American Mineralogist, Volume 75, pages 37–45, 1990

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

GERALD K. CZAMANSKE, STEVEN R. BOHLEN
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, U.S.A.

ABSTRACT

The Stillwater Complex, emplaced 2700 ± 40 Ma, is exposed at the edge of a 4000-km^2 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 mineralogic 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-stratabound 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 A_0 magma with olivine- or pyroxene-saturated, U_0 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. U_0 parental magma (olivine boninite) was considered to be relatively rich in MgO and SiO_2 relative to midoceanic-ridge basalt, enriched in light rare-earth elements (LREEs), and depleted in heavy rare-earth elements (HREEs); the proposed A_0 magma (silica-undersaturated high-alumina basalt) contained less MgO and more Al_2O_3, was less LREE enriched, and was not HREE depleted. On the basis of detailed study of the system CaO-MgO-Al_2O_3-SiO_2, Irvine and Sharpe (1982) found "rather compelling indications that U_0 liquids came from deep in the upper mantle (from perhaps 180–200 km), whereas the A_0 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 U_0 magma and, along with REE contents, are strongly de-

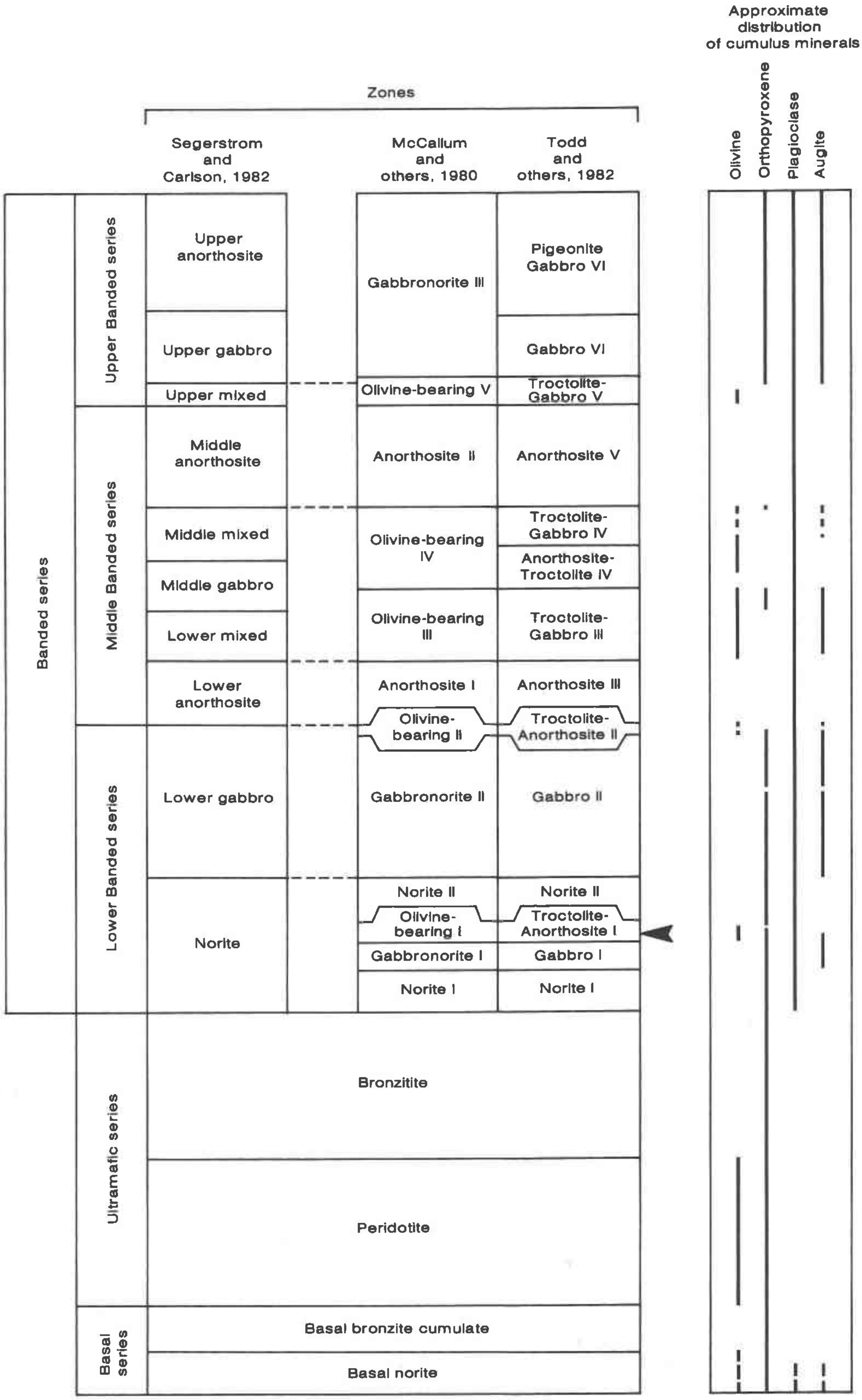

Fig. 1. Subdivisions of Stillwater Complex stratigraphy and approximate stratigraphic distribution of cumulus minerals. Arrow marks location of the J-M Reef. After Zientek et al. (1985).

pendent on degree of partial melting and relative depletion of the mantle source. The origin of U_0 magmas at these shallower depths by hydrous partial melting may be more compatible with isotopic indications for a subduction-enriched mantle.

Workers in the Bushveld Complex, from which the compositions of the U_0 and A_0 liquids had been inferred (Irvine and Sharpe, 1982), were able to establish from initial 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 indications that generation of the A_0 magma involved crustal interaction and the great sensitivity of Pb-isotopic measurements for detecting crustal contamination in Archean rocks, Pb-isotopic analyses were obtained for plagioclase separates from a comprehensive suite of Stillwater cumulates. It was hoped that some light would be shed on the origin of the Stillwater anorthosites. The results indicate 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 Gabbronorite I, DePaolo and Wasserburg (1979) reported a precise mineral-isochron age of 2701 ± 8 Ma and an initial Nd-isotopic