite-Anorthosite Zone I of Todd et al. (1982) (or Olivine-bearing Zone I of McCallum et al. (1980)) and is hosted by a texturally distinct subdivision called the Reef Package (Corson et al., 2002). The Reef Package is roughly 1 to 3 m thick and is composed of layers of varying thicknesses of troctolite, anorthosite, peridotite/dunite and norite; the most common rock type is troctolite. The individual layers vary from 0 to 2 meters thick. The base of the Reef Package is a continuous layer of olivine-rich pegmatoidal rocks with coarse-grained post-cumulus orthopyroxene lying discordantly on footwall gabbros, norites, and anorthosites. The hanging wall contact of the Reef Package is a textural boundary between coarse-grained anorthosite/norite and an overlying medium-grained anorthosite/norite with oikocrystic orthopyroxene. Pegmatites are common within the Reef Package, but not directly above it in the hanging wall.

#### *Mineralogy*

The predominant magmatic minerals in the Stillwater Complex are plagioclase, olivine, orthopyroxene, clinopyroxene (augite), inverted pigeonite, and chromite with lesser amounts of apatite, phlogopite, graphite, quartz, amphibole, magnetite, ilmenite, and sulfides. Ore minerals in the J-M Reef include sulfides, tellurides, alloys, bismuthides, and arsenides. Common alteration minerals in the J-M Reef include chlorite, serpentine, talc, calcite, zeolites, zoisite/clinozoisite, actinolite, and clays (McCallum, 2002).

#### *Mineralization*

Both massive and disseminated sulfides in the Basal Series host subeconomic copper, nickel, and chromite deposits. The chromite horizons were mined during the late

1800's and early 1900's but are now subeconomic.

The Pt-Pd-rich J-M Reef is distinguished by concentrations of chalcopyrite, pyrrhotite, and pentlandite with tiny grains of various platinum-group minerals (Todd et al., 1982) (braggite, Pt-Fe alloy, sperrylite, moncheite, cooperite, kotulskite, stillwaterite, cubanite, vysotskite, telluropalladinite, keithconnite, and several other rare PGE-rich phases). It has been described as a “continuous zone of discontinuous mineralization” traceable over a strike length of more than 25 km. The mineralization is typically 1-3 meters thick. Approximately 80% of the Pd recovered by Stillwater Mining Company is found in solid solution in pentlandite, 15% recovered from other sulfides, and 5% from tellurides (Hyese, 1983).

The third mineralized zone is the Picket Pin Horizon. It is a zone of disseminated PGE-bearing sulfide that is very similar to the J-M Reef but has a lower grade of PGE mineralization (consistently running 0.1 ounces per ton combined PGE). The Picket Pin Horizon occurs in the upper 150 meters of AN-II in the Middle banded series (Boudreau and McCallum, 1986) and is traceable for over 22 km. Mineralization generally occurs ~10 meters below the top of AN-II at a contact between a coarse-grained anorthosite and an overlying medium-grained anorthosite—similar to the hanging wall contact of the Reef Package. According to McCallum (2002), sulfides occur as podiform and discontinuous lenticular accumulations that are continuously discontinuous within the top of AN-II.

#### *Mineralization Models*

Several models for the formation of the J-M Reef have been proposed. These models fall into two general categories. Those forming ore directly from magmatic

processes (Campbell et al 1983, Barnes and Naldrett 1985, Irvine et al. 1983, Vermaak 1976, and Von Gruenewaldt 1979 ) and those forming ore from Cl-rich hydrothermal fluids (Boudreau and McCallum, 1992, and Boudreau, 1999).

Lambert and Simmons (1988) show evidence that a magma mixing event happened at about the same time the Reef Package was formed. Campbell et al. (1999) and Barnes and Naldrett (1985) proposed that platinum-group-element-enrichment occurred during a magma-mixing event that led to immiscible sulfide liquid saturation. The immiscible sulfide liquid then settled to the bottom of the magma chamber through several kilometers of silicate magma and scavenged PGEs to form the J-M Reef. Irvine et al. (1983) developed an alternative model where a suspended layer of silicate melt becoming strongly PGE-enriched as a result of fractional crystallization in a sulfide-undersaturated magma chamber undergoing double-diffusive convection. Upon sulfide saturation, a PGE-enriched sulfide liquid separated from this PGE-enriched melt. Vermaak (1976) and Von Gruenewaldt (1979) published similar models of PGE concentration by upward expulsion of PGE-enriched intercumulus melt from an underlying cumulus pile. This enriched melt was the result of incompatible PGEs becoming concentrated in the sulfide undersaturated residual melt by fractional crystallization. The PGE-enriched melt then accumulated along the boundary between the cumulate pile and the overlying melt. In a similar model that used an aqueous fluid instead of melt, Boudreau and McCallum (1992) and Boudreau (1999) suggested that PGE enrichment was caused by the rise of orthomagmatic hydrothermal fluid that stripped a sulfide-saturated cumulate pile of its sulfides and PGEs and then deposited

them as sulfides in the J-M Reef near the floor of the magma chamber. Sulfide precipitation was triggered by the hydrothermal fluid becoming sulfide saturated when it reacted with the intercumulate melt present at the top of the cumulate pile just below the base of the magma chamber. This fluid-melt reaction also caused the resorption of orthopyroxene and precipitation of olivine and Cl-rich phlogopite and apatite.

Regardless of the origin of the ore minerals, McCallum et al. (1999) show evidence of sulfide remobilization and PGE redistribution in the J-M Reef. Pb isotopes in sulfides in the J-M Reef have incorporated radiogenic Pb during regional metamorphic event at 1.7 Ga (McCallum et al. 1999). Secondary phases from this event include serpentine, zoisite/clinozoisite, talc, chlorite, sericite, and calcite. In addition sulfides exhibit textures consistent with remobilization. However, this low temperature hydrothermal event appears to have left the silicate Pb isotope ratios unaltered. Lechler et al. 2002 and Dunn (1986) shows that plagioclase and whole rock O isotopes in the Reef area were altered by a low temperature fluid. However, Dunn (1986) inferred that the alteration is the result of weathering in the environment. Low temperature remobilization of sulfides may have enhanced PGE mineralization already present (McCallum et al., 1999).

## ANALYTICAL TECHNIQUES

Stillwater Mining Company has opened up and is actively mining a significant portion of the J-M Reef and ballrooms. In order to determine the nature and origin of mineralization in ballrooms and their relation to the J-M Reef, ballrooms in the Stillwater Mine were scrutinized. Three months were spent studying ballrooms in situ at the

Stillwater Mine. As stopes were driven along the J-M Reef, the mining was followed and changes in size of the ballrooms and constituent rock types were recorded. Drill core from ballrooms were also studied. Ballrooms are named by their location in the mine, referenced from feet above sea level and feet east or west of the shaft.

### *Sampling*

Thirty-two samples were taken from 85 meters of core from diamond drill hole no. 19108. This hole was drilled from the footwall below the base of one of the largest ballrooms (drill log in Appenix A) before it was mined out in 2002. The samples were taken from below the PGE mineralization, throughout the 20.1 meters of mineralization, and into the overlying hanging wall rocks (Figure 3).

From the 3800 E1700 ballroom, 17 samples were taken in stratigraphic sequence from just below the base of mineralization through the 11.85 m of mineralization and into the hanging wall rocks. Sample locations from ballroom 3800 E1700 are shown on a stratigraphic column of the ballroom (Figure 4).

Another 48 samples from the J-M Reef and various ballroom stopes were collected for comparison.

Powdered specimens were also obtained from Stillwater Mining Company's Pd and Pt assay samples from both drill core and hand samples from stopes. Two J-M Reef samples from the East Boulder Mine were collected by Sam Corson for comparison with the samples from the Stillwater Mine.

### *Petrography*

Sixty-three polished thin sections were made from hand and core samples and



analyzed petrographically with a Nikon Eclipse E600 POL petrographic microscope to determine mineral proportions, textural relationships, alteration, and to assess the role of magmatic and postmagmatic (hydrothermal) processes. Photomicrographs were taken with a Spot Diagnostics Instruments digital camera mounted to the microscope.

#### *Electron Microprobe Analyses*

Minerals in 55 thin sections were analyzed with an updated Cameca SX-50 electron microprobe. Pyroxene and olivine were analyzed using a 20 nA beam with an accelerating voltage of 15 kV with count times of 20 seconds for each element. Plagioclase, apatite, and biotite was analyzed using a 10 um 10 nA beam with an accelerating voltage of 15 kV and count times of 20 seconds for each element. Element maps of Pd, Pt, Cu, Fe, Ni, and S were made by rastering a 100 nA 25 kv electron beam over selected sulfides and silicates. These were used to determine composition, zonation, and morphology of sulfides.

#### *Chemical Analyses*

One hundred samples (17 from the 3800 E1700 ballroom, 32 from the 19108 core samples, 49 from the assay powders, and 2 from the East Boulder Mine) were analyzed in a Siemens SRS-303 X-ray fluorescence spectrometer to determine major and trace element compositions of unmineralized and mineralized rocks. Samples were powdered in a tungsten carbide shatter box and dried overnight at 105° C. The powders were pressed into pellets backed by Whatman fibrous cellulose and analyzed for both major and trace element concentrations using international reference materials for calibration. The whole rock analyses were then normalized to 100% on a dry weight basis. Elements

analyzed include the major elements SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, and the trace elements Ba, Cr, Cu, Nb, Ni, Rb, S, Sc, Sr, V, Y, Zn, and Zr.

Glass disks were made by fusing one gram of rock powder with a flux of lithium metaborate and lithium tetraborate for 12 of these specimens. The glass disks were then analyzed for major element concentrations. The glass disks were used to determine the quality of major element analyses from the pressed pellets. Pressed pellets were used for both major and trace element analyses because the majority of the powdered samples have sulfur concentrations of more than 1000 ppm. The high sulfur concentrations deteriorate the platinum crucibles used to fuse the powder into glass. Comparisons of analyses of the glass disks and pressed pellets of the same samples show that the major element analyses are accurate to within  $\pm 10\%$  relative (Appendix B).

#### BALLROOM CLASSIFICATION

Ballrooms are anomalously large volumes of mineralized (Pt-Pd-S) rock, which for the purposes of this paper, must be at least 6 meters thick (perpendicular to strike) and 5 meters in length (parallel to strike). Ballrooms have keel-like shapes (Childs et al., 2002) and extend several meters below the J-M Reef. However, in detail ballrooms are highly variable in size and shape. Generally ballrooms are roughly 6 to 15 m thick by 5 to 20 m long and occur in and below the J-M Reef (Ennis Geraghty, oral communication 2001). In contrast, typical reef mineralization is nearly continuous with a width of one to two meters. The amount of sulfide mineralization in the reef is variable and is sometimes absent (Raedeke and Vian, 1986). Mineralization contacts are irregular but marked by a dramatic decrease in sulfide content (from one to two percent in ballrooms to less than a

ppm in the footwall rock) in a very short distance (approximately 1 m; Childs et al. (2002).

Ballrooms are divided into two types depending upon the host rock (Figure 5). The first and most common type of ballroom consists of thickened economic mineralization extending from the top of the Reef Package into footwall rocks (predominantly gabbro, norite, and anorthosite) (Figure 5a). The second type of ballroom is subdivided into two categories (A and B). In type 2A ballrooms the Reef Package and mineralization both widen to a thickness greater than 6 meters (Figure 5b). M. Pasecznyk (oral communication, 2002) noted that type 2 ballrooms are more common in the upper westernmost area of the Stillwater Mine. Type 2B ballrooms is the least common and consists of sulfide mineralization isolated as strata-bound pods or discordant zones of Reef Package rocks (i.e., troctolite or dunite) that are found within the footwall rocks (Figure 5c). Type 2B is generally found about 6 to 10 meters below the base of the Reef Package. Type 2A and B ballrooms have the same cumulate mineralogy, mineralization, and are located in the same general area of the mine. The major difference between types 2A and B is that type 2B ballrooms are not “connected” to the reef as are type 2A ballrooms. For the purposes of this study, type 2A and B ballrooms are considered together because of similarities in silicate mineralogy and mineralization (Table 1).

Jim Dahy (oral communication 2002) from Stillwater Mining Company has examined the stratigraphic setting and morphologies of ballrooms in the Stillwater Mine and noted that almost all ballrooms regardless of type occur below a downwarp in the

hanging wall.

Ballrooms are similar to Raedeke and Vian's (1986) four levels of mineralization. Type 1 ballrooms are roughly equivalent to level 2, type 2A ballrooms are most similar to level 3 of typical reef hosted mineralization extending to widths and depths greater than 6 meters. Type 2B ballrooms are most analogous to level 1 mineralization. However, Childs et al. (2002) believe that the abrupt boundaries, keel-like shape, lateral continuity, and rich grade of the mineralization justify the use of the new term of "ballroom."

## RESULTS

In this study, type 1 ballrooms are represented by samples from Stillwater Mining Company's drill hole 19108. In this ballroom, footwall norite with lesser anorthosite and troctolite host sulfide mineralization. Plagioclase is the main cumulus phase, with lesser amounts of cumulus orthopyroxene and olivine.

Type 2 ballrooms are represented by hand samples from the 3800 E1700 ballroom. In this ballroom, Reef Package troctolite, dunite, and anorthosite host the sulfide mineralization. Pegmatitic textures are also present in the type 2 ballroom. Olivine and orthopyroxene with lesser amounts of plagioclase and rare pegmatitic phlogopite are the main cumulus phases.

Secondary phases in the ballrooms consist of sericite, zoisite/clinozoisite. Serpentine, magnetite, talc, pyrite, chlorite, calcite, and a very fine grained pargasite. The type 1 ballroom has more pargasite, sericite, and zoisite/clinozoisite than the type 2 ballroom. Type 2 has more serpentine, magnetite, and chlorite, with some sericite. Generally secondary phase concentrations in ballroom is controlled by cumulate phase

proportions. However, type 1 had significantly more pargasite in pyroxene than type 2 although type 2 has more pyroxene.

### *Mineralogy/Petrography*

Table 1 lists representative electron microprobe analyses from minerals in ballrooms.

*Plagioclase.* In both ballroom types cumulus plagioclase grains are intergrown with one another with only a few exhibiting euhedral crystal faces. Plagioclase grains range anywhere from a few millimeters to a couple of centimeters long. Tiny fractures extending in all directions through plagioclase grains are commonly lined with highly birefringent sericite and some have tiny sulfide grains.

Plagioclases from ballrooms are relatively uniform (Appendix C) with an average composition of  $An_{82} \pm 0.03$  (1 sigma) and a range of  $An_{84}$  to  $An_{74}$  (Figure 6) regardless of host-rock type, type of ballroom, or presence of mineralization. Element maps and probe traverses across grains show no noticeable zonation. McCallum (2002) reported plagioclase compositions in the Banded Series range from  $An_{88}$  to  $An_{60}$ . Czmanske and Loferski (1996) noted that the only distinct variation in plagioclase from Anorthosite zones I and II (Figure 2) was due to sericite alteration along numerous tiny fractures. This sericite alteration, probably a low-temperature hydrothermal process is especially abundant in the type 1 ballroom where plagioclase is the dominant phase. Type 2 ballrooms do not exhibit the sericitic alteration to the same degree as type 1 ballrooms mainly because there is less plagioclase in type ballrooms. However, individual plagioclase grains in ballrooms appear to have about the same degree of alteration.

*Olivine.* Olivine in ballrooms has been extensively altered. Olivine grains are subrounded and commonly occur in clusters of grains in dunites and as individual grains in troctolite. In pegmatitic rocks, olivine grains are sometimes poikilitically surrounded by large pegmatitic pyroxene. Most olivine is severely fractured and has been pseudomorphically replaced by black masses of serpentine and magnetite with small grains of chalcopyrite scattered among the serpentine during low temperature alteration. Compositions of fresh olivine (Appendix D) in ballrooms range from Fo<sub>79</sub> to Fo<sub>76</sub> and have an average composition of Fo<sub>77</sub> ±0.01 (1 sigma) (Figure 7). There is no distinct compositional difference in olivine from the two types of ballrooms. McCallum (2002) reports olivine compositions from the Banded Series range from Fo<sub>79</sub> to Fo<sub>64</sub>. Ballroom olivines tend to be among the most iron-rich of the range reported for the Banded Series. This iron enrichment in olivine may be caused by resorption of pyroxene when an aqueous fluid mixed with melt. This process of pyroxene resorption in the presence of magmatic fluid is explained by Boudreau (1999) and is inferred as the origin for the majority of olivine in ballrooms.

*Pyroxene.* Orthopyroxene is the dominant cumulate pyroxene in both types of ballrooms. Cumulus clinopyroxene is present in some ballrooms and the J-M Reef when the host-rock is a gabbro; otherwise all clinopyroxene grains in ballrooms are small grains exsolved from orthopyroxene.

In the two ballroom types, cumulus and most intercumulus pyroxene in the ballrooms was originally precipitated as orthopyroxene (or pigeonite that inverted to orthopyroxene) with clinopyroxene formed later as exsolution lamellae. Small blebs of

clinopyroxene are also located along the rims of orthopyroxene grains and were likely exsolved out of the orthopyroxene. The small clinopyroxene grains are rounded and their shapes appear to be controlled by the surrounding plagioclase and the orthopyroxene grain that the clinopyroxene exsolved from.

Pyroxene analyses (Appendices E and F) show clinopyroxene has an average composition of  $Wo_{45} En_{45} Fs_{10} \pm 0.01$  (1 sigma) and the host orthopyroxene has an average composition of  $Wo_2 En_{77} Fs_{21} \pm 0.009$  (1 sigma). These were used to calculate an equilibration temperature of 914°C using the QUILF program of Andersen et al. (1993). Exsolution of the clinopyroxene probably occurred at approximately the same time as the precipitation of sulfides in the ballrooms. Some orthopyroxene grains have small round sulfide grains included. However, other orthopyroxene show that clinopyroxene exsolution lamellae are commonly replaced with sulfide grains apparently after crystallization (Figure 8).

*Phlogopite.* Phlogopite in ballrooms is found in pegmatoidal olivine-bearing rocks and occurs mainly in large pegmatitic clusters that encompass several embayed olivine grains. Pegmatitic phlogopite appears to have crystallized from fluid saturated magma. Occasionally, phlogopite is found as small intercumulate grains in the same olivine-bearing rocks.

Ballroom phlogopites (Appendix G) are similar to those in the J-M Reef analyzed by Buodreau et al. (1997). Phlogopite has an average Fe/Mg ratio of  $0.41 \pm 0.031$  (1 sigma). Ballroom phlogopite and those analyzed by Boudreau et al. (1997) are all fairly Cl-rich (about 0.33 wt%) (Cl:F:OH+O 0.4:0.2:1.92 apfu). This Cl-enrichment is likely

the result of equilibration with a Cl-rich aqueous fluid (Munoz, 1984), interpreted to be the same high-temperature orthomagmatic hydrothermal fluid or melt that formed the olivine and sulfides from which magmatic sulfides precipitated.

*Apatite.* Apatites in the ballrooms are rare and very small, only two to three microns across and three to four microns long, and are commonly euhedral. They are found in pegmatitic textures in olivine-bearing rock. Apatite is also found with phlogopite (often as inclusions). According to McCallum (2002) a similar relationship between apatite, pegmatitic olivine-bearing rocks, and phlogopite also exists within other parts of the J-M Reef.

Apatites from ballrooms are extremely Cl-rich (Table 1). The majority of these apatites have the hydroxyl site completely filled with Cl. End member chloroapatites are uncommon in most igneous rocks. Other apatite analyses in and below the J-M Reef are also Cl-rich (6.68 wt. % max, and 1.60 wt. % min., 4.36 wt. % average  $\pm 1.61$  1 sigma) while apatite above the reef is more F-rich (McCallum 2002).

Boudreau and McCallum (1989) suggest that the chloroapatite in the J-M Reef is the product of high-temperature orthomagmatic hydrothermal activity. It is assumed that because of the petrographic and chemical similarities between apatite from the J-M Reef and from both types of ballrooms, that they also formed by hydrothermal processes.

*Amphibole.* Ballrooms have a very fine-grained disseminated pargasitic amphibole (less about one micron across and about one to two microns long). The amphiboles are very fine, tabular grains that are usually aligned along exsolution lamellae of augite in orthopyroxene. They also occur as interstitial material replacing



post-cumulus augite blebs and locally bronzite. Like the biotite and apatite, Energy Dispersive Spectrum (EDS) electron microprobe analysis indicates the pargasite is Cl-rich but not easily quantifiable due to small size.

Pargasite and phlogopite tend to be mutually exclusive in the ballrooms, a characteristic also noted by McCallum (2002) for Ultramafic Series of the complex. Amphibole is also more abundant in type 1 than type 2 ballrooms. This is because amphibole replaces pyroxene and type 1 ballroom rocks are relatively pyroxene-rich and olivine-poor rocks (norite, anorthosite, gabbro-norite, and olivine gabbro-norite). Type 2 ballrooms (mainly troctolite, dunite, and anorthosite), have rare pargasite. Textures also indicate that pargasite in ballrooms formed as a secondary phase after crystallization of the complex.

*Sulfide/Ore Minerals.* Figure (8) shows typical sulfide morphologies of intercumulate blebs, fracture-filling veinlets, rims around plagioclase, inclusions within plagioclase and pyroxene grains, and as clusters of multiple small subrounded grains associated with clinozoisite and serpentine. Childs et al. (2002) noted that coarse sulfide clots with irregular veinlets extending up to 5 cm away from them are especially common in gabbro- and/or norite-hosted ballroom mineralization. Sulfides are also commonly found in networks aligned in a single direction through a given sample. These features along with the pegmatitic textures (Figures 3 and 4) and the presence of hydrous phases suggest that both reef and ballroom mineralization is from a magmatic/hydromagmatic origin and was later redistributed by a low-temperature hydrothermal event.

Pyrrhotite, pentlandite, and chalcopyrite are the most abundant sulfide phases in

ballrooms. All three commonly occur in one sulfide bleb or network of connected blebs (Figure 8). This is consistent with sulfide crystallization from a homogenous magmatic sulfide liquid that exsolved the different phases as it cooled. Pyrrhotite, pentlandite, chalcopyrite, and other rare PGE bearing sulfides are also present in veinlets and as small grains inside altered pyroxenes (Figure 8d and 8f). This is indicative of post-magmatic remobilization of sulfides at least on a small scale (centimeters to several meters).

According to Heyse (1983), most of the Pd recovered from the J-M Reef is in solid solution in pentlandite. Element maps constructed with an electron microprobe show that this is also true in ballrooms. However, Pd is also concentrated in the veinlets and in small sulfide and telluride grains inside altered pyroxenes (Figure 8d). Platinum is mainly found in small grains of braggite (Figure 8d) that are often separated from the three main sulfide phases, but it is also found in the veinlets, and to a lesser extent in the altered pyroxenes. Based upon petrographic and microprobe analyses, palladium- and platinum-bearing tellurides and metal alloys with iron and gold are also present but are very rare, the latter more rare than the former.

Sulfides hosted in altered pyroxene and surrounded by halos of zoisite/clinozoisite and serpentine are more common in type 1 ballrooms, whereas large blebs and networks or veinlets of sulfides are more common in type 2 ballrooms. These differences are likely influenced by associated silicate mineral assemblages and the amount of fractures present when a hydrothermal fluid moved through a given area. Sulfides in type 1 ballrooms commonly occur at junctions of multiple grain boundaries and are commonly associated with if not surrounded by halos of clinozoisite.

*Clinzoisite.* In samples from the 19108 type 1 ballroom, clinzoisite appears to have formed at the expense of plagioclase along or near orthopyroxene. Clinzoisite is probably a low-temperature alteration similar to sericite in the plagioclase. It is less common in type 2 ballrooms because the host rocks are mainly dunite and troctolite wherein the low temperature alteration is dominantly expressed as serpentinization of the olivine.

#### *Whole Rock Geochemistry*

Table 2 lists representative whole rock analyses from rock types in the ballrooms. The results of X-ray fluorescence analyses of 100 whole-rock samples are listed in Appendix 2. Ballroom rocks are mafic to ultramafic with SiO<sub>2</sub> ranging from 43 to 51 % and MgO ranging from 2 to 32%. Since the rocks are cumulates, elemental compositions strongly correlate with mineral proportions. For example, Al<sub>2</sub>O<sub>3</sub> concentrations are proportional to the amount of plagioclase in a rock and Fe<sub>2</sub>O<sub>3</sub> concentrations are proportional to the amount of olivine and orthopyroxene in a rock (clinopyroxene is much less abundant in these samples). Fe<sub>2</sub>O<sub>3</sub> and MgO correlate strongly with abundance of mafic phases, but Fe<sub>2</sub>O<sub>3</sub> has a stronger correlation with the other major elements than MgO.

