INVESTIGATIONS OF THE STILLWATER COMPLEX:
PART I. STRATIGRAPHY AND STRUCTURE
OF THE BANDED ZONE

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ABSTRACT. The plagioclase-rich rocks of the Stillwater Complex have been subdivided into three major zones and twelve subzones. A detailed stratigraphic sequence has been determined for the entire section in the Contact Mountain area (4468 m) and for a partial section in the Picket Pin area (935 m). The relative proportions of cumulus minerals and whole rock modes have been determined as a function of stratigraphic height. Whereas the major zones show a fair degree of lateral continuity in terms of thicknesses and lithologies, many of the subzones and members within these subzones show significant lateral variations in thicknesses, modes, and textures.

The dominant lithologic units in the Lower Banded zone are norite and gabbro-norite with minor anorthosite, troctolite, and gabbronite members. Repetitive cycles of magmatic sedimentation have been recognized within the lower olivine-bearing subzone. Throughout the Middle Banded zone anorthosites are dominant; plagioclase comprises 82 percent (by volume) of this zone. Two exceptionally complex olivine-bearing subzones are sandwiched between the thick anorthosites. Attempts to identify repetitive cycles within these olivine-bearing subzones have been only partially successful. The Upper Banded zone is composed of a lower olivine-bearing subzone and a thick upper subzone of uniform gabbro-norite showing planar lamination. Although thick sections of the Banded zone are characterized by isomodal layering, the occurrence of modally graded layers, inch-scale layering, disturbed layering, cross-bedding (rare), cut-and-fill structures, and discordant contacts attest to the action of currents during the formation of the Banded zone.

The overall sequence of rock types, mineral proportions, and compositional variations in plagioclase and mantle minerals in the Lower and Upper Banded zones are in general accord with those predicted under conditions of fractional crystallization by phase equilibria studies. However, the rocks in the Middle Banded zone show no such predictable variations. In addition, cyclic sequences within the olivine-bearing units, particularly those in the Middle Banded zone, are seldom compatible with phase equilibria predictions. We believe that this is due, in part, to the unique role played by plagioclase during crystallization of the Banded zone. The distribution of plagioclase within the magma is dependent on local magma compositions, temperature, pressure, and current velocities, and slight variations in these parameters will have a profound effect on the behavior of plagioclase. We believe the evidence strongly favors a model of plagioclase accumulation on the floor of the magma chamber during the formation of the Lower and Upper Banded zones.

Since this model is inadequate to explain the plagioclase-rich Middle Banded zone, we have developed an alternative hypothesis involving crystallization in a pressure gradient. Plagioclase was crystallizing in the upper, convecting part of the magma chamber while olivine and/or pyroxene were crystallizing in the lower, non-convecting part of the chamber. Insofar as plagioclase has a density very close to that of the melt, there is little tendency for differential plagioclase-liquid movement or for the generation of density currents. Plagioclase was eventually deposited at an intermediate level within the chamber marked by a density reversal, thereby forming anorthositic layers.

The reappearance of cumulus olivine at irregular intervals throughout the Banded zone is most likely the result of repeated injections of olivine-saturated magma accompanied by mixing of fractionated and fresh magma. The irregular and discordant basal contacts of some troctolites are consistent with this hypothesis.

INTRODUCTION

It is a pleasure to contribute to a volume honoring Dale Jackson. Students of layered intrusions owe him considerable debt for his pioneering studies on the mineralogy, petrology, and origin of layered igneous rocks. However much interpretations change with time, Jackson's
(1961) detailed observations on the mineralogy and textures of the ultramafic zone of the Stillwater Complex will remain the standard of comparison.

The Stillwater Complex has continually attracted the attention of geologists both because it is the best example of a layered intrusion in the United States and because it is a source of mineral wealth. The recent discovery of laterally extensive units containing platinum-group metals, the extensive but not yet fully explored deposits of Cu-Ni sulfides in the basal portions of the intrusion, and the large reserves of chrome ore combine to make the complex a significant repository of magmatic ore deposits.

The general geology of the intrusion and surrounding rocks has been described in numerous publications, most notably those of Jones, Peoples, and Howland (1960), Hess (1960), Jackson (1961), and Page (1977). The latter contains an excellent summary and extensive bibliography on geologic studies published up to 1974 together with a detailed discussion of the metamorphic rocks at the base of the complex. To date, most of the detailed petrologic and geochemical studies have been made on the rocks of the Ultramafic zone (Jackson, 1961, 1963, 1967, 1968, 1969, 1970, 1971; Page, Shimek, and Huffman, 1972; and Page, 1977). However, since the publication of the memoir by Hess (1960), there has been no comprehensive discussion of the rocks above the ultramafic zone. Page (1977) summarized the names assigned by various authors for mappable units within the complex and suggested a two-fold subdivision of the plagioclase-rich rocks into a Banded zone and an overlying Upper zone. He placed the boundary between these zones at the base of the first olivine-plagioclase cumulate. However, recent work has shown that the first olivine-plagioclase cumulate occurs much lower in the section than previously recognized. We can see no compelling reason to retain the two-fold subdivision and simply refer to all those rocks above the Ultramafic zone as the Banded zone.

As a result of reconnaissance work by the senior author in the late sixties, it was clear that the stratigraphic section presented by Hess (1960) represented a simplification of the actual stratigraphy. Accordingly, a program of field work was initiated in 1976 and continued in 1977 and 1978 to elucidate the details of the stratigraphy. Concurrent with this study, K. Segerstrom and R. Carlson of the United States Geological Survey have been mapping the Banded zone. Their preliminary maps of the western half of the complex are now available (Open-File Reports 77-370 and 78-704). To avoid duplication, we have restricted our efforts to the section exposed in the East Boulder Plateau-Contact Mountain area and to a smaller section north of Picket Pin Mountain. This paper describes in detail the stratigraphy, lithologies and modal abundances, mineralogy, and structure of the Banded zone. It is the first of a series aimed at a comprehensive description and interpretation of the petrology, geochemistry, physical evolution, and later alteration of the complex.
The age of the Stillwater Complex has been determined most recently by DePaolo and Wasserburg (1979) using the Sm-Nd method. Data obtained from mineral separates and whole rocks yield a well defined isochron and allow a precise age determination of 2701 ± 8 m.y.

FIELD AND LABORATORY METHODS

Approximately 8 man-months were spent in the field. In addition to determining the stratigraphy in the Contact Mountain section we investigated lateral variations of key marker units and examined part of the section exposed north of Picket Pin Mountain. Sample locations (fig. 1) were recorded on aerial photographs (scale 1:15840), and detailed stratigraphic sections were prepared in the field.

Due to the unique mode of formation of cumulate rocks, mineral proportions may vary dramatically on the scale of a few centimeters. As a result, the standard technique of modal analysis by point counting thin sections is useful only for those samples that are representative of relatively thick uniform (isomodal) layers. In cases where thin sections are not representative, mineral proportions have been estimated from the outcrop itself. Such a determination of "macromodes" is also essential for samples with large olivine crystals and for those with low concentrations of a particular cumulus mineral. This is true for many of the olivine-bearing units that commonly contain less than 5 percent cumulus olivine. For these rocks, modes were determined by counting the number of olivine crystals in a given surface area (usually one square meter) of outcrop. The mineral proportions shown in figure 2 represent a judicious combination of field measurements and standard point counts.