composition of $\epsilon_{Nd} = -2.8 \pm 0.2$ for the Stillwater Complex. On the basis of five whole-rock analyses that fell on this mineral isochron, 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 appear to preclude formation of the intrusion from a single, isotopically homogeneous magma. Initial ϵ_{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 significant heterogeneities in initial Os-isotopic composition and imply that two magmas of distinct Os-isotopic composition contributed to the complex; however, the variations do not correlate well with the Nd-isotopic variations, especially within the lower Ultramafic series. Lambert et al. (1989a) noted that (1) Nd- and Os-isotopic data for U-type cumulates are consistent with enrichment of a mantle source by about 9% of recycled Early to Middle Archean continental crust approximately 500 m.y. older than the Stillwater Complex and (2) a short, lower-crustal residence time for juvenile basalt could account for the apparently high initial Os-isotopic composition of A-type cumulates, while preserving the relatively high $^{143}Nd/^{144}Nd$ ratio inherited from the mantle source. Both Nd- and Os-isotopic data suggest that in situ contamination of the Stillwater magmas was insignificant, except in restricted parts of the complex.

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 injection of magmas derived by multistage dynamic partial melting of a garnet-bearing source extremely enriched in LREEs. 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 crystallized from magmas that were distinctly less LREE enriched, 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 ϵ_{Sr} values range from −1.0 to +34.0 in Banded series cumulates and from impossibly low values of −260 to −13.1 in Ultramafic series cumulates. They estimated an initial Sr-isotopic ratio of 0.70200 to 0.70235 (ϵ_{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. Corroborating 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 combination 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 contamination as the cause for any significant petrologic or trace-element complexity observed in the Stillwater Complex (Wooden et al., 1990). Because the A_0 magmas had Pb-isotopic compositions virtually indistinguishable from those of the mantle-derived U_0 magmas, they could have been derived by partial melting of mafic rocks (Irvine and Sharpe, 1982) that were relatively new components 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 systematics cannot resolve crustal- from mantle-source rocks if crustal residency has been short.