Al<sub>2</sub>O<sub>3</sub> concentrations range widely (from about 3 to 30%) and serve well to show the mineralogic controls. For example, when Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> are plotted against one another with the average fresh plagioclase, orthopyroxene, clinopyroxene, and olivine compositions (Figure 9) the rocks form a trend that lies between the plagioclase and orthopyroxene/olivine compositions--the main cumulus phases. Al<sub>2</sub>O<sub>3</sub> correlates

positively with CaO, Na<sub>2</sub>O, and K<sub>2</sub>O while MgO, MnO, and Fe<sub>2</sub>O<sub>3</sub> have a strong negative correlation. TiO<sub>2</sub> exhibits a weak negative correlation with Al<sub>2</sub>O<sub>3</sub>. Similarly, trace elements correlate with the major constituents in their host phases. Sr exhibits strong positive correlations with Al<sub>2</sub>O<sub>3</sub> because it is controlled by plagioclase, while Ba and Rb have a weak positive correlation. Vanadium, Cr, Zn, and Zr are all negatively correlated with Al<sub>2</sub>O<sub>3</sub>. The inverse is true for each of these elements when plotted against Fe<sub>2</sub>O<sub>3</sub>. Strontium, Ba, and Rb are controlled by plagioclase, while Zr and Zn are controlled by orthopyroxene and olivine. Chromium is controlled by olivine and chromite.

Type 1 and 2 ballrooms do not show any distinct difference in their chemistries. Samples from type 1 and 2 ballrooms are included in Figure 9. It is remarkable to note that there is little difference in the major element chemistry between mineralized and unmineralized rocks. Mineralized rocks have slightly higher Fe<sub>2</sub>O<sub>3</sub> because the major sulfide phases are all Fe-rich.

Three high Ba, Rb, and K<sub>2</sub>O samples that are not correlated with Al<sub>2</sub>O<sub>3</sub> are attributed to the presence of phlogopite in troctolite and K-rich sericite and clay minerals in altered anorthosite.

Powders obtained from Stillwater Mining Company had been analyzed for Pt and Pd. Pt and Pd concentrations in rock samples collected for this study could not be analyzed by XRF spectrometry, so Cu was used as a proxy, Cu behaves like PGEs and may be used to monitor their behavior. In S-rich samples, Cu shows a strong correlation with Pd and Pt (Figure 10). A small subset of five samples have low Cu concentrations but high Pd and Pt concentrations. These samples also have very low Ni, Fe, S, and Al.

The high Pd and Pt in the S-poor samples is presumed to be caused by the presence of tellurides, arsenides, and alloys which host Pd and Pt instead of Sulfides which concentrate Cu as well (Zientek et al. 1990). Thus, Cu appears to be a reasonable proxy for understanding PGE- related processes.

In many mafic magmas, Cu, Ni, S, and Cr, are strongly compatible elements and correlate strongly with Mg and Fe in rocks crystallized from such magmas. However Figure 11 shows that unmineralized samples correlate along a magmatic trend while mineralized samples do not. In the ballrooms of the J-M Reef Cu, Ni, and S are not correlated with the major elements (Figure 12a) or with Cr. Copper, Ni, and S are strongly correlated with one another (Figure 12b). This indicates that Cu, Ni, and S abundances are not controlled by cumulus phases or by the magmatic processes which dictated the behavior of major elements and most trace elements including Cr. Further, the intercorrelations suggest Cu, Ni, and S were mobilized and then deposited as a group by a post-magmatic process (McCallum et al., 1999).

The correlation of Cu with Pd, Pt, Ni, and S implies that the Pd and Pt in ballrooms have the same history as Cu, Ni, and S. Pt/Cu, Pd/Cu, and Pd/Pt ratios of 0.03, 0.09, and 0.27 respectively were calculated for samples from the type 1 ballroom. All other trace elements analyzed show some correlation with the cumulate phase proportions, and the major elements, indicating that the processes controlling these ore-related elements, that have been redistributed, was non-magmatic.

## DISCUSSION

Any model for the J-M Reef and its enriched ballrooms must explain the

following observations:

1. The well-defined nature of the reef with sharp upper and lower boundaries that pinch and swell
  2. Multiple sulfide horizons in the complex
  3. Restriction of ballrooms (at least 6 m perpendicular to strike and 5 m parallel to strike) to the Stillwater Mine
  4. High grades of PGE mineralization in ballrooms
  5. Chaotic disruptions of the cumulate pile synchronous with the formation of the reef
  6. Chemical and isotopic evidence for magma mixing
  7. Evidence for the presence of magmatic fluid including resorption of pyroxene and olivine crystallization and Cl-rich apatite and phlogopite
  8. Downwarps in the hanging wall above ballrooms
  9. Strong correlation of major and most trace element concentrations with mineral modes, but a lack of correlation of Ni, S, Cu, (and by inference Pd and Pt) with magmatic modal or chemical variations, but strong correlation of Ni, S, Cu, (Pd and Pt) with one another
  10. Evidence of late metamorphism of the complex including secondary phases associated with sulfides, sulfide replacement textures in pyroxene, and remobilization of sulfides and Pb isotopes
  11. Paragenetic sequence listed in Figure 13
- Ballrooms have been found only in the workings of the Stillwater Mine and their

distribution is erratic. They are less abundant in the upper west and east workings of the mine and they are mainly found in the central portion of the mine. It is remarkable to note that none have been found in the East Boulder Mine or the Picket Pin Horizon (Figure 2). The Picket Pin does, however, have small pods of sulfide PGE mineralization isolated below the main horizon. The distribution of ballrooms may be indicative of processes controlling their formation.

Ballrooms also have the highest grades of palladium and platinum in the entire complex (0.3 opt to as much as 3-7 ounces per ton) compared to the Stillwater Mine J-M Reef (0.0 to 3.0 opt roughly), East Boulder Mine Portion of the J-M Reef (0.1 to 0.3 opt), and the Picket Pin Horizon (0.1 opt). It is also important that mineralization in the reef is “patchy” or highly variable--ranging from being locally absent to a few ounces per ton over short distances (1 to 10 meters). This is not the case in the East Boulder Mine where mineralization is more continuous both in distribution along the reef and in grade. As distance increases from ballrooms, reef mineralization becomes more continuous, even in dimensions, and has a lower but consistent grade of mineralization.

Zientek et al. (1990) predicted that the PGE content of the footwall sulfides (here called type 1 ballrooms) would be less than in the cumulus sulfides within the reef because the footwall sulfides were unable to scavenge PGE's from the magma chamber according to a model of sulfide precipitation from a magma mixing event. However, our work shows that the PGE content of these rocks is as high and often higher than the J-M Reef and the Pt/Cu, Pd/Cu, and Pd/Pt ratios in ballrooms are within the middle to upper part of the range reported by Zientek et al. (1990).

The occurrence of magmatic phlogopite is an example of late magmatic to nonmagmatic processes altering the reef area. Phlogopite likely formed from the interaction of fluid, melt, and pre-existing crystals (Boudreau, 1999). Fluid-melt interaction resorbed pyroxene and precipitated olivine and phlogopite. Magmatic phlogopite, along with the presence of chloroapatite and pegmatitic textures provides strong evidence for the interaction of silicates, melt (in type 2 ballrooms), and a Cl-rich fluid in ballrooms at the time of magmatic precipitation of sulfide in the J-M Reef.

Below the forming Reef Package in the footwall where there was no melt to resorb the pyroxene and crystallize olivine and phlogopite, rare euhedral chloroapatite shows that a Cl-rich fluid was also present at least on a localized scale.

It is possible that the sulfide horizon of the J-M Reef is the result of a magma mixing event that caused the magma to become sulfide saturated and precipitate sulfide. However, Boudreau's (1999) model for the formation of Olivine-bearing zone 5 provides a more complete model of the processes that formed the J-M Reef, pegmatites, and ballrooms. He envisions the generation of a Cl-rich fluid as a result of the crystallization of intercumulate melt in the cumulate pile at the base of the complex. This exsolved aqueous fluid is driven upward by buoyancy and by upward migration of the crystallization front. The fluid strips the cumulate pile of Pd, Pt, Cu, Ni, and S by dissolving previously precipitated sulfides or by direct partitioning into the fluid from remaining melt (Mathez and Peach, 1989 and; Fleet et al., 1991). When this rising fluid reaches a point just below the top of the cumulate pile where the intercumulate melt is not water saturated, the S-rich fluid reacts with the melt and its crystals. This reaction



caused an immisible sulfide solution to separate and form the sulfides now found in the reef and ballrooms. This fluid appears to have been ubiquitous across the floor of the chamber to form the sulfide enriched J-M Reef. This fluid mitigated event may have caused Ni-Cu-S-(Pd-Pt) to depart from magmatic trends as shown by their lack of correlation with MgO (Figure 11) or Al<sub>2</sub>O<sub>3</sub> (Figure 9). When this fluid reached the top of the cumulate pile, it may have been resorbed back into the magma, upon cooling, the sulfide blebs exsolved into chalcopyrite, pyrrhotite, pentlandite, pyrite, alloys, arsenides, and tellurides.

Focusing the fluid to form ballrooms could be the result of several factors, including: local permeability contrasts in the cumulate pile creating concentrated flow pathways, greater melt interaction causing larger areas of fluid saturation, or even that the volume of fluid originated from the intercumulate melt was not uniform across the base of the complex, creating greater fluxes in given areas. Additionally, downwarps in the hanging wall above ballrooms may be the result of this fluid moving upward through the cumulate pile. The increased localized flux could cause a higher degree of fluid-melt reactions and cause the top of the cumulate pile (hanging wall contact) to either “sag” down into the fluid-rich zone beneath or cause resorption and recrystallization to extend deeper into the cumulate pile. This would effectively shift down the entire stratigraphic sequence and thus lower the top of the cumulate pile (hanging wall contact) because of the greater volume of fluid/melt toward the top.

The “sharp” upper and lower boundaries of the reef and ballrooms are evidence for a short-lived event that repeated itself several times creating multiple sulfide

horizons. The fluid separation and subsequent migration may have been triggered by a decrease in pressure in the magma chamber (Figure 14). A sudden short-lived decrease in pressure could have been caused by the eruption of lava from the chamber. Helz (1995) and Lipin and Zientek (2002) suggest that eruption from the magma chamber was not only likely but probable but did not specifically link eruption to mineralization. The combination of opening a vent to the atmosphere and eruption of even a small amount of magma could generate a large enough pressure decrease to induce fluid saturation in the evolved melt remaining in the cumulate pile. When eruption ceased the fluid may have mixed with or dissolved into the magma remaining in the chamber. Evidence for eruption may include disruption of the cumulate pile recorded as slumping and offsets of cumulate stratigraphy in the footwall rocks. Moreover, it is possible that eruption was triggered by a magma mixing event like those detected by Lambert and Simmons (1988).

Eruption and mineralization may have been repeated each time lava erupted from the evolving chamber, creating the multiple sulfide horizons. The Stillwater Complex hosts at least nine sulfide horizons through its exposed section, the J-M Reef being the lowest major stratigraphic sulfide horizon. However, none of the other horizons are as enriched in PGE as the J-M Reef. This is probably the result of a greater PGE concentration in the mafic base of the complex which was stripped and redeposited in the first episode.

There are multiple lines of evidence that the sulfides have been remobilized after magma had completely solidified and pyroxene exsolved. Veinlets and sulfide inclusions in hydrothermally altered pyroxene are evidence of nonmagmatic processes working in

the reef and ballrooms to redistribute the PGE mineralization. Silicates were locally to extensively highly altered. Secondary phases associated with type 1 ballrooms are paragonitic amphibole in pyroxene, sericite and clinozoisite after plagioclase surrounding sulfides and veinlets of sulfide. Those associated with type 2 ballrooms are serpentine, chlorite, and magnetite after olivine, pyrite, calcite, and to a lesser extent sericite and clinozoisite after plagioclase and paragonite after clinopyroxene. This indicates as McCallum et al. (1999) says remobilization by a low temperature hydrothermal fluid associated with a 1.7 Ga regional metamorphic event.

If S, Cu, PGE, and other chalcophile elements were remobilized and redistributed by a low temperature metamorphic event, it is likely that the redistribution would deplete some rocks in these elements (Polovina et al. 2004) and possibly enrich others. Evidence of remobilization is abundant in the Stillwater Mine portion of the J-M Reef as stated above.

According to McCallum et al. (1999) the J-M Reef was affected by the wide development of greenschist facies mineral assemblages (Figure 14). Pb isotope ratios in sulfides readily re-equilibrated with the hydrothermal fluid while plagioclase experienced minimal alteration and retained more primitive values.

Other factors that may be related to a metamorphic event at 1.7 Ga include the change in  $\delta^{18}\text{O}$  of the Reef Package and surrounding rocks from +6 per mil to values of +2 to 3 per mil. It is unclear if the oxygen isotope ratios were changed at the same time as the Pb isotopes but the event was likely associated with the serpentinization of olivine (Lechler et al. 2002).

Post-magmatic fluid flow would be controlled by fracture patterns, density, and geometry (McCallum et al., 1999). Fracture control of fluids could also then control the redistribution of ore in ballrooms. Redistribution was likely only on a scale of mm to cm and perhaps to a few meters. Fleet et al. (1991) also concluded that, even if the PGE deposits in layered intrusions initially formed by sulfide liquid immiscibility, that the extensive PGE enrichment was probably the result of rock-fluid processes during alteration stages.

Much of the wide range in ore grade may be due to the effect of the low temperature hydrothermal fluids remobilizing and transporting metals within and near the reef. The ore grade may be changed locally by mixing with PGE-rich or PGE-poor components added during reactions with externally derived low temperature hydrothermal fluids (McCallum et al., 1999).

#### SUMMARY

Figure 14 illustrates the sequence of processes that may be responsible for the present distribution of the PGE ore in ballrooms and the J-M Reef. The silicate and sulfide mineralogy of ballrooms are very similar to the rest of the J-M Reef as described by McCallum (2002) and others. Size and silicate mineralogy were the controlling factors for defining ballroom types.

The ballrooms likely formed by the process of fluid saturation and migration described by Boudreau (1999). This fluid saturation was likely generated by a pressure decrease in the magma chamber. An eruption of lava from the magma chamber may have triggered the pressure decrease. Sulfides in ballrooms and the J-M Reef were later

remobilized by a low temperature hydrothermal event at 1.7 Ga that created secondary phases (sericite, clinozoisite, pargasite, serpentine, magnetite, chlorite, and calcite), remobilized textures, and made reef mineralization patchy in the Stillwater Mine.

A similar model also probably explains the Picket Pin Horizon and other sulfide bearing horizons throughout the complex. Corkery (2002) noted similar resorption textures, secondary alteration phases, and PGE sulfide grains inside altered pyroxenes of the Picket Pin Horizon.

The absence of ballrooms in the East Boulder Mine and Picket Pin Horizon may be the result of a significantly smaller volume of fluid that moved through the cumulate pile in that area. Evidence for this includes the lower grade of mineralization and narrow mineralized interval throughout the East Boulder Mine and the Picket Pin Horizon. Also, the East Boulder Mine and Picket Pin Horizon, have more continuous, finer grained stratigraphy (fewer pegmatites) in these mineralized intervals.

## REFERENCES

- Andersen, D.J., Lindsley, D.H., Davidson, P.M.; 1993, QUILF; a Pascal program to assess equilibria among Fe-Mg-Mn-Ti oxides, pyroxenes, olivine, and quartz: *Computers-and-Geosciences*, v. 19, p. 1333-1350.
- Barnes, S.J., and Naldrett, A.J., 1985, Geochemistry of the J-M (Howland) Reef of the Stillwater Complex, Minneapolis Adit Area. I. Sulfide Chemistry and Sulfide-Olivine Equilibrium: *Economic Geology*, v. 80, p. 627-645.
- Barnes, S.J., and Naldrett, A.J., 1986, Geochemistry of the J-M Reef of the Stillwater Complex, Minneapolis Adit Area II. Silicate Mineral Chemistry and Petrogenesis: *Journal of Petrology*, v. 27, p. 791-825.
- Boudreau, A.E., 1999, Fluid fluxing of cumulates: the J-M Reef and associated rocks of the Stillwater Complex, Montana: *Journal of Petrology*, v. 40, p. 755-772.
- Boudreau, A.E., and McCallum, I.S., 1992, Concentration of platinum-group elements by magmatic fluids in layered intrusions: *Economic Geology*, v. 87, p. 1830-1848.
- Boudreau, A.E. and McCallum, I.S., 1986. Investigations of the Stillwater Complex. Part III. The Picket Pin Pt-Pd deposit: *Economic Geology*, v. 81, p. 1953-1975.
- Boudreau, A.E., Mathez, E.A., McCallum, I.S., 1986, Halogen geochemistry of the Stillwater and Bushveld Complexes: Evidence for transport of the platinum-group elements by Cl-rich fluids: *Journal of Petrology*, v. 27, p. 967-986.
- Boudreau, A. E., Stewart, M. A., Spivack, A. J., 1997, Stable Cl isotopes and origin of high-Cl magmas of the Stillwater Complex, Montana: *Geology*, v. 25, No. 9, p. 791-794.
- Campbell, I.H. Naldrett, A.J., Barnes, S.J., 1983, A model for the origin of the platinum-rich sulfide horizons in the Bushveld and Stillwater complexes: *Journal of Petrology*, v. 24, p. 133-165.
- Childs, J.F., Evans, J.R., Wood, K.Y., Koski, M.S., Evans, J.D., 2002, Some preliminary descriptive aspects of ballroom mineralization at the Stillwater palladium-platinum Mine, Stillwater Mining Company, Nye, Montana: 9<sup>th</sup> International Platinum Symposium, Abstract with Program, 21-25 July 2002, Billings Montana, p. 91-92.
- Corkery, J. T., 2002, Petrographic Implications for the Picket Pin PGE Deposit, Stillwater Complex, Montana: 9<sup>th</sup> International Platinum Symposium, Abstract with Program, 21-25 July 2002, Billings Montana, p. 97-100.

- Corson, S.R., Childs, J.F., Dahy, J.P., Keith, D.W., Koski, M.S., LeRoy, L.W., 2002, The Reef Package Stratigraphy that Contains the J-M Platinum-Palladium Reef of the Stillwater Complex, Montana: 9<sup>th</sup> International Platinum Symposium, Abstract with Program, 21-25 July 2002, Billings Montana, p. 101-102.
- Czmanske, G.K., and Loferski, P.J., 1996, Cryptic trace-element alteration of anorthosite, Stillwater Complex, Montana: *Canadian Mineralogist*, v. 34, p. 559-576.
- Czmanske, G.K. and Zientek, M.L., eds., 1985, Stillwater Complex: Montana Bureau of Mines and Geology Special Publication 92, 396p.
- De Paolo, D.J., and Wasserburg, G.J., 1979, Sm-Nd age of the Stillwater Complex and the mantle evolution curve for neodymium: *Geochimica et Cosmochimica Acta*, v. 43 p. 999-1008.
- Fleet, M.E., Stone, W.E., Crocket, J. H., 1991, Partitioning of palladium, iridium, and platinum between sulfide liquid and basalt melt: effects on melt composition, concentration, and oxygen fugacity: *Geochimica et Cosmochimica Acta*, v. 55, p. 2545-2554.
- Helz, R.T., 1985, Compositions of fine-grained mafic rocks from sills and dikes associated with the Stillwater Complex, *in* Czmanske, G.K. and Zientek, M.L., eds., *The Stillwater Complex, Montana: Geology and Guide: Montana Bureau of Mines and Geology Special Publication 92*, p. 97-117.
- Helz, R.T., 1995, The Stillwater Complex, Montana: A subvolcanic magma chamber: *American Mineralogist*, v. 80, p. 1343-1346.
- Heyse, J. V., 1983, The mineralogy of the stillwater platinum-palladium ore in the Frog Pond and Minneapolis adits: Chevron Research Company Report, Richmond, California, 41 p.
- Irvine, T.N., Keith, D.W., Todd, S.G., 1983, The J-M platinum-palladium reef of the Stillwater Complex, Montana: II. Origin by double-diffusive convective magma mixing and implications for the Bushveld Complex: *Economic Geology*, v. 78, p. 1287-1334.
- Jones, W.R., Peoples, J.W. and Howland, A.L., 1960, Igneous and tectonic structures of the Stillwater Complex, Montana.:U.S.G.S. Bulletin, 1071-H, p. 281-340.
- Lambert, D.D., and Simmons, E.C., 1988, Magma evolution in the Stillwater Complex, Montana: II. Rare earth element evidence for the formation of the J-M Reef: *Economic Geology*, v. 83, p. 1109-1126.

- Langston, R. B., 1995, Thickness contour studies of PGE mineralization and the relationship between ore zone types in the JM Reef, Stillwater mine, Nye, Montana: Geological Society of America Abstracts with Programs, Rocky Mountain Section, p. 43.
- Lechler, P. J., Arehart, G. B., Knight, M., 2002, Multielement and isotopic geochemistry of the J-M Reef, Stillwater intrusion, Montana: 9<sup>th</sup> International Platinum Symposium, Abstract with Program, 21-25 July 2002, Billings Montana, p. 245-248.
- Lipin, B. R. and Zientek, M. L., 2002, The Stillwater Complex, Montana: The root of a flood basalt province?: 9<sup>th</sup> International Platinum Symposium, Abstract with Program, 21-25 July 2002, Billings Montana, p. 265-268.
- Mathez, E.A. and Peach, C.L., 1989, The geochemistry of the platinum-group elements in mafic and ultramafic rocks, *in* Whitney, J.A., and Naldrett, A.J., eds., *Ore Deposits Associated with Magmas*, *Reviews in Economic Geology*, v. 4, p. 33-43.
- McCallum, I.S., 2002, The Stillwater Complex: A review of the geology, *in* 9<sup>th</sup> International Platinum Symposium Geology and Guide, Stillwater Complex, Montana, USA, p. A-1- A-25.
- McCallum I.S., Thurber D.W., O'Brien H.E., and Nelson B.K., 1999, Lead isotopes in sulfides from the Stillwater Complex, Montana: Evidence for subsolidus remobilization: *Contributions to Mineralogy and Petrology*, v. 137, p. 206-219.
- McCallum, I.S., Raedeke, L.D., and Mathez, E.A., 1980. Investigations in the Stillwater Complex: Part I. Stratigraphy and structure of the Banded zone: *American Journal of Science*, v. 280A, p. 59-87.
- Morimoto, N., Fabries, J., Ferguson, A.K., Ginzberg, I.V., Ross, M., Seifert, F.A., Zussman, J., Aoki, K., and Gottardi, G., 1988, Nomenclature of pyroxenes: *American Mineralogist*, v. 73, p. 1123–1133.
- Munoz, J. L., 1984, F-OH and Cl-OH exchange in micas with applications to ore deposits, *in* Bailey, S. W., ed., *Reviews in Mineralogy, Micas*, v. 13, p. 469-493.
- Page, N. J., Zientek, M. L., Czamanske, G. K., Foose, M. P., 1985, Sulfide mineralization in the Stillwater Complex and underlying rocks, *in* Czamanske, G.K. and Zientek, M.L., eds., *The Stillwater Complex, Montana: Geology and Guide: Montana Bureau of Mines and Geology Special Publication 92*, p. 93-96.
- Polovina, J.S., Hudson, D.M., and Jones, R.E., 2004, Petrographic and geochemical characteristics of postmagmatic hydrothermal alteration and mineralization in the J-M Reef, Stillwater Complex, Montana: *The Canadian Mineralogist*, v. 42, p.



261-277.

- Premo, W. R., Helz, R. T., Zientek, M. L., Langston, R. B., 1990, U-Pb and Sm-Nd ages for the Stillwater Complex and its associated sills and dikes, Beartooth Mountains, Montana: Identification of a parent magma?: *Geology*, v. 18, p. 1065-1068.
- Raedeke, L.D., and Vian, R.W., 1986, A three dimensional view of mineralization in the Stillwater J-M Reef: *Economic Geology*, v. 81, p. 1187-1195.
- Todd, S.G., Keith, D.W., LeRoy, L.W., Shissel, D.J., Mann, E.L., and Irvine, T.N., 1982, The J-M platinum-palladium reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology: *Economic Geology*, v. 77, p. 1454-1480.
- Vermaak, C.F., 1976, The Merensky Reef; thoughts on its environment and genesis: *Economic Geology*, An issue devoted to platinum-group elements, v. 71, p. 1270-1298.
- Von Gruenewaldt, 1979, A review of some recent concepts of the Bushveld Complex, with particular reference to sulfide mineralization: *Canadian Mineralogist*, v. 17, p. 233-256.
- Zientek, M.L., Fries, T.L., Vian, R.W., 1990, As, Bi, Hg, S, Sb, Sn, and Te geochemistry of the J-M Reef, Stillwater Complex, Montana: constraints on the origin of PGE-enriched sulfides in layered intrusions: *Journal of Geochemical Exploration*, v. 37, p. 51-73.

## FIGURE CAPTIONS

Fig. 1

Simplified geologic map of the Stillwater Complex showing major subdivisions, faults, and the J-M Reef and the Picket Pin Horizon. Inset map shows the location of the complex along the front of the Beartooth Mountains. Redrawn from McCallum (2002).

Fig. 2

Stratigraphy of the Stillwater Complex. Subdivisions based on McCallum et al. (1980) and Todd et al. (1982). Revised from Zientek et al. (1985). Letters A-K represent chromite horizons, P represents transgressive pegmatites, and S represents sulfide horizons. This study uses the subdivisions of Todd et al. (1982). The J-M Reef is located near the bottom of Troctolite-Anorthosite Zone 1.

