The Stillwater Complex: A review of the geology

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INTRODUCTION

The Stillwater Complex crops out on the northern edge of the Beartooth Range, one of the major exposed blocks in the Wyoming Archean Province (Fig. 1). The complex is separated from the main Beartooth block by the Mill Creek-Stillwater Fault Zone and from the North Snowy Block by the West Boulder Fault (Fig. 1, inset). The intrusive contact between the complex and the underlying metasedimentary rocks is locally exposed between the Boulder River and Chrome Mountain and in the Mountain View area (Fig. 1). Between Chrome Mountain and the West Fork of the Stillwater River, the lower part of the complex is in fault contact with the hornfels. From the West Fork to the main Stillwater River, the complex is in fault contact with a younger quartz monzonite along the Bluebird Thrust, while east of the Stillwater River the complex has been intruded by the same quartz monzonite. Along its northern margin, the complex is overlain by Paleozoic and Mesozoic sedimentary rocks. For most of its length this contact is an angular unconformity except for the area between the West Fork and the Stillwater River where the contact is marked by the Horseman Thrust. The exposed part of the complex covers an area of ~180 km^2 with a maximum length of 47 km and a maximum width of 8 km (Fig. 1).

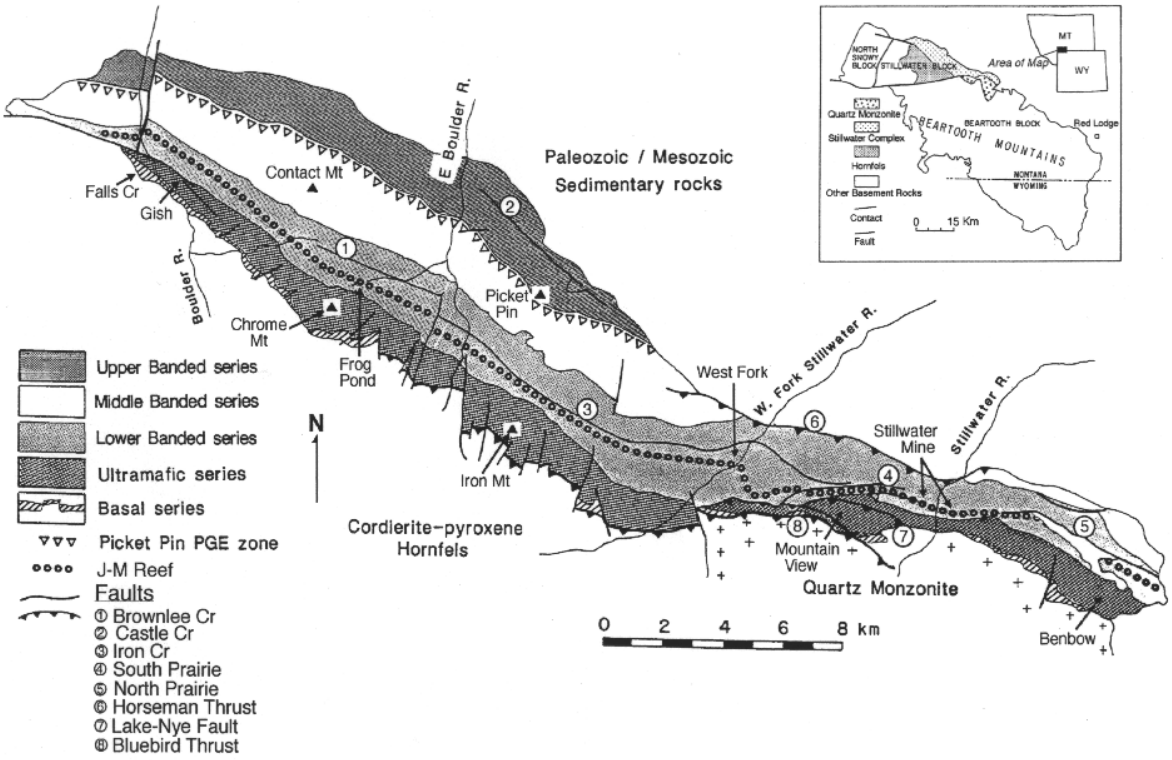

Figure 1. Map of the Stillwater Complex showing the major subdivisions, major faults, and mineralized zones. Inset shows the complex in relation to the major blocks that make up the Beartooth Mountains.

Evidence for a major crust-forming episode that extended from ~3000 to 2740 Ma is preserved in the Beartooth block (Wooden and Mueller, 1989). This episode culminated in the production of voluminous granodiorites and granites of the Long Lake Suite between 2780 and 2740 Ma and isotopic data indicate that the intrusion of the Stillwater mafic magma at 2700 Ma was related to this same event. During the Proterozoic, mafic dikes were emplaced throughout the Beartooth Range and the complex and surrounding rocks were subjected to a low-grade regional metamorphism. The area was uplifted, tilted towards the north, and eroded during late Proterozoic. Subsidence and sedimentation from Middle Cambrian through Lower Cretaceous covered the complex with a sequence of sedimentary rocks up to 3000 meters thick. Laramide deformation during the late Cretaceous to early Tertiary resulted in uplift, tilting, and erosion which exhumed the late Proterozoic erosional surface.

A Sm-Nd isochron on mineral separates from a gabbronorite from the West Fork Adit portal gave a crystallization age of 2701 ± 8 Ma (DePaolo and Wasserburg, 1979). Nunes (1981) determined an age of 2713 ± 3 Ma on zircons from the Basal series and Premo *et al.* (1990) determined a U-Pb zircon age of 2705 ± 4 Ma for the dike/sill suite that is associated with the Basal series, indicating that the sills are coeval with the main complex.

The complex contains important reserves of base and noble metals. Sulfide-rich rocks associated with the Basal series, adjacent hornfels, and lowermost Ultramafic series have been extensively explored as a source of copper and nickel since the late nineteenth century. Chromite-rich seams associated with peridotites of the Ultramafic series have also been extensively explored. During wartime periods when the demand for chromium was high, these deposits were mined in the Benbow, Mountain View and Gish areas. Stillwater chromites represent about 80% of the identified chromium reserves in the United States. The occurrence of platinum and palladium minerals in the complex has been known since the thirties but it was not until 1973 that the major PGE zone, the J-M reef, was discovered. The reef, which is composed of disseminated sulfides in a narrow zone within the lower part of the Banded series, is presently being mined in the Stillwater Valley and East Boulder plateau.

GEOLOGY OF THE COMPLEX

STRUCTURE AND LAYERING

Approximately 6 km of Laramide uplift has exposed the pre-Middle Cambrian erosional surface at a mean elevation of ~3000 meters (Jones, Peoples and Howland, 1960). Five major high-angle reverse faults of Laramide age with strikes subparallel to the layering and steep northeast dips have affected the Banded series (faults 1-5, Fig. 1). On each of these faults, the hanging wall has been elevated preserving remnants of Cambrian sedimentary rocks adjacent to the fault in the footwall block. Much of the movement along these faults appears to be along planes coincident with the igneous layering, e.g., the South Prairie fault (Fig. 2).

A set of south-dipping thrust faults occurs in the eastern half of the complex (Page and Nokleberg, 1974).

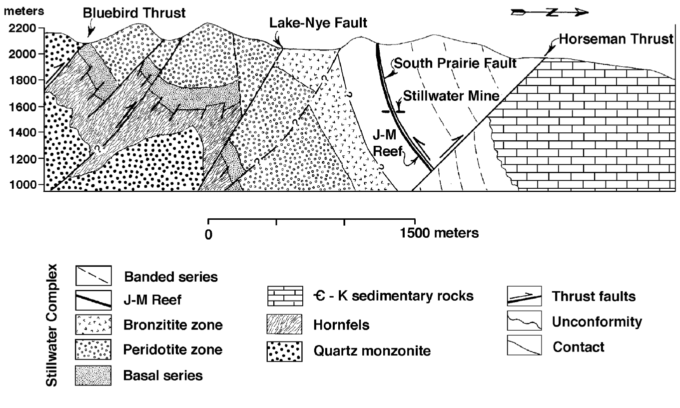

Figure 2. Structural section through the complex at Mountain View (after Turner et al., 1985)

The northern fault of the Bluebird Thrust system has juxtaposed Ultramafic series rocks against Banded series rocks in the West Fork area (Fig. 1). Further to the east, movement along this fault system has rotated a large wedge of the Ultramafic series to form the Mountain View Block which is bounded on the north by the Lake-Nye Fault, which merges with the Bluebird Thrust toward the west. This fault has truncated the chromitite deposits of the Mountain View block and removed about 1000 meters of the Ultramafic series in the Nye Creek area. The Horseman Thrust, which forms the northern boundary of the complex from Picket Pin Creek to Little Rocky Creek, has thrust slices of the complex over the Paleozoic strata (Fig. 2). Closely spaced, steeply dipping transverse faults with displacements ranging from less than a meter to several hundred meters are common in the Basal series and the Ultramafic series but seldom extend far into the Banded series rocks (Fig. 1). Many of these faults may represent reactivated basin margin growth faults that developed during the formation of the complex. The latest movement along these transverse faults postdated that along the south dipping thrusts.

The fraction of Stillwater rocks which display layering is relatively small. The typical outcrop is modally uniform although many rocks show an igneous lamination defined by preferred orientation of plagioclase and augite. Anorthosites and bronzitites form megalayers up to several hundred meters thick, which can be traced across the entire complex. Thinner layers can be traced for distances of a few tens to a few hundreds of meters. Modally graded layers and rhythmic layering occur but are not common and size-graded and cross-bedded layers are rare. The most spectacular example of rhythmic layering is the inch-scale layering composed of alternating plagioclase-rich and pyroxene-rich layers. Macrorhythmic layers, which grade upwards over a distance of several meters from a pyroxene-rich base to a plagioclase-rich top, are locally preserved in gabbronorites on Contact Mountain.