The Late Archean igneous suite of the eastern Beartooth Mountains consists of three units that crop out over more than 4000 km² (in decreasing volumetric importance): Long Lake granite, andesitic amphibolite, and Long Lake granodiorite. Wooden and Mueller (1988) have shown that, within analytical uncertainty, the initial Nd-,

TABLE 1. Comparison of initial isotopic characteristics of the Stillwater Complex, the Late Archean igneous suite, and the Mouat quartz monzonite

	Stillwater Complex*	Late Archean igneous suite*	Mouat quartz monzonite*
$^{206}Pb/^{204}Pb$	13.95 (1)	13.86 (5)	15.65 (1)
$^{207}Pb/^{204}Pb$	14.95–15.01 (1)	14.96 (5)	15.49 (1)
$^{208}Pb/^{204}Pb$	33.6 (1)	34.0 (5)	34.95 (1)
ϵ_{Nd}	−2.8 ± 0.2 (2) −3.2 to +1.7 (3)	−3.2 to −1.5 (5)	—
$^{87}Sr/^{86}Sr$	0.70200–0.70235 (4)	0.7022 ± 0.0002 (5)	—

* References, given by numbers in parentheses, are (1) Wooden et al. (1990), (2) DePaolo and Wasserburg (1979), (3) Lambert et al. (1989a), (4) Lambert et al. (1989b), and (5) Wooden and Mueller (1988).

Pb-, and Sr-isotopic characteristics of these compositionally diverse units are identical and remarkably similar to those of the Stillwater Complex (Table 1). Wooden and Mueller (1988) and Wooden et al. (1989) have argued that radiogenic upper-crustal contamination was not a significant factor in the origin of the Late Archean igneous suite, which was emplaced in crust as old as 3.4 b.y. They have proposed that the radiogenic character of the Late Archean igneous suite was derived from subcontinental mantle that had been enriched by subduction of older continental detritus. Additional support for an enriched Late Archean mantle beneath the region is provided by study of Tertiary basalts (e.g., Menzies et al., 1983; Hart, 1985).

Wooden and Mueller (1988) reported U-Pb zircon ages for units of the Late Archean igneous suite as follows: Long Lake granite, 2739 ± 25 Ma; Long Lake granodiorite, 2783 ± 3 Ma; and andesitic amphibolite, 2789 ± 5 Ma. Recent work by Fred Barker and Paul Mueller (oral communication, 1989) shows that meta-andesite dikes cut the oldest members of this suite, for which a U-Pb zircon age of 2810 Ma has been obtained. The granitoids of this suite must have originated by partial melting of more mafic, lower- to middle-crustal rocks that were derived from enriched mantle and had a relatively short crustal-residence time. Wooden et al. (1989) noted that the REE data require genesis of the granitoid rocks at crustal P and T with involvement of plagioclase and that relations among Na, K, Si, and various trace elements strongly favor an origin by partial melting of a mafic source that contained residual amphibole or clinopyroxene.

The final relevant igneous event in the Late Archean of the eastern Beartooth Mountains was intrusion of the composite Mouat quartz monzonite at 2700 Ma (Nunes and Tilton, 1971). Isotopic ratios for the Mouat quartz monzonite, which intrudes the southeastern margin of the Stillwater Complex, are unique among the Late Archean granitoids (Table 1) and indicate that only immediately after intrusion of the Stillwater Complex is there evidence for melting of distinctly radiogenic older crust.