Fig. 3

Stratigraphy of a type 1 ballroom (19108 drill core, the core log for this drill core is in Appendix B). Mineralization is continuous from the base of mineralization to the hanging wall (HW) contact. All units are in meters. Lithologic labels are: p) plagioclase, o) olivine, b) bronzite, L) leucocratic, C) cumulate, P) pegmatite. Photomicrograph labels are: pl) plagioclase, opx) orthopyroxene (enstatite), cpx) clinopyroxene (augite), ol) olivine, s) sulfide, ap) apatite, and am) amphibole, clz) clinozoisite, pr) pyrrhotite, pt) pentlandite, cp) chalcopyrite, br) braggite. Photomicrographs taken at 20x magnification in cross polarized light. A) Pegmatitic norite with a sulfide vein cutting through the sample from the top left to bottom right. B) Anorthosite with a vein of clinozoisite cutting horizontally across the top of the photo. C) Pegmatitic textures in norite from the Reef Package. D) Unmineralized sample that has been only lightly altered by secondary

processes.

Fig. 4

Stratigraphy of a typical type 2 ballroom (3800 E1700 ballroom). Photomicrographs taken at 20x magnification in cross polarized light. Mineralization is continuous

throughout the 11.6 m of ore zone “ballroom.” All units are in meters. Lithologic labels are: p) plagioclase, o) olivine, b) bronzite, L) leucocratic, C) cumulate, P) pegmatite.

Photomicrograph labels are: pl) plagioclase, opx) orthopyroxene (bronzite), ol) olivine, s) sulfide, am) amphibole. A) Dunite with a large magmatic sulfide bleb in the lower left

hand corner. Small veins of remobilized sulfide extend up through the altered olivine above the sulfide. B) Troctolite common in the Reef Package. C) Dunite that has

extensive serpentinization of the olivine and sericitization of the plagioclase.

Remobilized sulfide has moved into and replaced part of the fractured plagioclase. D)

Anorthosite with small sulfides in fractures in an intercumulus orthopyroxene. E) Norite with sulfide replacing orthopyroxene.

Fig.5

Schematic cross-sections of ballroom morphologies in the Stillwater Mine.

Mineralization is represented by gray shading over rock units. A) Type 1 ballroom where mineralization (gray) extends into footwall lithologies. B) Type 2 ballroom where both

the reef package (poCP and pC) and mineralization abruptly thicken. C) Type 3 ballroom hosted in reef package rock, mineralization isolated in a stratabound lens below the Reef

Package. Labels: p) plagioclase, b) bronzite (orthopyroxene), a) augite (clinopyroxene)

o) olivine, C) cumulate, P) pegmatite, HW) hanging wall, FW) footwall. The base of the

Reef Package is represented by the base of the olivine-bearing units in each cartoon. The hanging wall of the J-M Reef is represented by a black line at the top of the mineralization.

Fig. 6

Compositions of plagioclase from both ballroom types. There is very little variation in composition of plagioclase and they are not zoned. The small group of four analyses that are the most Ab-rich are from sample 3817-5 where the plagioclase has more sericitic alteration than the other samples.

Fig. 7

Olivine and pyroxene compositions from ballrooms in the Stillwater Mine. Olivine from both types of ballrooms forms a tight population with an average composition of Fo<sub>77</sub>. Two distinct populations of pyroxene are present in ballrooms-Mg-rich orthopyroxene (enstatite) and Ca-rich clinopyroxene (augite). The most Di-rich analyses are from intercumulate grains of clinopyroxene. All other clinopyroxene analyses are from exsolution lamellae in host orthopyroxene (Morimoto et al. 1988).

Fig.8

Photomicrographs from type 1 and 2 ballrooms showing sulfide textures. All photomicrographs taken at 20x magnification. pl) plagioclase, cpx) clinopyroxene, opx) orthopyroxene, ol) olivine, ap) apatite, s) sulfide, pt) pentlandite, pr) pyrrhotite, cp) chalcopyrite, br) braggite. A) Anorthosite with small intercumulate magmatic sulfide blebs. B) Orthopyroxene and clinopyroxene replaced by sulfide that exsolved into pentlandite, pyrrhotite, and chalcopyrite. C) Norite where sulfide replaced part of orthopyroxene. D)

Orthopyroxene with small sulfide grains replacing clinopyroxene exsolution lamellae. E) Pegmatitic dunite with large sulfide blebs orthopyroxene is partially replaced. F) Veinlet with sulfide cutting through plagioclase and orthopyroxene from top to bottom.

Fig. 9

Fe<sub>2</sub>O<sub>3</sub> vs. Al<sub>2</sub>O<sub>3</sub> concentrations in whole-rock samples from the Stillwater Mine. Average plagioclase, orthopyroxene, clinopyroxene, and olivine plotted to show cumulate mineral control on whole rock major element composition. Mineralized rocks are defined by sulfur concentrations > 300 ppm, Cu > 100 ppm, and Ni > 300 ppm. The trend shows that mineralization did little to disrupt the magmatic trends, but mineralized rocks are slightly enriched in Fe due to sulfide addition. Parent magma composition is taken from Helz (1995).

Fig. 10

Whole-rock compositions of rocks from ballrooms. Cu (contained in sulfides) correlates well with Pd and Pt when they are also in sulfides. However, if PGE are in tellurides, arsenides, or alloys there is no correlation with Cu. The correlation between Cu and Pd and Pt can be used to approximate Pd and Pt contents in samples that have no Pd and Pt assays. A group of five samples (circled) with low Cu concentrations do not correlate with Pd or Pt. These samples likely host Pd and Pt in tellurides, arsenides, and as alloys and lack Cu-rich sulfides.

Fig. 11

MgO vs. Ni concentrations in whole-rock analyses from the Stillwater Mine.

Mineralized rocks are defined by sulfur concentrations > 300 ppm. There is a distinct

correlation of unmineralized samples that is likely the magmatic fractionation trend.

However, Ni and MgO in mineralized samples do not correlate. This lack of correlation shows that Ni (Cu, S, and by inference Pd and Pt) behave independently from the major elements and were probably controlled by processes independent of magmatic controls.

Fig. 12

Whole rock compositions of samples from ballrooms. A) No correlation between Cu, Ni, and S and  $Al_2O_3$ . B) Strong correlation between Cu, Ni, and S. This correlation shows that Cu, Ni, and S behave independently from the major elements, which were controlled by magmatic processes, and behave the same as each other. This suggests that these chalcophile elements were controlled by processes independent of magmatic controls.

Fig. 13

Chart showing the paragenetic sequence of minerals found in ballrooms.

Fig. 14

Model for formation of J-M Reef and ballrooms at the Stillwater Mine. A) A convecting magma chamber with multiple injections of new magma forms at 2.7 Ga. B) Eruption of flood lava generates a pressure decrease that triggers fluid saturation of the cumulate pile. The fluid migrates upward through the cumulate pile carrying with it sulfides and PGEs. C and D) The fluid forms pegmatites, hydrous phases, and deposits sulfides and PGEs just below the base of the magma chamber as the J-M Reef and ballrooms. E and F) Low temperature hydrothermal alteration associated with a 1.7 Ga regional metamorphic event remobilizes sulfides, chalcophile elements, and PGEs and locally redistributes them. Labels: pl) plagioclase, ol) olivine, opx) orthopyroxene, clz) clinozoisite, serp) serpentine, sc) sericite, s) sulfide.

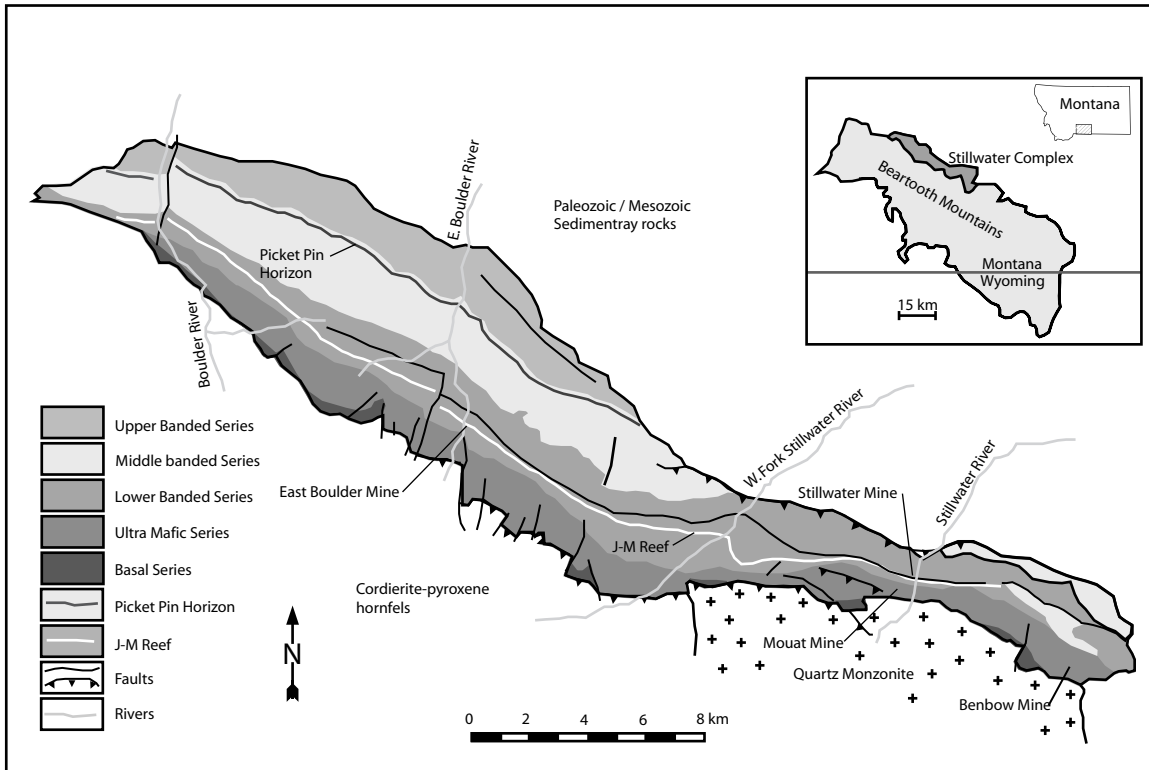


Fig. 1

Approximate distribution of cumulus minerals

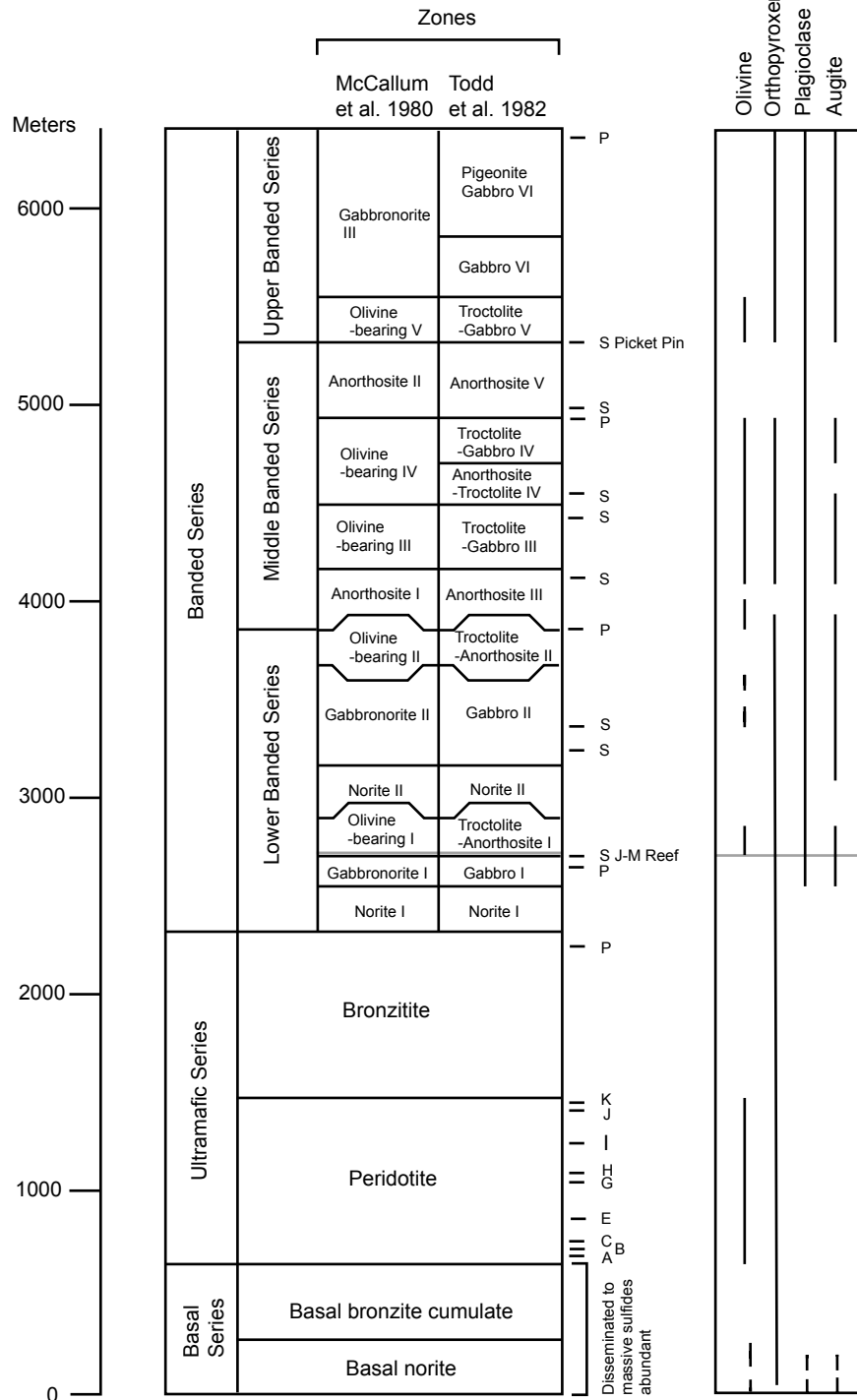
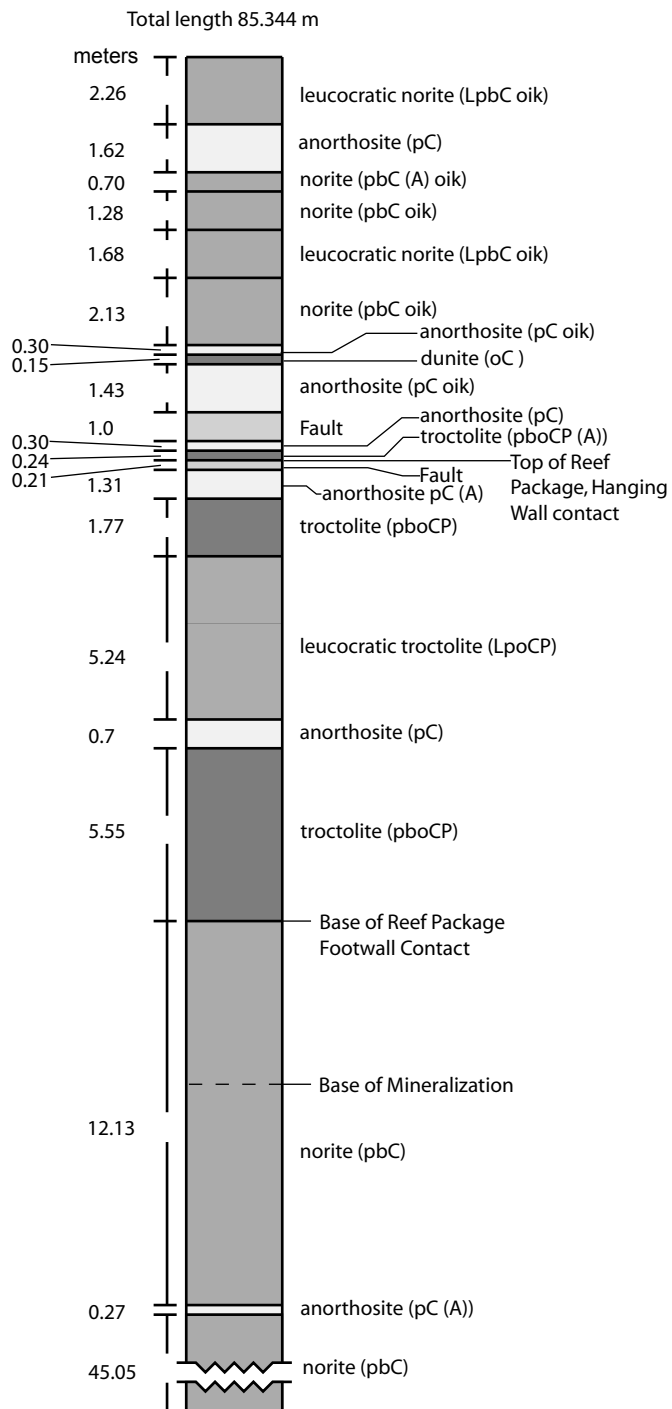
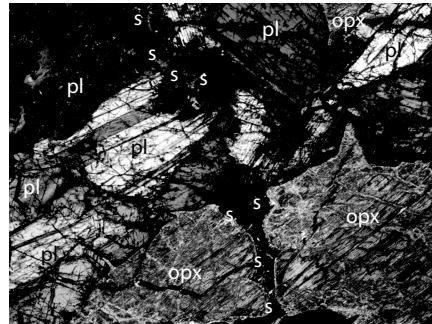


Fig. 2

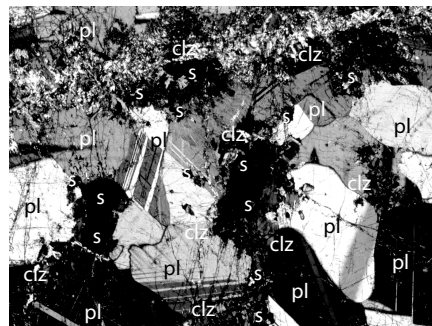




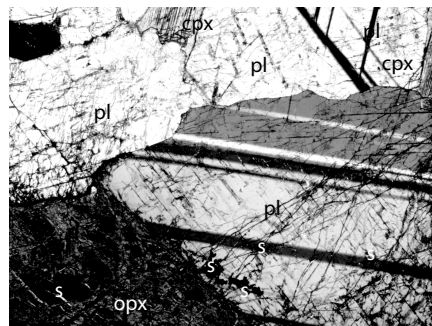
A. Pegmatitic norite with vein of sulfide



B. Anorthosite with vein of clinzoisite



C. Pegmatitic norite



D. Lightly altered anorthosite

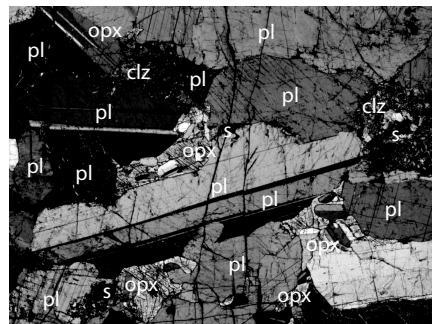
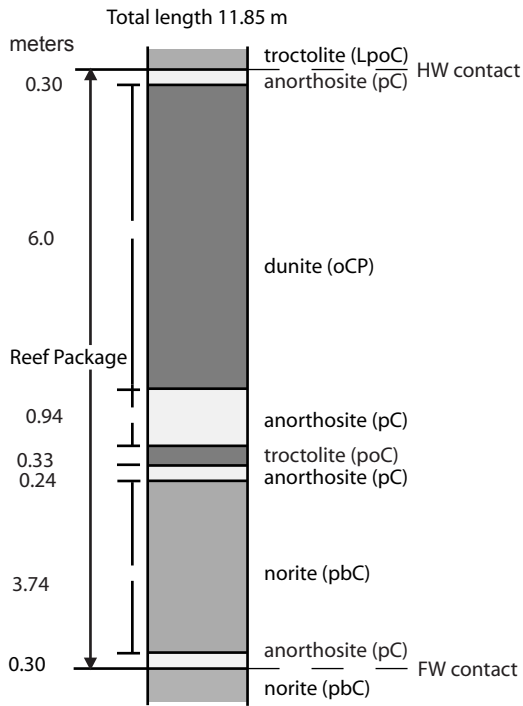
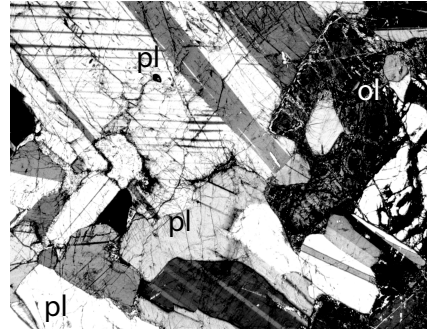