The East Boulder Plateau-Contact Mountain area was chosen for detailed study, because here the Banded zone is thickest, the rocks are well exposed and relatively fresh, and the location of and displacement on faults is well known. In addition, the strike of units is relatively constant (~N 60° W) and the steep dip (~60° NE) permits a thick sequence to be measured (see fig. 1). The Picket Pin section is also well exposed and relatively fresh. Farther eastward, in the vicinity of the West and Main Forks of the Stillwater River, a much thinner stratigraphic section through the Banded zone is exposed, it is more extensively faulted and sheared, and the rocks are more highly altered. A section along the western side of the main Stillwater valley was examined and sampled but found to be inadequate for detailed stratigraphy. However, several key horizons can be traced from the East Boulder Plateau to the Stillwater River.

Over 600 well-documented samples were collected, sectioned, and examined petrographically. Samples could be located within ~1 m, which is also the "resolution" of our stratigraphic section. Several samples were oriented for petrofabric analysis. Point counts (~2000 points per sec) were made on samples from isomodal layers. To date, approx 100 samples have been examined by microprobe techniques, and some of these data are included in this paper. Probe analyses were carried out on polished
thin sections using an ARL-EMX five channel microprobe. Standard analytical procedures were followed, and the data were corrected using a modified version of the EMPADR VII program (Rucklidge and Gasparrini, 1969). More extensive discussions of the microprobe data will be presented in subsequent papers.

STRUCTURE

Figure 1 is a map of the East Boulder Plateau showing major units, faults, sample locations, and lines along which the stratigraphic section was measured.

Nearly all the rocks of the Banded zone of the Stillwater Complex are plagioclase-rich, in sharp contrast to the underlying ultramafic sequence. The contact between the Banded and Ultramafic zones is defined as the horizon at which plagioclase first appears as a cumulus phase. This phase contact is sharp and easily recognizable from the abrupt increase of modal plagioclase from <5 percent in the orthopyroxenite at the top of the Ultramafic zone to ~50 percent in the overlying norite. The contact can be traced the entire length of the intrusion.

A complete stratigraphic sequence is nowhere obtainable for the Stillwater Complex, because an unknown portion of its top is overlain by the Paleozoic sedimentary sequence. On the East Boulder Plateau, the complex reaches its maximum stratigraphic thickness, which we have measured at 4468 m (see below). We know of no other location where rocks higher in the section are both exposed and in clear stratigraphic succession.

At the angular unconformity at the top of the intrusion, the dip of the sedimentary sequence is less than that of igneous layering; so presumably a thicker sequence of cumulate rocks lies beneath the sedimentary cover. In Jackson's (1967) view, the exposed portion of the intrusion represents the edge of a much larger saucer-shaped body that dips steeply to the northeast.

The Banded zone on the East Boulder Plateau remains structurally relatively intact. The major offset appears to have occurred along a set of nearly vertical, west-northwest trending faults that are subparallel to the strike of igneous layering. The largest of these that cut our stratigraphic sections are the Castle Creek fault north of Picket Pin Mountain and the Brownlee Creek fault south of Contact Mountain. According to Page (1977), the latter dips ~50° N. However, in localities examined by us, and from its trend across topography, the fault is vertical or dips very steeply to the south. The downthrown blocks of both faults are to the south; therefore, the geometry dictates some repetition of the section. On the downthrown blocks of both faults, small wedges of Paleozoic limestone have been preserved. The unconformity representing the basement surface on which the Paleozoic sequence was deposited was probably not much higher than the present elevation of Contact Mountain. This places a lower limit on the offset
Fig. 1. Sample location map including simplified geology and structure: East Boulder Plateau, Stillwater Complex, Montana.
on the Brownlee Creek fault of \( \sim 170 \) m. Maximum offset allowed by
stratigraphic control is \( \sim 190 \) m. The measured stratigraphic thickness
of 4468 m does not take into account fault repetition of the section.
However, our calculations of bulk composition are based on a 170 m
repetition.

The East Boulder Plateau is also cut by a series of near-vertical
faults, trending N 10 E to N 40 E and having apparent horizontal
displacements of \(< 50 \) m. These faults appear to be extensions of a
much more pervasive set of faults cutting the rocks of the Ultramafic
zone in the Chrome Mountain area. On figure 1, only those faults that
intersect the line of section are shown.

Precambrian mafic dikes cut the rocks of the Banded zone (for a
description, see Page, 1977). The largest dikes encountered are \( \sim 100 \) m
wide, but most have widths \(< 20 \) m. Even the large ones exhibit essentially
no contact effects. The dikes are readily distinguished by their diabasic
character from rocks of the Stillwater Complex. A small elongate body
of dacite porphyry, presumably of Cretaceous or Tertiary age, has
intruded the upper members of the Banded zone. This body pinches
out both to the east and west and shows little or no contact effects.

**Terminology**

*Rock names.—* Few igneous rocks have generated as much semantic
confusion as those from layered intrusions. Despite attempts to produce
a uniform nomenclature, for example, Wager, Brown, and Wadsworth
(1960), Jackson (1967), no single system has been fully accepted. There
are two approaches to naming layered igneous rocks. In the first, the

<table>
<thead>
<tr>
<th>Name</th>
<th>Cumulus minerals</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anorthosite</td>
<td>plagioclase</td>
<td>pc</td>
</tr>
<tr>
<td>Norite</td>
<td>plagioclase, low-Ca pyroxene</td>
<td>phc</td>
</tr>
<tr>
<td>Gabbro</td>
<td>plagioclase, augite</td>
<td>pac</td>
</tr>
<tr>
<td>Orthopyroxenite</td>
<td>low-Ca pyroxene</td>
<td>hc</td>
</tr>
<tr>
<td>Gabbronorite</td>
<td>plagioclase, low-Ca pyroxene</td>
<td>phac</td>
</tr>
<tr>
<td>augite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Troctolite</td>
<td>plagioclase, olivine</td>
<td>poc</td>
</tr>
<tr>
<td>Olivine gabbro</td>
<td>plagioclase, augite, olivine</td>
<td>paoc</td>
</tr>
<tr>
<td>Olivine gabbbronorite</td>
<td>plagioclase, augite, olivine, low-Ca pyroxene</td>
<td>pahoc</td>
</tr>
</tbody>
</table>

*\( \ast \)c = cumulate; p = plagioclase; h = low-Ca pyroxene; a = augite; o = olivine.
In the shorthand notation, the cumulus minerals are listed in order of decreasing
abundance (see Page, 1977).
rock is named on the basis of the total mode. While this method has
the advantage of being free of genetic assumptions, it commonly requires
different names to be applied to rocks that are closely related and ob-
viously formed by the same process, that is, significant patterns tend
to be obscured for the sake of classificatory rigor. The second method
assumes that a distinction can be made between cumulus and post-
cumulus minerals on the basis of textures. The rock is named on the
basis of cumulus minerals with modifiers added to express the total
mode (Jackson, 1967). This method has obvious genetic implications
but it has the advantage that it does not obscure relationships among
the rocks. In this paper, we use a slightly modified version of this latter
method (table 1). In a departure from normal usage, however, we
ignore the relative proportions of cumulus minerals in assignment of
the name. For example, a rock containing cumulus olivine and cumulus
plagioclase is called a troctolite regardless of the olivine/plagioclase
ratio. Rock names used are those recommended by the IUGS (Strecke-

Modifiers have been used in the following manner:

Anorthositic—modifier applied to gabbro, norite, gabbronorite, or
troctolite that contain plagioclase significantly in
excess of coticetic proportions (see table 3 for esti-
mated coticetic proportions).

