The Stillwater Complex and its anorthosites: An accident of magmatic underplating?

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ABSTRACT

The Stillwater Complex, emplaced 2700 ± 40 Ma, is exposed at the edge of a 4000-km² block of Late Archean rocks that formed 40 to 110 m.y. earlier. Voluminous plagioclase cumulates (anorthosites) within the Middle Banded series of the complex are difficult to explain either by in situ fractionation of mafic magma or by popular models for mixing of two magma types. Many samples from the complex have radiogenic Nd- and Pb-isotopic compositions that are indistinguishable from those of the Late Archean igneous suite of the eastern Beartooth Mountains, composed largely of granitoid rocks. Because these voluminous granitoids could only have been derived from a mantle source by a two-stage process, the crust from which they were derived must have had little time to evolve in Nd- and Pb-isotopic composition. Current models for the evolution of the lowermost continental crust by magmatic underplating suggest that a major crust-forming event of about 100-m.y. duration would satisfy geologic and geochemical constraints for the formation of the Stillwater Complex and the related granitoids. As a component of this process, a large mafic magma chamber near the crust/mantle interface would allow an unexplored open-system aspect for rationalizing significant features of Stillwater Complex geology that have not yet been satisfactorily explained, in particular, the major anorthosite zones.

BACKGROUND

Since the 1930s, when Ed Sampson recognized it as a world-class layered mafic intrusion and Bushveld analogue, the Stillwater Complex has provided exceptional petrologic insights and challenges (for references, see Czamanske and Zientek, 1985). Hess (1960) published a superb mineralogical and petrologic overview of the complex and was particularly challenged by the “anorthosite problem.” Jackson (1961, 1967, 1970, 1971) based his landmark papers, which formalized interpretation of cumulus minerals, cumulates, and cyclic units, on studies of the Stillwater Complex.

The discovery in 1973 of the J-M Reef inspired many new studies and shifted focus to the Banded series, then relatively poorly known (for stratigraphic terminology, see Fig. 1 and Zientek et al., 1985). Geologists were challenged to explain the platinum-group-element (PGE) enrichment that characterizes this irregular, thin, quasi-stratiform horizon. Field observations and consideration of phase equilibria led Todd et al. (1982) and Irvine et al. (1983) to propose that a second, plagioclase-saturated liquid had entered the chamber and that interaction of this Ao magma with olivine- or pyroxene-saturated, Uo magma derivatives already within the chamber was crucial to PGE deposition. The reappearance of olivine and the appearance of plagioclase cumulates (anorthosite) in association with the J-M Reef stimulated development of this model, which ultimately led to the introduction of a new stratigraphic subdivision to reflect two principal crystallization orders caused by these two proposed parental magmas (Fig. 1; Todd et al., 1982). Numerous subsequent studies, exemplified by those of Barnes and Naldrett (1986) and Lambert and Simmons (1988), focused on the narrow stratigraphic interval represented by Olivine-bearing zone I and produced mineralogic and geochemical data that support a two-magma hypothesis. Uo parental magma (olivine boninite) was considered to be relatively rich in MgO and SiO₂, relative to midoceanic-ridge basalt, enriched in light rare-earth elements (LREEs), and depleted in heavy rare-earth elements (HREEs); the proposed Ao magma (silica-undersaturated high-alumina basalt) contained less MgO and more Al₂O₃, was less LREE enriched, and was not HREE depleted. On the basis of detailed study of the system CaO-MgO-Al₂O₃-SiO₂, Irvine and Sharpe (1982) found “rather compelling indications that Uo liquids came from deep in the upper mantle (from perhaps 180–200 km), whereas the Ao liquids probably melted from the bottoms of thick (40–50 km) segments of continental crust.” Concurrently, however, Tatsumi (1981, 1982) and Tatsumi and Ishizaka (1982) conducted melting experiments that led to their proposal that high-Mg andesites and related magmas of boninitic composition could be derived by hydrous melting of mantle peridotite at relatively shallow mantle depths (<15 kbar). Whole-rock compositions studied by Tatsumi (1981, Table 1) encompass that of the proposed Uo magma and, along with REE contents, are strongly de-
Fig. 1. Subdivisions of Stillwater Complex stratigraphy and approximate stratigraphic distribution of cumulus minerals. Arrow marks location of the J-M Reef. After Zientek et al. (1985).
dependent on degree of partial melting and relative deple-
tion of the mantle source. The origin of Uₐ magmas at
these shallower depths by hydrous partial melting may
be more compatible with isotopic indications for a sub-
duction-enriched mantle.