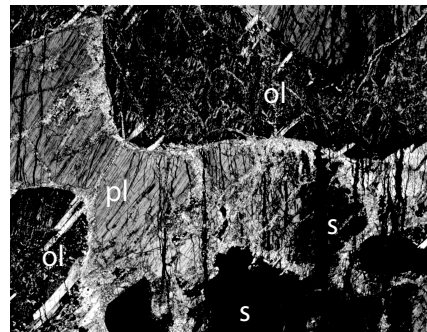
Fig.3



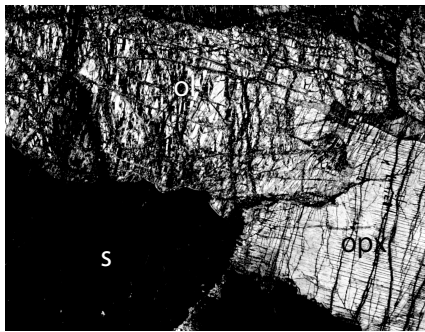
B. Troctolite



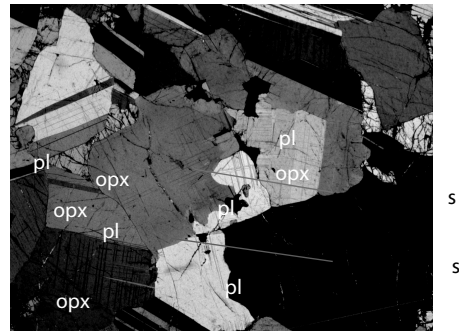
C. Dunite with sericitized plagioclase



A. Dunite with large magmatic sulfide bleb



D. Anorthosite



E. Norite with sulfide replacing orthopyroxene

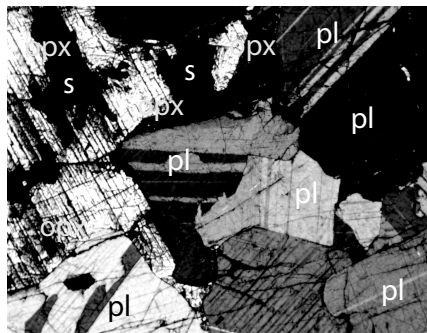


Fig.4

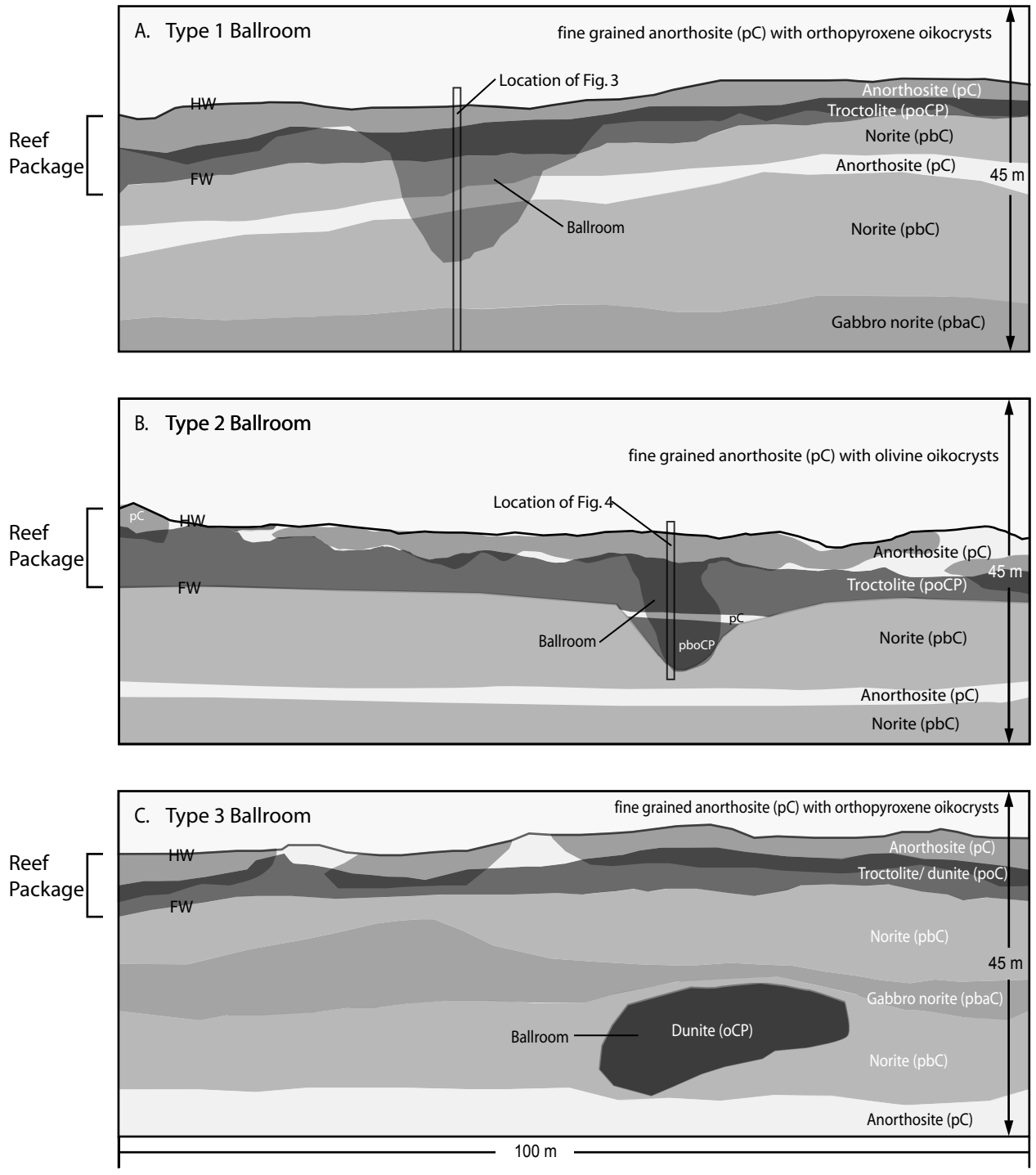


Fig.5

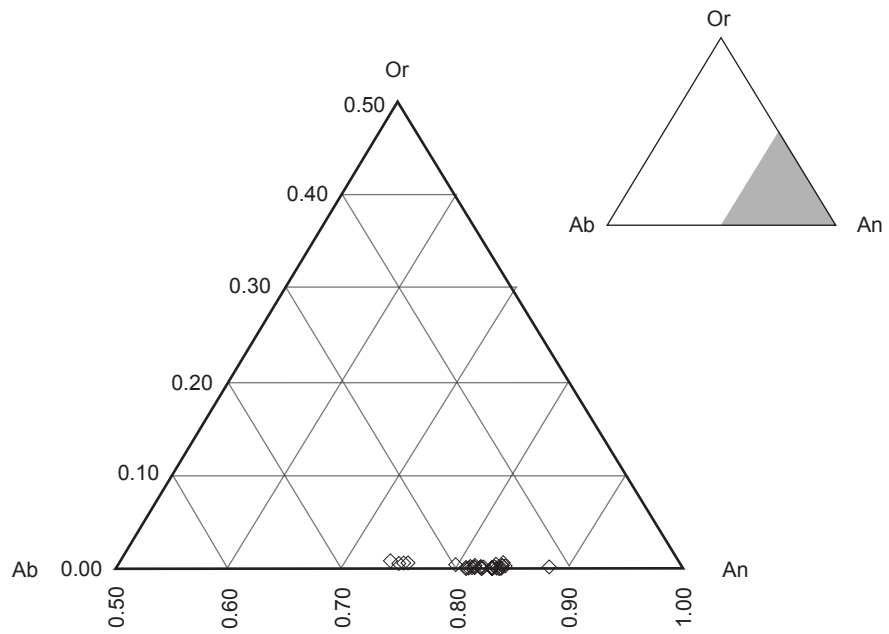


Fig. 6

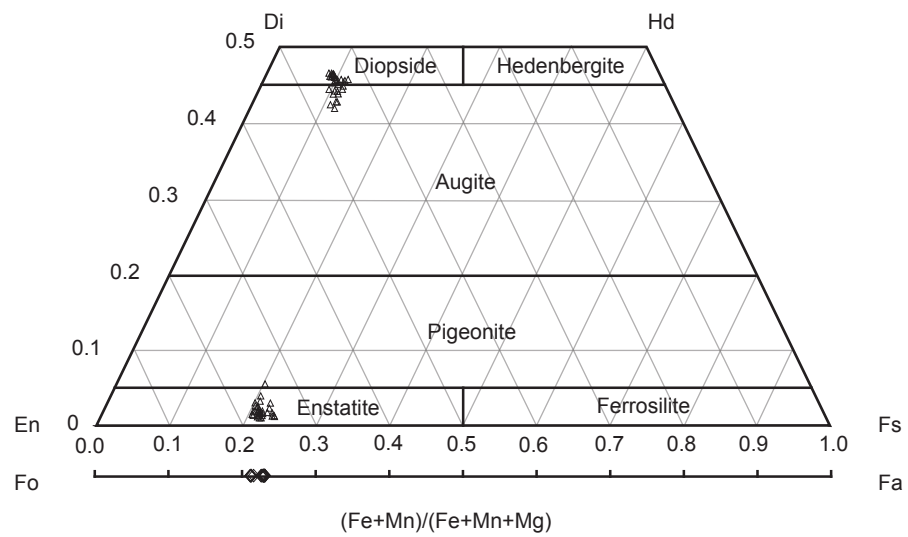


Fig. 7



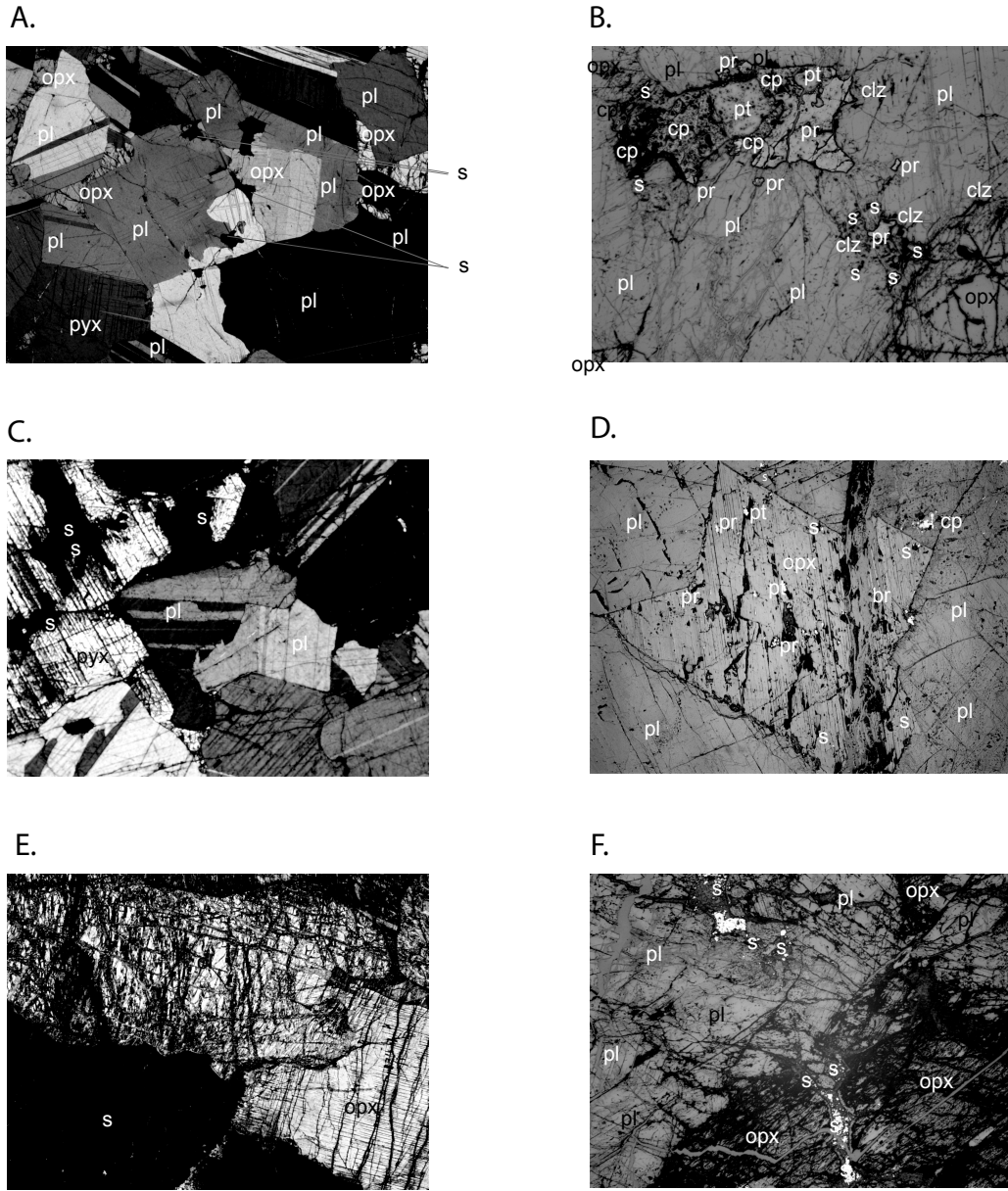


Fig.8.

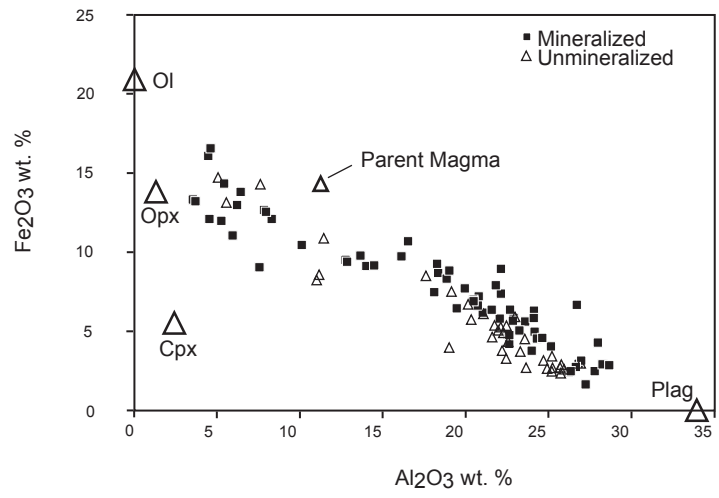


Fig. 9

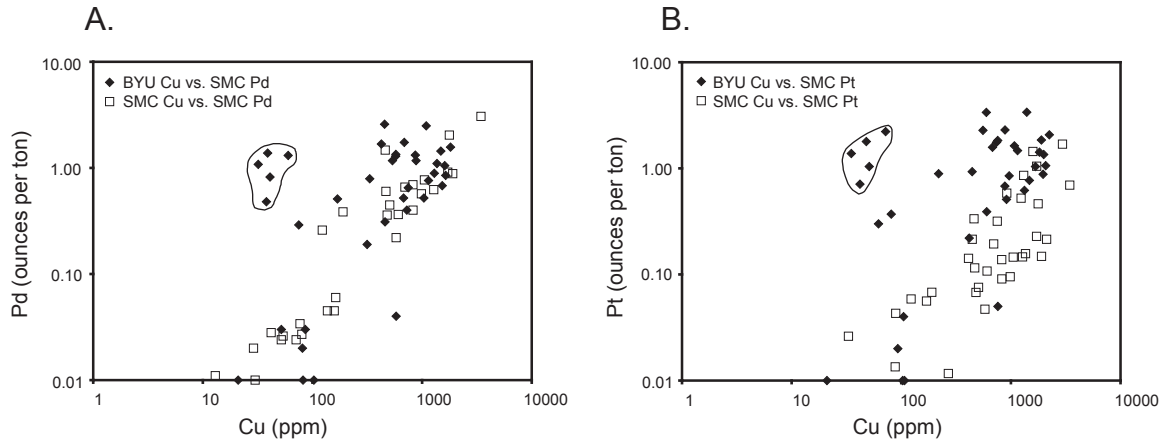


Fig. 10

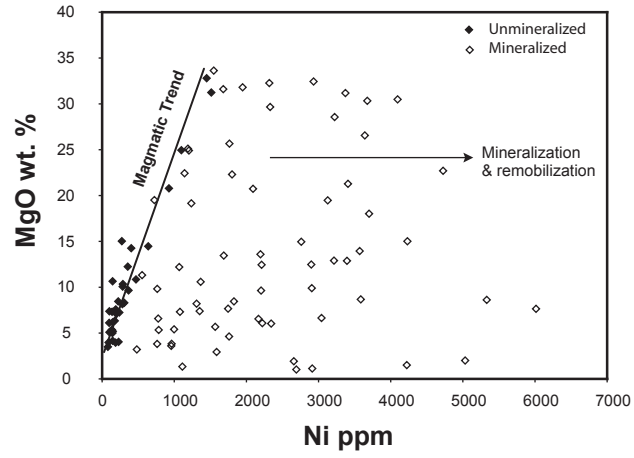


Fig. 11



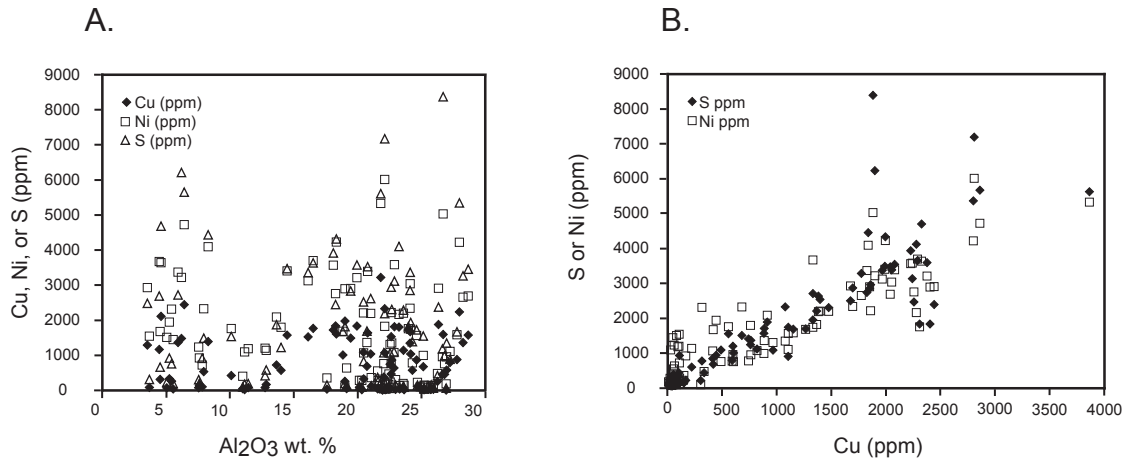


Fig. 12

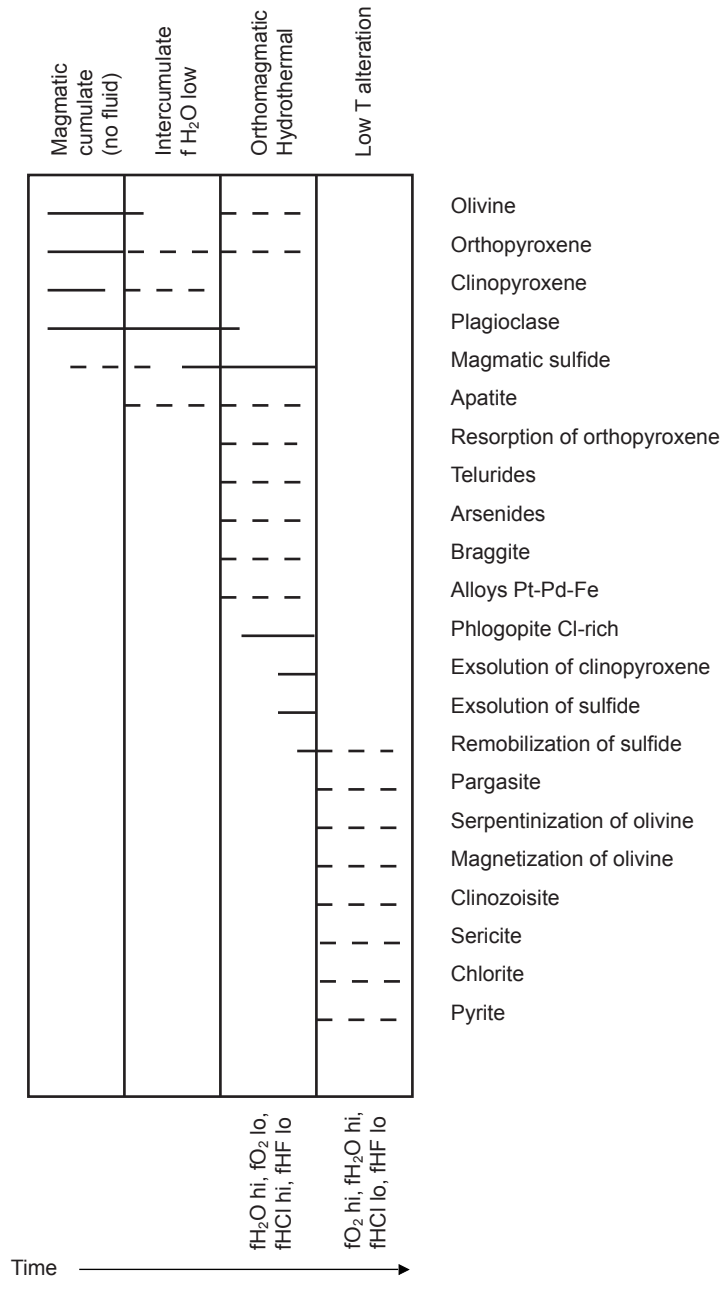


Fig. 13

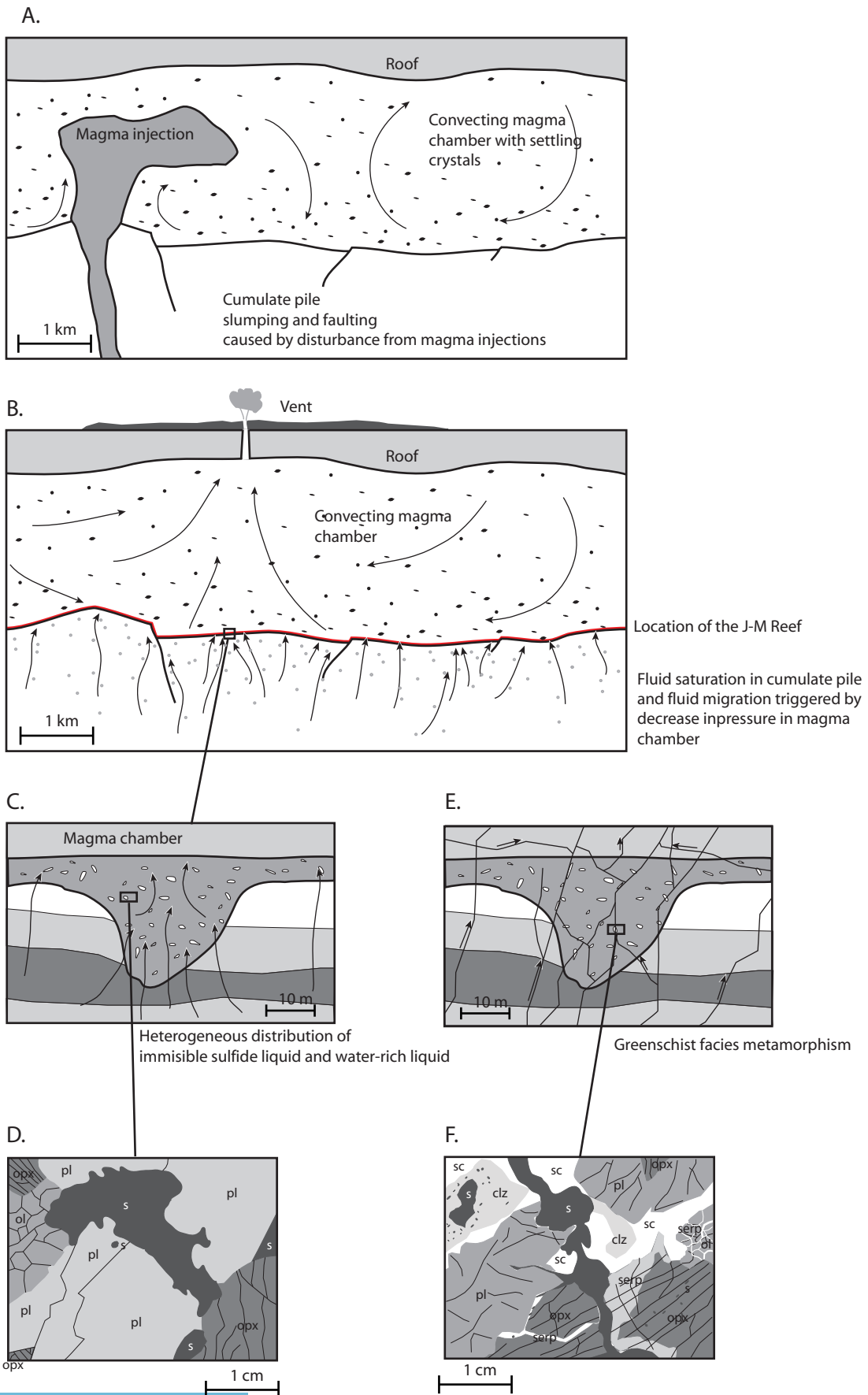


Fig.14

Table 1. Representative mineral analyses from ballrooms.

	Plagioclase <sup>2</sup>	Olivine <sup>3</sup>	Orthopyroxene <sup>4</sup>	Clinopyroxene <sup>4</sup>	Biotite <sup>5</sup>	Apatite <sup>6</sup>
SiO <sub>2</sub>	46.64	38.44	54.74	51.59	38.30	1.03
TiO <sub>2</sub>		0.01	0.31	0.32	3.97	
Al <sub>2</sub> O <sub>3</sub>	34.58	0.01	0.95	2.97	15.73	
Cr <sub>2</sub> O <sub>3</sub>			0.26	0.15		
FeO		21.98	13.94	6.21	8.21	
Fe <sub>2</sub> O <sub>3</sub>	0.00					0.74
MnO		0.25	0.23	0.91	0.03	
MgO		38.82	28.66	15.66	20.20	
CaO	17.11	0.06	0.84	21.94	0.00	51.97
Na <sub>2</sub> O	1.77		0.00	0.25	0.62	0.20
K <sub>2</sub> O	0.06				8.77	
P <sub>2</sub> O <sub>5</sub>						38.87
F					0.09	0.30
Cl					0.30	6.95
H <sub>2</sub> O					4.03	
An. Total	100.16	99.57	99.92	99.99	100.14	99.97
Cations						
Si	2.14	1.00	1.96	1.90	2.77	0.18
Al	1.87	0.00	0.04	0.13	1.34	
Ti		0.00		0.01	0.22	
Cr			0.01	0.00		
Mg		1.51	1.53	0.86	2.18	
Fe <sup>3+</sup>	0.00		0.00	0.06		0.10
Fe <sup>2+</sup>		0.48	0.42	0.13		
Fe t					0.50	
Mn		0.01	0.01	0.03	0.00	
Ca	0.84	0.00	0.03	0.87	0.00	9.86
Na	0.16			0.02	0.09	0.04
K	0.00				0.81	
P						5.82
F					0.02	0.17
Cl					0.04	2.08
Sum	5.00	3.00	4.00	4.00	7.00	8.07
End Members						
	Ab 16	Fo 76	Wo 1.62	Wo 44.51	Ph 72.6	
	An 84	Fa 24	En 77.01	En 44.21	Sid 14.6	
	Or 0	Te 0	Fs 21.37	Fs 11.28	Ann 12.8	
	Cs 0	La 0				

1. An. Total = Analytical total

2. Cations calculated on the basis of 8 oxygens

3. Normalized to 3 cations per formula unit

4. Normalized to 4 cations per formula unit

5. Normalized to 7 octahedral and tetrahedral cations per formula unit

6. Normalized to 16 cations per formula unit

Table 2. Major and trace element whole rock analyses of representative rock types from the Stillwater Mine.