Noritic—modifier applied to anorthosite, gabbro, or troctolite
with more than 10 percent postcumulus low-Ca
pyroxene.

Gabbroic—modifier applied to anorthosite, norite, or troctolite
with more than 10 percent postcumulus augite.

Gabbronoritic—modifier applied to anorthosite or troctolite with
more than 10 percent postcumulus augite and low-
Ca pyroxene.

The proposed scheme is not intended to be used as a general classi-
fication scheme. However, it is adequate to describe the rocks of the
Banded zone of the Stillwater Complex which, with very few exceptions,
contain more than 50 percent (by volume) plagioclase. In addition, it
has the advantage of using common rock names which petrologists ap-
parently prefer.

Textures.—Textures of cumulates in the Stillwater Complex have
been extensively discussed and illustrated by Jackson (1961) and Hess
(1960). Only those textures not previously documented will be discussed
in this paper. The terms cumulus, postcumulus, and intercumulus have
become firmly entrenched in the literature. Although these terms pre-
suppose some knowledge of the origin of the rocks and their continued
use has been questioned (A. R. Mc Birney, personal commun.), they
are used here in the sense defined by Jackson (1967). The petrographic
criteria we have used to distinguish between “cumulus” and “postcumu-
lus” are summarized in table 2.
Plagioclase is a cumulus mineral throughout the Banded zone. With the possible exception of some ambiguous troctolites at the base of the thick anorthosite units, olivine also appears to be a cumulus phase in all olivine-bearing rocks. Pyroxenes crystallize as both cumulus and postcumulus crystals. In approx 5 percent of the pyroxene-bearing rocks, however, the textures of pyroxenes are such that an unambiguous assignment is not possible. It has become clear that large poikilitic crystals can form not only by crystallization from an intercumulus liquid but also by postcumulus recrystallization of cumulus crystals. Ambiguous cases are discussed in a later section.

Mineral proportions.—In the measurement of modes we found it impractical to determine the amount of postcumulus overgrowths on cumulus crystals. Such material is counted as part of the cumulus mineral. This undoubtedly gives rise to an overestimation of the volume of cumulus minerals but probably does not have an appreciable effect on their relative proportions. Obvious exceptions are those troctolites that show extensive overgrowths on cumulus plagioclase and extensive resorption of cumulus olivine.

In subsequent sections we make frequent reference to “cotectic proportions” of cumulus minerals. At any stage in the crystallization of a multiply saturated magma, the solid phases will precipitate in definite relative proportions. Assuming steady-state accumulation, these

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Cumulus</th>
<th>Postcumulus*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habit</td>
<td>Columnar, tabular, equant rounded, embayed</td>
<td>Oikocrystals, space fillings, replacements of cumulus crystals</td>
</tr>
<tr>
<td>Shape</td>
<td>Subhedral, euhehdral</td>
<td>Anhedral</td>
</tr>
<tr>
<td>Size</td>
<td>0.1 - 1.0</td>
<td>&gt;0.5 - 30 cm</td>
</tr>
<tr>
<td>Crystal orientation</td>
<td>Multiple crystallographic orientations in single thin section</td>
<td>Commonly &lt;3 crystallographic orientations in single thin section</td>
</tr>
<tr>
<td>Twinning</td>
<td>Simple (100) twins in augite</td>
<td>Augite rarely twinned</td>
</tr>
<tr>
<td></td>
<td>Relict (100) twins in inverted pigeonite</td>
<td>Pigeonite rarely twinned</td>
</tr>
<tr>
<td>Exsolution lamellae</td>
<td>Multiple crystallographic orientations of relict &quot;001&quot; augite lamellae in inverted pigeonite in single thin section</td>
<td>Commonly &lt;3 crystallographically continuous sets of relict &quot;001&quot; augite lamellae in inverted pigeonite in single thin section</td>
</tr>
<tr>
<td>Inclusions</td>
<td>Few</td>
<td>Commonly abundant</td>
</tr>
</tbody>
</table>

*No attempt has been made in this work to identify the extent of postcumulus overgrowths on cumulus minerals.
proportions will be preserved in the resulting cumulate. The difficulty lies in determining these cotectic proportions, because the position and curvature of the relevant cotectic surfaces are seldom known with sufficient precision. Irvine (1970, 1977) has examined phase equilibria in the olivine–clinopyroxene–plagioclase–silica system, which is an appropriate system for modelling the crystallization of layered intrusions. Using data from synthetic systems as a guide, Irvine (1970) constructed two phase diagrams: (1) an ol projection in which the field boundary surfaces are projected onto the plag–cpx–opx plane, and (2) a cpx projection in which the field boundary surfaces are projected onto the plag–ol–Q plane. The positions of the field boundaries were then refined on the basis of published data on melting relations at 1 atm of basalts and the border facies of layered intrusions. These phase diagrams are therefore strictly applicable to dry basaltic systems at low pressure. The effect of increasing pressure is to decrease the primary phase volume of plagioclase relative to those of the mafic phases. Insofar as the Stillwater magma was of overall basaltic composition, was essentially water-free, and crystallized at low pressure (McCallum, ms), it seems reasonable to use Irvine's (1970) phase diagrams to infer approximate cotectic proportions. These proportions, recalculated as volumetric percentages, are listed in table 3. It should be emphasized that these "cotectic proportions" are subject to fairly large uncertainties.

**STRATIGRAPHY**

The detailed stratigraphic section measured on the East Boulder Plateau is shown in figure 2 (foldout). The left-hand column shows the lithologic variations in terms of volumetric percentages of the cumulus minerals only; the right-hand column shows the variation in terms of the total mode. For any given horizon the proportions of the cumulus minerals and the total mode can be read directly off the diagram. The location of major faults and later intrusions are shown together with the stratigraphic position of sulfide-rich zones. Sample locations are indicated along the margins. The section has been divided into three main zones: Lower Banded zone, Middle Banded zone, and Upper Banded zone. Figure 3 (foldout) is a simplified stratigraphic column showing the

**Table 3**

Crystallizing phases and cotectic proportions (volume percent)

<table>
<thead>
<tr>
<th>Plagioclase</th>
<th>Olivine</th>
<th>Augite</th>
<th>Orthopyroxene</th>
<th>Rock type</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-75</td>
<td>25-30</td>
<td>--</td>
<td>--</td>
<td>Troctolite</td>
</tr>
<tr>
<td>65-70</td>
<td>--</td>
<td>30-35</td>
<td>--</td>
<td>Norite</td>
</tr>
<tr>
<td>55-60</td>
<td>10-15</td>
<td>25-36</td>
<td>--</td>
<td>Olivine Gabbro</td>
</tr>
<tr>
<td>55-60</td>
<td>--</td>
<td>15-20</td>
<td>20-25</td>
<td>Gabbro norite</td>
</tr>
</tbody>
</table>
major zones and subzones. An abbreviated description of the various units is included on figure 3 along with preliminary probe data on the compositions of cumulus plagioclase and olivine.

1. Lower Banded zone (0-1590 m)—The lower contact of this zone 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. These boundaries are well defined and can be traced across the entire intrusion. The dominant lithologies in this zone are norite and gabbronorite with minor anorthosite, troctolite, and gabbro members.