Workers in the Bushveld Complex, from which the com-
positions of the U₀ and A₀ liquids had been inferred
(Irvine and Sharpe, 1982), were able to establish from ini-
tial Sr-isotopic ratios that two isotopically distinct magmas were involved in the formation of that complex
(Harmer and Sharpe, 1985; Sharpe, 1985). This result
stimulated a similar test of the evolution of the Stillwater
Complex, but the Sr-isotopic systematics of the complex
are notably disturbed (see below). Because of indica-
tions that generation of the A₀ magma involved crustal in-
teraction and the great sensitivity of Pb-isotopic mea-
surements for detecting crustal contamination in Archean
rocks, Pb-isotopic analyses were obtained for plagioclase
separates from a comprehensive suite of Stillwater cu-
mulates. It was hoped that some light would be shed on
the origin of the Stillwater anorthosites. The results in-
dicate that Stillwater parental magmas had a very limited
range of initial Pb-isotopic compositions (Czamanske et
al., 1986; Wooden et al., 1990); any Pb-isotopic contrast
between magma types is at the limit of resolution.

**ISOTOPIC AND TRACE-ELEMENT STUDIES**

Using a sample of Gabbronite I, DePaolo and Was-
serburg (1979) reported a precise mineral-isochron age of
2701 ± 8 Ma and an initial Nd-isotopic composition of
$\varepsilon_{Nd} = -2.8 ± 0.2$ for the Stillwater Complex. On the basis
of five whole-rock analyses that fell on this mineral iso-
chron, the complex was assumed to be homogeneous in
initial Nd-isotopic composition.

Recently, however, Lambert et al. (1989a, 1989b) have
reported whole-rock Nd- and Os-isotopic data that ap-
pear to preclude formation of the intrusion from a single,
isotopically homogeneous magma. Initial $\varepsilon_{Nd}$ values for
U- and A-type cumulates range from -3.2 to -0.8 and
from -0.7 to +1.7, respectively. Re-Os data reveal sig-
nificant heterogeneities in initial Os-isotopic composition
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nificant heterogeneities in initial Os-isotopic compositions (Czamanske et
al., 1986; Wooden et al., 1990); any Pb-isotopic contrast
between magma types is at the limit of resolution.

On the basis of REE data for orthopyroxenes, Lambert
and Simmons (1987) suggested that the Ultramafic series
of the Stillwater Complex was formed by multiple injec-
tion of magmas derived by multistage dynamic partial
melting of a garnet-bearing source extremely enriched in
REEs. They compared these magmas with those that
formed the Sanukitoid suite of Shirey and Hanson (1984).
Analyses of plagioclase (Lambert and Simmons, 1988)
and orthopyroxene (Lambert et al., 1989b) reveal that
rocks stratigraphically associated with the J-M Reef crys-
tallized from magmas that were distinctly less LREE en-
riched, with Ce/Yb ratios of approximately 4 versus 8–
18 and Dy/Yb ratios of approximately 1 versus 2 (based
on chondrite-normalized values).

Kistler et al. (1969), Fenton and Faure (1969), DePaolo
and Wasserburg (1979), Stewart and DePaolo (1987), and
Lambert et al. (1989a and 1989b) reported that the Sr-
isotopic systematics of the Stillwater Complex have been
disturbed as a result of one or more metamorphic events.
Lambert et al. (1989b) reported that $\varepsilon_{Sr}$ values range from
-1.0 to +34.0 in Banded series cumulates and from im-
possibly low values of -260 to -13.1 in Ultramafic se-
cumulates. They estimated an initial Sr-isotopic ratio
of 0.70200 to 0.70235 ($\varepsilon_{Sr}$ value of +14 to +19), distinctly
more radiogenic than primitive mantle at 2700 Ma,
suggesting a long-term history of Rb enrichment relative
to Sr in the mantle source.