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 emplacement 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 cratonic evolution of the lower to middle crust to allow generation of granodioritic to granitic magmas, as products of either fractional crystallization or partial remelting 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 boundary. Although proposed as a model for flood-basalt 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 U_0 parental magmas. These characteristics need not be restricted to magmas of proposed A_0 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 U_0 parent 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 1000 m of the 4500-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 1000 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 polymerized-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 A_0 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). Fujii and Kushiro (1977) showed that plagioclase of composition An_{78} 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 tholeiitic to komatiitic composition accumulated and commenced fractionation 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 lunar 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 "flotation 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 intracrustal 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 well-layered stratigraphy of the Stillwater Complex, there seemingly would be little challenge to this proposal. No alternative proposal satisfactorily accounts for many significant features of AN I and II or addresses the fact that these two vast sheets of plagioclase cumulate are separated by a 700-m thickness of typical Stillwater cumulates and occur well down in the stratigraphy of the complex. The staging chamber is conceived as a transient component of new crust formed by extensive magmatic underplating. Virtually all known details of Stillwater isotopic and trace-element systematics are accommodated by derivation of the anorthosite sheets from such a chamber. These data are compatible with derivation of A_0 magmas from the same, or a comparable, chamber. Our conclusions in no way challenge those of the numerous studies that call upon intrachamber interaction of two magma types as an explanation for many features of Stillwater 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.

References cited

Arndt, N.T., Bickle, M.J., Jenner, G.A., Nisbet, E.G., and Zindler, A. (1986) The nature and composition of the Archean mantle (meeting report). EOS, 67, 173–174.

Ashwal, L.D., and Burke, K. (1987) Types and characteristics of terrestrial anorthosites. In Eighteenth Lunar and Planetary Science Conference Abstracts of Papers, 34–35.

Ashwal, L.D., and Wiebe, R.A. (1989) Isotopic disequilibrium in the internal Sm-Nd and Rb-Sr systematics of Proterozoic anorthosites. EOS, 70, 486.

Barnes, S.J., and Naldrett, A.J. (1986) Geochemistry of the J-M Reef of the Stillwater Complex, Minneapolis adit area. II. Silicate mineral chemistry and petrogenesis. Journal of Petrology, 27, 791–825.

Bohlen, S.R., and Mezger, K. (1989) Origin of granulite terranes and the formation of the lowermost continental crust. Science, 244, 326–329.

Boudreau, A.E. (1988) Investigations of the Stillwater Complex. IV. The role of volatiles in the petrogenesis of the J-M Reef, Minneapolis adit section. Canadian Mineralogist, 26, 193–208.

Boudreau, A.E., and McCallum, I.S. (1986) Investigations of the Stillwater Complex: Part III. The Picket Pin Pt/Pd deposit. Economic Geology, 81, 1953–1975.

Boudreau, A.E., Mathez, E.A., and McCallum, I.S. (1986) Halogen geochemistry of the Stillwater and Bushveld Complexes: Evidence for transport of the platinum-group elements by Cl-rich fluids. Journal of Petrology, 27, 967–986.

Campbell, I.H., and Hill, R.I. (1988) A two-stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia. Earth and Planetary Science Letters, 90, 11–25.

Campbell, I.H., and Jarvis, G.T. (1984) Mantle convection and early crustal evolution. Precambrian Research, 26, 15–56.

Campbell, I.H. Naldrett, A.J., and Barnes, S.J. (1983) A model for the origin of the platinum-rich sulfide horizons in the Bushveld and Stillwater Complexes. Journal of Petrology, 24, 133–165.

Campbell, I.H., Griffiths, R.W., and Hill, R.I. (1989) Melting in the Archean mantle: Heads its basalts, tails its komatiites. Nature, 339, 697–699.

Cobbing, E.J., and Pitcher, W.S. (1983) Andean plutonism in Peru and its relationship to volcanism and metallogenesis at a segmented plate edge. Geological Society of America Memoir 159, 277–291.

Cox, K.G. (1980) A model for flood basalt vulcanism. Journal of Petrology, 21, 629–650.

Czamanske, G.K., and Scheidle, D.L. (1985) Characteristics of the Banded-series anorthosites. In G.K. Czamanske and M.L. Zientek, Eds., The Stillwater Complex, Montana: Geology and guide. Montana Bureau of Mines and Geology Special Publication 92, 334–345.

Czamanske, G.K., and Zientek, M.L., Eds. (1985) The Stillwater Complex, Montana: Geology and guide. Montana Bureau of Mines and Geology Special Publication 92, 394 p.

Czamanske, G.K., Wooden, J.L., and Zientek, M.L. (1986) Pb isotopic data for plagioclase from the Stillwater Complex (abs.). EOS, 67, 1251.