1.1 Norite I (0-270 m): Orthopyroxene and plagioclase are in approximate cotectic proportions in the lower uniform part of the norite, but plagioclase increases in abundance in the upper 100 m and layering becomes more pronounced. Layering is defined by alternating pyroxene-rich and plagioclase-rich units from a few centimeters to more than 1 m thick. The thinner layers commonly bifurcate, are laterally discontinuous, and may show right-side-up modally graded layering, scours-and-fill, and slumping structures (pl. 1-A). In the upper part of this subzone there is a complex, laterally extensive, unit characterized by highly disturbed layering and irregular intermixing of norite, anorthosite, and coarse grained pyroxenite. This zone appears to be the result of strong currents and/or slumping at the floor of the magma chamber.

The magma was doubly saturated during formation of the norite, and both cumulus phases appear to have accumulated on the floor of the magma chamber. Much of the layering can be ascribed to current action (Irvine, 1979), but those sharply bounded layers of anorthosite (max 3 m thick), having no complementary mafic layers associated, cannot be readily explained by this mechanism.

1.2 Gabbronorite I (270-400 m): The lower contact of this unit is placed at the first appearance of cumulus augite, that is, the magma was triply saturated. However, the proportions of orthopyroxene, augite, and plagioclase are non-cotectic principally because of a decrease in clinopyroxene mode coupled with a complementary increase in plagioclase (fig. 2). Ellipsoidal inclusions of orthopyroxenite, texturally identical to that in the Ultramafic zone, are abundant in the uppermost 30 m of this unit.

1.3 Olivine-bearing subzone I (400-504 m): The basal contact of this complex subzone is marked by the reappearance of cumulus olivine. The contact is well defined but highly irregular and may represent an “erosional” unconformity. Pods of pegmatitic pyroxenite (up to 2 m across) are sporadically developed along the contact and in the underlying gabbronorite. The sequence troctolite–anorthosite–norite–gabbronorite is repeated five times with minor variations. An exception to this order is the narrow anorthosite immediately below the fourth troctolite (fig. 2). The basal troctolite is locally very olivine-rich, while the fourth troctolite contains abundant sulfides. The noritic members in the lower part of
Fig. 8. Ignems stratigraphy including (a) abundance of cumulus rocks and whole rock model abundance in right column. Contact Mountain and Picket Pin sections.
A. Modally graded layering in upper part of Norite I. “Up” is toward the left.
B. Contact between uppermost anorthosite of OBZ I (right) and inch-scale layering in anorthositic norite (Norite II). Dark spots in anorthosite are postcumulus pyroxenes. “Up” is toward the left.
C. Plagioclase segregations in olivine gabbronite of OBZ III. “Up” is toward the top of photo.
D. Troctolite (lower left) in contact with gabbro (upper right). Contact is discordant to layering which trends ~NNW in photo. “Up” is toward top right.
this subzone are characterized by a distinctive wispy banding; higher in
the subzone, layering in the norites becomes progressively more regular.
While this zone can be traced for at least 20 km along strike, indi-
vidual members are laterally variable, both in thickness and mode.
Modal proportions are highly variable and generally non-cotectic. The
reappearance of olivine (± sulfides), the unconformable nature of the
basal contact together with the occurrence of pegmatitic pyroxenites
and orthopyroxenite xenoliths indicate a major perturbation in the
conditions of crystallization. The reappearance of cumulus olivine, in
particular, is consistent with the hypothesis of one or more injections of
olivine-saturated magma followed by a prolonged period of mixing
before the magma returned to a relatively uniform composition rep-
resented by the overlying norite subzone.

1.4 Norite II (504-745 m): The lower boundary of this subzone is
placed at the contact between anorthosite and an anorthositic norite
which shows well developed inch-scale layering (pl. 1-B). The layering
is best developed in those norites with a high plagioclase/orthopyroxene
ratio. As modal proportions approach cotectic values, the norite becomes
correspondingly more uniform. Toward the upper part of the norite
the habit of the cumulus orthopyroxene changes from subrounded to
highly elongate (10-15 mm in length). Grains of orthopyroxene oriented
with their long axes in the plane of layering impart a pronounced
planar lamination. A distinctive, laterally extensive, mafic layer (2 m
thick) and a complementary anorthosite layer occur ~20 m below the
top of this subzone (fig. 2).

1.5 Gabbronorite II (745-1538 m): The base of this unit is marked
by the reappearance of cumulus augite. The lower 100 m are characterized
by alternating layers of anorthosite and gabbronorite. Mineral propor-
tions in the gabbronorite are variable. Anorthosite layers range in thick-
ness from ~10 cm to 15 m; two are sulfide bearing. The lower sulfide
unit is a conformable, laterally continuous, layer about 10 cm thick
which in outcrop is sharply defined by a characteristic rusty stain (fig.
4A).

In the central part of this subzone, mineral proportions in the
gabbronorite are near-cotectic, and planar lamination is well developed.
The upper 50 m are composed of five well developed but laterally
discontinuous cyclic units showing modally graded layering defined by
an upward increase in plagioclase/pyroxene ratio. These cycles may
be the result of localized, periodic, density currents interspersed with
periods of relatively quiescent crystallization and differential settling.

1.6 Olivine-bearing subzone II (1538-1590 m): The upper 8 m of
this subzone is a remarkable association of gabbro, troctolite, and gabb-
broic pegmatite The contact between gabbro and overlying troctolite is
sinuous and discordant in contrast to the planar and concordant contact
between the troctolite and overlying anorthosite. Irregular patches of
gabbro are enclosed within troctolite and vice versa (fig. 4B). Associated
pegmatites contain pyroxene and plagioclase megacrysts up to 25 cm in
Fig. 4A. Conformable sulfide layer in uniform anorthosite of lower Gabbronorite II. Dark patches in anorthosite are oikocrysts of pyroxene. "Up" is toward the top. Traced from photograph.

B. Contact relations of gabbro and troctolite in OBZ II. Irregular patterned areas in troctolite are anebooidal olivine crystals. "Up" is toward the top. Traced from photograph.

C. Disturbed layering in troctolite-anorthosite-gabbro sequence of OBZ III. Concentration of stippling is proportional to mafic mineral content of the rock. "Up" is toward the top. Traced from photograph.

D. Irregular layering in troctolite of OBZ V. "Up" is toward the right. Traced from photograph.
A. Acanthoid—olivine with plagioclase inclusions. This texture is found in uniform troctolites of all olivine-bearing subzones.

B. Euhedral intergrown postcumulus overgrowth of plagioclase and phlogopite from Anorthosite II. Myrmekite intergrowths of quartz and plagioclase at plagioclase–hornblende I. Microcline grain in plagioclase aggregate.

C. Mafic granulite overgrowth of plagioclase from gabbronite III. Note: relic (000) twin plane relief from orthopyroxene.

D. Relic crystals of inverted pigeonite and dunite. Secondary fine augite leached from orthopyroxene.
diameter. Olivine in the troctolite occurs as large (>10 mm) “ameboidal” grains with inclusions of plagioclase set in a matrix of relatively small (1-2 mm) plagioclase crystals (pl. 2-A). The troctolite does not have the appearance of a typical cumulate. We believe that the unusual texture is the result of the coalescence and recrystallization of individual cumulus olivine crystals. The simplest explanation of the reappearance of olivine and the sinuous contact with the underlying gabbrö is that it represents an erosional unconformity related in some way to injection of a batch of olivine-saturated magma. However, other mechanisms of formation of troctolite, for example, by metasomatic replacement of gabbrö, cannot be ruled out at this time.

2. Middle Banded zone (1590-3338 m).—The stratigraphic boundaries of this zone are arbitrarily placed at the base of the first thick anorthosite (anorthosite I) and the top of the second thick anorthosite. Throughout this zone, anorthosites and olivine-bearing rocks are dominant.