Czamanske et al. (1986) and Wooden et al. (1990) have
reported a narrow range of radiogenic, apparent initial
Pb-isotopic compositions (Table 1) for plagioclase from
samples that encompass Stillwater stratigraphy. Corro-
borating the Nd- and Os-isotopic studies, samples from
near the base of the complex show evidence of minor in
situ contamination. The Pb-isotopic data—in combina-
don with low Pb, Th, and U contents in Stillwater whole
rocks and plagioclase and the nearly uniform calculated
long-term Th/U ratios of approximately 4 defined by the
Pb-isotopic data—virtually eliminate upper-crustal con-
tamination as the cause for any significant petrologic or
trace-element complexity observed in the Stillwater
Complex (Wooden et al., 1990). Because the A₀ magmas
had Pb-isotopic compositions virtually indistinguishable
from those of the mantle-derived U₀ magmas, they could
have been derived by partial melting of mafic rocks (Ir-
vine and Sharpe, 1982) that were relatively new compo-
nents of the lower crust, by fractional crystallization of
more mafic liquids in a lower-crustal staging chamber, or
by a combined process involving assimilation of young
crustal components into this chamber. Resolution of this
issue may come from further study of the Rh-Os-isotopic
systematics of the complex; Sr-, Nd-, and Pb-isotopic sys-
tematics cannot resolve crustal- from mantle-source rocks
if crustal residency has been short.

The Late Archaean igneous suite of the eastern Bear-
tooth Mountains consists of three units that crop out over
more than 4000 km$^2$ (in decreasing volumetric impor-
tance): Long Lake granite, anodesitic amphibolite, and Long
Lake granodiorite. Wooden and Mueller (1988) have
shown that, within analytical uncertainty, the initial Nd-
,
The magmatic underplating event

That major contiguous rock units of diverse composition consistently share the same isotopic characteristics requires ultimate derivation of the parental magmas from a common (enriched) mantle-source region over a period of at least 110 m.y. Furthermore, it requires that a significant thickness of crust, from which the granitoids were derived by a second-stage process, was still so young that the Pb-isotopic system had not undergone detectable in situ evolution. Regional thermal anomalies of comparable duration have been suggested by several studies. (1) McKenzie and Weiss (1975) argued that 100 m.y. is an appropriate time scale for mantle convection and the dissipation of thermal anomalies in the upper mantle. (2) Cobbing and Pitcher (1983) found plutonic replacement to span at least 70 m.y. in the Lima segment of the Coastal batholith of Peru. (3) Campbell and Hill (1988) suggested that a thermal anomaly of 100-m.y. duration, caused by a series of widespread partial-melting events within the mantle, led to development of the granite-greenstone terranes of the Kalgoorlie-Norseman area, Western Australia. Finally, (4) Mezger et al. (1990) have suggested that episodic magmatic activity over a period of 100 to 120 m.y. is directly responsible for the development of regional granulite terranes.

We suggest that the rocks of the Late Archean igneous suite and Stillwater Complex were part of a major magmatic-underplating/crust-forming event of more than 100-m.y. duration. This event followed an indeterminate period of time required for subduction(?), generation of a relatively homogeneous, enriched mantle prism, and, before 2810 Ma, sufficient crustal evolution of the lower to middle crust to allow generation of granodioritic to granitic magmas, as products of either fractional crystallization or partial melting of newly solidified crust derived from enriched mantle. Mechanical underplating of lithospheric slabs could have occurred during the events that generated the enriched mantle wedge or as an accompaniment to magmatic underplating. Although mechanical underplating may facilitate some aspects of Nd- and Os-isotopic interpretation, we focus here on the magmatic aspects of underplating as it relates to formation of the Stillwater Complex.

Proposal of a magmatic-underplating event of long duration gains support from recent studies by Bohlen and Mezger (1989) and Mezger et al. (1990). On the basis of U-Pb age data for zircon, garnet, monazite, titanite, and rutile, Mezger et al. (1990) found clear evidence that major discrete magmatic events at about 2740, 2700, 2640, and 2600 Ma were responsible for driving metamorphic reactions and partial melting in Archean granulites of the Pikwitonei domain, Manitoba, Canada. Similar relations between metamorphism and the influx of mafic to felsic magmas into the lower crust have been deduced recently in the Adirondacks by K. Mezger et al. (unpublished data, 1989), who have documented magmatic/metamorphic
episodes at about 1150, 1070, and 1035 Ma. A notable similarity exists between the number of, and the intervals between, episodic magmatic events in the Pikwitonei and Adirondack granulite terranes and those of the Stillwater area (noted above at approximately, 2810, 2790, 2740, and 2700 Ma). Bohlen and Mezger (1989) have suggested that such episodic magmatic underplating is responsible for the addition of 10–40 km of material to the base of the existing crust. The role of magmatic accretion beneath existing continental material, as opposed to lateral accretion of arc material at continental margins, may have been underestimated as an important mechanism for the growth of the continental crust.