CONTACT AUREOLE

In the East Boulder Plateau, pelitic rocks have been thermally metamorphosed to pyroxene hornfels near the contact. A distinctive blue quartzite occurs as thin layers within the hornfels and Banded Iron Formations form extensive outcrops at Iron Mountain and south of Chrome Mountain. Hornfels occurs as quartz-bearing and quartz-free varieties (Page, 1977). Quartz-bearing hornfels in the vicinity of the contact consists mainly of quartz-hypersthene-plagioclase-cordierite assemblages. At some distance from the contact, cummingtonite take the place of hypersthene (Labotka, 1985). Quartz-free hornfelses are less common and restricted to contact zones and xenoliths within the complex. They consist dominantly of hypersthene and cordierite with minor plagioclase and locally contain abundant sulfide. Assemblages in the iron-formation are consistent with peak metamorphic temperatures around 825°C (Labotka, 1985) and pressures between 3 and 4 kilobars.

MAJOR SUBDIVISIONS OF THE COMPLEX

The complex has been subdivided into five major units: Basal series, Ultramafic series, Lower Banded Series, Middle Banded series, and Upper Banded series (Figs. 1 and 3). Each series has been further subdivided into a number of zones and subzones (Fig. 3). Also shown in Fig. 3 is the stratigraphic distribution of the cumulus minerals and a compressed version of the variation in mode of cumulus minerals as a function of stratigraphic height for sections through the Banded series in the Contact Mountain area and the Ultramafic series in the Mountain View area. Each of the series and zone boundaries is based on the appearance or disappearance of one or more cumulus minerals. An additional unit, the Sill/Dike suite, is associated with the Basal series.

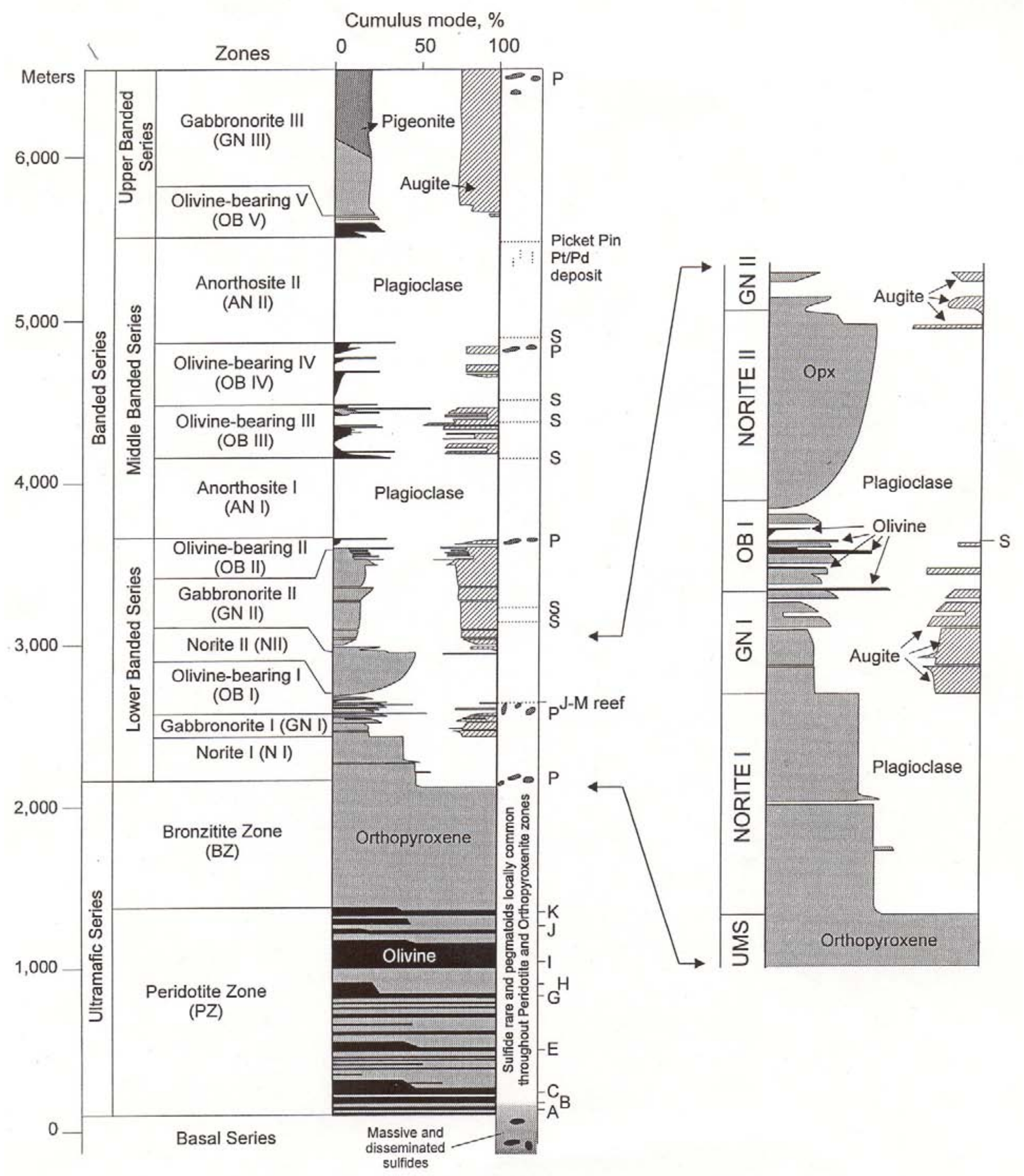

Figure 3. Composite stratigraphic section compiled from detailed sections of McCallum et al. (1980), Raedeke and McCallum (1984) showing the zones and modal stratigraphy (cumulus minerals only). "S" denotes sulfide-enriched zones, "A – K" denotes the major chromitites, and P denotes podiform concentrations of sulfide of limited lateral extent.

MINERALOGY

The most abundant primary minerals are olivine, orthopyroxene, clinopyroxene, inverted pigeonite, plagioclase, and chrome spinel. Minor primary minerals are quartz, phlogopite, amphibole, apatite, magnetite, ilmenite, and sulfides. A large variety of secondary minerals are present, the most abundant being serpentine and talc (after olivine and orthopyroxene), zeolites and zoisite (after plagioclase) and chlorite and actinolite (after pyroxene). The mineral assemblages are summarized in Table 1.

Table 1. Rock names and terminology

Rock name	Cumulus Minerals	Postcumulus Minerals	Notation*
Peridotite	Ol (±Chr)	Opx, Cpx, Plag, Phl, (Amph, Ap)	oC/ocC
Harzburgite	Ol, Opx (± Chr)	Cpx, Plag, (Phl, Amph, Ap)	obC
Chromitite	Chr (±Ol)	Opx, Cpx, Plag, (Phl, Amph, Ap)	cC
Bronzitite	Opx	Plag, Cpx, (Qtz, Phl, Ap)	bC
Norite	Plag, Opx/Pig	Cpx, (Ap, Qtz)	pbC
Olivine gabbro	Plag, Cpx, Ol	Opx (Ap)	paoC
Gabbronorite	Plag, Opx/Pig, Cpx	(Qtz, Ap, Mt)	pbaC
Troctolite	Plag, Ol	Opx, Cpx (Ap)	poC
Olivine gabbronorite	Plag, Opx, Cpx, Ol	(Ap)	pbaoC
Anorthosite	Plag	Opx/Pig, Cpx, Qtz, (Mt)	pC

*Abbreviations: C = Cumulate, p = plagioclase (plag); o = olivine (ol); c = chromite (chr); b = orthopyroxene/pigeonite (opx/pig); a = augite (cpx); qtz = quartz; ap = apatite; amph = amphibole; phl = phlogopite, mt = magnetite. Parentheses indicate minor phase that is not always present. Sulfides may occur as interstitial minerals in any assemblage.

Olivine:

Olivine occurs as a cumulus mineral in peridotites, harzburgites, troctolites and olivine gabbros and is the major constituent in "discordant dunite" masses. In the Ultramafic series, olivine ranges from Fo_{90} to Fo_{79}. The more Fe-rich olivines are from the lowermost cycles of the Peridotite zone while the most Mg-rich olivines are associated with chromitites. In all other Ultramafic series samples the olivines show a restricted compositional range (Fo_{86-84}). In troctolites and olivine gabbros from the Banded series, olivine ranges from Fo_{79} to Fo_{64}. The lack of a compositional overlap between Ultramafic series and Banded series olivines is consistent with the stratigraphic gap between the last occurrence of olivine in the Peridotite Zone and its reappearance in Lower Banded series. Alteration of olivine in the Ultramafic series varies from the formation of a few veins of serpentine (+magnetite) to complete replacement of entire outcrops with serpentine + magnetite ± talc ± calcite. In troctolites of the Banded series, olivine is commonly altered to a pale brown amphibole which is surrounded by a rim of pale green chlorite adjacent to plagioclase.

Pyroxenes:

Orthopyroxene occurs as a cumulus mineral in bronzitites, harzburgites, norites, and gabbronorites and as a postcumulus mineral in all other rocks. In virtually all samples containing coexisting olivine and orthopyroxene, the orthopyroxene is slightly more magnesian than the olivine indicating a close approach to equilibrium between these two minerals. The main charge-balanced substitutions are $^{[6]}[Al,Cr]^{[4]}Al \Leftrightarrow {}^{[6]}Mg^{[4]}Si$ and $^{[6]}Ti^{[4]}Al_2 \Leftrightarrow {}^{[6]}Mg^{[4]}Si_2$, where [6] and [4] refer to octahedral and tetrahedral sites, respectively. Orthopyroxenes are unzoned and contain fine lamellae of augite along (100). The rims of orthopyroxenes generally have many fewer augite lamellae and are depleted in Ca and REE relative to the cores due to the exsolution of augite components out of the grain and their reprecipitation as blebby augite along grain boundaries.