DePaolo, D.J., and Wasserburg, G.J. (1979) Sm-Nd age of the Stillwater Complex and the mantle evolution curve for neodymium. Geochimica et Cosmochimica Acta, 43, 999–1008.

Emslie, R.F. (1978) Anorthosite massifs, rapakivi granites, and Late Proterozoic rifting of North America. Precambrian Research, 7, 61–98.

Fenton, M.D., and Faure, G. (1969) The age of the igneous rocks of the Stillwater Complex of Montana. Geological Society of American Bulletin, 80, 1599–1604.

Fujii, T., and Kushiro, I. (1977) Density, viscosity, and compressibility of basaltic liquid at high pressures. Carnegie Institution of Washington Year Book, 76, 419–424.

Griffin, W.L., and O'Reilly, S.Y. (1987) The composition of the lower crust and the nature of the continental Moho—Xenolith evidence. In P.H. Nixon, Ed., Mantle xenoliths, p. 413–430. Wiley, New York.

Harmer, R.E., and Sharpe, M.R. (1985) Field relations and strontium isotopic systematics of the marginal rocks of the eastern Bushveld Complex. Economic Geology, 80, 813–837.

Hart, W.K. (1985) Chemical and isotopic evidence for mixing between depleted and enriched mantle, northwestern U.S.A. Geochimica et Cosmochimica Acta, 49, 131–144.

Hess, H.H. (1960) Stillwater igneous complex, Montana—A quantitative mineralogical study. Geological Society of America Memoir 80, 230 p.

Irvine, T.N. (1975) Olivine-pyroxene-plagioclase relations in the system Mg_2SiO_4-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-SiO_2 and their bearing on the differentiation of stratiform intrusions. Carnegie Institution of Washington Year Book, 74, 492–500.

Irvine, T.N., and Sharpe, M.R. (1982) Source-rock compositions and depths of origin of Bushveld and Stillwater magmas. Carnegie Institution of Washington Year Book, 81, 294–303.

Irvine, T.N., Keith, D.W., and Todd, S.G. (1983) The J-M platinum-palladium Reef of the Stillwater Complex, Montana: II. Origin by double-diffusive convective magma mixing and implications for the Bushveld Complex. Economic Geology, 78, 1287–1334.

Jackson, E.D. (1961) Primary textures and mineral associations in the Ultramafic zone of the Stillwater Complex, Montana. U.S. Geological Survey Professional Paper 358, 106 p. [reprinted in 1984 as Montana Bureau of Mines and Geology Reprint 4].

——— (1967) Ultramafic cumulates in the Stillwater, Great Dyke, and Bushveld intrusions. In P.J. Wyllie, Ed., Ultramafic and related rocks, p. 20–38. Wiley, New York [reprinted in 1979 by R.E. Krieger, Chicago, Illinois].

——— (1970) The cyclic unit in layered intrusions, a comparison of repetitive stratigraphy in the ultramafic parts of the Stillwater, Muskox, Great Dyke, and Bushveld Complexes [with discussion]. In D.J.L. Visser and G. von Gruenewaldt, Eds., Symposium on the Bushveld igneous complex and other layered intrusions. Geological Society of South Africa Special Publication 1, 391–424.

——— (1971) The origin of ultramafic rocks by cumulus processes. Fortschritte der Minéralogie, 48, 128–174.

Jarvis, G.T., and Campbell, I.H. (1983) Archean komatiites and geotherms: Solution to an apparent contradiction. Geophysical Research Letters, 10, 1133–1136.

Kistler, R.W., Obradovich, J.D., and Jackson, E.D. (1969) Isotopic ages of rocks and minerals from Stillwater Complex, Montana. Journal of Geophysical Research, 74, 3226–3237.

Lambert, D.D., and Simmons, E.C. (1987) Magma evolution in the Stillwater Complex, Montana: I. Rare-earth-element evidence for the formation of the Ultramafic series. American Journal of Science, 287, 1–32.