On the basis of the magmatic-underplating model, we suggest that the Stillwater area underwent a long period of magmatic activity preceding emplacement of the various components of the complex itself. The evolution of such a section of crust, thickened substantially by episodes of magmatic underplating, could well encompass fractionation of mafic magma in a reservoir near the crust/mantle interface. Although proposed as a model for floodbasalt volcanism, the ideas of Cox (1980), cartooned in his Figure 7, are similar to ours. Analysis of xenolith suites and considerations of the density and rheology of the lower crust led Griffin and O’Reilly (1987, p. 428–429) to conclude that large volumes of basaltic magma pond at the petrological Moho and form layered cumulate complexes. It was long held that all of the magmas parental to the Stillwater Complex were derived directly from the mantle. The two-magma hypothesis of Todd et al. (1982) was the first to suggest that a crustal component may have been significant in magmas parental to the complex. We now suggest that a major staging chamber, analogous to the Stillwater magma chamber, existed near the crust/mantle interface.

Three principal complexities of Stillwater Complex petrology would be dramatically influenced by, and may indeed suggest the existence of, a lower-crustal staging chamber. (1) A mechanism is provided for generation of the two major anorthosite zones that so uniquely characterize the Stillwater Complex. Anorthosite zones I and II (AN I and II) virtually require a lower-crustal staging chamber in which to crystallize and collect large volumes of plagioclase for subsequent intrusion as crystal-rich magma. (2) A source is provided for magmas with isotopic characteristics distinct from those of the so-called Uo parental magmas. These characteristics need not be restricted to magmas of proposed A0 composition. Uo magmas would have equilibrated with garnet-bearing rocks in the mantle and A-type magmas with plagioclase-bearing rocks in the lower crust, consistent with data that show that calculated A-type magmas are less LREE enriched and not HREE depleted (Lambert and Simmons, 1988; Lambert et al., 1989b). (3) An additional processing stage can be considered in models for evolution of the PGE-enriched J-M Reef and, possibly, for the Stillwater chromitites. Current models for formation of the reef fall into three groups. Campbell et al. (1983) and Barnes and Naldrett (1986) have called upon vigorous buoyant injection of fresh magma, followed by turbulent magma mixing to allow scavenging of PGEs from large magma volumes. The injections are suggested by Campbell et al. to have been picritic in composition and by Barnes and Naldrett to have been high-pressure (10-kbar) differentiates of Uo parental magma. Boudreau et al. (1986) and Boudreau (1988) have suggested that Cl-rich fluids traversed great thicknesses of ultramafic cumulates to provide the PGE concentrations of the J-M Reef. Finally, the double-diffusive convection model of Irvine et al. (1983) is predicated on the existence of geochemically distinct magmas. Lambert and Simmons (1987, 1988) and Lambert et al. (1989a, 1989b) have presented REE and isotopic data that support the interpretation that mixing of distinct magma types was related to reef formation. Moreover, the data of Lambert et al. (1989a) suggest that A-signature magmas were injected into the chamber during development of the chromitite seams of the Ultramafic series.

THE ANORTHOSITE PROBLEM

Hess (1960) first called attention to the Stillwater “anorthosite problem,” to which he devoted 3½ pages of discussion. The two major anorthosite zones of the Stillwater Complex constitute 1,000 m of the 4,500-m thickness of the Banded series in the Contact Mountain section—nearly 18% of the total exposed thickness of the complex. Five additional anorthosite subzones form 20- to 90-m-thick layers in associated Olivine-bearing zones II, IV, and V. AN I is near the middle of the exposed Stillwater Complex, with more than 2,500 m of cumulates preserved above it, and AN II is overlain by more than 1,000 m of cumulates. An indeterminate thickness of strata is missing from the top of the steeply tilted complex.