Clinopyroxene (augite) is present in all zones but in the complex as a whole it is less abundant than orthopyroxene. It occurs as a cumulus mineral in gabbronorites and olivine gabbros and as an intercumulus mineral in all other rock types. Fe and Mg distribution between coexisting pyroxene suggests a close approach to equilibrium at high temperature. Element substitutions are the same as those outlined above for orthopyroxene with the addition of a minor $^{[8]}Na^{[6]}Al \Leftrightarrow {}^{[8]}Ca^{[6]}Mg$ substitution. Cumulus augites tend to be elongated along the *c* axis and in most gabbros and gabbronorites the long axes of augite grains are randomly oriented in the plane of lamination. Postcumulus augites reach dimensions of 20 cm in some anorthositic samples and may show a decrease in Mg/Mg+Fe of ~8 mol. % from center to edge. In Mg-rich augite, fine orthopyroxene and pigeonite lamellae have exsolved on (100) of the augite host, whereas more Fe-rich augites from the Banded series contain both (001) and (100) lamellae of low-Ca pyroxene. These lamellae were initially exsolved at high temperature as pigeonite and during slow cooling, the lamellae coarsened with the (001) lamellae growing much faster due to the more rapid diffusion of Ca, Mg and Fe along *c*. At some point during the cooling cycle, transformation of pigeonite to orthopyroxene was initiated in the (001) lamellae with eventual complete transformation to orthopyroxene.

Cumulus pigeonite (now inverted to orthopyroxene) is restricted to gabbronorites in the Upper Banded series. The inversion process has produced an unusual poikilitic texture in which each orthopyroxene grain contains multiple domains of (001) exsolution lamellae, which each domain delineating an original cumulus pigeonite. The relict (001) and (100) augite lamellae which exsolved prior to inversion commonly form a herring bone pattern consistent with a precursor pigeonite twinned on (100). In many samples the regular lamellae are accompanied by blebby augite. After inversion, the orthopyroxene exsolved fine augite lamellae on (100). Oikocrysts of inverted pigeonite, commonly in epitaxial intergrowths with augite, are common in anorthosites.

Plagioclase:

Plagioclase is the most abundant cumulus mineral throughout the Banded series and it occurs as an intercumulus mineral throughout the Ultramafic series. Grain sizes of cumulus plagioclase vary widely from <0.1 cm to ~1 cm even within a single thin section. In the Middle Banded series, the average grain size of plagioclase is 2 to 3 times that of plagioclase in the Lower and Upper Banded series [McCallum *et al.*, 1980.] Sharp grain size discontinuities also occur within anorthosites within a few meters of the contacts (Boudreau and McCallum, 1986). In most norites, gabbros, and gabbronorites, tabular plagioclase crystals define a distinct igneous lamination. Lamination is less pronounced in anorthosites and troctolites.

Plagioclase ranges from An_{88} to An_{60} in the Banded series. A similar range is observed in the intercumulus plagioclase of the Ultramafic series. Systematic decreases in *average* An content with stratigraphic height occur in the Lower and Upper Banded series, but no such systematic variation is observed in the Middle Banded series. FeO contents range up to 0.52 wt % and correlate with FeO contents in coexisting pyroxenes. Cumulus plagioclase is relatively homogeneous in norites and gabbronorites while plagioclase in anorthosites and troctolites shows more extensive zoning with normal, reversed and patchy zoning patterns, often within the same grain. Within the Banded series, alteration of plagioclase to zoisite may affect only part of a grain or it may be pervasive throughout entire outcrops.

Chromite:

In the Ultramafic series the highest concentrations of chromite occur in the peridotite member of each cyclic unit. Chromite is present in minor amounts in harzburgites and bronzitites and in the olivine-bearing rocks of the J-M reef.. Within peridotite, chromite occurs as massive seams from a few cm to ~1 meter thick, as irregular patches of chromitite, and as disseminated grains. In massive chromitites, chromite reaches its maximum MgO and Cr_2O_3 contents and minimum Al_2O_3 and Fe_2O_3 contents while in rocks with sparsely disseminated chromites, the reverse is the case (Campbell and Murck, 1993). The primary compositions of chromites are retained in massive layers whereas disseminated chromites have undergone extensive subsolidus exchange with silicates. Chromites in the J-M reef are more Fe-rich than those in the Ultramafic series.

Apatite:

Apatite is an important minor mineral throughout the complex (Boudreau *et al.,* 1986). Cl-rich apatite (> 6.0 % Cl) is characteristic of the lower third of the complex and a change to more F-rich apatite (>1.4 % F) occurs within OB-I just above the J-M reef. Within the J-M reef, chlorapatite, which is associated with pegmatitic olivine- and phlogopite-bearing rocks, contains >2.0 % total rare earth elements (REE) with a typical LREE-enriched pattern. Apatites with such high chlorine contents are rare in igneous rocks and available evidence indicates that Stillwater chlorapatite is a product of high-temperature hydrothermal activity (Boudreau and McCallum, 1989).

Phlogopite and amphibole:

Phlogopite is a minor intercumulus mineral in peridotites from the Ultramafic series and occurs as an interstitial mineral in the olivine-bearing rocks of OB-I. Compositional inhomogeneities are common but, in general, the major element compositions indicate a close approach to equilibrium with the other major silicates. Page and Zientek (1987) showed that phlogopite in peridotite contains 74% to 80% of the phlogopite end-member and roughly equal amounts of the annite and siderophyllite end-members. Cr and Ti occupy octahedral sites in the phlogopite structure. For Cr, the substitution mechanism is $^{[6]}Mg^{[4]}Si \Leftrightarrow {}^{[6]}Cr^{[4]}Al$ while for Ti, two substitutions are involved, i.e., $^{[6]}Mg_2 \Leftrightarrow {}^{[6]}Ti^{[6]}$€ and $^{[6]}Mg_2{}^{[4]}Si \Leftrightarrow {}^{[6]}Ti^{[4]}Al_2$. Stillwater phlogopites are enriched in Cl (up to 0.5 %) and F (up to 0.5 %) compared to those from other layered intrusions, with the exception of the Bushveld Complex.

Primary amphibole is rare and restricted to the lowermost peridotite members of the Ultramafic series. Phlogopite and amphibole tend to be mutually exclusive. Brown amphibole, which is invariably a late crystallizing, interstitial mineral, occurs as rims around chromites and as interstitial material replacing postcumulus augite indicative of a melt reaction relationship. Amphibole compositions are somewhat variable but most are pargasite or pargasitic hornblende with up to 4.5 % TiO_2 and 1.8 % Cr_2O_3 (Page and Zientek, 1987).

Sulfides, Tellurides, Arsenides, Alloys:

In the Basal series, sill/dike complex, and adjacent hornfels, sulfides are common and locally form massive concentrations. Mafic norite dikes are particularly rich in sulfides with pyrrhotite being the most abundant followed by chalcopyrite and pentlandite. In the Ultramafic series, sulfides are not abundant although most samples contain minute amounts of interstitial sulfide. The largest concentrations of sulfide minerals in the Ultramafic series are associated with chromite-rich layers. In the Banded series, 10 sulfide-bearing zones have been mapped by McCallum *et al*. (1980). By far the most important of these is the J-M reef in which sulfides occur as disseminated grains and patches in troctolite and/or anorthosite in a 1-2 meter thick mineralized zone. The most abundant minerals in the reef are pyrrhotite, chalcopyrite, and pentlandite with much smaller amounts of moncheite, braggite, cooperite, kotulskite, Pt-Fe alloy, cubanite, sperrylite, vysotskite, telluropalladinite, keithconnite, stillwaterite and several other rare PGE-rich species. Pentlandite is the major host for Pd.

BASAL SERIES AND SILL/DIKE COMPLEX

BASAL SERIES

The Basal series forms an irregular sheet-like mass from ~60m to ~400m (average ~160 m) thick separating the cumulates of the Ultramafic series from the hornfels. The upper contact of the Basal series is placed at the base of the first cyclic unit of the Ultramafic series. The lower contact is more irregular and cuts across stratigraphic units suggesting emplacement of the Stillwater magma along an unconformity. Page (1979) included within the Basal series all igneous rocks below the first appearance of cumulus olivine whereas Zientek (1983) considered the sill/dike complex as a separate unit. The Basal series has been cut out by thrust faults in the central part of the complex (Fig. 1).

The dominant lithology is a uniform bronzitite cumulate which forms a laterally extensive upper layer. This unit is underlain by a variety of cumulate-textured rocks which are most commonly norites but also include anorthosites, gabbros, peridotites, and sulfide-bearing assemblages. Xenoliths of cordierite-pyroxene hornfels are fairly common. Although the same rock types occur in all areas where the Basal series has been examined, there is a lack of continuity along strike and each area is unique in terms of lithologic sequences.

Page (1979) has documented an upward decrease in intercumulus mineral content, and a general upward increase in Mg/(Mg+Fe) through the basal bronzitite. Orthopyroxene shows a wide range in composition from En_{30-90} with the bulk of the grains in the range En_{60-80}, while plagioclase ranges from An_{60} to An_{83}. Major Fe-Ni-Cu sulfide concentrations occur in Basal series rocks and adjacent hornfels in the Benbow, Nye Basin, and Mountain View areas. Sulfides occur as massive accumulations, interconnected matrix sulfide, and as isolated blebs and aggregates. Textures are suggestive of crystallization from a sulfide melt although, in some samples, there is evidence for subsolidus remobilization of sulfide. Ni/Cu ratios are variable but average around 1.0 with an average Cu+Ni content of 0.5 %.

SILL/DIKE SUITE

Zientek (1983) described two petrographically distinct types of sills and dikes which intrude the rocks at the base of the complex. One type has a diabasic texture, with compositions ranging from norite to gabbronorite, and is generally sulfide-poor. The other type is a mafic norite in which sulfides make up from 2 to 40 % of the rock. Mafic norites are spatially associated with the Basal series rocks while the diabases are associated with hornfels. The non-porphyritic texture and chilled margins of both types indicate that they were intruded as liquids. Field relations and age determinations indicate that the intrusion of the sills and dikes was contemporaneous with or slightly predated the formation of the main layered series (Premo *et al.,* 1990), lending credence to the suggestion that some of these intrusions may have formed from the same magmas that gave rise to the layered series.