SMC Powder	18845-1	17120-1	255	17151-2	17119-3
Rock Name	Anorthosite	Troctolite	Norite	Dunite	Gabbro norite
Rock Type	pC	poCP	pbC	oCP	pbaC
SiO <sub>2</sub>	48.60	45.68	49.93	49.90	48.86
TiO <sub>2</sub>	0.07	0.04	0.09	0.18	0.38
Al <sub>2</sub> O <sub>3</sub>	25.22	23.57	22.25	17.58	7.82
Fe <sub>2</sub> O <sub>3</sub>	2.70	5.63	4.91	8.51	12.67
MnO	0.04	0.06	0.08	0.14	0.20
MgO	5.00	9.64	7.58	12.24	19.51
CaO	16.19	14.26	13.61	10.34	10.19
Na <sub>2</sub> O	2.08	1.06	1.44	1.01	0.30
K <sub>2</sub> O	0.08	0.06	0.09	0.07	0.05
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.02	0.02	0.03
LOI	1.73	2.56	1.32	0.30	1.67
An. Total	100.20	100.00	99.86	101.98	103.88
ppm					
Ba	21	9	21	15	8
Cr	174	143	523	953	937
Cu	40	1474	42	42	107
Nb	nd	nd	nd	nd	nd
Ni	143	2203	189	355	724
Rb	1	1	nd	2	2
S	64	2311	102	177	939
Sr	145	123	140	83	43
V	42	18	63	109	238
Y	7	9	8	10	16
Zn	16	35	32	59	85
Zr	17	21	20	36	49
ounces per ton					
Pt	nd	0.01	nd	0.23	nd
Pd	nd	0.76	nd	0.48	0.01
Pt+Pd	nd	0.77	nd	0.71	0.01

1. Normalized to 100% on a volatile free basis.

2. An. Total = Analytical total

3. LOI = loss on ignition at 1000°C for 4 hours.

4. Pt & Pd analyzed by ICP-MS at Stillwater Mining Company's Assay lab. Other elements by XRF at BYU.

5. nd = not detected

6. Rock type abbreviations: L) leucocratic, M) melanocratic, C) cumulate, P) pegmatite, (A) altered, p) plagioclase, b) orthopyroxene (bronzite), o) olivine, a) clinopyroxene (augite)

**Table 3. Ballroom type comparison**

	Type 1	Type 2
Host Rock Type	Footwall norite and anorthosite with Reef Package rocks on top	Reef package troctolite, dunite, and anorthosite
Texture	Coarse grained	Coarse grained
Shape	Keel like shape see Fig. 5	Keel like shape see Fig. 5
<b>Mineralogy</b>		
Plagioclase	An <sub>84</sub> to An <sub>74</sub>	An <sub>84</sub> to An <sub>74</sub>
Orthopyroxene	Wo <sub>2</sub> En <sub>77</sub> Fs <sub>21</sub>	Wo <sub>2</sub> En <sub>77</sub> Fs <sub>21</sub>
Clinopyroxene	Wo <sub>45</sub> En <sub>45</sub> Fs <sub>10</sub>	Wo <sub>45</sub> En <sub>45</sub> Fs <sub>10</sub>
Olivine	Fo <sub>77</sub> Fa <sub>23</sub> less abundant	Fo <sub>77</sub> Fa <sub>23</sub> more abundant
Phlogopite	Fe/Fe+Mg 0.187 rare	Fe/Fe+Mg 0.187 abundant
Pargasite	More abundant	Less abundant
Apatite	Less abundant	More abundant
Mineralization	No distinct difference: 0.5 to several ounces per ton as sulfide blebs, networks, veinlets and minor tellurides, arsenides, and alloys	No distinct difference: 0.5 to several ounces per ton as sulfide blebs, networks, veinlets and minor tellurides, arsenides, and alloys
Size	Minimum of 6 m thick and 5 m long no upper limit on size	Minimum of 6 m thick and 5 m long no upper limit on size
Location	More common in the central workings of the Stillwater Mine stratigraphically below the J-M Reef	Spread throughout Stillwater Mine within the J-M Reef
Secondary Alteration	Abundant clinozoisite and sericitic alteration of plagioclase	Abundant serpentinization and magnetization of olivine, but less sericitic alteration of plagioclase
Proposed Genesis	No intercumulate melt present: mineralization is the result of fluid concentration and sulfide saturation and precipitation in a localized area below the J-M Reef.	Melt present: mineralization is the result of fluid melt interaction causing sulfide saturation and precipitation in a localized area of the J-M Reef.

## APPENDICES

## APPENDIX A



**STILLWATER MINING COMPANY**

**DIAMOND DRILL LOG**

**HOLE NO. 19108**

COLLAR  
ELEV.  
LOCATION 4100 West 8362

INCL. 27°  
AZIM. 000°

STARTED 02/08/21  
COMPLETED 02/08/22  
TOTAL DEPTH 280.00'  
CORE SIZE BQ

SHEET 1 OF 5  
SCALE 1" = 10'

LOGGED BY MPH

DATE 02/08/26

Depth (ft)	STRUCTURE AND ALTERATION	Struc Min Lith	LITHOLOGY AND MINERALIZATION	Fm	UCS	Core Rec %	RQD	Fill	ASSAYS							
									Fm	To	Int	Pt	Pd			
0	2.90' fracture @ 10° to core axis	/	0.0-147.8' pbC													
5																
10																
15																
20																
25	27.20' strong serpentine fracture @ 53° to core axis	/														
30	30.50' serpentine carbonate fracture @ 75° to core axis	/														
35	31.80' fracture @ 40° to core axis	/														
40																
45	43.60' (0.10) serpentine rubble gouge	/														
50	45.90' serpentine carbonate fracture @ 62° to core axis	/														
55																
60	58.90' carbonate fracture @ 60° to core axis	/														
COMMENTS: Purple Hole; 70' of good ore; HW @ 242.1'; medium to good ground									08-26-2002 11:28:34							

STILLWATER MINING COMPANY				DIAMOND DRILL LOG				HOLE NO. 19108											
COLLAR		INCL. 27°		STARTED 02/08/21		SHEET 2 OF 5													
ELEV.		AZIM. 000°		COMPLETED 02/08/22		TOTAL DEPTH 280.00'		SCALE 1" = 10'											
LOCATION 4100 West 8362				CORE SIZE BQ		LOGGED BY MPH		DATE 02/08/26											
Depth (ft)	STRUCTURE AND ALTERATION	Struc	Min	Lith	LITHOLOGY AND MINERALIZATION	UCS		RQD		ASSAYS									
						Flag	Core Rec %	00	00	00	00	00	00	Fm	To	Int	Pt	Pd	
	66.50' (0.80) zeolite carbonate shear zone friable gouge @ 20° to core axis				0.0-147.8' pbC														
65	68.20' (0.30) fracture @ 37° to core axis. Bleached Core																		
70	74.50' strong serpentine fracture @ 60° to core axis																		
75	81.30' carbonate fracture vein @ 90° to core axis																		
80	83.40' fracture @ 36° to core axis																		
85	84.60' fracture @ 36° to core axis																		
90	86.20' serpentine carbonate fracture vein @ 90° to core axis																		
95	91.60' serpentine carbonate fracture @ 80° to core axis			pbC															
100	93.00' fracture @ 25° to core axis																		
105	97.90' severe serpentine carbonate fracture @ 90° to core axis																		
110	98.80' serpentine fracture @ 18° to core axis																		
115	102.20' carbonate serpentine fracture @ 90° to core axis																		
120	109.50' carbonate shear clay gouge @ 32° to core axis																		
	112.30' carbonate serpentine fracture @ 20° to core axis																		

COMMENTS: Purple Hole; 70' of good ore; HW @ 242.1'; medium to good ground

08-26-2002 11:28:34

STILLWATER MINING COMPANY

DIAMOND DRILL LOG

HOLE NO. 19108

COLLAR

INCL. 27°  
AZIM. 000°

STARTED 02/08/21  
COMPLETED 02/08/22  
TOTAL DEPTH 280.00'  
CORE SIZE BQ

SHEET 3 OF 5  
SCALE 1" = 10'

ELEV.

LOCATION 4100 West 8362

LOGGED BY MPH

DATE 02/08/25

Depth (ft)	STRUCTURE AND ALTERATION	Struc Min Lith	LITHOLOGY AND MINERALIZATION	Flag	UCS	Core Rec #	RQD	Fill	ASSAYS									
									Fm	To	Int	Pt	Pd					
125	120.70' serpentine carbonate fracture @ 65° to core axis		0.0-147.8' pbC															
130	131.00' severe serpentine carbonate fracture @ 90° to core axis																	
135	134.00' (0.50) carbonate veinlets @ 50° to core axis		pbC															
145	145.20' carbonate vein @ 62° to core axis																	
150	148.70' severe serpentine carbonate fracture @ 50° to core axis		147.8-148.7' pbC (R) 148.7-188.5' pbC															
155	153.20' serpentine fracture @ 65° to core axis																	
160	157.40' fracture @ 35° to core axis																	
165	164.20' shear fracture @ 60° to core axis																	
170	173.40' fracture @ 30° to core axis		pbC															
175	175.40' serpentine talc fracture @ 30° to core axis																	
175	175.90' carbonate fracture @ 90° to core axis		171.80-173.00' Sulfides 1-2% bl															
180	179.10' fracture @ 30° to core axis. Bleached core		176.70-186.70' Sulfides 1/2-1% bl, in															

COMMENTS: Purple Hole; 70' of good ore; HW @ 242.1'; medium to good ground

08-26-2002 11:28:34

STILLWATER MINING COMPANY

DIAMOND DRILL LOG

HOLE NO. 19108

COLLAR  
ELEV. LOCATION 4100 West 8362  
INCL. 27°  
AZIM. 000°

STARTED 02/08/21  
COMPLETED 02/08/22  
TOTAL DEPTH 280.00'  
CORE SIZE BQ

SHEET 4 OF 5  
SCALE 1" = 10'

LOGGED BY MPH

DATE 02/08/26

Depth (ft)	STRUCTURE AND ALTERATION	Struc Min Lith	LITHOLOGY AND MINERALIZATION	UCS		Core Rec %	RQD				FILL	ASSAYS						
				Frag	Com		0-25	25-50	50-75	75-100		Fm	To	Int	Pt	Pd		
182.20'	serpentine fracture @ 35° to core axis		148.7-188.5' pbC															
183.00'	serpentine vein @ 30° to core axis	pbC	176.70-186.70' Sulfides 1/2-1% bl, in															
185.30'	carbonate fracture @ 20° to core axis		188.5-206.7' pbcCP oikocrysts															
188.50'	BOR																	
190.00'	carbonate serpentine vein @ 90° to core axis	pbcCP																
190.50'	(0.30) serpentine rubble broken core																	
200.30'	broken core																	
209.30'	serpentine fracture @ 44° to core axis	pC	206.7-209.0' pC ic pyx															
212.60'	shear fracture @ 30° to core axis		209.0-226.2' LpoCP															
211.70'	(2.70) carbonate veinlets. random vein orientations	LpoCP	188.40-233.00' Sulfides 1/2-1% bl															
220.00'	carbonate vein diskings		226.2-232.0' pbcCP															
224.30'	mylonite shear @ 90° to core axis		232.0-236.3' pC (A) ic pyx															
236.3-237.0'		pbcCP	236.3-237.0' Fault (A)															
234.50-238.40'			234.50-238.40' Sulfides 1/2-1% bl, ds															
237.0-237.8'		pC	237.0-237.8' pbcCP (A)															
237.8-238.8'		FLT	237.8-238.8' pC															
238.8-242.1'		pC	238.8-242.1' Fault															
		FLT																

COMMENTS: Purple Hole; 70' of good ore; HW @ 242.1'; medium to good ground

08-26-2002 11:28:34

**STILLWATER MINING COMPANY**

**DIAMOND DRILL LOG**

**HOLE NO. 19108**

COLLAR  
ELEV.  
LOCATION 4100 West 8362

INCL. 27°  
AZIM. 000°

STARTED 02/08/21  
COMPLETED 02/08/22  
TOTAL DEPTH 280.00'  
CORE SIZE BQ

LOGGED BY MPH

SHEET 5 OF 5  
SCALE 1" = 10'  
DATE 02/08/26

Depth (ft)	STRUCTURE AND ALTERATION	Struc Min	Lith	LITHOLOGY AND MINERALIZATION	Fln	UCS	Core Rec %	RQD	Fill	ASSAYS								
										Fm	To	Int	Pt	Pd				
238.80'	(3.30) fault gouge mylonite. SPF		FLT	238.8-242.1' Fault														
242.10'	HW		pC	242.1-246.8' pC oikocrysts														
245.90'	carbonate vein @ 35° to core axis		pC	246.8-247.3' oC buckshot olivine														
247.30'			pC	247.3-248.3' pC oikocrysts														
250.70'	shear @ 30° to core axis		pbC	248.3-255.3' pbC oikocrysts														
254.00'	fracture @ 22° to core axis		LpbC	255.3-260.8' LpbC oikocrysts														
258.10'	carbonate vein @ 70° to core axis		pbC	260.8-265.0' pbC oikocrysts														
264.50'	shear gouge @ 35° to core axis		pbC	265.0-267.3' pbC (A) oikocrysts														
267.00'	(3.50) carbonate broken core. broken core flooded and cemented with CO3		pC	267.3-272.6' pC														
275.80'	fracture @ 20° to core axis		LpbC	272.6-280.0' LpbC oikocrysts. Ghosted opx														
280.00'	End of Hole																	

COMMENTS: Purple Hole; 70' of good ore; HW @ 242.1'; medium to good ground

08-26-2002 11:28:34

Appendix B. Major and trace element whole rock analyses of rocks from the Stillwater Mine

	1	2	3	4	5	6
SMC Powder	13836-1	13842-1	13842-2	17119-2	17119-2	17119-3
Rock Type	LpbC	pC/Fault	oC/Fault	poCP	oC	pbaC
SiO <sub>2</sub>	49.43	46.64	44.58	45.03	48.43	48.86
TiO <sub>2</sub>	0.07	0.07	0.10	0.06	0.09	0.38
Al <sub>2</sub> O <sub>3</sub>	23.62	11.14	11.42	12.74	22.54	7.82
Fe <sub>2</sub> O <sub>3</sub>	2.71	8.59	10.89	9.52	4.35	12.67
MnO	0.05	0.09	0.18	0.13	0.08	0.20
MgO	6.18	24.95	25.11	24.91	7.25	19.51
CaO	15.48	8.21	7.49	7.33	16.12	10.19
Na <sub>2</sub> O	0.16	0.05	0.16	0.25	1.08	0.30
K <sub>2</sub> O	2.29	0.25	0.06	0.02	0.04	0.05
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.02	0.03
LOI	5.85	10.31	5.82	0.49	0.58	1.67
An. Total	100.07	110.75	107.47	104.09	94.41	103.88
ppm						
Ba	30	6	8	6	7	8
Cr	319	487	5107	424	1138	937
Cu	21	27	93	103	72	107
Nb	nd	nd	nd	nd	nd	nd
Ni	146	1098	1189	1203	238	724
Rb	14	2	1	1	1	2
S	115	201	213	442	83	939
Sr	62	63	65	63	99	43
V	28	51	92	49	71	238
Y	12	10	9	7	9	16
Zn	22	42	58	59	29	85
Zr	36	35	34	30	27	49
ounces per ton						
Pt	nd	nd	nd	nd	0.91	nd
Pd	0.01	nd	0.02	0.01	1.31	0.01
Pt+Pd	0.01	nd	0.02	0.01	2.22	0.01

1. Normalized to 100% on a volatile free basis.
2. An. Total = Analytical total
3. LOI = loss on ignition at 1000°C for 4 hours.
4. Pt & Pd analyzed by ICP-MS at Stillwater Mining Company's Assay lab. Other elements by XRF at BYU.
5. Nd = not detected
6. Rock type abbreviations: L) leucocratic, M) melanocratic, C) cumulate, P) pegmatite, (A) altered, p) plagioclase, b) orthopyroxene (bronzite), o) olivine, a) clinopyroxene (augite)
7. Glass disk analysis

Appendix B continued.

	7	8	9	10	11	12
SMC Powder	17120-1	17120-2	17131-1	17134-1	17151-2	17151-1
Rock Type	poCP	LpoCP	LpoCP	pC	oCP	MpbaC
SiO <sub>2</sub>	45.68	45.35	47.47	44.65	49.90	50.61
TiO <sub>2</sub>	0.04	0.04	0.04	0.09	0.18	0.26
Al <sub>2</sub> O <sub>3</sub>	23.57	20.77	27.76	16.11	17.58	10.99
Fe <sub>2</sub> O <sub>3</sub>	5.63	7.21	2.49	9.74	8.51	8.25
MnO	0.06	0.07	0.03	0.10	0.14	0.15
MgO	9.64	12.88	2.94	19.48	12.24	14.26
CaO	14.26	12.84	17.61	9.24	10.34	14.70
Na <sub>2</sub> O	1.06	0.77	1.56	0.54	1.01	0.68
K <sub>2</sub> O	0.06	0.06	0.10	0.05	0.07	0.07
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.02	0.03
LOI	2.56	3.26	1.29	4.23	0.30	0.80
An. Total	100.00	101.00	94.47	108.71	101.98	103.06
ppm						
Ba	9	9	11	12	15	15
Cr	143	184	182	294	953	2744
Cu	1474	2078	1150	1965	42	51
Nb	nd	nd	nd	nd	nd	nd
Ni	2203	3394	1587	3127	355	403
Rb	1	2	2	2	2	2
S	2311	3551	1693	3379	177	121
Sr	123	113	146	82	83	49
V	18	27	19	46	109	205
Y	9	nd	8	7	10	11
Zn	35	43	17	60	59	50
Zr	21	22	15	29	36	45
ounces per ton						
Pt	0.01	0.21	0.3	0.2	0.23	nd
Pd	0.76	0.85	1.17	0.68	0.48	nd
Pt+Pd	0.77	1.06	1.47	0.88	0.71	nd



Appendix B continued

	13	14	15	16	17	18
SMC Powder	17153-1	17157-1	17157-2	17159-1	17164-1	17167-1
Rock Type	MpbCP	oC	pC	poCP	LpoCP	oCP
SiO <sub>2</sub>	43.96	45.65	45.39	47.32	43.56	47.82
TiO <sub>2</sub>	0.10	0.08	0.08	0.11	0.15	0.05
Al <sub>2</sub> O <sub>3</sub>	8.28	22.87	18.32	22.66	7.94	26.79
Fe <sub>2</sub> O <sub>3</sub>	12.11	5.86	8.70	6.37	12.56	2.96
MnO	0.12	0.07	0.09	0.08	0.17	0.03
MgO	30.49	8.67	15.01	7.40	29.66	3.81
CaO	4.88	15.36	11.64	14.70	5.83	16.99
Na <sub>2</sub> O	0.00	1.34	0.70	1.27	0.04	1.47
K <sub>2</sub> O	0.03	0.09	0.05	0.07	0.07	0.06
P <sub>2</sub> O <sub>5</sub>	0.02	0.01	0.01	0.01	0.02	0.01
LOI	6.74	2.91	3.50	1.52	4.62	0.92
An. Total	112.99	94.78	101.75	98.87	110.21	95.57
ppm						
Ba	5	14	9	15	8	5
Cr	421	213	629	220	450	170
Cu	1836	2240	1993	1076	679	602
Nb	nd	nd	nd	nd	nd	nd
Ni	4096	3585	4231	1352	2329	762
Rb	2	2	2	2	2	0
S	4459	3140	4340	2331	1512	1011
Sr	41	138	101	122	47	147
V	49	32	50	66	81	25
Y	6	10	9	9	9	nd
Zn	79	43	51	42	83	21
Zr	37	19	25	23	41	15
ounces per ton						
Pt	nd	0.5	0.3	0.31	0.41	0.08
Pd	nd	1.57	1.05	1.32	1.17	0.31
Pt+Pd	nd	2.07	1.35	1.63	1.58	0.39



Appendix B continued

	19	20	21	22	23	24
SMC Powder	17225-1	18696-1	18697-1 <sup>7</sup>	18697-2 <sup>7</sup>	18697-3	18698-1 <sup>7</sup>
Rock Type	LpoCP	poCP	oCP	LpoC	pbC	poC
SiO <sub>2</sub>	45.82	44.35	44.89	47.87	46.63	48.36
TiO <sub>2</sub>	0.06	0.20	0.06	0.08	0.12	0.08
Al <sub>2</sub> O <sub>3</sub>	13.64	5.05	21.72	22.96	21.01	25.67
Fe <sub>2</sub> O <sub>3</sub>	9.79	14.73	5.38	5.92	6.19	2.72
MnO	0.12	0.18	0.08	0.09	0.08	0.04
MgO	20.74	31.24	15.03	8.30	13.59	6.11
CaO	9.55	4.07	11.48	13.48	10.22	14.57
Na <sub>2</sub> O	0.26	0.00	0.71	1.18	0.69	1.37
K <sub>2</sub> O	0.03	0.17	0.65	0.12	1.46	1.05
P <sub>2</sub> O <sub>5</sub>	0.01	0.02	0.01	0.01	0.01	0.01
LOI	5.31	9.68	5.63	1.10	4.77	3.52
An. Total	106.30	112.55	101.72	98.94	102.91	98.55
ppm						
Ba	nd	19	22	20	47	30
Cr	471	1114	239	984	459	601
Cu	912	81	51	35	1380	48
Nb	nd	nd	nd	nd	nd	nd
Ni	2092	1513	273	307	2195	98
Rb	1	5	5	1	12	8
S	1897	253	189	181	2641	89
Sr	69	47	150	137	166	175
V	45	87	24	54	43	45
Y	9	13	9	9	10	10
Zn	57	83	34	40	59	13
Zr	32	48	18	19	17	13
ounces per ton						
Pt	0.11	0.08	nd	nd	nd	0.41
Pd	0.4	0.29	nd	nd	nd	1.38
Pt+Pd	0.51	0.37	nd	nd	nd	1.79

Appendix B continued

	25	26	27	28	29	30
SMC Powder	18701-1	18701-2	18703-1	18711-1	18714-1	18715-1 <sup>7</sup>
Rock Type	pC	LpoC	LpoC	LpobC	pC	LpoC
SiO <sub>2</sub>	47.55	47.96	48.40	48.48	46.64	47.96
TiO <sub>2</sub>	0.08	0.07	0.10	0.07	0.05	0.06
Al <sub>2</sub> O <sub>3</sub>	22.04	25.12	25.75	26.95	24.14	25.91
Fe <sub>2</sub> O <sub>3</sub>	5.81	4.05	2.91	3.15	4.98	2.61
MnO	0.07	0.04	0.04	0.03	0.06	0.04
MgO	9.82	5.41	4.16	3.60	7.66	5.37
CaO	13.50	15.81	16.89	15.72	14.88	16.16
Na <sub>2</sub> O	0.97	1.25	1.64	1.28	1.14	1.35
K <sub>2</sub> O	0.14	0.28	0.11	0.70	0.43	0.52
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.01	0.01
LOI	2.31	1.62	0.89	3.15	3.48	2.90
An. Total	101.10	97.98	95.61	98.58	99.25	98.48
ppm						
Ba	18	23	19	45	20	24
Cr	434	279	253	177	224	225
Cu	488	881	51	761	1329	35
Nb	nd	nd	nd	nd	nd	nd
Ni	764	997	146	958	1746	135
Rb	nd	2	1	5	3	4
S	1096	1573	179	1373	1959	89
Sr	115	143	156	146	140	149
V	51	40	46	25	25	31
Y	8	8	9	8	9	8
Zn	47	31	26	42	41	14
Zr	23	17	17	17	17	15
ounces per ton						
Pt	nd	0.16	0.22	0.01	0.1	0.3
Pd	nd	0.52	0.82	0.04	0.52	1.08
Pt+Pd	nd	0.68	1.04	0.05	0.62	1.38

Appendix B continued

	31	32	33	34	35	36
SMC Powder	18715-2	18740-1	18740-2	18740-3	18843-1	18843-2
Rock Type	LpbC	opCP	opCP	opCP	pC/breccia	pobCP
SiO <sub>2</sub>	48.11	46.52	46.01	46.67	47.40	47.32
TiO <sub>2</sub>	0.06	0.14	0.18	0.10	0.03	0.10
Al <sub>2</sub> O <sub>3</sub>	26.63	4.53	3.52	5.92	18.99	6.19
Fe <sub>2</sub> O <sub>3</sub>	2.75	12.11	13.34	11.07	3.99	12.99
MnO	0.03	0.20	0.14	0.12	0.12	0.13
MgO	3.83	31.61	32.44	31.18	7.38	28.57
CaO	16.69	4.85	4.30	4.90	21.56	4.67
Na <sub>2</sub> O	1.61	0.00	0.00	0.00	0.52	0.00
K <sub>2</sub> O	0.28	0.04	0.05	0.02	0.01	0.02
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.02	0.01	0.01	0.01
LOI	2.12	4.98	7.10	4.87	2.35	7.55
An. Total	96.42	115.02	115.55	110.90	99.00	111.73
ppm						
Ba	26	5	6	nd	nd	2
Cr	196	1858	1588	4834	390	764
Cu	597	417	1674	1824	302	1897
Nb	nd	nd	nd	nd	nd	nd
Ni	963	1679	2931	3372	100	3222
Rb	2	1	2	1	nd	1
S	1205	687	2506	2745	224	6235
Sr	155	28	20	25	98	22
V	31	97	110	96	26	60
Y	8	6	8	7	9	8
Zn	65	71	88	64	20	79
Zr	14	36	43	36	25	39
ounces per ton						
Pt	0.79	0.03	0.15	0.32	nd	0.41
Pd	2.58	0.19	0.89	1.1	nd	1.44
Pt+Pd	3.37	0.22	1.04	1.42	nd	1.85