2.1 Anorthosite I (1590-1939 m): This subzone is composed entirely of a uniform plagioclase cumulate with postcumulus augite and inverted pigeonite. The average grain size of the plagioclase is coarser and more uniform than in the two and three phase cumulates above and below. Disseminated sulfides occur in the upper 8 m of this unit and reach a maximum concentration in the upper 2 m. This sulfide unit has been traced along strike for more than a kilometer to the east and the west of the main line of section.

2.2 Olivine-bearing subzone III (1939-2339 m): This 400 m of section is very complex. The predominant rock types are troctolite, anorthositic troctolite, anorthositic gabbrö, olivine gabbrö, and olivine gabbronorite. The various members are complexly interlayered, often on a centimeter scale. The lower boundary of this subzone is placed at the base of a banded troctolite unit in which layering is defined by subparallel stringers of olivine grains set in a matrix of cumulus plagioclase. Olivine is present as a cumulus mineral through 80 percent of the subzone, but, except for eight narrow troctolite layers in which it comprises 40 modal percent, olivine abundances are low, making up between 1 and 10 modal percent of the cumulus mineral assemblage. The major units can be traced laterally, but there are substantial lateral variations in the thickness, modes, and textures of the thinner members.

While systematic stratigraphic variations are not immediately obvious, we believe we can identify two distinct cyclic sequences that are repeated several times in the lower 275 m of this subzone. Idealized examples are illustrated in figure 5. The units overlying the second and third troctolites, respectively, represent good examples of the two cyclic sequences. The base of each cycle is commonly marked by a sharp but irregular contact which again may represent an erosional unconformity.

Olivine gabbrö and gabbronorites are generally isomodal with a well defined planar lamination. A distinctive feature of these rocks is
the occurrence of polycrystalline aggregates of plagioclase (~2.5 × 2.0 × 1.0 cm), the long axes of which are aligned parallel to the lamination (pl. 1-C). By contrast, the anorthositic gabbros commonly show an erratic layering defined by alternating mafic and felsic layers. Between 1990 and 2020 m there is a laterally extensive zone of disturbed layering (fig. 4-C). This zone also contains irregular masses of anorthosite and appears to be the result of slumping of a partly consolidated crystal mush. Associated with this zone, but not necessarily genetically related, are troctolite lenses and pipes (up to 2 m across) which crosscut or are enclosed within olivine gabbro.

The upper 125 m of this subzone are characterized by a four-phase cumulate. In some samples, small embayed olivines are present in the cores of orthopyroxenes, clearly indicating a reaction relationship. In other samples, however, coexisting orthopyroxene and olivine do not show the reaction relationship and both appear to be cumulus minerals. The apparent stable coexistence of cumulus olivine and orthopyroxene is also observed in granular harzburgites of the Ultramafic zone (Jackson, 1961). However, the distinction between cumulus and postcumulus orthopyroxene (including that formed by reaction from olivine) is not always obvious and reflects in part our limited understanding of the formation of “cumulate” rocks.

2.3 Olivine-bearing subzone IV (2339-2768 m): The lower boundary of this subzone is placed at the base of a well banded troctolite and the upper boundary at the base of the second thick anorthosite (fig. 2). The sequence troctolite–anorthosite–anorthositic troctolite–olivine gabbro (± gabbronorite) is repeated three times. The gabbronorite unit at
the top of the third cycle (see fig. 2) is variable in thickness and not always present. The uppermost troctolite may represent the basal member of an incomplete fourth cycle.

In the anorthositic troctolites of the first cycle, orthopyroxene and inverted pigeonite coexist as postcumulus phases with the former occurring exclusively as reaction rims around olivine, while the latter form large oikocrysts.

The contact between troctolite and underlying olivine gabbro ranges from gradational to sharp, sinuous, and discordant, whereas the upper contact between troctolites and overlying anorthosites is invariably sharp, planar, and concordant. The contact relations of the uppermost troctolite are illustrated in plate 1-D. This troctolite is structureless, highly discordant, contains ameboid olivine aggregates, is associated with pyroxene and plagioclase megacrysts, and is virtually identical to the troctolite at the base of the first thick anorthosite described previously and illustrated in figure 4B.

2.4 Anorthosite II (2768-3338 m): This uniform unit is the thickest anorthosite in the Banded zone. Postcumulus augite and inverted pigeonite (pl. 2-B) make up 10 to 12 percent of the rocks, and disseminated sulfides are concentrated in two narrow layers near the base and top of this unit. The average grain size of plagioclase is approximately twice that of plagioclase in two- and three-phase cumulates.

3. Upper Banded zone (3338-4468 m).—This zone is arbitrarily divided into two subzones, a lower olivine-bearing subzone and an upper subzone of uniform gabbronorite. Sections were measured in both Contact Mountain and Picket Pin areas (fig. 1). The latter section is particularly well exposed. Major lithologic units correlate fairly well between the two areas, but significant variations in thickness, mode, and textures within individual members are common (fig. 2).

3.1 Olivine-bearing subzone V (3338-3432 m): This subzone is substantially thicker in the Picket Pin section. In both areas, the basal member is a well banded troctolite (fig. 4D) containing varied amounts of plagioclase, normally in excess of coticetic proportions. Modally graded layering, cross bedding, and cut-and-fill structures are locally present indicating strong current action during the deposition of this troctolite. At Contact Mountain, the sequence of lithologies in this subzone can be summarized as: TANG/ANG, while at Picket Pin the sequence is: TAN/ANG/ANG/ANG/ANG where T = troctolite, A = anorthosite, N = norite, and G = gabbronorite. Irregular layering, characterized by alternating mafic and felsic layers, is well developed in norites and gabbronorites. As noted earlier, layering is most conspicuous in those members containing "excess" plagioclase.

3.2 Gabbronorite III (3432-4468 m): Throughout this uniform subzone, plagioclase, augite, and low-Ca pyroxene occur in approximately coticetic proportions (fig. 2). While planar lamination is almost always present, there is no preferred mineral orientation within the plane of layering. The most interesting aspect of this subzone is the change in
morphology and composition of the low-Ca pyroxenes. Below 3765 m (Contact Mountain section) orthopyroxene is clearly a cumulus mineral. Between 3765 and 3975 m, orthopyroxene occurs as poikilitic crystals (up to 15 cm in diam) containing abundant “inclusions” of small rounded augites. Above 3975 m, orthopyroxene occurs as poikilitic crystals containing numerous sets of oriented “001” augite exsolution lamellae. These sets of lamellae outline domains corresponding to original cumulus pigeonite crystals. Similar features have been described by von Grunewaldt (1970) in pigeonites from the Bushveld Complex. Insofar as there is no significant change in mineral proportions associated with these textural changes, we conclude that low-Ca pyroxene formed as a cumulus mineral throughout this subzone, the poikilitic texture being the result of postcumulus recrystallization accompanying the inversion reaction.