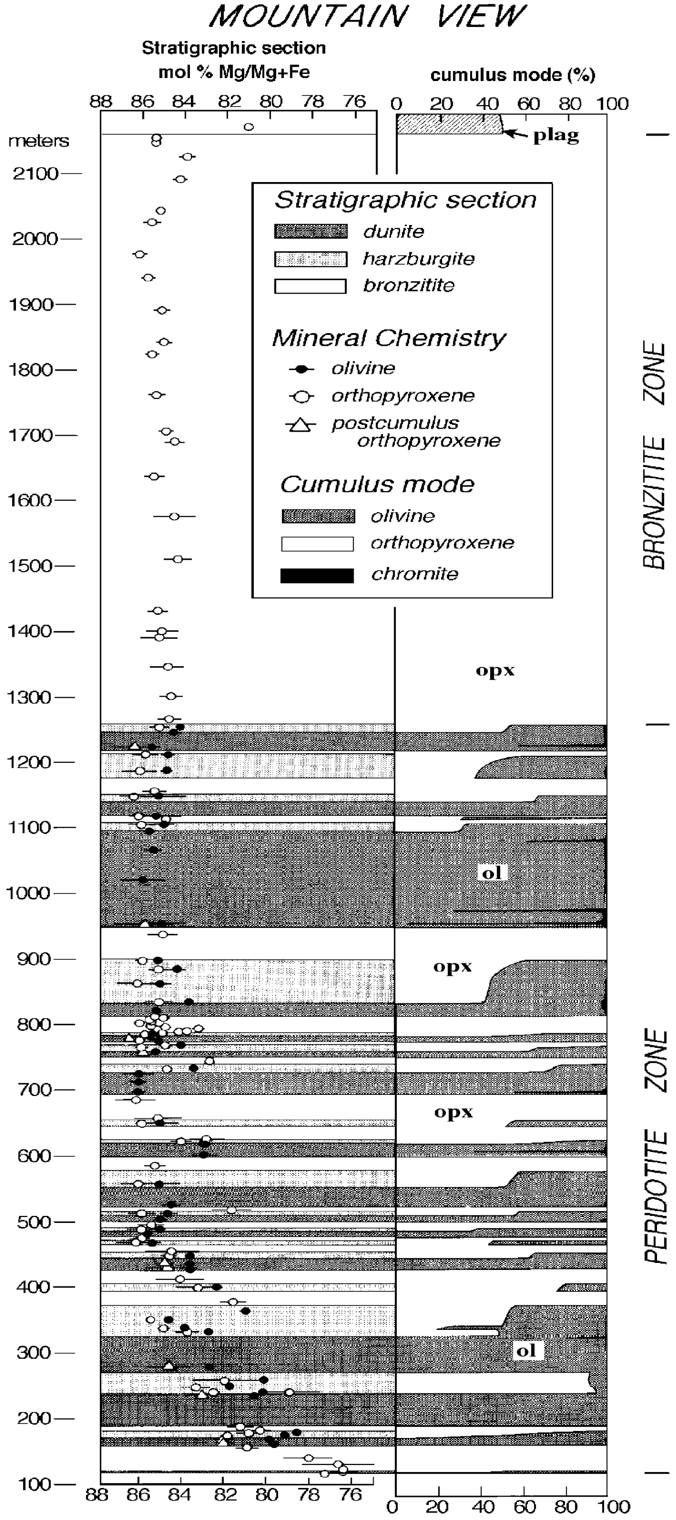

Figure 4. Stratigraphy, cryptic variation and modal variation in the Ultramafic series at Mountain View. Thickness is measured from the base of the Basal series (after Raedeke and McCallum, 1984)

Helz (1985) distinguished five chemical groups, four of which correspond to Zientek's diabase group and the remaining group corresponds to the mafic norite. The different groups cannot be related to each other by any simple fractionation process and the relative abundances of each type varies along strike. The mafic norite and the Mg-gabbronorite groups are the most promising candidates for a Stillwater parental magma. These suites have Mg/Mg+Fe appropriate for the crystallization of Mg-rich olivines and pyroxenes of the Ultramafic series, their high SiO_2 and MgO contents are consistent with the early crystallization of orthopyroxene, and their low alkali contents are consistent with the crystallization of calcic plagioclase.

ULTRAMAFIC SERIES

The base of the Ultramafic series is placed at the first appearance of significant quantities of cumulus olivine, while the upper boundary is placed at the horizon where plagioclase appears as a cumulus phase. The basal contact of the Ultramafic series is preserved in the western part of the complex and locally in the Mountain View and Benbow areas while the upper contact is exposed at intervals along the length of the complex (Fig. 1). The Ultramafic series is subdivided into a lower **Peridotite zone [PZ]** in which olivine ± orthopyroxene ± chromite are cumulus phases and an upper **Bronzitite zone [BZ],** in which orthopyroxene is the cumulus phase (Jackson, 1961). The Peridotite zone comprises a repetitive sequence of cyclic units; a complete cyclic unit consists of peridotite – harzburgite - bronzitite. The Bronzitite zone is relatively uniform except for a few thin layers containing olivine ± chromite. Variations in thickness of the Ultramafic series range from 2000m at Mountain View to 840m at Chrome Mountain and most likely reflect topographic relief on the floor of the complex during emplacement. The stratigraphic section and cryptic variation through the Ultramafic series at Mountain View are shown in Fig. 4.

PERIDOTITE ZONE

Raedeke and McCallum (1984) described 21 cyclic units at Mountain View and 20 at Chrome Mountain. Of the 21 cyclic units at Mountain View, 15 have the complete sequence, five are missing the peridotite member and one does not contain the bronzitite member. The number of cycles depends on the status accorded textural and modal variations within otherwise uniform lithologies. For example, Page *et al.* (1972) subdivided the peridotite member in cyclic unit 2 from the Nye Basin into nine subunits on the basis of abrupt changes in olivine grain sizes and abundance of chromite. The lower contacts of the peridotite units are sharp. Olivine, commonly accompanied by a small amount of chromite, forms the framework of cumulus grains and orthopyroxene occurs as oikocrysts enclosing partially resorbed olivines. Intercumulus plagioclase makes up between 2 and 15 % of the peridotites at Mountain View. Late-crystallizing augite, phlogopite, and amphibole are minor interstitial constituents. Apatite and sulfides are present in trace amounts.

Layers of massive and disseminated chromite occur in the peridotite member of many of the cyclic units. The main chromitite seams are traditionally referred to as **A** (lowermost) through **K** (uppermost). Mining has been restricted to the **G** and the **H,** which are well-exposed at Mountain View (Fig. 5). Individual layers of chromitite range from a single crystal thick to a meter or more. Layers thicken and thin over short distances and a single layer may bifurcate into two or more sublayers. In the units below and between massive chromitites, pegmatites are common. In the G chromitite, some pegmatites contain up to 10% of coarse-grained phlogopite and higher than normal abundances of sulfides. The most abundant interstitial mineral in chromitites is chrome-rich augite.

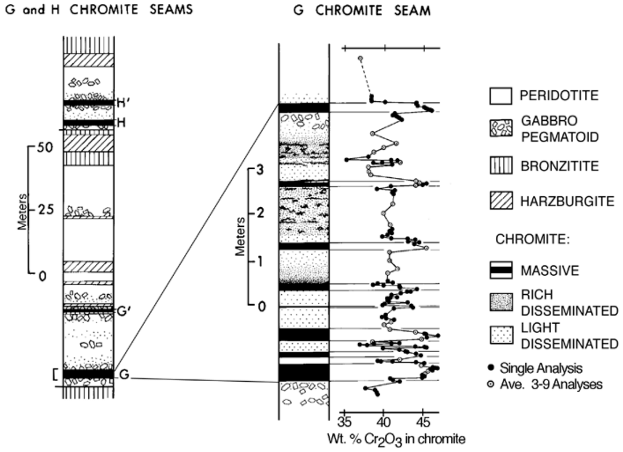

Figure 5. Stratigraphy in the vicinity of G and H chromitites at Mountain View and variations of chromite compositions through the G chromitite (after Campbell and Murck, 1993).

The contact between peridotite and overlying harzburgite is marked by an abrupt increase in the amount of orthopyroxene and a gradational change in texture from poikilitic to equigranular. Layering in harzburgite occurs on a centimeter scale in the form of layers alternately rich in olivine or orthopyroxene. Olivine makes up, on average, ~35% of the harzburgite and, with few exceptions, the olivine to orthopyroxene ratio decreases up section. In some harzburgites, both olivine and orthopyroxene show evidence of secondary enlargement, while in a few others, olivine shows evidence of resorption and reaction with interstitial melt. Augite forms sparse oikocrysts, and plagioclase occurs as space-filling grains. Chromite, phlogopite, amphibole, apatite and sulfides are rare.

The contact of harzburgite with bronzitite is marked by the abrupt disappearance of olivine. Bronzite crystals adjacent to plagioclase are generally euhedral while those enclosed by poikilitic augite are highly embayed which suggests the reaction: bronzite + liquid → augite. Chromite and interstitial quartz are present in small amounts while phlogopite, apatite and sulfides are very rare. Irregular patches of pegmatite occur randomly throughout the bronzitites. These pegmatitic patches are modally similar to the "normal" bronzitite, suggesting an isochemical grain-coarsening mechanism.

Textures and abundances of minerals in the Peridotite zone are consistent with an overall crystallization sequence of olivine (± chromite) → orthopyroxene → plagioclase → clinopyroxene → phlogopite → amphibole with reaction relationships between olivine and orthopyroxene, orthopyroxene and clinopyroxene, and clinopyroxene and amphibole.

BRONZITITE ZONE

The Bronzitite zone at Mountain View appears to be uniform. However, exposure is not complete and minor amounts of other lithologic units may be present. At Chrome Mountain, a narrow harzburgite outcrops near the bottom of the zone and a thin chromite-bearing harzburgite occurs approximately 30 meters below the upper contact. Intercumulus minerals in the Bronzitite Zone are the same as those in bronzitites in the cyclic units. In the uppermost 20 meters of this zone, intercumulus plagioclase and augite become more abundant.

Textures range from orthocumulate to adcumulate. In orthocumulates, most bronzite grains have morphologies and shapes that are consistent with homogeneous nucleation and crystal settling. In some adcumulates, coalescence of grains, grain growth, and subsolidus annealing have modified the primary textures. Zoning in bronzites is minor although some grains contain concentrically arranged arrays of exsolved lamellae of Fe-Ti oxides. Interstitial plagioclases show a range of composition and zoning patterns as might be expected for crystallization from an intercumulus melt.