No modern model for the origin of these anorthosites within the Stillwater magma chamber is more reasonable than that proposed by Hess (1960). He suggested that once plagioclase became a liquidus phase (defining the base of the Banded series), buoyant plagioclase crystals and rejected solute were continually displaced from the chamber floor by convective overturn of denser magma. These plagioclase crystals were suggested to have been resorbed upon mixing with hotter, undifferentiated magma in the central part of the chamber, creating a layer of magma enriched in plagioclase constituents. In passing, Morse (1986a, 1986b, 1988) has alluded to, if not endorsed, this theory in terms of “a metastable polymerized layer of buoyant RS” (rejected solute). Hess rejected the idea (later championed by Raedeke, 1982) that the anorthosite zones represent a plagioclase-crystal accumulation that complements the Ultramafic series, reasoning that such a process could not be so thoroughly effective that no trapped cumulus plagioclase is to be found in the Ultramafic series. A major problem with both the poly-
merized-liquid and buoyant-crystal-accumulate models is that there are two virtually indistinguishable, major anorthosite zones and five lesser anorthosite subzones. AN I is 370 m thick and AN II 630 m thick; the two are separated by the 700-m-thick sequence of typical Stillwater cumulates containing cumulus pyroxene and olivine that form Olivine-bearing zones III and IV. The two-magma hypothesis adds significant complexity to contemplation of the development and persistence of a proposed liquid or crystal-accumulate layer.

As applied to the Stillwater Complex, the two-magma hypothesis was developed initially to explain the origin of the J-M Reef and broadened into an entirely new view of the petrologic and stratigraphic evolution of the complex (e.g., Todd et al., 1982; Irvine et al., 1983). In our opinion, no presentation of this model effectively deals with the scale of the “anorthosite problem.” How can a model that postulates generation of the J-M Reef upon the first substantial injection of An liquid account for the Stillwater anorthosites? To our knowledge, only Todd et al. (1979, p. 467) have implicitly acknowledged that formation of the major anorthosite zones is a problem distinct from that of formation of Olivine-bearing zone I; they suggested that “a third primitive melt . . . could be parental to the very thick (500+ m) anorthosite layers observed higher in the stratigraphic section.” It seems inconceivable to us that introduction of any new liquid could promote in situ crystallization of 370- and 630-m-thick layers of plagioclase cumulates that contain 85 to 95 vol% plagioclase and vary insignificantly in composition. McCallum et al. (1980) were among the first to reject the idea that subtleties in the curvature or relative orientation of phase boundaries as a function of P, T, and X would drive liquids along paths that could account for the volume of plagioclase cumulate in the two thick anorthosite zones by magma mixing (Irvine, 1975; Todd et al., 1982; Irvine et al., 1983). Moreover, large plagioclase grain size, glomerocrysts, complex zoning patterns, and other characteristics noted below are difficult to explain by in situ crystallization upon mixing of dissimilar magmas.

On the basis of textures and field observations, Scheidle et al. (1982), Scheidle (1983), and Czamanske and Scheidle (1985) proposed that AN I and II were emplaced into the evolving magma chamber as crystal-laden mushes. They noted such features as the transgressive basal contacts of the two units and the presence of finer-grained, commonly laminated facies at these contacts. Additional features of the major anorthosite zones that are fully compatible with, if not suggestive of, emplacement as plagioclase-laden intrusions are as follows.

1. The anorthosite zones and subzones contain no mafic crystals recognizable as cumulus, but are true plagioclase cumulates containing 7 to 16 mol% normative mafic minerals (Czamanske and Scheidle, 1985, Table 2). Despite extensive search, including grain-size measurements on outcrops, no grain-size or modal layering of even a discontinuous character has been discerned within AN I and II; typical specimens from the two zones are indistinguishable.

2. Although they show substantial variation in thickness, AN I and II show little variation in major- and minor-element chemistry in over 80 samples taken in traverses as much as 35 km apart along the strike length of the complex. Because plagioclase concentrates Eu and Sr, one might expect in situ crystallization to cause larger Eu anomalies and lesser Sr concentrations in stratigraphically higher samples. Neither relation is detected; Sr contents for over 60 plagioclase separates range from 160 to 200 ppm with no correlation to stratigraphy.

3. Plagioclase grains in the anorthosite zones are predominantly 2–3 times larger than those in adjacent cumulates, although a wide range of sizes is typical (Czamanske and Scheidle, 1985, Fig. 7). Because of this feature and the fact that plagioclase grains commonly form complex glomerocrysts, the anorthosites are texturally distinct from other rocks in the complex.