——— (1988) Magma evolution in the Stillwater Complex, Montana: II. Rare-earth-element evidence for the formation of the J-M Reef. Economic Geology, 83, 1109–1126.

Lambert, D.D., Morgan, J.W., Walker, R.J., Shirey, S.B., Carlson, R.W., Zientek, M.L., and Koski, M.S. (1989a) Rhenium-osmium and samarium-neodymium isotopic systematics of the Stillwater Complex. Science, 244, 1169–1174.

Lambert, D.D., Walker, R.J., Shirey, S.B., and Carlson, R.W. (1989b) Magma evolution in the Stillwater Complex, Montana: REE, Sr, Nd and Os isotopic evidence for Archean lithospheric interaction. In L.D. Ashwal, Ed., Workshop on the Archean mantle. Lunar and Planetary Science Institute Technical Report 89-05, 53-56.

Loferski, P.J. (1986) Multiphase inclusions in plagioclase from the Stillwater anorthosites: Implications for REE geochemistry. International Mineralogical Association Abstracts with Program, 158.

Longhi, J., and Ashwal, L.D. (1985) Two-stage models for lunar and terrestrial anorthosites: Petrogenesis without a magma ocean. In Proceedings of the Fifteenth Lunar and Planetary Science Conference, pt. 2. Journal of Geophysical Research, 90, supplement C571–C584.

McCallum, I.S., Raedeke, L.D., and Mathez, E.A. (1980) Investigations of the Stillwater Complex: Part I. Stratigraphy and structure of the Banded zone. American Journal of Science, 280-A, 59–87.

McKenzie, D., and Weiss, N. (1975) Speculations on the thermal and tectonic history of the Earth. Royal Astronomical Society Geophysical Journal, 42, 131–174.

Menzies, M.A., Leeman, W.P., and Hawkensworth, C.J. (1983) Isotopic geochemistry of Cenozoic volcanic rocks reveals mantle heterogeneity below western USA. Nature, 303, 205–209.

Mezger, K., Bohlen, S.R., and Hanson, G.N. (1990) Metamorphic history of the Archean Pikwitonei granulite domain and the Cross Lake subprovince, Superior province, Manitoba, Canada. Journal of Petrology, in press.

Miller, J.D., Jr., and Weiblen, P.W. (1990) Anorthositic rocks of the Duluth Complex: Examples of rocks formed from plagioclase crystal mush. Journal of Petrology, in press.

Morse, S.A. (1986a) Thermal structure of crystallizing magma with two-phase convection. Geological Magazine, 123, 205–214.

——— (1986b) Convection in aid of adcumulus growth. Journal of Petrology, 27, 1183–1214.

——— (1988) Motion of crystals, solute, and heat in layered intrusions. Canadian Mineralogist, 26, 225–234.

Nunes, P.D., and Tilton, G.R. (1971) Uranium-lead ages of minerals from the Stillwater igneous complex and associated rocks, Montana. Geological Society of America Bulletin, 82, 2231--2249.

Phinney, W.C. (1982) Petrogenesis of Archean anorthosites. In Workshop on magmatic processes of early planetary crusts: Magma oceans and stratiform layered intrusions. Houston, Texas, Lunar and Planetary Institute Technical Report 82-01, 121–124.

Phinney, W.C., Morrison, D.A., and Ashwal, L.D. (1981) Implications of Archean anorthosites for crust-mantle evolution. In Twelfth Lunar and Planetary Science Conference Abstracts of Papers, 830–832.

Raedeke, L.D. (1982) Petrogenesis of the Stillwater Complex, 212 p. Ph.D. thesis, University of Washington, Seattle, Washington [see also Dissertation Abstracts International, 42, 4719-B].

Romey, W.D. (1968) An evaluation of some "differences" between anorthosite in massifs and in layered complexes. Lithos, 1, 230–241.

Salpas, P.A., Haskin, L.A., and McCallum, I.S. (1983) Stillwater anorthosites: A lunar analog? In Proceedings of the Fourteenth Lunar and Planetary Science Conference, pt. 1. Journal of Geophysical Research, 88, supplement, B27–B39.