At Picket Pin, the change from cumulus orthopyroxene to cumulus pigeonite is complicated by a reversal about midway through the gabbronorite (fig. 2). The break occurs at a thin but complex zone in which the sequence: fine grained gabbronorite–anorthositic gabbronorite pegmatite–mafic gabbronorite pegmatite, is developed. Above this zone, the transitional change to pigeonite resumes. The upper gabbronorite

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<td>Abundances of principal minerals (volumetric percentage)*</td>
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<td></td>
</tr>
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<td>Norite I</td>
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<td>Gabbronorite I</td>
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<td>OBZ I</td>
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<td>Norite II</td>
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<td>Gabbronorite II</td>
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<td>OBZ II</td>
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<td>Total (Lower Banded zone)</td>
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<tr>
<td>Anorthosite I</td>
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<td>OBZ III</td>
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<td>OBZ IV</td>
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<td>Anorthosite II</td>
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<td>Total (Middle Banded zone)</td>
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<tr>
<td>OBZ V</td>
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<tr>
<td>Gabbronorite III</td>
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<tr>
<td>Total (Upper Banded zone)</td>
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<td>Total (Banded zone)</td>
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*Abundances determined by planimetric analysis of figure 2 (total modes).
contains numerous veins and dikes of pegmatitic hornblende-plagioclase-quartz up to 50 cm in width. These rocks may have formed during a late magmatic stage.

MINERALOGY

In this section we discuss briefly the abundances, compositions, textures, and alteration products of the primary minerals in the Banded zone. The relative abundances in each subzone have been carefully measured on figure 2 and are summarized in table 4.

Plagioclase is the dominant mineral throughout the Banded zone. Grain sizes are varied and reach a maximum in the thick anorthosite members. In most samples plagioclases are relatively homogeneous, although examples of normal, oscillatory, and patchy zoning are not uncommon. As illustrated in figure 3, the maximum variability in any one sample is ~10 mole percent An. Most of this variation is the result of secondary overgrowths. In the Lower and Upper Banded zones plagioclase shows a distinct trend of increasing Ab/An+Ab with stratigraphic height, but no such systematic variation is observed in the Middle Banded zone. The extent and nature of secondary alteration is quite varied; it is not uncommon to find completely altered plagioclase and fresh plagioclase in the same thin section. Alteration is clearly related to fractures which provided channelways for the infiltration of water. Secondary mineral assemblages are dependent on the nature of the coexisting mafic minerals (if any) and include prehnite (+pumpellyite), albite + clinzoizite/epidote ± chlorite ± clinoamphibole, and tremolite + talc + chlorite. In the uppermost zones, plagioclase shows extensive myrmekitic rims composed of wormy intergrowths of quartz + plagioclase (pl. 2-C). These may represent the exsolution of silica originally present in solid solution as Schwanke's molecule (Ca₀.₅AlSi₅O₈), or the simultaneous crystallization of plagioclase plus quartz.

Orthopyroxene and augite exhibit a wide range of textures. Both occur as euhedra to partially resorbed cumulus crystals, as subpoikilitic grains with cumulus cores and inclusion-filled postcumulus rims, as reaction rims around embayed olivines, and as oikocrysts from 0.5 to 36 cm in diameter. In addition, orthopyroxene occurs as poikilitic grains formed by the decomposition and recrystallization of cumulus pigeonite. Extensive secondary overgrowths on augite crystals in many gabbro units have resulted in an unusual interfingered texture.

Inverted pigeonite is a common postcumulus mineral, particularly in the anorthosite members. It occurs as a cumulus mineral only near the top of the exposed section. Epitaxial intergrowths of augite and pigeonite oikocrysts (sharing the (100) plane) are common in anorthosites (pl. 2-B).

The compositional range of pyroxenes is shown in figure 6. While there is an overall increase in Fe²⁺/Fe³⁺ + Mg with stratigraphic height, there are numerous reversals in the trend. Zoning is minimal, but subsolidus reequilibration has modified compositions of grain boundaries.
Exsolution and inversion features in Stillwater pyroxenes are considerably more complex than originally described by Hess (1960). Single crystal X-ray, optical, and microprobe studies indicate that pyroxenes can be subdivided into four major types and several subtypes. I. Augite (X<0.135, where X = Fe<sup>2+</sup>/Fe<sup>3+</sup> + Mg) has exsolved orthopyroxene on (100); the (100) lattice planes of both phases are parallel and coincident with the composition plane. II. Augite (X>0.135) has exsolved (A) pigeonite (later totally inverted to hypersthene) on “001”, and (B) pigeonite on (100) partially inverted to hypersthene — diffuse streaks parallel to a* connect corresponding reflections; in (A), the (001) lattice planes of the two phases are not coincident (Δc* ~ 1.5°), and the angle between the composition plane and c<sub>aug</sub> is variable but commonly greater than β<sub>aug</sub>. III. Orthopyroxene has exsolved twinned augite on (100). IV. Inverted pigeonite (X>0.320) contains relict “001” and “100” augite exsolution formed prior to inversion along with oriented, subospherial blebs of augite. Orthopyroxene formed by inversion may share (100) with the monoclinc precursor but commonly does not. This orthopyroxene has exsolved augite on (100). Subtypes are recognized on the basis of the crystallographic orientation of secondary lamellae, degree of inversion, lamella size, and the presence or absence of exsolved oxide phases. Blebby and wormy exsolution in pigeonite appears to be favored when the crystallization temperature is close to the inversion temperature.

Olivine is a cumulus mineral in the Banded zone. Grains are commonly embayed and rimmed by orthopyroxene or pigeonite and/or augite. In some samples the reaction has gone virtually to completion such that only minute remnants of olivine remain in the cores of pyroxene grains. It is possible, even likely, that some orthopyroxene grains with poikilitic margins originally formed by replacement of cumulus olivine.

Two textural extremes are observed. In massive coarse grained troctolites, such as those at the base of thick anorthosite units, olivine occurs as “ameboidal” single crystals (pl. 2-A) that appear to have formed by coalescence and recrystallization of single grains. In banded troctolites, olivine occurs as stringers of isolated, subrounded crystals, partially rimmed by orthopyroxene. Gradations between the two textural types are common.

![Fig. 6. Compositions of coexisting pyroxenes (mole percent).](image-url)
Olivine compositions are shown in figure 3 as a function of stratigraphic height. Although the currently available data set is limited, it is clear that no systematic variation exists. Secondary alteration of olivine is very common and quite varied. Commonly, olivine has altered to serpentine + talc + magnetite. In most troctolites, however, olivines have altered to a talc + tremolite assemblage surrounded by a rim of pale green chlorite which appears to have formed largely at the expense of plagioclase. In both cases, expansion cracks radiate from olivine grains into the surrounding plagioclase. An example showing the incipient development of these cracks is illustrated in plate 2-A.

Disseminated sulfides are concentrated in eight zones which are generally concordant with the layering. These sulfide layers vary from well defined (fig. 4A) to diffuse. In the latter case, sulfides are only slightly more abundant than in the remainder of the section. Sulfides are associated with anorthosites and always accompanied by extensive secondary alteration of the coexisting silicate assemblage.

Predominant sulfide phases are pyrrhotite and chalcopyrite with minor pentlandite. Pyrite is locally a common constituent along with a variety of as yet unidentified secondary Cu–Ni–Fe sulfide minerals.

**DISCUSSION**

The main purpose of this paper is to describe in detail the stratigraphic sequence and modal abundances of the lithologic units making up the Banded zone of the Stillwater Complex in order to complement the comprehensive data already available on the Ultramafic zone. Without this information, attempts to model the petrogenesis of the complex are meaningless. It must be pointed out, however, that even on the relatively large scale chosen in figure 2 to represent the lithologic variations, many fine-scale, and possibly significant, details cannot be shown. Examination of the modal data presented in figure 2 reveals complexities that cannot be explained by any simple mechanism. An adequate explanation will require, as a minimum, a comprehensive analysis of layering features, an extensive body of data on the composition of the constituent minerals and some knowledge of the dynamics of the flow of fluids and suspensions in systems of this type. The paper by Irvine (1979) in this volume represents the first comprehensive attempt at understanding the latter process. Even with the limited data set currently available, it is instructive to consider possible models to explain some of the large-scale features if only to identify problem areas and stimulate additional research.