Appendix B continued

	37	38	39	40	41	42
SMC Powder	18845-1	18845-2	18845-3	18848-1	18848-2 <sup>7</sup>	18867-1
Rock Type	pC	pobCP	pobCP	pboCP	poC	poCP
SiO <sub>2</sub>	48.60	44.66	46.38	43.51	46.52	47.53
TiO <sub>2</sub>	0.07	0.28	0.12	0.23	0.08	0.08
Al <sub>2</sub> O <sub>3</sub>	25.22	3.68	5.24	5.55	19.13	22.53
Fe <sub>2</sub> O <sub>3</sub>	2.70	13.23	11.99	13.15	7.52	4.77
MnO	0.04	0.14	0.12	0.19	0.11	0.07
MgO	5.00	33.63	31.81	32.80	14.47	8.20
CaO	16.19	4.24	4.30	4.42	11.27	15.62
Na <sub>2</sub> O	2.08	0.00	0.00	0.00	0.84	1.12
K <sub>2</sub> O	0.08	0.11	0.03	0.10	0.06	0.06
P <sub>2</sub> O <sub>5</sub>	0.01	0.03	0.01	0.05	0.01	0.01
LOI	1.73	7.60	5.51	6.45	2.47	1.91
An. Total	100.20	116.78	114.19	113.91	104.10	99.80
ppm						
Ba	21	20	4	20	14	22
Cr	174	999	2549	551	1853	399
Cu	40	105	443	47	62	964
Nb	nd	nd	nd	nd	nd	nd
Ni	143	1547	1947	1449	639	1309
Rb	1	5	1	4	nd	nd
S	64	336	945	219	174	1091
Sr	145	22	29	42	94	147
V	42	121	85	89	62	48
Y	7	10	7	9	8	9
Zn	16	76	61	95	47	37
Zr	17	55	37	45	27	18
ounces per ton						
Pt	nd	0.01	0.14	nd	0.01	0.2
Pd	nd	0.03	0.79	nd	0.03	0.65
Pt+Pd	nd	0.04	0.93	nd	0.3	0.85

Appendix B continued

	43	44	45	46	47	48
SMC Powder	18868-1 <sup>7</sup>	18875-1	18875-2	18875-3	18875-4	18875-5
Rock Type	LpoCP	LpoCP	LpoCP	pC	poCP	poCP
SiO <sub>2</sub>	46.66	47.61	46.19	48.33	46.65	45.52
TiO <sub>2</sub>	0.06	0.10	0.08	0.17	0.08	0.07
Al <sub>2</sub> O <sub>3</sub>	22.44	20.72	20.45	24.27	12.83	13.99
Fe <sub>2</sub> O <sub>3</sub>	5.37	6.64	7.00	4.55	9.40	9.14
MnO	0.07	0.09	0.08	0.06	0.12	0.12
MgO	10.85	10.59	12.45	5.34	22.43	22.31
CaO	13.45	13.12	12.85	15.55	8.18	8.50
Na <sub>2</sub> O	1.04	1.06	0.84	1.62	0.26	0.31
K <sub>2</sub> O	0.06	0.07	0.06	0.09	0.03	0.04
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.02	0.01	0.01
LOI	2.07	2.43	3.47	2.11	5.05	4.48
An. Total	103.81	101.78	103.34	98.18	108.56	109.33
ppm						
Ba	10	13	16	24	10	7
Cr	693	867	187	204	704	1844
Cu	55	884	1395	740	219	758
Nb	nd	nd	nd	nd	nd	nd
Ni	469	1366	2210	784	1142	1801
Rb	1	1	1	2	nd	1
S	163	1714	2545	1414	606	1248
Sr	112	106	107	139	70	70
V	35	70	46	58	56	54
Y	7	9	8	9	8	6
Zn	32	42	41	31	49	50
Zr	23	26	24	22	30	28
ounces per ton						
Pt	nd	0.56	0.89	0.42	0.38	0.54
Pd	nd	1.74	2.49	1.34	0.51	1.29
Pt+Pd	nd	2.3	3.38	1.76	0.89	1.83

Appendix B continued

Hand Samples	49 18875-6	50 3210-1	51 3237-1	52 3817-1 <sup>7</sup>	53 3817-10	54 3817-11 <sup>7</sup>
Rock Type	poCP	pC	pC	pbC	pC poCP	pC
SiO <sub>2</sub>	46.75	46.22	47.51	49.23	47.92	48.69
TiO <sub>2</sub>	0.08	0.20	0.08	0.10	0.11	0.11
Al <sub>2</sub> O <sub>3</sub>	10.09	26.68	23.22	22.18	22.61	24.67
Fe <sub>2</sub> O <sub>3</sub>	10.47	6.68	5.06	3.78	4.21	3.17
MnO	0.13	0.03	0.04	0.07	0.08	0.05
MgO	25.67	2.00	6.55	7.44	6.58	4.04
CaO	6.72	16.40	16.09	16.11	17.25	17.74
Na <sub>2</sub> O	0.05	1.66	1.37	1.01	1.17	1.46
K <sub>2</sub> O	0.04	0.10	0.06	0.06	0.05	0.06
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.01	0.01
LOI	3.94	1.27	2.33	0.82	1.12	0.52
An. Total	107.77	94.62	98.40	98.48	98.33	97.31
ppm						
Ba	7	25	15	10	5	10
Cr	1261	57	633	1086	377	501
Cu	556	1880	2277	26	590	143
Nb	nd	nd	nd	nd	nd	nd
Ni	1764	5032	2167	178	777	228
Rb	1	1	1	1	nd	nd
S	1560	8394	4126	71	797	175
Sr	59	145	134	99	115	131
V	60	67	69	73	95	82
Y	7	10	8	9	9	9
Zn	52	29	30	24	31	21
Zr	31	21	17	26	22	19
ounces per ton						
Pt	0.60					
Pd	1.68					
Pt+Pd	2.28					

Appendix B continued

	55	56	57	58	59	60
Hand Samples	3817-12	3817-14	3817-15	3817-16	3817-17	3817-2 <sup>7</sup>
Rock Type	pC	pC	oCP	oCP	pC	pbC
SiO <sub>2</sub>	47.77	46.67	43.88	44.83	46.31	48.84
TiO <sub>2</sub>	0.04	0.09	0.12	0.16	0.11	0.08
Al <sub>2</sub> O <sub>3</sub>	26.92	22.61	4.46	4.59	24.10	25.19
Fe <sub>2</sub> O <sub>3</sub>	2.98	4.76	16.09	16.57	6.31	3.43
MnO	0.03	0.07	0.19	0.19	0.08	0.06
MgO	3.96	6.08	30.33	26.56	6.65	5.19
CaO	16.60	18.32	4.89	7.06	15.21	15.94
Na <sub>2</sub> O	1.61	1.30	0.00	0.00	1.15	1.21
K <sub>2</sub> O	0.08	0.07	0.03	0.02	0.06	0.05
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.01	0.01
LOI	1.69	3.96	8.73	7.71	1.72	0.47
An. Total	94.68	97.84	107.71	106.31	95.45	97.15
ppm						
Ba	17	11	2	4	14	4
Cr	24	592	1959	1808	168	555
Cu	8	1858	1330	2325	2051	38
Nb	nd	nd	nd	nd	nd	nd
Ni	186	2220	3675	3641	3041	148
Rb	nd	2	2	2	1	1
S	89	2966	2713	4706	3391	69
Sr	159	150	52	56	124	110
V	7	74	91	108	54	46
Y	nd	11	13	15	9	8
Zn	20	32	107	66	41	26
Zr	12	17	40	46	21	23

Appendix B continued

	61	62	63	64	65	66
Hand Samples	3817-4 <sup>7</sup>	3817-5	3817-6	3817-7	3817-8	3817-9
Rock Type	pbC	pbC	poC	pC	poCP	poCP
SiO <sub>2</sub>	49.36	50.44	48.38	47.41	44.56	43.30
TiO <sub>2</sub>	0.11	0.22	0.07	0.07	0.06	0.07
Al <sub>2</sub> O <sub>3</sub>	21.05	6.41	26.24	27.95	14.46	5.41
Fe <sub>2</sub> O <sub>3</sub>	6.11	13.82	2.43	4.29	9.17	14.35
MnO	0.10	0.21	0.04	0.03	0.12	0.15
MgO	9.66	22.70	3.21	1.51	21.28	32.27
CaO	12.52	6.01	18.01	16.98	10.00	4.41
Na <sub>2</sub> O	1.02	0.13	1.54	1.66	0.30	0.00
K <sub>2</sub> O	0.05	0.04	0.06	0.09	0.03	0.03
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.01	0.01
LOI	0.43	1.05	0.89	0.91	5.20	9.51
An. Total	99.75	99.51	95.48	94.50	104.20	111.64
ppm						
Ba	12	9	11	19	10	5
Cr	1096	2853	452	39	1222	3027
Cu	148	2859	333	2799	1989	313
Nb	nd	nd	nd	nd	nd	nd
Ni	366	4726	481	4223	3408	2317
Rb	1	3	1	1	1	1
S	154	5675	444	5369	3494	782
Sr	88	31	139	143	103	55
V	74	164	47	23	42	65
Y	8	13	8	7	8	10
Zn	40	86	18	26	48	43
Zr	28	53	17	15	24	35



Appendix B continued

	67	68	69	70	71	72
DDH 19108	147.9	165 <sup>7</sup>	170	172	175	177.5
Rock Type	pbC (A)	pbC	pbC	pbC	pbC	pbC
SiO <sub>2</sub>	49.82	48.84	49.03	48.17	48.95	48.58
TiO <sub>2</sub>	0.11	0.10	0.08	0.07	0.11	0.09
Al <sub>2</sub> O <sub>3</sub>	20.32	22.10	23.55	24.60	20.13	22.83
Fe <sub>2</sub> O <sub>3</sub>	5.75	5.27	4.52	4.59	6.71	5.68
MnO	0.11	0.09	0.07	0.06	0.11	0.08
MgO	10.07	8.45	7.10	5.68	10.35	7.31
CaO	12.57	14.05	14.39	15.46	12.62	14.18
Na <sub>2</sub> O	1.19	1.03	1.14	1.26	0.95	1.15
K <sub>2</sub> O	0.05	0.05	0.09	0.08	0.06	0.07
P <sub>2</sub> O <sub>5</sub>	0.02	0.02	0.02	0.01	0.01	0.02
LOI	2.12	0.60	0.93	0.86	0.76	0.87
An. Total	101.55	95.36	98.82	95.36	96.65	97.01
ppm						
Ba	8	14	10	15	11	10
Cr	1558	1049	857	736	1311	982
Cu	21	31	100	1104	109	818
Nb	nd	nd	nd	nd	nd	nd
Ni	285	223	197	1567	288	1079
Rb	1	1	2	1	1	1
S	117	82	128	1748	149	1126
Sr	90	98	103	114	94	106
V	83	64	52	46	79	63
Y	9	10	8	9	10	9
Zn	38	37	32	32	45	39
Zr	30	27	25	22	28	25

Appendix B continued

	73	74	75	76	77	78
DDH 19108	179.5	185.0	190.0	192.0	201.0	202.5 <sup>7</sup>
Rock Type	pbC	pbC	pboCP	pboCP	pboCP	pboCP
SiO <sub>2</sub>	48.78	47.88	48.27	46.17	47.41	50.49
TiO <sub>2</sub>	0.11	0.08	0.11	0.07	0.12	1.15
Al <sub>2</sub> O <sub>3</sub>	19.44	24.09	22.11	20.46	22.11	7.60
Fe <sub>2</sub> O <sub>3</sub>	6.46	5.85	7.39	6.91	8.96	14.30
MnO	0.10	0.07	0.10	0.09	0.10	0.22
MgO	9.90	6.03	8.46	12.20	7.64	20.78
CaO	13.76	14.64	12.22	13.09	12.24	4.99
Na <sub>2</sub> O	1.13	1.26	1.28	0.94	1.34	0.38
K <sub>2</sub> O	0.32	0.08	0.06	0.05	0.07	0.08
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.02	0.02
LOI	2.25	0.64	1.54	3.70	1.76	0.91
An. Total	96.42	96.12	99.34	101.50	97.92	102.81
ppm						
Ba	37	18	14	13	18	nd
Cr	995	672	303	497	252	1149
Cu	1849	1694	1364	412	2807	165
Nb	nd	nd	nd	nd	nd	12
Ni	2906	2343	1827	1069	6014	926
Rb	15	2	1	1	1	4
S	2858	2874	2212	850	7196	226
Sr	117	120	116	116	111	35
V	77	54	62	41	64	192
Y	11	8	9	9	10	13
Zn	37	37	49	43	53	96
Zr	22	20	23	23	26	153

Appendix B continued

	79	80	81	82	83	84
DDH 19108	207	209.6	212	220.5	223.5	224.5
Rock Type	pC	LpoCP	LpoCP	LpoCP	LpoCP	LpoCP
SiO <sub>2</sub>	47.80	48.82	48.27	46.26	47.61	47.31
TiO <sub>2</sub>	0.04	0.10	0.09	0.04	0.05	0.10
Al <sub>2</sub> O <sub>3</sub>	28.24	22.42	21.58	21.55	28.64	18.83
Fe <sub>2</sub> O <sub>3</sub>	2.92	3.29	4.64	6.37	2.86	8.34
MnO	0.02	0.06	0.06	0.07	0.02	0.11
MgO	1.93	6.34	8.15	11.32	1.02	13.45
CaO	17.16	17.40	15.75	13.28	17.43	11.01
Na <sub>2</sub> O	1.67	1.51	1.40	1.03	2.10	0.78
K <sub>2</sub> O	0.21	0.06	0.04	0.06	0.25	0.05
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.01	0.01	0.01
LOI	1.03	4.64	8.67	7.10	2.58	4.29
An. Total	94.49	98.56	101.03	101.53	94.43	100.02
ppm						
Ba	26	9	3	5	26	8
Cr	38	635	282	36	24	168
Cu	1773	48	64	53	2038	1263
Nb	nd	nd	nd	nd	nd	nd
Ni	2657	175	281	554	2692	1686
Rb	3	nd	nd	nd	3	1
S	3289	138	279	394	3479	1702
Sr	154	146	188	150	179	112
V	14	78	65	12	10	56
Y	7	11	13	11	9	10
Zn	18	22	32	40	21	52
Zr	12	20	15	19	9	24

Appendix B continued

	85	86	87	88	89	90
DDH 19108	226.5	230	232	234.5	236	237
Rock Type	pboCP	pboCP	pC	pC	pC (A)	pboCP
SiO <sub>2</sub>	45.70	46.52	47.04	51.58	50.85	47.89
TiO <sub>2</sub>	0.08	0.14	0.08	0.09	0.05	0.12
Al <sub>2</sub> O <sub>3</sub>	18.26	21.80	19.00	23.96	27.22	19.93
Fe <sub>2</sub> O <sub>3</sub>	9.27	7.92	8.85	3.78	1.65	7.72
MnO	0.11	0.08	0.10	0.05	0.03	0.07
MgO	14.96	8.62	12.48	4.63	1.34	12.90
CaO	10.94	13.58	11.87	13.13	14.05	10.01
Na <sub>2</sub> O	0.64	1.28	0.49	1.77	2.50	1.07
K <sub>2</sub> O	0.03	0.06	0.08	0.99	2.29	0.28
P <sub>2</sub> O <sub>5</sub>	0.01	0.02	0.01	0.01	0.01	0.01
LOI	5.87	4.12	9.13	8.07	5.33	4.70
An. Total	100.68	97.07	103.62	100.55	99.97	102.04
ppm						
Ba	4	18	9	42	80	11
Cr	144	103	290	199	21	103
Cu	2255	3862	2402	2307	1103	2375
Nb	nd	nd	nd	nd	nd	nd
Ni	2760	5331	2899	1760	1112	3214
Rb	1	1	2	12	46	3
S	2471	5631	1841	1841	912	3600
Sr	111	135	130	157	164	128
V	44	52	43	63	8	50
Y	10	10	12	12	12	8
Zn	54	46	51	104	14	46
Zr	24	25	24	18	13	21

Appendix B continued

	91	92	93	94	95	96
DDH 19108	238.5	241.8	244	246	255	268
Rock Type	pC	Fault	pC	pC	pbC	pC
SiO <sub>2</sub>	49.98	37.98	50.42	49.20	49.93	50.89
TiO <sub>2</sub>	0.04	0.12	0.12	0.11	0.09	0.11
Al <sub>2</sub> O <sub>3</sub>	26.32	7.54	23.28	25.71	22.25	21.94
Fe <sub>2</sub> O <sub>3</sub>	2.49	9.06	3.73	2.36	4.91	5.07
MnO	0.03	0.11	0.06	0.04	0.08	0.07
MgO	1.13	19.15	7.32	3.50	7.58	10.65
CaO	15.91	26.01	12.86	16.75	13.61	8.65
Na <sub>2</sub> O	1.75	0.00	1.87	2.03	1.44	2.25
K <sub>2</sub> O	2.35	0.00	0.34	0.28	0.09	0.37
P <sub>2</sub> O <sub>5</sub>	0.01	0.02	0.02	0.02	0.02	0.01
Total	4.03	15.66	4.08	2.91	1.32	6.02
An. Total	199.52	109.79	97.27	95.59	99.86	99.01
ppm						
Ba	117	nd	32	20	21	36
Cr	22	1066	326	174	523	457
Cu	2440	59	52	34	42	11
Nb	nd	nd	nd	nd	nd	nd
Ni	2912	1236	138	80	189	145
Rb	56	1	3	2	nd	7
S	2399	329	104	92	102	152
Sr	128	39	195	184	140	188
V	5	89	83	50	63	66
Y	13	22	10	10	8	11
Zn	16	466	24	20	32	30
Zr	17	55	9	13	20	13

Appendix B continued

DDH 19108	97	98	E. Boulder	99	100
Rock Type	LpbC	LpbC		poC	poCP
SiO <sub>2</sub>	49.62	49.79		43.68	47.93
TiO <sub>2</sub>	0.07	0.08		0.07	0.10
Al <sub>2</sub> O <sub>3</sub>	25.18	24.89		16.51	18.08
Fe <sub>2</sub> O <sub>3</sub>	2.48	2.65		10.70	7.48
MnO	0.04	0.04		0.11	0.07
MgO	3.97	5.09		18.02	13.95
CaO	16.70	15.49		10.31	11.67
Na <sub>2</sub> O	1.84	1.88		0.54	0.66
K <sub>2</sub> O	0.08	0.08		0.06	0.06
P <sub>2</sub> O <sub>5</sub>	0.01	0.01		0.01	0.01
LOI	0.93	2.75		3.05	3.32
An. Total	96.32	97.07		93.44	103.35
ppm					
Ba	16	12		14	9
Cr	275	284		370	120
Cu	26	81		2288	2225
Nb	nd	nd		nd	nd
Ni	89	101		3700	3570
Rb	nd	1		1	1
S	86	144		3659	3941
Sr	156	157		95	103
V	47	46		32	55
Y	8	8		10	7
Zn	17	26		57	44
Zr	15	16		26	23

**Appendix C. Electron microprobe analysis of plagioclase from ballrooms.**

	1	2	3	4	5	6
Sample	3817-3	3817-3	3817-4	3817-4	3817-4	3817-4
SiO <sub>2</sub>	46.51	46.27	46.82	47.41	46.64	47.75
Al <sub>2</sub> O <sub>3</sub>	33.57	33.77	34.65	33.84	34.58	33.66
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.01	0.00	0.00	0.00	0.00
CaO	16.56	17.22	17.27	16.81	17.11	16.74
Na <sub>2</sub> O	1.85	1.76	1.76	2.07	1.77	1.79
K <sub>2</sub> O	0.39	0.11	0.05	0.06	0.06	0.69
An. Total	98.87	99.13	100.54	100.19	100.16	100.63

**Cations on basis of 8 oxygens**

Si	2.16	2.15	2.14	2.17	2.14	2.18
Al	1.84	1.85	1.87	1.83	1.87	1.81
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.82	0.86	0.85	0.82	0.84	0.82
Na	0.17	0.16	0.16	0.18	0.16	0.16
K	0.02	0.01	0.00	0.00	0.00	0.04

**End Members**

Ab	0.16	0.16	0.16	0.18	0.16	0.16
An	0.81	0.84	0.84	0.82	0.84	0.81
Or	0.02	0.01	0.00	0.00	0.00	0.04
Cs	0.00	0.00	0.00	0.00	0.00	0.00

Appendix C continued.

	7	8	9	10	11	12
Sample	3817-4	3817-5	3817-5	3817-5	3817-5	3817-6
SiO <sub>2</sub>	46.59	49.04	49.49	48.79	48.99	46.71
Al <sub>2</sub> O <sub>3</sub>	34.47	33.06	33.06	33.67	33.16	33.90
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.01	0.01	0.00	0.00
CaO	17.07	15.46	15.23	15.47	15.41	17.27
Na <sub>2</sub> O	1.77	2.83	2.89	2.71	2.75	1.86
K <sub>2</sub> O	0.05	0.10	0.15	0.11	0.10	0.08
An. Total	99.96	100.49	100.82	100.75	100.41	99.82

Cations on basis of 8 oxygens

Si	2.14	2.23	2.24	2.21	2.23	2.15
Al	1.87	1.77	1.77	1.80	1.78	1.84
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.84	0.75	0.74	0.75	0.75	0.85
Na	0.16	0.25	0.25	0.24	0.24	0.17
K	0.00	0.01	0.01	0.01	0.01	0.00

End Members

Ab	0.16	0.25	0.25	0.24	0.24	0.16
An	0.84	0.75	0.74	0.75	0.75	0.83
Or	0.00	0.01	0.01	0.01	0.01	0.00
Cs	0.00	0.00	0.00	0.00	0.00	0.00



Appendix C continued.

	13	14	15	16	17	18
Sample	3817-10	3817-10	3817-10	3817-10	3817-10	3817-10
SiO <sub>2</sub>	46.54	46.42	46.38	45.84	45.57	46.88
Al <sub>2</sub> O <sub>3</sub>	34.20	34.14	34.43	34.30	31.05	33.64
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.01	0.00	0.00	0.00
CaO	17.00	16.86	17.14	17.21	19.77	16.92
Na <sub>2</sub> O	1.89	1.89	1.86	1.81	1.45	2.01
K <sub>2</sub> O	0.01	0.01	0.01	0.01	0.04	0.00
An. Total	99.64	99.30	99.82	99.18	97.88	99.45

Cations on basis of 8 oxygens

Si	2.14	2.15	2.13	2.13	2.16	2.16
Al	1.86	1.86	1.87	1.87	1.74	1.83
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.84	0.83	0.85	0.86	1.00	0.84
Na	0.17	0.17	0.17	0.16	0.13	0.18
K	0.00	0.00	0.00	0.00	0.00	0.00

End Members

Ab	0.17	0.17	0.16	0.16	0.12	0.18
An	0.83	0.83	0.84	0.84	0.88	0.82
Or	0.00	0.00	0.00	0.00	0.00	0.00
Cs	0.00	0.00	0.00	0.00	0.00	0.00

Appendix C continued.

	19	20	21	22	23	24
Sample	3817-10	3817-10	3817-10	3817-10	3817-10	3817-10
SiO <sub>2</sub>	47.10	46.08	46.58	46.37	46.58	46.59
Al <sub>2</sub> O <sub>3</sub>	33.73	34.30	34.22	34.48	34.17	34.47
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.02	0.01
CaO	16.49	16.93	16.91	16.88	16.83	17.00
Na <sub>2</sub> O	2.07	1.89	2.01	1.98	2.01	1.90
K <sub>2</sub> O	0.02	0.02	0.03	0.03	0.04	0.00
An. Total	99.41	99.22	99.76	99.74	99.63	99.96

Cations on basis of 8 oxygens

Si	2.17	2.13	2.14	2.14	2.15	2.14
Al	1.83	1.87	1.86	1.87	1.86	1.87
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.81	0.84	0.83	0.83	0.83	0.84
Na	0.19	0.17	0.18	0.18	0.18	0.17
K	0.00	0.00	0.00	0.00	0.00	0.00

End Members

Ab	0.19	0.17	0.18	0.17	0.18	0.17
An	0.81	0.83	0.82	0.82	0.82	0.83
Or	0.00	0.00	0.00	0.00	0.00	0.00
Cs	0.00	0.00	0.00	0.00	0.00	0.00

Appendix C continued.

	25	26	27	28	29	30
Sample	3817-10	3817-10	3817-10	3817-10	3817-10	3817-10
SiO <sub>2</sub>	46.34	47.12	47.25	46.96	47.07	46.25
Al <sub>2</sub> O <sub>3</sub>	34.11	34.09	33.76	33.71	34.23	34.16
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.00	0.01
CaO	16.92	16.92	16.46	16.95	16.64	16.54
Na <sub>2</sub> O	1.81	2.02	2.11	2.10	2.06	2.10
K <sub>2</sub> O	0.00	0.02	0.01	0.02	0.03	0.04
An. Total	99.18	100.18	99.60	99.73	100.03	99.08

Cations on basis of 8 oxygens

Si	2.14	2.16	2.17	2.16	2.16	2.14
Al	1.86	1.84	1.83	1.83	1.85	1.87
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.84	0.83	0.81	0.84	0.82	0.82
Na	0.16	0.18	0.19	0.19	0.18	0.19
K	0.00	0.00	0.00	0.00	0.00	0.00

End Members

Ab	0.16	0.18	0.19	0.18	0.18	0.19
An	0.84	0.82	0.81	0.82	0.82	0.81
Or	0.00	0.00	0.00	0.00	0.00	0.00
Cs	0.00	0.00	0.00	0.00	0.00	0.00

Appendix C continued.