Scheidle, D.L. (1983) Plagioclase zoning and compositional variation in Anorthosite I and II along the Contact Mountain traverse, Stillwater Complex, Montana, 112 p. M.S. thesis, Stanford University, Stanford, California.

Scheidle, D., Czamanske, G.K., and Wandless, G.H. (1982) Chemical and textural variations within anorthosite of the Middle-banded zone of the Stillwater Complex, Montana. EOS, 63, 1143.

Sharpe, M.R. (1985) Strontium isotopic evidence for preserved density stratification in the main zone of the Bushveld Complex, South Africa. Nature, 316, 119–126.

Shirey, S.B., and Hanson, G.N. (1984) Mantle-derived Archean monzodiorites and trachyandesites. Nature, 310, 222–224.

Stewart, B.W., and DePaolo, D.J. (1987) Sr-isotope stratigraphy of the Stillwater Complex, Montana: Evidence for multiple magma injections. EOS, 68, 429.

Tatsumi, Y. (1981) Melting experiments on a high-magnesian andesite. Earth and Planetary Science Letters, 54, 357–365.

——— (1982) Origin of high-magnesian andesites in the Setouchi volcanic belt, southwest Japan, II. Melting phase relations at high pressures. Earth and Planetary Science Letters, 60, 305–317.

Tatsumi, Y., and Ishizaka, K. (1982) Origin of high-magnesian andesites in the Setouchi volcanic belt, southwest Japan, I. Petrographical and chemical characteristics. Earth and Planetary Science Letters, 60, 293–304.

Taylor, S.R., Campbell, I.H., McCulloch, M.T., and McLennan, S.M. (1984) A lower crustal origin for massif-type anorthosites. Nature, 311, 372–374.

Todd, S.G., Schissel, D.J., and Irvine, T.N. (1979) Lithostratigraphic variations associated with the platinum-rich zone of the Stillwater Complex, Montana. Carnegie Institution of Washington Year Book, 78, 461–468.

Todd, S.G., Keith, D.W., LeRoy, L.W., Shissel, D.J., Mann, E.L., and Irvine, T.N. (1982) The J-M platinum-palladium Reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology. Economic Geology, 77, 1454–1480.

Wetherill, G.W. (1975) Possible slow accretion of the Moon and its thermal and petrological consequences. In Papers presented to the Conference on Origins of Mare Basalts and Their Implications for Lunar Evolution, p. 184–188. Lunar and Planetary Institute, Houston, Texas.

Windley, B.F. (1973) Archean anorthosites: A review. Geological Society of South Africa Special Publication 3, 319–332.

Wooden, J.L., and Mueller, P.A. (1988) Pb, Sr, and Nd isotopic compositions of a suite of Late Archean, igneous rocks, eastern Beartooth Mountains: Implications for crust-mantle evolution. Earth and Planetary Science Letters, 87, 59–72.

Wooden, J.L., Mueller, P.A., and Mogk, D.W. (1989) A review of the geochemistry and geochronology of the Archean rocks of the northern part of the Wyoming Province. In W.G. Ernst, Ed., Metamorphism and crustal evolution of the western United States. Rubey volume VII, p. 383–410. Prentice-Hall, Englewood Cliffs, New Jersey.

Wooden, J.L., Czamanske, G.K., and Zientek, M.L. (1990) Lead isotopic study of the Stillwater Complex, Montana: Constraints on crustal contamination and source regions. Contributions to Mineralogy and Petrology, in press.

Yoder, H.S., Jr. (1968) Experimental studies bearing on the origin of anorthosites. In Y.W. Isachsen, Ed., Origin of anorthosites and related rocks. New York State Museum and Science Service Memoir 18, 13–22.

Zientek, M.L., Czamanske, G.K., and Irvine, T.N. (1985) Stratigraphy and nomenclature for the Stillwater Complex. In G.K. Czamanske and M.L. Zientek, Eds., The Stillwater Complex, Montana: Geology and guide. Montana Bureau of Mines and Geology Special Publication 92, 21–32.

Manuscript received June 5, 1989
Manuscript accepted September 29, 1989