4. Typically, plagioclase grains are complexly zoned over 6 to 10 mol% An (Czamanske and Scheidle, 1985, Figs. 9 and 10). The best estimate for the average An content of plagioclase within AN I and II—based on electron-microprobe analyses, edxrf analyses of plagioclase separates, and normative An calculations from whole-rock analyses—is 78 ± 1 mol%, with no more than 1 mol% difference between the two zones. There is no recognizable variation in plagioclase composition as a function of stratigraphy within either zone.

5. Significant thicknesses of cumulus plagioclase were immersed in an interstitial liquid phase, as reflected by infallen blocks of overlying cumulates and apparent dissolution along grain boundaries (Czamanske and Scheidle, 1985, Figs. 4 and 9). Morse (1986a) indicated that a thick, unconsolidated cumulus pile is anomalous in layered intrusions; it could have resulted from intrusion of a crystal-laden mush.

6. The two most conspicuous sulfide-bearing horizons in the entire Banded series occur just beneath the upper contacts of AN I and II (the horizon at the top of AN II is the PGE-enriched Picket Pin zone; Boudreau and McCallum, 1986). (In contrast, outcrops of the JM Reef are virtually unrecognizable.) Concentration of sulfide-bearing fluids at the upper contact of a sill-like intrusion is an attractive explanation for these horizons. Notable are the transgressive pipelike concentrations of disseminated sulfide that occur as much as 150 m below the Picket Pin zone.

7. Loferski (1986) concluded from study of multiphase inclusions within plagioclase grains that the liquid from which the plagioclase crystallized was unusual in composition. The inclusions themselves have a mineralogy reminiscent of nelsonite, a common ilmenite + apatite-rich component of anorthosite massifs.

8. On the basis of trace- and REE-element anomalies, Salpas et al. (1983) concluded that the intercumulus pyroxene in the anorthosites has a cumulus-adcumulus chemical signature and cannot represent “typical” trapped
liquid. They found AN I and II to be impressively depleted in trace elements and concluded that these plagioclase cumulates contain less than 1 vol% of a trapped-liquid component. They noted that evidence for little vertical evolution in plagioclase or trace-element compositions suggests derivation of the anorthosites from a huge volume of magma that is prohibitively difficult to dispose of. Several of the “enigmas” detailed by Salpas et al. are readily addressed if AN I and II represent discrete intrusions into the Stillwater magma chamber.

With an average composition of An_{78}, the Stillwater anorthosites are comparatively calcic, though well within the range observed for Archean anorthosites. The higher An content of Archean anorthosites relative to those of Proterozoic and younger age is well established (Windley, 1973; Ashwal and Burke, 1987). We suggest that this characteristic may simply reflect the fact that the pre-2.5-Ga mantle was hotter than the Proterozoic mantle, leading to production of more mafic melts, including komatiites. Arndt et al. (1986) have suggested that in the Archean, the average mantle temperature at 100- to 120-km depth was 1600 °C, in comparison with 1350 °C estimated for the present-day mantle. However, Jarvis and Campbell (1983), Campbell and Jarvis (1984), and Campbell et al. (1989) have argued convincingly that the Archean mantle may have been, on average, only 100 °C hotter and that komatiites are the products of Archean mantle plumes. [Interpreting Campbell et al. (1989), we note in passing that the Nd-isotopic distinction of U- and A-type magmas could result if different plumes or parts of plumes were tapped into the crust/mantle chamber versus directly into the Stillwater magma chamber.]

The idea that plagioclase crystal mushes might be mobilized to migrate upward from deep-seated magma chambers is by no means novel; it was suggested more than 20 years ago by Yoder (1968) and developed by Emslie (1978). Uniquely proposed here, however, is that enormous volumes of anorthositic magma carrying crystalline plagioclase repetitively followed a pathway that “accidentally” entered the evolving Stillwater magma chamber. Proterozoic massif-type anorthosites have relatively thin, sheetlike or slablike forms of broad horizontal extent, and construction by multiple intrusion is considered an important feature of their origin (Emslie, 1978). Emslie concluded from study of anorthosite massifs that a deep source region, near or below the base of a cratonic crust, maintained its integrity over considerable time.