DISCORDANT DUNITES

At Chrome Mountain, Iron Mountain and the Gish area, discordant dunites crop out over large areas. These rocks have a smooth, tan-weathering surface which is distinct from that of the “normal” cumulates. In most outcrops, the dunites appear to *replace* previously formed cumulates while in a few locations, the dunites *crosscut* the cumulate layers. In the former, contacts between the discordant dunite and primary cumulates tend to be irregular or sinuous while in the latter the contacts tend to be planar. In both cases the contacts are sharp. The dunites are extensively serpentinized, olivine-rich rocks containing minor chrome spinel and sparse orthopyroxene oikocrysts. While the discordant dunites occur in all cyclic units, they are most abundant in the lower units where they form veins and irregular masses which both cross and are crossed by the cumulate layering, indicating formation at the same time as the cumulates. The compositions of olivine and orthopyroxene in the discordant dunites are not significantly different from those in the “normal” cumulates. Pyroxene-rich pegmatites are commonly associated with the discordant dunites. Contacts between these pegmatites and surrounding cumulates are sinuous and coarse-grained chromite is concentrated along the contact. The observations are consistent with a process in which dissolution of bronzite releases Cr which is precipitated as chrome spinel.

MINERAL COMPOSITIONS

The change in mineral composition with stratigraphic height through the Peridotite zone shows a systematic trend of *upward* Mg-enrichment (from En_{76} to En_{86}) through the lowermost 400 meters of the complex followed by little compositional variation through the remainder of the series (Fig. 4). Minor elements in olivines and pyroxenes follow a similar pattern. Throughout the Bronzitite zone, orthopyroxene compositions remain constant ($En_{85\pm2}$). Minor and trace elements show a larger range but such variation as exists again shows no systematic variation with stratigraphic position: Cr contents are high (average Cr_2O_3 = 0.6 %) and rare earth element (REE) abundances show a typical HREE-enriched pattern with $[Ce/Yb]_n < 0.15$ (Papike *et al*., 1995). The total range in REE abundances is small, the patterns are subparallel, and there is a significant negative Eu anomaly (Lambert and Simmons, 1987).

Intercumulus plagioclase in ultramafic samples shows some zoning ranging in one sample of bronzitite from An_{69} to An_{86}; however, all but a few points lie between An_{75} and An_{80}. Clinopyroxene oikocrysts, which increase in abundance towards the top of the Bronzitite zone, are largely unzoned and have compositions indicating equilibrium with coexisting orthopyroxenes at near-solidus temperatures. During subsolidus cooling, element redistribution is limited to grain boundaries and to intracrystalline exsolution lamellae.

Data of Campbell and Murck (1993) on coexisting minerals from the G and H chromitite show that the maximum Cr_2O_3 content in chromite occurs in the massive layers (Fig. 5) and there is a positive correlation among X_{Mg}, X_{Cr} and the modal abundance of chromite. In chromite-rich layers, both olivine and chromite have higher X_{Mg} than in chromite-poor layers which has been attributed to extensive subsolidus exchange of Fe and Mg between coexisting chromite and silicates ***within*** layers (Irvine, 1967). With the exception of Mg-rich olivines associated with massive chromitites, the olivines are relatively constant in composition (Fo_{84-87}).

BANDED SERIES

The Banded series comprises all rocks in which *cumulus* plagioclase is a major constituent. On the basis of detailed sections in the Contact Mountain and Picket Pin areas, McCallum *et al.* (1980) split the Banded series into the Lower Banded series (LBS), Middle Banded series (MBS) and Upper Banded series (UBS) and further subdivided these units into twelve zones. The boundaries between units are placed at distinctive lithologic breaks that are easily identified in the field. In their map of the Banded series, Segerstrom and Carlson (1982) identified most of the same zones. The Lower Banded series is composed of norites and gabbronorites with minor amounts of olivine-bearing cumulates that host the J-M reef. The Middle Banded series is made up of anorthosites, olivine gabbros and troctolites and the Upper Banded series comprises gabbronorites with minor troctolite and norite.

The most complete sections through the Banded series are exposed from Contact Mountain to the Picket Pin area (Fig. 1). An unknown thickness of stratigraphically higher cumulates lie beneath the sedimentary cover. East of Picket Pin, Paleozoic sediments progressively onlap the uppermost cumulates covering the Upper Banded series and eventually the Middle Banded series. In the eastern third, only the Lower Banded series is exposed south of the Horseman Thrust. A simplified stratigraphic section and compositions of the primary minerals in the Banded series are shown in Fig. 6.

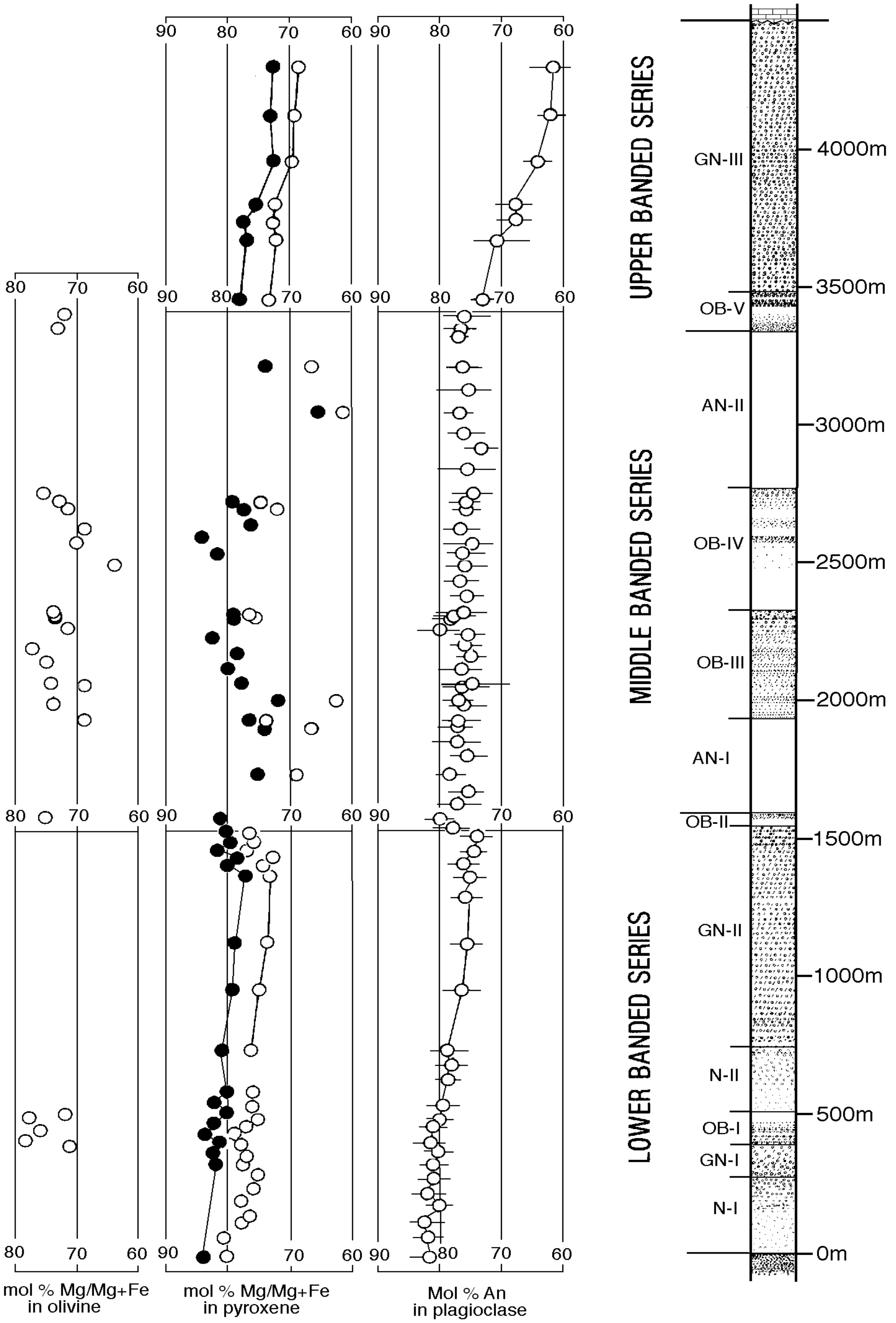

Figure 6. Stratigraphic variations in compositions of plagioclase, pyroxene, and olivine through the Banded series. Data sources:McCallum et al (1980), Criscenti (1984), Page and Moring (1987), Meurer and Boudreau (1996), Haskin and Salpas (1992), Boudreau and McCallum (1986). In pyroxene column: open circles (opx), filled circles (cpx)

LOWER BANDED SERIES (LBS)

The lower contact of the LBS is placed at the horizon marking the first appearance of cumulus plagioclase and the upper contact is placed at the base of the first thick anorthosite unit (Fig. 3). The Lower Banded series has been subdivided into six zones: Norite I (N-I), Gabbronorite-I (GN-I), Olivine-bearing I (OB-I), Norite-II (N-II), Gabbronorite-II (GN-II), and Olivine-bearing-II (OB-II).

Norite-I zone (N-I) and Gabbronorite-I zone (GN-I)

Cumulus orthopyroxene and plagioclase are in approximately cotectic proportions in N-I with oikocrysts of clinopyroxene making up 1 to 10 % of the rock. Minor amounts of sulfide, apatite and quartz are commonly present. Modally graded and rhythmic layering are common, particularly in the more leucocratic members. A prominent anorthosite about 2 meters thick occurs about midway through the N-I zone. This sharply-bounded layer of anorthosite has no complementary mafic layer indicating that *localized* crystal sorting is not the mechanism responsible for the concentration of plagioclase. The contact between N-I and GN-I is placed at the first appearance of cumulus augite. In the upper part of GN-I, there is a complex, laterally extensive unit characterized by layers of norite, gabbronorite, and anorthosite which are locally disturbed and associated with abundant pyroxenite xenoliths which are commonly surrounded by a narrow rim of chrome spinel.

Page and Moring (1987) have identified seven subzones within N-I and GN-I on the basis of distinctive modal changes in outcrops located close to the west portal of the Stillwater Mine. These outcrops display spectacular rhythmic layering with many of the layers showing modal grading, cross bedding, channel structures, onlap and offlap structures, and slump structures which are clearly syndepositional. Orthopyroxene ranges from En_{83} to En_{75} and plagioclase from An_{83} to An_{78} (Fig. 6).