	31	32	33	34	35	36	37
Sample	3817-10	3817-10	3817-10	3817-10	3817-10	3817-8	3817-8
SiO <sub>2</sub>	46.88	46.75	46.95	46.64	46.49	47.36	46.77
Al <sub>2</sub> O <sub>3</sub>	33.57	34.82	33.86	34.27	34.01	33.63	34.35
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.00	0.33	0.32
CaO	16.65	16.83	16.46	16.81	17.09	16.33	16.92
Na <sub>2</sub> O	2.17	1.87	2.15	1.88	1.81	2.24	1.85
K <sub>2</sub> O	0.02	0.02	0.00	0.01	0.00	0.07	0.03
An. Total	99.29	100.29	99.41	99.62	99.41	99.96	100.25
Cations on basis of 8 oxygens							
Si	2.17	2.14	2.17	2.15	2.15	2.17	2.14
Al	1.83	1.88	1.84	1.86	1.85	1.82	1.86
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Ca	0.82	0.82	0.81	0.83	0.85	0.80	0.83
Na	0.19	0.17	0.19	0.17	0.16	0.20	0.16
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00
End Members							
Ab	0.19	0.17	0.19	0.17	0.16	0.20	0.17
An	0.81	0.83	0.81	0.83	0.84	0.80	0.83
Or	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cs	0.00	0.00	0.00	0.00	0.00	0.00	0.00

**Appendix D. Electron microprobe analysis of olivine from ballrooms.**

	1	2	3	4	5	6
Sample	3817-6a	3817-6a	3817-6c	3817-6e	3817-6f	3817-6g
SiO <sub>2</sub>	38.58	37.78	38.80	38.26	38.76	38.34
TiO <sub>2</sub>	0.01	0.00	0.00	0.01	0.01	0.01
Al <sub>2</sub> O <sub>3</sub>	0.01	0.01	0.02	0.00	0.01	0.01
FeO	21.12	21.71	21.94	21.48	21.22	21.42
MnO	0.27	0.26	0.29	0.29	0.29	0.21
MgO	39.01	38.93	38.84	38.32	38.74	38.34
CaO	0.04	0.04	0.06	0.04	0.05	0.04
An. Total	99.03	98.73	99.95	98.39	99.08	98.37

**Basis of 3 Cations**

Si	1.01	0.99	1.01	1.01	1.01	1.01
Al	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.52	1.52	1.51	1.51	1.51	1.51
Fe <sup>2+</sup>	0.46	0.48	0.48	0.47	0.46	0.47
Mn	0.01	0.01	0.01	0.01	0.01	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Sum	3.00	3.00	3.00	3.00	3.00	3.00

**End Members**

Fo (Mg)	76	76	76	76	76	76
Fa (Fe)	23	24	24	24	23	24
Te (Mn)	0.00	0.00	0.00	0.00	0.00	0.00
La (Ca)	0.00	0.00	0.00	0.00	0.00	0.00

1. An. Total= Analytical total

Appendix D continued.

	7	8	9	10	11	12
Sample	3817-6g	3817-6h	3817-6i	3817-6j	3817-6j	3817-9a
SiO <sub>2</sub>	38.36	38.53	38.28	38.53	38.44	38.75
TiO <sub>2</sub>	0.01	0.04	0.01	0.00	0.01	0.00
Al <sub>2</sub> O <sub>3</sub>	0.03	0.01	0.00	0.01	0.01	0.00
FeO	21.55	21.59	21.31	21.62	21.98	19.21
MnO	0.28	0.24	0.25	0.30	0.25	0.30
MgO	38.57	38.49	38.47	38.46	38.82	40.22
CaO	0.06	0.06	0.06	0.07	0.06	0.04
An. Total	98.85	98.95	98.39	98.99	99.57	98.50

Basis of 3 Cations

Si	1.01	1.01	1.01	1.01	1.00	1.01
Al	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.51	1.51	1.51	1.50	1.51	1.56
Fe <sup>2+</sup>	0.47	0.47	0.47	0.47	0.48	0.42
Mn	0.01	0.01	0.01	0.01	0.01	0.01
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Sum	3.00	3.00	3.00	3.00	3.00	3.00

End Members

Fo (Mg)	76	76	76	76	76	79
Fa (Fe)	24	24	24	24	24	21
Te (Mn)	0.00	0.00	0.00	0.00	0.00	0.00
La (Ca)	0.00	0.00	0.00	0.00	0.00	0.00

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Appendix D continued.

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	13	14	15
Sample	3817-9b	3817-9c	3817-9c
SiO <sub>2</sub>	38.70	38.65	39.00
TiO <sub>2</sub>	0.00	0.01	0.00
Al <sub>2</sub> O <sub>3</sub>	0.02	0.01	0.00
FeO	19.05	19.38	19.36
MnO	0.28	0.28	0.22
MgO	40.05	40.16	40.51
CaO	0.04	0.04	0.04
An. Total	98.14	98.52	99.13

Basis of 3 Cations

Si	1.01	1.01	1.01
Al	0.00	0.00	0.00
Ti	0.00	0.00	0.00
Mg	1.56	1.56	1.56
Fe <sup>2+</sup>	0.42	0.42	0.42
Mn	0.01	0.01	0.00
Ca	0.00	0.00	0.00
Sum	3.00	3.00	3.00

End Members

Fo (Mg)	79	78	79
Fa (Fe)	21	21	21
Te (Mn)	0.00	0.00	0.00
La (Ca)	0.00	0.00	0.00

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**Appendix E. Electron microprobe analysis of orthopyroxene from ballrooms.**

	1	2	3	4	5	6
Sample	3817-2a	3817-2b	3817-2c	3817-6a	3817-6b	3817-2d
SiO <sub>2</sub>	54.85	55.04	54.95	52.82	52.81	54.97
TiO <sub>2</sub>	0.23	0.23	0.26	0.08	0.09	0.27
Al <sub>2</sub> O <sub>3</sub>	1.05	0.87	0.81	2.34	2.33	0.91
Cr <sub>2</sub> O <sub>3</sub>	0.27	0.28	0.27	0.27	0.21	0.27
FeO	14.04	14.27	14.05	14.76	14.60	14.08
MnO	0.21	0.17	0.18	0.52	0.64	0.23
MgO	28.50	28.47	28.97	27.25	27.31	28.15
CaO	0.58	0.59	0.66	0.66	0.72	0.74
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.02	0.00
An. Total	99.73	99.91	100.14	98.70	98.71	99.61

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.97	1.98	1.96	1.93	1.92	1.98
Al <sub>t</sub>	0.04	0.04	0.03	0.10	0.10	0.04
Al <sub>iv</sub>	0.03	0.02	0.03	0.07	0.08	0.02
Al <sub>vi</sub>	0.02	0.01	0.00	0.03	0.02	0.02
Cr	0.01	0.01	0.01	0.01	0.01	0.01
Fe <sup>3+</sup>	0.00	0.00	0.00	0.02	0.03	0.00
Ti	0.01	0.01	0.01	0.00	0.00	0.01
Mg	1.53	1.52	1.54	1.48	1.48	1.51
Fe <sup>2+</sup>	0.42	0.43	0.42	0.43	0.41	0.42
Mn	0.01	0.01	0.01	0.02	0.02	0.01
Ca	0.02	0.02	0.03	0.03	0.03	0.03
Na	0.00	0.00	0.00	0.00	0.00	0.00

End Members (%)

Wo	1.12	1.14	1.27	1.31	1.43	1.44
En	76.96	76.96	77.40	75.07	75.07	76.69
Fs	21.90	21.90	21.33	23.63	23.63	21.87

1. An. Total= Analytical total



Appendix E. continued.

	7	8	9	10	11	12
Sample	3817-2e	3817-2f	3817-2g	3817-2h	3817-2i	3817-2j
SiO <sub>2</sub>	54.91	54.74	54.63	54.79	54.63	54.68
TiO <sub>2</sub>	0.26	0.31	0.28	0.28	0.31	0.26
Al <sub>2</sub> O <sub>3</sub>	0.86	0.95	0.83	0.93	0.82	1.04
Cr <sub>2</sub> O <sub>3</sub>	0.25	0.26	0.32	0.28	0.27	0.28
FeO	14.01	13.94	14.19	14.03	13.96	13.65
MnO	0.21	0.23	0.16	0.22	0.15	0.26
MgO	28.64	28.66	28.22	28.69	28.47	28.65
CaO	0.74	0.84	0.87	0.92	0.94	1.00
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00
An. Total	99.89	99.92	99.50	100.13	99.54	99.82

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.97	1.96	1.97	1.96	1.97	1.96
Al <sub>t</sub>	0.04	0.04	0.04	0.04	0.03	0.04
Al <sub>iv</sub>	0.03	0.04	0.03	0.04	0.03	0.04
Al <sub>vi</sub>	0.01	0.00	0.01	0.00	0.00	0.01
Cr	0.01	0.01	0.01	0.01	0.01	0.01
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.01	0.01	0.01	0.01	0.01	0.01
Mg	1.53	1.53	1.52	1.53	1.53	1.53
Fe <sup>2+</sup>	0.42	0.42	0.43	0.42	0.42	0.41
Mn	0.01	0.01	0.00	0.01	0.00	0.01
Ca	0.03	0.03	0.03	0.04	0.04	0.04
Na	0.00	0.00	0.00	0.00	0.00	0.00

End Members (%)

Wo	1.43	1.62	1.70	1.77	1.82	1.93
En	77.09	77.01	76.48	76.82	76.81	77.07
Fs	21.49	21.37	21.83	21.83	21.37	21.00

Appendix E. continued.

	13	14	15	16	17	18
Sample	3817-2k	3817-2l	3817-2m	3817-2n	3817-2o	3817-2p
SiO <sub>2</sub>	54.79	54.80	54.93	54.81	54.91	54.63
TiO <sub>2</sub>	0.30	0.29	0.25	0.30	0.13	0.20
Al <sub>2</sub> O <sub>3</sub>	0.92	0.93	1.05	0.97	1.12	1.15
Cr <sub>2</sub> O <sub>3</sub>	0.26	0.27	0.23	0.28	0.23	0.26
FeO	13.84	14.19	13.73	13.43	13.42	13.31
MnO	0.21	0.17	0.21	0.22	0.33	0.34
MgO	28.73	28.46	28.49	28.46	28.52	28.17
CaO	1.02	1.05	1.17	1.35	1.36	1.72
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00
An. Total	100.08	100.17	100.05	99.80	100.00	99.77

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.96	1.96	1.97	1.97	1.96	1.96
Al <sub>t</sub>	0.04	0.04	0.04	0.04	0.05	0.05
Al <sub>iv</sub>	0.04	0.04	0.03	0.03	0.04	0.04
Al <sub>vi</sub>	0.00	0.00	0.01	0.01	0.01	0.01
Cr	0.01	0.01	0.01	0.01	0.01	0.01
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.01	0.01	0.01	0.01	0.00	0.01
Mg	1.53	1.52	1.52	1.52	1.52	1.51
Fe <sup>2+</sup>	0.41	0.42	0.41	0.40	0.40	0.40
Mn	0.01	0.01	0.01	0.01	0.01	0.01
Ca	0.04	0.04	0.04	0.05	0.05	0.07
Na	0.00	0.00	0.00	0.00	0.00	0.00

End Members (%)

Wo	1.96	2.03	2.26	2.61	2.62	3.33
En	76.92	76.35	76.68	76.74	76.65	76.00
Fs	21.12	21.62	21.06	20.66	20.73	20.66

Appendix E. continued.

	19	20	21	22	23	24
Sample	3817-2q	3817-2r	3817-6c	3817-1a	3817-1b	3817-6d
SiO <sub>2</sub>	54.52	54.54	53.69	54.81	54.74	53.64
TiO <sub>2</sub>	0.20	0.19	0.10	0.18	0.16	0.14
Al <sub>2</sub> O <sub>3</sub>	1.07	1.09	2.21	0.95	1.06	2.05
Cr <sub>2</sub> O <sub>3</sub>	0.26	0.26	0.28	0.27	0.25	0.29
FeO	13.17	13.14	14.70	13.35	13.23	14.48
MnO	0.35	0.28	0.52	0.30	0.30	0.52
MgO	28.10	27.68	27.64	28.89	28.99	27.38
CaO	2.09	2.91	0.70	0.76	0.83	0.90
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00
An. Total	99.74	100.10	99.83	99.50	99.55	99.39

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.96	1.96	1.93	1.97	1.96	1.94
Al t	0.05	0.05	0.09	0.04	0.04	0.09
Al <sub>iv</sub>	0.04	0.04	0.07	0.03	0.04	0.06
Al <sub>vi</sub>	0.00	0.00	0.03	0.01	0.01	0.03
Cr	0.01	0.01	0.01	0.01	0.01	0.01
Fe <sup>3+</sup>	0.01	0.01	0.01	0.00	0.00	0.00
Ti	0.01	0.01	0.00	0.00	0.00	0.00
Mg	1.50	1.48	1.48	1.55	1.55	1.48
Fe <sup>2+</sup>	0.39	0.38	0.43	0.40	0.40	0.44
Mn	0.01	0.01	0.02	0.01	0.01	0.02
Ca	0.08	0.11	0.03	0.03	0.03	0.03
Na	0.00	0.00	0.00	0.00	0.00	0.00

End Members (%)

Wo	4.03	5.61	1.36	1.46	1.60	1.78
En	75.58	74.20	75.35	77.89	77.97	75.13
Fs	20.39	20.20	23.29	20.65	20.43	23.10

Appendix E. continued.

	25	26	27	28	29	30
Sample	3817-6e	3817-1c	3817-6f	3817-1d	3817-1e	3817-1f
SiO <sub>2</sub>	54.48	54.97	54.30	54.43	54.39	52.67
TiO <sub>2</sub>	0.28	0.19	0.31	0.16	0.14	0.20
Al <sub>2</sub> O <sub>3</sub>	1.43	0.93	1.58	1.06	1.53	4.61
Cr <sub>2</sub> O <sub>3</sub>	0.26	0.27	0.27	0.19	0.24	0.31
FeO	14.51	13.89	13.63	13.24	13.32	13.68
MnO	0.17	0.32	0.24	0.31	0.33	0.36
MgO	27.86	28.69	28.31	28.93	28.84	26.49
CaO	0.94	0.96	0.99	1.00	1.06	1.18
Na <sub>2</sub> O	0.00	0.00	0.01	0.00	0.00	0.01
An. Total	99.94	100.22	99.62	99.31	99.84	99.50

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.96	1.97	1.95	1.96	1.95	1.90
Al <sub>t</sub>	0.06	0.04	0.07	0.04	0.06	0.20
Al <sub>iv</sub>	0.04	0.03	0.05	0.04	0.05	0.10
Al <sub>vi</sub>	0.02	0.00	0.02	0.00	0.01	0.10
Cr	0.01	0.01	0.01	0.01	0.01	0.01
Fe <sup>3+</sup>	0.00	0.00	0.00	0.02	0.02	0.00
Ti	0.01	0.01	0.01	0.00	0.00	0.01
Mg	1.49	1.53	1.52	1.55	1.54	1.43
Fe <sup>2+</sup>	0.44	0.42	0.41	0.38	0.38	0.41
Mn	0.01	0.01	0.01	0.01	0.01	0.01
Ca	0.04	0.04	0.04	0.04	0.04	0.05
Na	0.00	0.00	0.00	0.00	0.00	0.00

End Members (%)

Wo	1.84	1.85	1.93	1.93	2.38	2.41
En	75.76	76.81	76.93	77.66	77.41	75.21
Fs	22.24	21.34	21.14	20.41	20.55	22.38

Appendix E. continued.

	31	32	33
Sample	3817-1g	3817-6g	3817-1h
SiO <sub>2</sub>	54.82	53.50	54.62
TiO <sub>2</sub>	0.15	1.12	0.17
Al <sub>2</sub> O <sub>3</sub>	1.07	1.34	1.04
Cr <sub>2</sub> O <sub>3</sub>	0.27	0.26	0.26
FeO	13.23	14.28	12.95
MnO	0.30	0.17	0.30
MgO	28.79	27.33	28.45
CaO	1.42	1.57	1.61
Na <sub>2</sub> O	0.00	0.01	0.00
An. Total	100.05	99.58	99.40

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.96	1.94	1.96
Al <sub>t</sub>	0.04	0.06	0.04
Al <sub>iv</sub>	0.04	0.06	0.04
Al <sub>vi</sub>	0.00	0.00	0.01
Cr	0.01	0.01	0.01
Fe <sup>3+</sup>	0.01	0.00	0.00
Ti	0.00	0.03	0.00
Mg	1.53	1.48	1.53
Fe <sup>2+</sup>	0.39	0.43	0.39
Mn	0.01	0.01	0.01
Ca	0.05	0.06	0.06
Na	0.00	0.00	0.00

End Members (%)

Wo	2.72	3.08	3.12
En	76.98	74.73	76.80
Fs	20.30	22.19	20.08

**Appendix F. Electron microprobe analysis of clinopyroxene from ballrooms.**

	1	2	3	4	5	6
Sample	3817-9a	3817-1a	3817-6a	3817-9b	3817-9c	3817-9d
SiO <sub>2</sub>	51.42	51.74	51.65	51.85	51.83	52.14
TiO <sub>2</sub>	0.24	0.34	0.23	0.27	0.25	0.29
Al <sub>2</sub> O <sub>3</sub>	3.12	2.31	3.02	2.87	2.97	2.81
Cr <sub>2</sub> O <sub>3</sub>	0.16	0.11	0.10	0.09	0.11	0.10
FeO	6.02	5.95	6.07	6.15	5.80	5.40
MnO	1.10	0.72	1.07	0.96	1.08	1.07
MgO	16.23	16.47	16.06	16.29	15.82	15.94
CaO	20.37	20.77	20.93	21.17	21.44	21.66
Na <sub>2</sub> O	0.36	0.21	0.26	0.31	0.31	0.42
An. Total	99.00	98.64	99.38	99.95	99.61	99.82

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.91	1.92	1.91	1.90	1.91	1.92
Al <sub>t</sub>	0.14	0.10	0.13	0.12	0.13	0.12
Al <sub>iv</sub>	0.09	0.08	0.09	0.10	0.09	0.08
Al <sub>vi</sub>	0.04	0.03	0.04	0.03	0.04	0.04
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>3+</sup>	0.05	0.03	0.05	0.07	0.05	0.05
Ti	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.90	0.91	0.88	0.89	0.87	0.87
Fe <sup>2+</sup>	0.13	0.15	0.14	0.12	0.13	0.11
Mn	0.03	0.02	0.03	0.03	0.03	0.03
Ca	0.81	0.83	0.83	0.83	0.85	0.85
Na	0.03	0.02	0.02	0.02	0.02	0.03

End Members (%)

Wo	41.99	42.47	42.84	42.86	43.91	44.29
En	46.53	46.86	45.74	45.89	45.08	45.36
Fs	11.48	10.67	11.43	11.24	11.01	10.35

1. An. Total = Analytical total

2. All analyses are exsolution lamellae unless otherwise noted

3. \* = intercumulate grain

Appendix F. continued.

	7	8	9	10	11	12
Sample	3817-9e	3817-6b	3817-6c	3817-9f	3817-6d	3817-9g
SiO <sub>2</sub>	51.88	51.19	51.59	51.63	51.31	51.41
TiO <sub>2</sub>	0.22	0.21	0.32	0.20	0.70	0.20
Al <sub>2</sub> O <sub>3</sub>	3.02	2.99	2.97	3.14	2.72	3.06
Cr <sub>2</sub> O <sub>3</sub>	0.11	0.15	0.15	0.07	0.11	0.11
FeO	5.65	5.91	6.21	5.29	5.65	5.26
MnO	1.12	1.04	0.91	1.17	0.38	1.10
MgO	15.91	15.35	15.66	15.56	15.72	15.51
CaO	21.75	21.86	21.94	21.97	22.06	22.08
Na <sub>2</sub> O	0.38	0.28	0.25	0.38	0.18	0.41
An. Total	100.02	98.98	99.99	99.41	98.83	99.13

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.90	1.90	1.90	1.91	1.91	1.90
Al <sub>t</sub>	0.13	0.13	0.13	0.14	0.12	0.13
Al <sub>iv</sub>	0.10	0.10	0.10	0.09	0.09	0.10
Al <sub>vi</sub>	0.03	0.04	0.03	0.04	0.03	0.04
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>3+</sup>	0.07	0.06	0.06	0.06	0.03	0.07
Ti	0.01	0.01	0.01	0.01	0.02	0.01
Mg	0.87	0.85	0.86	0.86	0.87	0.86
Fe <sup>2+</sup>	0.11	0.13	0.13	0.10	0.15	0.09
Mn	0.03	0.03	0.03	0.04	0.01	0.03
Ca	0.85	0.87	0.87	0.87	0.88	0.88
Na	0.03	0.02	0.02	0.03	0.01	0.03

End Members (%)

Wo	44.23	44.93	44.51	45.14	45.36	45.41
En	45.01	43.90	44.21	44.48	44.96	44.37
Fs	10.76	11.17	11.28	10.37	9.68	10.22

Appendix F. continued.

	13	14	15	16	17	18
Sample	3817-9h	3817-1b	3817-6e	3817-1c	3817-1d	3817-1e
SiO <sub>2</sub>	51.73	52.56	51.25	51.82	52.25	52.39
TiO <sub>2</sub>	0.22	0.32	0.68	0.36	0.30	0.33
Al <sub>2</sub> O <sub>3</sub>	3.02	2.01	2.61	2.53	1.90	1.75
Cr <sub>2</sub> O <sub>3</sub>	0.14	0.10	0.14	0.14	0.16	0.06
FeO	5.36	5.52	5.50	5.45	5.09	5.29
MnO	1.15	0.63	0.40	0.84	0.58	0.61
MgO	15.28	15.76	15.58	15.65	15.94	15.81
CaO	22.27	22.46	22.47	22.51	22.80	22.95
Na <sub>2</sub> O	0.38	0.21	0.21	0.24	0.17	0.21
An. Total	99.56	99.57	98.84	99.54	99.19	99.39

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.91	1.94	1.91	1.91	1.94	1.94
Al <sub>t</sub>	0.13	0.09	0.11	0.11	0.08	0.08
Al <sub>iv</sub>	0.09	0.06	0.09	0.09	0.06	0.06
Al <sub>vi</sub>	0.04	0.03	0.02	0.02	0.02	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>3+</sup>	0.05	0.02	0.04	0.05	0.03	0.04
Ti	0.01	0.01	0.02	0.01	0.01	0.01
Mg	0.84	0.87	0.86	0.86	0.88	0.87
Fe <sup>2+</sup>	0.12	0.15	0.14	0.12	0.13	0.12
Mn	0.04	0.02	0.01	0.03	0.02	0.02
Ca	0.88	0.89	0.90	0.89	0.90	0.91
Na	0.03	0.02	0.02	0.02	0.01	0.01

End Members (%)

Wo	45.80	45.67	46.09	45.76	46.14	46.32
En	43.72	44.57	44.47	44.25	44.89	44.38
Fs	10.22	9.76	9.45	10.00	8.97	9.30



Appendix F. continued.

	19	23	24	25	26	27
Sample	3817-1f	3817-2a*	3817-2b*	3817-6f	3817-6g	3817-6h
SiO <sub>2</sub>	52.30	52.64	52.60	50.25	50.68	50.91
TiO <sub>2</sub>	0.35	0.51	0.44	0.23	0.26	0.23
Al <sub>2</sub> O <sub>3</sub>	1.89	1.73	1.72	3.07	3.22	3.10
Cr <sub>2</sub> O <sub>3</sub>	0.15	0.15	0.13	0.14	0.09	0.17
FeO	5.14	6.19	5.38	5.85	5.89	6.05
MnO	0.59	0.33	0.57	1.01	0.94	1.03
MgO	15.77	16.16	16.24	15.09	15.27	14.92
CaO	23.01	21.55	21.84	22.13	22.15	22.23
Na <sub>2</sub> O	0.22	0.19	0.20	0.29	0.27	0.30
An. Total	99.43	99.44	99.10	98.05	98.78	98.95

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.93	1.95	1.95	1.89	1.89	1.90
Al <sub>t</sub>	0.08	0.08	0.07	0.14	0.14	0.14
Al <sub>iv</sub>	0.07	0.05	0.05	0.11	0.11	0.10
Al <sub>vi</sub>	0.02	0.02	0.02	0.02	0.03	0.03
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>3+</sup>	0.03	0.00	0.00	0.09	0.08	0.06
Ti	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.87	0.89	0.90	0.84	0.85	0.83
Fe <sup>2+</sup>	0.13	0.19	0.16	0.10	0.10	0.13
Mn	0.02	0.01	0.02	0.03	0.03	0.03
Ca	0.91	0.85	0.87	0.89	0.88	0.89
Na	0.02	0.01	0.01	0.02	0.02	0.02

End Members (%)

Wo	46.55	43.87	44.50	45.65	45.45	45.81
En	44.39	45.77	46.03	43.29	43.60	42.78
Fs	9.06	10.36	9.47	11.06	10.95	11.42

Appendix F. continued.