Yoder (1968) showed that subsolidus reaction of plagioclase with orthopyroxene or olivine at high pressure restricts the generation of anorthosite to crustal environments (<35-km depth). Fuji and Kusihio (1977) showed that plagioclase of composition An_{58} becomes increasingly buoyant in olivine tholeiite at pressures above 4 kbar. Phinney et al. (1981) and Phinney (1982) noted that the overall major- and trace-element compositions of Archean anorthosite complexes do not relate well to known volcanic compositions, and they suggested that substantial volumes of complementary mafic cumulates remain at depth. They proposed that melts of these komatiitic composition accumulated and commenced fractional crystallization at the base of the crust; eventually, plagioclase formed as a cotectic phase, accumulated, and was brought up in melts carrying diverse crystal concentrations. That plagioclase in the Stillwater anorthosite zones has a compositional range similar to that of plagioclase in the surrounding cumulates indicates, not surprisingly, that the magma in the lower-crustal chamber had a bulk composition comparable to that of magmas that crystallized entirely within the Stillwater magma chamber.

Following arguments of Wetherill (1975), Longhi and Ashwal (1985) proposed that the anorthositic lunular crust was formed by remobilization of anorthositic diapirs from multiple overlapping layered complexes in the outer 200 km of the Moon. In passing, they further proposed “that many Proterozoic anorthosite massifs formed as the result of multiple diapiric intrusions of plagioclase-rich crystalline mushes detached from magma chambers ponded in the lower crust or at the crust/mantle boundary. The diapirs would have developed from layers of suspended plagioclase in the upper portions of these chambers.” Ashwal and Wiebe (1989) have shown that the plagioclase in several Proterozoic anorthosite massifs is isotopically primitive in comparison with paragenetically later pyroxene. They have proposed that deep-crustal ponding allowed fractional crystallization of plagioclase and that the residual melt that accompanied ascent of this suspended plagioclase experienced crustal contamination. Although the idea was first suggested by Romey (1968), Ashwal and Burke (1987) re-emphasized that there may be a continuum of processes relating massif-type anorthosites and the anorthosites of layered mafic intrusions, and they reiterated that Proterozoic massif-type anorthosites may represent “floatation cumulates” from mantle-derived melts, which ascended as mushes to upper-crustal emplacement sites. Miller and Weiblen (1990) have suggested fractionation of mafic phases and equilibration of plagioclase in a lower-crustal to subcrustal magma chamber, with subsequent emplacement of plagioclase-rich magmas, as a model for the generation of anorthositic rocks in the Duluth Complex.

We acknowledge the contribution of Taylor et al. (1984) and its possible relevance to the problem at hand. They proposed that Proterozoic massif-type anorthosites may have evolved from partial melting of an aluminous lower-continental crustal residuum that developed by extraction of granitic melt during an earlier period of intra-crustal melting. Ian Campbell (oral communication, 1989) has argued that the plagioclase-laden melts that we envision as having been intruded into the Stillwater magma chamber also could have originated in this manner. Our prejudice against this possibility stems from the An-rich composition of Stillwater plagioclase, the complex normal and reverse zoning patterns displayed by large plagioclase grains, and the trace-element composition of this plagioclase. Concentrations of Pb (0.16 to 0.28 ppm), Th (~0.08 ppm), and U (~0.02 ppm) are very low in the
plagioclase of the Stillwater anorthosites and comparable to those in plagioclase in the remainder of the complex (Wooden, et al., 1990). Calculated Th/U ratios are about 4 for all analyzed plagioclase from the complex. In contrast, granitoids of the Late Archean igneous suite have Pb contents ranging from 21 to 45 ppm and Th/U ratios ranging from 4.7 to 26.5 (Wooden and Mueller, 1988).

CONCLUSIONS

Whereas students of massif anorthosites have longed to associate them with a mafic complement, association of the Stillwater anorthosites with the mafic cumulates of the complex has led to no better understanding of their origin. Instead, we find the evidence persuasive that the Stillwater anorthosites represent concentrations of plagioclase from a vast staging chamber near the crust/mantle interface. Indeed, were they not an integral part of the complex stratigraphy, they would seem little challenge to this proposal. No alternative proposal satisfactorily accounts for many significant features of the complex stratigraphy, including chromite and PGE deposition.

ACKNOWLEDGMENTS

We thank Lew Ashwal, Ian Campbell, Richard Carlson, Fred Barker, Floyd Gray, David Lambert, Klaus Mezger, Stephen Moorbath, Norman Page, Craig Simmons, and Michael Zientek for their helpful reviews of the manuscript, but absolve them of responsibility.

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MANUSCRIPT RECEIVED June 5, 1989
MANUSCRIPT ACCEPTED September 29, 1989