Olivine-bearing Zone I (OB-I)

The basal contact of OB-I, which was placed by McCallum *et al.* (1980) at the first appearance of cumulus olivine in the Banded series, is well-defined but irregular and may represent an unconformity. The upper contact of OB-I is placed at a horizon marked by a distinctive textural change from mottled anorthosite to layered norite. The reappearance of olivine in a series of cyclic units, the unconformable lower contact, and the occurrence of bronzitite xenoliths are consistent with multiple injections of olivine-saturated magma followed by a prolonged period of mixing before the magma returned to a relatively uniform composition represented by the overlying norite zone.

Surface maps, drill core logs, and maps of exploration adits and mine exposures have revealed a remarkable degree of lateral variation in OB-I. Stratigraphic sections through OB-1 in the Frog Pond, West Fork, and Stillwater River areas are shown in Fig. 7 although these sections may not be representative of the entire zone. The Frog Pond area, which represents the most complete section through OB-I, is approximately 120 meters thick. Ten olivine-bearing members (O_1-O_{10}) composed of coarse-grained to pegmatitic peridotites and/or troctolites have been recognized by Todd *et al.* (1982). In the part of OB-I below the J-M reef, these units are interlayered with norites, gabbronorites, and minor anorthosites. Above the reef, anorthosite predominates (Fig. 7). Troctolitic layers grade into norite layers along strike, individual layers commonly pinch out, and there are local unconformities and onlapping sequences. Todd *et al.* (1982) noted the existence of cyclic units within the upper part of OB-I with a typical cycle composed of peridotite, troctolite and anorthosite. In the West Fork area, OB-I is well exposed in the West Fork Cliffs where the first discovery of the J-M reef in outcrop was made in 1974 (Mann *et al.*, 1985). Here, olivine zones O_1 through O_4

are absent although they may be represented by pyroxene-rich layers (Mann and Lin, 1985). The lowermost olivine layer at West Fork is correlated with O_5 from Frog Pond since both are associated with the mineralized J-M reef. The section above the reef at West Fork is similar to that at Frog Pond (Fig. 7).

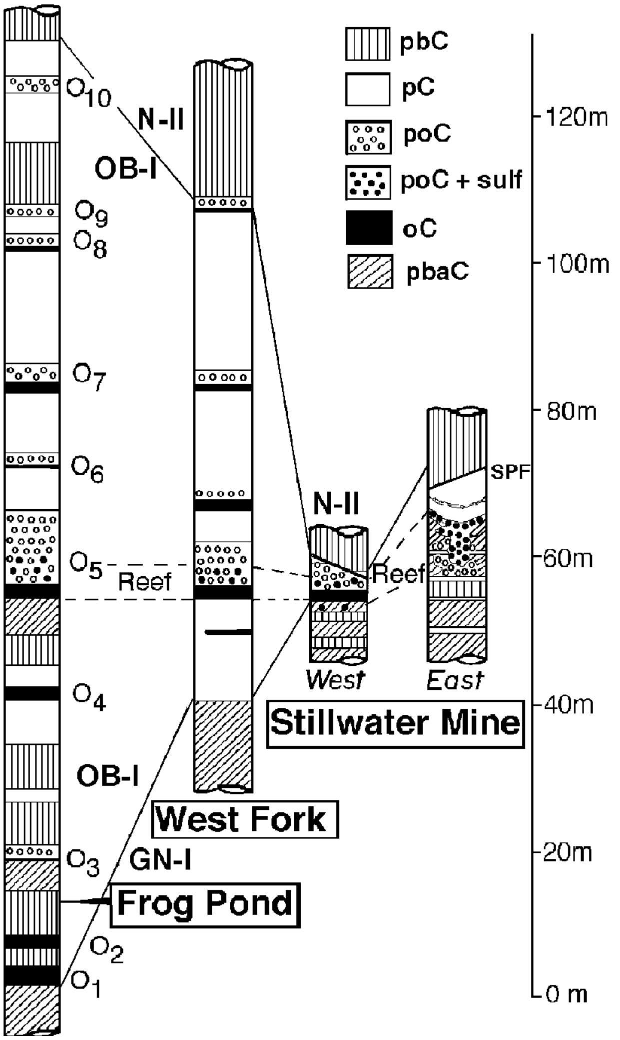

Figure 7. Stratigraphic sections through OB-I at the Frog Pond adit (Todd et al., 1982), West Fork adit (Mann et al., 1985), and Stillwater Mine (Turner et al., 1985; Barnes and Naldrett, 1986).

In the eastern part of the complex, where the reef is being mined, stratigraphy in OB-I is less regular, in part because of Laramide faults and in part because of thinning of units across basement highs. Mapping in the Stillwater Mine reveals that GN-I and OB-I become progressively thinner as they are traced west from the Stillwater Valley until GN-I disappears and OB-I is reduced in thickness. The South Prairie reverse fault has disrupted OB-I in this region. The main strand of this fault is confined to the hanging wall norites but numerous splays affect the reef package in the Mountain View area. Towards the west and east the South Prairie Fault cuts progressively higher into the hanging wall. With the exception of the olivine-bearing member that hosts the J-M reef, the olivine-bearing units, which are prominently developed in the Frog Pond-West Fork areas, are absent, or poorly developed, in the Stillwater Mine.

J-M Reef

The J-M reef is not restricted to a single stratigraphic position within OB-I. At Frog Pond and West Fork, the reef, which contains 1-2% disseminated sulfides through 1-3 meters, is associated with the O_{5B} unit which consists of a 1-1.5 m thick pegmatitic peridotite overlain by a troctolite up to 3.5 meters thick which is the host of the main PGE mineralization (Fig. 7). The reef is generally confined to the troctolite but it varies considerably in thickness and grade and in some localities it is absent (Leroy, 1985). The most common sulfides are pyrrhotite, pentlandite (containing up to 5% Pd), and chalcopyrite with minor moncheite, cooperite, braggite, kotulskite, Pt-Fe alloy and various arsenides. The reef averages 20-25 ppm Pt + Pd over a thickness of ~2 meters with a Pd/Pt ratio of ~3.6 (Leroy, 1985). In the West Fork and Frog Pond adits, localized downwarps in the stratigraphy in which the mineralized zone is significantly thickened, have been compared to the pothole structures of the Merensky Reef.

In the Stillwater Mine, OB-I (commonly referred to as the reef package) is quite different from that at Frog Pond and West Fork. The mineralized zone is correlated with the

O_{5B} unit at Frog Pond but the underlying, and several of the overlying, olivine-bearing units are not present (Fig. 7). The base of the reef package is placed at the first stratigraphically continuous olivine-rich layer which lies *discordantly* on a rhythmically layered sequence of gabbronorites, norites and anorthosites. A typical reef package is composed of a basal pegmatitic olivine-rich rock overlain by a variety of coarse-grained to pegmatitic assemblages containing ameboidal olivine in a matrix of plagioclase and pyroxene, informally referred to as "mixed rock" (Bow *et al.*, 1982). The mixed rock is overlain by a sequence of troctolite, mottled anorthosite, and norite. The upper contact of the reef package is placed at the point where the olivine-bearing norite grades into olivine-free norite. PGE mineralization in the mine occurs at four levels relative to the base of the reef package: (1) Footwall zone in GN-I just below the lower contact of the reef package, (2) Basal zone which straddles the basal contact, (3) Main zone, and (4) Upper zone (Raedeke and Vian, 1986). Mineralized zones are generally less than 3 meters thick except where several of the zones have coalesced to form thickened zones, referred to as "ballrooms" by mine geologists. Ore is patchily developed; areas of high grade ore are separated by low grade areas up to 100 meters wide. In the eastern part of the Stillwater Mine, the highest grade PGE-sulfides occur in Upper and Main zone. As the reef package is traced west, the rocks become progressively richer in pyroxene at the expense of olivine and the highest ore grades in the reef progressively cut down section and occur primarily in the Main, Basal and Footwall zones. Turner *et al.* (1985) suggested that the westward progression from olivine-rich to pyroxene-rich reef rocks appear to be related to pothole-like structures.

McCallum *et al.* (1999) measured Pb isotopic compositions of multiply leached sulfides and plagioclases from the J-M reef and vicinity. The plagioclase data define a tight cluster close to a 2.7 Ga "source" isochron reinforcing the assumption that the most primitive values represent the initial Pb isotopic composition of the complex. In contrast, the least radiogenic sulfides show a much wider range indicating that a component of post-emplacement Pb has been incorporated into their structures during low-temperature recrystallization. The sulfide data are consistent with mixing of initial lead and radiogenic lead derived from a younger hydrothermal source around 1.7 Ga. However, the bulk of the Pb and other chalcophile elements were derived from the mantle around 2.7 Ga.

In summary, the J-M reef is broadly continuous across the entire complex but remarkably variable in detail. PGE-bearing sulfides are restricted to stratigraphically narrow zones and in some areas mineralized zones may be stacked. The basal contact of the reef, while regionally conformable, is marked by local depressions and highs which are not necessarily correlated with ore grade. Pegmatoids are abundantly developed in all lithologies, hydrous minerals are common and evidence for remobilization and recrystallization is widespread. Chlorapatite, phlogopite and chromite are distinctive accessory phases. Petrologic evidence supports the hypothesis that OB-I initially formed in response to the injection of olivine (± plagioclase) saturated magma into a chamber containing fractionated magma but this mechanism alone cannot explain all the features observed in this zone.

Norite-II Zone (N-II) and Gabbronorite-II Zone (GN-II)

N-II is a fairly uniform norite although modal proportion are somewhat variable. Drilling has confirmed the occurrence of several olivine-bearing members in N-II although none are exposed. The boundary between N-II and GN-II is marked by the transition from intercumulus to cumulus augite. In the Contact Mountain area, the lowermost 100 meters of GN-II contain numerous layers of anorthosite within gabbronorite. The anorthosites range from ~10 cm to ~15 m in thickness and two of them contain conformable layers of sulfides.