During the field work we attempted to identify and describe repetitive cycles of magmatic sedimentation in the hope that these would provide insights into the processes of formation of the Banded zone. Cyclic sequences have been observed ranging in thickness from less than one meter to tens of meters; however, lithologic sequences within cycles are seldom compatible with those predicted from simple phase equilibria considerations. We believe that this is due in large
part to the unique role played by plagioclase during the crystallization of the Banded zone. Plagioclase, which makes up >50 percent of the rocks in the Banded zone, has a density very close to that of the magma from which it crystallized (table 5). As a result, the distribution of plagioclase crystals within the magma chamber is strongly dependent on magma compositions, temperature, pressure, and current velocities. Slight fluctuations in these parameters may have a profound effect on the behavior of plagioclase.

The primary processes operating during formation of the Banded zone were (A) fractional crystallization, (B) multiple injections of fresh magma, (C) magma mixing, and (D) convection and/or density currents. These processes are interdependent and each cannot be considered in isolation.

Fractional crystallization was an important, even dominant, process particularly during the formation of the Lower and Upper Banded zones. In general, the sequence and proportions of minerals precipitated and the systematic variation of plagioclase compositions in these zones (fig. 3) are compatible with those predicted from phase equilibria. In the upper part of the Ultramafic zone and in the Lower Banded zone the cumulus minerals appear in the order: orthopyroxene, orthopyroxene + plagioclase, orthopyroxene + plagioclase + augite. Plagioclases become progressively more albite and mafic minerals more iron-rich upward in the sequence. Superimposed on this pattern, however, are subzones in which olivine reappears, for example, OBZ I in which cumulus olivine forms the base of poorly developed cyclic units, and OBZ II in which olivine occurs as discordant bodies of troctolite. In addition, there are numerous stratigraphic intervals composed of relatively thin anorthosites and intervals in which the minerals in norites and grabbronorites deviate significantly from eutectic proportions. The bulk of the Lower Banded

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<td>Plagioclase and magma densities (g cm⁻³).</td>
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<td>T(°C)</td>
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*Density calculated by the method of Bottinga and Weill (1970) using the chilled margin composition from the Stillwater Complex analyzed by Jackson (1971).
**Density calculated using the chilled margin composition of the Stillwater Complex reported by Hess (1960).
***Density calculated using measured plagioclase densities at room temperature (Walker and Hays, 1977) corrected to cited temperatures using coefficients of thermal expansion from Skinner (1966). Feldspar composition is that of the first cumulus plagioclase at the base of the Banded Zone.
****Density calculated using composition of plagioclase on the liquidus at 1170°C as experimentally determined in our laboratory for the Jackson (1971) chilled margin composition.
zone shows isomodal layering suggesting uniform conditions during crystallization. Layering defined by modal variation is not uncommon but appears to be largely restricted to (or most easily recognized in) those units showing an excess of plagioclase. This observation suggests a close relationship between the mechanism of deposition of non-cotectic layers and layering. In the Lower Banded zone, as a whole, plagioclase makes up 60 volume percent and combined mafic phases 40 volume percent (table 4). These values are reasonably consistent with the approximate cotectic proportions listed in table 3.

The gabbronorite of the Upper Banded zone is the most uniform unit in the complex. While planar lamination is commonly developed, layering, in the sense of small scale modal or grain size variations, is conspicuously absent. Plagioclase (60 volume percent) becomes more albitic and pyroxenes (40 volume percent) more iron-rich with stratigraphic height. The near-cotectic proportions, predictable compositional changes, and absence of modal layering again imply fairly uniform depositional conditions.

The observations summarized above provide strong evidence for the accumulation of crystals at the bottom of the magma chamber during the formation of the Lower and Upper Banded zones. This does not necessarily imply that plagioclase settled through the magma; a more likely process is the deposition of plagioclase and mafic minerals from density currents which periodically spread across the floor of the magma chamber. Irvine (1979) has modelled this process experimentally, and his data clearly show that plagioclase can accumulate along with mafic minerals on the floor of a magma chamber even under conditions in which the density of plagioclase is less than that of the magma. Internal flow patterns in these relatively dense crystal-liquid suspensions are such that suspended crystals are subject to a downward-acting velocity component which carries them to the floor. Uniform layers may have formed under more "quiescent" conditions during which dilute crystal-liquid suspensions were carried to the floor of the chamber in the general convective circulation.

The stratigraphic sequence in the Middle Banded zone presents a major problem in interpretation. This zone contains two thick subzones of anorthosite and one thinner anorthosite at the base of OBZ IV. Plagioclase makes up approx 82 volume percent of this zone. Since there is no known magma with a composition capable of producing rocks with this amount of plagioclase, we are forced to conclude that plagioclase has been significantly enriched within the Middle Banded zone. The following questions arise: (1) What is the source of this excess plagioclase? (2) Why did plagioclase accumulate at an intermediate level within the intrusion? (3) What mechanisms were responsible for the accumulation of plagioclase? Two observations mentioned earlier are worth repeating at this point: the average grain size of plagioclase crystals within the thick anorthosites is greater than twice that of plagioclase in the two- and three-phase cumulates, and secondly,
there is no systematic stratigraphic variation in plagioclase compositions within the Middle Banded zone; with one exception all average plagioclase compositions lie between $\text{An}_{80}$ and $\text{An}_{75}$. These two observations can be interpreted to mean that plagioclase in the rocks of the Middle Banded zone remained in contact with the magma for a longer time than did plagioclase in other units and that the system was fairly well mixed.

Two possibilities are worth considering for the source of the excess plagioclase. Firstly, the excess plagioclase may represent that which failed to accumulate on the floor of the magma chamber during the crystallization of the Ultramafic zone and the Lower Banded zone. This possibility was considered by Hess (1960) who marshalled strong arguments against it, most notably the absence of cumulus plagioclase in the Ultramafic zone, the exceptionally sharp basal contact of the norite I subzone, and the high anorthite content of plagioclase at this horizon. The latter arguments are still valid; however, we have found small amounts of cumulus plagioclase in a few samples from the Ultramafic zone. These occurrences are so rare, however, that major conclusions based on them are probably not justified.

The second possibility is that the excess plagioclase in the Middle Banded zone represents that which failed to accumulate on the floor of the magma chamber during the crystallization of the Lower Banded zone only, that is, the magma was not saturated in plagioclase during formation of the Ultramafic zone. At this point it should be noted that the Upper Banded zone formed after the Lower and Middle Banded zones (see mineral composition data in fig. 3); therefore, it should not be included in any mass balance calculations. The combined Lower and Middle Banded zones contain 72 percent (by volume) plagioclase with olivine and pyroxenes comprising the remaining 28 percent (table 4). Although, admittedly, the coticetic proportions are not accurately known, it appears that this amount of plagioclase is considerably in excess of coticetic proportions (see table 3).