	28	29	30	31	32	33
Sample	3817-2c*	3817-1g	3817-2d*	3817-2e*	3817-2f*	3817-2g*
SiO <sub>2</sub>	52.58	52.27	52.75	52.26	52.44	52.68
TiO <sub>2</sub>	0.43	0.31	0.48	0.47	0.46	0.45
Al <sub>2</sub> O <sub>3</sub>	1.71	1.62	1.41	1.67	1.66	1.61
Cr <sub>2</sub> O <sub>3</sub>	0.12	0.12	0.13	0.10	0.15	0.14
FeO	4.86	5.13	5.40	5.03	4.96	5.25
MnO	0.61	0.56	0.30	0.57	0.55	0.48
MgO	15.90	15.67	15.88	15.77	15.78	15.77
CaO	22.68	22.74	22.82	22.85	22.93	22.95
Na <sub>2</sub> O	0.23	0.22	0.17	0.20	0.19	0.20
An. Total	99.12	98.62	99.34	98.91	99.12	99.53

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.95	1.95	1.95	1.94	1.95	1.95
Al <sub>t</sub>	0.07	0.07	0.06	0.07	0.07	0.07
Al <sub>iv</sub>	0.05	0.05	0.05	0.06	0.05	0.05
Al <sub>vi</sub>	0.02	0.02	0.02	0.02	0.02	0.02
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>3+</sup>	0.01	0.02	0.01	0.02	0.01	0.01
Ti	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.88	0.87	0.88	0.87	0.87	0.87
Fe <sup>2+</sup>	0.14	0.14	0.16	0.13	0.14	0.15
Mn	0.02	0.02	0.01	0.02	0.02	0.02
Ca	0.90	0.91	0.91	0.91	0.91	0.91
Na	0.02	0.02	0.01	0.01	0.01	0.01

End Members (%)

Wo	46.22	46.42	46.23	46.47	46.62	46.49
En	45.06	44.51	44.76	44.62	44.62	44.43
Fs	8.73	9.07	9.01	8.91	8.76	9.08

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Appendix F. continued.

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Sample	3817-2h*
SiO <sub>2</sub>	52.99
TiO <sub>2</sub>	0.37
Al <sub>2</sub> O <sub>3</sub>	1.36
Cr <sub>2</sub> O <sub>3</sub>	0.13
FeO	4.86
MnO	0.43
MgO	15.92
CaO	22.96
Na <sub>2</sub> O	0.19
An. Total	99.22

Normalized to 4 Cations per formula unit and charge balanced (IMA recommendation, Morimoto, 1988)

Si	1.96
Al t	0.06
Al_iv	0.04
Al_vi	0.02
Cr	0.00
Fe <sup>3+</sup>	0.00
Ti	0.01
Mg	0.88
Fe <sup>2+</sup>	0.15
Mn	0.01
Ca	0.91
Nas	0.01

End Members (%)

Wo	46.64
En	44.98
Fs	8.38

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Appendix G. Electron microprobe analyses of biotite from ballrooms.

	1	2	3	4	5	6
Sample	50D6-2	50D6-2	50D6-2	50D6-2	50D6-2	50D6-2
Sample no.	biot 10 h	biot 10c	biot 10b	biot 10e	biot 10d	biot 7c
SiO <sub>2</sub>	38.20	38.67	38.89	38.77	38.82	38.23
TiO <sub>2</sub>	2.56	2.54	2.48	2.59	2.45	3.08
Al <sub>2</sub> O <sub>3</sub>	16.24	15.93	15.90	16.19	16.09	15.95
Fe	8.16	8.04	8.14	8.31	8.60	7.65
MnO	0.01	0.02	0.04	0.00	0.03	0.03
MgO	20.99	21.06	21.07	20.80	20.97	20.36
CaO	0.03	0.03	0.02	0.03	0.01	0.00
Na <sub>2</sub> O	0.89	0.95	0.92	0.79	0.81	0.52
K <sub>2</sub> O	8.59	8.89	8.74	8.89	8.88	8.09
F	0.32	0.32	0.29	0.38	0.41	0.02
Cl	0.27	0.28	0.32	0.26	0.26	0.30
Sum	96.26	96.73	96.80	97.03	97.31	94.22
H <sub>2</sub> O*	3.95	3.95	3.96	3.94	3.94	4.03
Total	100.02	100.48	100.56	100.75	101.02	98.17

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.75	2.78	2.79	2.78	2.77	2.78
Al	1.38	1.35	1.34	1.37	1.35	1.37
Al iv	1.26	1.22	1.21	1.22	1.23	1.22
Al vi	0.12	0.13	0.13	0.14	0.12	0.15
Ti	0.14	0.14	0.13	0.14	0.13	0.17
Fe	0.49	0.48	0.49	0.50	0.51	0.47
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	2.25	2.25	2.25	2.22	2.23	2.21
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.12	0.13	0.13	0.11	0.11	0.07
K	0.79	0.82	0.80	0.81	0.81	0.75
F	0.07	0.07	0.07	0.09	0.09	0.01
Cl	0.03	0.03	0.04	0.03	0.03	0.04
OH*	1.89	1.89	1.90	1.88	1.88	1.96

End

X phlog	0.750	0.751	0.750	0.740	0.743	0.737
X sid	0.144	0.134	0.132	0.144	0.140	0.145
X ann	0.106	0.115	0.118	0.116	0.117	0.118

\*= OH and H<sub>2</sub>O calculated assuming full occupancy of hydroxyl site

Appendix G. Continued.

Sample	7	8	9	10	11	12
Sample no.	4048-1 biot 1g	50D6-2 biot 7b	4048-1 biot 1b	50D6-2 biot 8h	50D6-2 biot 7d	50D6-2 biot 10i
SiO <sub>2</sub>	37.43	38.20	37.56	37.92	38.01	37.82
TiO <sub>2</sub>	3.49	3.34	3.37	2.48	3.27	2.57
Al <sub>2</sub> O <sub>3</sub>	15.59	15.59	15.76	15.74	15.70	15.48
Fe	8.19	7.98	8.60	7.97	7.97	8.31
MnO	0.02	0.02	0.00	0.03	0.02	0.02
MgO	19.80	20.30	19.93	20.53	20.59	20.59
CaO	0.02	0.03	0.02	0.01	0.01	0.01
Na <sub>2</sub> O	0.76	0.63	0.57	0.95	0.63	0.93
K <sub>2</sub> O	8.57	8.26	8.65	8.68	8.35	8.66
F	0.12	0.14	0.01	0.34	0.09	0.25
Cl	0.30	0.26	0.34	0.25	0.32	0.32
Sum	94.27	94.75	94.80	94.90	94.96	94.96
H <sub>2</sub> O*	3.92	3.98	4.00	3.87	4.00	3.89
Total	98.08	98.62	98.72	98.57	98.85	98.67

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.76	2.78	2.75	2.78	2.76	2.77
Al t	1.36	1.34	1.36	1.36	1.35	1.34
Al iv	1.24	1.22	1.25	1.22	1.24	1.23
Al vi	0.12	0.12	0.11	0.13	0.11	0.10
Ti	0.19	0.18	0.19	0.14	0.18	0.14
Fe	0.51	0.49	0.53	0.49	0.48	0.51
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	2.18	2.21	2.18	2.24	2.23	2.25
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.11	0.09	0.08	0.14	0.09	0.13
K	0.81	0.77	0.81	0.81	0.77	0.81
F	0.03	0.03	0.00	0.08	0.02	0.06
Cl	0.04	0.03	0.04	0.03	0.04	0.04
OH*	1.94	1.94	1.96	1.89	1.94	1.90

End member

X phlog	0.726	0.735	0.725	0.747	0.743	0.748
X sid	0.151	0.140	0.154	0.138	0.139	0.133
X ann	0.123	0.125	0.121	0.115	0.118	0.119

Appendix G. Continued.

	13	14	15	16	17	18
Sample	50D6-2	4048-1	50D6-2	4048-1	50D6-2	4048-1
Sample no.	biot 6e	biot 9g	biot 7a	biot 9f	biot 10f	biot 9b
SiO <sub>2</sub>	37.80	37.87	38.16	37.89	37.25	37.22
TiO <sub>2</sub>	3.92	3.50	3.16	3.50	2.44	3.23
Al <sub>2</sub> O <sub>3</sub>	15.50	15.71	15.80	15.55	15.84	15.61
Fe	8.11	8.09	8.03	8.49	10.17	9.82
MnO	0.04	0.02	0.05	0.03	0.03	0.14
MgO	20.05	20.04	20.62	20.02	20.38	19.92
CaO	0.00	0.00	0.03	0.00	0.12	0.03
Na <sub>2</sub> O	0.61	0.83	0.61	0.65	0.67	0.38
K <sub>2</sub> O	8.60	8.72	8.38	8.71	8.00	8.67
F	0.15	0.08	0.10	0.11	0.25	0.07
Cl	0.30	0.34	0.30	0.37	0.22	0.29
Sum	95.06	95.20	95.24	95.32	95.36	95.38
H <sub>2</sub> O*	3.95	3.97	4.01	3.96	3.96	4.00
Total	98.88	99.06	99.14	99.16	99.16	99.28

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.76	2.77	2.76	2.77	2.70	2.71
Al t	1.34	1.36	1.35	1.34	1.35	1.34
Al iv	1.24	1.23	1.24	1.23	1.30	1.29
Al vi	0.10	0.13	0.11	0.11	0.05	0.05
Ti	0.22	0.19	0.17	0.19	0.13	0.18
Fe t	0.50	0.50	0.49	0.52	0.62	0.60
Mn	0.00	0.00	0.00	0.00	0.00	0.01
Mg	2.19	2.19	2.23	2.18	2.20	2.16
Ca	0.00	0.00	0.00	0.00	0.01	0.00
Na	0.09	0.12	0.09	0.09	0.09	0.05
K	0.80	0.81	0.77	0.81	0.74	0.81
F	0.03	0.02	0.02	0.03	0.06	0.02
Cl	0.04	0.04	0.04	0.05	0.03	0.04
OH*	1.93	1.94	1.94	1.93	1.92	1.95
End member						
X phlog	0.729	0.728	0.472	0.727	0.733	0.721
X sid	0.144	0.149	0.140	0.146	0.153	0.156
X ann	0.127	0.123	0.118	0.127	0.114	0.123

Appendix G. Continued.

Sample	19	20	21	22	23	24
Sample no.	4048-1	4048-1	4048-1	50D6-2	50D6-2	50D6-2
	biot 1e	biot 9d	biot 9c	biot 10a	biot 6b	biot 8e
SiO <sub>2</sub>	38.11	37.92	37.95	38.11	37.94	38.05
TiO <sub>2</sub>	3.61	3.61	3.57	2.44	3.91	2.48
Al <sub>2</sub> O <sub>3</sub>	15.75	15.72	15.91	15.71	15.46	15.86
Fe	8.01	8.10	8.35	8.17	8.14	8.28
MnO	0.02	0.06	0.00	0.05	0.02	0.02
MgO	20.24	20.13	19.70	20.64	20.33	20.83
CaO	0.02	0.02	0.00	0.05	0.01	0.01
Na <sub>2</sub> O	0.77	0.90	0.72	0.95	0.68	0.85
K <sub>2</sub> O	8.46	8.58	8.84	8.74	8.74	8.81
F	0.10	0.12	0.16	0.42	0.07	0.37
Cl	0.32	0.34	0.35	0.28	0.32	0.23
Sum	95.43	95.48	95.55	95.57	95.60	95.79
H <sub>2</sub> O*	3.99	3.96	3.93	3.84	4.01	3.90
Total	99.30	99.31	99.34	99.17	99.51	99.48

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.77	2.77	2.78	2.78	2.76	2.76
Al t	1.35	1.35	1.37	1.35	1.33	1.36
Al iv	1.23	1.23	1.23	1.22	1.24	1.24
Al vi	0.12	0.12	0.15	0.13	0.09	0.11
Ti	0.20	0.20	0.20	0.13	0.21	0.14
Fe t	0.49	0.49	0.51	0.50	0.50	0.50
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	2.19	2.19	2.15	2.24	2.20	2.25
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.11	0.13	0.10	0.14	0.10	0.12
K	0.79	0.80	0.83	0.81	0.81	0.81
F	0.02	0.03	0.04	0.10	0.02	0.08
Cl	0.04	0.04	0.04	0.04	0.04	0.03
OH*	1.94	1.93	1.92	1.87	1.95	1.89
End member						
X phlog	0.731	0.729	0.716	0.747	0.735	0.750
X sid	0.146	0.148	0.159	0.136	0.139	0.138
X ann	0.123	0.123	0.125	0.117	0.126	0.112

Appendix G. Continued.

Sample	25	26	27	28	29	30
Sample no.	50D6-2	4048-1	4048-1	4048-1	50D6-2	50D6-2
	biot 8f	biot 9e	biot 1a	biot 9a	biot 6f	biot 6d
SiO <sub>2</sub>	37.94	38.11	38.17	38.18	38.10	38.14
TiO <sub>2</sub>	2.51	3.55	3.55	3.54	3.73	3.96
Al <sub>2</sub> O <sub>3</sub>	15.96	15.75	15.80	15.84	15.78	15.78
Fe	8.44	8.18	8.38	8.15	8.35	8.25
MnO	0.01	0.00	0.02	0.02	0.03	0.02
MgO	20.64	20.14	20.09	20.23	20.27	20.14
CaO	0.01	0.00	0.00	0.00	0.00	0.00
Na <sub>2</sub> O	0.97	0.80	0.68	0.74	0.65	0.68
K <sub>2</sub> O	8.74	8.84	8.70	8.79	8.56	8.59
F	0.32	0.11	0.08	0.11	0.12	0.11
Cl	0.26	0.33	0.35	0.28	0.31	0.30
Sum	95.80	95.80	95.82	95.86	95.91	95.96
H <sub>2</sub> O*	3.91	3.98	4.00	4.01	4.00	4.01
Total	99.51	99.66	99.71	99.76	99.78	99.86

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.75	2.77	2.77	2.77	2.76	2.76
Al t	1.37	1.35	1.35	1.36	1.35	1.35
Al iv	1.25	1.23	1.23	1.23	1.24	1.24
Al vi	0.12	0.12	0.12	0.13	0.10	0.11
Ti	0.14	0.19	0.19	0.19	0.20	0.22
Fe t	0.51	0.50	0.51	0.49	0.51	0.50
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	2.23	2.18	2.17	2.19	2.19	2.17
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.14	0.11	0.10	0.10	0.09	0.10
K	0.81	0.82	0.81	0.81	0.79	0.79
F	0.07	0.03	0.02	0.03	0.03	0.02
Cl	0.03	0.04	0.04	0.03	0.04	0.04
OH*	1.89	1.93	1.94	1.94	1.93	1.94
End member						
X phlog	0.744	0.728	0.724	0.729	0.729	0.724
X sid	0.144	0.147	0.150	0.148	0.147	0.150
X ann	0.112	0.125	0.126	0.123	0.124	0.126



Appendix G. Continued.

Sample	31	32	33	34	35	36
Sample no.	4048-1	4048-1	50D6-2	50D6-2	50D6-2	50D6-2
	biot 1c	biot 1f	biot 8d	biot 8c	biot 8b	biot 10g
SiO <sub>2</sub>	38.07	38.15	38.33	38.49	38.28	38.13
TiO <sub>2</sub>	3.61	3.83	2.57	2.59	2.58	2.64
Al <sub>2</sub> O <sub>3</sub>	16.03	15.75	15.96	15.80	16.05	16.14
Fe	8.09	8.22	8.25	8.19	8.18	8.33
MnO	0.04	0.02	0.03	0.05	0.01	0.04
MgO	20.21	20.16	20.78	20.77	20.84	20.73
CaO	0.03	0.02	0.00	0.02	0.02	0.03
Na <sub>2</sub> O	0.74	0.75	0.80	0.89	0.89	0.87
K <sub>2</sub> O	8.78	8.74	8.86	8.76	8.85	8.71
F	0.05	0.09	0.32	0.37	0.27	0.35
Cl	0.32	0.29	0.23	0.23	0.25	0.25
Sum	95.97	96.02	96.13	96.13	96.19	96.21
H <sub>2</sub> O*	4.03	4.02	3.94	3.91	3.96	3.92
Total	99.90	99.94	99.88	99.84	99.98	99.93

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.76	2.77	2.77	2.78	2.76	2.75
Al t	1.37	1.35	1.36	1.35	1.37	1.37
Al iv	1.24	1.23	1.23	1.22	1.24	1.25
Al vi	0.13	0.11	0.13	0.13	0.13	0.12
Ti	0.20	0.21	0.14	0.14	0.14	0.14
Fe t	0.49	0.50	0.50	0.49	0.49	0.50
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	2.18	2.18	2.24	2.24	2.24	2.23
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.10	0.11	0.11	0.12	0.12	0.12
K	0.81	0.81	0.82	0.81	0.81	0.80
F	0.01	0.02	0.07	0.08	0.06	0.08
Cl	0.04	0.04	0.03	0.03	0.03	0.03
OH*	1.95	1.94	1.90	1.89	1.91	1.89
End member						
X phlog	0.728	0.726	0.745	0.745	0.747	0.743
X sid	0.153	0.148	0.140	0.136	0.141	0.146
X ann	0.119	0.126	0.115	0.119	0.112	0.111

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Appendix G. Continued.

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Sample Sample no.	37	38
	50D6-2 biot 6a	50D6-2 biot 8a
SiO <sub>2</sub>	38.30	38.53
TiO <sub>2</sub>	3.97	2.59
Al <sub>2</sub> O <sub>3</sub>	15.73	15.91
Fe	8.21	8.07
MnO	0.03	0.04
MgO	20.20	20.76
CaO	0.00	0.04
Na <sub>2</sub> O	0.62	0.93
K <sub>2</sub> O	8.77	8.82
F	0.09	0.34
Cl	0.30	0.23
Sum	96.22	96.26
H <sub>2</sub> O*	4.03	3.93
Total	100.14	99.99

Atoms per formula unit. Normalized to 7 Octahedral + Tetrahedral Cations

Si	2.77	2.78
Al t	1.34	1.35
Al iv	1.23	1.22
Al vi	0.11	0.14
Ti	0.22	0.14
Fe t	0.50	0.49
Mn	0.00	0.00
Mg	2.18	2.23
Ca	0.00	0.00
Na	0.09	0.13
K	0.81	0.81
F	0.02	0.08
Cl	0.04	0.03
OH*	1.94	1.89

End member

X phlog	0.726	0.744
X sid	0.146	0.138
X ann	0.128	0.118

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## Appendix H. Standards used in major and trace element whole rock analyses

Standard	BHVO-1 Analysis 1	BHVO-1 Analysis 2	BHVO-1 Analysis 3	BHVO-1 Accepted
SiO <sub>2</sub>	46.76	46.73	46.42	49.94
TiO <sub>2</sub>	2.74	2.75	2.73	2.71
Al <sub>2</sub> O <sub>3</sub>	13.80	13.77	13.76	13.83
Fe <sub>2</sub> O <sub>3</sub>	12.58	12.59	12.59	12.34
MnO	0.17	0.17	0.17	0.17
MgO	5.45	5.43	5.42	7.32
CaO	11.30	11.25	11.27	11.40
Na <sub>2</sub> O	2.45	2.43	2.43	2.26
K <sub>2</sub> O	0.50	0.50	0.50	0.52
P <sub>2</sub> O <sub>5</sub>	0.18	0.17	0.17	0.27
LOI	0.25	0.25	0.25	0.25
An. Total	95.92	95.39	95.46	100.67
ppm				
Ba	98	92	87	139
Cr	332	334	332	289
Cu	24	24	23	19
Nb	137	138	137	121
Ni	9	9	9	11
Rb	105	102	103	102
S	32	31	31	32
Sr	277	282	278	317
V	29	29	29	28
Y	116	116	117	105
Zn	149	149	149	179

1. Normalized to 100% on a volatile free basis.
2. An. Total = Analytical total
3. LOI = loss on ignition at 1000°C for 4 hours.

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Appendix H continued.

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Standard	BR Analysis 1	BR Analysis 2	BR Accepted
SiO <sub>2</sub>	40.99	40.71	38.20
TiO <sub>2</sub>	2.73	2.73	2.60
Al <sub>2</sub> O <sub>3</sub>	11.01	11.06	10.20
Fe <sub>2</sub> O <sub>3</sub>	12.90	12.85	12.87
MnO	0.20	0.20	0.20
MgO	13.51	13.51	13.28
CaO	14.46	14.42	13.80
Na <sub>2</sub> O	3.50	3.48	3.05
K <sub>2</sub> O	1.53	1.53	1.40
P <sub>2</sub> O <sub>5</sub>	1.10	1.09	1.04
LOI	3.00	3.00	3.00
An. Total	100.64	100.31	95.37
ppm			
Ba	1120	1143	1150
Cr	407	409	380
Cu	113	114	270
Nb	288	288	260
Ni	49	50	47
Rb	295	290	390
S	38	40	25
Sr	220	220	235
V	34	34	30
Y	165	165	160
Zn	98	100	250

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Appendix H continued.

Standard	NIM-P Analysis 1	NIM-P Analysis 2	NIM-P Analysis 3	NIM-P Accepted
SiO <sub>2</sub>	51.76	51.49	51.20	51.10
TiO <sub>2</sub>	0.20	0.20	0.20	0.20
Al <sub>2</sub> O <sub>3</sub>	5.36	5.45	5.47	4.18
Fe <sub>2</sub> O <sub>3</sub>	13.49	13.38	13.38	12.77
MnO	0.24	0.24	0.24	0.22
MgO	25.53	25.77	25.70	25.33
CaO	2.89	2.90	2.90	2.66
Na <sub>2</sub> O	0.30	0.29	0.30	0.37
K <sub>2</sub> O	0.12	0.12	0.12	0.09
P <sub>2</sub> O <sub>5</sub>	0.03	0.03	0.03	0.02
LOI	0.34	0.34	0.34	0.34
An. Total	98.57	98.55	98.20	95.68
ppm				
Ba	32	34	35	46
Cr	24441	24384	24438	2.4
Cu	25	25	25	25
Nb	590	588	589	560
Ni	3	3	3	5
Rb	113	112	114	
S	3	3	3	29
Sr	269	271	276	230
V	10	10	10	5
Y	116	116	116	100
Zn	42	42	42	30

Appendix H continued.

Standard	PCC-1 Analysis 1	PCC-1 Analysis 2	PCC-1 Analysis 3	PCC-1 Accepted
SiO <sub>2</sub>	42.17	42.14	42.07	41.67
TiO <sub>2</sub>	0.01	0.01	0.01	0.01
Al <sub>2</sub> O <sub>3</sub>	0.62	0.87	0.78	0.67
Fe <sub>2</sub> O <sub>3</sub>	9.53	9.46	9.45	8.34
MnO	0.13	0.13	0.13	0.12
MgO	43.06	43.62	43.53	43.43
CaO	0.57	0.57	0.57	0.52
Na <sub>2</sub> O	nd	nd	nd	0.01
K <sub>2</sub> O	nd	nd	nd	0.00
P <sub>2</sub> O <sub>5</sub>	0.02	0.01	0.01	0.00
LOI	5.30	5.30	5.30	5.30
An. Total	95.16	95.87	95.61	94.94
ppm				
Ba	nd	nd	nd	0.12
Cr	2888	2872	2877	2730
Cu	11	10	11	11
Nb	2660	2648	2647	2380
Ni	nd	nd	nd	0
Rb	80	77	75	20
S	nd	nd	nd	8
Sr	33	34	33	31
V	nd	nd	nd	0.1
Y	55	54	54	42
Zn	nd	nd	nd	0
Zr	nd	nd	nd	10

Appendix H continued.

Standard	QLO-1 Analysis 1	QLO-1 Accepted	STM-1 Analysis 1	STM-1 Accepted
SiO <sub>2</sub>	66.24	65.55	61.10	59.64
TiO <sub>2</sub>	0.64	0.62	0.13	0.14
Al <sub>2</sub> O <sub>3</sub>	14.45	16.18	17.13	18.39
Fe <sub>2</sub> O <sub>3</sub>	4.53	4.32	5.19	5.19
MnO	0.09	0.09	0.22	0.22
MgO	0.98	1.00	0.39	0.10
CaO	3.28	3.17	1.10	1.09
Na <sub>2</sub> O	4.00	4.20	8.52	8.94
K <sub>2</sub> O	3.61	3.60	4.34	4.28
P <sub>2</sub> O <sub>5</sub>	0.18	0.25	0.14	0.16
LOI	0.56	0.56	1.72	1.72
An. Total	97.55	98.56	97.74	99.87
ppm				
Ba	1407	1370	585	560
Cr	21	29	20	4
Cu	12	10	269	269
Nb	20	6	19	3
Ni	77	74	121	118
Rb	56	30	72	43
S	7	9	nd	1
Sr	35	54	nd	9
V	28	24	48	46
Y	59	61	225	235
Zn	172	185	1238	1210