GN-II is the host for the spectacular outcrops of inch-scale rhythmic layering that occur in a variety of forms. The most common type is composed of pyroxene-rich layers approximately 1 to 2 cm thick separated by plagioclase-rich layers 2 to 4 cm thick. Doublet layers, in which two closely-spaced pyroxene layers are separated by a thicker layer of plagioclase, are a common variant. A third variation involves two superimposed layering patterns involving different repeat distances. The layering is best developed in norites and gabbronorites that contain plagioclase in excess of cotectic proportions suggesting that the magma may have been slightly undersaturated in pyroxene. Toward the top of the sequence, the layering becomes progressively diffuse and the rock grades into a homogeneous norite.

Boudreau (1987) observed that, in many instances, the layer spacing is proportional to crystal grain size and suggested that layering develops in response to crystal aging within crystal suspensions. Because larger crystals have a lower surface free energy per mole than small crystals, the smaller crystals are more easily dissolved. As the crystal + liquid system evolves, initial minor perturbations in crystal size distribution are enhanced as larger crystals tend to grow at the expense of smaller crystals to diminish the total surface free energy of the system. The aging process leads to a long-range order similar to that observed in inch-scale layering. Boudreau (1987) has successfully modeled the formation of both singlet and doublet layers in a computer simulation in which layer growth by crystal aging was simulated by solving the differential equations for diffusion/reaction and crystal growth.

Layering of a different type occurs in the uppermost 50 meters of GN-II as a series of macrorhythmic units which are primarily defined by variations in the plagioclase/pyroxene ratio (Fig. 8.) Criscenti (1984) mapped 10 macrorhythmic units in the Cairn Ridge-East Boulder Peak areas ranging from 18 meters to 2 meters in thickness; the thickest units can be traced for several kilometers along strike. Units 1 to 8 show a sharp lower contact and a upward increase in plagioclase content and pyroxene grain size. Units 8 to 10 show large modal variations but no sharp internal contacts. The frequency of pyroxenes (number of grains per cm^3) varies by several orders of magnitude throughout the macro-rhythmic units whereas plagioclase frequency fluctuates only slightly (Fig. 8) indicating that an oscillatory nucleation and growth mechanism was involved in the formation of these units.

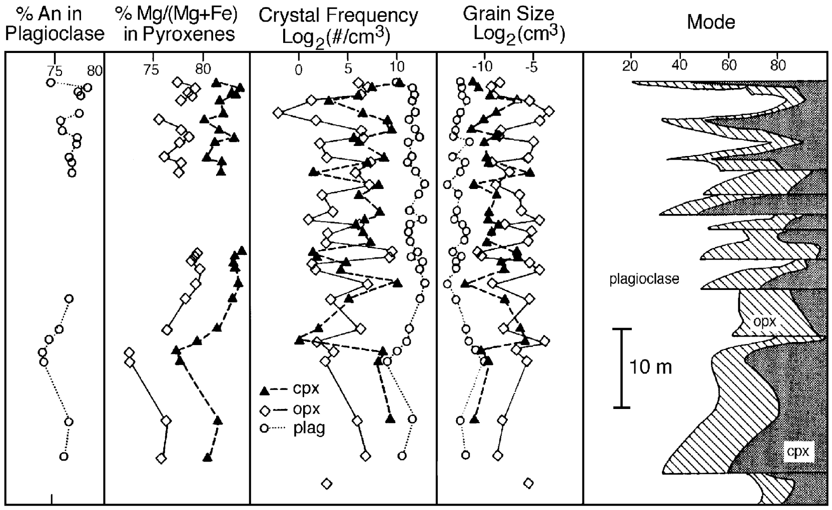

Figure 8. Stratigraphic section through the macrorhythmic units at the top of GN II showing modal variations, grain sizes, crystal frequency, and mineral compositions.

Olivine-Bearing Zone II (OB-II)

The lower contact of OB-II is placed at the base of an anorthosite which overlies the uppermost macrorhythmic unit. The anorthosite is overlain by a laminated *gabbro*. The uppermost 5-8 m of OB-II is a remarkable assemblage in which irregular masses of troctolite up to football size are set in a matrix of anorthosite producing a distinctive pattern in outcrop, referred to as “pillow troctolite” by Hess (1960). The contact between the troctolite/anorthosite and the underlying gabbro is sinuous and highly discordant. Irregular patches of gabbro are isolated within troctolite/anorthosite and patches of troctolite are spotted throughout the gabbro close to the contact. Pegmatites containing plagioclase and pyroxene megacrysts up to 20 cm across are common. Olivine in troctolite occurs as large *ameboidal* grains containing abundant inclusions of small plagioclases. The upper contact of OB-II with the overlying anorthosite of the Middle Banded series is sharp.

The origin of the unusual assemblages in OB-II remains one of the unsolved problems of Stillwater petrology. McCallum *et al.* (1977) suggested that troctolite formed by metasomatic replacement of gabbro by incongruent dissolution of pyroxene induced by an increase in the activity of water with the overlying anorthosite acting as an impermeable cap to migrating fluids. The presence of a volatile phase also promoted grain coarsening. Problems with this model include the source of the fluid, which has not been identified, and the absence of hydrous phases and fluid inclusions. Alternatively, the relations in OB-II could be explained by thermal erosion in response to the influx of magma. In this model, the sinuous contacts could be an erosional effect and the troctolite could represent the first "cumulate" formed from the new magma. This model, however, has difficulty in explaining the unique textures, the presence of pegmatoids and the apparently isolated gabbro blocks within troctolite.

MIDDLE BANDED SERIES (MBS)

The Middle Banded series lithologies are distinctly different from those of both the Lower and Upper Banded series. Plagioclase makes up 82 vol. % of the MBS, olivine and augite are the most common *cumulus* mafic minerals, and cumulus orthopyroxene is relatively minor. The major lithologies are anorthosite, troctolite, and olivine gabbro; gabbronorites are rare and norites are absent. The sequence of crystallization is olivine/plagioclase → augite → orthopyroxene. The *average* grain size of plagioclase crystals in anorthosites is 2 to 3 times that in the cumulates of LBS and UBS and the plagioclases show complex zoning patterns. The most plausible explanation for these features is crystallization of the MBS from a magma significantly different in composition from that which produced the Ultramafic and Lower Banded series as suggested by Raedeke (1982) and Irvine *et al.* (1983).

Anorthosite Zones I and II (AN-I and AN-II)

AN-I and II are relatively uniform anorthosites containing oikocrysts of augite, orthopyroxene or inverted pigeonite and quartz (1-5%) along with minor intercumulus magnetite, sulfides (pyrrhotite, pentlandite, chalcopyrite ± pyrite), and rare fluorapatite. Prominent zones of disseminated sulfides occur just below the upper contacts of both AN-I and AN-II. The thickness of AN-I is variable from a maximum of 400 meters in the eastern part of Contact Mountain to less than 200 meters west of the Boulder River. AN-II varies from 600 meters thick in the Contact Mountain area to less than 200 meters at Picket Pin.

In most samples, plagioclase shows a range in grain sizes with almost all grains falling between 1 and 10mm. Preferred orientation of plagioclase is rare. Plagioclase grains enclosed within pyroxene and adjacent to quartz are commonly subhedral and tabular while those in pyroxene-poor areas are anhedral with textures characteristic of annealed rocks. Anorthosites contain pyroxene-rich and pyroxene-poor domains on a scale of decimeters to dekameters which led Haskin and Salpas (1992) to conclude that the anorthosites are built up by the coalescence of meter-sized masses (rockbergs) of partially consolidated plagioclase cumulates.

Average compositions of plagioclase in AN-I (An_{77}) and AN-II (An_{76}) are virtually constant (Fig. 6) and there is no systematic variation in major and trace element compositions with stratigraphic height (McCallum *et al.*, 1980; Salpas *et al.*, 1983). This large scale homogeneity contrasts sharply with the heterogeneous nature of plagioclases on a cm scale.

A single thin section may show grains with normal, reversed, patchy, convoluted and asymmetric zoning patterns (Czamanske and Scheidle, 1985). In a sample from AN-II, 80 % of points analyzed lie between An$_{74}$ and An$_{78}$, 90 % between An$_{73}$ and An$_{79}$, 99 % between An$_{69}$ and An$_{83}$ and it is just as common for rims to be reversely zoned as normally zoned. Most of the zoning appears to be a primary feature although compaction, dissolution and reaction with migrating interstitial fluid have also modified plagioclase compositions. Pyroxene oikocrysts are also zoned; two large pyroxene oikocrysts analyzed in detail show a range in Mg/Mg+Fe from 0.66 to 0.60 which is much smaller than the range predicted for fractional crystallization of pyroxene from a trapped intercumulus liquid.

The Picket Pin Pt-Pd zone

The Picket Pin deposit is a zone of disseminated, PGE-bearing sulfide that occurs in the upper 150 meters of AN-II (Boudreau and McCallum, 1986). The sulfide zone is traceable at the same stratigraphic position over 22 km. Sulfides are concentrated in a zone ~10 meters below the top of AN-II at a contact between a coarse-grained anorthosite containing up to 20% intercumulus pyroxene and an overlying medium-grained anorthosite adcumulate (Fig. 9). Sulfides occur as podiform and discontinuous lenticular accumulations which are grossly conformable. Discordant sulfide-bearing pipes, which occur to a depth of 150 m in the footwall anorthosite, lead directly to the stratabound lenses. Boudreau and McCallum (1992) have suggested that the anorthosite in the upper 10 m of AN-II is the result of infiltration of interstitial liquids into the overlying troctolite during compaction of the thick anorthosite pile. The pipe-like nature of the footwall mineralization strongly supports a model of sulfide concentration by migration of a residual melt and/or fluid upward through footwall anorthosite.