The chilled margin of the complex throws little light on the subject. Tilley, Yoder, and Schairer (1963) showed plagioclase to be the liquidus phase for the chilled margin sample reported by Hess (1960). Unpublished data from our laboratory show olivine and plagioclase to be on the liquidus at 1170°C and $\text{FO}_2 = 10^{-10}$ for the chilled margin sample reported by Jackson (1971). There are good reasons for believing that neither sample is representative of the original magma composition; firstly, the liquidus olivine ($\text{FO}_{75-76}$) in Jackson's composition is much more iron-rich than olivines in olivine cumulates of the Ultramafic zone ($\text{FO}_{54-87}$); secondly, the Hess composition gives a crystallization sequence at variance with the observed sequence; thirdly, the initial $^{143}\text{Nd}/^{144}\text{Nd}$ values (DePaolo and Wasserburg, 1979) of samples from all major zones in the complex deviate significantly from the chondrite evolution curve and are most readily interpreted as indicating contamination with LREE-enriched country rock. While we feel it is
Inadvisable to draw firm conclusions from data on chilled margin samples, the possibility that plagioclase was the liquidus phase (at least at low pressure) cannot be dismissed.

Irvine (1975) has proposed an alternative hypothesis for the genesis of anorthositic layers which does not require the existence of "excess" plagioclase. Irvine suggested that, as a consequence of the curvatures and relative orientations of the plagioclase-olivine and plagioclase-orthopyroxene field boundaries in the \( \text{Ol-An-SiO}_2 \) system, mixing of compositions on these cotectics produces melts saturated only in plagioclase. This model for the formation of anorthosite layers fails on two counts when applied to the Stillwater rocks. Geometrical analysis of the phase diagram shows that the volumes of magma required to produce the two thick anorthosite subzones (combined thickness = 920 m) are prohibitively large. In addition, while one component of the mixed magma would be plagioclase saturated, lithologic sequences in the Ultramafic zone indicate that the other component, that is, the magma component being injected into the chamber, would probably be within the olivine phase volume. Although these discrepancies argue against this mechanism as a means to form the thick anorthosite units, it is possible that some of the thin anorthosites members may have formed in the manner suggested by Irvine (1975).

It is instructive to consider the effects of crystallization in a pressure gradient. It is well known that pressure will depress the temperature of crystallization of plagioclase relative to that of mafic phases. Experiments by Green and Ringwood (1967) on an olivine tholeite composition showed that \( dT/dP \) for the first appearance of plagioclase is \( \sim -5^\circ/\text{kb} \) while \( dT/dP \) for olivine is \( \sim +1.5^\circ/\text{kb} \). A composition with plagioclase on the liquidus at low pressure may have olivine or pyroxene on the liquidus at higher pressure. In a magma chamber approx 3 km thick a 1 kb pressure gradient will exist from top to bottom. It is conceivable, indeed even likely, that such a magma may be saturated with plagioclase near the top but saturated with olivine and/or pyroxene near the base.

During the formation of at least part of the Ultramafic zone, plagioclase may have been crystallizing in the upper part of the magma chamber. There would be little tendency for this plagioclase to settle since its density was essentially the same as that of the magma (see table 5). Furthermore, it is likely that the yield strength of the magma was sufficiently large to prevent differential crystal-liquid movement (McBirney and Noyes, ms). Plagioclase would tend to "follow" the melt if, as seems probable, the system was convecting. It is of interest to consider the fate of a parcel of magma containing suspended plagioclase crystals as it is carried downward by convection. A number of possibilities exist depending on the initial state of the magma and the boundary conditions. We shall consider only one.

In the first place, the magma plus crystals will undergo adiabatic compression. Given an adiabatic gradient of \( \sim 0.3^\circ/\text{km} \), the increase in
temperature would be very small. Secondly, the magma will be subjected to increased crystallization insofar as the liquidus temperature increases with depth at a rate of \( \sim 2.3^\circ \text{km} \). The increase in crystals due to this effect will be minor especially since latent heat is released during crystallization. Thirdly, the parcel of magma plus crystals will absorb heat from the surrounding magma which we assume to be slightly superheated, at least in the initial stages. The net result of these processes is to resorb plagioclase crystals and thereby produce a slight compositional gradient in the liquid. Since resorption is strongly endothermic, the process described can be an effective method of transferring heat from the interior of the magma. As the system cools by heat loss at the upper contact, plagioclase crystals will be carried to increasingly greater depths before they are resorbed. The system would ultimately “stabilize” itself close to the melting point gradient. According to Wood (1975), in magmatic systems of this type, “... the adiabatic gradient ... would eventually accommodate itself rather closely to the melting curve.”

Owing to heat loss through the floor of the magma chamber, crystallization (presumably of olivine and/or pyroxene) was occurring at the base of the intrusion. Jackson (1961) has argued that the basal portion of the magma was not involved in the general pattern of convective circulation as a result of the increase in density produced by partial crystallization of dense mafic minerals. The absence of size/density sorting and current structures in the ultramafic cumulates provides strong evidence in support of Jackson’s hypothesis.

One can, therefore, visualize a situation in which plagioclase crystallization was taking place in the upper, convecting, part of the chamber while the Ultramafic zone was forming at the base. Crystallization of the norite zone may have begun when the intrusion had cooled to a temperature that permitted plagioclase crystals to reach the floor, or when a sufficient quantity of orthopyroxene had crystallized in the upper part of the magma chamber to initiate density currents.

It is worth pointing out that this model does not require either settling or flotation of plagioclase in the initial stages of cooling. However, accumulation of plagioclase is required at later stages to produce the anorthosite subzones. The lack of systematic compositional variation in the plagioclases of the Middle Banded zone suggests that this accumulation did not necessarily occur from either the bottom up or the top down. Irvine (1979) has examined this process of plagioclase accumulation in some detail and concludes that plagioclase carried upward in the return flow of a convection current might be “deposited” at some intermediate level in the magma chamber below which the liquid was denser than the plagioclase, whereas that above was less dense.

There are obviously many variations on the model briefly outlined above. These will be discussed at greater length in a later paper. However, it does not seem unreasonable to conclude that processes of the
type described were involved in the formation of anorthosite subzones in the Stillwater Complex.

The reappearance of cumulus olivine at irregular intervals throughout the Banded zone is strongly suggestive of the addition of fresh batches of olivine-saturated magma. Under normal fractional crystallization, relatively Mg-rich olivine should not reappear as a cumulus mineral. As discussed above, it is likely that the magma prior to the addition of olivine-bearing fresh magma was a dilute plagioclase-liquid suspension. Olivine was not necessarily stable in the resulting mixed magma, that is, the bulk composition remained within the plagioclase crystallization volume. Some of the olivine may have been deposited on the floor of the chamber (large $\Delta f$) and been preserved in cumulates before it could be completely resorbed. The irregular and discordant nature of the basal contacts of troctolites and the resorption textures in olivine crystals are consistent with this hypothesis of multiple injections of olivine-saturated magma.

As stated earlier in this discussion, the complexities of layered intrusions are such that a comprehensive petrogenetic model remains elusive. Existing hypotheses are to a large extent ad hoc and are inadequate to explain all the observed features. Future progress in our understanding of these important rocks will depend on careful and detailed field observations, extensive major and trace element analyses, advances in our understanding of relevant phase equilibria, particularly in the ol-cpx-plag-$SiO_2$ system, modelling experiments and/or theoretical analysis of flow processes, compare Irvine (1979), and the re-determination and evaluation of physical properties of melts and suspensions. The fact that many of our current ideas on the origin of layered intrusions have not changed greatly in the last 40 yrs is testimony to the thoroughness and ingenuity of early workers. However, it is essential that alternative hypotheses be considered, for example, McBirney and Noyes (ms).

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Investigations of the Stillwater Complex: Part I