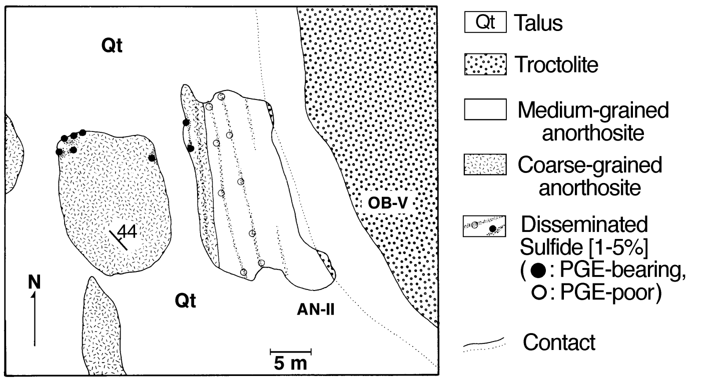

Figure 9. Geologic map of part of the Picket Pin PGE deposit ~75 meters northwest of the summit of Picket Pin. "Up" is to the right. The PGE-bearing sulfides are located in the coarse-grained anorthosite.

Olivine-bearing Zones III and IV (OB-III and OB-IV)

The stratigraphy of these zones was defined by McCallum *et al.* (1980) for a section across Contact Mountain and extended to the east and west by Meurer and Boudreau (1995). The major stratigraphic units are traceable laterally over considerable distances but the thickness of these units varies significantly. Troctolites and anorthosites, which are predominant in the lower parts of each zone, are overlain by olivine gabbro. The uppermost unit in both OB-III and OB-IV is a unique olivine gabbronorite in which *both* olivine and orthopyroxene appear to be cumulus minerals in addition to plagioclase and clinopyroxene (Fig. 3). Olivine gabbros and gabbronorites are generally cotectic and well laminated. Cyclic units in OB-III consist of a troctolite-anorthositic troctolite-olivine gabbro sequence. The sharp but irregular contact basal contact of the cyclic units most likely represents an erosional unconformity. Troctolites come in two types. *Banded troctolites* contain olivine as equant grains which define a wispy layering and are commonly cross-bedded. *Discordant troctolites*, which occur as isolated blobs and as finger-like protrusions *within* laminated gabbro, contain ameboidal grains of olivine up to 2 cm with small inclusions of plagioclase, similar to those at the top of OB-II.

There is no *systematic* variation of plagioclase, olivine, or cumulus pyroxene compositions as a function of stratigraphic position or lateral position (Fig. 6). Plagioclase grains show complex zoning patterns and compositional ranges identical to those in AN-I and II. The average value of all plagioclase is An_{77}. Plagioclase in anorthositic layers tends to have a blocky habit whereas plagioclase in gabbro is generally tabular which led Meurer and Boudreau (1995) to suggest that anorthosites formed by the coalescence of plagioclase grown in a stress-free environment whereas the cotectic gabbros were subjected to a uniaxial stress in a compacting cumulate pile. Intercumulus pyroxenes tend to be more variable in composition and generally richer in FeO.

Many petrographic and geochemical features suggest a petrogenetic link between OB-III and IV and AN-I and AN-II which together make up the Middle Banded series. These include plagioclase in excess of cotectic proportions, the similarity of grain size in plagioclase throughout the MBS, the complex zoning patterns, the constancy of mineral compositions and the similarity of Pb and Nd isotopic ratios (Wooden *et al.,* 1991; Lambert *et al.,* 1994).

UPPER BANDED SERIES (UBS)

Olivine-bearing zone V (OB-V)

The basal member of this zone, which is very well exposed on Picket Pin Peak, is a banded troctolite similar to that at the base of OB-III (Fig. 3). Olivine-rich lenses occur locally along the basal contact. Modally graded layers, cross bedding, and scour-and-fill structures are pervasive in this troctolite indicating strong current action during its formation. The banded troctolite is overlain by an 80m thick anorthosite which passes upward into a repetitive sequence of anorthosite-norite-gabbronorite. The gabbronorites exhibit a unique texture in which large blocky orthopyroxene, up to 1 cm, are associated with small acicular augite which, along with the plagioclase, define a strong lamination. The gabbronorite also shows evidence of current action in the form of rip-up clasts and xenoliths of anorthosite and unusual gabbronoritic snowballs within a layered gabbronorite.

Gabbronorite III (GN-III)

The lower contact of this zone is placed at the base of a thick sequence of uniform, laminated gabbronorite. Throughout this zone, plagioclase, augite and low-Ca pyroxene are present in cotectic proportions. In the lower part of GN-III, orthopyroxene is clearly a cumulus mineral while in the central and upper parts of the zone, orthopyroxene occurs as poikilitic crystals formed by the inversion of cumulus pigeonite. Magnetite becomes an important postcumulus mineral in this zone. In the central part of GN-III, irregular zones of pegmatite, some discordant some conformable, are common as are xenoliths of anorthosite within fine-grained gabbro. Veins and dikes of pegmatitic hornblende-plagioclase-quartz up to 50 cm wide, formed during a late magmatic stage, are common in the upper part of GN-III.

Mineral compositions in GN-III show smooth variations with stratigraphic height consistent with fractional crystallization (Fig. 6). Plagioclase ranges from An_{75} at the base to An_{62} at the top of GN-III while the Mg/Mg+Fe ratio in low-Ca pyroxene ranges from 0.75 to 0.67 over the same interval (Raedeke, 1982). There is a continuum in mineral compositions from GN-II to GN-III even though the Middle Banded series is sandwiched between (Fig. 3).

FRACTIONATION TRENDS

Fractionation trends in the Banded series are summarized in Figure 10. The oblique trend, which is defined by norites and gabbronorites from the Lower and Upper Banded series, is continuous even though the MBS is sandwiched between the LBS and UBS. The main vertical trend is defined largely by anorthosites from the Middle Banded series while anorthositic rocks from OB-I define a subsidiary vertical trend and Ultramafic series samples define a broad horizontal trend. Plagioclases in the MBS have a restricted compositional range and plot close to the intersection of the LBS and UBS.

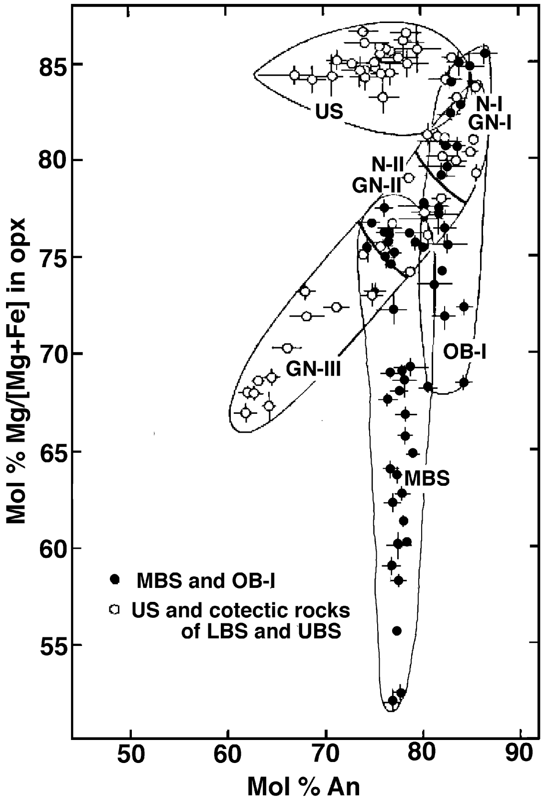

Figure 10. Fractionation trends in the Stillwater Complex. The Fe-rich part of the vertical trends are defined by intercumulus pyroxenes.

The oblique trend can be modeled by a system undergoing progressive fractional crystallization with minerals crystallizing in roughly cotectic proportions. The vertical trend, which is also observed in lunar anorthosites, has been modeled by Raedeke and McCallum (1980) by equilibrium crystallization of a mixture of plagioclase (well in excess of cotectic proportions), minor "cumulus" pyroxene plus the products of crystallization of a variable amount of trapped melt. The abundance of plagioclase relative to intercumulus liquid buffers the plagioclase composition at a near-constant value while the pyroxene composition is determined by the relative amounts of "cumulus" pyroxene and trapped melt. The vertical trend can be reproduced using trapped liquid contents from 1 to 20%. The horizontal trend for the Ultramafic series can be similarly modeled by orthopyroxene fractionation with the variation in plagioclase composition resulting from crystallization of trapped melt.

SUMMARY

In the past two decades research in the Stillwater Complex has seen the completion of new maps, the measurement of detailed stratigraphic sections and the establishment of a precise age. A greatly expanded geochemical data base has compelled the reassessment of old petrogenetic models and the development of new ones. The single most important event was the discovery of a world-class deposit of platinum group elements (J-M reef) associated with the reappearance of olivine in the Banded series rocks. Although the J-M reef is similar in many respects to the Merensky Reef of the Bushveld Complex there are significant differences in the tenor of the ore and the relative abundances of platinum and palladium. An abundance of information has been obtained on the ore zone and the rocks in its immediate vicinity, much of which remains to be interpreted.

Field and geochemical evidence for multiple magma injections into an evolving magma chamber is very strong but much remains to be learned about the physics of the processes of magma influx and mixing. The realization that at least two chemically distinct parental magmas were involved has spurred effort to determine the compositions, sources, and frequency of injection of these magmas. There is a growing body of evidence that samples of the parental magmas have been preserved in the coeval dike/sill sequence at the base of the complex. The magma that formed the Ultramafic series had major element characteristics similar to those of modern boninites while the magma that formed the olivine-bearing rocks of the Banded series had tholeiitic affinities. Trace elements and radiogenic isotopes have proven useful in distinguishing these different magma types and indicate that two mantle sources and a crustal contaminant are required. However, there is no consensus on whether the crustal component was incorporated into the mantle source via subduction or was added by assimilation during storage and transit in the crust.

Anorthosites, which are abundant in the Stillwater Complex, continue to attract interest, in part because lunar anorthosites are believed to have formed in a similar manner to those in layered intrusions. Evidence has accumulated that anorthosites have formed by the coalescence of plagioclase-rich suspensions (rockbergs) which themselves formed by large-scale sorting in a convecting magma. Anorthosites also provide evidence for large-scale migration of intercumulus melts and fluids.

A result of first order importance was the discovery of the critical role of fluids during the crystallization of the complex. This has led to development of a hypothesis that transport of ore-forming components in chlorine-rich hydromagmatic fluids was the mechanism for producing enrichments in platinum group elements. However, it is safe to say that such fluid-based models are not universally accepted and models involving a strictly magmatic origin for the ore zones have considerable support.

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